CLEANING AND RESTORING OLD MASONRY BUILDINGS — INVESTIGATIONS OF PHYSICAL AND CHEMICAL CHARACTERISTICS OF MASONRY STONES AND CLAY BRICKS DURING CLEANING

by

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PhD Thesis

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AUTHORSHIP DECLARATION

I, Humayun Reza, confirm that my dissertation and the work presented in it are my own achievement.

Where I have consulted the published work of others this is always clearly attributed.

Where I have quoted from the work of others the source is always given. With the exception of such quotations this dissertation is entirely my own work.

I have acknowledged all main sources of help.

If my research follows on from previous work or is part of a larger collaborative research project I have made clear exactly what was done by others and what I have contributed myself.

I have read and understood the penalties associated with plagiarism.

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ABSTRACT

Historic buildings and monuments are a precious finite asset and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The stone cleaning and restoration of historic buildings is a crucial element in keeping the good look, integrity and quality of the fine art, method of construction and architecture of previous civilisations. Stone cleaning is one of the most noticeable changes a building can be subjected to, which changes its appearance, persona and environmental context. In this study, a series of physical and chemical tests were conducted to further investigate, evaluate and improve the efficiency of building cleaning. Seven different abrasives were adopted for air abrasive cleaning, including copper slag (fine, medium and coarse), recycled glass (fine, medium and coarse) and hazelnut/almond shell (natural abrasive), on a total of eight masonry stones and clay bricks, including yellow sandstone, red sandstone, limestone, marble, granite, white clay brick, yellow clay brick and red clay brick.

Physical investigations included sieve tests and impact tests on the abrasives, greyscale image analysis, thickness reduction measurements, Vickers surface hardness tests, Charpy impact tests and water absorption tests. Chemical investigations included Scanning Electron Microscope (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDX) analyses.

Sieve tests and impact tests confirmed that the abrasives utilised were fairly reliable, and the abrasives with high bulk densities were stronger and tougher than those with low bulk density.

Greyscale digital image analysis indicated a lower greyscale value corresponded to a dirtier masonry surface. In general, the greyscale continuously increased with the increasing cleaning time and tended to be stable when the surface became fully cleaned. The cleanness was also introduced for assessing the effectiveness of the building cleaning. Similar trends could be observed. Both parameters proved to be significantly useful.

For most of the samples, monotonic increase trends were observed between the greyscale and thickness reduction. The image analysis on greyscale and the thickness measurement were two useful methods for assessing the cleaning degree of a masonry stone or clay brick. Based on the analysis on all the testing data, it is possible to recommend a more suitable abrasive for each masonry stone or brick. For granite and red clay brick, medium glass produced the best performance, while for limestone, marble and red sandstone, fine glass was promising. For yellow clay brick, fine slag could be the best option, while for yellow sandstone the natural abrasive was found to be the most suitable.

The Vickers hardness test results indicated that a larger hardness corresponded to a harder masonry surface. Also the surface hardness continuously increased with the increasing cleaning time but at a decrease rate. Most of the increasing trends of the surface hardness could be approximately expressed using parabolic relationships. Granite was found to be the hardest, and followed by marble and limestone. However, there were no big differences in the surface hardness between yellow clay brick, yellow sandstone, red sandstone and white clay brick.

The impact resistances of seven masonry stones and bricks were obtained by conducting the Charpy impact resistance tests. Granite showed the highest impact resistance among all the stones and bricks and was followed by marble, limestone, clay bricks and sandstones. The stones and bricks with higher impact resistances also had higher hardness values but lower water absorptions.

The water absorbing capacity of the seven masonry stones and bricks was quantitatively determined. Two types of clay bricks showed the highest water absorptions, and the water absorptions for limestone, yellow sandstone and red sandstone were also quite high. However, the water absorption of marble and granite was found to be very low. Larger water absorption corresponded to a softer stone or brick, while smaller water absorption corresponded to a harder stone or brick.

The chemical investigations by using the SEM and EDX techniques showed that the chemical substances on the masonry surface varied largely for different types of stones and bricks. This study showed the way to detect such soiling using chemical analysis by monitor the changes in chemical elements and compounds during the building cleaning.

Finally, comprehensive conclusions were presented, together with useful suggestions for future work.

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CHAPTER 1 INTRODUCTION

1.1 Overview of Restoration and Cleaning of Historic Buildings

Historic buildings and monuments are precious finite assets and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The stone cleaning and restoration of old and historic buildings is a crucial element in keeping the good look, integrity and quality of the fine art, method of construction, and architecture of previous civilisations.

Stone cleaning is one of the most noticeable changes a building can be subjected to and changes its appearance, persona and environmental context. A clean building can reflect well on the occupants. Stone cleaning has been dated back for over 40 years, peaking in the 1970s and 1980s and growing into a multimillion pound industry (Laing and Urquhart 1997; Ball et al 2000; Ball 2002; Feilden 2003). At this time the cleaning was, however, inappropriately aggressive, causing damage to many historic structures. Poor or inappropriate selected methods of cleaning or the right method performed by unskilled operatives can lead to permanent damage to the structures of a building. The correct choice of mortar for restoration work is also important to the life of stones in a masonry building by stopping the damage caused by stone decay. A decision to clear or repair a historic building must be undertaken only if there is a strong reason to do so. Preliminary investigations have to be carried out first before deciding on the best method of cleaning and right type of mortar for repair to avoid any unnecessary damage to the building (Historic Scotland 1991, 1994; Ashurst 1994a, 1994b).

Cleaning methods nowadays have become more finely tuned and less aggressive because new legislation has protected historic, listed buildings and conservation areas from any detrimental treatments (Mynors and Charles 1989).

Building façades pass through cycles of change as soiling accumulates on the surface of the stone. All building stones alter in appearance after long exposure to various pollutions from the atmosphere. Stonework should not be cleaned unless the soiling and pollutants are having a harmful effect on the masonry. Improper cleaning can accelerate the deteriorating effect of the pollutants by 15-20% (Historic Scotland 1991, 1994; Ashurst 1994a, 1994b). Some stone cleaning effects may take place after a number of years, and recently there has been a growing interest into large scale stone replacement and repairs on façades that have been cleaned badly years ago.

Every building considered for stone cleaning will differ over a range of parameters including, for example, stone type, surface texture, architectural style, microclimates and the nature and patterns of the soiling. There are many types of cleaning methods which include water washing, sandblasting (air abrasive) and chemical cleaning (Historic Scotland 1991, 1994; Ashurst 1994a, 1994b; Andrew 1994).

1.2 Significance of the Research

As time goes on, people have now paid more attention to this area and studies about stone cleaning have been published. New legislations have protected the listed buildings and conservation areas from any detrimental treatments, which promotes the cleaning method to a higher level (Ashurst, 1994).

Masonry buildings considered for cleaning vary in the types, surface texture and architectural style and also suffer from different types of natural decay even man-made pollutions. Cleaning methods include water jetting, steam cleaning and other chemical cleaning. However, the method of removing the soiling from the stone façade without affecting the underlying stone and causing longer-term damage to stone has not been devised yet. It is discovered that physical cleaning methods such as grit blasting will lead to some abrasive damage to the stone façade. Chemical cleaning method may dissolve some stone components along with the soiling and leave a lot of chemical residues in porous stone (Young et al. 2003). Some damaging effects may become apparent many years after cleaning and large scale of stone repair and replacement need to be taken to solve the problem caused by the cleaning in the past. Hence it is necessary to conduct investigations and tests on pre-cleaning in order to reduce the harm or damage to minimum and also divert our attention from the aesthetic qualities to the post-effects or consequences on the stone which has been cleaned previously.

1.3 Aims and Objectives of the Dissertation

The soiling of building façades is a constant natural reoccurrence for years. There are many ways to remove soiling. There are different methods of cleaning to overcome different individual problems each case brings, such as type of stone, different types of soiling, maintaining its architectural style and condition of the surface, and condition and types of mortar.

The aims of this research are to conduct systematic investigations into the physical and chemical characteristics of masonry stones and clay bricks subjected to progressive stages of air abrasive cleaning by using different types of abrasives and to eventually evaluate the effectiveness of the cleaning based on different techniques. Physical investigations included sieve tests, greyscale imaging analysis, thickness reduction measurements, surface hardness tests, impact tests and water absorption tests. Chemical investigations included the scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDX) analyses.

The objectives of this research are given as follows:

- To carry out a comprehensive literature review on the geology of rock formation types of stone used in construction, legislations and laws around listed buildings and conservation areas. The review also includes collecting data on the environmental factors responsible for soiling of building façades and the techniques, equipment and materials used in cleaning soiled building façades;
- To conduct tests using water washing, chemical cleaning and sandblasting (air abrasive) and to determine its effectiveness on cleaning different types of soiling and the potential damage these methods can cause;
- To collect different soiled masonry stones and bricks from sites to carry out comprehensive laboratory tests before and after cleaning in order to assess the effectivenesses of the material and methods used in cleaning;
- To conduct tests before and after cleaning, on specimens of thin sections cut out from different stones using the electronic microscope to study the micro pore structure of the stones and bricks and the effectiveness and damage caused by water jet cleaning, sandblasting and chemical cleaning;

- To conduct chemical analyses on different masonry stones and bricks before and after cleaning to study the chemical compositions of the natural stones and masonry bricks and the nature of the soiling cumulated for many years on the surface of the stones and bricks;
- To search for and determine new abrasive materials and techniques for cleaning building façades, based on previous works, case studies and the results of the comprehensive tests proposed to be carried out in the laboratory and on site during the investigation;
- To utilise the availability of recycled materials like glass, by-product granite sand, etc., instead of the blast furnace slag used commonly for sandblasting;
- To collect case studies of old, listed historic masonry stone/brick buildings restored and cleaned previously using different abrasive materials and methods of cleaning.

1.4 Research Methodologies of the Dissertation

The research methods in this research include:

- Obtaining information through reading books and searching on the internet;
- Understanding pollution conditions and appearance of buildings through site visits;
- Collecting data of the effects of environmental conditions on masonry buildings;
- Carrying out physical and chemical investigations on various masonry stones and bricks during cleaning process;
- Analysing the test results using commercial software and drawing conclusions.

1.5 The Structure of the Dissertation

This dissertation is to focus on the restoration and cleaning of the old historical buildings and monuments by carrying out various physical and chemical investigations on masonry stones and bricks. The whole dissertation is divided into a total of eight chapters with sixteen appendices.

Chapter 1 of this dissertation overviews the restoration and cleaning of historic buildings and illustrates the significance of the research, the aims and objectives of the research and the research methodologies of the dissertation.

Chapter 2 introduces the formation of natural rocks, including igneous rocks, sedimentary rocks and metamorphic rocks, and various types of natural stones for buildings and walls, and briefly presents various types of soiling and decay which may form on building façades. It also summarises various issues for the listed buildings for their architectural features worldwide, including selecting criteria, grading, spotting, updating, removal and appearing, and provides useful information about listing, building consent and conservation areas, together with scheduled monuments and historic building repair funding scheme. This chapter extensively describes the soiling and decay of building façades and discusses potential biological and non-biological soiling and also different types of stone decays. It also indicates the reasons and precautions for cleaning masonry buildings and categorises the building cleaning types as water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting). Meanwhile, it clarifies the advantages and disadvantages for each method and details the stone cleaning process including pre-cleaning measures and trial cleaning.

Chapter 3 summarises the material properties of basic masonry stones and clay bricks, including granite, limestone, marble, red sandstone, yellow sandstone, red clay brick and yellow clay brick, and illustrates the preparation of the masonry stones and clay brick samples using air abrasive cleaning for further physical and chemical testing. It also indicates the detail of three main types, or seven sub-types of abrasives, for building cleaning, including coarse slag, medium slag, fine slag, coarse glass, medium glass, fine glass and natural abrasive, and summarises the impact tests and sieve tests on these abrasives. This chapter also illustrates the measurement of the thickness reductions of the masonry stones and clay bricks cleaned to different stages using the same abrasives. The effectiveness of air abrasive cleaning using different abrasives on different masonry stones and clay bricks could be accurately assessed together with the greyscale imaging technique. The suitability of each abrasive on different types of masonry stones and clay bricks is to be judged and ranked.

Chapter 4 introduces the greyscale imaging technique and recommends its applications for assessing the effectiveness of cleaning on masonry stones and clay bricks of listed historic buildings. It details the procedure of determining the surface greyscales of the masonry stone and clay brock samples cleaned with fine recycled glass to different stages using "Colorpad" and analyses the progressive trends of the greyscale with the cleaning time in the preliminary digital image analysis using greyscale technique. A larger greyscale value normally implies a cleaner and brighter surface. A term of cleanness is also introduced for evaluating the effectiveness of cleaning together with greyscale. This chapter also extends the application of the greyscale imaging technique on analysing the surface images of the masonry stones and clay bricks using the commercial software Abode Photoshop. Seven different types of masonry stones and clay bricks are cleaned to different stages by using seven different abrasives and the corresponding greyscale values are assessed. Similar but extensive development trends of the greyscales with the cleaning time are illustrated and the suitability of each abrasive for cleaning each type of masonry stone and clay brick is discussed.

Chapter 5 introduces the Vickers hardness as a parameter for assessing the surface physical properties of the masonry stones and clay bricks during cleaning and specifies the Vickers hardness testing procedure. It illustrates the changes in the hardness with the cleaning time on the masonry stone and clay brick samples, cleaned with the fine recycled glass abrasive, and links the changes closely to the corresponding cleanness degrees. Normally, a lower hardness corresponds to a softer masonry stone or clay brick and it becomes more difficult to remove the soling on the softer stone or brick. This chapter also introduces the Charpy impact resistance as a parameter for assessing the material strength properties of the masonry stones and clay bricks and details the impact testing results. It illustrates a similar trend between the tested masonry stones and clay bricks to the trend for the Vickers hardness, but with a smaller variation.

Chapter 6 introduces the water absorption as a parameter for assessing the physical properties of the masonry stones and clay bricks and details the water absorption testing results. It illustrates an inverse trend between the tested masonry stones and clay bricks to the trend for the Vickers hardness and Charpy impact resistance. A masonry stone or clay brick with a larger water absorption capacity normally has a lower hardness and impact resistance and easily attracts soiling.

Chapter 7 indicates the significance of applying the chemical analysis into exploring the formation and development of soling on masonry stones and clay bricks for listed historic buildings, and specifies two chemical methods for this study including the Scanning Electron Microscope (SEM) and the Energy-Dispersive X-Ray Spectroscopy (EDX). The former can illustrate clear microscopic surface structures of the studied masonry stones and bricks at different cleaning stages, while the latter can detect the chemical elements and compounds on the surfaces. Detailed chemical test results on the carbon coated masonry stone and clay brick samples are presented and analysed. This can help qualitatively and quantitatively assess the soiling substances on the building façades and determine the efficient and effective ways to remove these soiling substances.

Chapter 8 presents extensive conclusions, including summary of the conducted physical and chemical testing, adopted types of masonry stones and clay bricks, and individual concluding remarks for each technical chapter. This chapter also discusses the problems of the current study and proposes suggestions for future work on the cleaning of listed historic buildings.

1.6 Summary

This chapter briefly overviews the restoration and cleaning of historic buildings and illustrates the significance of the research, the aims and objectives of the research, the research methodologies of the dissertation and the structure of the dissertation.

CHAPTER 2   LITERATURE REVIEW

2.1 Natural Building Stones

2.1.1 General

Stone is one of the foremost traditional building materials over a wide range of countries throughout the world. The extraction of stone from the earth has proven to be a valuable source for the construction of many wonders of the world today. One of the wonders is Stonehenge which was dated back to 1800 BC, and is still as strong and durable to this very day. Also the use of limestone in the construction of the temples of Malta has been dated back as far as 4000 BC.

One of the attractions of natural building stones is the wide variety to colours and textures available to architects and designers. The problem associated with such a wide range is to choose the best stone for a specific purpose. The variety of stone is not restricted to colour or texture. Wide variations in durability and other properties may also be encountered.

Every type of rock found in a local area has been put to use in some form, either for buildings or walls or tools. A study of the geological map of Great Britain will show the variety of rocks available. Every town or village will have historic buildings and monuments built from the most common rocks that are available to them in the local area. However, not every rock found is suitable for building purposes. A building stone must be capable to withstand the hard weathering and be durable to last a life time for a building.

The geology of stones is extensive and intricate. This section gives the reader sufficient background and appreciation of the origins of stones, their natures and their basic classifications.

2.1.2 Rock formation

Rocks are natural materials and their colour, strength, weathering resistance and other physical properties are controlled by the method of formation and their geological history. Nature building stones are classified by the formation of their parent rock. Rocks are naturally occurring solids composed of one or more minerals. Rocks are identified by the minerals they contain and are grouped according to their origin. Each group is subdivided on the basis of texture and mineral composition (www.uky.edu/KGS/rocksmn/rocks.htm). There are three types of rocks: igneous, sedimentary and metamorphic. All of them are used as building stones.

2.1.2.1 Igneous rocks

There are two types of igneous rocks: intrusive and extrusive. Intrusive rocks are most commonly used as building stones in this part of the world. Intrusive rocks originated well below the earth's outer solid crust and were forced towards the surface as a liquid magma. They are largely made up of silicates and classified according to the percentage of silicon dioxide. Those with a high proportion of silicon dioxide are known as acid rocks and contain quartz which is a crystalline form of silica. Those with a low proportion of silicon dioxide are referred to as basic or ultra-basic rocks. There is no huge difference in the percentage of silica content in acid and basic rocks, with the acid rocks containing more than 60% and the basic rocks between 45% and 55% (Hill and David 1995). Extrusive rocks form from magma at the surface of the earth, and rapid cooling leads them not to have crystals, more smooth.

Igneous rocks vary not only by their chemical compositions but also their positions in the earth when cooling of the rocks occurred. When volcanic activity forced them to the surface they may occur in two ways: either as sheets which have poured out onto the earth's surface or in dykes where they have been forced to the surface through a fissure. These are known as volcanic rocks. One of the most commonly igneous rocks used in this country for building is basalt which has a fine-grained structure formed due to the rapid cooling of the volcanic magma at the surface.

Plutonic rock is another type of igneous rock with coarser grain structure formed by slower cooling of magma at the outer solid crust of the earth. Granite is one of the most common types of this rock used in construction. Gabbro is another basic rock which was formed in the same way as the plutonic and granite rocks. Fig. 2.1 illustrates a typical building constructed with granite in Edinburgh.

Fig. 2.1 – A building constructed with sandstone in Edinburgh.

2.1.2.2 Sedimentary rocks

Sedimentary rocks are products of physical and chemical weathering which are formed at the earth's surface. They form in rivers, beaches, lakes, reefs, deserts as well as many other locations. Sedimentary rocks are divided into two main groups depending on the nature of the weathering producing the materials in the rock: clastic and chemical/biochemical. Clastic rocks are formed from the materials (boulders, Cobbles, sand, silt and clay) produced by physical weathering (wind, waves, stream currents and glaciers). Chemical and biological sedimentary rocks are formed from chemical reactions and biological processes. Familiar rocks such as rock salt, gypsum and coal are examples of chemical/biochemical sedimentary rocks, and commonly form in environments such as salty lakes, swamps, reefs and lagoons (http://www.geosci.ipfw.edu/GeoGarden/geotourNolmg.pdf). Sandstone has been more largely used in the North of Britain and limestone predominates in the South.

2.1.2.3 Metamorphic rocks

Metamorphic rocks are created by the mineralogical and textural transformation of pre-existing rocks under conditions of high temperature and high pressure. Most metamorphic rocks are formed during the creation of mountain ranges when conditions of elevated temperature and pressure are achieved. There are two general types of metamorphic rocks: foliated and non-foliated. Foliated metamorphic rocks are characterised by a distinct orientation of mineral grains to form flat or wavy planes which are produced by folding of the rock under conditions of directed pressure. Non-Foliated rocks are characterised by a uniform granular texture, lack a pronounced foliation, and are formed under conditions of non-directed pressure (http://www.geosci.ipfw.edu/GeoGarden/geotourNolmg.pdf).

There are two main types of metamorphic rocks: slate and marble. Slate is a common source of metamorphic rock that can be found mostly in Scotland but has traces in North Wales and Cornwall.

2.1.3 Natural building stones

There are constraints inherent in stone which demand that the material is properly used in accordance with its unique characteristics. Some of the minerals that are found in igneous rocks may break down and cause serious damage to the stone if they are exposed to the atmosphere. Rising salts may cause spalling. Of prime importance with sedimentary rocks is the placing of the bedding plane so that it is at right angles to the thrust imposed upon it. Metamorphic rocks have been found to have some harmful minerals within the rock. The greatest restraint in the use of metamorphic stone is that of the jointing. All rocks are jointed and the size of a block that can be wrought from a quarry is controlled by joints (http://www.buildingconservation.com/articles/stone/stones.htm).

There is a wide variety of beautiful natural stones available; however there are only few suitable for building purposes. Before selecting a stone for buildings it must meet certain requirements of strength, hardness, workability, porosity, durability and appearance. Some of the stones that satisfy these requirements are granite, sandstone, limestone, marble and slate.

2.1.3.1 Granite

Granite (Fig. 2.2) is an intrusive igneous rock formed by the crystallisation of magma beneath the earth's crust. It is a medium-grained rock that is rich in quartz and feldspar. Granite can be recognised easily because of its lighter colour. It is made up of pinks, whites or light greys throughout the stone. Granite is a very strong, durable stone. It is one of the oldest and hardest stones available and is used for many decorative features as well as building and paving stone.

Fig. 2.2 – Granite (http://homepage.smc.edu/robinson_richard/rocktest/igneous_web/images/granite.jpg).

2.1.3.2 Limestone

Limestone (Fig. 2.3) makes up about 20% of the sedimentary group of rocks. It is composed of the mineral calcrite (calcium carbonate) but it also contains certain amounts of clay, silt, chard and dolomite. Most limestone contains fossils of shellfish and many other animals that lived in shallow seas. Limestone can vary in colour from pure limestone bring bluish grey to tan white. Limestone with any impurities, such as iron oxide, will be brown and yellow and the colours from dark grey to black are caused by organic minerals. It is a very soft, porous material and its texture can vary from being coarsely crystalline to very fine grained. Crushed limestone is used extensively for agricultural purposes, road surfacing and cement and also as a concrete aggregate.

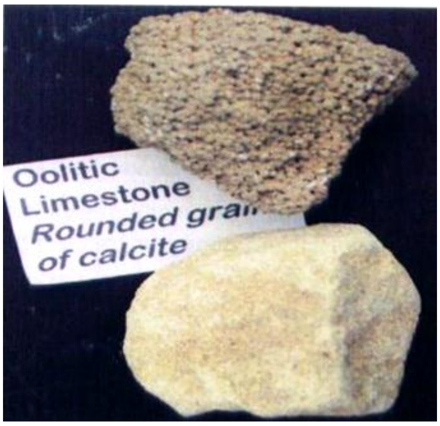


Fig. 2.3 – Limestone (http://homepage.smc.edu/robinson_richard/rocktest/sedimentary_web/images/oolitic%20limestone.jpg).

2.1.3.3 Sandstone

Sandstone (Fig. 2.4) is a coarse grained sedimentary rock composed of small grains cemented by siliceous, felspathic or calcareous cementing material. It is formed by the consolidation and aggregation of sand and held together by natural cement, such as silica, iron oxide, or calcium carbonate (Rabbani and Jamshidi 2014; Zhao et al 2014). Its durability largely depends on the cementing material.

Sandstones are typically grey, white, brown or red. The colour varies, depending on the natural cementing materials. Iron oxides produce red or reddish-brown sandstone while other materials produce white, greyish or yellowish sandstone. Sandstone is a rough, gritty, coarse material and can be easily crushed into smaller sandy pieces.

Sandstone is widely used in both commercial and domestic uses. It is highly noted for its natural beauty and so is used both internally, for ornaments, sculptures and other decorative features, and also externally for many large architectural buildings.

2.1.3.4 Marble

Marble (Fig. 2.5) is part of the metamorphic group of rocks. It is formed by limestone being put under great heat and pressure and melted so as to re-solidify as marble. This process is called re-crystallisation.

Some marbles show a very decorative colourful pattern once hardened. The minerals that are produced from the impurities in the limestone give a wide variety of colours.

Limestone free from any impurities forms the purest calcite marble and is white in colour. Impurities such as limonite, hematite and serpentinite spread the colours into red, yellow and green through the marble.

Fig. 2.4 – Sandstone (http://homepage.smc.edu/robinson_richard/rocktest/sedimentary_web/images/sandstone%202.jpg).

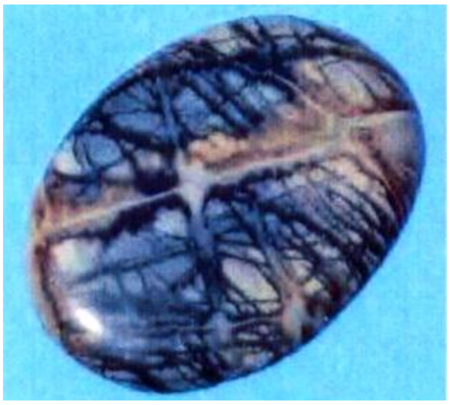


Fig. 2.5 – Marble stone.

Great care must be taken when mining marble as it is a very brittle stone. Explosive may cause the marble to shatter and break so it must be mined by cutting the marble into large blocks. Their low porosity and water absorption gives marble a good resistance to weathering (Valentini et al 2012; Tozsin et al 2014). However, they erode by acidic rain and are affected by acidic gases. Marble, because of its extravagant colours, is widely used as a decorative feature for both interior and exterior.

2.1.3.5 Slate

Slate (Fig. 2.6) is a fine grained, metamorphic rock that forms when sedimentary material such as shale and mudstone are under the strains of heat and pressure beneath the earth's surface, causing them to change to slate over a long period of time. The pressures not only harden the clay minerals but also realign the flakes of mica and other minerals into planes of cleavage at right angles to the applied pressure. There are two lines of breakability, cleavage and grain. It is along these planes that the slate can be so easily cut into sheets.

Fig. 2.6 – Slate (http://www.vermontstone.com/images/slate_wallpaper.jpg).

Typical colour for slates is grey but it can range from dark grey to black. Impurities such as iron oxide and chlorite create a reddish green in the slate. It is texture and lustre that can vary, with some slates having a dull matte finish, and others can be shiny as mica. Better grades of slate are used for slating roofs, flooring and even sidewall cladding. It has also been used in pool table tops and blackboards.

2.1.3.6 Clay brick

Clay bricks are artificial stones made mainly of clay and sand (Fig. 2.7). It is subjected to physical and chemical process until they achieve certain strength. Their properties are relative to their chemical compositions (Sagin and Boke 2013).

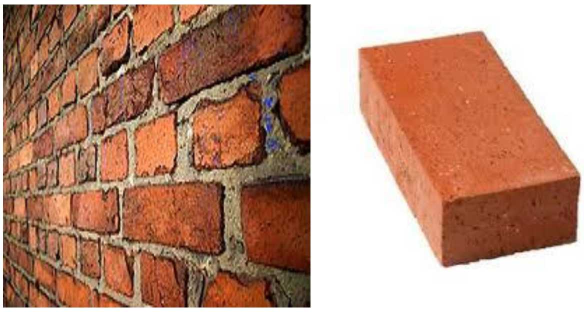


Fig. 2.7 – Clay brick (http://en.wikipedia.org/wiki/Brick).

2.1.4 Types of stone walling

2.1.4.1 Ashlar

Ashlar (Fig. 2.8) has defined and carefully worked beds and joints. These joints are no wider than 4.5 mm, and set in horizontal courses. The stones within each course are of the same height, although successive courses may be in different heights. Ashlar can be described according to its final surface finish (Homeowner et al 1998; Hendry and Khalaf 2001; Khatib 2009; Taly 2010; Angulo-Ibanez et al 2012).

Fig. 2.8 – Ashlar walling.

2.1.4.2 Black-in-course

This was rather an old-fashioned term to describe the large blocks of masonry walls seen in dock and railway engineering. The blocks are squared and brought to fair joints, and the faces are usually rock-faced. Massive solidity rather than sophistication was the keynote of this class of work (Homeowner et al 1998; Hendry and Khalaf 2001; Khatib 2009; Taly 2010; Angulo-Ibanez et al 2012).

2.1.4.3 Rubble

The majority and ancient buildings in the UK were built in coursed of random rubble, and many have stood for centuries without any maintenance. Rubble was much more cost effective than ashlar. Rubble depends more on the hold of the mortar than ashlar (Homeowner et al 1998; Hendry and Khalaf 2001; Khatib 2009; Taly 2010).

2.2 Listed Buildings

2.2.1 General

Historic buildings are an invaluable finite asset, and are proud reminder of our heritage and the way of life of our ancestors. Towns worldwide are identified by their historic architectural features, streets, monuments and buildings. Listing does not just cover the building itself and it also covers all the features within the boundaries of the property, such as the construction methods, any historic association by people or an event of national importance.

In 1877, William Morris founded the Society for Protection of Ancient Buildings (SPAB). This foundation is a non-statutory body whose opinion regarding historical building repair is held in high regard. Over the past few years there has been an increasing concern into the protection of historic buildings. Since 1967 local authorities have started designating conservation areas. The Town and Country Planning Act 1971 (HMSO 1971), following all the Planning Acts since 1947 (HMSO 1947), recognises that historic buildings are not only just important but also as of special architectural or historic interest. Therefore for those buildings the Secretary of State has the responsibility for compiling or approving lists of such buildings. Any unauthorised works to a listed building without building consent could be penalised.

2.2.2 Listing building selection

2.2.2.1 Principles of selection

Listed buildings are chosen according to a set of definite criteria, drawn up by the Historic Buildings Council, the forerunner of the Historic Buildings and Monuments

Commission (HBMC) and approved by the Secretary of State. There are five groups in total (Mynors and Charles 1989):

- Before 1700: Any buildings that preserve some original conditions are listed;
- Between 1700-1840: Most buildings are listed, and through selection is necessary;
- Between 1840-1914: Only buildings of definite quality and character are listed, and selection is based on the principal works of the principal architects;
- Between 1914-1939: Selected buildings of high quality are listed;
- Few outstanding buildings erected after 1939.

In choosing buildings, particular attention was paid to the followings (Mynors and Charles 1989):

- Special value within certain types, whether for architectural or planning reasons or as illustrating social and economic history, e.g. industrial buildings, railway stations, schools, hospitals, theatres, town halls, markets, exchanges, almshouses, prisons, lock-ups, mills, etc.;
- Technological innovation or virtuosity, e.g. cast iron, prefabrication, early use of concrete, etc.;
- Association with well-known characters or historic events, or group values, especially as examples of town planning, e.g. squares, terraces, model villages, etc.

As to more recent times, buildings of high quality are now being listed from the inter-war period. The criteria here are designed to enable full recognition to be given to the varied architectural output of the period. The building types may be considered over the following nine categories (Mynors and Charles 1989):

- Churches, chapels and other places of public worship;
- Cinemas, theatres, hotels and other places of public entertainments;
- Commercial and industrial premises including shops and offices;
- Schools, colleges and other educational buildings;
- Blocks of flats;
- Houses and housing estates;
- Municipal and other public buildings;

- Railway stations, airport terminals, and other places associated with public transport;
- Miscellaneous.

2.2.2.2 Grades

Every listed building has its own special features and needs to be graded differently. They are classified into three categories as follows:

- Category A: Building of national or international importance, either architectural or historic, fine little-altered examples of some particular period, style or building type.
- Category B: Buildings of regional or more than local importance, or major examples of some particular period, style or building type which may have been altered.
- Category C(S): Buildings of local importance, lesser examples of any period, style or building type, originally constructed or altered; and simple, traditional buildings which group well with others in categories A and B or are part of a planned group such as estate or an industrial complex.

There are about 600,000 buildings that are listed in Great Britain, which amount to nearly 2% of the total housing stock. Each listed building is graded according to its architectural or historic importance, Category A in Scotland, or Grade 1 in England and Wales, being the most important. Grading each building will determine its age and rarity, but now there are many other factors which need to be taken into consideration like technological innovation, townscape value or connection with a particular historical event (http://www.historic-scotland.gov.uk/index/historicbuildings/listingcategoires.htm).

2.2.2.3 Spot listing

Spot listing occurs when a building is brought to the attention of the Secretary of State, and he requests it to be included on the statutory list. Anyone may request a building to be accessed. The Secretary of State then decides whether it should be listed or not after a survey of the building in question is completed.

2.2.2.4 Up-date listing

The list is regularly reviewed and updated whereby buildings are added regularly using the following methods:

- Comprehensive re-survey of geographical areas;
- Thematic study looking at one particular building type (e.g. hospitals);
- Individual proposals for buildings to be added to the list.

2.2.2.5 Removal of a building from listing

A building may be removed from the list whenever the building has been substantially altered by accident or if it has been decided that it is no longer of special architectural or historic interest. If a building has been demolished then it will also be removed from the list.

2.2.2.6 Appeals against listing

A building is listed on the ground that it is of an architectural or historic interest. Anyone can appeal against listing. A written form is to be sent to the Secretary of State claiming that the building should not be listed, after an acceptable survey is completed. If the Secretary of State deems that the original survey was wrong in its way and the building is not of special interest it is then removed from the list.

2.2.3 Listed building consent

A listed building is restricted from any changes or developments to its original style and structure. This means that consideration must be given to preserve its historic character. Once a building has been listed, it is of special importance and every effort is made to keep it in its original style. Before any alteration or preservation is carried out a listed building consent is needed. This can be obtained from the local planning authority or in special cases from the Secretary of State. It is a simple procedure which needs to be carried otherwise any attempts to demolish or alter the building without the required consent will result in a fine of unlimited amount or up to twelve months imprisonment, or both.

Listed building consent is required when it has been decided to alter the character of a listed building, regardless of what grade it is in. Before any alterations take place the listed building may also require other consent such as planning permission and a building warrant. Listed building consent is required for all large or small scale projects. This includes stone cleaning of all or part of the building, any alterations of replacement of windows or installation of roof lights, etc. Large alterations may also be required such as structural, partial or total demolition, etc.

2.2.4 Conversation areas

There are over 650 conservation areas in Scotland. The planning authorities have to decide what areas are of historic interest and need to designate conservation areas. This designated area affects a large area and most of the buildings in this area may not even be listed but they are still of special interest (http://www.historic-scotland.gov.uk/index/historicbuildings/conservationareas.htm).

It is the character or historic interest of an area created by individual buildings and open spaces and their relationship with the other that the legislation covering conservation area seeks to preserve, see Memorandum of Guidance on Listed Buildings and Conservation Areas (Historic Scotland 1998).

Conservation areas include the following:

- Building groups, where the whole is more than the sum of the parts;
- Visible archaeology, such as historic street, plot layouts, and town walls;
- Important set pieces of public realm (squares, railings, settled street surfaces);
- Trees, rivers land for both amenity and cultural value;
- Open spaces, public parks, designed gardens and landscapes;
- Places of memory.

Under the Town and Country Planning Act 1971 (HMSO 1971a, 1971b) as amended by the Town and Country Amenities Act 1974 (HMSO 1974) requires that if anyone wants to demolish an unlisted building in the conservation area, he must first apply for conservation area consent. It is only available if it is going to contribute to the preservation or enhancement of the character or appearance of a conservation area.

2.2.5 Scheduled monuments

Scheduled monuments are of national importance and are scheduled under the Ancient Monuments and Archaeological Areas Act 1979 (HMSO 1979). Before any improvements can be made to the monument the Secretary of State must firstly give 'Scheduled Monument Consent'. A full detailed specification about the monument must be recorded.

2.2.6 Historic building repair grants scheme

There are many grants available for the restoration of buildings which have an architectural or historic interest (http://www.historicscotland.gov.uk/index/historicbuildings/historicbuildingsgrants.htm).

The planning authorities award grants to repair or maintenance of historic building under the Housing (Scotland) Act 1987 (HMSO 1987). They can only give these grants if they deem the building to be of architectural or historic merit. However grants are only given for particular types of restoration. Grants are given for re-roofing, treating dry rot and other structural repairs. Grants are not however given towards decoration features or works of regular maintenance. Owners must prove that they can find the complete project without support and in some cases details of assets and income may have to be produced. Grants must be approved before any work starts, and it will not be given to work started or completed. The same applies for churches and places of worship.

Other grants are available for major projects from other sources, including the European Union, Local Enterprise Companies, Heritage Lottery Fund and Housing Agencies. Statistics showed that between 1999 and 2004, grants totalling more than £48 million were approved to assist repairs worth over £200 million.

2.3 Soiling and Decay of Building Façades

2.3.1 General

Soiling of building façades has been a continuous problem for decades and has received much attention in recent years. Soiling is a build of a various number of urban air pollutants and various types of growths that have built up on the façade. These types of pollutants can be categorised in two groups:

- Biological soiling: bacteria, algae, fungi, lichens, etc.
- Non-biological soiling: airborne particles, e.g. atmospheric constituents and pollutants (e.g. carbonation), aerosols, soot, paint, aerosol-paint (graffiti), iron staining of sandstones.

In almost every case both types of soiling are present in every stone. Soiling is inevitable and as pollution increases there will be the variable appearance on the façade of buildings. Soiling can however make a building much more beautiful and more aseptically pleasing. It gives the building age and character, making it much more appealing to the public.

Soiling does not occur evenly across the surface of every stone. The pattern of soiling could be affected by the architectural features, causing water to follow in patterns on the façade. Each stone will have some similarities of soiling but stronger effects of soiling will occur on different stones. This is due to the porosity, pore size and its distribution, capillary system, surface tension forces and surface texture of the stone. Each of these characteristics affects the absorption and evaporation of moisture in the stone. The weathering pattern of a façade can never be lost, and it will reappear after cleaning.

2.3.2 Biological soiling

This type of soiling is surface and sub-surface growth and larger scale plant life. The effects of biological soiling are mostly aesthetic but in some minor cases it can cause stone decay. The main forms of biological soiling are bacteria, algae, fungi, lichens, moss and higher plant life.

For any type of biological soiling to grow and survive it needs to satisfy certain requirements such as water, light, temperature, pH value and nutrition. If there is an alteration of any of these requirements it may kill off the growth, e.g. photosynthetic organisms need light and carbon dioxide to develop (Ashurst 1994a, 1994b).

2.3.2.1 Bacteria

Bacteria are a group of very small organisms with many different forms that are too small to be visible to the naked eye. They can survive in the most severe conditions either extreme temperatures or drought. Bacteria on building façade cause aesthetic damage or stone decay. Certain bacteria organisms assimilate nitrogen from the atmosphere to form ammonia and other nitrogenous compounds whilst others oxidise ammonia to form nitrous and nitric acids. All of these attack limestone, marble and other calcareous substrates which provide a habitat suited to their own growth (Ashurst 1994a, 1994b).

It must be noted that cleaning off micro-biological with chemicals may improve the aesthetic look and can improve the growth conditions on the surface of the stone for some harmful types of bacteria. Some micro-organisms may become even better after such treatment.

2.3.2.2 Algae

Algae growths are found in damp areas and are usually green and moist when wet and tended to be black and flaky as they dry out (Fig. 2.9). There are other common species of algae that can be found to be brown, red, blue/green. The algae surface is wet and slimy and it will grow in rising damp areas or areas where there is excessive water run-off, e.g. a leaking pipe. Algae are photosynthetic and require light to grow. Algae growth that lacks moisture or light will turn black, which will become weak and can be easily removed by pressure washing (Ashurst 1994a, 1994b).

2.3.2.3 Fungi

Fungi can be termed as moulds or mildews. Their surfaces are usually grey, green, black or brown in colour and can be noticed as furry spots or patches on the surface. They are not photosynthetic and do not need light to grow but they survive on organic materials as a source of food. They can be found growing near bird droppings, leaf litter or near the dead remains of other organisms. Some fungi secrete organic acids as they grow. These include oxalic, citric, acids and many more. These are capable of dissolving mineral grains. Although fungal secretions are capable of dissolving minerals in stone, they are unlikely in most circumstances to cause serious damage to the stone substrate. However they can cause disfiguring staining (Andrew 1994; Ashurst 1994a, 1994b).

Fig. 2.9 – Algae growth (http://www.nsiuk.org/bwss.html/algae.html).

2.3.2.4 Lichens

Lichens are a symbiotic intergrowth of algae and fungi. A large portion of the lichen is penetrated into the surface of the substrate and can be easily identified by its green, grey, yellow and orange colour. Organic acids from the lichens penetrate into the stone and may damage the stone. Lichens are very slow to grow and more commonly do not cause any deterioration of the stone. The age of the stone can sometimes be verified by how much lichen has actually grown on it. The different colours and amounts of growth can sometimes visually look pleasant but in some cases lichens can be overgrown and cause blistering and spalling on the stones (Fig. 2.10).

Fig. 2.10 – Lichens' growth (http://www.nsiuk.org/bwss/html/lichens.html).

2.3.2.5 Mosses and higher plants

Plants and mosses need high moisture levels and particles of soil before they can take root and grow (Fig. 2.11). They can be found mostly in gutters or ledges or in any crevice and will grow tall enough to be visibly seen. Plants' roots can cause destruction to the building material, leaving the general area in a rundown manner.

Fig. 2.11 – Moss growth (http://www.nsiuk.org/bwss/html/moss.html).

2.3.3 Non-biological soiling

Non-biological soiling is airborne pollutant matter deposited on the building façade, such as carbonation, soot, vehicle exhaust and industrial chemical emissions. Soiling occurs in porous and permeable stones which allow soluble material to travel through the stone. As the moisture evaporates through the stone the soluble material is drawn to the surface of the stone. Over a space of time such movement of materials will result in soiling on the surface of the stone.

Back in the early 20th century there was a lot of smoke and diesel causing most of the soiling in urban areas. New legislation has improved the air quality by not allowing the burning of many materials; however there are many other man-made pollutants.

2.3.3.1 Carbonation

Carbonation mainly occurs to lime mortar or concrete blocks for building façades and it is a two-stage process. First, carbon dioxide diffuses from the atmosphere into the partially dried capillary pores and combines with water to form carbonate acid. Then, calcium hydroxide (also known as portlandite) in cement based materials dissolves in the pore water and reacts with dissolved carbon dioxide to form calcium carbonate (calcite). This complete process is known as carbonation (Ferretti and Bažant 2006; Pinho et al 2008). Carbonation also happens to sodium and potassium hydroxides. This conversion process reduces the pH value of the lime mortar or concrete below 10, thus reducing the protective ability of the masonry materials and degenerating the building performance of the masonry façades.

2.3.3.2 Aerosols

Aerosols are very fine particles that float around in the air comprising of both particulate and gaseous pollutants. The particulate matters of aerosols include sulphates, nitrates, ammonia, silicates, metal particles, soot and hydrocarbons. The finest constituents of these (less than 0.1 μm) include products of the burning of fossil fuels. Aerosols particles can be deposited by either wet or dry form, but wet form is more common.

2.3.3.3 Soot

Soot particles range in size from 0.1 to 1 μm. Soot is more likely to fill pore spaces of many porous stones such as sandstone and to affect sloping façades like window ledges, architectural statue, etc. Soot can be deposited by either dry or wet form, and wet form is of less importance.

2.3.3.4 Other types of non-biological soiling

Paint

Through past years, many people just painted stonework surface to cover any soiling but through recent years it has become common to show the quality and pleasing aesthetic appearance of the stonework. Paint can be removed from walls by methylene chloride (paint stripper) applied as a poultice under a plastic film. Extreme care must be taken before applying the chemicals to the stone. The paint remover could very easily damage the stone if not correctly applied.

Aerosol paint

Cleaned surfaces are a vulnerable attack to graffiti artists rather than the reoccurrence of soiling. Ashurst (1994a, 1994b) listed a number of chemicals that can be used to remove the aerosol paint including water-rain soluble paint strippers, 1.5 solutions of water and tri-sodium phosphate, and sodium hydroxide poultices. As with removing paint extreme cautions need to be taken to prevent any damage to the stone.

2.3.4 Environmental decay of stones

The development of stone decay is influenced by many different factors such as its adjacent materials (mortar, various stone types, etc.), soiling, physical and chemical treatment, weathering and the quality of the stone itself.

The constant attacking of the weathering environment is causing erosion along with many pollutants, salt crystallisation, bio-deterioration and repeated wetting and drying cycles. A damper climate is susceptible to biological damage.

Decaying of the stone can occur on poor quality stone or by human errors such as laying the stones in the wrong bedding planes or misuse of equipment. If it is exposed the stone decay occurs on all sides. If the stone has a large crack or is loosen in place the decay occurs along the bedding plane. Stone that has been chipped off or broken by human errors is more susceptible to decay.

Mortar is the most common factor to stone decay, as it is used in every type of construction. Decaying will occur by the use of improper mortar mix, e.g. the mortar is too hard and impermeable (Fig. 2.12). General evidence exists that they are dramatically damaged due to attack of air pollutants present in today’s atmosphere (Baer et al 1991). The wrong mix can force the movement of moisture from the mortar into the stone and cause it to flake off. Cement, due to its high density and crystal structure, is non-porous. Cement renders will always crack eventually allowing water with no ability to evaporate. An increasing number of studies on degradation of structural elements have been performed both in the laboratory (Gauri and Gwinn 1982; Johansson et al 1988), field exposure tests (Baedecker et al 1992) and directly on historical buildings (Krumbein et al 1992). In the case of cement mortars the evaporation can only take place through the masonry. This may result in rapid spoiling of soft stone and brickwork leaving the mortar standing alone like a shelf, collecting yet more water and increasing the masonry's deterioration. Since walls breathe better and moisture can evaporate, using lime mortars has many advantages as follows:

- Mortars and renders do not set too hard;
- Thermal movement can be accommodated without damage;
- Expansion joints can be avoided;
- Insulation is improved and cold bringing is reduced;
- Risk of consideration is reduced, together with no risk of salt staining;
- Alterations can be effected and masonry revised;
- Masonry life is increased.

If a porous some like sandstone is placed over a less porous stone then the movement of moisture between the two is restricted and depending on the venerability of the stone, decaying can occur in the porous stone. Calcareous stones can leach damaging calcium salts into adjacent stones. Care must be taken when laying different types of stones (http://www.nsiuk.org/bwss/html/stone_decay.html).

Fig. 2.12 – Hard mortar causing decay of surrounding stones (http://www.nsiuk.org/bwss/stone_decay.htma).

Salts, e.g. chloride and sulphate, etc., are one of the most damaging agents to stones. The most common cause of decay of stones is the crystallisation of salts within the pores and frost damage. Sulphate attack on cement-based construction materials is one of the most frequent and damaging phenomenon evidenced through expansion, cracking, decomposition, etc., of the resulting products of cement hydration. Among the processes that can generate a decrease in mechanical strength, the formation of gypsum, monosulphoaluminate, sodium sulphate and ettringite have been recognised for many years (Veniale et al 2003). Porous stones are at high risk to soluble salts, sodium sulphate, magnesium sulphate, salt weathering, and sodium sulphate saturated solution. Leaked salts from cement based mortars into the adjacent stones are also extremely damaging, especially on sandstones, causing the stone to deteriorate immensely. During the last decade, cases of a new form of sulphate attack (the thaumasite form) have been discovered in buried concretes and/or mortars where significant damage of the matrix occurs as a consequence of the replacement of cement hydrates by thaumasite.

Efflorescence (Fig. 2.13) is a calcium salt which forms in a blotchy powdery manner on the surface of the stone. It is released from moisture leaking through the stone and combining with the calcium hydroxide in the cement, bringing the hydroxide to the surface in a solution which forms crystals when it combines with the carbon dioxide in the air. Early efflorescence typically occurs during the initial cure of a cementitious product. It often occurs on masonry construction, particularly brick, as well as some firestop mortars, when water moving through a wall or other structure, or water being driven out as a result of the heat of hydration as cement stone is being formed, brings salts to the surface that are not commonly bound as part of the cement stone. As the water evaporates, it leaves the salt behind, which forms a white, fluffy deposit. This can normally be brushed off. Later efflorescence is named such as it does not occur as a result of the forming of the cement stone or its accompanying hydration products. Rather, it is usually due to the external influence of concrete poisons, such as chlorides (http://www.continentalcaststone.com/csi/33.html).

Some of the more common sources of damaging salts include concrete and cement-based mortar, bricks and limestone, sea-salt and road salt, washing powder, other household cleaning agents and sulphur in the atmosphere.

Fig. 2.13 – Efflorescence on brick wall
(http://www.ebricksolutions.com/repair.frost/frost3.jpg).

2.4 Cleaning of Stone Buildings

2.4.1 Reasons for cleaning

The cleaning of stone buildings is surrounded by controversy concerning both the method and necessity. There is no doubt that cleaning restores the building to its original colour and appearance, which makes it visually nicer and can help prevent or reduce the chemical decay. However, objections to cleaning are often raised on the grounds that removal of dirt removes a part of history of the building. Others objectors base their views on the undoubted damage caused by cleaning to the stones.

Of all the changes to which buildings can be subjected during their life, stone cleaning is one of the most visually dramatic changes. Most cleaning is done for aesthetic reasons to improve the appearance of the building, although, on some more ancient buildings, removal of the natural ageing effects may be considered undesirable. On buildings of historic value, it will probably be more important to retain the patina and intricate details than to recover the original appearance of the stone.

Soiling may hide defects in the stone or joints. It is important that harmful or corrosive substance such as weathered crusts and soluble slats should be removed since these lead to increase rates of decay of the stone. Regular cleaning by removing dirt and soluble salts can prevent serious decay.

2.4.2 Precautions taken in stone cleaning

The visual appearance of buildings improved by stone cleaning but damage should also be considered. Stone cleaning can make the building more unsightly and can damage the walling materials. Increasingly, concerns have been expressed at the irreversible damage caused to some buildings by stone cleaning. Evidence abounds of situations where unskilled operatives with using inappropriate techniques and undue haste have caused permanent damage to buildings (Fig. 2.14).

Cleaning methods are usually destructive and cause irreversible damage. Cleaning should go ahead only if there are strong reasons for cleaning and confidence that the chosen methods and contractors will procedure acceptable results.

To avoid any damage to the stone an appropriate method of cleaning should be chosen. This is based on the type of stone, type of soiling as well as the cost and time available. It is essential that enough information collected about the nature and type of the stones to be cleaned before proceeding (Fig. 2.15).

2.4.3 Deciding to clean

Cleaning is best considered when other maintenance or repair work is needed for the building. These situations include:

- **Before carrying out maintenance:** repainting walls, repainting windows and doors, and re-pointing masonry walls;
- **After repair and alteration work to the building:** repairing or removing sections of wall, alterations to door or window sizes, adding extensions, drilling holes for cavity fill injection, stains or organic growths from water overflow or runoff from faulty plumbing.

Fig. 2.14 – Aesthetical reason for stone cleaning: soiled sandstone façade before and after cleaning.

Fig. 2.15 – Piecemeal cleaning of terraces inevitably producing poor aesthetic results.

2.4.4 Stone cleaning process

2.4.4.1 Measures taken before cleaning

As with any intervention in the cleaning process of an old building, a first step is to survey the building to establish the following:

- Cause and nature of the soiling;
- Precise type and composition of stone in the wall, and it is not just enough to specify if the stone is a limestone or sandstone;
- Nature and extent of any protection to vulnerable areas such as windows and open joints which must be sealed to prevent flooding;
- Presumed effect of the cleaning method in the short and long terms.

Some of the above points could be answered by carrying out a trial cleaning on selected typical areas to establish the standard of cleaning for the rest of building (Fig. 2.16).

Another aim of the survey must be to identify the carved or other significant detail which may be damaged by the general cleaning process and must therefore be protected and treated separately.

Each part of the building must be separately assessed, taking into account, among other factors, variations in the types of stone which need to be treated differently according to their particular circumstances and requirements.

Before cleaning it is necessary to make a risk assessment of the health and safety issues involved in the cleaning of the soiled building materials and to draw up a method statement for each cleaning method to be used. Trials of different cleaning methods in discrete areas representing typing and wall materials will be arranged. It is also important to ensure that the contractors and operatives are experienced in the particular types of cleaning work to be carried out.

2.4.4.2 Reasons for trial cleaning

The reasons for trial cleaning include the following:

- Success of all cleaning methods that might be appropriate to the building, masonry surfaces, working conditions and environment;

- Most effective, fastest and cheapest method of removing soiling;
- Most appropriate or acceptable final texture and colour of post-cleaned surfaces;
- Cleaning methods which remove the soiling but retain the patina of age or other characteristics unique to the building;
- Cleaning methods which cause the least surface damage and fresh soiling.

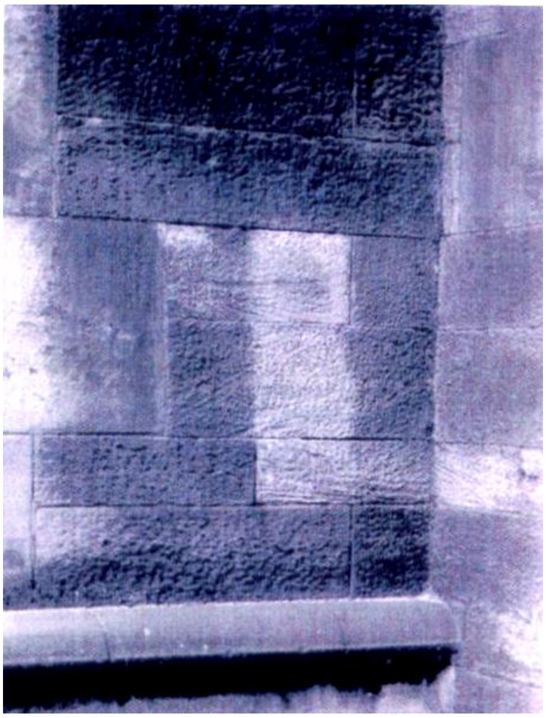


Fig. 2.16 – Example of test panel cleaned using low-pressure grit blasting.

Every building considered for stone cleaning will differ over a range of parameters including stone type, surface texture, architectural style, microclimates and the nature and pattern of soiling. Each poses a different set of problems when cleaning is considered. As a result, it has not always been possible to give answers to specific questions but the practitioners should seek to make better informed decisions, thus avoiding some of the mistakes and damage which have occurred in the past.

2.4.4.3 Information recorded in trial cleaning

The information recorded during and after a trial cleaning includes any damage to the wall façades caused by the method used (e.g. areas of different absorptions) and then it can be decided if gentle rather than aggressive methods are adequate. The chemical contents of the cleaning agent used, degree of safety and handling procedures must be considered. Information should be recorded when the surface is wet and any noticeable charges after drying. After a trial cleaning a decision to go ahead or not should be taken based on the benefits of cleaning and it is cost. If a decision was taken to go ahead, the sequence of cleaning associated renovation and repairs should be planned.

2.4.5 Water cleaning

When dirt is combined with gypsum ($CaSO_4$), relatively water soluble mineral cleaning methods are usually used. It is more commonly used on calcareous surfaces such as limestone and marble. Water-based methods are not effective on sandstone, brick or terracotta for removing soiling which is bound to these surfaces by insoluble compounds. Using water washing techniques on masonry surfaces with high natural salts, such as sandstone or brick, can mobilise the salts and lead to efflorescence. Desalination of such surfaces after cleaning has, in rare cases, occurred by water saturation followed by drying.

Limestone cleaning by water techniques is carried out in three forms: spraying, poultice and pressure. Much like rainwater, applying water softens the soiling and rinses it from the surface. Brushing and scraping can be used to assist in the removal of heavier and often more stubborn soiling. The combination of spraying, brushing and rinsing varies for each case and should be determined at the trail cleaning stage.

The content of the water is somewhat overlooked. Chlorinated water from the mains is commonly used. This water is rarely tested and if it contains high iron content it can lead to staining on light coloured stones. To prevent iron soiling, non-ferrous, non-corroding pipes, nozzles, fittings and booms should be used.

2.4.5.1 Types of water cleaning

Water jet spraying

Water is applied through small jets on booms which can be moved around the façade as required. The nozzles should be spaced in order to give even wetting throughout and be independently controlled so on waste occurs in cleaning areas or windows.

When greasy deposits exist hot water is rather effective. The solubility of gypsum increases with temperatures, thus hot water will be more effective than cold to remove gypsum crusts and skins. This could have a negative effect with the potential for gypsum-laden water to be absorbed by the stone.

Hot water is used with chemical cleaning to improve the efficiency and ability of rinsing. Sometimes hot water is used before applying the chemicals to increase the temperature of the surface in order to accelerate the effect of the agent used in cleaning.

Intermittent nebulous spraying

Nebulous spray, also known as intermittent mist spray, is low-pressure water washing. Its aim is to apply the minimum amount of water for the minimum duration to soften the dirt, thereby enabling its removal by scrubbing or other relatively gentle treatment. Low pressure water washing, by comparison, risks saturating the masonry, which could cause damage to the wall by mobilising salts and causing fixings to corrode and could cause damage to other features fixed to the wall such as internal plasterwork, timber or decorations. It can also lead to dry rot.

The spray is finer than most cleaning operations and is easily affected by draughts through sheeted scaffolding, even when situated near the masonry surface. Water will naturally follow the wither air flow direction and in this case cleaning the soiling is not effective. Therefore, the nebulous spray needs to remain directed at the area of soiling. Practical difficulties in achieving this have led to the use of slightly coarser water sprays which apply water to the soiled surface intermittently, hence the name intermittent nebulous spraying is given. The length and frequency of spray times are most commonly controlled by time clocks.

The optimum amount of water to wet the surface but not to cause cascading should be applied. Spraying then stops, allowing absorption of the applied water by the soiled surface ahead of the next spraying sounds. To control water flow a measuring device can be installed to determine the quantity of water being used (Ashurst 1994a, 1994b).

Intermittent nebulous spraying is an effective way in reducing the potential and effects of water cascades and water saturation (Fig. 2.17). When water is observed on soiling, the latter becomes softened, which makes it easy scrubbing and brushing at an early stage. It is essential that all equipment, e.g. nozzles, booms, timers and water flow meters, is used correctly to ensure quality of work.

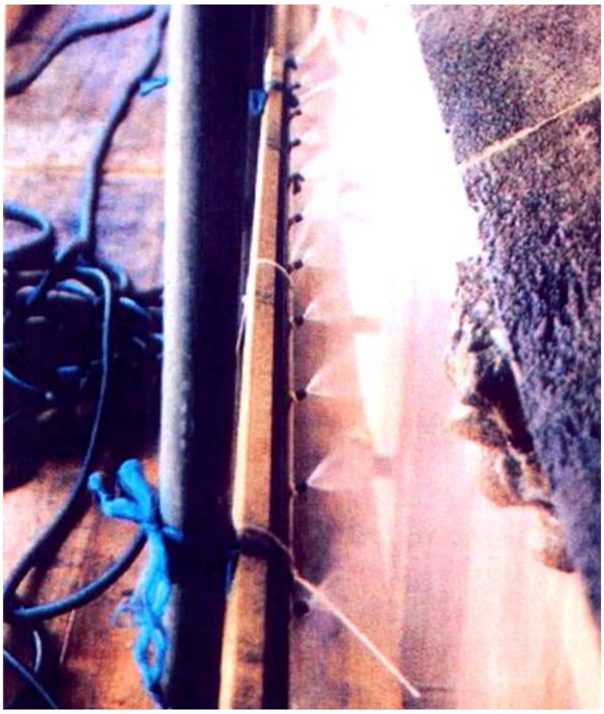


Fig. 2.17 – Fixed heads creating a nebulous mist effect on flat areas of masonry (photograph by Paye Stonework & Restoration Ltd).

<u>Water cleaning with pressure</u>

Pressure water washing is carried out at two different pressures: low water pressure and high water pressure. Both pressures are delivered through a lance which is held by the operator. The cutting action of the pressure gives an advantage when removing stubborn dirt, but it can also cause damage to the masonry or joints.

Low pressure cleaning will remove loose atmospheric and most organic soiling on limestone. Server soiling on sandstone will require pressure water cleaning and the mechanical removal of the soiling. Usually softening of the soiling by water is required before pressure cleaning so that the soiling can be successfully removed.

Low water pressure, up to 3.45 N/mm^2, is used in both dry and wet abrasive cleanings, for cleaning and rinsing the façade. It is also used with chemical cleaning to remove both the dirt and cleaning agents. The pressure of the water should only be sufficient to remove the softened soiling. Surfaces to be cleaned required maximum pressure for cleaning. These maximum pressures take into consideration the type and condition of the masonry and pointing. Surfaces should not be subjected to pressures which the stone can withstand but the joints cannot, because this will lead to removal of original material and required later re-pointing.

The following should be considered in deciding using water with pressure on masonry:

- Crumbly loose areas can be easily broken apart;
- Its effectiveness on severe soiling is limited,
- In cold weather there is a risk of frost damage;
- Penetration can damage the interior of the building.

High pressure cleaning relies on the cutting effect by water. There is not tome to allow for the water to soften the soiling. This method is rarely suitable for most traditional surfaces.

Pressures are specified with upper and lower limits in Newton per square millimetres (N/mm^2), but these are useless without other factors such as distance from the wall.

The erosive or cutting power of the jet of a pressure washer depends on the pressure produced by the pump, the flow rate, diameter and shape of the nozzle and distance between the nozzle and surface.

When abrasive particles are involved a range of characteristics should be considered such as the size, shape and volume of particles being applied, the shape and size of the nozzle, and the working distance.

Knowing the pressure capacity of the pump is meaningless when trying to establish the effect of pressure cleaning. Reducing the working distance of prescribed pressure could have a damaging effect on the wall, equally increasing the working distance of pressure result in waste of material and prolonged cleaning. Cleaning trials should therefore investigate and specify all the vital factors involved in acceptable pressure. Areas of delicate or crumbly stone should have separate specifications.

The shape of the nozzle is important. Pencil nozzle jets should be avoided, with fan spray tips of no less than 30° deemed acceptable for architectural cleaning. Rotating low pressure nozzles are gaining wider usage on more ornate surfaces in general masonry cleaning (Ashurst 1994a, 1994b). These suggestions to nozzle shape and size assumed low pressures to be 3.45 N/mm^2 and high pressures to be greater than 7.0 N/mm^2, a working distance of 250 mm, a fan tip nozzle of 30° and a water flow rate of 4 gallons per minute. There is no universally agreed standard, so specification of all important factors and pressure is necessary.

Steam cleaning

Steam is applied to the surface through a low pressure nozzle, and is generated on site. Steam softens and swells the soiling which can be removed from the surface by the pressure of the steam jet. Steam reduces the amount of necessary water and hence the risk of saturation and staining. The pressure applied by the steam jet must be established by trial cleaning beforehand. Steam cleaning has not been a mainstream method in use because of health and safety hazards.

The use of steam cleaning on soiled masonry surfaces, in particular limestone, is still used in certain circumstances. The technique has proved its ability to clean highly carved surfaces without mechanical damage. Steam cleaning is a useful method for softening oil, greasy or tarry deposits, for removing chewing gum, wax crayon and for killing mould and algae on damp surfaces.

Water cleaning with non-ionic soaps or detergents

Non-ionic soaps assist in reducing the adhesion between the soiling and the masonry beneath. They play an important role in the removal of particulate matter. Non-ionic soaps are most frequently used in the masonry cleaning field as they have better wetting ability and do not produce salts (ionic compounds) into masonry (Ashurst 1994a, 1994b). Synperonic-N and Lissapol are most commonly used in the UK, diluted with water or white spirit.

Failure to remove the detergent after cleaning may have three detrimental effects:

- The stone may be left uneven or patchy in colour;

- Residual inter-granular detergent can promote the entry of rain or other moisture into the stone and thereby accelerate rising or falling damp and decay;
- The biodegradable nature of most modern detergents means that they can be attached by bacteria and thus act as a medium for bacterial action in the masonry.

2.4.5.2 Problems associated with water cleaning

Control of water volume

Most of the problems encountered by using water washing techniques stem from excessive amounts of water, leading to saturation and penetration of water between the units. It was established that the minimum amount of water needed to soften the soiling should be used. Therefore water should only be applied to areas where soiling removal is needed.

The principals behind a successful water washing operation are as follows:

- Minimum amount of water should be used. Where continuous spraying is used, the minimum rate of water flow should be used. This may require water flow meter on the water supply. The amount of water required could be reduced by increasing the pressure applied.
- Water should be applied for a minimum period of time.
- Water should only be applied to areas to be cleaned in such a way that the spray or runoff does not saturate associated masonry unnecessarily.
- Natural bristle and fine-wired phosphor bronze brushes (not steel) should be used to remove softened soiling to reduce the wetting period of masonry (Ashurst 1994a, 1994b).

Control of water pressure

Surfaces should not be subjected not be subjected to water at pressures which are likely to cause damage by impact or cut of the surface.

Penetration and saturation

Penetration of water is a serious problem and is one of the biggest drawbacks in water washing. Water washing subjects building walls to a concentration of water which has never been experienced before. Water will penetrate any defective joints and fractures, which can result in the following:

- Accelerating the rusting of hidden iron clamps;
- Providing good conditions for the spreading of dry and wet rot in masonry;
- Rotting of timber beam ends and timber panels.

Most masonry stones and clay bricks are porous to a lesser or greater degree, which will allow water to penetrate into these masonry materials. In very wet weathers, water will fully fill in all those pores and the masonry materials become. Saturation of masonry may encourage efflorescence to appear on masonry walls. One of the most frequently raised complaints of saturation is the brown or orange surface staining which appears after drying out. This is due to the high iron content in water used or in the stones. Rainwater can, but not always, wash away this staining. The pattern of the brown and orange staining after cleaning is irregular and is similar to the soiling on the wall before cleaning.

Sugar will greatly increase the solubility in water, and this can help to create a strong set but it alters the patterns of the wall perhaps due to its pores structure.

The penetration and saturation of walls can be reduced by erecting horizontal catchment system along the façade. The cost and time of erecting such system are considerable and should be taken into account when deciding to carry out cleaning (Ashurst 1994a, 1994b).

Protection

Water washing may appear a simple way of cleaning in materials and equipment used. This is actually not the case, as the need for protecting of openings and other water control measures are time consuming. Temporally joint filling should be undertaken with non-staining, readily removable materials.

Surface condition

Decayed stones, especially where small scale detail is involved, are very vulnerable to washing with water sprays. Sulphate surface containing fine details of original carving can be easily dissolved by water washing. This can lead to unnecessary damage in this case other methods such as pencil air abrasive cleaning are used.

Thickness of soiling

During the cleaning of a façade a range of soiling thicknesses will be encountered. Areas under projections or within detailing will have thicker soiling than more exposed areas. Before general water based cleaning these thicker soiling deposits should be reduced to avoid damage to the adjacent areas with thinner deposits. In freezing conditions, water washing can damage the building due to the freezing of water within the masonry surface or its joints. Brushing and scrubbing assist in water cleaning and reduce the likelihood of saturation. Brushes stronger than the stone should never be used with water cleaning.

2.4.6 Chemical cleaning

Chemical cleaning methods work by the reactions between the cleaning agent, soiling and the masonry surface to which the soiling attached. Wide varieties of chemicals for cleaning masonry surfaces are available in the market, although they can be separated into a small number of groups according to their chemical and physical properties. The following part shows the key issues for chemical cleaning.

Chemical cleaning agent

There are two main types of chemical cleaners: acid and alkaline. The active ingredient of a cleaning agent can be a single component or a mixture and can vary greatly in concentration as well as strength.

Different manufactures specify different methods for using the acids and alkaline chemicals (Andrew 1994).

A liquid acid cleaning regime might involve the following steps:

- Pre-wet the stone;

- Apply alkaline degreasers and allow dwelling for an appropriate time length;
- Thoroughly wash off with high pressure water spray;
- Apply acid cleaner and allow dwelling for the correct length of time;
- Wash off with high pressure water spray.

An alkaline poultice cleaning programme might involve:

- Application of poultice to dry stones;
- Cover with plastic sheet to prevent drying;
- Leave for stated time,
- Unwrap and scrape off poultice;
- Rinse off with water;
- Apply neutralising wash and allow dwell for stated time;
- Wash with high pressure water spray.

The physical nature of the cleaning agents is usually modified by the addition of relatively inert materials which control the viscosity. Thus the acids and alkalis which are the active ingredients may be presented as fairly mobile liquids, thixotropes, gels or paste (poultices). Other additives may include detergents and biocides (Christopher Andrew 1994). Although technical information for use is usually supplied by the manufactures of the agent, cleaning trials may specify changes in concentration and dwelling times. This should be done on the basis of scientific analysis but not of the visual effects on the stone.

The most common acid cleaning agent is *hydrofluoric acid* (HF). It is the principal cleaning agent in acid products used on sandstone, brick, terracotta and unpolished granite. It is preferred for cleaning these types of masonry as it is effective and does not leave soluble salts behind. Hydrofluoric acids do, however, have the potential for depositing insoluble salts.

The most commercially available alkaline clearances are based on sodium hydroxide (NaOH). A few products are based on potassium hydroxide (KOH) or ammonium hydroxide (NH_4OH). Alkaline cleaning agents clean by breaking the greasy content. On sandstones and other siliceous masonry, this enables the hydrofluoric acid to have a more direct effect. This results in a reduction of acid concentrations and dwell times.

Chemical staining

Whether chemical cleaning is principally deemed successful or not depends on whether it modifies the surface colour. The biggest contributories to staining are minerals containing iron and manganese, which occur in small amounts within the stone.

Iron-containing minerals which were stable in the stone can be dissolved by some chemical cleaning agents. The dissolved iron travels through the stone by capillary action or moisture evaporation from the surface of the stone. The orange or brown staining visible on the surface is the deposited iron. Phosphoric acid (H_3PO_4) is added by some manufactures to the cleaning agent to prevent the orange and brown deposits.

The best illustration of the effects of chemical cleaning in relation to colour change can be seen when adjacent buildings are cleaned separately. Using chemicals at too high concentrations or allowing dwelling to occur for too long are the most common reasons for the unpleasant changes in colour. This situation is made worse by any time delays between cleanings of adjacent buildings.

In some cases, the use of hydrofluoric acid solutions can lead to siliceous minerals (e.g. quartz, feldspar, clay etc.) being dissolved and deposited on the surface. Again, this is a result of over-concentrated solutions or unwarranted dwell times. The minerals deposit on the surface in the form of hard, white, insoluble residues. The complex nature of chemical cleaning highlights the need for cleaning trials to examine the situation and to precede accurate specifications.

Applying chemicals to substrates

Chemical cleaning is usually used on materials with soiling which is insoluble with water, for example sandstone, brick, unglazed terracotta and unpolished granite. For the removal or reduction in thickness of encrusted soiling on limestone, a slightly different range of chemicals are being used. On siliceous materials (sandstone, brick, terracotta, granite), the cleaning process works by degreasing and breaking up the siliceous bonds. Usually the procedure involves and alkaline chemical followed by an acidic chemical based on hydrofluoric acid or the acidic product alone. Where an additional cleaning is not required after the alkaline cleaner is applied, an acetic acid-based neutraliser is used.

On calcareous surfaces, the break-down of the greasy component and cleaning is done by the alkaline cleaner which is based on a hydroxide. An acidic cleaner based on acetic acid is then applied to neutralise the alkaline residues which have not been rinsed out.

The following part shows the procedure followed in chemical cleaning.

Cleaning trial

Cleaning trails have previously been discussed. As far as chemical cleaning is concerned it is important that specifications should be established from scientific analysis. A clean surface, visually showing no signs of damage, might only show the negative effects of cleaning after period of time when specifications have already been made and work might have commenced.

Pre-wetting

Pre-wetting for chemical cleaning is not to soften the soiling, but to fill all the pores and capillaries of the stone. This is done to keep the chemical in contact with the soiling to be removed and to prevent its absorption by the stone. While pre-wetting cannot ensure that the surface will not be penetrated by the chemical applied it does reduce the potential of its happening. Pre-wetting is carried out by a lance at low pressure passing over the surface for a number of times. The chemical should be applied immediately afterwards. Care should be taken with pre-wetting so as not to saturate the masonry. The amount of pre-wetting required varies with each job and experience is needed when it is being carried out.

Chemical concentration

Manufacturers issue guidelines on the dilution of their chemicals. The contractor should follow these instructions carefully regarding the procedure and amounts when diluting the chemical. If it can be avoided diluting or storing of chemicals should be done off site. Chemicals which are supplied in dilute form minimise the risks during handling the mixing. During cleaning trials, testing the chemicals at different concentrations from the recommended and viewing the effects should be carried out.

Rinsing Chemicals

Through rinsing after dwell times is essential in chemical cleaning. This procedure is often much longer than contractors prefer. The bulk of the chemical should be rinsed by low or mains water pressure to reduce the possibility of hazardous splashing and spray drift during the rinsing. Work should be carried out from the bottom up making sure all runoffs are rinsed of the surfaces beneath. The remainder of the rinsing should be carried out at the selected pressure and should follow a planned rinse pattern. Water must not be allowed to accumulate sills or weathered joints and the surface should be sensed several times over. When rinsing is complete, the pH of the surface should be checked for neutral after 10 and 30 minutes with a stripe. It is quite common for the pH stripe to confirm the need for further rinsing.

Neutralisation

The reaction between alkali and acid produces soluble salts, making it undesirable for neutralisation of the surface. Despite this, it is a common occurrence in chemical cleaning and these salts need to be completely rinsed from the masonry pores. Rinsing is more important here than any other stage of chemical cleaning.

The main problems with using chemical cleaning involve the extent and effects of the retention of chemical residues and the possible mobilisation of salts within the stone. Another problem associated with chemical cleaning is the bleaching or staining of stone surfaces. All these aspects need to be understood and evaluated in relation to the nature of the stone treated and the chemical used. Chemical cleaning damage is irreversible and usually visually dramatic. It should only be used with extensive pre-testing to ensure confidently that there is no damage caused to the building.

2.4.7 Mechanical cleaning

Mechanical cleaning removes soiling by physical forces, cutting or abrasion. These methods involve the use of mechanical forces through hand-held implements or mechanised equipment.

Mechanical cleaning works by abrading the dirt or paint from the surface, unlike water and chemical methods which react with the dirt and masonry. Abrasives can permanently damage the masonry as they do not differentiate between the dirt and the masonry. This means that they result in removing the outer surface of the masonry with the dirt or paint. How much material is removed depends on the masonry involved, and bricks, architectural terra cotta, soft stones, detailed carvings and polished surfaces are especially susceptible to physical and aesthetic damage by abrasive methods. The condition of the masonry is another important factor in determining how much material is removed. Increase in surface roughening is another consequence of mechanical cleaning. Mortar joint, in particular lime mortar, can erode by mechanical or air abrasive cleaning. As a result, re-pointing will become necessary. The most common used methods in mechanical cleaning include the following.

Dry brushing and surface rubbing

This is the simplest form of mechanical cleaning. It is only effective in removing loose and lightly attached dirt and some loosely adherent materials such as moss and some lichens. Brushes with wire or fibre softer than the masonry should be used. Natural fibre brushes come in a range of hardness depending on the size and length of the bristles, and nylon and phosphor bronze brushes can do the same. Fine-wired compact phosphor bronze brushes are often the most effective type of brushes, and their soft wires are suited for many sound and partially sound surfaces. Steel wire brushes must never be used as their stiff wires have damaging effects on masonry. The size and shape of the brush is also of prime importance, followed by the force with which it is used, cleaning materials and processes.

On flat surfaces, hand held rubbing blocks made of materials such as carborundum will remove more surface dirt than brushes, but they are ineffective in removing dirt from within the surface unless layers of the stone surface are removed at the same time. This method is by itself insufficient and should be used in addition to other cleaning methods. Carborundum rubbing leaves soiling in the pores and crevices of the stone, which with time continue to cause damage to the stone.

Surface redressing

Surface redressing causes severe damage to the masonry surface as it uses abrasive discs attached to power tools to remove soiling by cutting back. The processes are very hard to control or to be fully accurate and therefore removal of soiling alone is virtually impossible.

In the past the use of disc cleaning was justified by the need to remove deep soiling or staining caused by paint application. However the use of this method is never justifiable even in those circumstances. Disc cleaning causes too much damage and other methods can bring better success and are usually less damaging if applied correctly.

In the UK the use of surface redressing is increasing. The work is carried out to a very high level by skilled operatives in many cases. The operation nevertheless constitutes the total removal of original or historic material (up to 6 mm deep in Masonry). It can be used in limited areas of masonry repair but not on a large-scale. The most likely reasons for the increase use are cost, the availability of masonry skills and the less prospective measures needed. The cost is minimal compared to the other methods such as water washing, sandblasting and chemical cleaning.

2.4.8 Air abrasive cleaning (sandblasting)

Air abrasive cleaning involves a stream of compressed air directing particles of abrasive materials onto the soiled masonry. Cleaning is accomplished by these particles dislodging the surface layer and the dirt adhering to it. The dislodging of the dirt deposits thus takes place by the breaking up, sometimes to a depth of several millimetres of the surface layer beneath the deposits (Verhoef 1988). Both dry and wet blasting methods have similar effects on cleaned masonry.

Air abrasive cleaning physically abrades the surface of the stone to remove the soiled materials embedded on the stone that have built up over the years. It works by an abrasive material being forced at high air pressure through a nozzle directed at the masonry. The shear force of the abrasive particles removes any dirt, paint, rust and coloration from the surface of the stone. The dislodging of the surface of the stone may go several millimetres deep. The technique requires various abrasive materials and mechanical plant. It is a quick method and is usually considered for large areas of masonry which have few design features. There are two main types of air abrasive cleaning: dry blasting and wet blasting.

The abrasive cleaning does not differentiate between removing soiling and masonry, and the effect of the jet and the abrasive material is largely controlled by the operator. When wrongly applied, it could have a long lasting damaging effect on the wall. It is very time-consuming and expensive to use on historic buildings. It is desirable for heavy soiling as long as it does not cause harm to the fragile and friable fabrics of the building.

Abrasive cleaning is a quick method and is therefore usually considered for large areas of metals or masonry constructions which have few design features. This includes the interiors of factories and warehouses. Parameters must still be established for appropriate use by trial to a small area before proceeding.

The most commonly used system is air pressure blast equipment. The equipment can be transported to the site. Nozzle pressures of 0.02 to 14.0 kPa are typical. Compressed air is fed to a pressure pot containing the abrasive and the two travels along a hose to a blasting gun.

An alternative system to the pressure pot is venture system ‘suction gun’. This is operated by a trigger which is easily controllable by an instant response to the operator requirement. There are various pressure pots and gun sizes in use. The smallest types allow the operator to control the spread of abrasive material and the use of the gun on carved areas. Arrears would be more vulnerable to wide spread of abrasive material than using the larger guns. This method is only suitable for finer abrasives, therefore making it ideal for the cleaning on a small scale and complex architectural details. Usual nozzle pressures are the same as air pressure blast, but the design of the nozzle selected can reduce these significantly (Ashurst 1994a, 1994b).

The following part shows the key issues for air abrasive cleaning (Clifton 1986; Ashurst 1994a, 1994b).

Dry abrasive techniques

The advantages of dry grit blasting (Fig. 2.18) are summarised as follows (Hutchings 1998; Rossi et al 2006):

- The risk of water penetration and saturation of masonry is reduced and therefore efflorescence due to the activation of inherent salt in the stone is avoided;
- It is simple, quick and cheap cleaning method to use;
- There is a great deal of versatility in the materials, equipment and methods in application the abrasive;
- There are a wide range of abrasive materials available;
- Chemical interaction with the masonry is avoided, thus eliminating the possibility of colour changes, bleaching and the deposition of soluble salts;
- It can be used in the removal of heavy deposits, leaving the remaining soiling integrated with the surface for removal by another means;
- For the contractor, it is as easily manageable one-pass system;
- It reduces the risk of stains;
- It is non-seasonal;
- It allows specific areas of stone with soiling to be cleaned;
- The results could be seen immediately.

Fig. 2.18 – Dry grit blasting.

The disadvantages of dry grit blasting are given as follows:

- Because control of cleaning depends solely on the operator, he should have good experience and work with high levels of concentration and observation, and should also consider any variations in the condition of the surface he is cleaning;
- The temptation to work at higher pressures and increased speed is hard to resist, so slight variations to work distance can have considerable damaging effect due to the variation in the pressure applied;
- Despite legislation and localised bans, silica sand is still used as a cleaning abrasive, so inhalation of siliceous dust can cause terminal lung disease which called silicosis and proper protective gear is essential for all operators in the vicinity;
- Because dust penetration can be just as problematic as water penetration, protection must be applied to all the openings and windows, but difficulties in controlling the dust problem frequently lead to the selection of a wet abrasive method;
- Soiling within pores can crevice and can only be removed by removing part of the masonry surface;
- Soft lime based mortar is readily removed by cleaning, even when initially sound, which leads to additional re-pointing;
- Collecting, cleaning and deposing of abrasive material after completion is time consuming;
- Dry blasting surfaces need to be pressure rinsed with water to remove pulverized and embedded material, so staining may result from the next heavy rain shower and dirt left on the stone will go back into the pores;
- Damage to carved, moulded, very smooth or smoothly polished surfaces is very likely if operator is not carful;
- Even when applied as delicately as possible terracotta and faience are easily damaged by abrasive cleaning;
- It is unsuited to many brickwork surfaces;
- The noise of the gun and the impact of the abrasive material will cause the problem when using this method of cleaning, and in some situation the noise

is the main reason for not using the method, with dry and wet abrasive cleaning procedures producing similar noise levels (Ashurst 1994a, 1994b).

Wet abrasive techniques

Wet abrasive cleaning is simply introducing water into dry abrasive cleaning, and this can be done at the gun. Some equipment combines abrasive and water in the pot and enables the use of water for rinsing down of surfaces so as to improve visibility of the surfaces to be cleaned (Hansel 1999, Sitek et al 2013).

It has all the advantages of dry abrasive cleaning listed above except 9 and 10. Also wet abrasive cleaning should be avoided for the same reason except 3 and 4.

The main benefits of introducing water are softening the water-soluble soiling, rinsing down the surface and controlling the dust generated. Although it is easy to assume that the addition of water reduces the severity of cleaning on the wall it is not completely true. The addition of water is more likely to increase the potential for damage. With the reduction of dust brought about comes the addition of a mist containing abrasive material, soiling and masonry particles, which has its own set of problems regarding health and safety. Wet abrasive techniques can induce efflorescence by activating the existing salt loading. It can also stain light coloured stones if too much iron-contaminated water is used.

The operator can clean to a higher quality if he has better control of air, abrasive material and water, which enables him to rinse down the surface. In general, wet abrasive cleaning is messy on the building face, scaffolding and ground.

Pencil abrasive technique

Pencil microblasting works on the same principal as abrasive cleaning but on a much smaller scale (Fig. 2.19). In turn, a smaller amount of damage can be caused. Finer, softer material (50 to 100 µm) is used as abrasive material. The nozzle is about the size of a pencil. Moisture in the abrasive is a problem when used on site, as flow will be affected by moisture. Because much time and skill is needed to properly operate this technique, it is mainly used in cleaning small features and artefacts in museums.

Fig. 2.19 – Pencil abrasive blaster.

The parameters which need to be considered in an abrasive cleaning can be summarised as follows (Clifton 1986; Ashurst 1994a, 1994b).

The substrate

The type and nature of the substrate and its soiling are the biggest factors influencing the effect of abrasive cleaning. Terracotta, certain bricks and some types of sandstone are particularly vulnerable to damage by abrasive cleaning.

The operator

The operator is an important factor affecting how much cleaning finished on time and damage caused. He controls the amount of abrasive material each area receives by controlling the speed and distance at which he works as well as the amount of times he passes the nozzle over an area.

Air pressure

The inverse square law states that, if the distance between the nozzle end and the masonry in halved with all other aspects being equal, the effective working pressure will increase by a factor of four.

Abrasive material

The main characteristics of abrasive materials are their shape and size. Round particles are more effective in removing hard brittle soiling whereas angular particles are effective in removing soft or non-brittle soiling. Siliceous abrasives are cheaper but should not be used. Despite being forbidden by The Health and Safety at Work Act (1974), siliceous materials are still being used.

A range of different types of abrasive material exist, including non-siliceous grit, copper slag, mineral slag, carborundum, aluminium oxide powder, olivine, dolomite, crushed walnut shells, olive pips, nutshells, minute glass beads and flour. One of the largest entrants on the UK abrasive cleaning market is a calcium carbonate fine powder, wounded with roughened edges.

The finest abrasive materials available are aluminium oxide (10, 27 and 50 µm), silicon carbide (50 µm) and crushed glass (75 µm). The type and condition of stone, the equipment used and the operator's skills and experience contribute to the effectiveness of sandblasting cleaning.

The shape and size of the nozzle appropriate to the job in the hand must be determined before the main work begins. Long venture nozzles are more efficient and give an even particle spread over a greater impact area if applied at a constant distance from the surface at any pressure. They are ideal for flat areas or consistent soiling conditions. Long and short straight nozzles, whilst less efficient, provide a more pencil-shaped blast which is ideal for cleaning window seals and channels and taking out poor pointing. Angles nozzles are also available. Large nozzles spread abrasive material too widely on moulded or decorative surfaces. Cleaning in these instances is taking place over a range of distances and leading to some damage. Selecting a nozzle of appropriate size is very important when carrying out quality abrasive cleaning. Nozzles which have worn and are used outside their design life are more likely to cause damage to the stone surface.

Air/abrasive mixture

An even flow of air and abrasive needs to be delivered to the masonry surface. Damage was observed by using excessive supply of abrasive material. Efforts should be made to apply as little abrasive material as possible to gain as much cleaning effect.

2.5 Summary

This chapter has systematically introduced the formation of natural rocks, including igneous rocks, sedimentary rocks and metamorphic rocks, and various types of natural stones for buildings and walls. It has also briefly introduced various types of soiling and decay which may form on the building façades.

Various issues for the listed buildings for their architectural features worldwide have been summarised, including selecting criteria, grading, spotting, updating, removal and appearing. Useful information about listing, building consent and conservation areas has also been provided, together with scheduled monuments and historic building repair funding scheme.

The soiling and decay of building façades and potential biological and non-biological soiling have been extensively introduced and discussed. Biological soiling contains bacteria, algae, fungi, lichens, mosses and higher plants, while non-biological soiling contains aerosols, soot and other non-biological contaminants like paints and aerosol paint. Stone decay includes environmental decay, mechanical decay, mortar decay and salt decay.

This chapter has indicated the reasons and precautions for cleaning stone buildings by categorising the building cleaning types as water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting) and clarifying the advantages and disadvantages for each method. It has also detailed the stone cleaning process including pre-cleaning measures and trial cleaning.

CHAPTER 3 EXPERIMENTAL INVESTIGATIONS

Great Britain and the masonry stones have, since the beginning of the human history, shared an extensive common narrative. The first sculpted stones (Neolithic period, 2000 BC) have been found in Scotland (Zenil 2011). This relationship is still highly significant due to the great variety of monuments and buildings built with masonry stones in the UK. Anyone who travels around the UK would notice its numerous castles built with stones. Take Scotland for example, this fact is quite relevant in City of Edinburgh. One of the greatest castles in Scotland is Edinburgh Castle, which is surrounded by hundreds of ancient buildings. Almost all the buildings in the Old and New Towns of Edinburgh were built with masonry stones or clay bricks. The masonry stones and clay bricks that are most commonly used for these buildings are: granite, limestone, marble, red sandstone, yellow sandstone, red clay brick, and yellow clay brick. In this Chapter, firstly, a brief introduction on the different types of masonry stones and abrasive materials will be given, followed by extensive investigations of the impact of air abrasive cleaning on the mechanical and material properties of the masonry stones and bricks. The investigations include the impact tests and sieve tests on the abrasives, and thickness reduction measurements on the masonry stone and brick samples during the cleaning process.

3.1 Samples of Masonry Stones and Clay Bricks

In this research, a total of seven types of masonry stones and clay bricks are to be studied. General material properties of these stones have been discussed in Chapter 2. To obtain a better understanding of these masonry stones and clay bricks, it is important to illustrate their main properties and divide them accordingly into one of the three groups according to their hardness: hard stones, medium hard stones and soft stones. Hard stones include limestone and granite, medium hard stones include marble, and soft ones include red sandstone, yellow sandstone, red clay brick and yellow clay brick.

According to Hyslop et al (2006) and STATS (2007), the main characteristics of these masonry stones and clay bricks are described as follows.

Granite

Granite is an igneous rock and is essentially composed of quartz, feldspar and mica (Fig. 3.1). It is one of the most common igneous rocks and is widely used in Scotland, especially in Aberdeen, which is known as 'the granite city'. This rock is of a high strength and it is also quite resistant to chemical reactions.

Limestone

Limestone is a sedimentary rock, mainly composed of calcium carbonate (Fig. 3.2). This rock is quite easy to recognise because it normally contains small fossils. It is one of the most popularly used stones in construction. Normally, it is not really stable when undergoing chemical reactions but it does not have a high strength.

Fig. 3.1 – Granite (Piedra, 2013). **Fig. 3.2** – Limestone (Piedra, 2013).

Marble

Marble is a heavily compacted metamorphic rock and is created as a result of limestone's susceptibility to both high temperatures and high pressures (Fig. 3.3). Marble is weaker than granite but stronger than limestone and it can be easily chemically modified.

Sandstone

Sandstone is a sedimentary rock, formed mainly of quartz. It has a cement matrix of clay and/or calcite (Fig. 3.4), but it is less popularly used in construction than limestone because it is easily degraded.

Fig. 3.3 – Marble (Piedra, 2013).

Fig. 3.4 – Sandstone (Piedra, 2013).

The main physical and chemical properties of the studied stones suggested by Mineral Zone (Piedra 2013) are shown in Tables 3.1 and 3.2, respectively.

Table 3.1 – Physical properties of natural stones.

Stone	Hardness	Density	Compressive Strength	Water Absorption
	Mohs' Scale	kg/cm^3	N/mm^2	%
Granite	6 to 7	2.6 to 2.8	140 to 210	0.1 to 0.6
Limestone	3 to 4	2.5 to 2.7	60 to 170	> 1
Marble	4 to 4	2.55 to 2.7	70 to 18	> 0.5 %
Sandstone	6.5 to 7	2.3 to 2.4	90 to 140	1.0 to 1.2

Clay bricks

Cay bricks are artificial stones made mainly of clay and sand. It is subjected to physical and chemical process until they achieve certain strength. Their properties are relative to their chemical compositions. According to Punmia et al (2005) the general chemical compositions of typical clay bricks are shown in Table 3.3.

Table 3.2 – Chemical properties of natural stones.

Stone	Granite	Limestone	Marble	Sandstone
Chemical component	%	%	%	%
Silica (SiO_2)	70 to 75	15 to 18	3 to 30	95 to 97
Alumina (Al_2O_3)	10 to 15	3 to 5	x	1 to 1.5
Lime (CaO)	x	38 to 42	28 to 32	> 0.5
Magnesia (MgO)	x	0.5 to 3	20 to 25	> 0.5
CaO + MgO Lime + Magnesia	> 0.5	x	x	x
Oxides of Iron (FeO + Fe_2O_3)	2 to 4	1 to 1.5	1 to 3	x
Alkalis	4 to 6	1 to 1.5	x	x
Titanium dioxide (TiO_2)	> 0.5	x	x	x
Loss on Ignition (LOI)	> 0.5	30 to 32	20 to 45	> 0.5
Na_2O + Kro Soda + Potash	x	x	x	> 1
Ferric Oxide (Fe_2O_3)	x	x	x	0.5 to 1.5

Table 3.3 – Chemical compositions of clay bricks.

Chemical component	%
Silica (SiO_2)	50 to 60
Alumina (Al_2O_3)	20 to 30
Oxide of Iron (Fe_2O_3)	5 to 6
Lime (CaO)	2 to 5
Magnesia (MgO)	< 1

3.2 Abrasive Materials

Depending on the function of the used abrasives, abrasive cleaning has different consequences. In this project, three main types, with seven sub-types, of abrasives are adopted so as to provide a wide range of combinations. They are Copper slag (coarse, medium and fine), Recycled glass (coarse, medium and fine) and Natural abrasive (such as recycled coconut abrasive). Both slag and glass abrasives are industrial by-products and are regarded as non-natural abrasives. Table 3.4 illustrates these abrasives in more detail.

Natural abrasive is made of recycled agricultural materials such as husk of coconut almond or walnut, etc. Since they are naturally grown materials, they have no harm to the environment when being produced or used during the cleaning. As naturally grown materials, they have little negative impact on the residential buildings being cleaning. As recycled materials they are economical to be used in stone cleaning. They are different from unnatural abrasives such as slag and recycled glasses, which are artificial materials, according to SCANGRIT (2010), and are made from iron silicate, which forms an inert synthetic material. They do have some level of impact to the environments when being produced. However, they do not produce chemical reactions when projected onto the stone, and they also produce little or no dust. The particles are mainly angular in shape. The main physical properties of slag abrasives are listed in Table 3.5.

Table 3.4 – Abrasives used for this research.

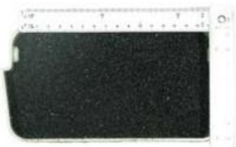
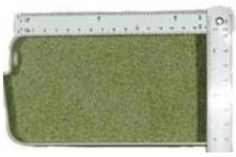
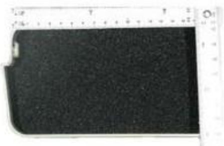
No	Abrasive	Photograph	No	Abrasive	Photograph
1	Coarse Slag		5	Medium Glass	
2	Medium Slag		6	Fine Glass	
3	Fine Slag		7	Natural Abrasive	
4	Coarse Glass				

Table 3.5 – Physical properties of slag abrasives.

Slag	Particle Size	Hardness	Bulk Density
	μm	Mohs' Scale	g/cm^3
Fine	200 to 850	7 to 8	1.7
Medium	200 to 1700		
Coarse	500 to 2000		

The main physical properties of Recycled glass, according to SCANGRIT (2004), are presented in Table 3.6. This type of abrasive is made from 100% recycled glass. It holds an angular shape, and it produces little or no dust like slag.

There is a trend of using environmentally friendly natural abrasives in recent years. One of the most common natural abrasives, also commercially named as 'Granalla', is a natural product which is composed of grains of coconut and almond shells. It has a slightly angular and polyhedral shape, giving a less satisfactory performance. The main physical properties of this material are shown in Table 3.7 (MPA n.d.). Here *n.d.* stands for *No Date*.

Table 3.6 – Physical properties of recycled glass.

Recycled glass	Particle Size	Hardness	Bulk Density
	μm	**Mohs' Scale**	g/cm^3
Fine	200 to 500	5 to 6	1.3
Medium	500 to 1250		
Coarse	1000 to 2000		

Table 3.7 – Physical properties of natural abrasive.

Particle Size	Hardness	Bulk Density
μm	**Mohs' Scale**	g/cm^3
300	3	0.7 to 0.8

3.3 Air Abrasive Cleaning

Air abrasive cleaning has been selected from all the cleaning methods available in the market because it utilises a wide range of abrasives. This has turned out to be a big number of combinations of masonry stones and clay bricks with abrasives. Furthermore, the application of this method is quite simple.

The main features of air abrasive cleaning are given as follows (Ashurst and Ashurst 1988; Verhoef 1988; Ashurst 1994):

- The cleaning uses a pressure jet with mixed air and abrasive particles;

- Air abrasive cleaning can be seen as a faster and more effective cleaning method, which depends on the size, strength, pressure applied and distance to the stones of the particles used;
- The operator needs to be well trained for this method and be adequately protected from the abrasive particles, dust and noise;
- It is suitable for plain surfaces;
- It does not stain the surface of the masonry stones or bricks, since no water is involved;
- It can be used all year around and on almost every type of soiling;
- When it comes to soft stones, or non-uniform soiling on the area of the stone, this type of cleaning can produce an excessive loss of material.

As shown above, seven masonry stones and clay bricks and seven types of abrasives have been selected for this study, which has formed a total of forty-nine combinations. The test samples were obtained from stones and bricks subjected to weathering. Because the stone samples were collected from different locations they did not have the same initial conditions. The main stones and bricks were cut into small samples with dimensions between 3 cm and 7.5 cm (Figs. 3.5 and 3.6).

Fig. 3.5 – The builder was cutting Red sandstone.

Fig. 3.6 – Red sandstone samples.

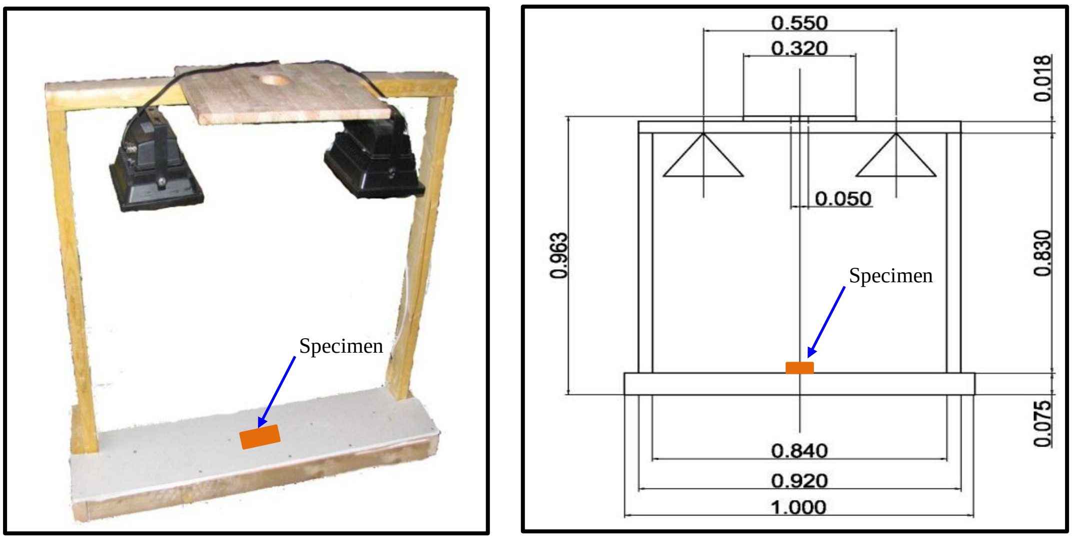
Specific equipment was used to carry out masonry cleaning, including a shot blasting cabinet (Fig. 3.7) and a compressor (Fig. 3.8).

Fig. 3.7 – Shot blasting cabinet. **Fig. 3.8** – Compressor.

The procedure to clean each stone or brick sample is summarised as follows:

- A photograph of the stone or brick sample under the initial conditions was taken, together with a measure of the initial thickness. The sample was placed in a timber frame specially designed for this study (Figs. 3.9(a) and (b)). This frame allowed all the photographs being taken from a fixed distance, under the same intensity of light. Two lamps of 400 Watts were used to illuminate the samples. To measure the sample thickness at each cleaning stage, an electronic digital calliper was used on the same point of each sample.
- The shot blasting cabinet was filled with abrasives.
- The operator put his hands into the safety gauntlets. Through the side door, the stone or brick sample was placed inside the cabinet, so that the operator could hold the sample.
- The stone or brick sample was cleaned over a certain time, normally for a few seconds. The operator kept the nozzle 15 to 20 cm away from the sample. Afterwards, the sample was taken out and placed in the frame in order to assess the changes in the sample. Also, the reduction in the thickness was measured and recorded. Thereafter, the sample was returned to the shot blasting cabinet to be further cleaned.
- This procedure was repeated until the stone or brick sample was considered to be completely cleaned.

A flow chart of the cleaning procedure is shown in Fig. 3.10.



(a) – The timber frame. **(b)** – Dimensions of the frame (m).

Fig. 3.9 – Detail of the timber frame.

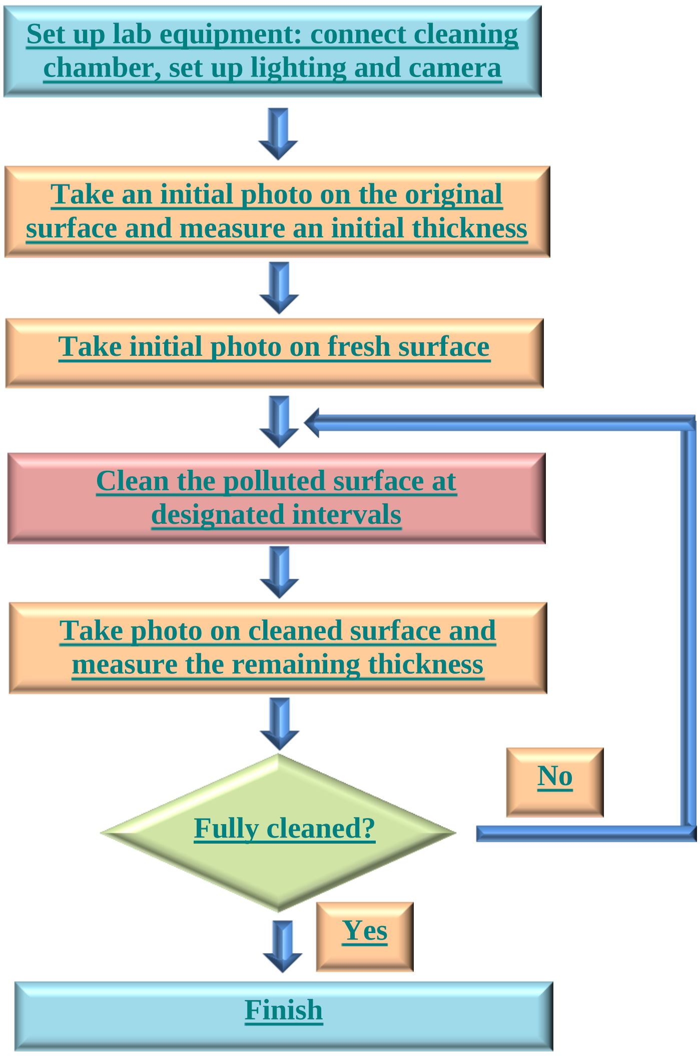


Fig. 3.10 – Flow chart of air abrasive cleaning procedure.

The number of cleaning stages and the time length for each stage depended on the type of masonry stone or clay brick and the type of abrasives used. The minimum number of cleaning stages was six and the maximum number was twenty-three, such as in the case of the red clay brick.

In order to identify each cleaned masonry stone or clay brick, a numbering system was created. The abrasives were numbered from 1 to 7, and as shown in Table 3.4, the stones cleaned with that abrasive had the same number. For example, when a sample of marble was cleaned using the medium slag abrasive it was designated as "2. Marble". The marble sample corresponding to the initial conditions was defined as "2-1 Marble", and the following cleaning stage was defined as "2-2 Marble", and so on, until the sample was fully cleaned.

Throughout this cleaning series two problems occurred:

- Coarse glass particle sizes reached almost the same size as the inner diameter of the nozzle, which reduced the amount of the abrasive that could be blown out. However, it did not cause any significant inconvenience to the continuation of the trial.
- Although the frame provided a fixed brightness, not all the photographs were exposed to the same degree of brightness. This happened because it was possible for light to come indirectly through the opened door and shine onto the samples. This means that light conditions were inconsistent.

3.4 Impact Tests and Sieve Tests on the Abrasives

Both impact tests and sieve tests were carried out for assessing variations of the abrasives. Because each abrasive had a distinct nature, e.g. size, fineness, hardness, etc., each one showed a different performance. It is interesting to analyse the relations between the characteristics of these abrasives and their performances on each masonry stone or masonry brick.

3.4.1 Impact tests

Impact tests have been conducted to assess the mechanical resistance of each abrasive to impact loading. To carry out this test an impact tester was needed. This apparatus included a metal frame as shown in Fig. 3.11, which held a metal hammer of 13.5 kg. A cylindrical steel container was also provided to hold the abrasives.

To carry out the test the first step was to fill in the container with the abrasives (Fig. 3.12(a)). Then the weight of the sample was measured using an electronic scale (Fig. 3.12(b)). The next step was to drop the hammer onto the abrasive sample 10 times. The weight after the impact test was also measured (Fig. 3.12(c)).

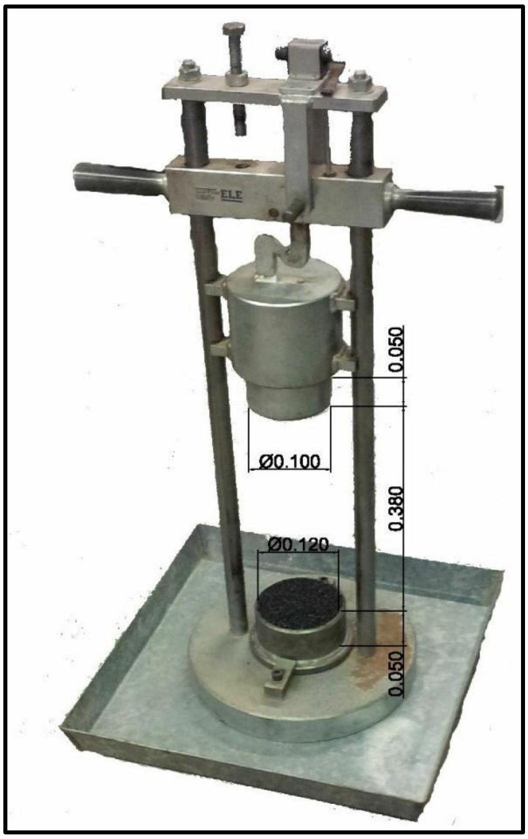


Fig. 3.11 – Impact Tester.

(a) Filling the cup **(b)** Before impact test **(c)** After impact test

Fig. 3.12 – Weight measurement of the fine slag before and after the impact tests.

The same procedure was repeated for each of the seven abrasives.

3.4.2 Sieve tests

According to the suppliers, each abrasive was composed of particles with a range of sizes. By conducting sieve tests, the mechanical resistance of each abrasive could be assessed, and also according to Garber (2006) the accurate values of the Fineness Modules (FM) of each abrasive could be determined before and after the impact tests. The fineness modules can also have great impact on the performance of the stone cleaning. It will be very useful to combine the outcomes of the abrasive FM from the sieve tests and the data detailed in Table 3.8 to decide an effective method of cleaning for different type of stones.

BS EN 933-1 (2012) specifies that sieve test "consists of dividing and separating a material into several particle size classifications of decreasing sizes by means of series of sieves."

The sieve sizes used were 4000 µm, 2000 µm, 1000 µm, 500 µm, 250 µm, 125 µm and 63 µm (Fig. 3.13). The sieves were placed on the shaking machine as shown in Fig. 3.14. A weight of approximate 1 kg for each abrasive was poured into the sieves.

Each sample was shaken for 15 minutes in the shaking machine. Thereafter, the materials retained in each sieve (Fig. 3.15) were weighed using an electronic scale as shown in Fig. 3.16. This procedure was repeated for each abrasive before and after the impact tests.

3.4.3 The results of the impact tests and sieve tests

The results obtained from the impact tests are listed in Table 3.8. The abrasive which lost the smallest amount of materials was the coarse glass, while the abrasive which lost the largest amount of materials was the natural abrasive. These lost abrasive particles bounced out of the plate onto the floor and could not be collected back, but this would not affect the final results. Furthermore, the abrasives with less weight placed in the cylindrical container would have smaller bulk densities, with the following order from high to low: medium slag, coarse slag, fine slag, coarse glass, medium glass, fine glass and natural abrasive.

Fig. 3.13 – Sieves.

Fig. 3.14 – Shaking machine.

Fig. 3.15 – Coarse slag retained in the 500 µm sieve.

Fig. 3.16 – Weighing of the retained sample.

Table 3.8 – Impact test results.

No	1	2	3	4	5	6	7
Abrasive	**Coarse slag**	**Medium slag**	**Fine slag**	**Coarse glass**	**Medium glass**	**Fine glass**	**Natural abrasive**
W_i (g)	793.22	814.50	788.68	609.09	602.00	575.84	256.00
W_f (g)	779.11	801.68	777.13	601.21	588.48	554.17	224.90
ΔW (%)	1.78	1.57	1.46	1.29	2.25	3.76	12.15

Note: W_i = Weight before the impact tests, W_f = Weight after the impact tests, ΔW = Weight reduction in percentage.

To analyse the output data from the sieve tests before and after the impact tests, it was necessary to calculate the cumulative percentages of mass that either passed each sieve or retained in it, as suggested by BS EN 933-1 (2012). The weight of the abrasives that pass through the sieve n, $W_{passing,n}$, can be calculated from:

$$W_{passing,n} = W_{total} - W_{sieve,n} \tag{3.1}$$

where

W_{total} is the sum of the weights of the abrasive particles in all the sieves,

$W_{sieve,n}$ is the weight of the abrasive particles retaining in the sieve n and above.

The passing rate for the sieve n, $P_{passing,n}$,, can be calculated from:

$$P_{passing,n} = (W_{passing,n} / W_{total}) \times 100 \tag{3.2}$$

The weight of the abrasive particles retained in the sieve n, $W_{retaining,n}$, is given as:

$$W_{retaining,n} = W_{retaining,n-1} + W_{sieve,n} \tag{3.3}$$

Finally, the retaining rate of aggregate in the sieve n, $P_{retaining,n}$, is:

$$P_{retaining,n} = (W_{retaining,n} / W_{total}) \times 100 \tag{3.4}$$

An example of these calculations is showed in Table 3.9.

Table 3.9 – Sieve test results before the impact tests for the fine slag.

Sieve size	W_{sieve}	$W_{passing}$	$P_{passing}$	$W_{retaining}$	$P_{retaining}$
(µm)	(g)	(g)	(%)	(g)	(%)
4000	0.00	999.95	100.00	0.00	0.00
2000	0.00	999.95	100.00	0.00	0.00
1000	0.17	999.78	99.98	0.17	0.02
500	632.48	367.30	36.73	632.65	63.27
250	302.73	64.57	6.46	935.38	93.54
125	58.57	6.00	0.60	993.95	99.40
63	5.90	0.10	0.01	999.85	99.99
Pan	0.10	0.00	0.00	999.95	100.00
W_{Total}	**999.95**				

A set of tables with the test results for each abrasive, before and after the impact tests, have been created (see Appendix A). From the tables, the values of the weight of the abrasives retained in the sieve in percentage ($P_{retaining}$, %) have been plotted as a function of the sieve size in µm. Two sets of figures were created. In the first set of two figures, the relationships between $P_{retaining}$ and the sieve size for all the abrasives were plotted (see Figs. 3.17 and 3.18). In the second set with only one figure for each abrasive, the relationships between $P_{retaining}$ and the sieve size before and after the impact tests were compared. This is illustrated in Fig. 3.19. Complete sets of figures are presented in Appendix A.

Comparing Fig. 3.17 with Fig. 3.18 indicates that for all abrasives the particle size distribution curves adopt a similar shape. The biggest variation was found when testing the natural abrasive. After it underwent the impact test, the amount of abrasive material retained in the sieve of 250 µm had increased by more than 0.3%. The output data from the impact test showed that the finest abrasives for each type of abrasive had the highest changes in their size distributions. The abrasives with the smaller reductions in their weight after the impact tests were those with smaller changes in the particle size distribution.

A better appreciation of the effects of the impact tests on the particle size distribution can be seen in Fig. 3.19.

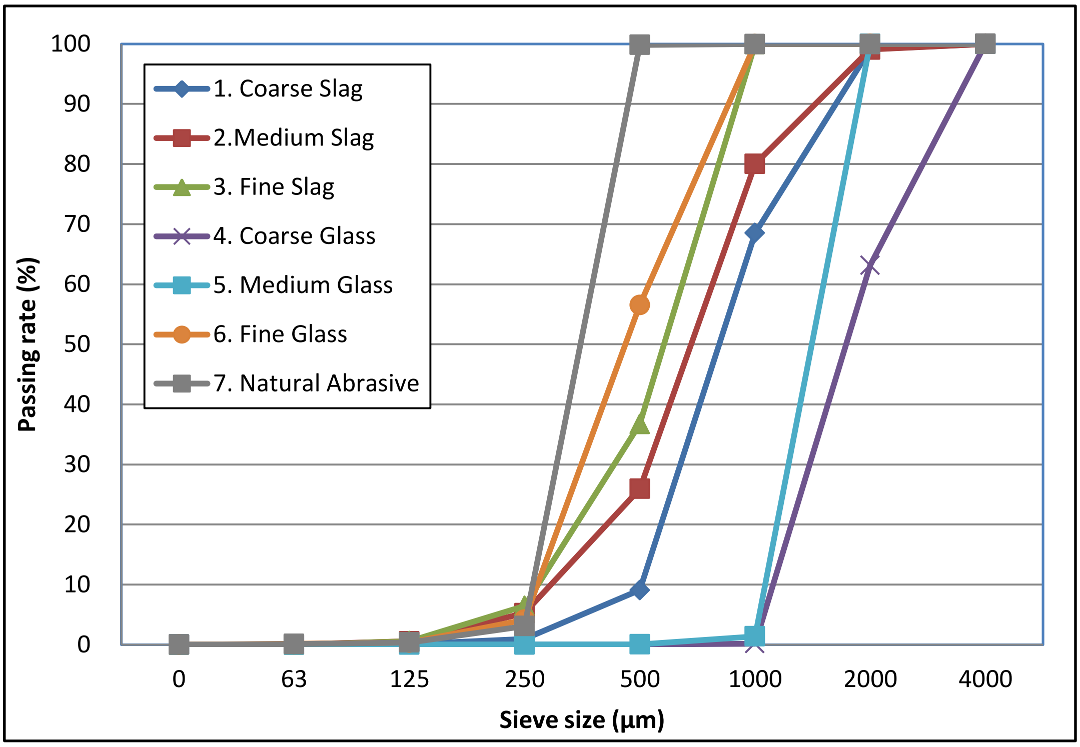


Fig. 3.17 – Sieve test results before the impact tests for all abrasives.

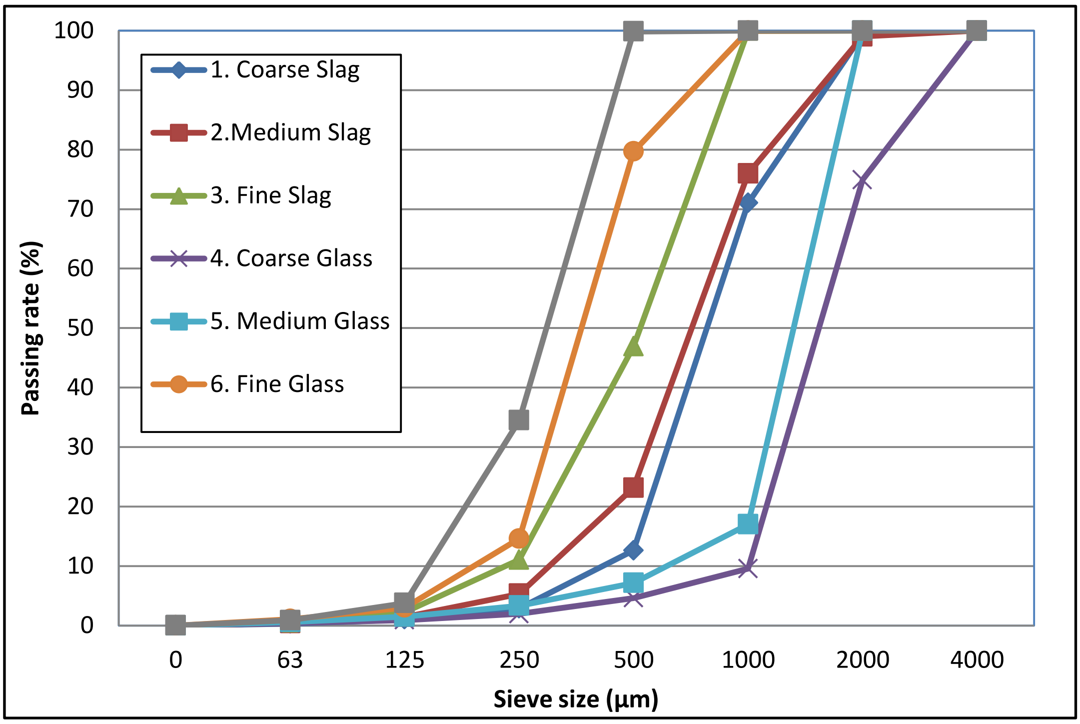


Fig. 3.18 – Sieve test results after the impact tests for all abrasives.

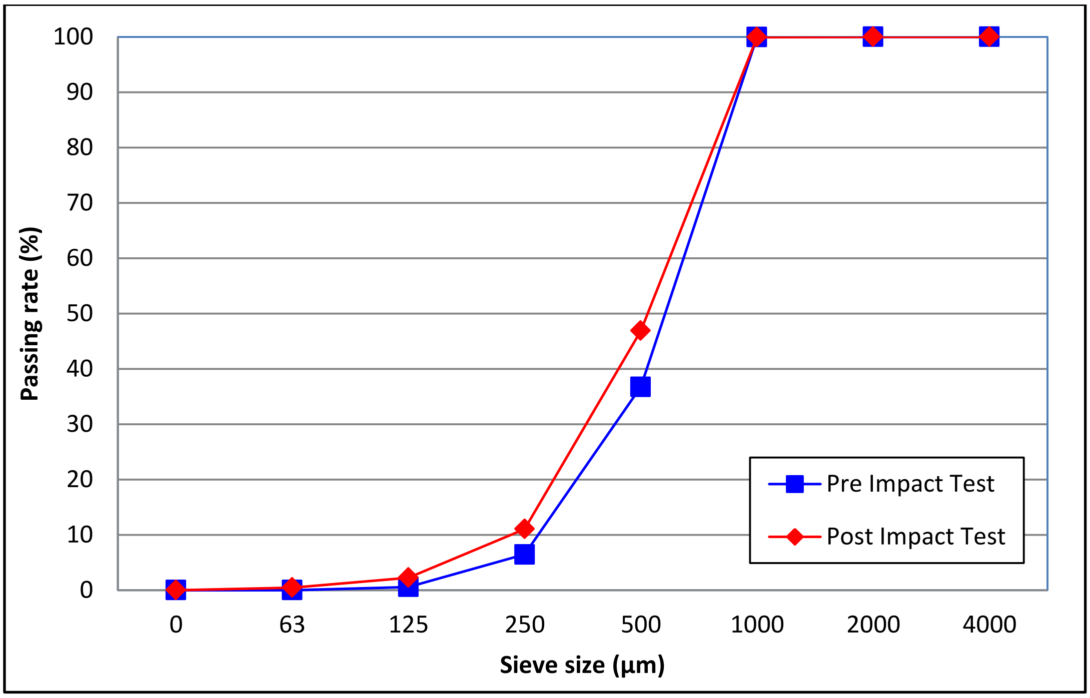


Fig. 3.19 – Sieve test results before and after the impact tests for the fine slag.

For the fine slag abrasive, the biggest change was noticeable when using the 500 µm sieve, with a difference of around 10 percentages, which was due to more finer abrasive particles produced during the impact tests. However, the fine slag together with the coarse slag, medium slag and coarse glass, showed smaller changes in their distributions before and after the impact tests. Thus, looking again at Table 3.8, these four abrasives showed the smaller weight reductions among the seven types of abrasives.

Based on the retaining percentage data, another parameter, the Fineness Modulus (FM), can be obtained. The FM is an empirical parameter obtained from the sum of all the $P_{retaining}$ values previously calculated, which must then be divided by 100, as suggested in CRD (1980) as:

$$FM = (P_{retaining,n} + P_{retaining,n+1} + \ldots + P_{retaining,n+m}) / 100 \qquad (3.5)$$

Using Eq.(3.5) on the data obtained from the sieve tests before and after the impact tests, the FM values have been determined and are listed in Table 3.10.

Table 3.10 – Fineness moduli for all abrasives studied.

No.	Abrasive	FM_{PreIT}	FM_{PostIT}	$FM_{PreIT} - FM_{PostIT}$
1	Coarse slag	5.22	5.13	0.09
2	Medium slag	4.89	4.85	0.04
3	Fine slag	4.56	4.39	0.17
4	Coarse glass	6.37	6.08	0.29
5	Medium glass	5.98	5.71	0.27
6	Fine glass	4.39	4.02	0.37
7	Natural abrasive	3.97	3.61	0.36

Table 3.10 shows that the higher FM values corresponded to the coarser abrasives, while the lower FM values corresponded to the finer abrasives. Moreover, the FM values for all abrasives decreased after the impact tests. Comparing the results in Table 3.10 with the abrasive sizes provided by the suppliers shows that the abrasives with higher reductions in the FM were those finer abrasives. Furthermore, the fineness moduli, before the impact tests for the coarse glass and natural abrasive, had extreme values, so fairly different performances can be expected after the impact tests for all the studied masonry stones and clay bricks.

After further investigations, the test results showed clearly that fine glass and natural abrasives could not be re-used after the cleaning process. On contrast, the slag abrasives could be re-used.

3.5 Thickness Reduction during Cleaning Process

Surface degrading is one of the key parameters that should be closely monitored during the cleaning process as it not only influences the texture of the building façade but also affects the structural strength of the masonry stones and bricks. The monitoring of cleaning effectiveness in this research is also based on the observation of the changes of the sample thickness during the cleaning. Thickness reductions for all masonry stone and brick samples were continuously measured throughout the whole cleaning process by using an electronic digital calliper with a precision of 0.01 mm following the procedure described in Section 3.3 (also see Appendix C). A large amount of data was obtained accordingly. Owing to the abrasion caused by the abrasive cleaning, all the stone and brick samples sustained a monotonic reduction in their thickness. However, not all of them behaved in the same way.

Several factors governed the amount of materials worn away by the abrasive cleaning. The material properties of the stones and abrasives were the most relevant influential factors. As indicated in Section 3.1, the properties of the selected stones and bricks in this project were largely different. Thus, depending on individual samples, distinct variations in their performance could be expected. Furthermore, Section 3.2 demonstrated that each type of abrasive offered unique characteristics with respect to its size, shape, strength and hardness. On top of these two factors, it is also very important to take into consideration the nature of the soiling on the stones and bricks. Nevertheless, soiling nature was more related to the number of cleaning stage and the time length of cleaning than the thickness reduction, although a relationship between the cleaning stage number and the concurrent thickness reduction was obvious. Figs. 3.20 and 3.21 show different trends of the thickness reduction Δa with the cleaning time t for two different stones (limestone and marble) cleaned with the same fine slag abrasive.

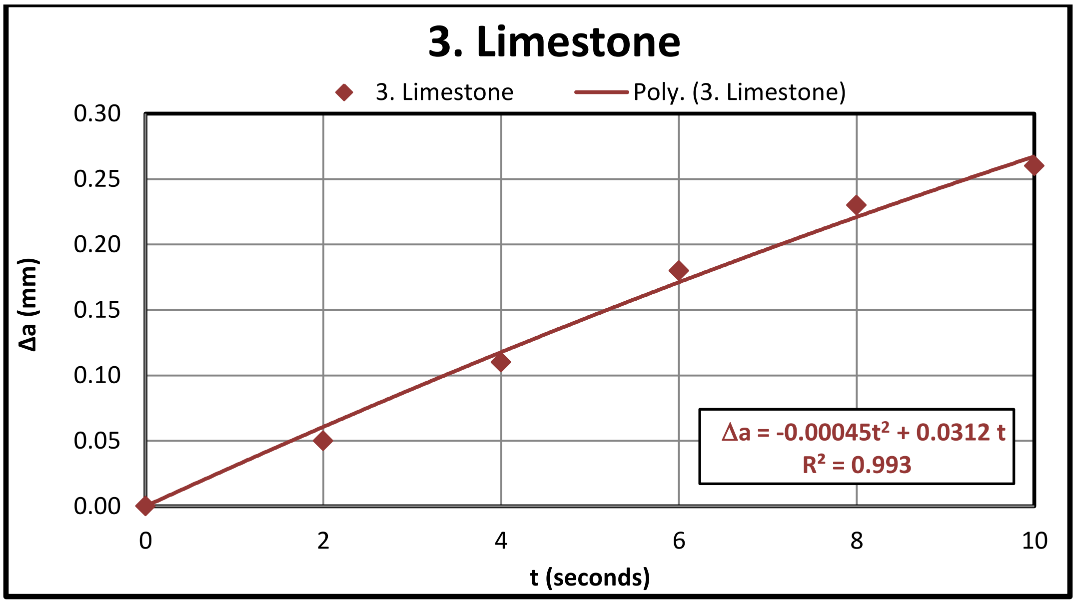


Fig. 3.20 – Thickness reduction versus cleaning time for the Limestone cleaned with the fine slag.

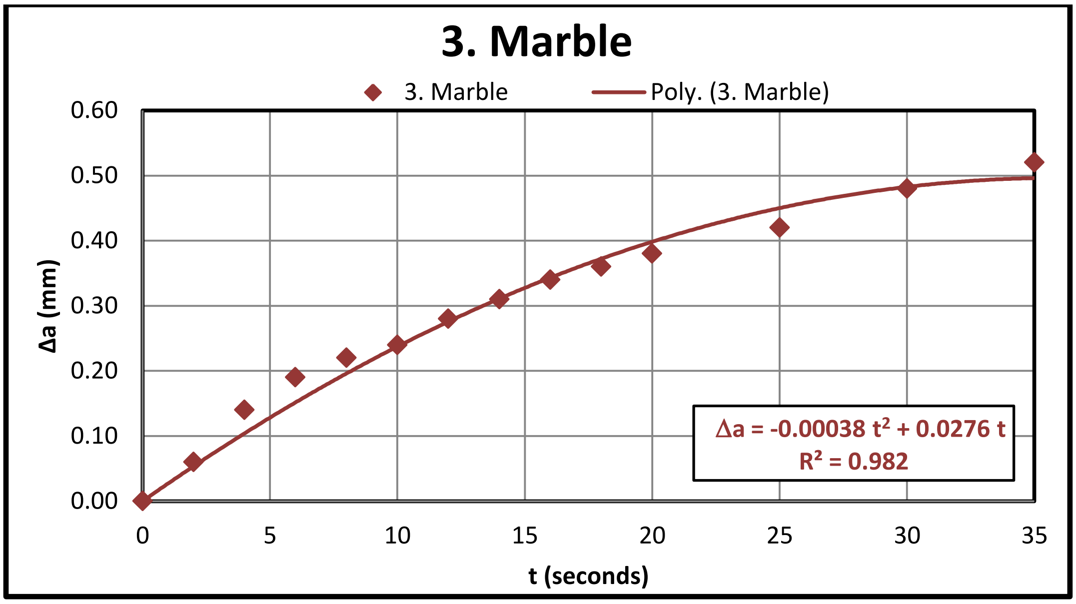


Fig. 3.21 – Thickness reduction versus cleaning time for the Marble cleaned with the fine slag.

For the limestone, only ten seconds were required to complete the cleaning process (Fig. 3.20), while for the marble, a time period three times longer was required (Fig. 3.21). Thus, the cleaning degree was also deeper for the marble than for the limestone. Also, the value of the thickness reduction for the marble was exactly twice as much as that for the limestone, 0.52 mm versus 0.26 mm, respectively. Both figures gave very high R^2 values, 0.994 versus 0.982. Appendix D includes all the output data on the thickness reduction. In Section D.1, all the thickness reductions for the granite are presented, and it can be observed that except for the cases where the coarse glass and natural abrasive were used, it only needed ten seconds to undergo the cleaning process. In addition, all the test results can be plotted using parabolic curves, with the R^2 values varying between 0.962 and 0.996 which are very high. Thus, a consistent performance could be assumed for the granite, using any abrasive. However, this is not applicable for all the cases. To achieve the same thickness reduction using the coarse slag and coarse glass, only 10 seconds were required for the former but 50 seconds were required for the latter. Furthermore, only six cleaning stages were required for the coarse slag, but eleven cleaning stages were required for the coarse glass.

By observing all seven plotted cases, in terms of the time required for completing the cleaning, both coarse glass and natural abrasive produced the worst performances due to their longer cleaning times. In terms of the thickness reduction, the coarse slag and coarse glass caused a higher loss in the material. This was to be expected since these two abrasives were the coarsest ones. Hence, the coarse slag, coarse glass and natural abrasive can be regarded to be less suitable for cleaning the granite.

The limestone had a wider range of results than the granite. The thickness reduction fluctuated between 0.10 mm (fine glass) and 0.64 – 0.67 mm (coarse glass and medium glass), and the time required varied between 10 seconds for the fine slag and fine glass and 140 seconds for the coarse glass and natural abrasive. However, all the results can be fairly well predicted using parabolic curves, with high R^2 values of over 0.90.

As for the results for the limestone, it seems that the fine glass was the most suitable abrasive to clean this type of stone and it is not advisable to use the coarse glass. This indicates that even if the same abrasive is used for cleaning the surface of a stone or a brick, the particle sizes play a decisive role in the final performance.

By looking into the results presented for the marble, except the coarse glass and natural abrasive, all other abrasives caused a thickness reduction within a range between 0.30 and 0.50 mm and had a cleaning time between 25 and 50 seconds. Again, the coarse glass and natural abrasives showed the worst performance when compared with the rest of the abrasives.

The red clay brick samples came out with the longest cleaning time. They required only 10 seconds when the fine glass was used, but 900 seconds were needed when the natural abrasive was used. The natural abrasive, although it required a much longer cleaning time, did not cause a large thickness reduction (only 1.23 mm). The largest thickness reduction was 1.48 mm, which was caused by using the coarse slag. For the red clay brick, the medium glass was less abrasive, with a thickness reduction of 0.34 mm. According to the test results and by taking into consideration that the clay brick was not a very homogeneous material, the most suitable abrasive for the red clay brick should be the medium glass because it caused the smallest thickness reduction and only took 14 seconds. On the other hand, the natural abrasive should be regarded as the least suitable for the red clay brick, since cleaning the sample took 900 seconds.

The test results show that the red sandstone may be one of the toughest stones to clean. The minimum cleaning time required was 60 seconds, which was attained by using the fine glass, and the maximum cleaning time was 420 seconds by using the coarse glass. The natural abrasive caused a thickness reduction of 2.15 mm and the fine glass only caused a thickness loss of 0.95 mm. Even so, the red sandstone still suffered a higher thickness reduction than the red clay brick. Thus, if an abrasive has to be considered as the least appropriate for cleaning the red sandstone, the coarse glass, due to its need for a longer cleaning time, would be the obvious one. The least harmful abrasive which could be used should be the fine glass. This is because even though it needed 20 seconds more than the fine slag for completing the cleaning, it was still the one that caused the smallest thickness reduction.

In contrast with the test results for the red clay brick, the results obtained from the yellow clay brick samples were quite consistent. Except the coarse glass, the results for all other abrasives illustrated similar values. The cleaning times varied between 10 and 20 seconds and the thickness reduction induced ranged between 0.20 mm and 0.30 mm. In the case of thickness reduction, the coarse slag was also regarded to be exceptional, causing a reduction of 0.66 mm in thickness. By analysing the test results, the coarse slag was demonstrably the least beneficial abrasive to use on the yellow clay brick, by causing a thickness reduction of 0.66 mm in 10 seconds. As a result of this rapid reduction, should the cleaning operator be insufficiently skilled, severe damage to the stone could occur. Contrastingly, the fine slag, since it produced the smallest thickness reduction over a time period of 10 seconds, could be regarded as the most suitable abrasive for the yellow clay brick.

Finally, the yellow sandstone underwent a range of thickness reductions. At one end, the coarse glass caused a reduction of 0.58 mm, while at the other end the fine slag caused a reduction of 1.82 mm. The natural abrasive required 120 seconds to finish the cleaning process, while the medium slag needed 540 seconds. All the figures show that the parabolic curves fitted well with the test results, with the R^2 values of no less than 0.95. In the case of the yellow sandstone, the natural abrasive could be regarded as the least harmful, because it only caused a loss of 0.90 mm in the thickness. It also required the shortest cleaning time. The fine slag, however, producing a thickness reduction of 1.82 mm and using a cleaning time of 300 seconds, should be regarded as the most harmful abrasive for the yellow sandstone.

In Appendix D, the distributions of the thickness reduction with the cleaning time are also summarised (Section D.8). These figures clearly demonstrate that the air abrasive cleaning is highly constrained by the factors such as the type of stone to be cleaned, the type of abrasive to be used, and soiling type. Besides, it is clear that the medium and fine abrasives provided more consistent results than the coarse ones. However if the particles are extremely fine, like those for the natural abrasive, abrasive cleaning could end up with being a highly time consuming task.

By comparing the figures in Section D.8, it can be observed that for the yellow clay brick, limestone and granite, most of the results corresponded to the base values of ten seconds for a full cleaning, and showed a thickness reduction of 0.20 mm to 0.30 mm. The majority of the test results for the marble showed that it required a maximum cleaning time of 50 seconds and a maximum thickness reduction of 0.40 mm. For the red clay brick these values became 20 seconds and 0.60 mm. The yellow sandstone and red sandstone had larger values, with 8 seconds and 1.20 mm for the red sandstone and 200 seconds and 0.80 mm for the yellow sandstone.

3.6 Summary

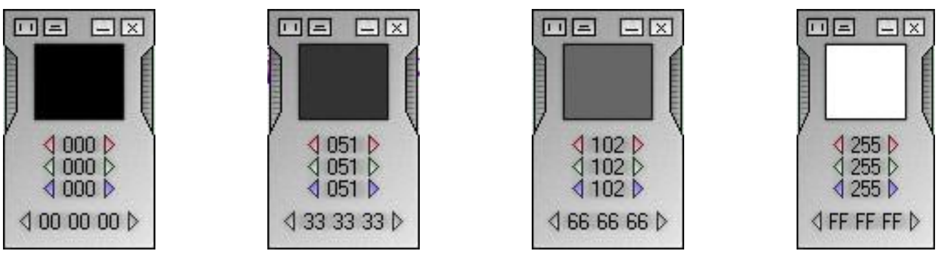
This chapter has summarised the material properties of commonly used masonry stones and clay bricks, including granite, limestone, marble, red sandstone, yellow sandstone, red clay brick and yellow clay brick, and illustrated the preparation of the masonry stones and clay brick samples using air abrasive cleaning for further physical and chemical testing. It has also indicated the detail of three main types, or seven sub-types, of abrasives for building cleaning, including coarse slag, medium slag, fine slag, coarse glass, medium glass, fine glass and natural abrasive, and summarised the impact tests and sieve tests on these abrasives. This chapter has also analysed the measured thickness reductions of the masonry stones and clay bricks cleaned to different stages using all seven abrasives. The effectiveness of air abrasive cleaning using different abrasives on different masonry stones and clay bricks can be accurately assessed together with the greyscale imaging technique which will be mentioned next. The suitability of each abrasive on different types of masonry stones and clay bricks will be comprehensively judged and ranked later.

CHAPTER 4 DIGITAL IMAGE ANALYSIS ON CLEANING USING GREYSCALE ECHNIQUES

4.1 Surface Greyscale of Masonry Stones and Clay Bricks Using Greyscale Technique in Preliminary Digital Image Analysis

In order to evaluate the performance of the cleaning, an image processing technique was employed to analyse the surface greyscale of the masonry stones and clay bricks at four cleaning stages in a controlled testing environment using fine glass only. The greyscale value is used to define the colour shades of the masonry surface. Digital greyscale image is an image composed of grey shades, varying from black at the weakest intensity to white at the strongest intensity, and only carries the intensity information in a direct way. Fig. 4.1 shows a variation of 255 levels of greyscale from pure black (Level 0) to pure white (Level 255). Greyscale digital image does not contain any hues like red (R), green (G) and blue (B), and the RGB values which equally stand for the greyscale. In this preliminary test, the photos are converted from colour to greyscale by using Photoshop. A simple software, showed in Fig. 4.2, called 'Colorpad' which had the ability to show the RGB values on the computer, was used to read the greyscale on the defined points on the greyscale digital image.

Fig. 4.1 – Grey level bars.

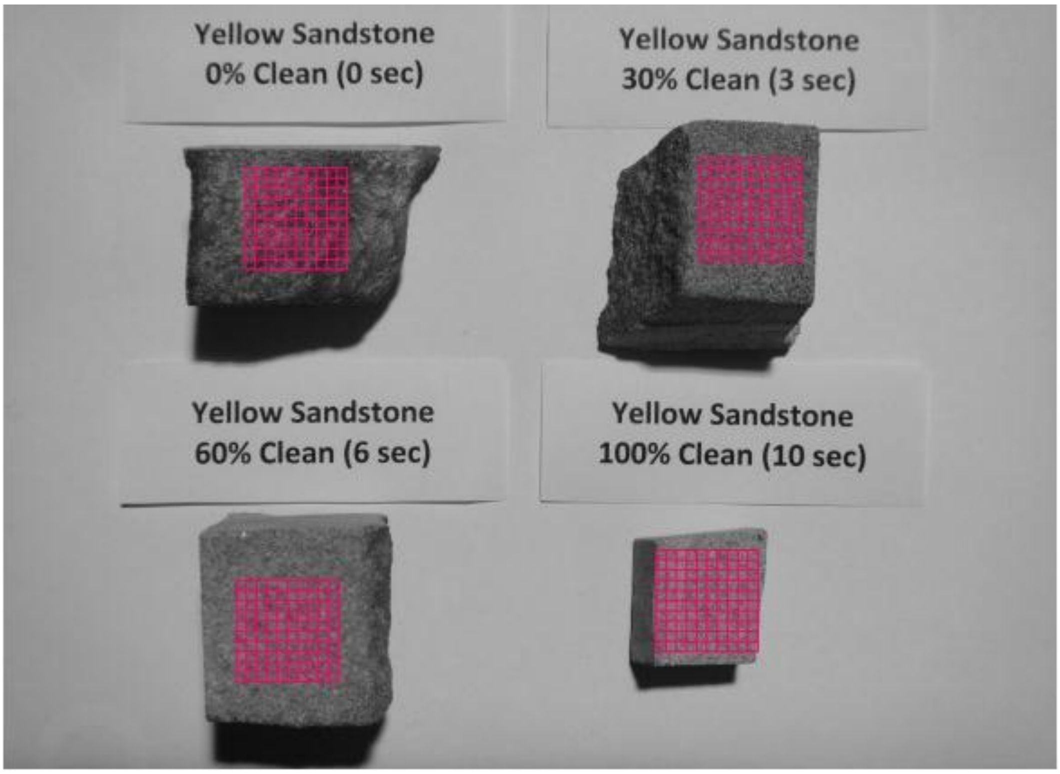


(a) Pure black **(b)** Grey 1 **(c)** Grey 2 **(d)** Pure white

Fig. 4.2 – Greyscale readings obtained using the Colorpad.

4.2 Grids on the Masonry Stone and Clay Brick Samples Cleaned at Different Stages

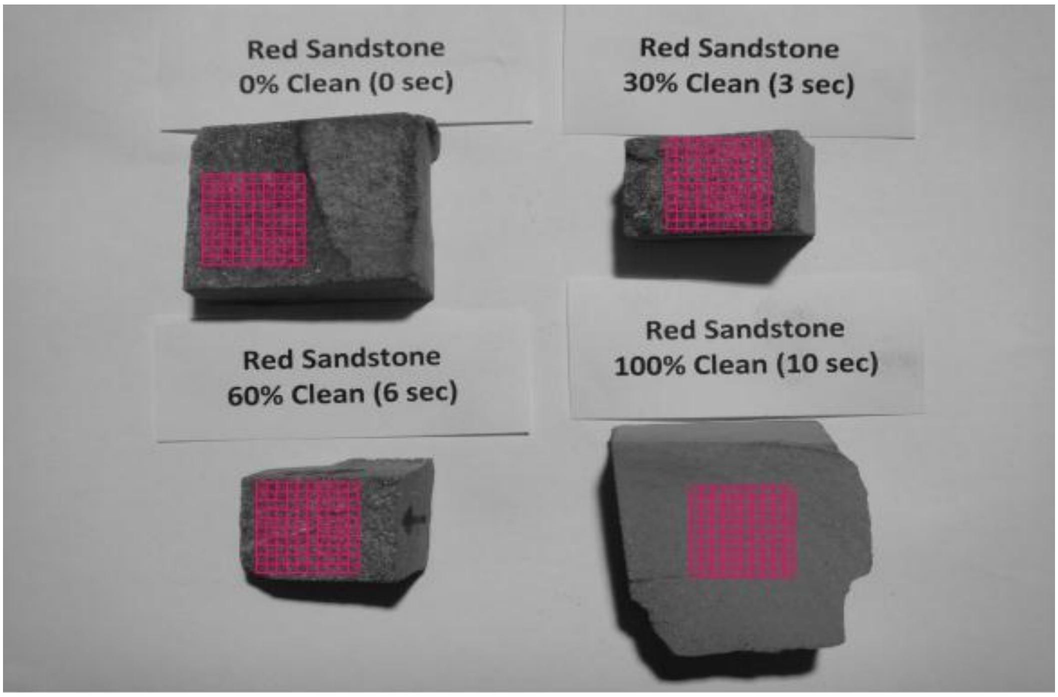
The basic information of greyscale came from the photos of the stone samples. All the photos were taken in a controlled environment using the frame and light mentioned in Chapter 3 and the focal distance of the camera was fixed at 2.3×zoom. Masonry stone and brick samples at four different cleaning stages were put together in one photo and then changed to the greyscale digital image using Photoshop. An area of 1 cm^2 with a 10×10 grid including one hundred sampling points was placed on top of the greyscale photos and the greyscale value at each point could be read using the Colorpad in order to get the surface greyness of each sample by averaging these readings. Figs. 4.3(a) to (g) show the sampling grids placed on the top of the sample photos of the yellow sandstone, red sandstone, limestone, marble, white clay brick, yellow clay brick and granite in turn. Here *100% clean* means *full clean*.



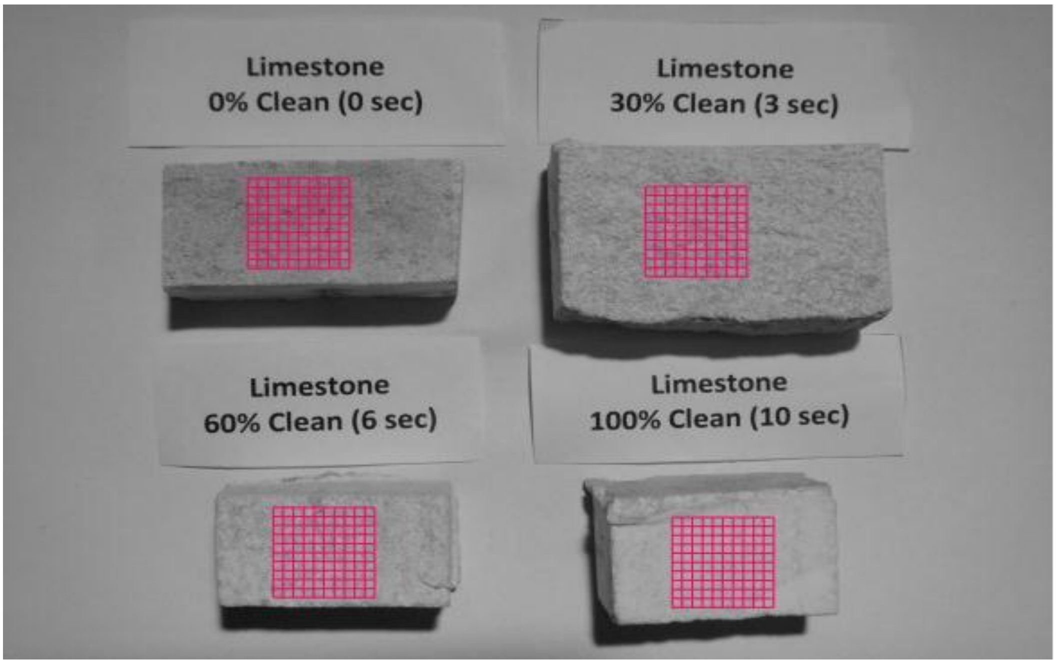
(a) Yellow sandstone

Fig. 4.3 – Grids on greyscale images of masonry stone and clay brick samples.

In this preliminary greyscale analysis, the fully cleaned surface of a sample was judged and determined by evaluating the surface colour of the sample at different cleaning stages until it matched the fresh cut surface. It was found that for most masonry stone and clay brick samples, 10 seconds were enough to reach the final clean stage, except for the yellow clay brick for which only 7 seconds were required.

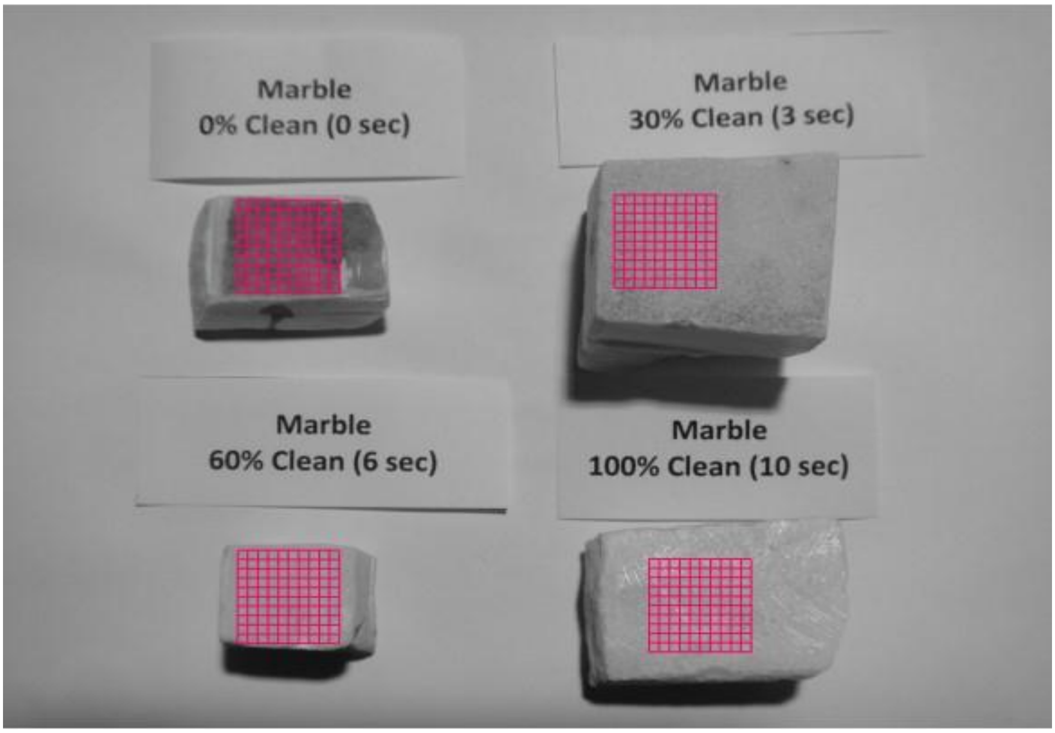


(b) Red sandstone

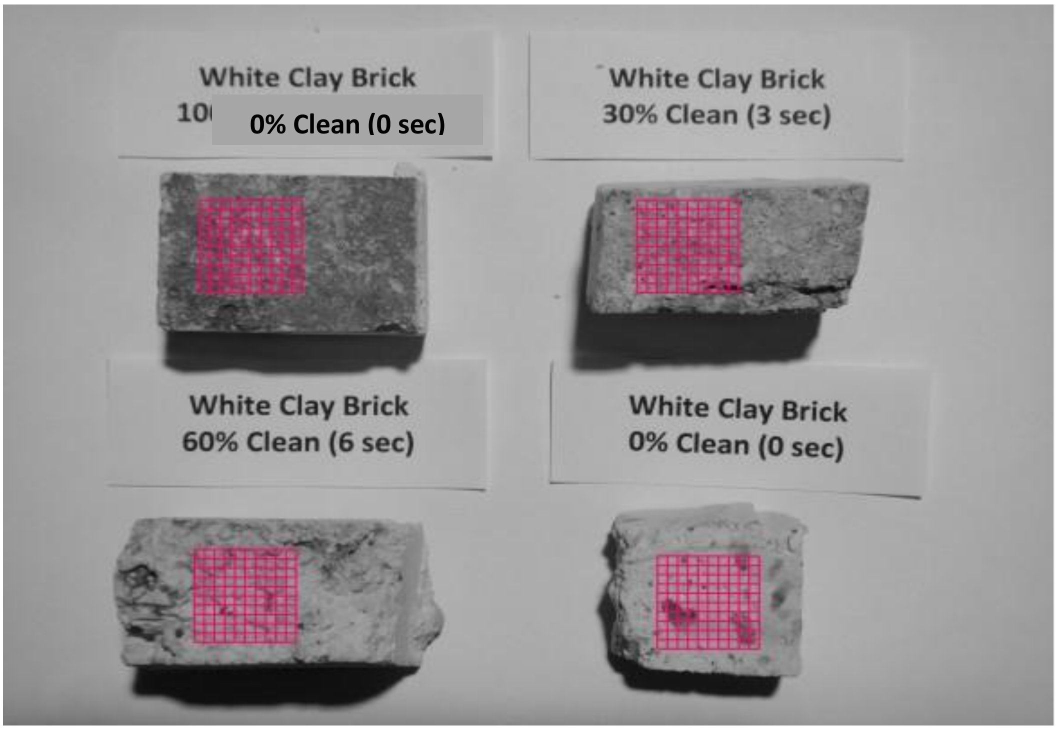


(c) Limestone

Fig. 4.3 – Grids on greyscale images of masonry stone and clay brick samples (cont.).

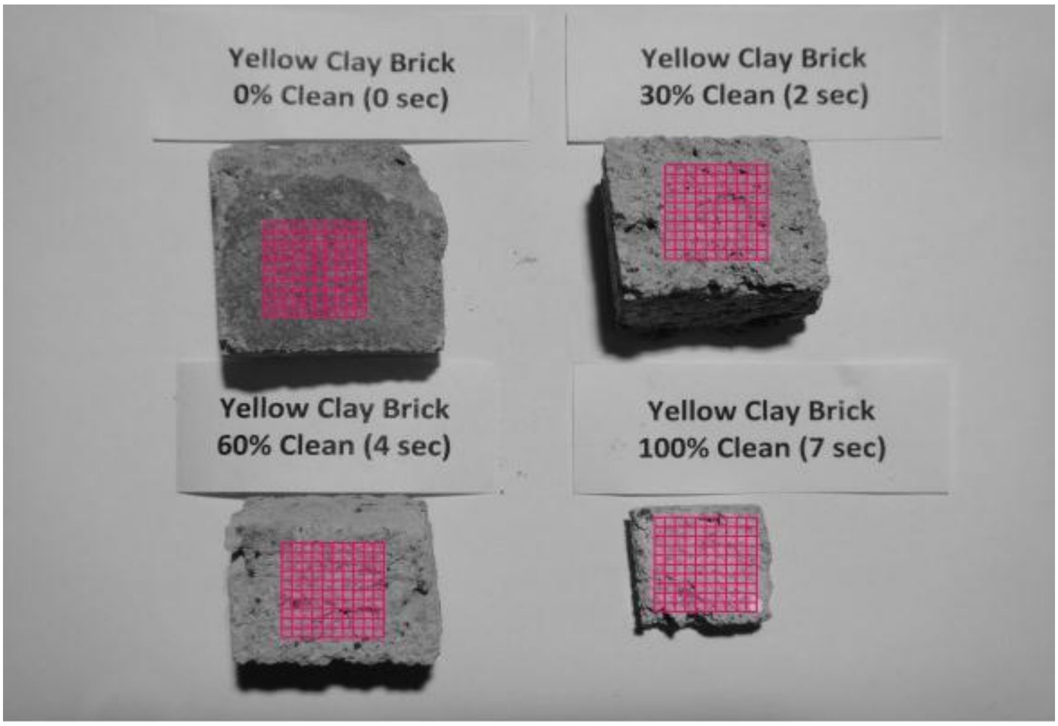


(d) Marble

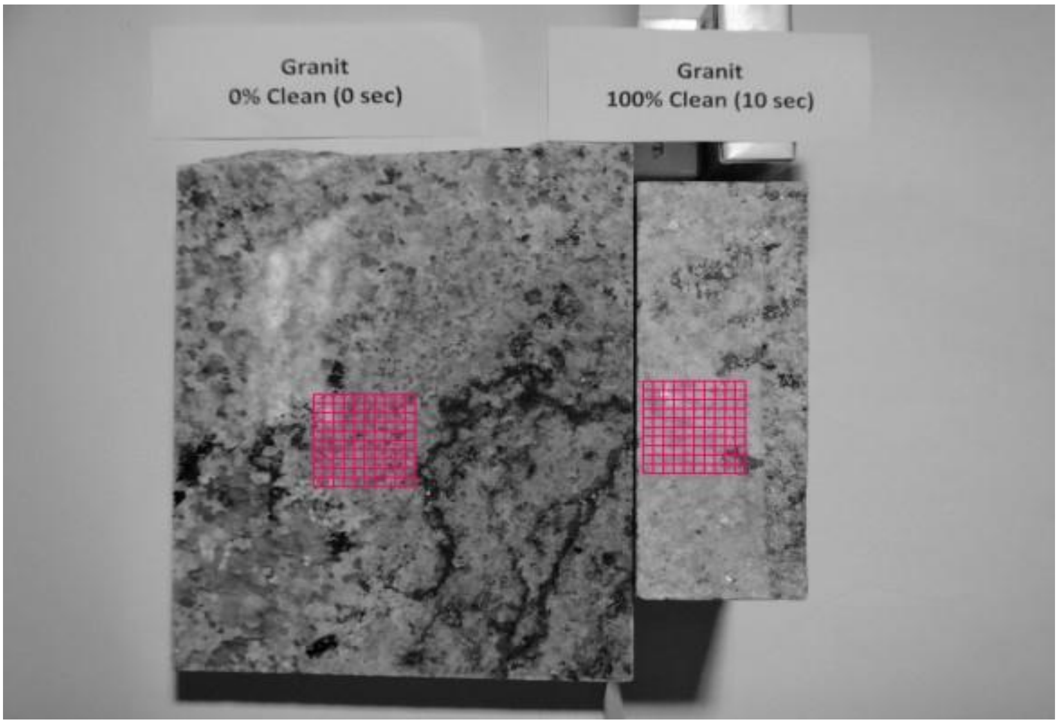


(e) White clay brick

Fig. 4.3 – Grids on greyscale images of masonry stone and clay brick samples (cont.).



(f) Yellow clay brick



(g) Granite

Fig. 4.3 – Grids on greyscale images of masonry stone and clay brick samples (cont.).

4.3 Determinations of Greyscale Values

Table 3.1 lists typical Greyscale (GS) readings on the sampling points on each image photograph for the Yellow sandstone. The complete GS readings for all the masonry stones and clay bricks are listed in Appendix B. Each set of data were collected by taking readings at the specified central positions of the girds. The mean value (M), the standard deviation (SD) and the coefficient of variation (C_v) for each sample were calculated and are listed in the bottom cells of each table.

Table 4.1 – Greyscale readings on the Yellow sandstone at various cleaning times.

(a) Greyscale readings on the Yellow sandstone at t = 0 s (0% clean)

GS	**Yellow sandstone (Cleaning time t = 0 s)**									
Grid	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	89	77	70	85	85	67	65	54	56	60
2	89	88	81	97	89	90	66	57	42	45
3	89	85	74	89	90	65	81	54	57	69
4	78	83	82	60	72	55	82	74	56	66
5	81	67	78	66	78	56	82	52	69	58
6	71	78	77	65	61	58	64	73	51	63
7	85	87	88	96	87	76	65	63	63	66
8	91	80	86	71	56	73	78	80	57	52
9	84	53	55	87	48	56	62	88	47	66
10	63	48	68	73	94	51	64	50	48	78
M = 70.44			**SD** = 13.83				$\mathbf{C_v}$ = 19.64%			

(b) Greyscale readings on the Yellow sandstone at t = 3 s

GS	**Yellow sandstone (Cleaning time t = 3 s)**									
Grid	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	89	84	76	97	98	91	91	90	84	83
2	94	88	89	73	83	95	107	97	81	95
3	112	93	100	83	88	81	107	94	86	88
4	102	95	92	83	114	82	96	84	102	95
5	95	92	93	107	96	85	92	102	98	98
6	95	92	105	89	105	87	88	94	93	88
7	78	108	110	113	82	107	101	83	85	93
8	80	88	98	96	88	95	109	107	83	83
9	86	109	90	102	101	101	86	86	91	96
10	101	104	99	96	90	87	86	102	108	74
M = 93.38			**SD** = 9.22				$\mathbf{C_v}$ = 9.87%			

Table 4.1 – Greyscale readings on the Yellow sandstone at various cleaning times (cont.).

(c) Greyscale readings on the Yellow sandstone at t = 6 s

GS	**Yellow sandstone (Cleaning time t = 6 s)**									
Grid	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	115	108	113	116	119	106	114	115	109	111
2	116	118	121	110	110	117	110	118	114	117
3	119	122	116	111	113	122	100	97	105	113
4	118	124	109	112	128	102	118	112	130	112
5	111	102	97	114	124	105	98	112	110	114
6	110	122	107	106	113	120	113	116	108	107
7	111	105	117	116	104	104	99	96	101	98
8	118	102	109	93	106	112	104	105	105	113
9	118	106	98	98	114	105	105	103	97	101
10	111	112	106	102	108	112	115	107	96	108
M = 110.09				**SD** = 7.62				**C_v** = 6.92%		

(d) Greyscale readings on the Yellow sandstone at t = 10 s (100% clean)

GS	**Yellow sandstone (Cleaning time t = 10 s)**									
Grid	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	109	128	115	118	104	138	108	113	117	110
2	120	119	125	116	114	113	130	111	107	118
3	111	129	127	123	119	105	111	111	119	113
4	103	124	128	109	121	125	107	122	115	120
5	107	109	118	109	120	111	115	126	109	94
6	115	119	118	102	118	117	136	119	101	121
7	106	121	114	104	116	103	121	122	118	110
8	102	124	119	105	127	122	122	112	104	110
9	124	116	105	114	124	106	125	109	121	113
10	117	118	108	115	116	129	116	103	132	129
M = 115.81				**SD** = 8.40				**C_v** = 7.26%		

4.4 Discussion on the Greyscale Results

The mean values (M) were calculated and then plotted against the cleaning time for each sample, as shown in Figs. 4.4 to 4.10. As a greater greyscale represents a cleaner surface, the increasing trend of the greyscale indicates that the surface of the stone would get cleaner as the cleaning time grew. It can be seen that a parabolic line can be used to describe the relationships between the greyscale (GS) and the cleaning time (t) for the yellow sandstone, red sandstone and limestone with very high R^2

values. The function displayed in the figure can also be used to model the relationship between the greyscale (GS) and the cleaning time (t):

$$y \approx f(x) = a\,x^2 + b\,x + c \tag{4.1}$$

where x is the cleaning time, and y is corresponding greyscale value.

The R value in the function below is the linear regression coefficient which indicates how well the parabola fits the data, but R^2 rather than R is normally used. The better the points fit the function, the closer the value of R^2 is to one. The definition of the R^2 value is given as follows:

$$R^2 = 1 - SS_{err} / SS_{tot} \tag{4.2}$$

where the term SS_{err} represents the red square with respect to the average value ($\overline{GS}$) in Fig. 4.11 and the blue squares represent the squared residuals to the linear regression in Fig. 4.12, with

$$SS_{err} = \sum_i (y_i - f_i)^2 \tag{4.3}$$

$$SS_{tot} = \sum_i (y_i - \bar{y})^2 \tag{4.4}$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{4.5}$$

In Fig. 4.4, a parabola is used to show the increasing trend for the greyscale of the yellow sandstone. The data and the parabola almost coincide since the R^2-value is equal to 0.999 which is almost equal to 1.0. The greyscale increased with the increasing cleaning time but at a decreasing rate and finally tended to be stable. The greyscale for the original dirty yellow sandstone sample was 70.44 and became 115.81 when the sample became fully cleaned. As the gap in greyscale between the un-cleaned or original dirty sample and the fully cleaned sample is 45.37 which is quite big, this indicates that the surface of the original yellow sandstone was extremely dirty.

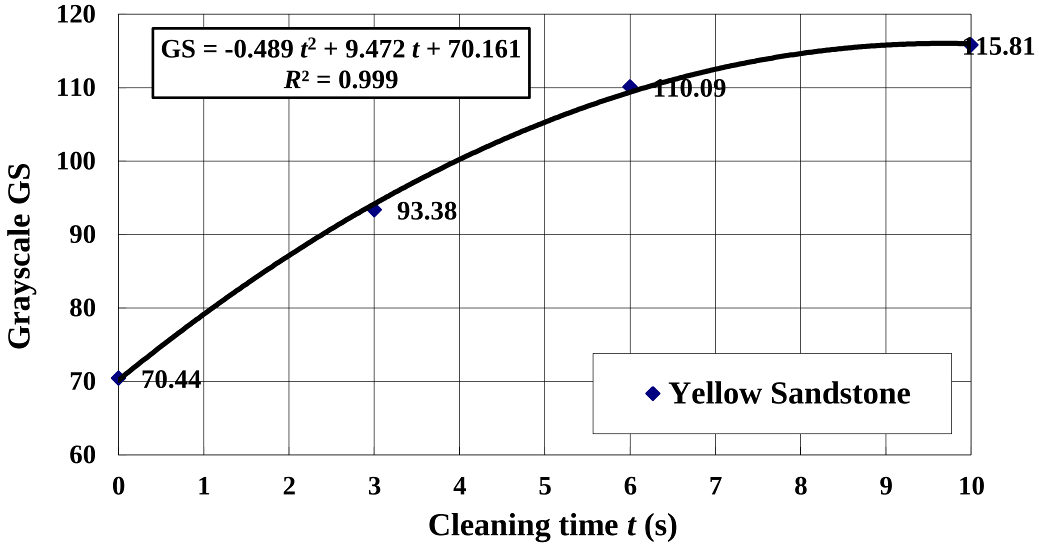


Fig. 4.4 – Greyscale (GS) versus the cleaning time for the Yellow sandstone.

In Fig 4.5, a parabolic line is used to represent the increasing trend for the greyscale of the red sandstone. The data and the parabola are very coincident since the R^2 value is equal to 0.996 which is also very close to 1.0. The trend of this parabola is quite similar to the one for the yellow sandstone. However, by comparison of the greyscale at ten seconds, the fully cleaned red sandstone is much darker than the yellow sandstone. This means that the un-cleaned sample was less dirty as the gap of the greyscale between the un-cleaned and fully cleaned samples is smaller.

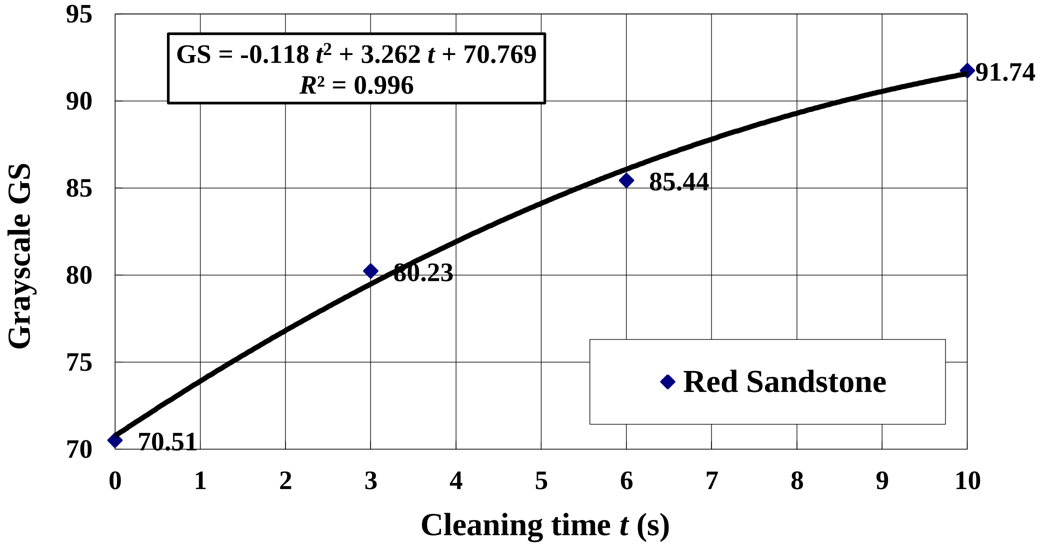


Fig. 4.5 – Greyscale (GS) versus the cleaning time for the Red sandstone.

In Fig. 4.6, a parabolic line is used to represent the increasing trend for the greyscale of the limestone. The data and the parabola are very coincident since the R^2 value is equal to 0.999 which is almost equal to 1.0. The rise of the greyscale of the limestone is quite uniform as the slope of the parabola slightly decreases. This indicates that as the cleaning time increased, the soiling on the limestone surface could be removed at a nearly constant rate.

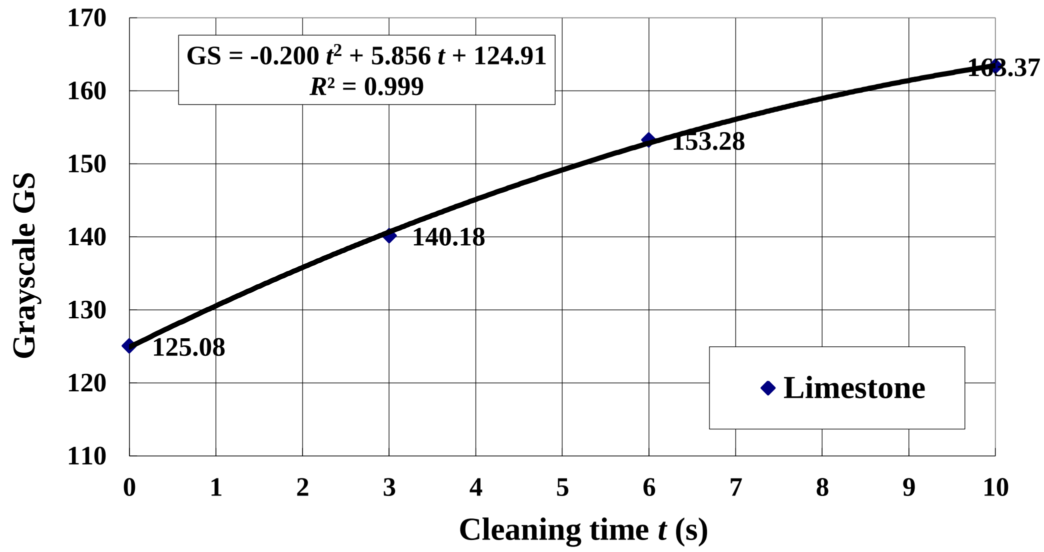


Fig. 4.6 – Greyscale (GS) versus the cleaning time for the Limestone.

As shown in Fig. 4.7, the greyscale versus the cleaning time for the marble can be expressed by a bi-linear relationship. The greyscale rose rapidly in the first three seconds and then the increase trend slowed down. Since the density of the marble is quite high, it is hard for soiling to penetrate into marble and it is loosely stuck to the marble surface. Most dirt could be easily removed in first three seconds and then further cleaning would not largely change the surface feature.

As shown in Fig. 4.8, the greyscales versus the cleaning time for the white clay brick can be expressed by a similar bi-linear relationship. The greyscale rose rapidly in the first three seconds and then the increase trend slowed down. Since the particles on the clay brick surface was very loose, the soiling could be removed quickly using fine glass blasting. In first three seconds, most soiling had been moved and thereafter the growth rate of greyscale became lower and the greyscale value tended to be stable.

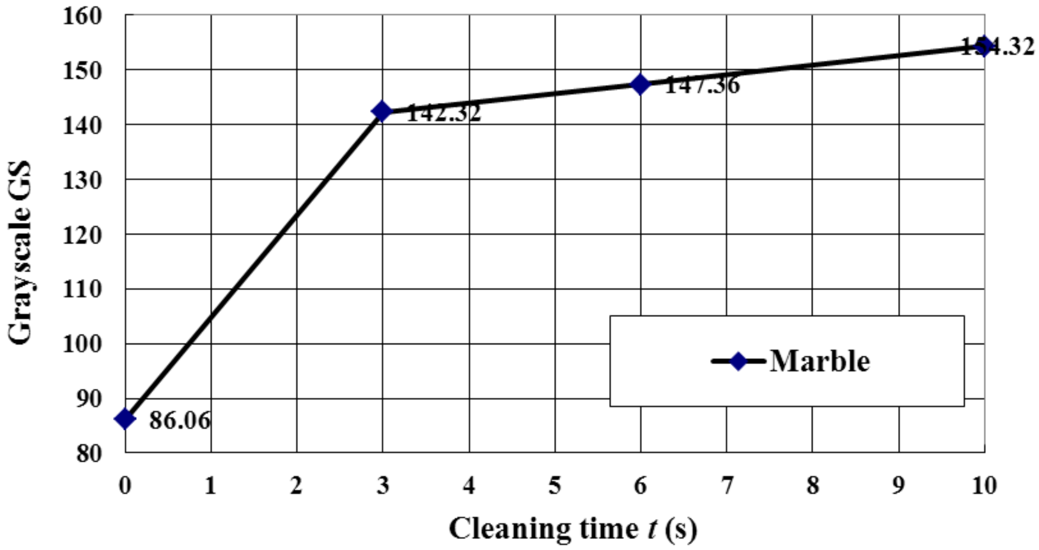


Fig. 4.7 – Greyscale (GS) versus the cleaning time for the Marble.

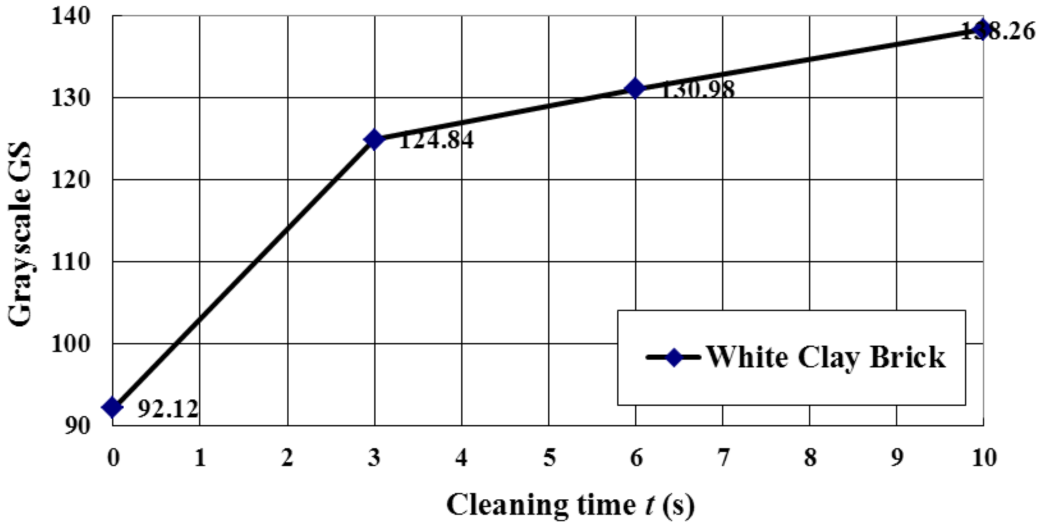


Fig. 4.8 – Greyscale (GS) versus the cleaning time for the White clay brick.

Again as shown in Fig. 4.9, the greyscale versus the cleaning time for the yellow clay brick can be expressed by a similar bi-linear relationship which is quite similar to the one for the white clay brick. Since the physical property of the yellow clay brick is similar to the white clay brick, it is normal to have a similar line like that. The increasing rate is also very high at the first three seconds and drops afterwards.

The granite only has two cleaning stages. Fig. 4.10 shows a straight line connects the two greyscale values. The greyscale of the granite increased by almost 35 grey levels from the un-cleaned sample to the fully cleaned one.

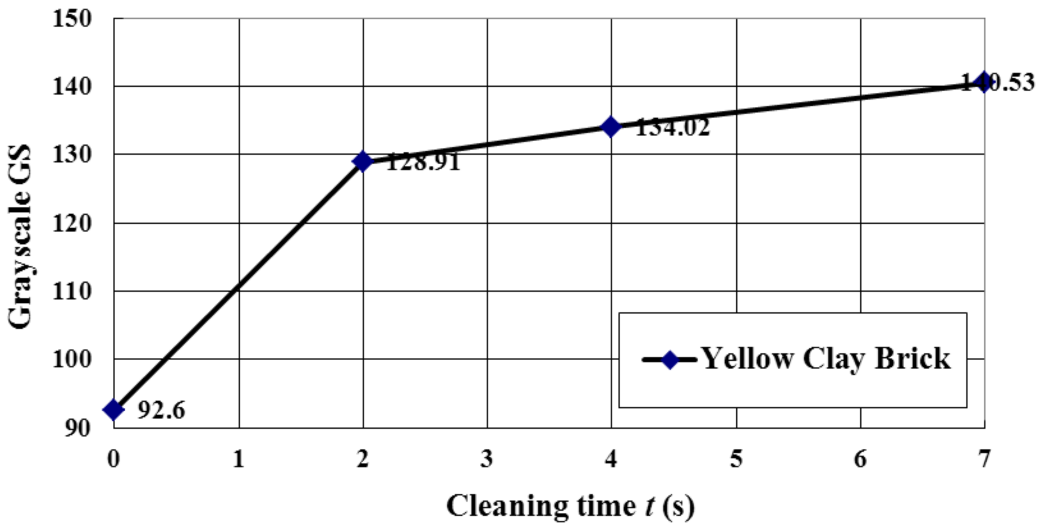


Fig. 4.9 – Greyscale (GS) versus the cleaning time for the Yellow clay brick.

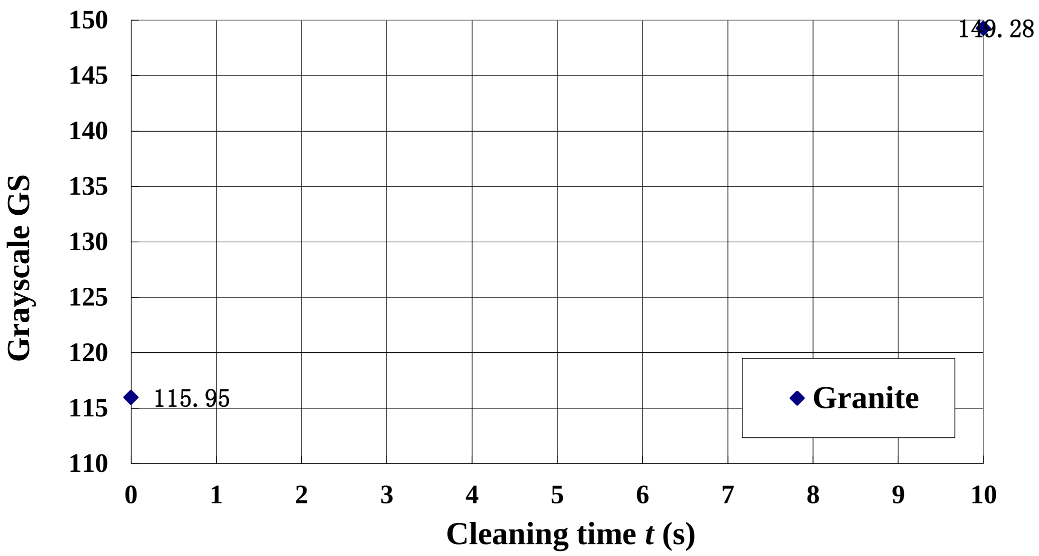


Fig. 4.10 – Greyscale (GS) versus the cleaning time for the Granite.

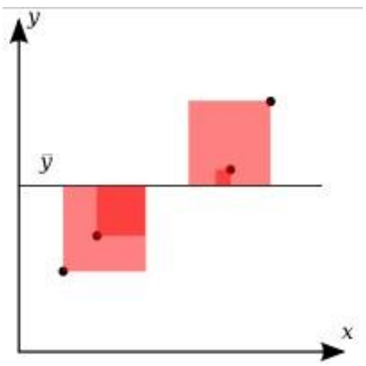


Fig. 4.11 – SS_{tot} (total sum of squares).

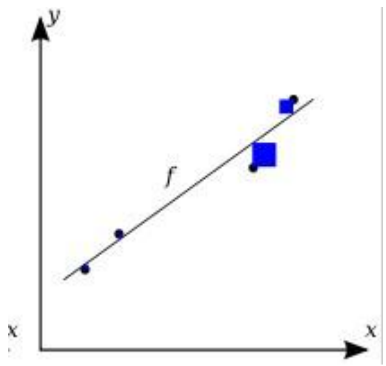


Fig. 4.12– SS_{err} (residual sum of squares).

Fig. 4.13 summarises the increasing trends of the greyscales with the cleaning time for all the masonry stones and clay bricks studied. It gives a clear comparison between the samples at a same cleaning time. It shows that the fresh surface of the limestone has a brightest colour while the fresh surface of the red sandstone has a darkest colour among all the stones and bricks.

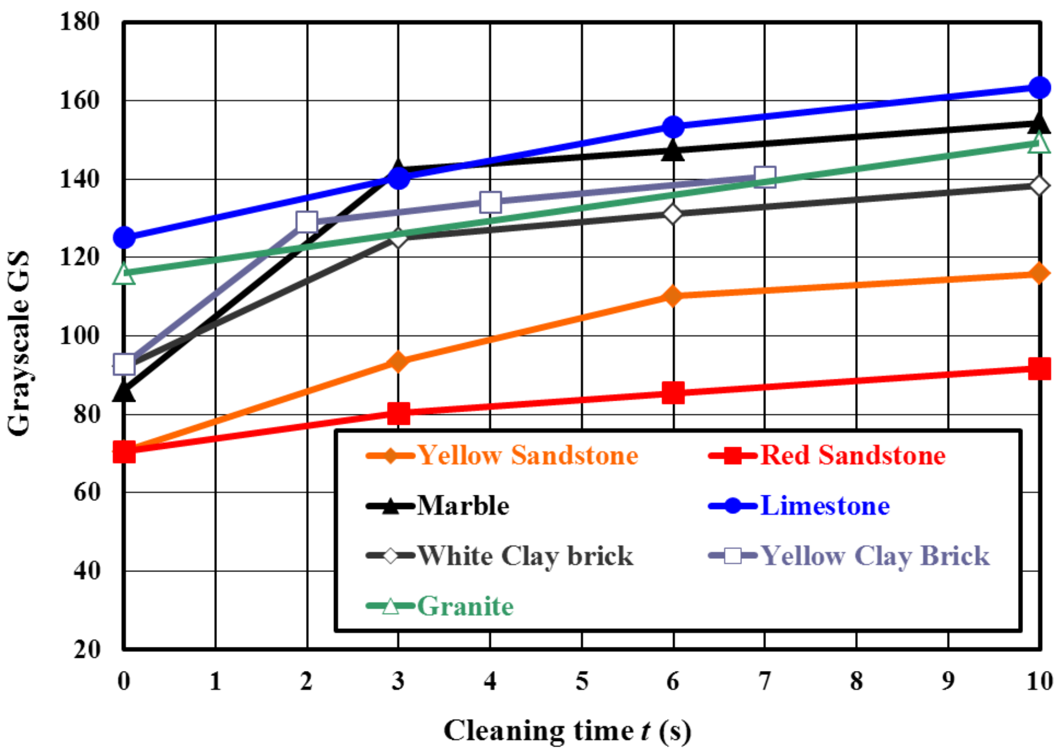


Fig. 4.13 – Greyscale (GS) versus the cleaning time for all types of stones and bricks.

4.5 Cleanness

In order to normalise the cleaning level for all types of the stones and bricks, a term of cleanness (CS) is introduced here. The cleanness value of a fully cleaned stone is defined as 1.0 and the cleanness of other cleaning levels can be determined by:

$$\text{Cleanness (CS)} = \frac{\text{Greyscale at certain cleaning level}}{\text{Greyscale at fully cleaned level}} \tag{4.6}$$

Figs. 4.14 to 4.20 show the relationships between the cleanness and the cleaning time for all masonry stone and clay brick samples, respectively. They can quantitatively represent the growth of the cleaning level as well.

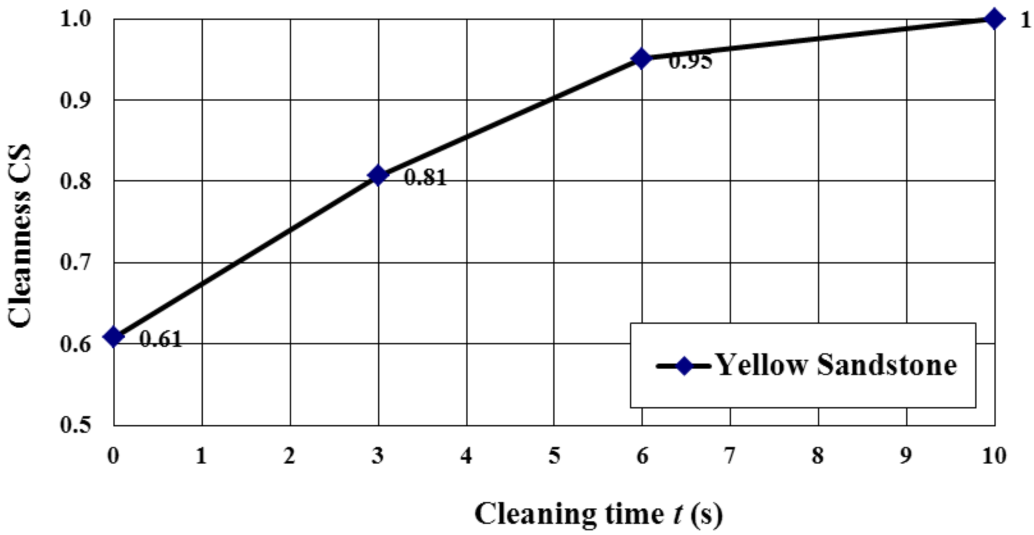


Fig. 4.14 – Cleanness (CS) versus the cleaning time for the Yellow sandstone.

As shown in Fig. 4.14, in the abrasive cleaning progress, the initial cleanness of the un-cleaned yellow sandstone was 0.61 and quickly increased to 0.81 after 3 seconds. Then it reached 0.95 after another 3 seconds and was equal to 1.0 for the fully cleaned sample at the 10^{th} second.

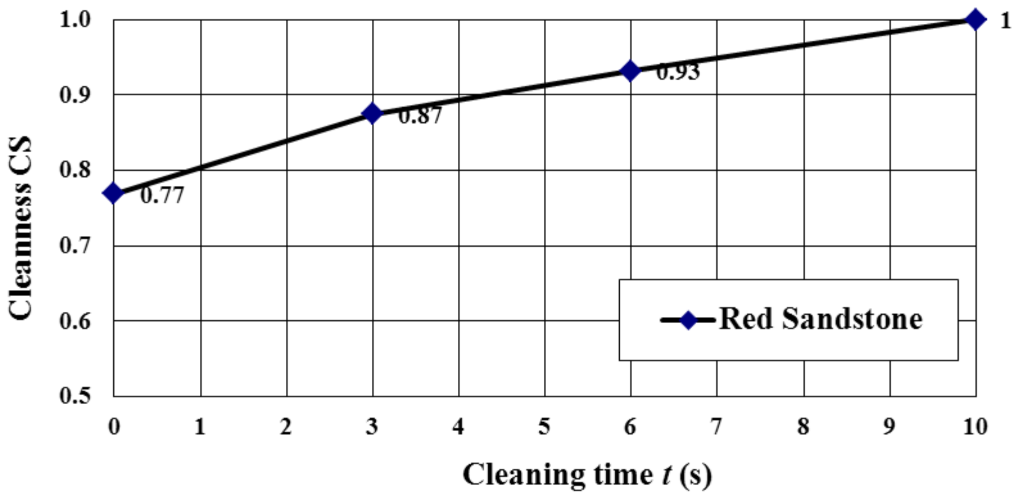


Fig. 4.15 – Cleanness (CS) versus the cleaning time for the Red sandstone.

As shown in Fig. 4.15, in the abrasive cleaning progress, the initial cleanness of the un-cleaned red sandstone was 0.77 and smoothly increased to 0.87 after 3 seconds. Then it reached 0.93 after another 3 seconds and was equal to 1.0 for the fully cleaned sample at the 10^{th} second. The trend is approximately linear.

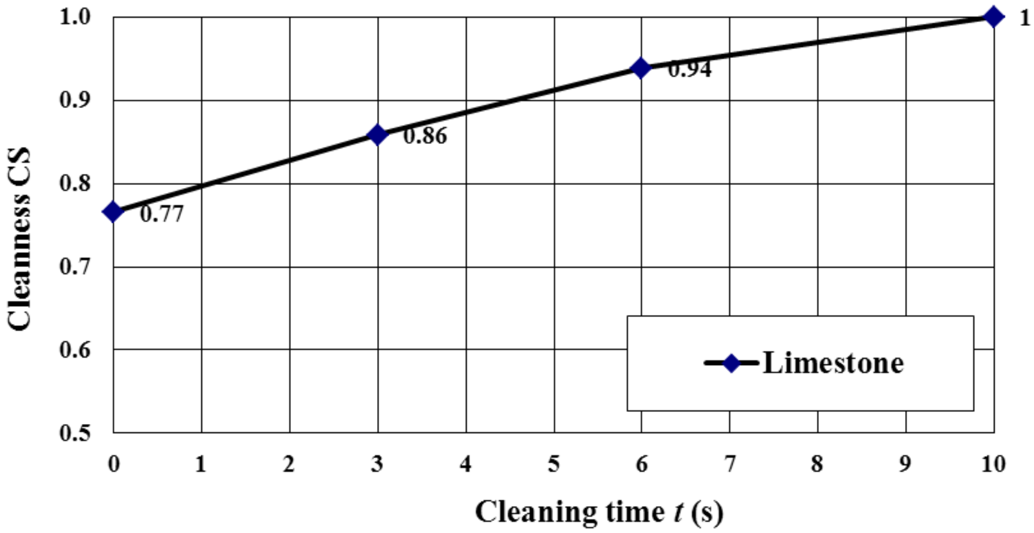


Fig. 4.16 – Cleanness (CS) versus the cleaning time for the Limestone.

As shown in Fig. 4.16, in the abrasive cleaning progress, the initial cleanness of the un-cleaned limestone was 0.77 and smoothly increased to 0.86 after 3 seconds. Then it reached 0.94 after another 3 seconds and was equal to 1.0 for the fully cleaned sample at the 10th second. The trend is approximately linear.

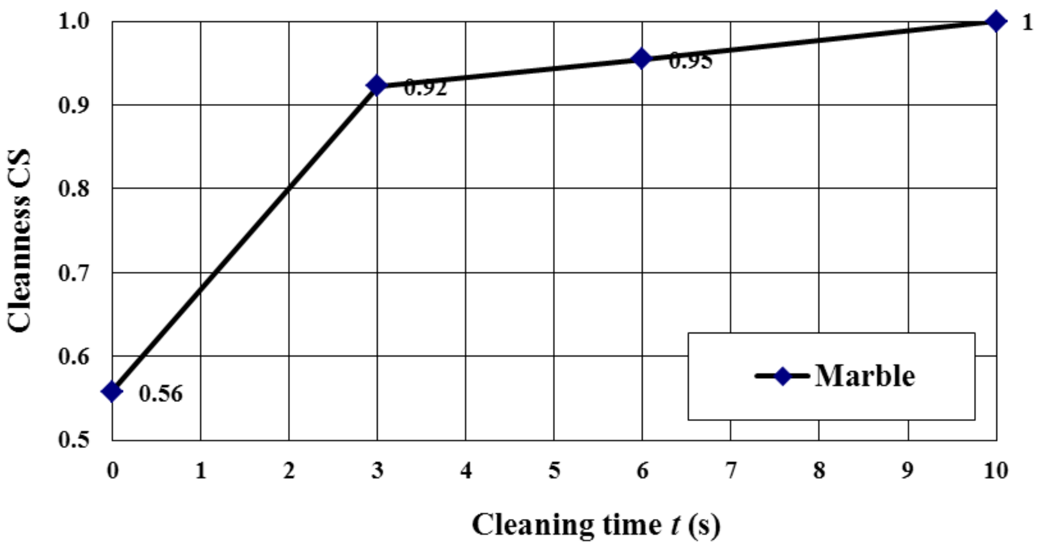


Fig. 4.17 – Cleanness (CS) versus the cleaning time for the Marble.

As shown in Fig. 4.17, in the abrasive cleaning progress, the initial cleanness of the un-cleaned marble was 0.56 and rapidly increased to 0.92 after 3 seconds. Then it reached 0.95 after another 3 seconds and was equal to 1.0 for the fully cleaned sample at the 10th second.

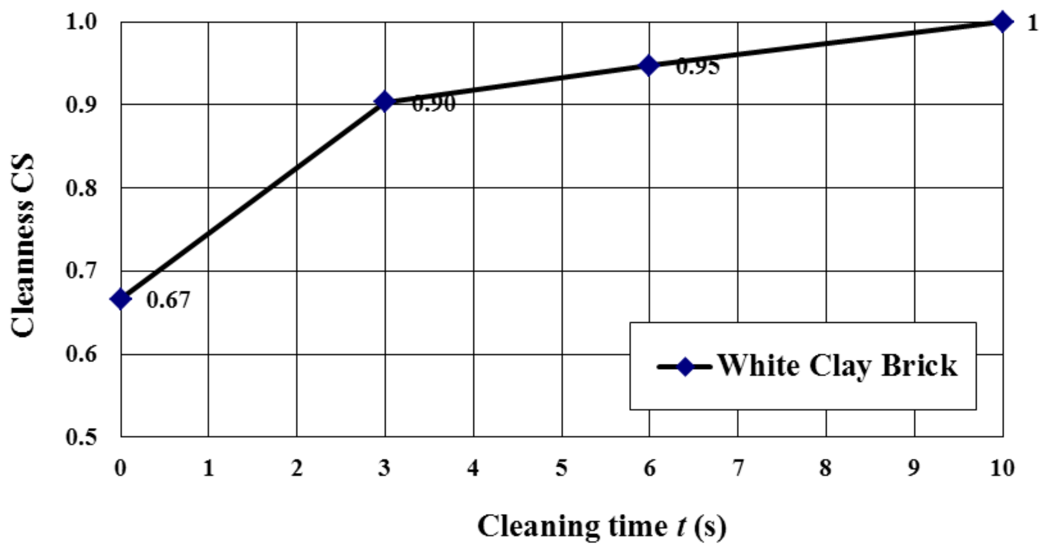


Fig. 4.18 – Cleanness (CS) versus the cleaning time for the White clay brick.

As shown in Fig. 4.18, in the abrasive cleaning progress, the initial cleanness of the un-cleaned white clay brick was 0.67 and rapidly increased to 0.90 after 3 seconds. Then it reached 0.95 after another 3 seconds and was equal to 1.0 for the fully cleaned sample at the 10th second.

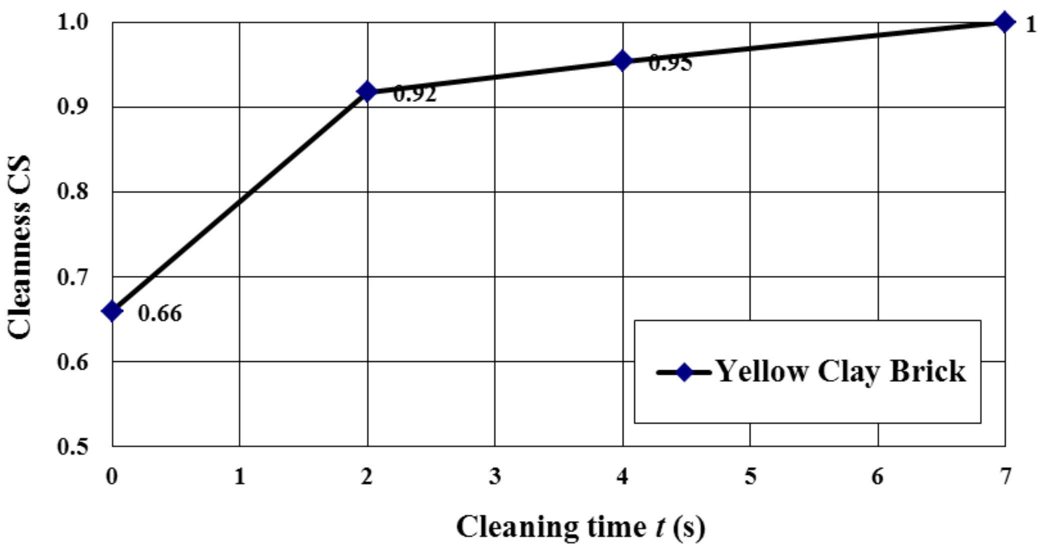


Fig. 4.19 – Cleanness (CS) versus the cleaning time for the Yellow clay brick.

As shown in Fig. 4.19, in the abrasive cleaning progress, the initial cleanness of the un-cleaned white clay brick was 0.66 and rapidly increased to 0.92 after 2 seconds.

Then it reached 0.95 after another 2 seconds and was equal to 1.0 for the fully cleaned sample at the 7th second.

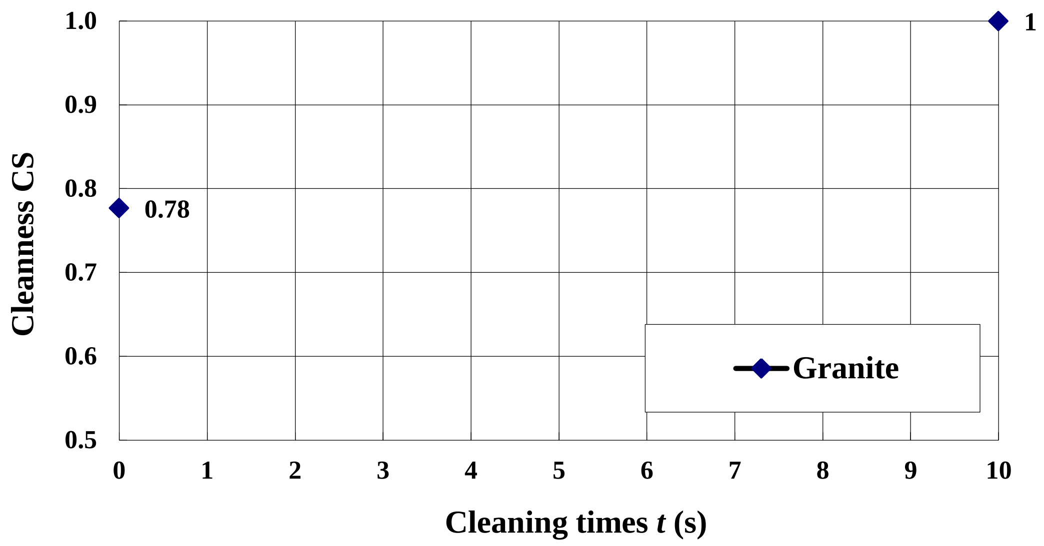


Fig. 4.20 – Cleanness (CS) versus the cleaning time for the Granite.

As shown in Fig. 4.20, the cleanness of the un-cleaned granite surface was 0.78 which was not too far away from 1.0 for the fully cleaned surface.

Fig. 4.21 shows the increasing trend lines of the cleanness with the cleaning time for all the masonry stones and clay bricks studied. It indicates that the marble had a worst original surface condition as it has a lowest cleanness at 0 second. On contrast, the granite had a best original surface condition as it had a highest cleanness at 0 second. Since the surface of the granite is well polished, it is hard for the soiling to attach on it.

In summary, the greyscale can be used to define the colour shade of the masonry stone or brick surface. A smaller greyscale represents a dirtier surface condition. The greyscale of the stone or brick surface continually increased with the increasing cleaning time and would finally tend to be stable when the surface became fully cleaned. In addition, the cleanness can be used to directly represent the cleaning level for all types of masonry stones and bricks. This digital image analysis method has been proved to be effective and applicable, and it can be applied for assessing different approaches of cleaning.

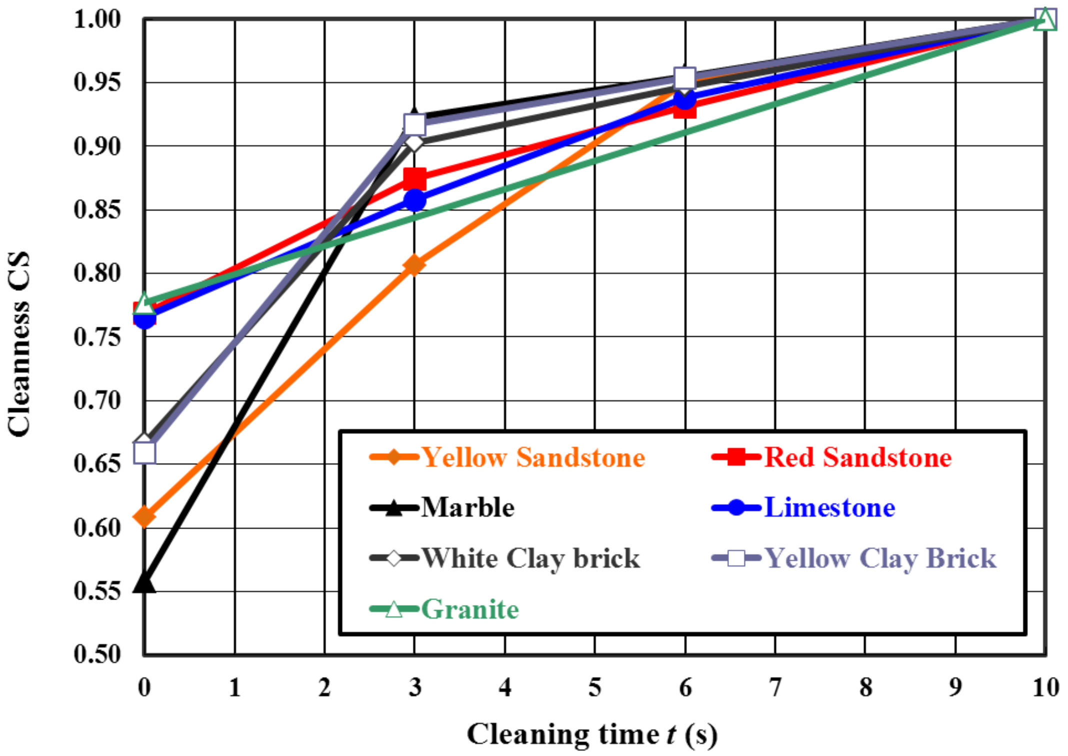


Fig. 4.21 – Cleanness (CS) versus the cleaning time for all types of stones and bricks.

4.6 Advanced Digital Image Analysis of Greyscale

4.6.1 Greyscale imaging photos using the Photoshop

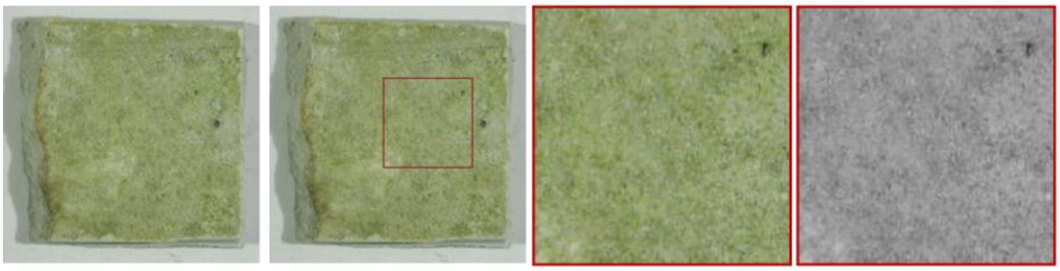
An advanced digital imaging analysis on the surface images of the masonry stones and clay bricks, which were taken following the procedures described in Section 3.3, was conducted using the Adobe Photoshop Software. Similar to the preliminary study, the aim of this advanced analysis was to accurately assess changes in the colour component of the stone or brick surface during the cleaning process. In order to provide an exploratory assessment of the physical degree of the cleaning of the masonry stones and clay bricks, the use of greyscale (GS) was extensively incorporated into this study. Resultantly, colour images were converted into greyscale images. Hence, all the images that were taken during the cleaning process were directly analysed using the Photoshop.

In the preliminary digital imaging analysis, all the photos were taken indoors under consistent illuminating conditions. However, during this analysis a problem was discovered. Because the environmental conditions during cleaning were inconsistent, inside a workshop but with the entrance door open, the images did not correspond to the actual levels of brightness. Although a frame was built on purpose to create a condition of constant luminosity, the cleaning was conducted in the workshop lit by daylight. This affected the intensity of the luminosity of the images when they were taken, and also caused heterogeneous brightness in them.

In order to solve this problem, firstly, all the images were treated using the software ColorPad (Fig. 4.2). As indicated in Section 4.1, this software identifies the RGB values of a selected area on a location of the image. These values show the degree of combination of these three primary colours. Each primary colour can obtain a value between 0 and 255, where 0 represents the darkest colour and 255 represents the brightest. In order to quantitatively assess the colour changes of the stone or brick samples, the background white paper was used as reference colour during the process of the analysis. With the help of this software, the background brightness of all the images was adjusted, taking the red value as a reference point, to a value of 200, after a trial and error process. After adjusting the brightness settings, these colour pictures were converted into greyscale images using the Photoshop.

Since not all the samples had the same dimensions, their central areas were used for the advanced greyscale analysis. This standardisation of the area for the digital imaging analysis allowed all the images to be compared. The next step required four separate actions. The original images were scaled and orientated. An area inside was selected by drawing a frame on the images, which were then cropped. Finally, the cropped area was converted into the greyscale image. Fig. 4.22 shows a typical example of this procedure, which was then applied to all the images of 49 masonry stone and brick samples at different cleaning stages. All these processed images are enclosed in Appendixes G to M.

Fig. 4.23 shows the greyscale images of the limestone which documented the use of the fine slag, in six cleaning stages. The surface on the last image can be considered 100% clean. From each greyscale image an average greyscale value was obtained using the Photoshop. All the greyscale values are listed in Appendix C, next to the column for the reduction in thickness. Thus, it would be possible to plot the greyscale (GS) against the cleaning time t. Fig. 4.24 shows the GS – t relationship for this limestone sample over the whole cleaning process.



(a) Original sample **(b)** Selected area **(c)** Colour photo of the selected area **(d)** Greyscale photo of the selected area

Fig. 4.22 – Four steps for processing the photos for the Limestone cleaned using the fine slag.

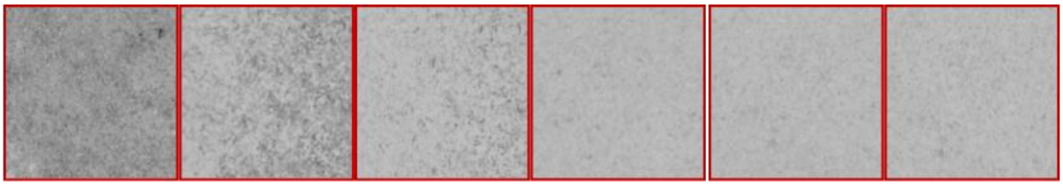


Fig. 4.23 – Greyscale photos for cleaning stages 1 to 6 for the Limestone using fine slag.

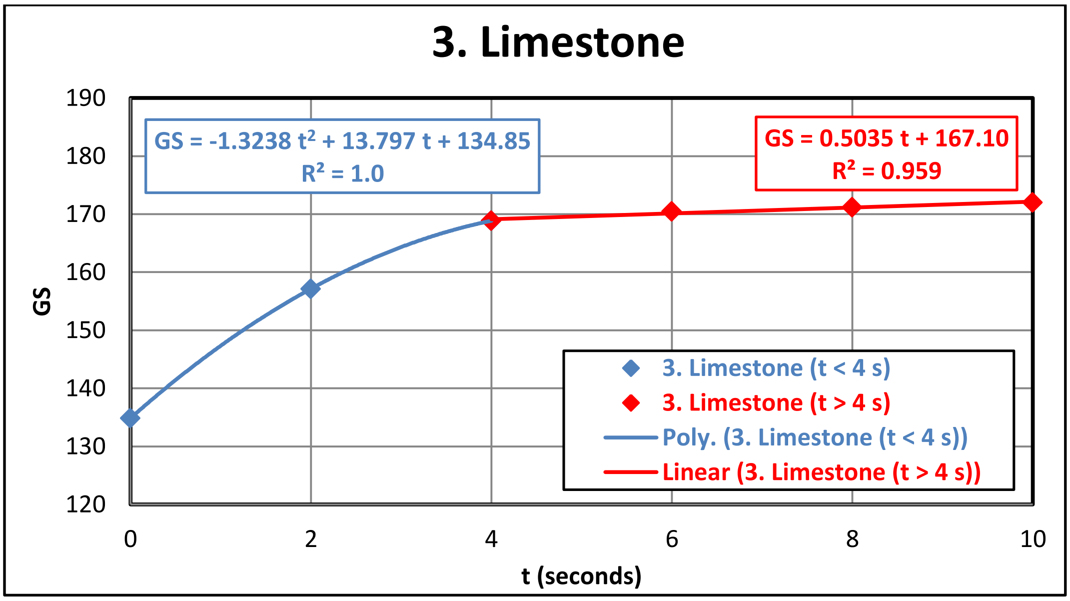
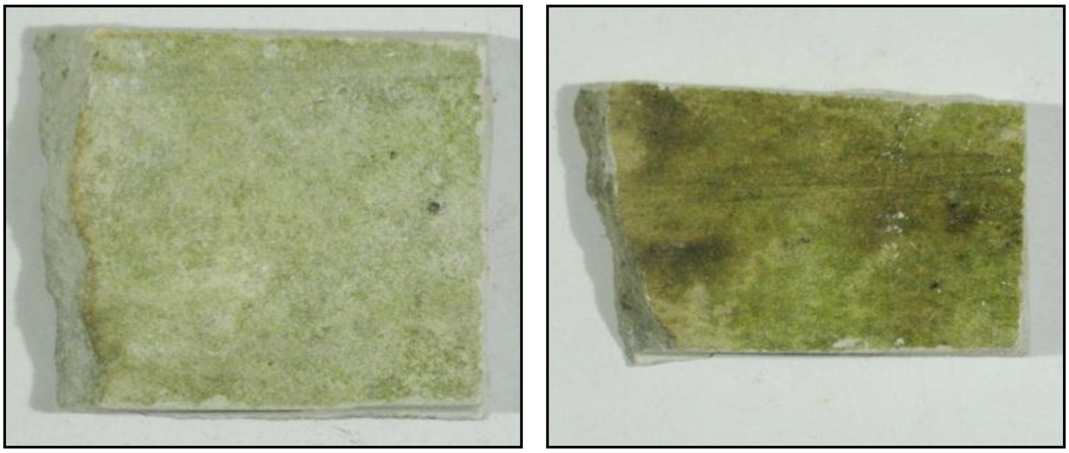


Fig. 4.24 – Greyscale versus cleaning time for the Limestone cleaned with the fine slag.

The complete GS – t relationship for the limestone cleaned with the fine slag can be represented by using a trend line with two portions. In the first stage up to 4 seconds, GS increased rapidly with t from 134.85 to 168.86 but at a decreasing rate, up by

34.01 or 25.2%, and this can be expressed using a parabolic curve with R^2 = 1.0. Thereafter, GS slowly increased with t from 168.86 to 171.99, only up by 3.13, and this can be expressed using a linear relationship with R^2 = 0.959 which is very high.

The initial greyscale value depended on the type of soiling which was on the surface and location of the masonry stone or brick sample. As a result of this, samples from the same stone may not have the same greyscale value because matching soiling types should not affect the greyscale. A good example of this can be seen when the limestone was cleaned with either the fine slag or medium glass (see Fig. 4.25).



(a) To be cleaned with the fine slag **(b)** To be cleaned with the fine glass

Fig. 4.25 – Initial states for the Limestone samples cleaned with the fine slag and fine glass.

In Fig. 4.25, a denser biological crust was placed on the right limestone sample, which was to be cleaned with the fine glass (Fig. 4.25(b)), than the one which was placed on the left sample and was to be cleaned with the fine slag (Fig. 4.25(a)). Thus, the left limestone sample (GS = 134) should produce, when compared to the right limestone sample (GS = 75), a larger greyscale value, which means to be brighter and more shining. However, the greyscale values for the final cleaning stage were fairly similar for majority of the samples. The limestone sample cleaned with the fine slag had a measured final greyscale value of 172, while the sample cleaned with the fine glass had a measured greyscale value of 160, both being quite close.

The greyscale values obtained by using a natural abrasive were largely affected by the nature of this abrasive. Natural abrasive is a very soft material and is composed of coconut and almond shells. After the impact on the stones' surfaces it easily turns into dust. This impact left the samples' surfaces lightly smudged with a brownish colour. As a result of this smudging, the greyscale values measured were different from those on the samples cleaned with other abrasives.

Furthermore, other factors may have also affected the results, especially those pertaining to the red clay brick and red sandstone. Due to the nature of their formation, they possessed several layers, each with different properties, which may have significantly affected the final results of the analysis (see Figs. 4.26 and 4.27). These layers did not always homogeneously distribute across a stone or brick's cross-section, so soiling may not always consistently embed over the same type of layer.

Fig. 4.26 – Cross-section of the Red clay brick sample.

Fig. 4.27 – Cross-section of the Red sandstone sample.

The above described phenomenon had a significant influence on the red sandstone sample that was cleaned with the natural abrasive (see Fig. 4.28). In this case, the measured greyscale value moved towards an inverse trend with the cleaning time, when their measurements were compared with the red sandstone samples that were cleaned with other abrasives. Instead of an increasing trend, the greyscale value decreased in conjunction with the cleaning time. This change in the trend may be a result of the fact that the underlying layer of the soiling was darker than the soiling itself. The effect of the natural abrasive should also be taken into account.

Furthermore, the complete GS – t relationship for the red sandstone cleaned with the natural abrasive can be represented by using a monotonic decrease trend line with two portions. In the first stage up to 40 seconds, GS decreased rapidly with t from

54.20 to 37.50 but at a decreasing rate, down by 16.70 or 30.8%, and this can be expressed using a parabolic curve with R^2 = 0.913. Thereafter, GS slowly decreased with t from 37.50 to 33.10, only down by 4.40, and this can be expressed using a linear relationship with R^2 = 0.949 which is very high.

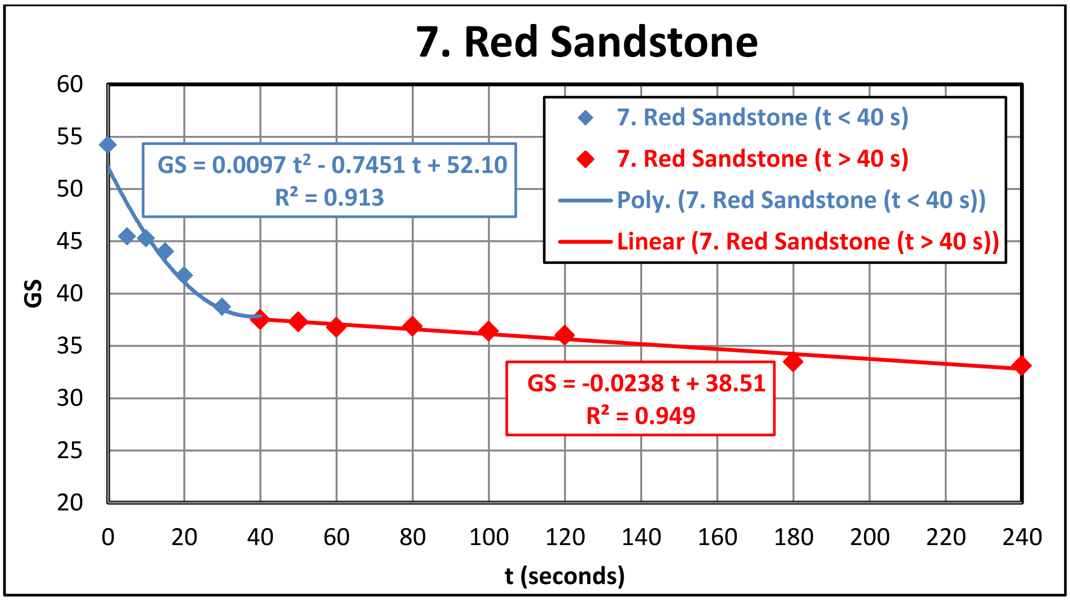
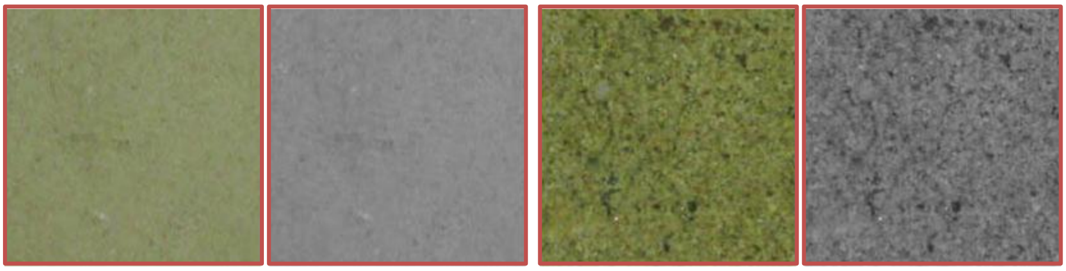


Fig. 4.28 – Greyscale versus cleaning time for the Red sandstone cleaned with the natural abrasive.

Similar situations also arose during the advanced greyscale analysis on the yellow clay brick samples. Therefore, the real colours of these clay brick samples were the colours of a darker type than those of the soiling deposited on it (see Section L.1 in Appendix L). Fig. 4.29 shows, for the yellow clay brick sample cleaned with the course slag, both in colour and greyscale form, a comparison of the brick's initial dirty surface with its final cleaned surface.



(a) Initial stage **(b)** Final stage

Fig. 4.29 – Colour and imaging photos for the Yellow clay brick cleaned with the coarse slag.

By observing the statistical analysis on the greyscale results for the granite samples in Section E.1 of Appendix E, it is clear that all the R^2 values were larger than 0.93 and some were very close to 1.0. Therefore, the parabolic relationships between the obtained greyscale values and the concurrent cleaning time may well predict the varying trends. However, the final greyscale values were not very similar. This could be a result of the fact that the surface of the granite samples was polished. Noting this, it is suggested that the most suitable cleaning method for a polished stone surface may be a manual cleaning, for example using a sponge or a brush together with washing-up liquid, instead of air abrasive cleaning. Nevertheless, the masonry samples cleaned with the recycled glass of three different sizes produced similar final greyscale values. At the same time, the differences in the greyscale between the initial and final cleaning stages were also quite similar, ranging from 20 to 25.

The limestone samples had, at the final cleaning stage, closer GS values to the granite samples. Most the final values GS were around 170, except for the sample cleaned with natural abrasive with GS = 152. The marble samples had fairly similar final GS values to the limestone samples. In other words, the final cleaning stages had greyscale values of around 170 for the limestone. This is true, except for the samples cleaned with the natural abrasive, which had the GS values of approximately 158 at the final stage. The lower value may be caused by the colouring by the natural abrasive.

As mentioned above, the red clay brick and red sandstone were highly influenced by their formation process. Hence, it is understandable that their greyscale values, at the final cleaning stages, were fairly heterogeneous. For the red clay brick, the maximum greyscale values belonged to the samples cleaned with the coarse slag and natural abrasive. This indicates that the original sample cleaned with the natural abrasive was darker than the rest of the samples after the final cleaning stage. It is important to mention that this sample was also the one which had the lowest original greyscale value. Its parabolic GS – t curve, with an R^2 value of 0.58, did not fit the results very well, compared with the rest of the samples. The R^2 values for the other samples ranged between 0.89 and 0.98.

Similar results were obtained if the red sandstone samples were compared with the red clay brick samples. The main difference observed from this comparison was that the final greyscale values for the red sandstone samples were higher than those of the red clay brick, even if the greyscale values at the initial cleaning stage were quite similar. In other words, the red sandstone samples ended up with a lighter colour than the red clay brick samples.

As highlighted above, the yellow clay brick samples yielded a negative slope for the GS – t curve instead of a positive one, but the results still reflect a real situation. In fact, the yellow clay brick samples held the highest homogeneity, at both initial and final cleaning stages. The initial greyscale values varied between 115 and 125, while the final greyscale values varied between 80 and 101.

For the yellow sandstone, parabolic curves did not properly fit the trends of the greyscale versus cleaning time curves when the greyscale was measured concurrently with the cleaning time. The R^2 values varied from 0.91 to 0.67. Higher order polynomial curves or multi-portion curves similar to Figs. 4.24 and 4.28 may be needed for a better fitting on those with lower R^2 values.

4.6.2 Discussion of the results

Following the analysis given above and the compiled information, it seems that an extensive discussion is possible and necessary. In order to further evaluate the results, the relationships between the greyscale and thickness reduction (GS – Δa curves) have been statistically established (see Appendix F). Applying the same criteria used in Chapter 3 and also the earlier sections of this chapter, this section will show how the scattered data for the greyscale values, compared with the thickness reductions, can be plotted using parabolic curves.

In general, the results showed the encouraging correlations between the greyscale values and thickness reductions. The yellow clay brick cleaned with the medium slag had the lowest average R^2 value of 0.761, while the marble cleaned with the same abrasive had the highest average R^2 value of 0.994.

By looking into the results obtained from the granite samples (Section F.1 of Appendix F), an accurate prediction of the GS – Δa relationship demonstrates the aforementioned relationship. A typical example, for the granite sample cleaned with the medium slag, with an R^2 value of 0.992, is shown in Fig. 4.30. For the granite, R^2

varied between 0.870 and 0.992. The former value is that for the granite cleaned with the coarse slag, while the latter pertains to the sample cleaned with the medium slag.

By looking further into the results, it can be seen that the granite samples cleaned with the medium and fine slag abrasives showed the smallest changes in both GS and Δa values between the initial and final cleaning stages. Contrastingly, the granite samples cleaned with the coarse and fine glass abrasives showed higher changes in both GS and Δa values. Therefore, by comparing the changes in both colour and thickness of the granite samples, it is clear that the best relevant performance was obtained by using medium and fine slag abrasives.

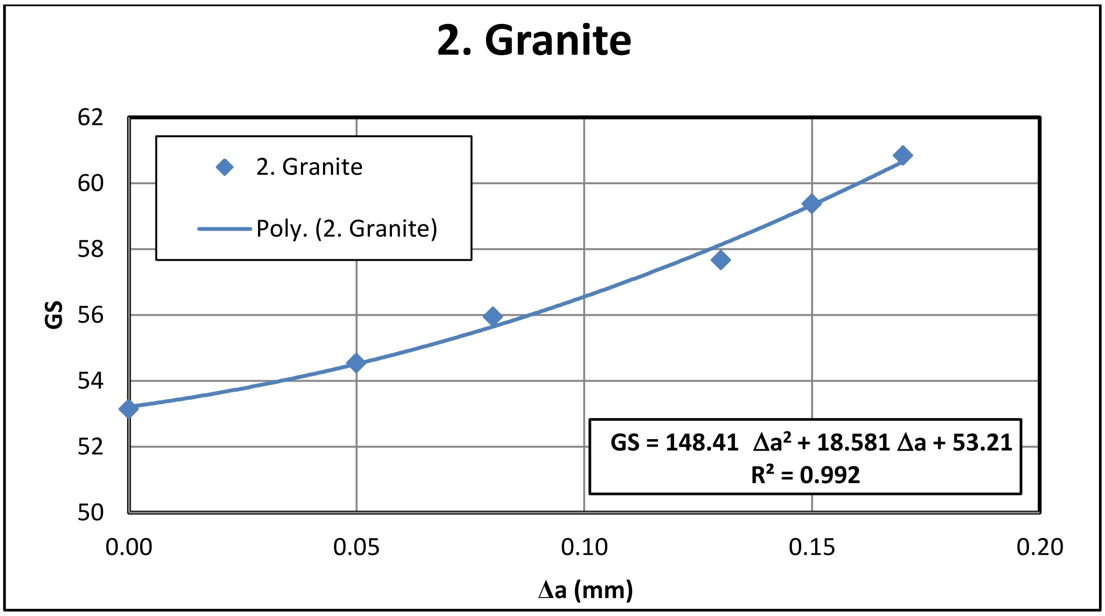


Fig. 4.30 – Relationship between greyscale and thickness reduction for the Granite cleaned with the medium slag.

The results for the limestone samples were quite similar to those for the granite samples in terms of the R^2 values. However, the changes in both greyscale values and thickness reductions between the initial and final stages showed a higher degree of fluctuation. For example, the limestone samples cleaned with the fine slag and natural abrasive showed smaller changes in both GS and Δa, whilst the limestone samples cleaned with the medium and coarse glass showed higher changes.

For the marble, the relationships between the greyscale values and thickness reductions are more reasonably fitted with the parabolic curves than those for the granite or limestone, with R^2 varying from 0.933 to 0.994. Nevertheless, the changes in both GS and Δa between the initial and final cleaning stages for the marble were higher than those for the granite or limestone. The marble samples cleaned with the medium glass and natural abrasive showed the smallest changes in GS and Δa, whilst the samples cleaned with the coarse slag and coarse glass showed the highest changes in GS and Δa.

By comparing the changes in the colour and thickness reduction for the red clay brick samples, it can be observed that the best correlation between these two parameters came from the sample cleaned with the medium glass (R^2 = 0.972), while the worst correlation came from the sample cleaned with the fine slag (R^2 = 0.891). Nevertheless, it can be seen that high correlations between the measured GS and Δa values were found for all the red clay brick samples. An analysis on the changes in both greyscale values and thickness reductions, between the initial and final cleaning stages for the red clay brick, shows an interesting fact. If the results obtained from the red clay brick samples are compared with those from the rest stones, the former showed the smallest variation in the colour, but experienced contrastingly the highest variation in the thickness reduction. The sample cleaned with the fine glass produced, between the initial and final cleaning stages, a variation of just seven points in the greyscale, while the corresponding thickness reduction was measured as 0.35 mm, which is quite reasonable. For the sample cleaned with the coarse slag, however, the thickness reduction was 1.48 mm, with a variation of 16 points in the greyscale.

The red sandstone provided slightly less accurate results than the previously analysed masonry stones and clay bricks. The maximum R^2 value was found to be 0.965, while the minimum R^2 value was 0.865. The former result was obtained by cleaning the red sandstone with the medium slag, while the latter was a result of the cleaning using the fine glass. Even if the sample cleaned by the fine glass showed a less convincing correlation between the greyscale and thickness reduction, it nonetheless produced the smallest fluctuations in GS and Δa between the initial and final cleaning stages. As mentioned above, the red sandstone sample cleaned with the natural abrasive possessed a negative slope for the greyscale versus thickness reduction relationship, instead of the positive slope that the other red sandstone samples produced (see Fig. 4.31). This sample also showed the largest reduction of

2.15 mm in the thickness within both the red sand stone group itself and the group which includes all the stone and brick samples. It also showed the smallest change of 21 points in the greyscale when compared with the other red sandstone samples.

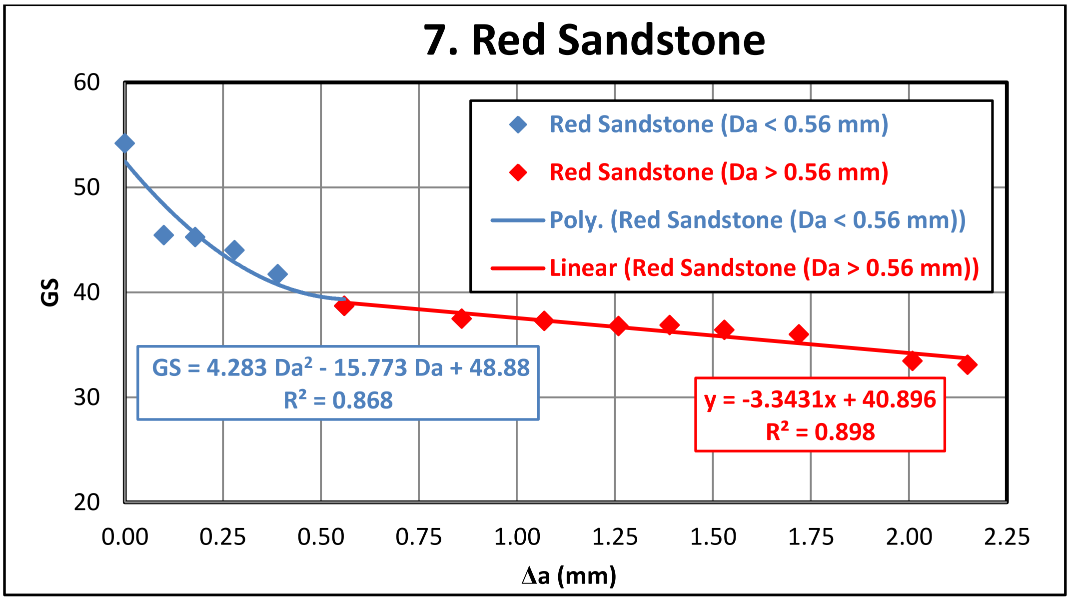


Fig. 4.31 – Greyscale versus thickness reduction for the Red sandstone cleaned with the natural abrasive.

Furthermore, the complete GS – Δa relationship for the red sandstone cleaned with the natural abrasive can be represented by using a monotonic decrease trend line with two portions. In the first stage up to Δa = 0.56 mm, GS decreased rapidly with t from 54.20 to 37.50 but at a decreasing rate, down by 16.70 or 30.8%, and this can be expressed using a parabolic curve with R^2 = 0.868. Thereafter, GS slowly decreased with Δa from 37.50 to 33.10, only down by 4.40, and this can be expressed using a linear relationship with R^2 = 0.898. Both R^2 values are fairly high.

The yellow clay brick samples, apart from the sample cleaned with the medium slag (R^2 = 0.761), provided an accurately observable relationship between the greyscale and thickness reduction, with all the R^2 values larger than 0.930. It is important to mention that the yellow clay brick samples produced negative slopes. Apart from this, these samples did not show any other peculiarities. Regarding the changes in colour and thickness between the initial and final cleaning stages, the smallest changes happened to the samples cleaned with the medium glass and the largest ones to the samples cleaned with the coarse slag and fine slag.

As it can be seen above, parabolic curves may not be good options for fitting the results from the yellow sandstone samples, because most of the R^2 values were under 0.93. By looking into the variations of the data, it is not easy to highlight any sample with the highest or lowest variations because the highest colour change did not correspond to the highest thickness reduction, and vice versa.

As a result of the above discussion, it is worthwhile to establish a summary of the data for all the masonry stones and clay bricks studied. In order to produce it, a table has been created including the following parameters (see Table C.50 in Appendix C):

- Total cleaning time,
- Total thickness reduction,
- Total change of greyscale,
- Final value of greyscale.

The purpose of this table is to determine the most suitable abrasives for each stone. The total cleaning time is analysed for each sample cleaned with all abrasives. It can be seen that 27% of the samples only needed 10 seconds to be fully cleaned (Fig. 4.32). These samples include the granite samples cleaned with the coarse slag, medium slag, fine slag, medium glass and fine glass, the limestone samples cleaned with the fine slag and fine glass, the red clay brick samples cleaned with the fine glass, and the yellow clay brick samples cleaned with the coarse slag, medium slag, fine slag, medium glass and fine glass. Usually, the smaller cleaning times corresponded to the fine and medium abrasives.

By looking into the levels of thickness reduction (Fig. 4.33), it can be seen that 49% of the samples had their thickness reduced by no more than 0.50 mm. This percentage group contained all the granite samples, because it was one of the hardest masonry stones, almost all the limestone samples except those cleaned with the coarse glass and medium glass, the marble samples cleaned with the medium slag, medium glass, fine glass and natural abrasive, the red clay brick samples cleaned with the fine slag, medium glass and fine glass, and finally the yellow clay brick samples cleaned with the fine slag, medium glass, fine glass and natural abrasive.

Again, with respect to the total cleaning time, the samples cleaned with the medium and fine abrasives showed smaller thickness reductions.

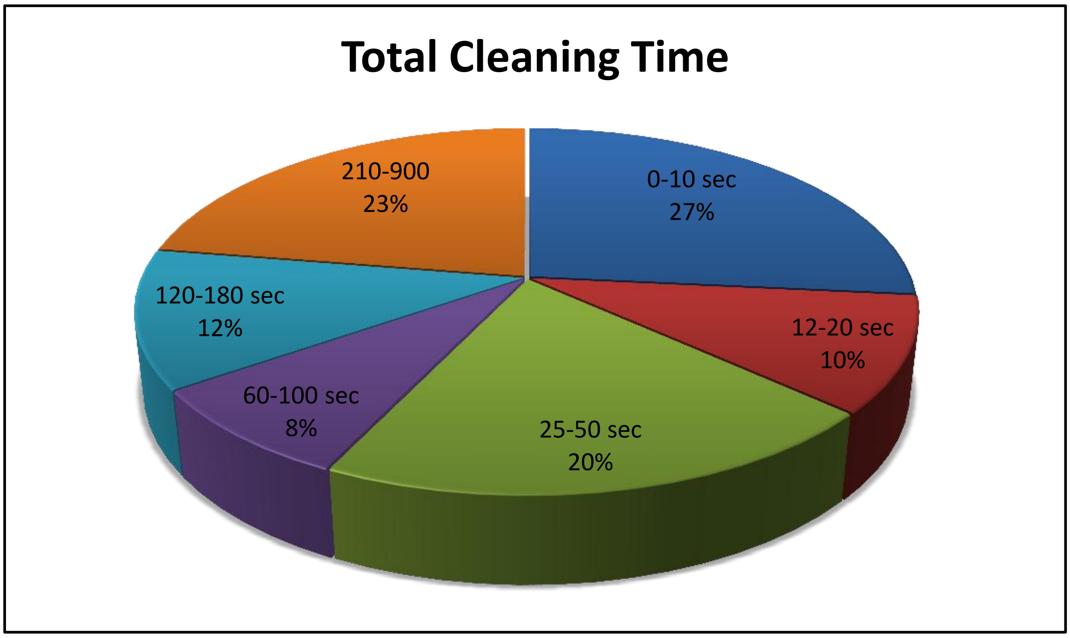


Fig. 4.32 – Percentage distribution of the total cleaning times.

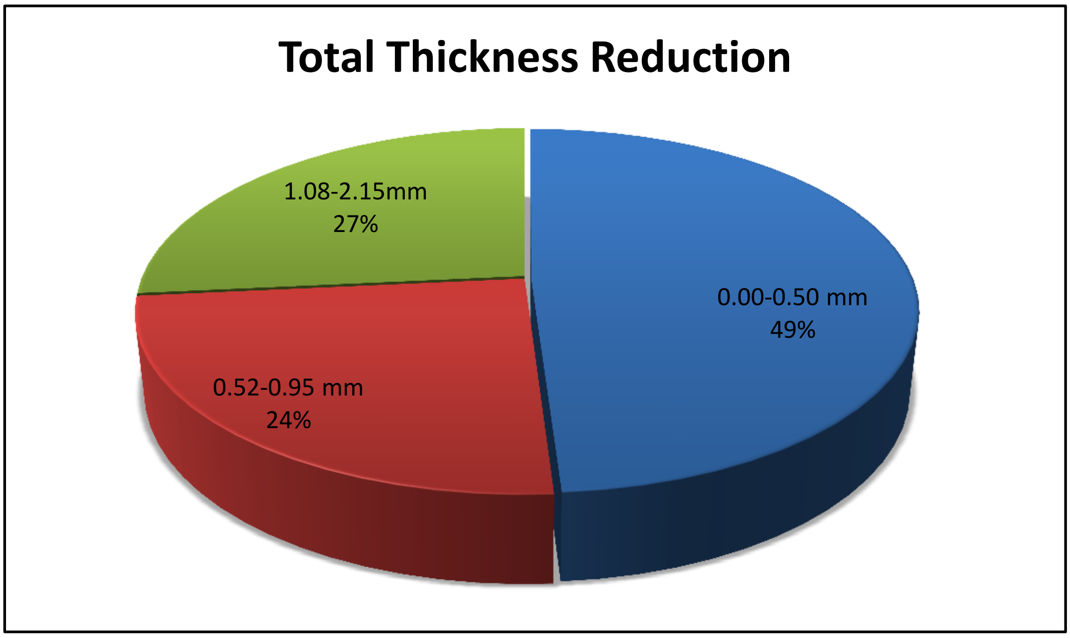


Fig. 4.33 – Percentage distribution of the total thickness reductions.

Fig. 4.34 shows that, for 37% of the samples, a colour change, represented by the change in the greyscale, occurred by almost 25 points. As previously stated, the greyscale value varies between 0 and 255. Furthermore, the greyscale values varied between 25 and 50 points for 35% of the samples. The samples that made up the group with smaller greyscale changes are as follows:

- all the granite samples,
- all the red clay brick samples,
- the red sandstone samples cleaned with the medium slag,
- the yellow sandstone samples cleaned with the natural abrasive,
- the yellow clay brick cleaned with the coarse glass and medium glass.

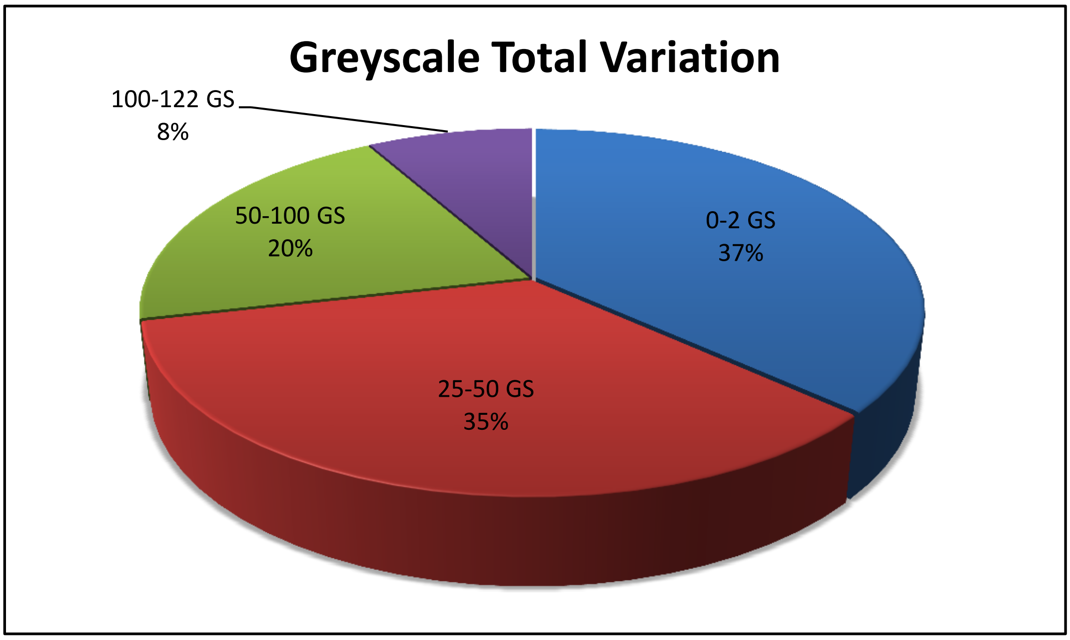


Fig. 4.34 – Percentage distribution of the total changes in the greyscale.

The analysis of the data represented in Fig. 4.36 was less accurate than the analysis of the previous figures. This is because the greyscale values were largely dependent on the original soiling on the surfaces of the masonry stone and clay bricks, and also on the natural colour of the stones and bricks. Therefore, even though they are interesting, the results cannot be used as a decisive factor for determining the most suitable abrasive.

Fig. 4.35 indicates that the final greyscale values for more than half of the samples fell between 50 and 100, which means that these samples are relatively darker after they were finally cleaned because their original colours were darker than the soiling colours. On the other hand, less than 30% of the samples ended up with the variations in the greyscale between 150 and 177, which means that the colours of the fully cleaned surfaces of these samples were brighter when compared with those of other stones and bricks.

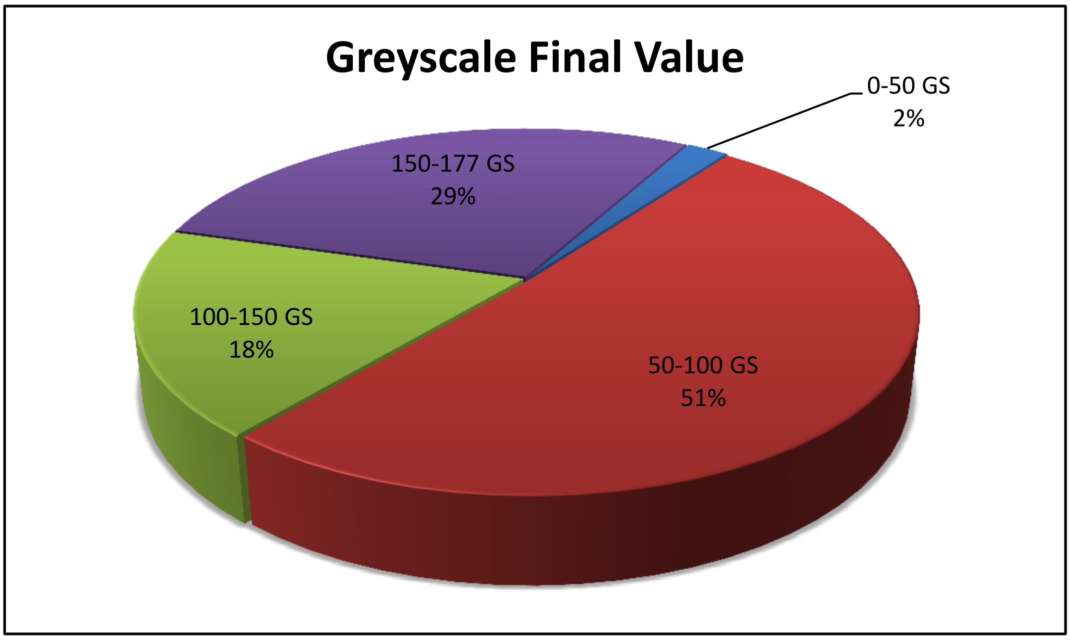


Fig. 4.35 – Percentage distribution of the final greyscale values.

After analysing all the data, it is possible to use the resultant final values to determine the most suitable abrasives for each type of masonry stone or clay brick.

As the time required to fully clean each sample is an important practical consideration due to a resultant increase in labour costs, the samples that required more than 210 seconds, when cleaned by a particular abrasive, will not be included since they could not produce a desirable performance. Furthermore, the samples, which showed a total thickness loss of over 1.0 mm, should not be taken into consideration either, because the stones might be significantly damaged.

Accepting that some samples did not have a desirable performance, by removing the corresponding rows from Table C.50 in Appendix C, Table 4.2 can be obtained. From this table, it can, for example, be seen that only one abrasive was suitable for cleaning the red sandstone. According to the established criteria, the fine glass produced the best performance.

Table 4.2 – Summary of suitable abrasives for all masonry stones and bricks.

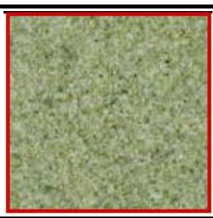
Stone/Brick	Cleaning abrasive	Total cleaning time t (sec)	Total thickness reduction **Δa** (mm)	Total greyscale change	Final greyscale value
Granite	Coarse slag	10	0.32	6.00	73.54
Granite	Medium slag	10	0.17	7.70	60.84
Granite	Fine slag	10	0.19	13.03	62.08
Granite	Coarse glass	50	0.31	24.15	86.83
Granite	Medium glass	10	0.15	18.61	89.59
Granite	Fine glass	10	0.25	24.41	79.24
Granite	Natural	50	0.21	11.43	74.46
Limestone	Coarse slag	30	0.41	75.54	171.65
Limestone	Medium slag	12	0.19	54.10	166.36
Limestone	Fine slag	10	0.26	37.14	171.99
Limestone	Coarse glass	140	0.64	59.04	176.83
Limestone	Medium glass	14	0.67	48.93	165.11
Limestone	Fine glass	10	0.10	85.59	160.53
Limestone	Natural	140	0.30	26.64	151.59
Marble	Coarse slag	45	0.53	105.62	166.94
Marble	Medium slag	50	0.33	103.09	159.29
Marble	Fine slag	35	0.52	89.15	172.33
Marble	Medium glass	25	0.40	90.46	170.31
Marble	Fine glass	25	0.39	104.72	172.81
Red Clay Brick	Fine slag	20	0.42	9.99	58.47
Red Clay Brick	Medium glass	14	0.35	7.64	58.38
Red Clay Brick	Fine glass	10	0.47	7.14	71.80
Red Sandstone	Fine glass	80	0.95	35.28	93.84
Yellow Clay Brick	Coarse slag	10	0.66	25.39	95.73
Yellow Clay Brick	Medium slag	10	0.23	32.12	88.78
Yellow Clay Brick	Fine slag	10	0.19	40.64	82.20
Yellow Clay Brick	Coarse glass	100	0.86	23.46	101.09
Yellow Clay Brick	Medium glass	10	0.25	19.64	94.96
Yellow Clay Brick	Fine glass	10	0.27	36.21	88.84
Yellow Clay Brick	Natural	12	0.29	42.33	80.04
Yellow Sandstone	Coarse slag	180	0.75	43.37	124.51
Yellow Sandstone	Natural	120	0.90	16.97	100.19

The red sandstone was fully cleaned with the fine glass for 80 seconds, together with a thickness reduced of 0.95 mm. However, although this abrasive was selected due to being superior to the others, it failed to provide an ideal performance. The fine glass abrasive reduced the thickness for the red sandstone by 1.0 mm.

There were only two options for the yellow sandstone: the coarse slag and natural abrasive. The natural abrasive caused a higher thickness reduction, 0.15 mm more than the coarse slag, but it took 60 seconds longer to clean the yellow sandstone than the coarse slag. Therefore, actions to conserve historic buildings built from the yellow sandstone should be limited so as to minimise damage to their façades.

Table 4.3 shows that the surface of the yellow sandstone sample cleaned with the coarse slag became rougher than those cleaned with the natural abrasive. This factor should also be taken into consideration because the surface finish would influence the posterior conservation of the stone. For example, any masonry stone or clay brick with high porosity would absorb high moisture, which could attract biological soiling, such as mosses, lichens, etc. Therefore, even if natural abrasive causes a higher thickness reduction, it is still regarded as the most suitable abrasive for the yellow sandstone because it would provide a better conservation of the yellow sandstone after the cleaning process.

Table 4.3 – Yellow sandstone samples cleaned with the coarse slag and natural abrasive.

			
Yellow sandstone 1-1	Yellow sandstone 1-10	Yellow sandstone 7-1	Yellow sandstone 7-10

The red clay brick samples required similar cleaning times, and hence the level of thickness reduction becomes the decisive factor. The abrasive that produced the smallest level of thickness reduction was the medium glass. Only a thickness of 0.35 mm for the red clay brick sample was eliminated, while the required cleaning time was 14 seconds.

By applying the same criteria to the marble samples, the medium slag and fine glass should be selected because they produced smaller thickness reductions at 0.33 mm and 0.39 mm respectively. However, it required 50 seconds to complete the cleaning procedure with the medium slag, but only 20 seconds with the fine glass. Besides this, the fine glass produced the highest value of greyscale (GS = 172.81). Therefore, the fine glass can be regarded as the most suitable abrasive for cleaning marble stones.

By looking into the results for the granite, the sample cleaned with the medium glass was the most promising, because it caused the smallest thickness reduction of 0.15 mm and required only 10 seconds to complete full cleaning. This abrasive is also the one which produced the highest greyscale of 89.59. Furthermore, although the criteria for evaluation that were applied to the granite samples were the same as those applied to the rest of the masonry stones and clay bricks, it is important to emphasise that these samples initially had polished surfaces. This is the best cleaning method because this particular case is not air abrasive cleaning, as previously mentioned.

Finally, for the yellow clay brick, the abrasive, which produced the smallest thickness reduction of 0.19 mm and required only a cleaning time of 10 seconds, was the fine slag. Therefore the fine slag can be suggested as the most suitable abrasive for the yellow clay brick.

The above discussion and remarks are mainly based on the quantitative analysis of the results from the current experimental investigations. However, to achieve one of the objectives of this project, i.e. to assess a cleaning stage during which the patina can be fully removed, a different approach has to be sought. Patina can be defined as the colour layer that all materials accumulate over the years, and it protects the surface of the stone or brickwork from further erosion, because it forms a natural barrier to preserve stones from weathering. Therefore, its elimination could cause further damaging and accelerate the decay of stone or brick work.

The granite samples have a polished surface. Polished materials technically have smooth surfaces that do not allow the easy growth of soiling. Thus, it can be assumed that in a case where a patina grows on a granite surface, having no historic relevance, its removal would not cause 'damage', and/or would not leave the stone unprotected against future weathering actions.

For the rest of the masonry stones and clay bricks considered, the samples to be analysed are those that have possessed the best cleaning results, as defined in this chapter. Hence, the samples to be further studied are:

- the limestone, marble and red sandstone cleaned with the fine glass,
- the red clay brick cleaned with the medium glass,
- the yellow clay brick cleaned with the fine slag,
- the yellow sandstone cleaned with the natural abrasive.

With regard to the limestone, by looking into the images in Appendix H it is clear that no significant changes occurred between the cleaning stages 4 and 6. Also, by studying the data presented in Appendix C, the variations in the greyscale for these stages were not very high (153 to 160). Therefore, for the limestone, only six seconds are sufficient to guarantee a precise level of cleaning, and also to ensure the conservation of the natural patina if the fine glass is used.

The images of the marble cleaned with the fine glass in Appendix I show that between the cleaning stages 6 to 10 there were no significant changes in colour. Table C.20 in Appendix C shows similar results, where the greyscale values between the fifth and final cleaning stages were quite similar. Moreover, the greyscale value for the cleaning stage 4 was quite different from the value for the stage 5: 135 versus 154, respectively. There was a difference of almost twenty points in the greyscale between the consecutive stages. This is almost the same as that between the cleaning stage 5 and the final cleaning stage even though there were only eight stages in total. Therefore, it could be confirmed that after eight seconds a reasonable degree of dirt or soiling could be removed from the sample, and at the same time the patina could be preserved as well.

Fig. J.9 from Appendix J shows the different images of the red clay brick cleaned with the medium glass. Only small changes were detected between the cleaning stages 3 and 4, and between the stages 4 and 5. As a result of this, it was difficult to assess in which stage a satisfactory degree of cleaning had been reached. Table C.26 shows that the greyscale values at all the cleaning stages for this particular red clay brick sample were very similar. However, the difference in the greyscale between the cleaning stages 4 and 5 (almost two points) was higher than the difference between the cleaning stages 3 and 4 (less than 0.75 points). By observing the data it is evident that the soiling attached to the surface of the red clay brick sample was eliminated at the fifth cleaning stage. As a consequence of this a cleaning time of only eight seconds should be needed to provide an acceptable degree of cleaning. This timing would at the same time preserve the original colour coating on the surface of the red clay brick.

Due to the nature of the red sandstone samples, no homogeneous materials distributed over the cross section. Hence, it is difficult to identify in which stage a change of colour would become critical for determining the boundaries between a precisely favourable cleaning and a damaging cleaning (see Fig. K.23). The same difficulty is evident if the cleaning process is considered for the yellow clay brick sample (Table C.34). In that case, two stages existed in which a reasonable change in the greyscale measured could be identified. These two stages were between the stage 3 and 4 (a change of 7.6 points), and between the stages 9 and 9-b (one of almost 10 points). By studying this information and relooking at the data contained in Fig. K.23, the notable differences still could not provide a sufficient level of clarity to identify the desired degree of cleaning. Nevertheless, when it comes to heritage matters, the safest option is to adopt a conservative value, therefore the cleaning stage 4 (with a cleaning time of 15 seconds) should be regarded as the cleaning point that could offer a reasonable balance between removing the soiling and preserving the patina.

Fig. L.9 in Appendix L shows a significant change between the initial and second cleaning stages. By comparing this fact with the results in Table C.38, a substantial difference of almost 26 points in the greyscale can be observed between these two stages. The following stages show only slight reductions in the greyscale, and it can be suggested that only two seconds would be needed to achieve a desirable degree of cleaning as well ensuring the protection of the patina.

The yellow sandstone samples cleaned with the natural abrasive possessed similar results as those samples mentioned above. By analysing the images in Fig. M.25, an important change occurred between the cleaning stages 1 and 2. Table C.49 shows that the highest change in the greyscale happened between the cleaning stages 1 and 2. By accepting this, it can be concluded that to achieve a suitable degree of cleaning, while preserving the patina of masonry stones or clay bricks, a cleaning time of ten seconds is suitable. This was confirmed in the earlier preliminary investigations on the greyscale in this chapter. By looking into the photos in Appendix H it could be seen that no significant changes occurred between cleaning the stages 4 and 6. Also by looking into the data presented in Appendix C, the variations in the greyscale for these stages were not very high (153 to 160). Therefore, it could be concluded that for the limestone only six seconds would be enough to guarantee a precise level of cleaning and also to ensure the conservation of the natural patina if using the fine glass.

4.7 Summary

This chapter has introduced the greyscale imaging technique and recommended its applications for assessing the effectiveness of cleaning on masonry stones and clay bricks of listed historic buildings. It has detailed the procedure of determining the surface greyscales of the masonry stone and clay brock samples cleaned with fine recycled glass to different stages using "Colorpad" and analysed the progressive trends of the greyscale with the cleaning time in the preliminary digital image analysis using greyscale technique. It has indicated that a larger greyscale value normally would imply a cleaner and brighter surface. A term of cleanness has also been introduced for evaluating the effectiveness of cleaning together with greyscale. This chapter has extended the application of the greyscale imaging technique on analysing the surface images of the masonry stones and clay bricks using the commercial software Abode Photoshop. Seven different types of masonry stones and clay bricks have been cleaned to different stages by using seven different abrasives and the corresponding greyscale values have been assessed. Similar but extensive development trends of the greyscales with the cleaning time have been illustrated and the suitability of each abrasive for cleaning each type of masonry stone and clay brick has been discussed.

CHAPTER 5 HARDNESS TESTS AND IMPACT TESTS ON MASONRY STONES AND CLAY BRICKS

In this study, two types of physical testing were carried out to investigate the hardness and strength of the studied masonry stones and clay bricks: surface hardness testing and impact testing. The aim of the former was to evaluate the changes in the surface hardness of the masonry stones and clay bricks during the cleaning process so as to appraise the effect of the surface harness of masonry stones and bricks on the effectiveness of cleaning. The aim of the latter was to assess the required energy absorbed by the masonry stones and clay bricks so as to measure the corresponding toughness and explore its influence on the effectiveness of cleaning.

5.1 Vickers Hardness and Test Procedure

The Vickers hardness testing can be used to assess the hardness of a stone or a brick at different cleaning stages. The Vickers hardness number (H_v), which is regarded as a physical property for assessing the material strength, can be obtained in the test to define the hardness of the material. In addition, a group of H_v values were to be analysed statistically in order to directly indicate the surface hardness changes during the cleaning. Fig. 5.1 shows the detailed instrument used for this test.

In this test, a stone or a brick sample was hit and pressed by a diamond indenter with a load (P) of 1000 g for 15 seconds. The pyramid shaped indenter had a square base diamond and an angle of 136° between the opposite faces, as shown in Fig. 5.2. After removing the load, a diamond indentation could be found on the stone or brick surface using the microscope. Fig. 5.3 shows a micrograph of the stone surface which contains a diamond indentation with two diagonals. The diagonal dimensions were measured separately based on the two mark lines along each direction in the microscope attached to the edges of the indentations and obtaining the values of the horizontal and vertical dimensions of the indentation, d_H and d_V, which were shown on the digital encoder. Then the two Vickers Hardness Numbers (H_V) corresponding to d_H and d_V could be obtained by checking against a table for Vickers Hardness

Number. The values in the table were all calculated based on the formulas below. The mean value of H_V denoted the average of the two H_V results for the horizontal and vertical directions.

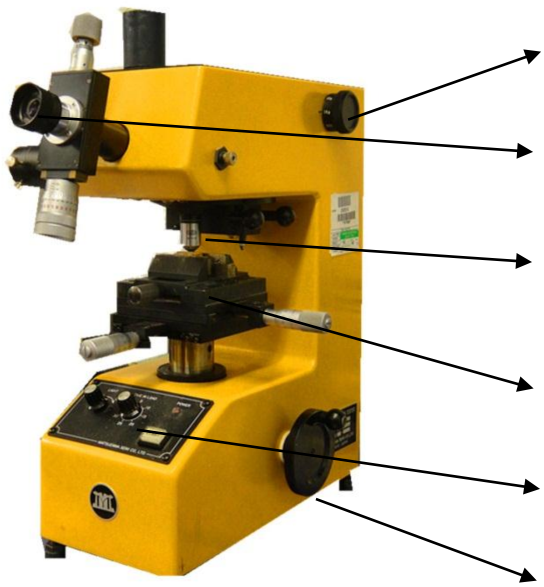


Fig. 5.1 – Detailed components of the Vickers hardness tester.

The Vickers Hardness Number H_V can be calculated from

$$H_V = \frac{\text{Applied load (kg)}}{\text{Contact area of indenter (mm}^2)} = \frac{2P \sin \theta/2}{d^2} \times 1000 = 1854.27 \frac{P}{d^2} \qquad (5.1)$$

where

H_v is the Vickers Hardness Number (kg/mm^2),

P is the applied load (g),

θ is the angle between the opposite faces (136°),

D is the diagonal of indentation (1 μm = 0.001 mm).

5.2 Vickers Hardness Test Results

Tables 5.1 to 5.7 list all the Vickers hardness results for the seven types of masonry stones and clay bricks. Each type of stone had four H_V values which represent the final Vickers hardness numbers at different cleaning stages.

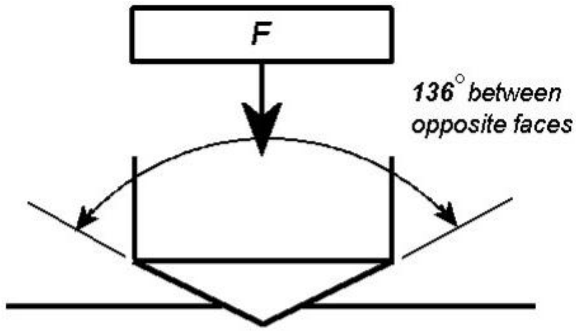


Fig. 5.2 – The pyramid shaped indenter.

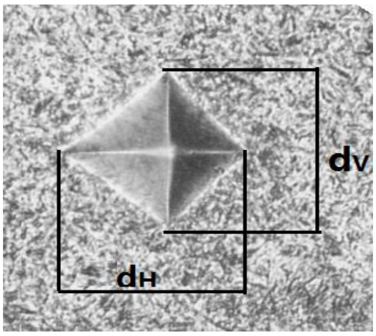


Fig. 5.3 – Diamond indentation on the stone surface.

Table 5.1 – Vickers hardness test results for the Yellow sandstone.

t (s)	d_H	H_V for H	d_V	H_V for V	Ave H_V
0	179.0	57.9	180.0	57.2	57.6
3	164.0	69.0	163.5	69.4	69.2
6	153.4	78.8	157.0	75.2	77.0
10	144.0	89.4	149.0	83.5	86.5

Table 5.2 – Vickers hardness test results for the Red sandstone.

t (s)	d_H	H_V for H	d_V	H_V for V	Ave H_V
0	202.0	45.5	206.5	43.5	44.5
3	180.0	57.2	179.4	57.6	57.4
6	155.5	76.7	171.6	63.0	69.9
10	153.2	79.0	159.0	73.4	76.2

Table 5.3 – Vickers hardness test results for the Limestone.

t (s)	d_H	H_V for H	d_V	H_V for V	Ave H_V
0	164.0	69.0	167.8	65.9	67.5
3	141.0	93.3	141.0	93.3	93.3
6	130.8	108.0	136.2	100.0	104.0
10	126.5	116.0	128.5	112.0	114.0

Table 5.4 – Vickers hardness test results for the Marble.

t (s)	d_H	H_V for H	d_V	H_V for V	Ave H_V
0	126.2	116.0	127.2	115.0	115.5
3	106.2	164.0	110.4	152.0	158.0
6	100.0	185.0	100.4	184.0	184.5
10	95.0	205.0	92.7	216.0	210.5

Table 5.5 – Vickers hardness test results for the White clay brick.

t (s)	d_H	H_V for H	d_V	H_V for V	Ave H_V
0	198.0	47.3	198.0	47.3	47.3
3	176.2	59.7	179.6	57.5	58.6
6	171.2	63.3	172.0	62.7	63.0
10	166.0	67.3	165.0	68.1	67.7

Table 5.6 – Vickers hardness test results for the Yellow clay brick.

t (s)	d_H	H_V for H	d_V	H_V for V	Ave H_V
0	183.4	55.1	178.5	58.2	56.7
2	164.4	68.6	163.5	69.4	69.0
4	155.5	76.7	156.3	75.9	76.3
7	149.5	83.0	150.5	81.9	82.5

Table 5.7 – Vickers hardness test results for the Granite.

t (s)	d_H	H_V for H	d_V	H_V for V	Ave H_V
0	63.2	464.0	63.0	467.0	465.5
10	62.5	475.0	61.5	490.0	482.5

5.3 Discussion on the Vickers Hardness Test Results

5.3.1 Vickers hardness number versus cleaning time

The Vickers hardness number can now be plot against the cleaning time. The curves in Figs. 5.4 to 5.10 indicate the changes of the surface hardness during the cleaning process. A linear regression method was used to assess the results. The function displayed in each figure could be used to represent the relationship between Vickers hardness number (H_V) and the cleaning time (t). The R^2 value below the function on each figure is the linear regression coefficient which indicates how well the parabolic line fits the test results. The closer R^2 is to one, the better the function fits the date. In general, the hardness for all samples in this study increased with the cleaning time because smaller hardness values at early cleaning stages were mainly contributed by the soft soiling on the masonry surface.

In Fig. 5.4, a parabola was used to show the increasing trend of the surface hardness of the yellow sandstone during the cleaning progress. The parabola almost coincides with the test data since the R^2-value is equal to 0.999 which is close to 1.0. The rise of the hardness of the yellow sandstone was quite uniform with a decreasing the slope of the parabola. The initial Vickers hardness number of the uncleaned yellow sandstone was 57.6 kg/mm^2 and it reached 86.5 kg/mm^2 after 10 seconds cleaning.

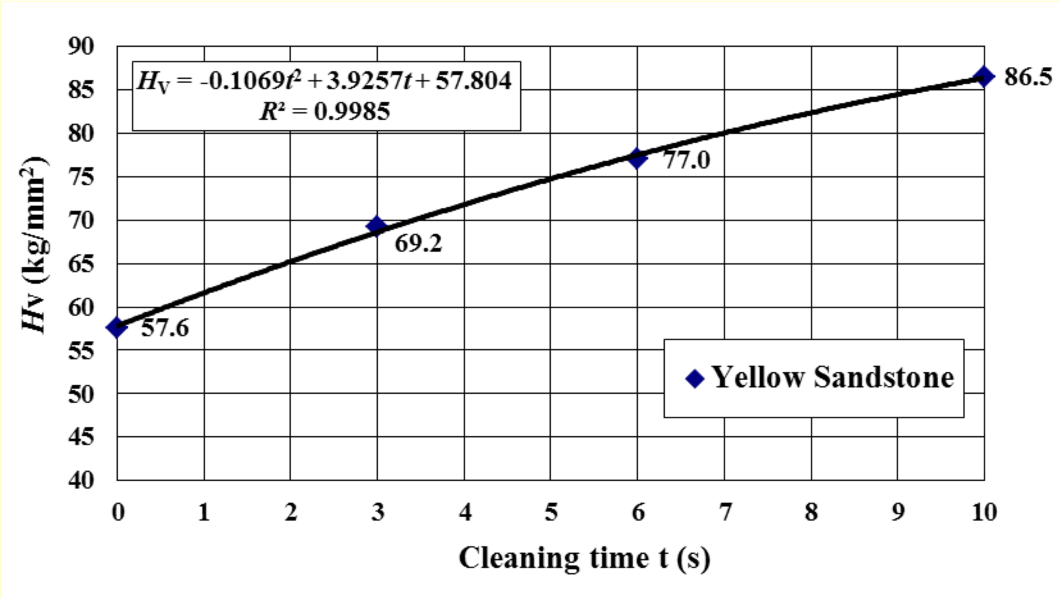


Fig. 5.4 – Vickers hardness number versus the cleaning time for the Yellow sandstone.

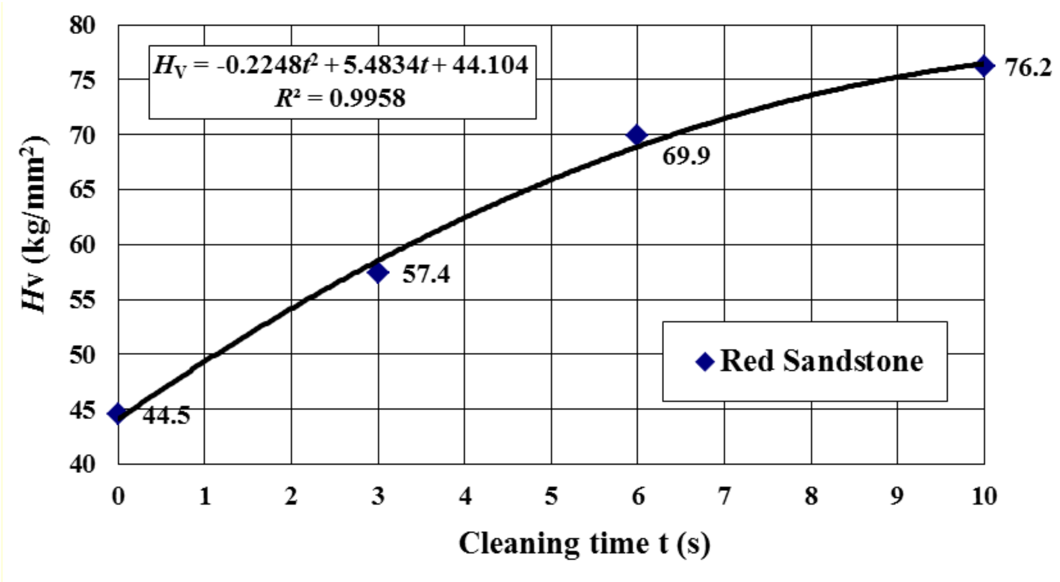


Fig. 5.5 – Vickers hardness number versus the cleaning time for the Red sandstone.

In Fig. 5.5, a parabola was used to show the increasing trend of the surface hardness of the red sandstone during the cleaning progress. The data and the parabola are very coincident since the R^2-value is equal to 0.996 which is close to 1.0. The initial Vickers hardness number of the uncleaned red sandstone was 44.5 kg/mm^2 and reached 76.2 kg/mm^2 after 10 seconds cleaning. Overall, the hardness of the red sandstone is lower than that of the yellow sandstone.

In Fig. 5.6, a parabola was used to show the increasing trend of the surface hardness of the limestone during the cleaning progress. The R^2-value is equal to 0.992 which is very close to 1.0 as well. The hardness of the limestone surface increased with the increasing cleaning time but at a decreasing rate and finally tended to be stable. The initial Vickers hardness number of the uncleaned limestone was 67.5 kg/mm^2 and quickly increased to 93.3kg/mm^2 after 3 seconds. Then the increasing rate slowed down. It reached 104.0 kg/mm^2 after another 3 seconds and stopped at 114.0 kg/mm^2 for the fully cleaned sample. The hardness of the limestone is higher than the sandstones.

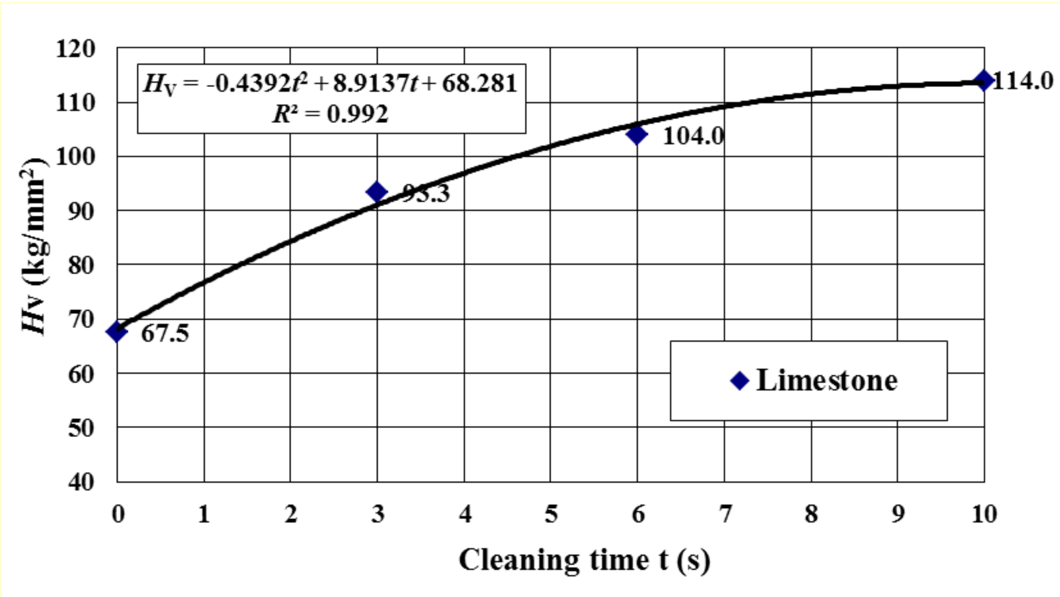


Fig. 5.6 – Vickers hardness number versus the cleaning time for the Limestone.

In Fig. 5.7, a parabola was used to show the increasing trend of the surface hardness of the marble during the cleaning progress. The data and the parabola almost coincide since the R^2-value is equal to 0.999 which is almost equal to 1.0. The initial Vickers hardness number of the uncleaned marble was 116.5 kg/mm^2 and it reached as high as 210.5 kg/mm^2 after 10 seconds cleaning. As the gap of the Vickers hardness number is quite large between different cleaning times, this indicates that the soiling has a large impact on the surface hardness of the marble.

In Fig. 5.8, a parabola was also used to show the increasing trend of the surface hardness of the white clay brick with the cleaning time during the cleaning progress. The data and the parabola are very coincident since the R^2-value is equal to 0.990. The hardness of the white clay brick surface increased with the increasing cleaning time but at a decreasing rate and finally tended to be stable. The initial Vickers hardness number of the uncleaned white clay brick was 47.3 kg/mm^2 and it reached 67.7 kg/mm^2 after 10 seconds cleaning. Overall, the surface hardness of the white clay brick is relatively low among all types of masonry stones and clay bricks.

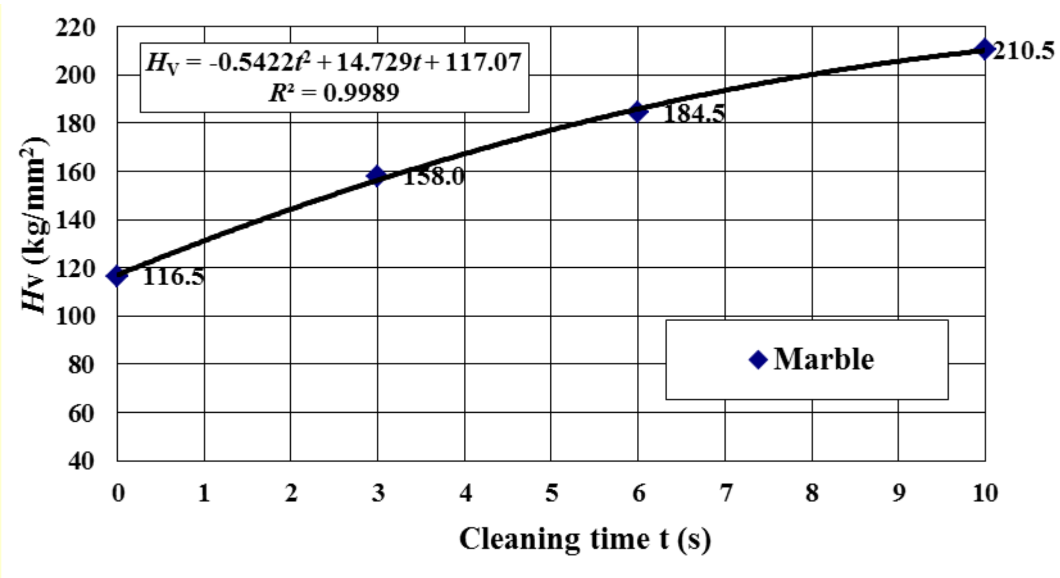


Fig. 5.7 – Vickers hardness number versus the cleaning time for the Marble.

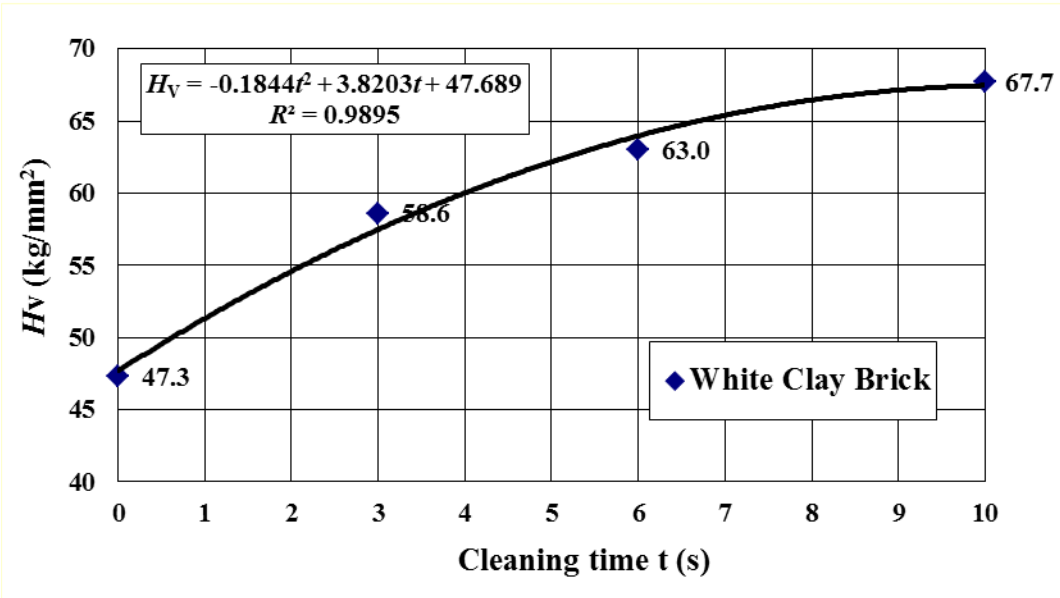


Fig. 5.8 – Vickers hardness number versus the cleaning time for the White clay brick.

In Fig. 5.9, a parabola was used to show the increasing trend of the surface hardness of the yellow clay brick during the cleaning progress. The data and the parabola almost coincide since the R^2-value is equal to 0.999 which is almost equal to 1.0. The trend of this parabola is quite similar to the one for the white clay brick, but the yellow clay brick is a little harder than the white clay brick in general. The initial Vickers Hardness Number of the uncleaned yellow clay brick was 56.7 kg/mm^2 and it reached 82.5 kg/mm^2 after 10 seconds cleaning.

Fig. 5.10 shows the change of the surface hardness between the uncleaned and fully cleaned granite samples. The Vickers hardness number of the uncleaned granite was 465.5 kg/mm^2 and it only increased by 3.7% when it was fully cleaned. It can also be seen that the surface of the granite is the hardest among all types of masonry stones and clay bricks.

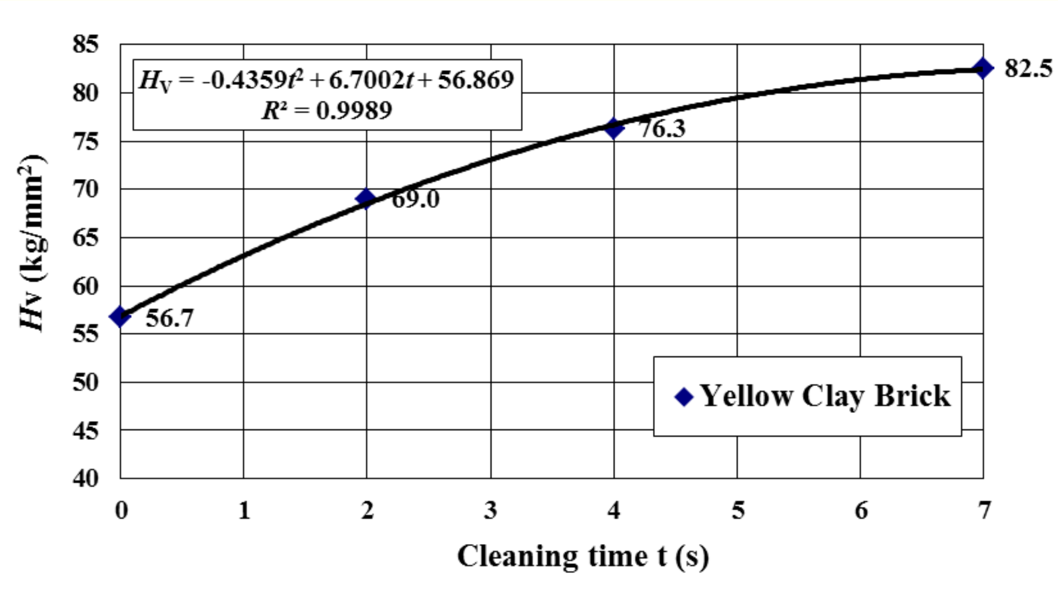


Fig. 5.9 – Vickers hardness number versus the cleaning time for Yellow clay brick.

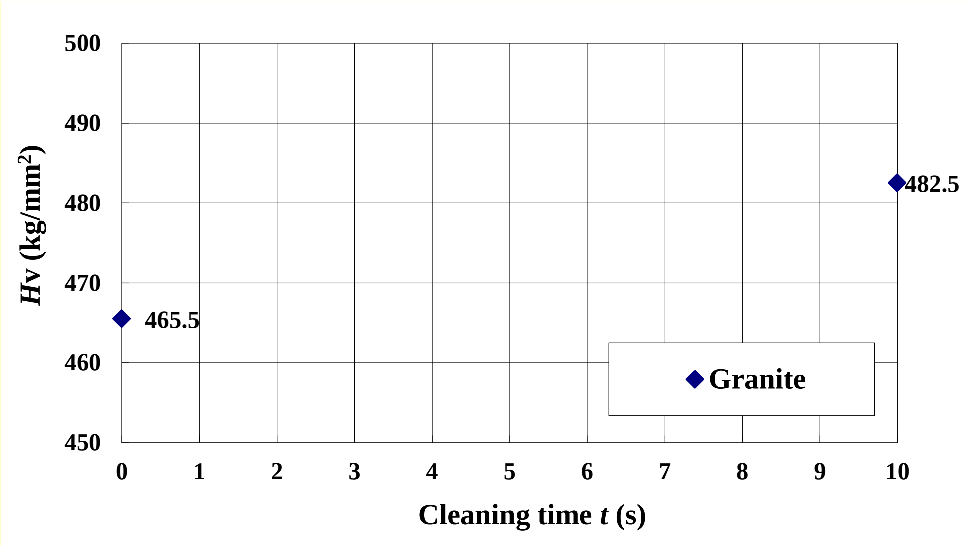


Fig. 5.10 – Vickers hardness number versus the cleaning time for the Granite.

Fig. 5.11 demonstrates the increase trend lines of the Vickers hardness number with the increased cleaning time for all the masonry stones and clay bricks tested. To view the trends more clearly, a small figure disregarding the results for the granite and marble is also inserted in the figure. It gives a clearly comparison of the hardness between the samples for the same cleaning time. This shows that granite had a hardest stone surface since the line is much higher than those for other masonry stones and clay bricks. On contrast, the clean surface of the white clay brick was the softest among all the cleaned masonry stones and bricks.

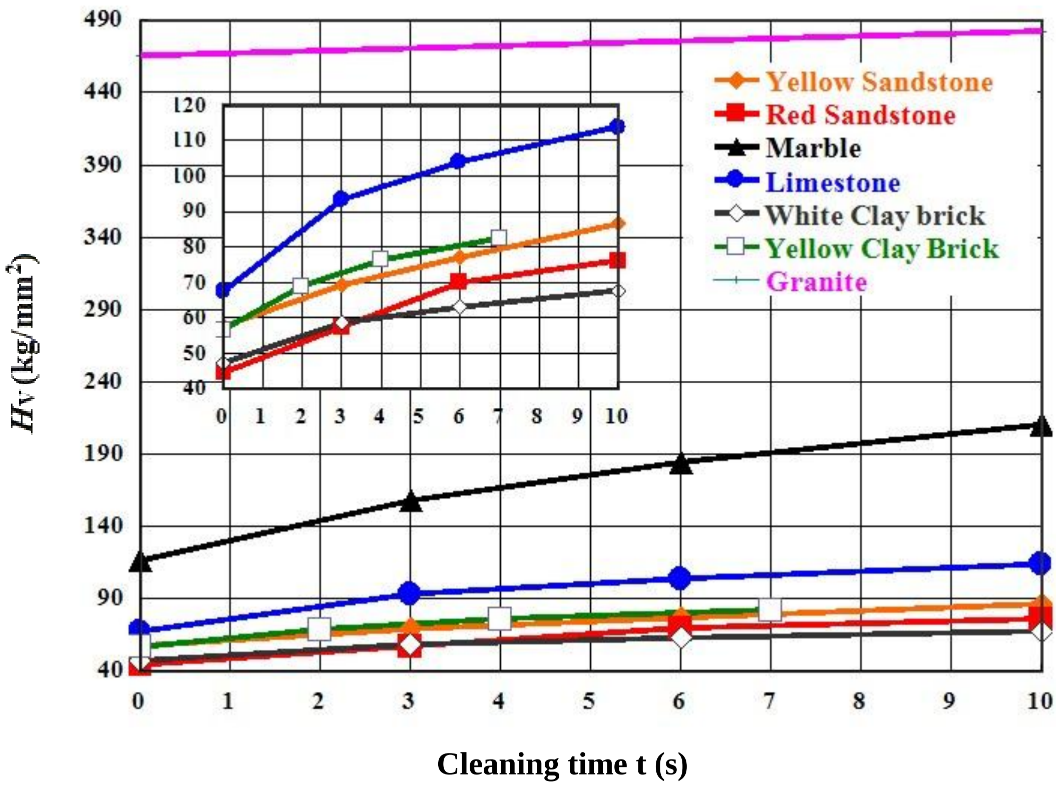


Fig. 5.11 – Vickers hardness number versus the cleaning time for all types of masonry stones and clay bricks.

5.3.2 Vickers hardness number versus cleanness

Figs. 5.12 to 5.18 show the Vickers hardness numbers versus the cleanness on those samples from the preliminary greyscale imaging analysis. It clearly shows the increase trends of the surface hardness with the rise of the cleaning levels.

As shown in Fig. 5.12, the Vickers hardness number versus cleanness trend for the yellow sandstone can be expressed by a bi-linear relationship. When the cleanness increased from 0.61 to 0.95, the surface hardness slightly increased. However, it grew rapidly from 77.0 kg/mm^2 to 86.5 kg/mm^2 in the final cleaning stage. This indicates that the sticky soiling on the yellow sandstone surface had a larger impact on the surface hardness than the easily removed dust. As shown in Fig. 5.13, the Vickers hardness number versus cleanness trend for the red sandstone can be expressed by an approximately linear relationship. The hardness of the red sandstone increased stably from 44.5 kg/mm^2 to 76.2 kg/mm^2 when the cleanness increased 0.77 to 1.0.

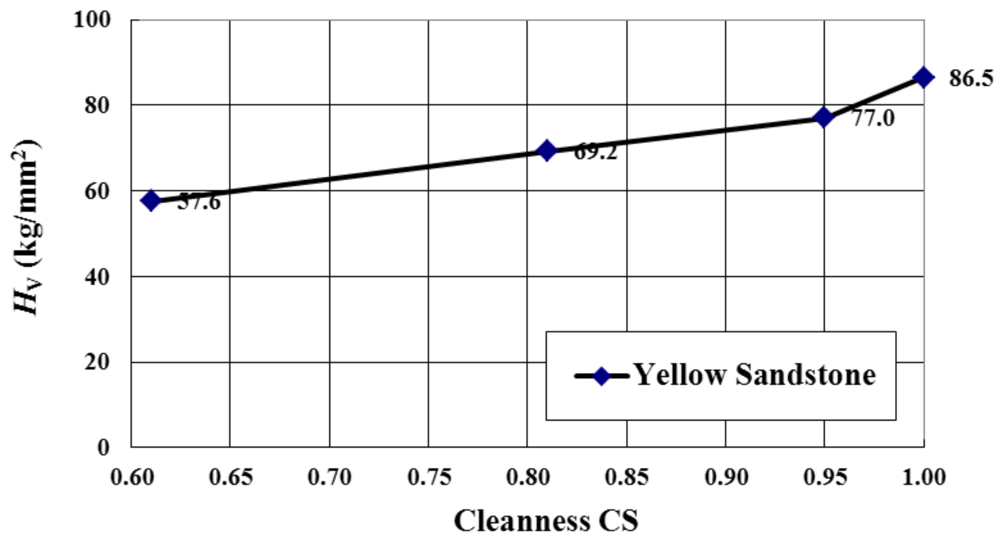


Fig. 5.12 – Vickers hardness number versus the cleanness for the Yellow sandstone.

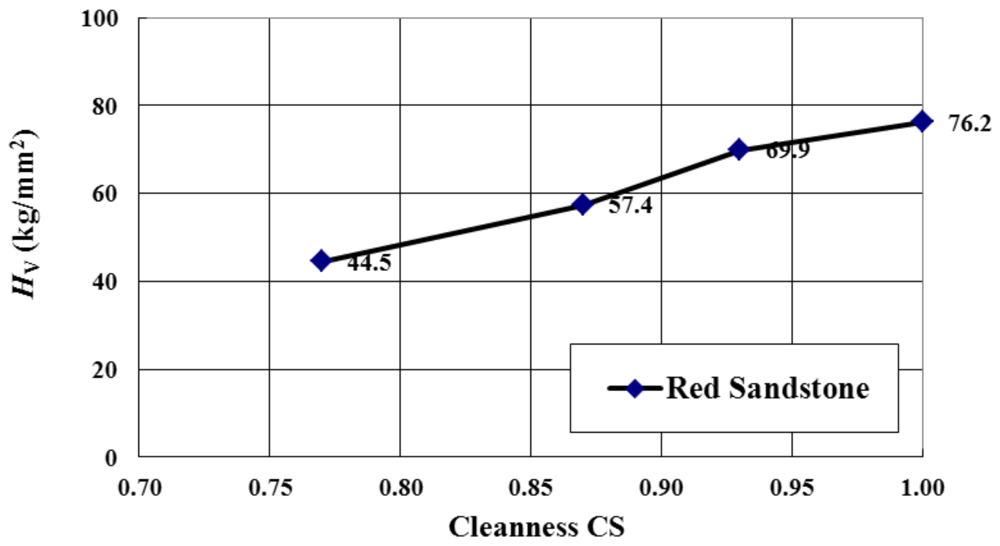


Fig. 5.13 – Vickers hardness number versus the cleanness for the Red sandstone.

As shown in Fig. 5.14, the Vickers hardness number versus cleanness trend for the limestone can be expressed by a bi-linear relationship. The hardness of the limestone increased stably from 67.5 kg/mm^2 to 114 kg/mm^2 when the cleanness increased from 0.77 to 1.0.

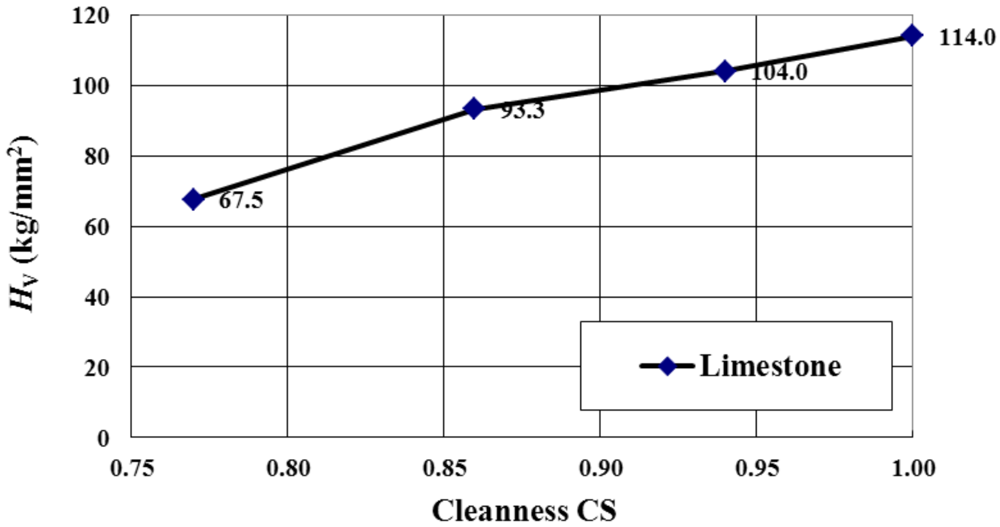


Fig. 5.14 – Vickers hardness number versus the cleanness for the Limestone.

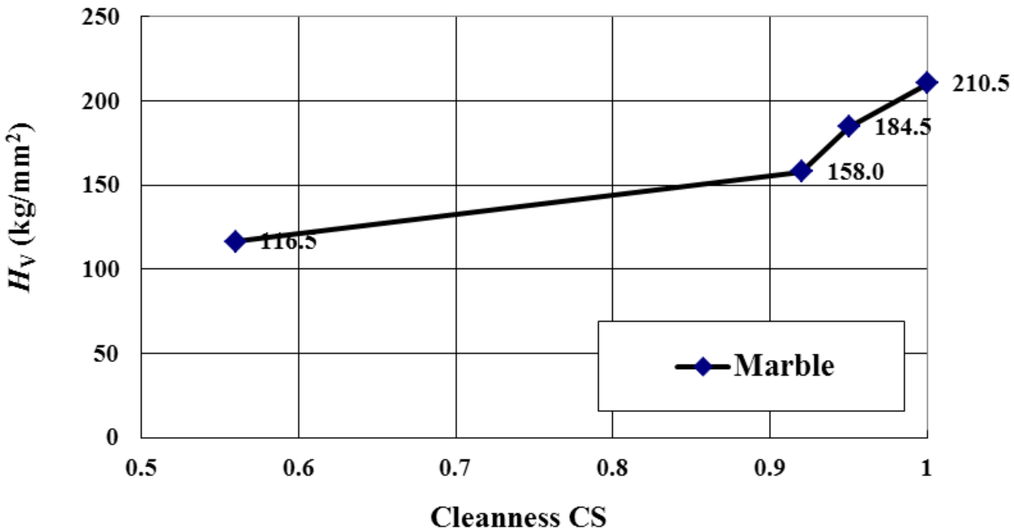


Fig. 5.15 – Vickers hardness number versus the cleanness for the Marble.

As shown in Fig. 5.15, the Vickers Hardness Number versus cleanness trend for the marble sandstone can be expressed by a bi-linear relationship. When the cleanness increased from 0.56 to 0.92, the surface hardness of the yellow sandstone did not rise too much. However, it grew quickly to 210.5 kg/mm^2 in the final cleaning stage. This indicates that the sticky soiling on the marble surface had larger impact on the surface hardness than the easily removed dust.

As shown in Fig. 5.16, the Vickers Hardness Number versus the cleanness for the white clay brick can be expressed by an approximately linear relationship. The surface hardness of the white clay brick increased slightly more quickly within the final 7 seconds than the first 3 seconds. This indicates that the surface hardness of the white clay brick is affected more significantly by the sticky soiling than the easily removed dust.

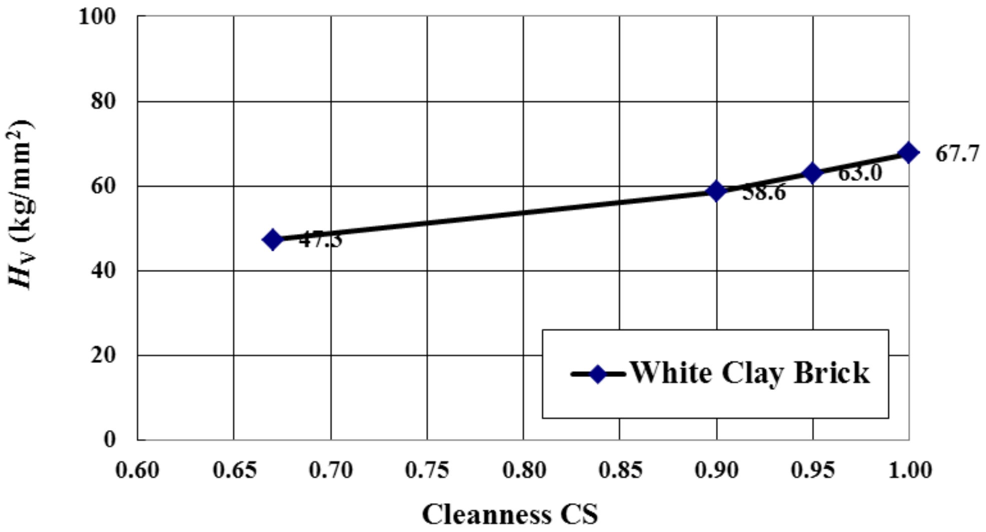


Fig. 5.16 – Vickers hardness number versus the cleanness for the White clay brick.

As shown in Fig. 5.17, the Vickers hardness number versus cleanness trend for the yellow clay brick can be expressed by a bi-linear relationship. The increase trend of the surface hardness of the yellow clay brick is quite similar to that of the white clay brick. When the cleanness increased from 0.66 to 0.92, the surface hardness of the yellow clay brick did not significantly increase. However, it grew rapidly to 82.5 kg/mm^2 in the final 7 seconds. This indicates that the surface dust which could be removed in the initial cleaning time had little influence on the surface hardness of the yellow clay brick.

Finally Fig. 5.18 shows the change of the surface hardness between the uncleaned and fully cleaned granite samples. The surface hardness increased from 465.5 kg/mm^2 to 482.5 kg/mm^2, while the cleanness increased from 0.78 to 1.0.

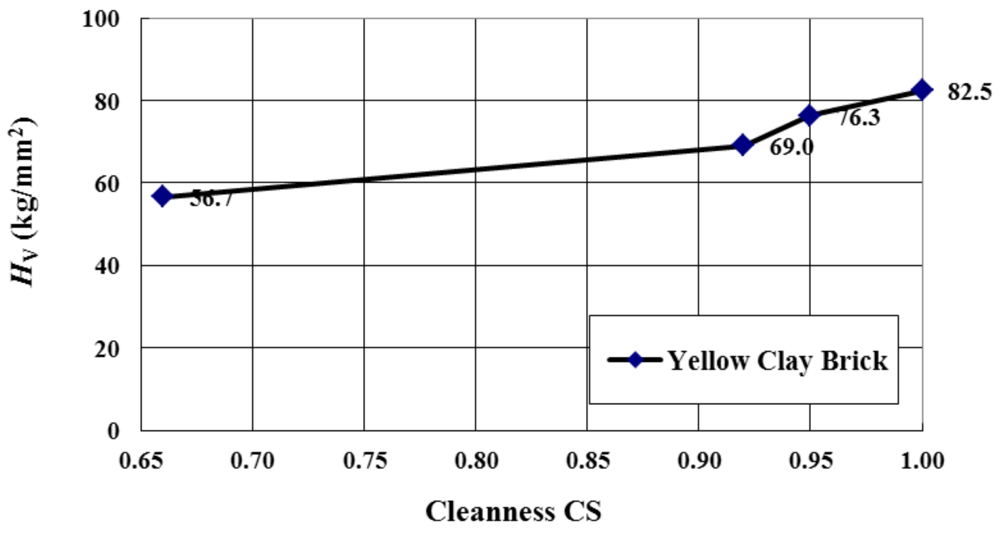


Fig. 5.17 – Vickers Hardness Number versus the cleanness for the Yellow clay brick.

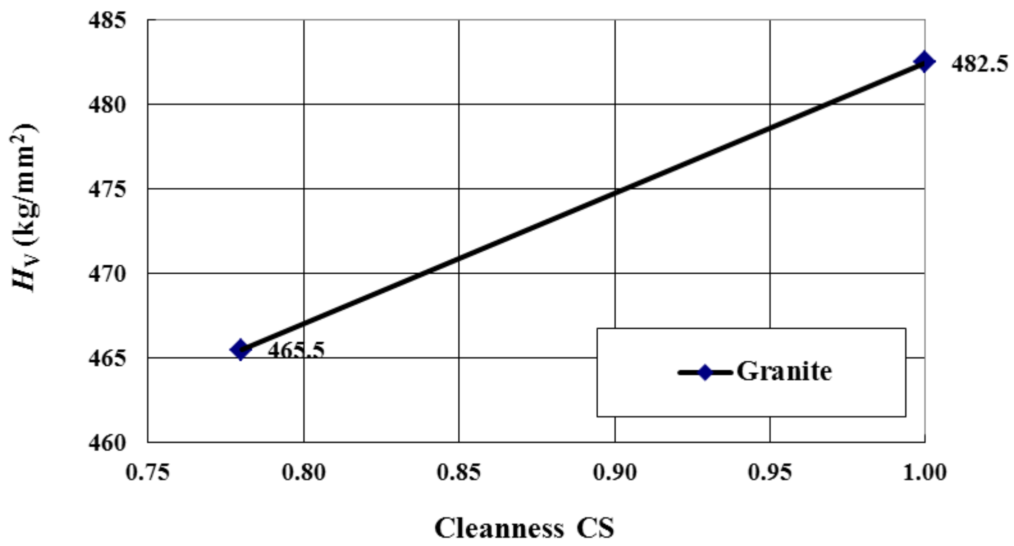


Fig. 5.18 – Vickers Hardness Number versus the cleanness for the Granite.

Fig. 5.19 shows the relationships of the Vickers hardness number with the greyscale for all types of masonry stones and clay bricks and Fig. 5.20 shows the relationships between the hardness and the cleanness. Similar monotonic increase trends in these two figures indicate that the hardness increased with both increased cleanness and greyscale. Small figures were inserted in both Figs. 5.19 and 5.20 to obtain a clear view of the trends. The two figures also show that the original granite had the hardest and cleanest surface among all the stones and bricks. The surface of the original marble was harder than any other stones except granite, and was extremely dirty.

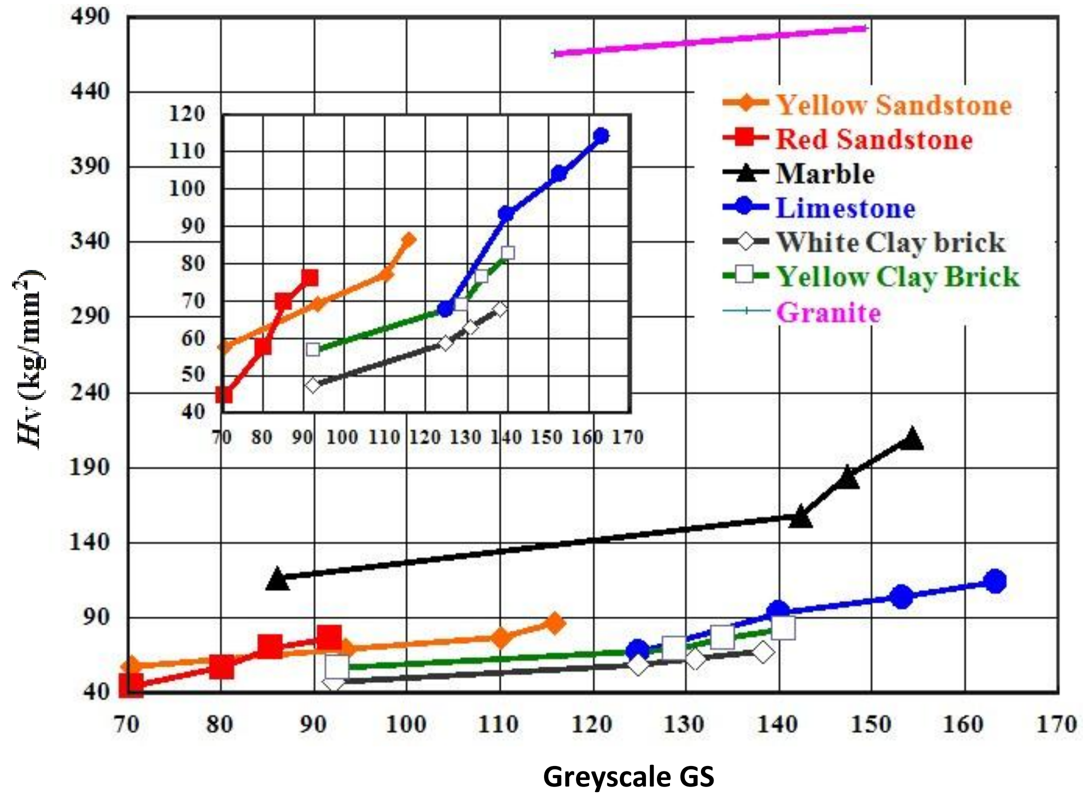


Fig. 5.19 – Vickers Hardness Number versus the greyscale for all types of masonry stones and clay bricks.

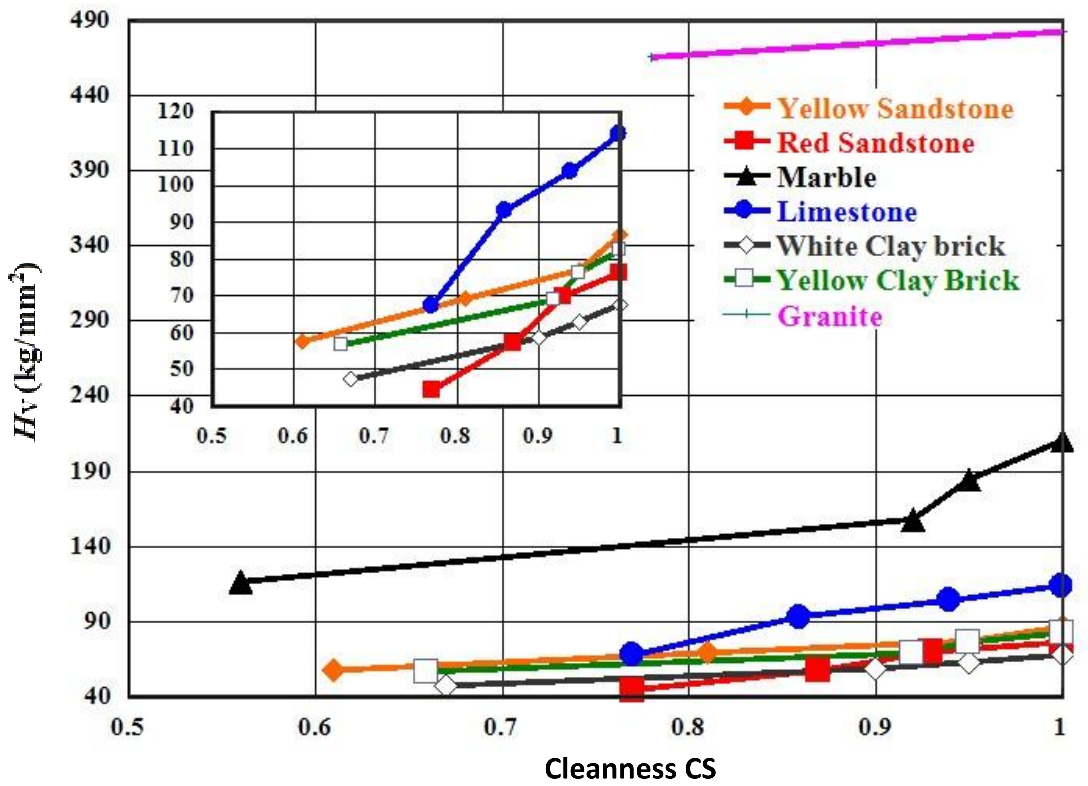


Fig. 5.20 – Vickers hardness number versus the cleanness for all types of masonry stones and clay bricks.

In summary, the Vickers hardness number can be used to assess the hardness of the stone surface. The bigger the value of the Vickers hardness number, the harder a stone or brick surface is. The surface hardness of a masonry stone or a clay brick continuously increased during the cleaning process and stopped when it was fully cleaned. The relationships between the Vickers hardness number and the cleanness could indicate the surface hardness and surface conditions of masonry stones and clay bricks at the same time. In addition, the sticky soiling on the stone or brick surface had a larger impact on the surface hardness than the easily removed dust.

5.4 Impact Tests on Masonry Stone and Clay Brick Samples

5.4.1 Impact resistance

It is well known that the impact resistance is one of the fundamental mechanical properties of solid materials. Here, the Charpy Impact testing was conducted to evaluate the toughness of the masonry stones or clay bricks. Figs. 5.21 and 5.22 illustrate the test equipment and its function in details. The Impact resistance number (R_i) can be calculated according to the test results. Besides, a set of R_i values are analysed to indicate whether the sample is ductile or brittle.

5.4.2 Masonry stone and clay brick samples

The impact tests were carried out on seven types of masonry stones and clay bricks including Yellow sandstone, Red sandstone, Yellow clay brick, Red clay brick, Limestone, Marble and Granite. For each type of masonry stone or clay brick, at least four samples were selected for the impact tests. The dimensions for the nominal square sections should be 6 mm for the width, 6 mm for the height and 50 mm for the length. However, due to the limitation of the sources of the samples, not all samples were exactly cut to the nominal dimensions. Figs. 5.23 to 5.29 show both the shapes and sizes of all the masonry stone and clay brick specimens.

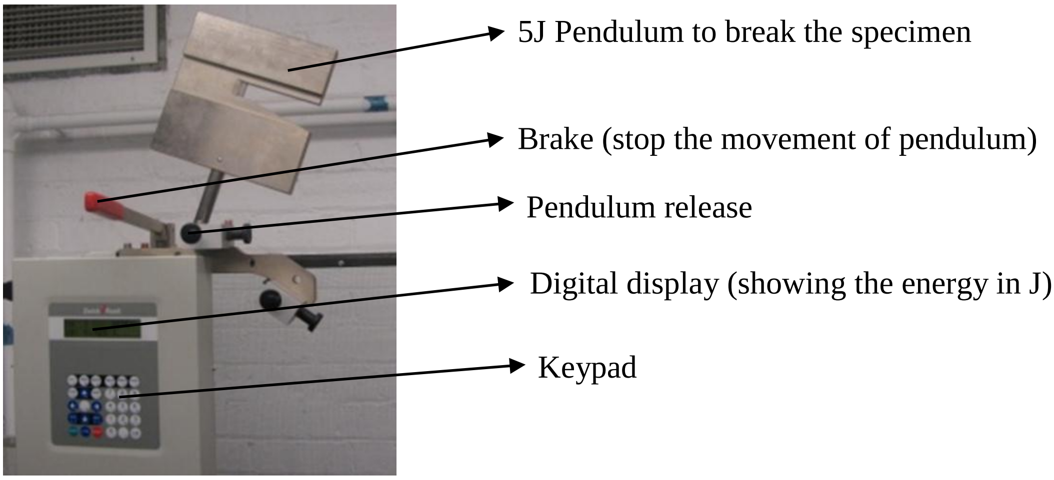


Fig. 5.21 – Components of the upper part of the Charpy Impact Machine.

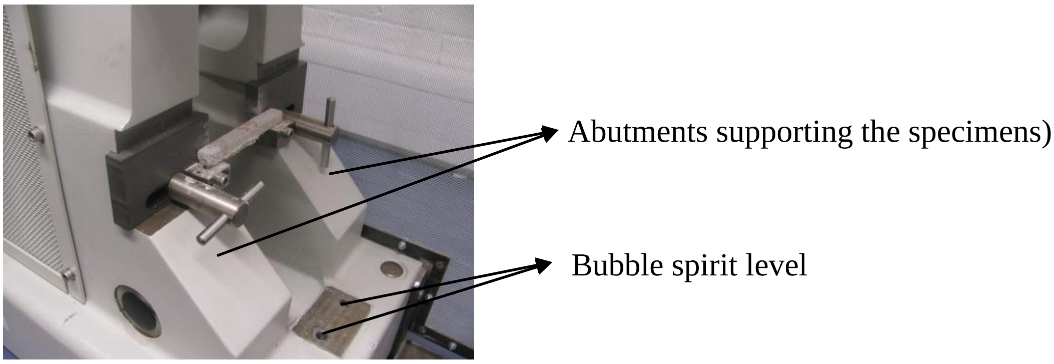


Fig. 5.22 – Components of the lower part of the Charpy Impact Machine.

Fig. 5.23 – Yellow sandstone.

Fig. 5.24 – Red sandstone.

Fig. 5.25 – Yellow clay brick.

Fig. 5.26 – Red clay brick.

Fig. 5.27 – Limestone.

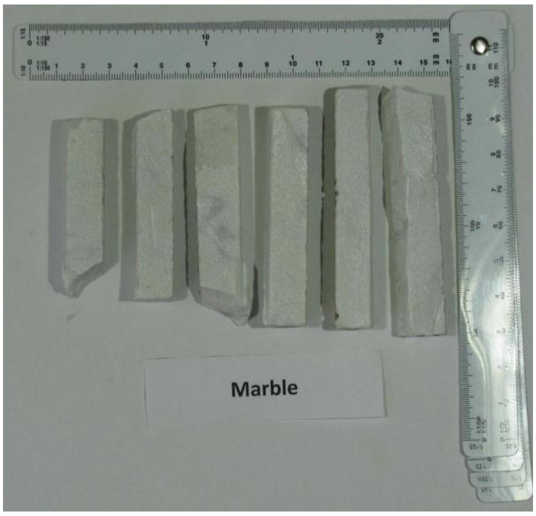


Fig. 5.28 – Marble.

Fig. 5.29 – Granite.

5.4.3 Charpy impact test procedure

In the Charpy impact tests, the stone or brick specimens sustained an impact to break by using a 5 J pendulum with a length of 225 mm and an impact velocity of 2.93 m/s. Before placing the samples on the two abutments which were used as simply supported beams, the unit scale was set to Joules. After releasing the pendulum at an angle of 160^o with the impact velocity of 2.93 m/s, the impact energy (E) could be read through the screen of the digital display. Then the dimensions of the fracture surface were measured three times by using a digital Vernier calliper with a precision of 0.01 mm as b_1, b_2, b_3, h_1, h_2 and $h_3$in mm. The mean values of R_i were the average of at least four results from one type of stone or brick samples.

The impact resistance number, R_i, can be calculated from

$$R_i = \frac{\text{Impact engergy E (J)}}{\text{Fracture surface area } A_i(mm^2)} = \frac{E}{A_i} = \frac{E}{b \times h}$$
$$= \frac{E}{(b_1 + b_2 + b_3)/3 \times (h_1 + h_2 + h_3)/3} \qquad (5.1)$$
$$= \frac{9E}{(b_1 + b_2 + b_3) \times (h_1 + h_2 + h_3)}$$

where

R_i	is the impact resistance number (J/mm^2),
E	is the impact energy (J),
A_i	is the fracture surface area (mm^2),
b_1, b_2, b_3	are the weights of the fracture surface at three locations (mm),
h_1, h_2, h_3	are the heights of the fracture surface at three locations (mm).

Figs. 5.30 to 5.36 illustrate the shapes of the fracture surface after failure for all seven types of masonry stone and clay brick specimens. It can be seen that the features of the fracture surface were irregular which led to the errors of the tests.

Fig. 5.30 – Yellow sandstone.

Fig. 5.31 – Red sandstone.

Fig. 5.32 – Yellow clay brick.

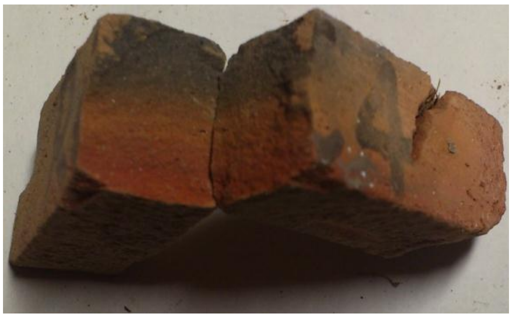


Fig. 5.33 – Red clay brick.

Fig. 5.34 – Limestone.

Fig. 5.35 – Marble.

Fig. 5.36 – Granite.

5.5 Charpy Impact Test Results

Tables 5.8 to 5.14 illustrate all the impact resistance results for seven types of masonry stones and clay bricks, including the average values, standard deviation (SD) and the coefficients of variation C_V which are the ratios of the SD values to the average ones. These results are also illustrated in Figs. 5.37 to 5.43.

Table 5.8 – Charpy impact test results for the Yellow sandstone.

	b (mm)			**h** (mm)			$\mathbf{A_i}$	**E**	$\mathbf{R_i}$
	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{h_1}$	$\mathbf{h_2}$	$\mathbf{h_3}$	(mm^2)	(J)	(kJ/m^2)
YS1	14.03	14.28	14.36	11.22	11.08	11.13	158.50	0.363	2.290
YS2	11.75	11.49	11.48	13.24	12.91	12.74	150.03	0.300	2.000
YS3	13.58	14.12	12.51	12.11	12.28	12.68	165.62	0.342	2.065
YS4	14.80	14.55	12.75	14.81	14.29	13.64	199.93	0.426	2.131
Average R_i = 2.121 kJ/m^2				**SD = 0.125 kJ/m^2**				**C_V = 5.88%**	

Table 5.9 – Charpy impact test results for the Red sandstone.

	b (mm)			**h** (mm)			$\mathbf{A_i}$	**E**	$\mathbf{R_i}$
	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{h_1}$	$\mathbf{h_2}$	$\mathbf{h_3}$	(mm^2)	(J)	(kJ/m^2)
RS1	15.74	15.66	15.67	10.61	11.30	12.50	179.96	0.469	2.606
RS2	15.39	15.20	14.76	8.70	9.16	10.91	144.97	0.342	2.359
RS3	15.71	15.47	14.70	15.26	14.94	14.07	225.68	0.513	2.273
RS4	14.31	12.58	11.30	15.13	15.16	15.28	193.37	0.513	2.653
RS5	15.37	15.27	14.85	8.71	8.90	9.48	136.92	0.300	2.191
RS6	17.49	17.20	17.10	9.22	10.01	9.23	163.77	0.384	2.345
Average R_i = 2.405 kJ/m^2				**SD = 0.185 kJ/m^2**				**C_V = 7.69%**	

Table 5.10 – Charpy impact test results for the Yellow clay brick.

	b (mm)			**h** (mm)			$\mathbf{A_i}$	**E**	$\mathbf{R_i}$
	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{h_1}$	$\mathbf{h_2}$	$\mathbf{h_3}$	(mm^2)	(J)	(kJ/m^2)
YC1	17.29	16.57	16.83	9.95	11.75	12.40	192.06	0.513	2.671
YC2	19.74	19.69	19.97	15.56	15.21	14.42	298.25	0.668	2.240
YC3	20.65	20.14	19.40	12.18	13.40	13.74	262.96	0.690	2.624
YC4	14.24	15.53	16.32	19.75	18.70	17.71	287.60	0.534	1.857
Average R_i = 2.348 kJ/m^2				**SD = 0.380 kJ/m^2**				**C_V = 16.19%**	

Table 5.11 – Charpy impact test results for the Red clay brick.

	b (mm)			**h** (mm)			$\mathbf{A_i}$	**E**	$\mathbf{R_i}$
	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{h_1}$	$\mathbf{h_2}$	$\mathbf{h_3}$	(mm^2)	(J)	(kJ/m^2)
RC1	14.72	15.08	15.01	13.44	14.52	14.78	212.80	0.426	2.002
RC2	16.43	16.65	16.43	15.01	15.47	15.71	254.10	0.645	2.538
RC3	14.30	14.02	13.72	13.57	14.70	15.28	203.43	0.623	3.063
RC4	14.90	15.20	15.07	13.33	12.65	12.06	190.92	0.469	2.457
Average R_i = 2.515 kJ/m^2				**SD = 0.435 kJ/m^2**				**C_V = 17.29%**	

Table 5.12 – Charpy impact test results for the Limestone.

	b (mm)			**h** (mm)			$\mathbf{A_i}$	**E**	$\mathbf{R_i}$
	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{h_1}$	$\mathbf{h_2}$	$\mathbf{h_3}$	(mm^2)	(J)	(kJ/m^2)
L1	20.79	20.81	19.79	12.85	13.69	14.42	279.39	0.713	2.552
L2	21.00	20.95	20.65	13.92	15.75	17.47	327.88	0.921	2.809
L3	20.95	20.94	20.88	11.63	12.38	12.60	255.33	0.690	2.702
L4	20.91	21.16	21.22	14.65	12.24	10.37	262.02	0.758	2.893
L5	20.83	21.09	21.10	15.26	12.94	12.08	282.05	0.690	2.446
Average R_i = 2.680 kJ/m^2				**SD = 0.313 kJ/m^2**				**C_V = 11.66%**	

Table 5.13 – Charpy impact test results for the Marble.

	b (mm)			**h** (mm)			$\mathbf{A_i}$	**E**	$\mathbf{R_i}$
	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{h_1}$	$\mathbf{h_2}$	$\mathbf{h_3}$	(mm^2)	(J)	(kJ/m^2)
M1	14.46	15.41	11.08	15.12	15.36	8.31	176.49	0.556	3.150
M2	13.73	13.21	11.15	13.60	13.99	7.49	148.47	0.534	3.597
M3	17.16	17.58	14.36	10.85	12.31	10.72	184.83	0.690	3.733
M4	14.09	13.62	10.21	13.29	13.86	9.35	153.79	0.448	2.913
M5	13.86	15.01	14.44	15.63	12.18	16.13	211.45	0.491	2.322
Average R_i = 3.134 kJ/m^2				**SD = 0.566 kJ/m^2**				**C_V = 18.00%**	

5.6 Discussion on the Impact Resistance

Fig. 5.37 shows the impact resistance values of four yellow sandstone samples with their average value. The impact resistances for the four samples varied from 2.000 kJ/m^2 to 2.290 kJ/m^2 with an average impact resistance of 2.121 kJ/m^2. The figure also shows that the results for two samples were modestly less than the average value. Furthermore, the standard deviation (SD) was 0.125 kJ/m^2, giving the coefficient of variation (C_V) of only 5.88%. This means that the results did not vary significantly.

Table 5.14 – Charpy impact test results for the Granite.

	b (mm)			**h** (mm)			$\mathbf{A_i}$	**E**	$\mathbf{R_i}$
	$\mathbf{b_1}$	$\mathbf{b_2}$	$\mathbf{b_3}$	$\mathbf{h_1}$	$\mathbf{h_2}$	$\mathbf{h_3}$	(mm^2)	(J)	(kJ/m^2)
G1	15.40	15.55	15.04	11.88	11.60	11.91	180.84	0.659	3.644
G2	15.55	15.77	15.64	10.30	10.53	11.07	166.45	0.668	4.013
G3	12.53	12.92	13.30	11.47	11.56	11.37	148.11	0.491	3.315
G4	14.90	13.46	13.04	10.82	10.82	11.14	150.79	0.491	3.256
G5	14.02	14.01	14.82	10.28	10.46	10.75	149.93	0.491	3.275
G6	12.44	12.66	13.21	13.09	12.62	11.58	158.73	0.513	3.232
Average R_i = 3.456 kJ/m^2				**SD = 0.313 kJ/m^2**				**C_V = 9.05%**	

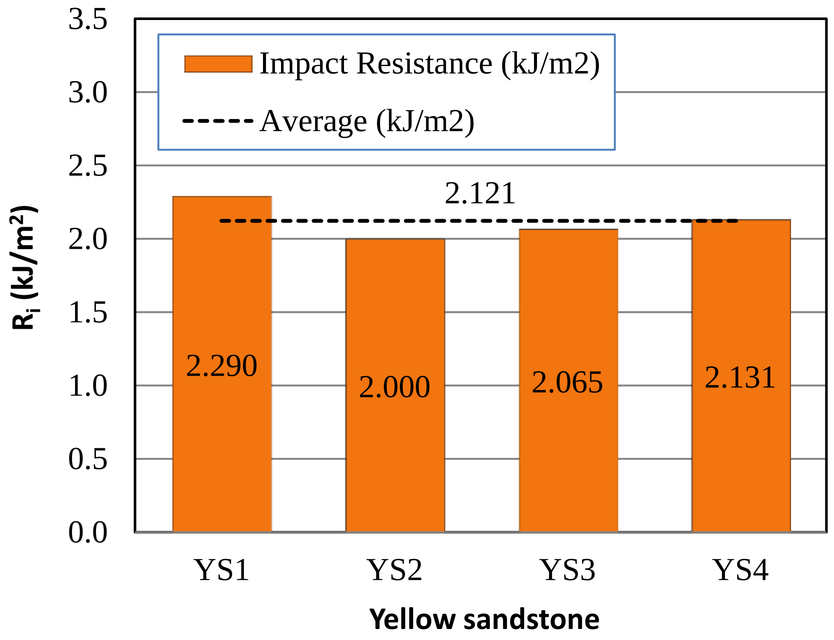


Fig. 5.37 – Impact resistances for the Yellow sandstone.

Fig. 5.38 illustrates the impact resistances values of six red sandstone samples together with their average value. The impact resistances for the six specimens varied from 2.191 kJ/m^2 to 2.653 kJ/m^2 with an average impact resistance of 2.405 kJ/m^2. The figure also shows that the results for only two samples outweighed the average value comparatively. Furthermore, the standard deviation (SD) was 0.185 kJ/m^2, giving the coefficient of variance (C_V) of 7.69%. Again this means that the test results varied insignificantly.

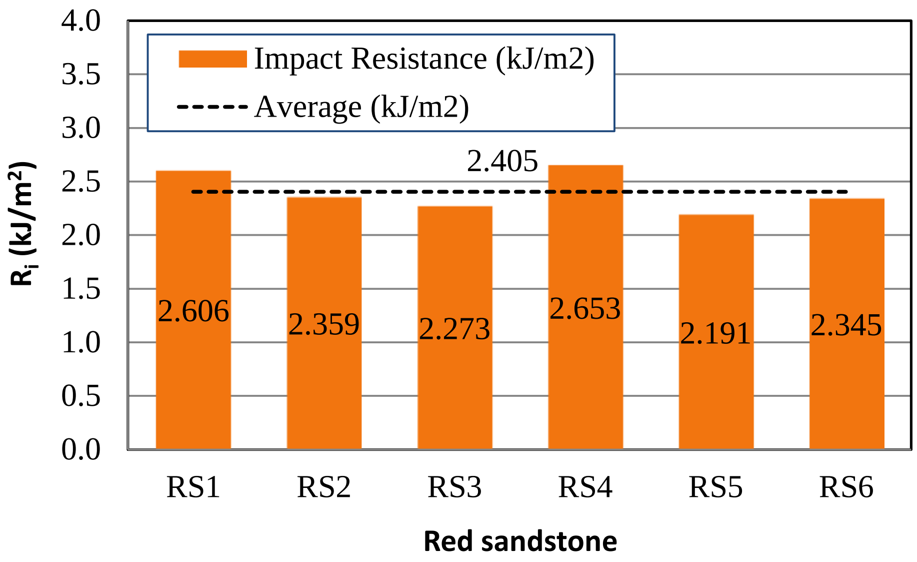


Fig. 5.38 – Impact resistances for the Red sandstone.

Fig. 5.39 illustrates the impact resistance values of four yellow clay brick samples with their average value. The impact resistances for the four samples varied from 1.857 kJ/m^2 to 2.671 kJ/m^2 with an average impact resistance of 2.348 kJ/m^2. The figure also shows that the results for two samples were below the average value, with one of these visibly slightly less than the average value. Furthermore, the standard deviation (SD) was 0.380 kJ/m^2, giving the coefficient of variance (C_V) of 16.19% which was moderately high.

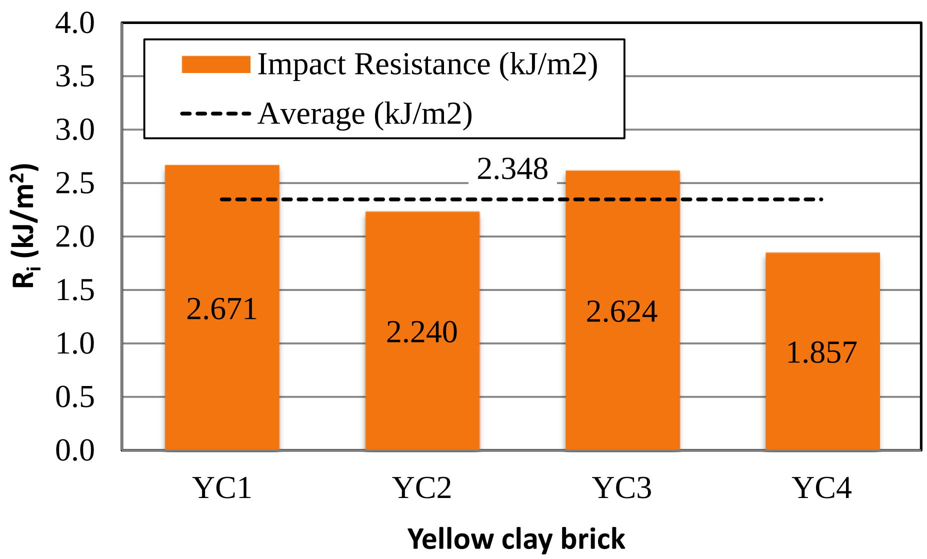


Fig. 5.39 – Impact resistances for the Yellow clay brick.

Fig. 5.40 illustrates the impact resistance values of four red clay brick with their average value. The impact resistances for these four samples varied from 2.002 kJ/m^2 to 3.063 kJ/m^2 with an average impact resistance of 2.515 kJ/m^2. The figure also indicates that the results for two samples outweighed the average value. One markedly exceeded the average value while the other was just minimally outnumbered it. Furthermore, the standard deviation (SD) was 0.435 kJ/m^2, giving the coefficient of variance (C_V) of 17.29% which was relatively high.

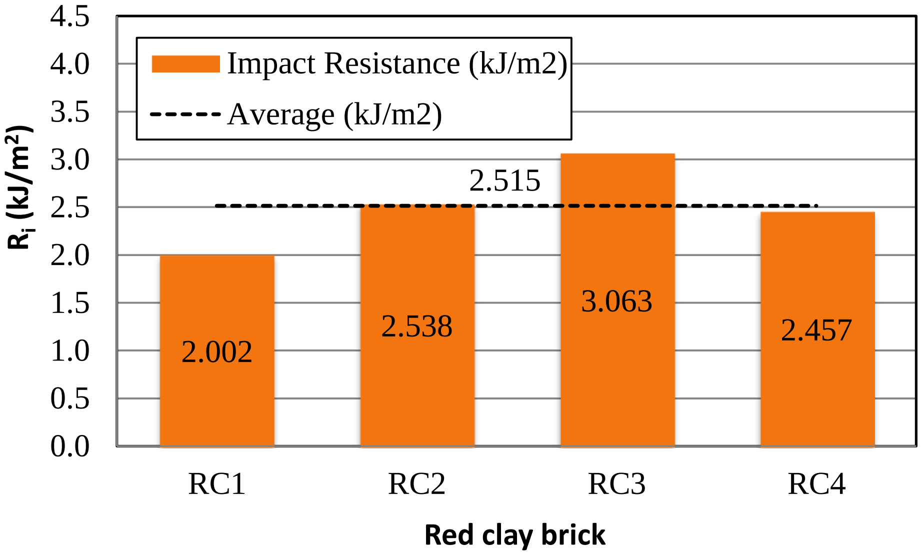


Fig. 5.40 – Impact resistances for the Red clay brick.

Fig. 5.41 shows the impact resistance values of five limestone samples with their average value. The impact resistances for the five samples varied from 2.446 kJ/m^2 to 2.893 kJ/m^2 with an average impact resistance of 2.680 kJ/m^2. The figure also shows that the results for three samples surpassed the average value. Two of them comparatively exceeded the average value while one just marginally outnumbered it. Furthermore, the standard deviation (SD) was 0.313 kJ/m^2, giving the coefficient of variance (C_V) of 11.66%.

Fig. 5.42 illustrates the impact resistance values of five Marble together with their average value. The impact resistances for the five samples varied from 2.322 kJ/m^2 to 3.733 kJ/m^2 with an average impact resistance of 3.134 kJ/m^2. The figure also shows that the results for three samples surpassed the average value. Two of them significantly exceeded the average value while one just marginally outnumbered it.

Besides, the standard deviation (SD) was 0.566 kJ/m^{2}withthe coefficient of variance (C_V) of 18.00% which was fairly high.

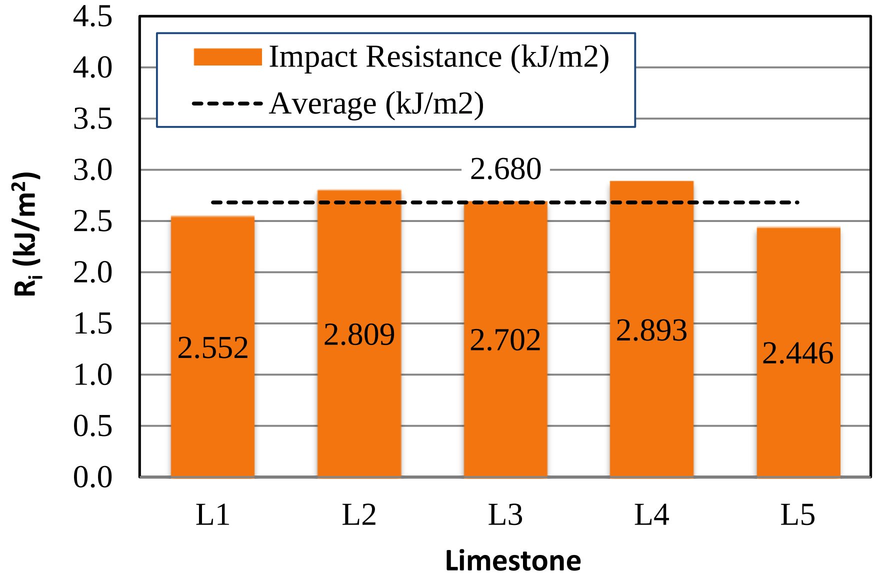


Fig. 5.41 – Impact resistances for the Limestone.

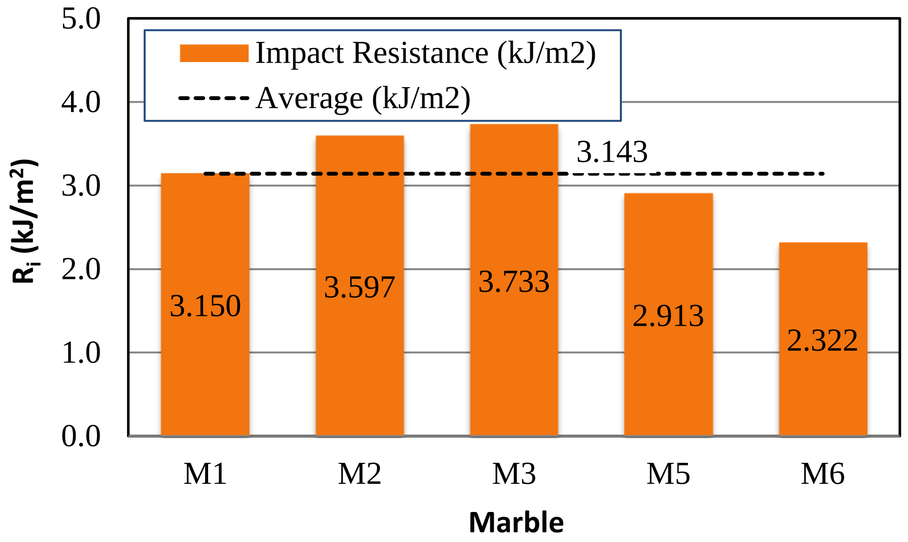


Fig. 5.42 – Impact resistances for the Marble.

Fig. 5.43 illustrates the impact resistance values of six granite samples with their average value. The impact resistances for the six samples varied from 3.232 kJ/m^2 to 4.013 kJ/m^2 with an average impact resistance of 3.456 kJ/m^2. The figure also shows that the results for two samples outweighed the average value. One of them just exceeded the average value by about 0.2 kJ/m^2 while the other dramatically surpassed it by about 0.6 kJ/m^2. Furthermore, the standard deviation (SD) was 0.566 kJ/m^2 with the coefficient of variance (C_V) of 18.00% which is quite high.

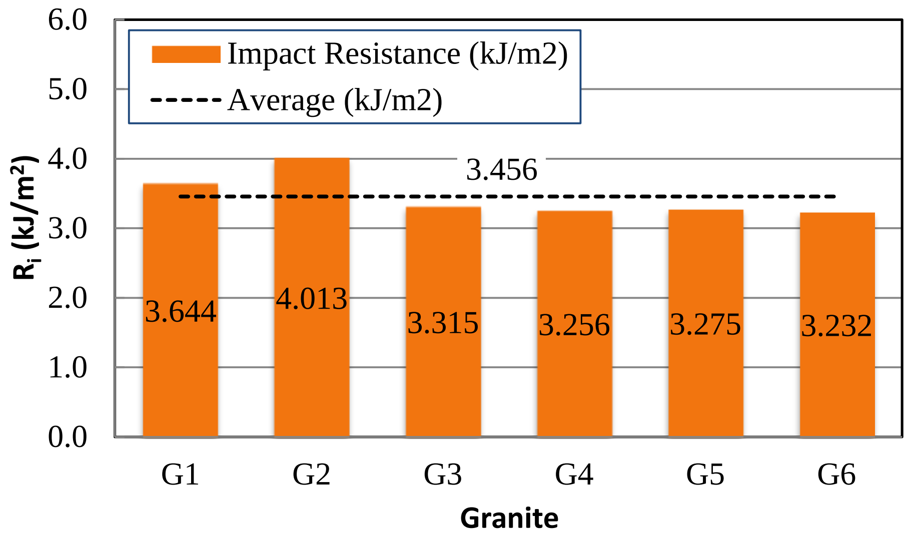


Fig. 5.43 – Impact resistances for the Granite.

Finally, Fig. 5.44 illustrates the average impact resistance values of each type of stone or brick with the overall average value for all the samples as well, which gives a clear comparison of the test results between different masonry stone and clay brick samples. The impact resistances for all the studied samples varied from 2.121 kJ/m^2 to 3.456 kJ/m^2 with an overall average impact resistance of 2.667 J/m^2. Obviously, the impact resistance for the granite was the highest so it should be the toughest masonry stone. Meanwhile the impact resistance for the yellow sandstone was the lowest so it should be the least tough masonry clay brick. Fig. 5.44 also shows that the average impact resistance values for two types of samples outweighed the average value. One of them just exceeded the average value by about 0.2 kJ/m^2 while the other dramatically surpassed it by about 0.6 kJ/m^2. Besides, the standard deviation (SD) for all the average impact resistance value was 0.566 kJ/m^2, giving the coefficient of variance (C_V) of 18.00% which is fairly high. The big variations in the impact resistance should be also due to inconsistent qualities of the studied masonry stones and clay bricks under long term environmental erosion.

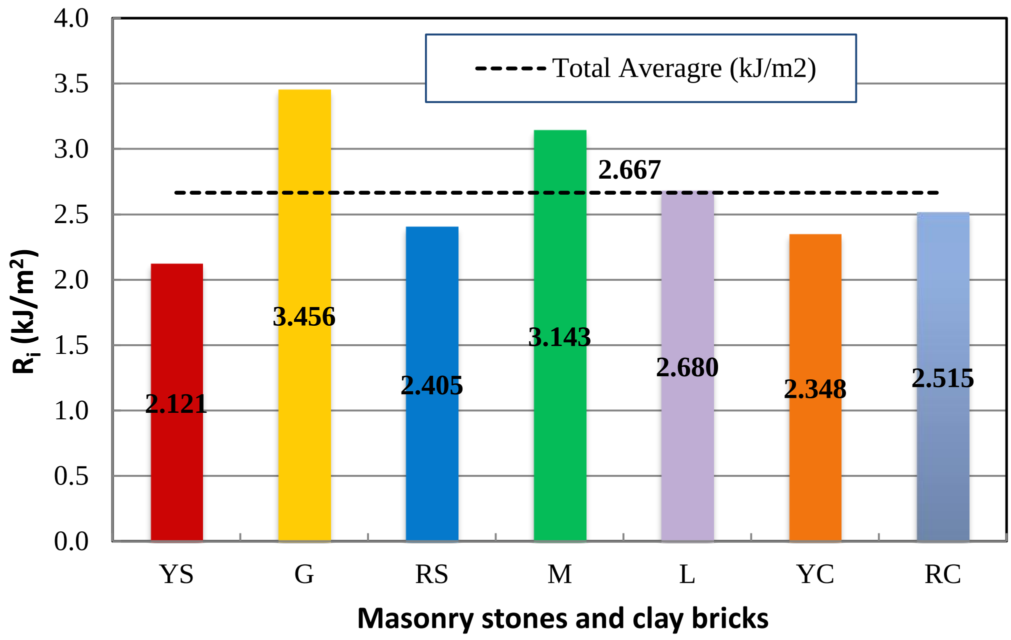


Fig. 5.44 – Impact resistances for all masonry stones and clay bricks.

5.7 Summary

This chapter has introduced the Vickers hardness as a parameter for assessing the surface physical properties of the masonry stones and clay bricks during cleaning and specified the Vickers hardness testing procedure. It has illustrated the changes in the hardness with the cleaning time on the masonry stone and clay brick samples, cleaned with the fine recycled glass abrasive, and links the changes closely to the corresponding cleanness degrees. It has been found that a lower hardness normally corresponded to a softer masonry stone or clay brick and it became more difficult to remove the soling on the softer stone or brick. This chapter has also introduced the Charpy impact resistance as a parameter for assessing the material strength properties of the masonry stones and clay bricks and detailed the impact testing results. It has illustrated a similar trend between the tested masonry stones and clay bricks to the trend for the Vickers hardness, but with smaller variations.

CHAPTER 6 MOISTURE CONTENTS AND WATER ABSORPTIONS

Water absorption is defined as the amount of water absorbed in a specified period time by a material when soaked in water. It will affect the stone surface's properties because the water, which is from rain, snow or other environmental conditions, percolates the wall. This will lead to cracks, efflorescence, rust staining, wood rotting, paint peeling, darkening and spalling. Furthermore, water absorption also has a significant impact on the optimum method of cleaning as water washing will not be efficient if the effects of saturation are not prevented. Smith (1999) specified that the water absorption can be measured by numerous methods, such as placing the samples in 2-3 mm of water and measuring the weight change over several days. However, in this dissertation, the measuring method was according to BS EN 13755 (2008).

6.1 Preparation of Masonry Stone and Clay Brick Samples

Seven types of masonry stones and clay bricks were tested, including yellow sandstone, red sandstone, yellow clay brick, red clay brick, limestone, marble and granite. For each type of stone or brick, three samples were used for testing. Figs. 6.1 to 6.7 show all the masonry stone and clay brick samples used.

Fig. 6.1 – Limestone samples.

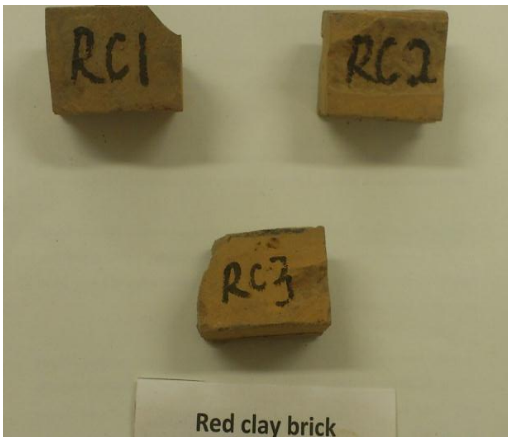


Fig. 6.2 – Red clay brick samples.

Fig. 6.3 – Yellow clay brick samples.

Fig. 6.4 – Granite samples.

Fig. 6.5 – Yellow sandstone samples.

Fig. 6.6 – Marble samples.

Fig. 6.7 – Red sandstone samples.

6.2 Moisture Contents and Water Absorptions

To measure the water absorption of a material, the test specimens were put in an oven for drying to a constant mass at a temperature of (70 ± 5)°C for 24h. Then the specimens were weighed both before and after being dried. Thereafter, the specimens were immersed in water and taken out again after another 24h. Before weighing the specimens, a damp cloth was used to quickly wipe the samples. The tests were continuously carried out up to 72h to ensure the masses of the specimens became constant.

The water absorption of each specimen at the atmospheric pressure, A_b, was then calculated by using the equation below:

$$A_b = \frac{m_s - m_d}{m_d} \times 100 \tag{6.1}$$

where

A_b is the water absorption at the atmospheric pressure, expressed as a percentage,

m_s is the mass of the saturated specimens after 72h (g),

m_d is the mass of the dry specimens (g).

6.3 Water Absorption Test Results

Tables 6.1 to 6.7 demonstrate all the test results of the water absorption for all seven types of masonry stones and clay bricks, where m_o is the mass in the original state.

Table 6.1 – Water absorption test results for the Yellow sandstone.

Sample	m_o (g)	m_d (g)	$m_{s,24h}$(g)	$m_{s,72h}$(g)	$m_{s,72h} - m_d$ (g)	A_b (%)
YS1	59.94	59.72	62.05	62.18	2.46	4.12
YS2	72.19	71.94	74.56	74.67	2.73	3.79
YS3	64.17	63.94	66.33	66.43	2.49	3.89
Average A_b = 3.94%			**SD = 0.17%**		**C_V = 4.22%**	

Table 6.2 – Water absorption test results for the Red sandstone.

Sample	m_o (g)	m_d (g)	$m_{s,24h}$ (g)	$m_{s,72h}$ (g)	$m_{s,72h} - m_d$ (g)	A_b (%)
RS1	62.45	62.25	65.44	65.56	3.31	5.32
RS2	77.59	77.28	81.31	81.36	4.08	5.28
RS3	62.18	62.02	65.02	65.12	3.10	5.00
Average A_b = 5.20%			**SD = 0.17%**		**C_V = 3.35%**	

Table 6.3 – Water absorption test results for the Yellow clay brick.

Sample	m_o (g)	m_d (g)	$m_{s,24h}$ (g)	$m_{s,72h}$ (g)	$m_{s,72h} - m_d$ (g)	A_b (%)
YC1	129.71	126.36	132.69	133.39	7.03	5.56
YC2	50.99	49.65	52.96	53.2	3.55	7.15
YC3	52.59	51.29	53.94	54.34	3.05	5.95
Average A_b = 6.22%			**SD = 0.82%**		**C_V = 13.30%**	

Table 6.4 – Water absorption test results for the Red clay brick.

Sample	m_o (g)	m_d (g)	$m_{s,24h}$ (g)	$m_{s,72h}$ (g)	$m_{s,72h} - m_d$ (g)	A_b (%)
RC1	65.82	65.74	70.65	70.87	5.13	7.80
RC2	53.22	53.16	57.44	57.85	4.69	8.82
RC3	49.17	49.61	53.56	53.76	4.15	8.37
Average A_b = 8.33%			**SD = 0.51%**		**C_V = 6.13%**	

Table 6.5 – Water absorption test results for the Limestone.

Sample	m_o (g)	m_d (g)	$m_{s,24h}$ (g)	$m_{s,72h}$ (g)	$m_{s,72h} - m_d$ (g)	A_b (%)
L1	86.7	86.65	90.78	91.01	4.36	5.03
L2	108.76	108.68	113.77	114.03	5.35	4.92
L3	103.6	103.6	108.45	108.64	5.04	4.86
Average A_b = 4.94%			**SD = 0.08%**		**C_V = 1.72%**	

Table 6.6 – Water absorption test results for the Marble.

Sample	m_o (g)	m_d (g)	$m_{s,24h}$ (g)	$m_{s,72h}$ (g)	$m_{s,72h} - m_d$ (g)	A_b (%)
M1	112.56	112.54	112.78	112.92	0.38	0.34
M2	108.86	108.84	109.09	109.12	0.28	0.26
M3	68.21	68.19	68.35	68.37	0.18	0.26
Average A_b = 0.29%			**SD = 0.04%**		**C_V = 15.58%**	

Table 6.7 – Water absorption test results for the Granite.

Sample	m_o (g)	m_d (g)	$m_{s,24h}$ (g)	$m_{s,72h}$ (g)	$m_{s,72h} - m_d$ (g)	A_b (%)
G1	86.42	86.33	86.59	86.67	0.34	0.39
G2	95.61	95.49	95.92	95.93	0.44	0.46
G3	105.19	105.06	105.47	105.53	0.47	0.45
Average A_b = 0.43%			**SD = 0.04%**		**C_V = 8.16%**	

6.4 Discussion

6.4.1 Water absorption for the studied masonry stones and clay bricks

Fig. 6.8 presents a bar chart which illustrates the average values of the water absorption for seven types of masonry stones and clay bricks and the average water absorption for the all studied stones and bricks. It should be noted that the values of water absorption had significant differences among the seven types of stones and bricks. To begin with, it was extremely difficult for the granite and marble to absorb water since the obtained water absorption results for the granite and marble were extraordinarily low, at 0.43% and 0.29%, respectively. However, the data for the clay bricks were the highest, with 6.22% for the yellow clay brick and 8.33% for the red clay brick samples, followed by the red sandstone at 5.20%, the limestone at 4.94% and the yellow sandstone at 3.94%.

Furthermore, the average water absorption for the seven types of stones/bricks was 4.19%. From a holistic point of view, the red clay brick and yellow clay brick were able to absorb much more water than the sandstones and limestone while the marble and granite could hardly absorb water.

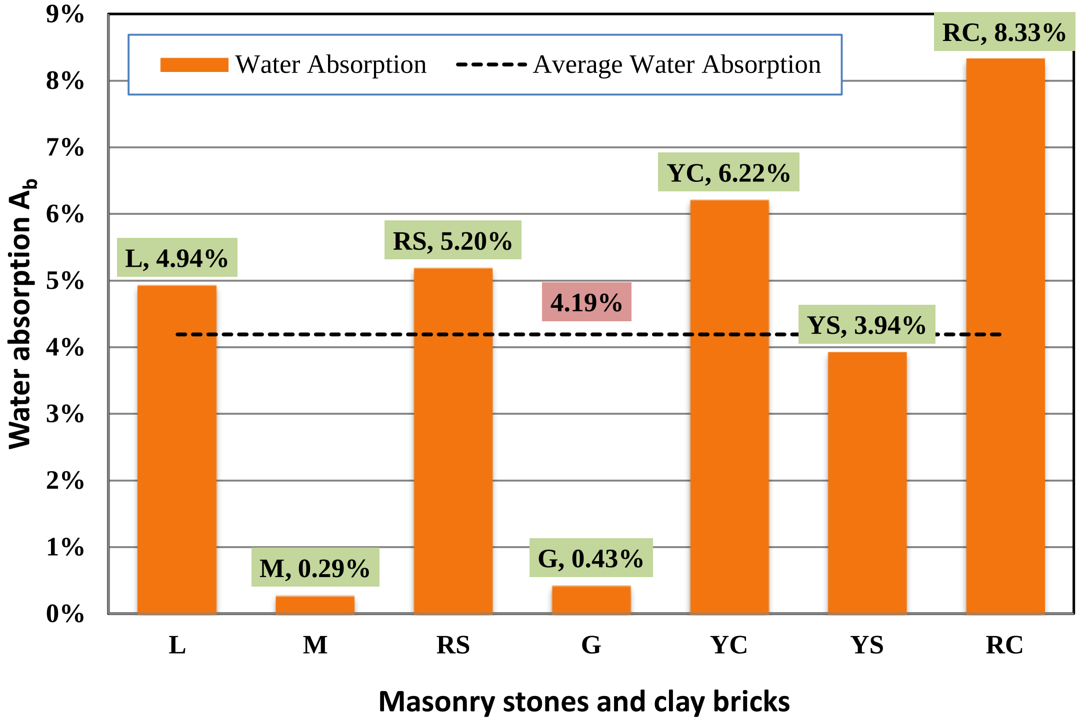


Fig. 6.8 – Water absorptions for the studied masonry stones and clay bricks.

6.4.2 Water absorption versus Charpy impact resistance

Fig. 6.9 presents a line chart which demonstrates the relationship between the water absorption and the Charpy impact resistance for seven types of masonry stones and clay bricks studied. From a holistic point of view, the trends for the water absorption versus the impact resistance were just opposite. In other words, the water absorption approximately diminished while in contrast, the impact resistance nearly escalated. The water absorption for the granite and marble were the lowest while the corresponding impact resistances were the highest, which means the less water a masonry stone or a clay brick could absorb the tougher it would be. Similarly, the water absorptions for the clay bricks were the highest while the corresponding impact resistances were almost the lowest, which means that they were more brittle.

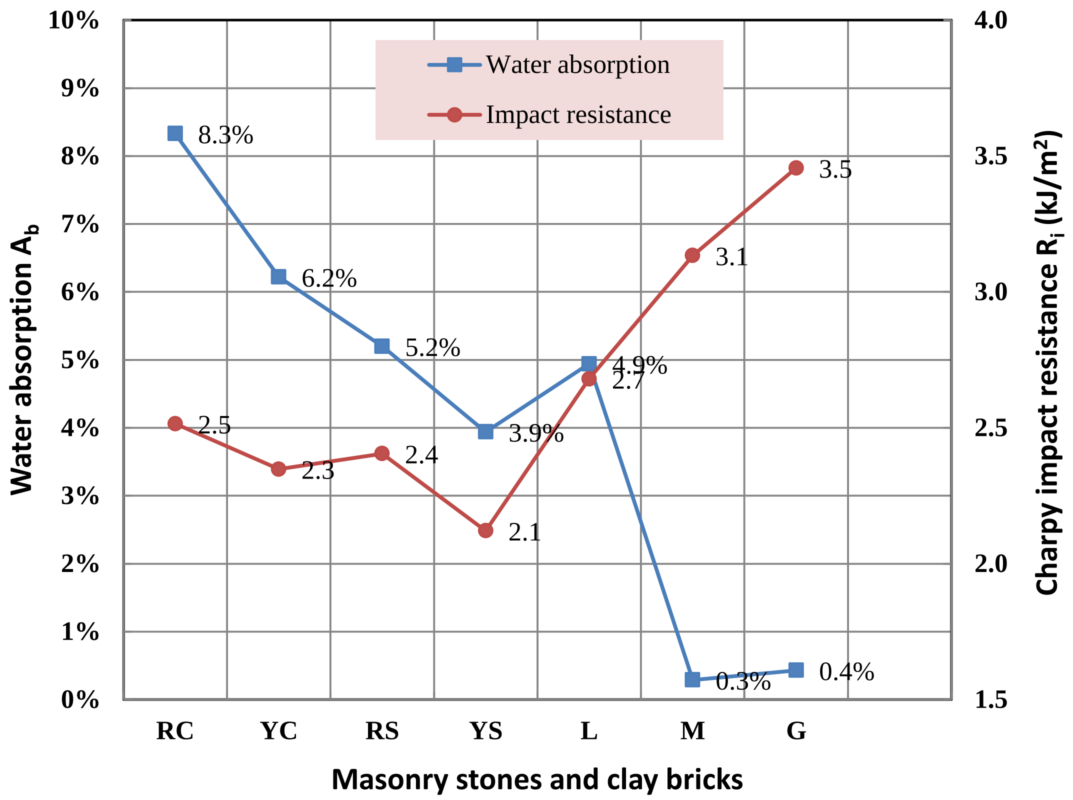


Fig. 6.9 – Comparison between water absorption and Charpy impact resistance for the studied masonry stones and clay bricks.

6.4.3 Water absorption versus Vickers hardness number

Fig. 6.10 presents a line chart which demonstrates the relationship between the water absorption and the hardness number of seven types of masonry stones and clay bricks. In general, the opposite trends for the two lines can be observed, which demonstrates that the water absorption approximately subsided whereas the hardness number almost proliferated. The hardness number for the granite and marble were the highest while the corresponding water absorption values were the lowest, which indicates that the less water a masonry stone or a brick could absorb the harder the sample's surface would be. Similarly, the water absorptions for the clay bricks were the highest while the corresponding hardness numbers were approximately the lowest, which indicates their surfaces were the softest.

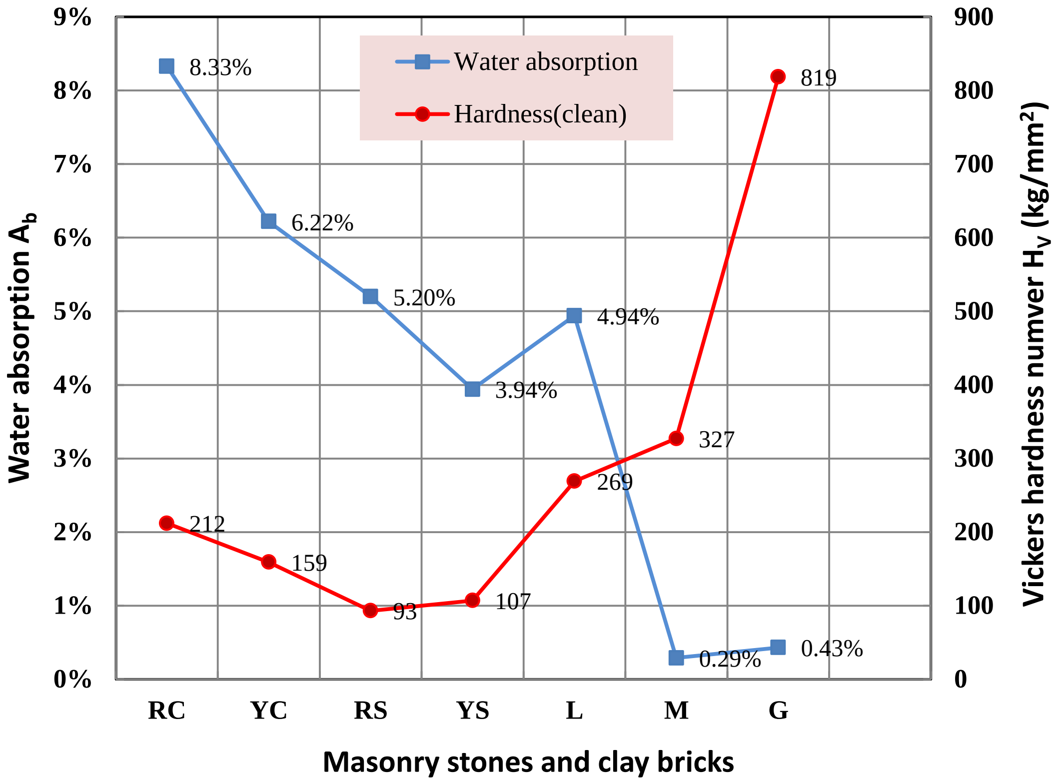


Fig. 6.10 – Comparison between water absorption and Vickers hardness number for the studied masonry stones and clay bricks.

6.5 Summary

This chapter has introduced the water absorption as a parameter for assessing the physical properties of the masonry stones and clay bricks and detailed the water absorption testing results. It has illustrated an inverse trend between the tested masonry stones and clay bricks to the trends for the Vickers hardness and Charpy impact resistance. It has indicated that a masonry stone or clay brick with a larger water absorption capacity normally had a lower hardness and impact resistance and could easily attract soiling.

CHAPTER 7 THE SEM AND EDX TESTS ON THE MASONRY STONE AND CLAY BRICK SAMPLES

As the soiling and decay have the ability to affect the chemical substances on the stone surface, the chemical characteristics of the dirty masonry stone or clay brick surface are largely different to the fully cleaned one. In the cleaning process, the chemical substances on the masonry stone or clay brick surface are continually changing. Some chemical elements and compounds may increase and some may decrease or even disappear during building cleaning. The aim of this part is to make a quantitative chemical analysis on the changes of chemical elements and compounds on the masonry stone or clay brick surface between the uncleaned and fully cleaned stages.

7.1 Test Instruments

Chemical analysis was conducted using the instrument including the SEM and EDX as shown in Fig. 7.1. The SEM stands for the Scanning Electron Microscope which is used to image a sample on a liquid crystal display (Fig. 7.2) by scanning it with a beam of electrons in a raster scan pattern. It can produce the signals containing the information about the surface topography and composition of the sample by the interactions between the electrons and atoms. The working mechanism of the SEM is shown in Fig. 7.3 (http://en.wikipedia.org/wiki/Scanning_electron_microscope).

Fig. 7.1 – SEM and EDX instrument.

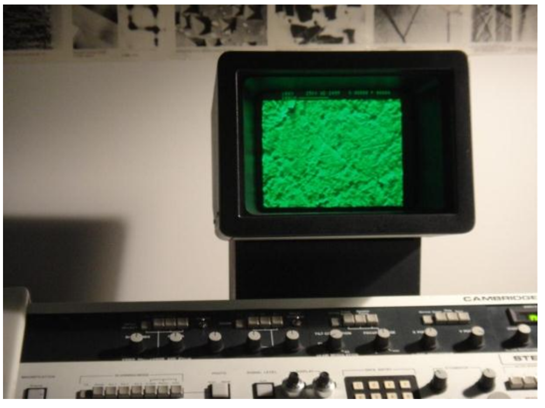


Fig. 7.2 – LCD for SEM.

The EDX stands for the Energy-Dispersive X-Ray Spectroscopy which is used to analyse the chemical elements and compounds of the sample. The EDX relies on the investigations of an interaction of some source of X-ray excitation with a sample. Its characterising capabilities are largely due to the fundamental principle that each element has a unique atomic structure allowing unique set of peaks on its X-ray spectrum. The principle of the EDX is shown in Fig. 7.4 with the SEM in combination with the EDX. It is possible to detect the elements on different parts of the sample. The instrument used in this test was the Scanning Electron Microscope LEOS430I, UK, coupled with an ISIS EDD detector from Oxford Instrument, UK, (http://en.wikipedia.org/wiki/Energy-dispersive_X-ray_spectroscopy).

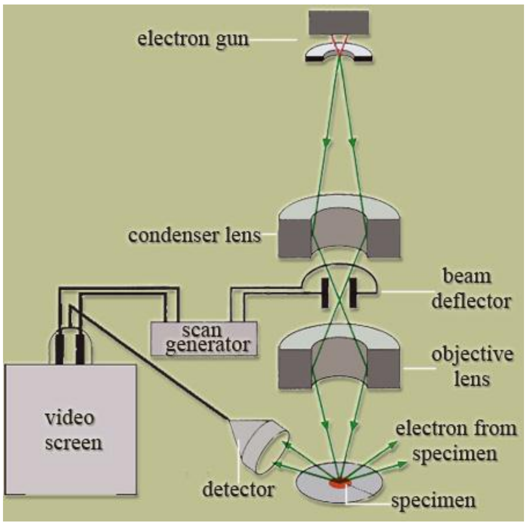


Fig. 7.3 – Mechanism of the SEM.

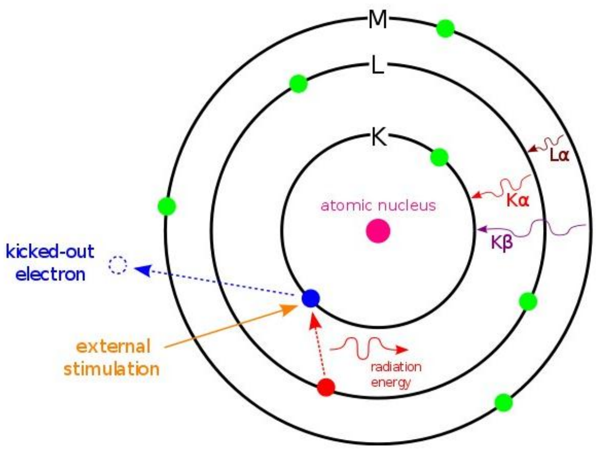


Fig. 7.4 – Mechanism of the EDX.

7.2 Preparation of Masonry Stone and Clay Brick Samples

The preparation of the sample is a vital stage for the Electron Microscope. The insulation materials require a thin layer of conducting coating (~100 Å) to avoid charging. For the EDX in this study, carbon coating was adopted. The materials could also be observed at low primary energy, at which the coefficient for secondary emission was about 1.0 and the charge build-up was negligible. The entire sample preparation consisted of mounting the sample on a metallic platform via a conducting path, carbon in this case.

Four types of masonry stones and clay bricks were adopted for testing:

- Yellow clay brick: Samples 1 (original) and 2 (clean),
- Yellow sandstone: Samples 3 (original) and 4 (clean),
- Limestone: Samples 5 (original) and 6 (clean),
- Marble: Samples 7 (original) and 8 (clean).

The surfaces of the clean samples were polished and cleaned with acetone. The surfaces of the original dirty samples were also rinsed with acetone. All the samples were dried under an IR lamp and coated with a thin layer of carbon to make them conductive. The samples were then mounted on the SEM stubs for the microstructural and compositional analysis.

7.3 Microscopic Image Photos

Six micrographs were recorded at different magnifications for each stone or clay sample by the SEM. In order to determine the local surface chemical compositions of all the tested samples, the EDX measurements were performed in the spot mode. Six sampling points were selected randomly on the surface of each sample. The percentage quantities of the chemical elements and compounds on each sampling point were made available.

7.3.1 Sample 1 – Original dirty Yellow clay brick

Fig. 7.5 shows a typical micrograph of Sample 1 and the other five micrographs are included in Figs. N.2 to N.6 in Appendix N. Fig. 7.6 shows a typical spectrum diagram of Sample 1 and the other five diagrams are included in Figs. O.2 to O.6 in Appendix O. Table 7.1 lists a set of typical EDX results for Sample 1 and the other results are included in Tables P.2 to P.6 in Appendix P.

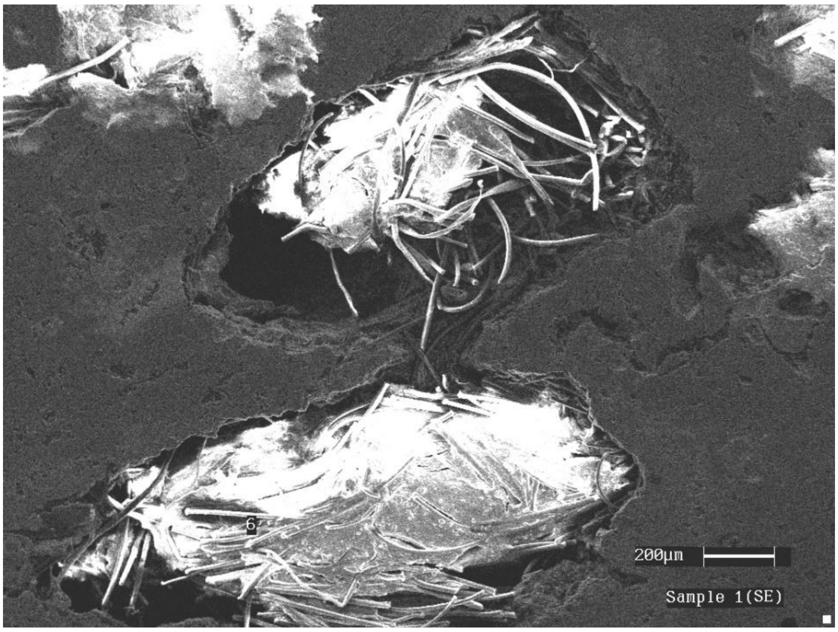


Fig. 7.5 – A typical micrograph of the original Yellow clay brick.

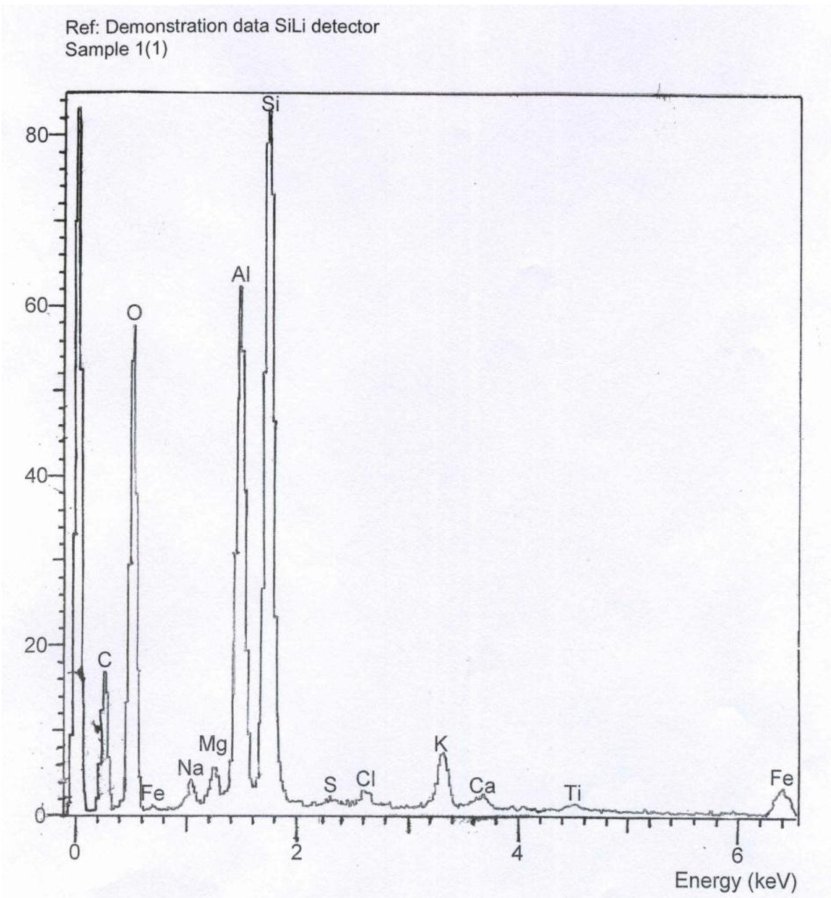


Fig. 7.6 – A typical spectrum diagram of the original Yellow clay brick.

Table 7.1 – Typical EDX results of the original Yellow clay brick.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 1(1)

System resolution = 61 eV

Quantitative method: ZAF(6 iterations).
Analysed all elements and normalised results.

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Na	K	Alibite 02/12/93
Mg	K	MgO 01/12/93
Al	K	Al203 23/11/93
Si	K	Quartz 01/12/93
S	K	FeS2 01/12/93
Cl	K	KCl 15/02/94
K	K	MAD-10 02/12/93
Ca	K	Wollas 23/11/93
Ti	K	Ti 01/12/93
Fe	K	Fe 01/12/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	25.98	36.09
O	K	ED	45.82	47.79
Na	K	ED	0.71	0.51
Mg	K	ED	0.62	0.43
Al	K	ED	8.91	5.51
Si	K	ED	13.47	8.00
S	K	ED	0.11	0.06
Cl	K	ED	0.31	0.15
K	K	ED	1.43	0.61
Ca	K	ED	0.33	0.14
Ti	K	ED	0.23	0.08
Fe	K	ED	2.08	0.62
Total			100.00	100.00

* = <2 Sigma

7.3.2 Sample 2 – Clean Yellow clay brick

Fig. 7.7 shows a typical micrograph of Sample 2 and the other five micrographs are included in Figs. N.8 to N.12 in Appendix N. Fig. 7.8 shows a typical spectrum diagram for Sample 2 and the other five diagrams are included in Figs. O.8 to O.12 in Appendix O. Table 7.2 lists a set of typical EDX results for Sample 2 and the other results are included in Table P.8 to P.12 in Appendix P.

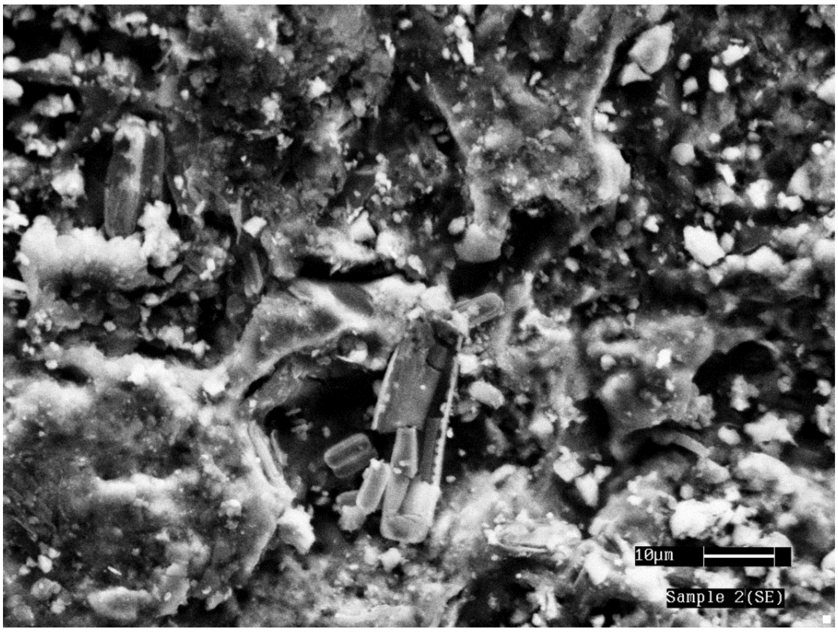


Fig. 7.7 – Atypical micrograph of the clean Yellow clay brick.

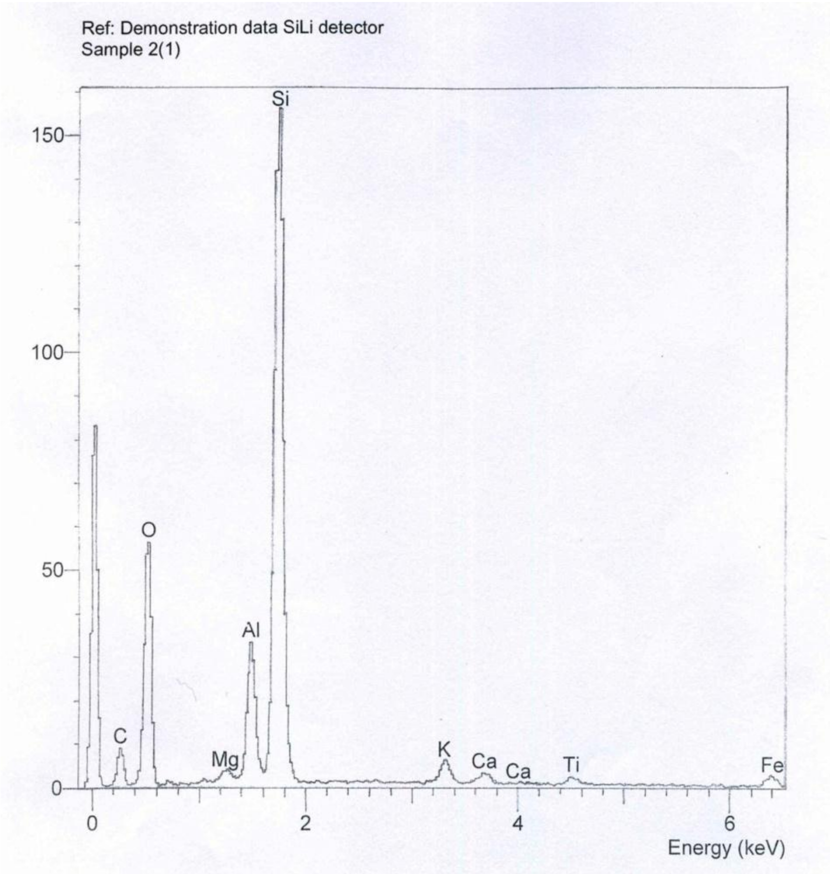


Fig. 7.8 – A typical spectrum diagram of the clean Yellow clay brick.

Table 7.2 – Typical EDX results of the clean Yellow clay brick.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 2 (1)

System resolution = 61 eV

Quantitative method: ZAF(6 iterations).
Analysed all elements and normalised results.

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Mg	K	MgO 01/12/93
Al	K	Al203 23/11/93
Si	K	Quartz 01/12/93
K	K	MAD-10 02/12/93
Ca	K	Wollas 23/11/93
Ti	K	Ti 01/12/93
Fe	K	Fe 01/12/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	19.31	28.22
O	K	ED	47.14	51.70
Mg	K	ED	0.46	0.33
Al	K	ED	4.66	3.03
Si	K	ED	24.14	15.08
K	K	ED	1.28	0.58
Ca	K	ED	0.65	0.28
Ti	K	ED	0.67	0.25
Fe	K	ED	1.69	0.53
Total			100.00	100.00

* = <2 Sigma

7.3.3 Sample 3 – Original Yellow sandstone

Fig. 7.9 shows a typical micrograph of Sample 3 and the other five micrographs are included in Figs. N.14 to N.18 in Appendix N. Fig. 7.10 shows a typical spectrum diagram for Sample 3 and the other five diagrams are included in Figs. O.14 to O.18 in Appendix O. Table 7.3 lists a set of typical EDX results for Sample 3 and the other results are included in Tables P.14 to P.18 in Appendix P.

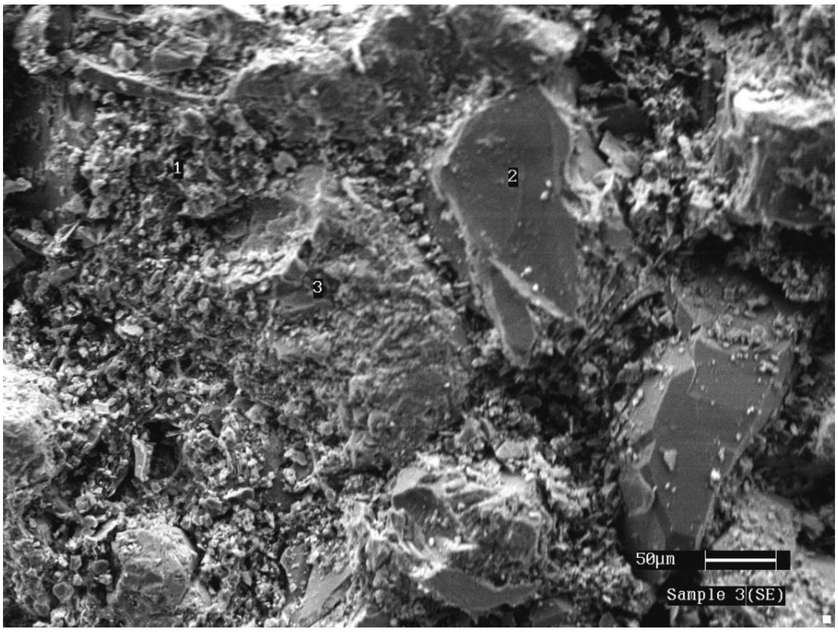


Fig. 7.9 – A typical micrograph of the original Yellow sandstone.

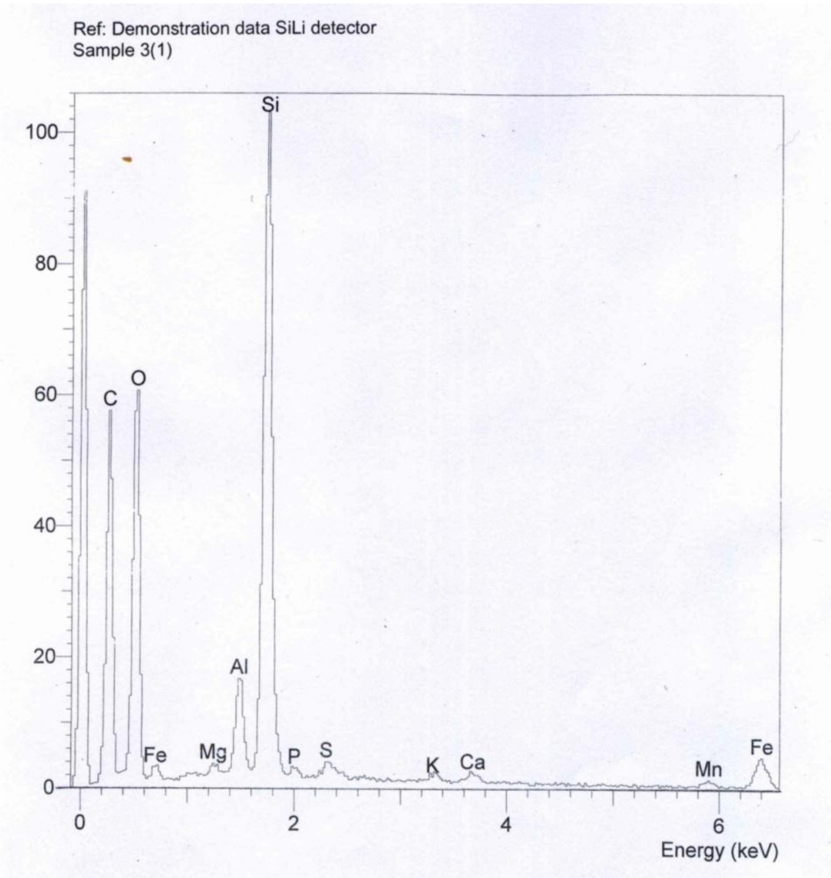


Fig. 7.10 – A typical spectrum diagram of the original Yellow sandstone.

Table 7.3 – Typical EDX results of the original Yellow sandstone.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 3 (1)

System resolution = 62 eV

Quantitative method: ZAF (7 iterations).
Analysed all elements and normalised results.

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Mg	K	MgO 01/12/93
Al	K	Al203 23/11/93
Si	K	Quartz 01/12/93
P	K	GaP 29/11/93
S	K	FeS2 01/12/93
K	K	MAD-10 02/12/93
Ca	K	Wollas 23/11/93
Mn	K	Mn 01/12/93
Fe	K	Fe 01/12/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	40.73	51.27
O	K	ED	43.13	40.76
Mg	K	ED	0.20	0.12
Al	K	ED	1.66	0.93
Si	K	ED	10.86	5.85
P	K	ED	0.20	0.10
S	K	ED	0.24	0.11
K	K	ED	0.20	0.08
Ca	K	ED	0.26	0.10
Mn	K	ED	0.38	0.10
Fe	K	ED	2.14	0.58
Total			100.00	100.00

* = <2 Sigma

7.3.4 Sample 4 – Clean Yellow sandstone

Fig. 7.11 shows a typical micrograph of Sample 4 and the other five micrographs are included in Figs. N.20 to N.24 in Appendix N. Fig. 7.12 shows a typical spectrum diagram for Sample 4 and the other five diagrams are included in Figs. O.20 to O.24 in Appendix B. Table 7.4 lists a set of typical EDX results for Sample 4 and the other results are included in Tables P.20 to P.24 in Appendix P.

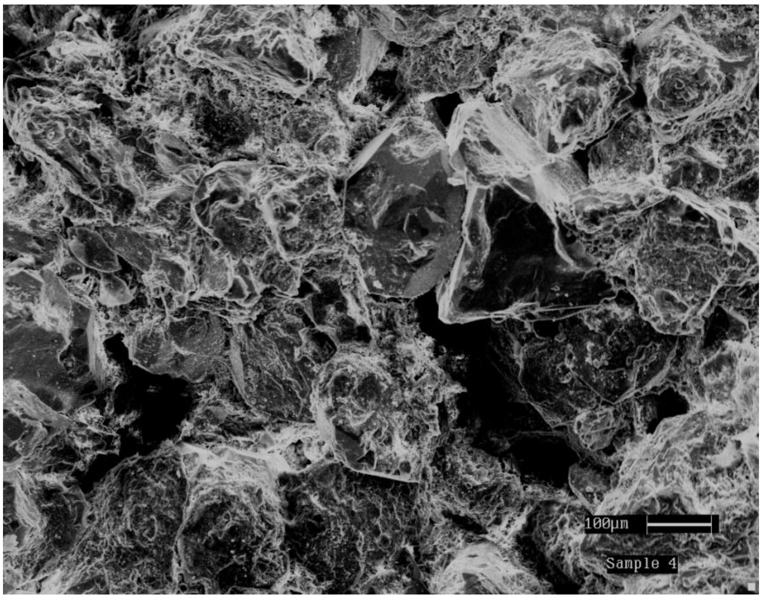


Fig. 7.11 – Atypical micrograph of the clean Yellow sandstone.

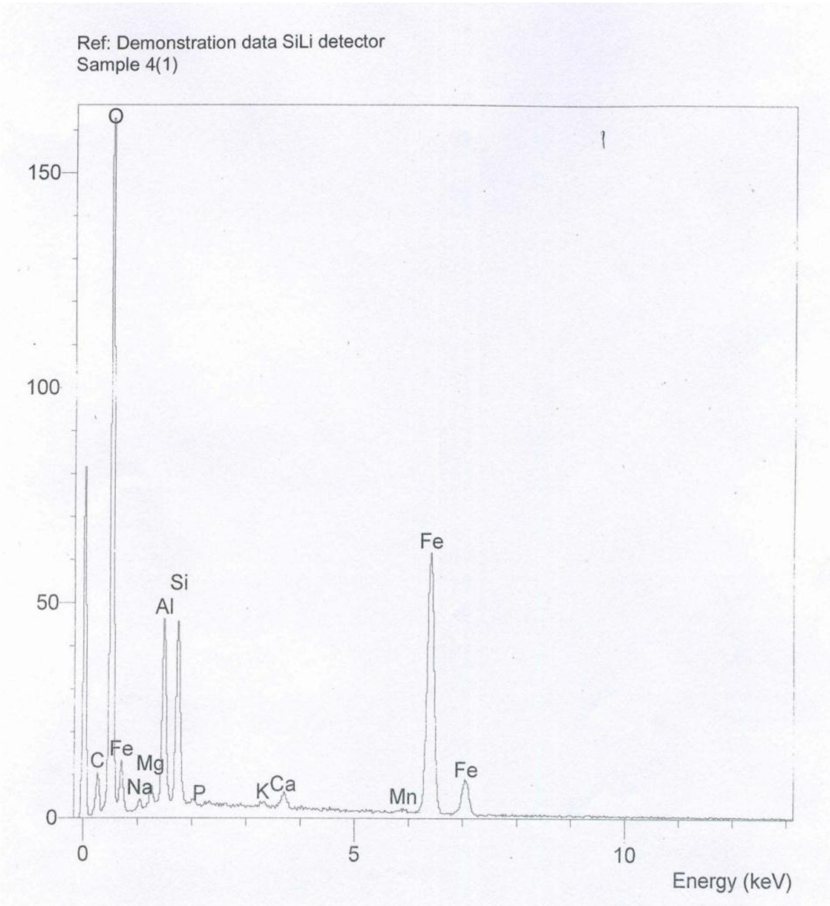


Fig. 7.12 – Atypical spectrum diagram of the clean Yellow sandstone.

Table 7.4 – Typical EDX results of the clean Yellow sandstone.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 4 (1)

System resolution = 62 eV

Quantitative method: ZAF (5 iterations).
Analysed all elements and normalised results.

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Na	K	Albite 02/12/93
Mg	K	MgO 01/12/93
Al	K	Al203 23/11/93
Si	K	Quartz 01/12/93
P	K	GaP 29/11/93
K	K	MAD-10 02/12/93
Ca	K	Wollas 23/11/93
Mn	K	Mn 01/12/93
Fe	K	Fe 01/12/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	9.28	15.67
O	K	ED	51.51	65.31
Na	K	ED	0.56	0.49
Mg	K	ED	0.73	0.61
Al	K	ED	5.46	4.10
Si	K	ED	5.20	3.76
P	K	ED	0.21	0.14
K	K	ED	0.15	0.08
Ca	K	ED	0.53	0.27
Mn	K	ED	0.23	0.08
Fe	K	ED	26.14	9.49
Total			100.00	100.00

* = <2 Sigma

7.3.5 Sample 5 – Original Limestone

Fig. 7.13 shows a micrograph of Sample 5 and the other micrographs are included in Figs. N.26 to N.30 in Appendix N. Fig. 7.14 shows a typical spectrum diagram for Sample 5 and the other five diagrams are included in Figs. O.26 to O.30 in Appendix O. Table 7.5 lists a set of typical EDX results for Sample 5 and the other results are included in Tables P.26 to P.30 in Appendix P.

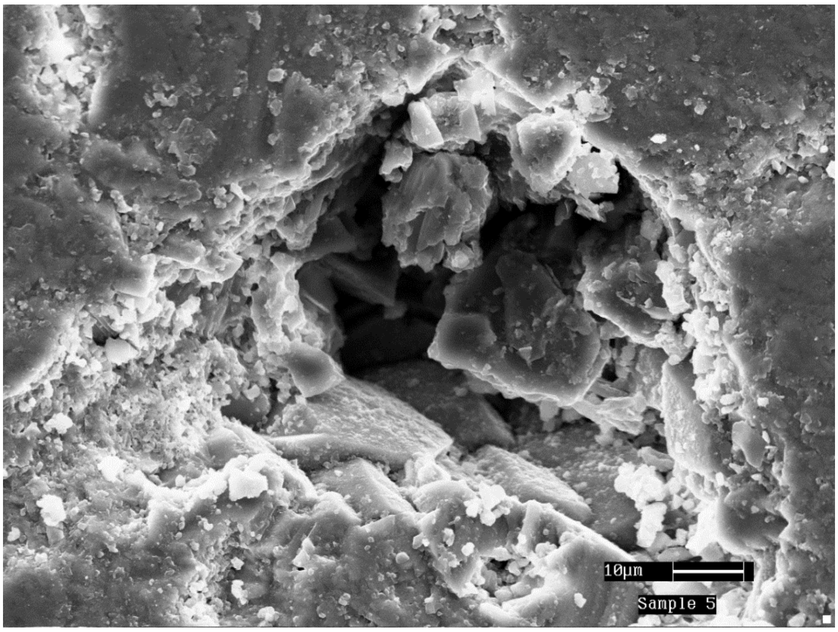


Fig. 7.13 – A typical micrograph of the original Limestone.

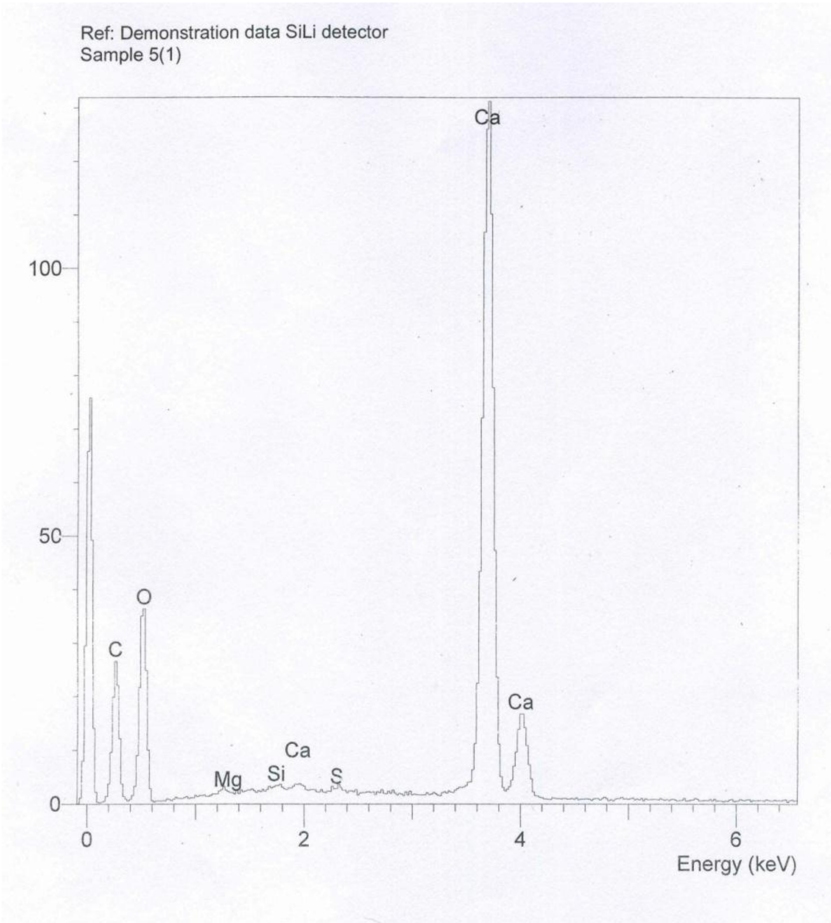


Fig. 7.14 – A typical spectrum diagram of the original Limestone.

Table 7.5 – Typical EDX results of the original Limestone.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 5 (1)

System resolution = 61 eV

Quantitative method: ZAF (6 iterations).
Analysed all elements and normalised results.

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Mg	K	MgO 01/12/93
Si	K	Quartz 01/12/93
S	K	FeS2 01/12/93
Ca	K	Wollas 23/11/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	15.88	24.44
O	K	ED	52.81	61.01
Mg	K	ED	0.22	0.17
Si	K	ED	0.19	0.12
S	K	ED	0.16	0.09
Ca	K	ED	30.74	14.18
Total			100.00	100.00

* = <2 Sigma

7.3.6 Sample 6 – Clean Limestone

Fig. 7.15 shows a micrograph of Sample 6 and the other five micrographs are included in Figs. N.32 to N.36 in Appendix N. Fig. 7.16 shows a typical spectrum diagram for Sample 6 and the other five diagrams are included in Figs. O.32 to O.36 in Appendix O. Table 7.6 lists a typical set of EDX results for Sample 6 and the other results are included in Tables P.32 to P.36 in Appendix P.

Fig. 7.15 – Atypical micrograph of the clean Limestone.

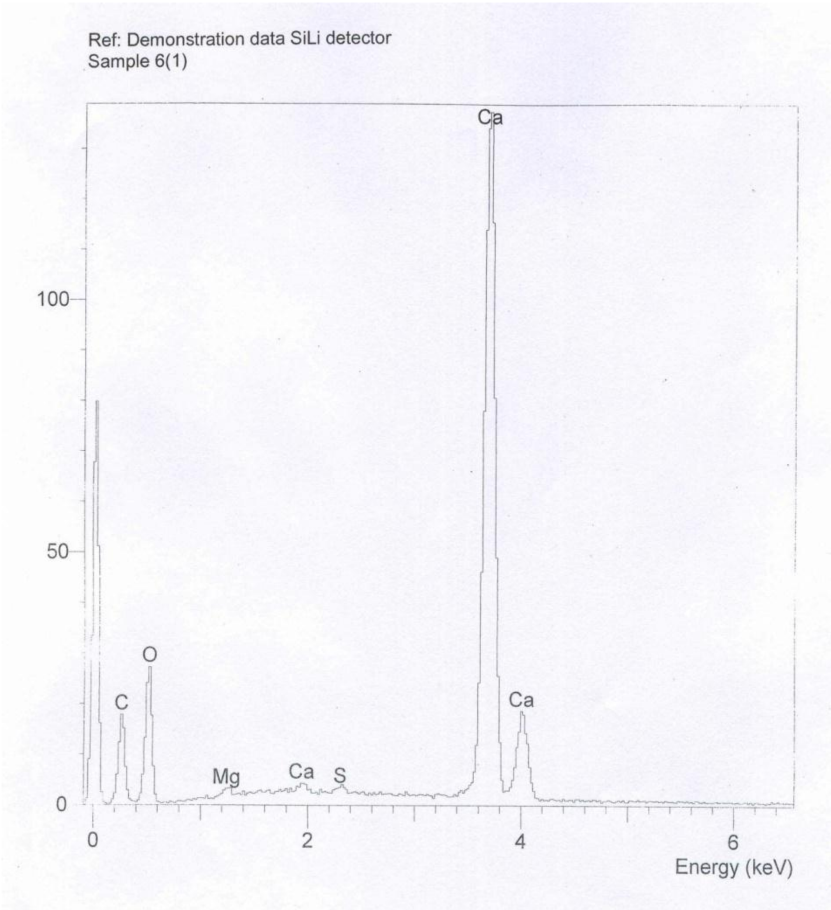


Fig. 7.16 – Atypical spectrum diagram of the clean Limestone.

Table 7.6 – Typical EDX results of the clean Limestone.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 6 (1)

System resolution = 61 eV

Quantitative method: ZAF (5 iterations).
Analysed all elements and normalised results.

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Mg	K	MgO 01/12/93
S	K	FeS2 01/12/93
Ca	K	Wollas 23/11/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	12.45	20.43
O	K	ED	49.08	60.49
Mg	K	ED	0.41	0.33
S	K	ED	0.23	0.14
Ca	K	ED	37.83	18.61
Total			100.00	100.00

* = <2 Sigma

7.3.7 Sample 7 – Original Marble

Fig. 7.17 shows a micrograph of Sample 7 and the other five micrographs are included in Figs. N.38 to N.42 in Appendix N. Fig. 7.18 shows a typical spectrum diagram for Sample 7 and the other five diagrams are included in Figs. O.38 to O.42 in Appendix O. Table 7.7 lists a set of typical EDX results for Sample 7 and the other results are included in Tables P.38 to P.42 in Appendix P.

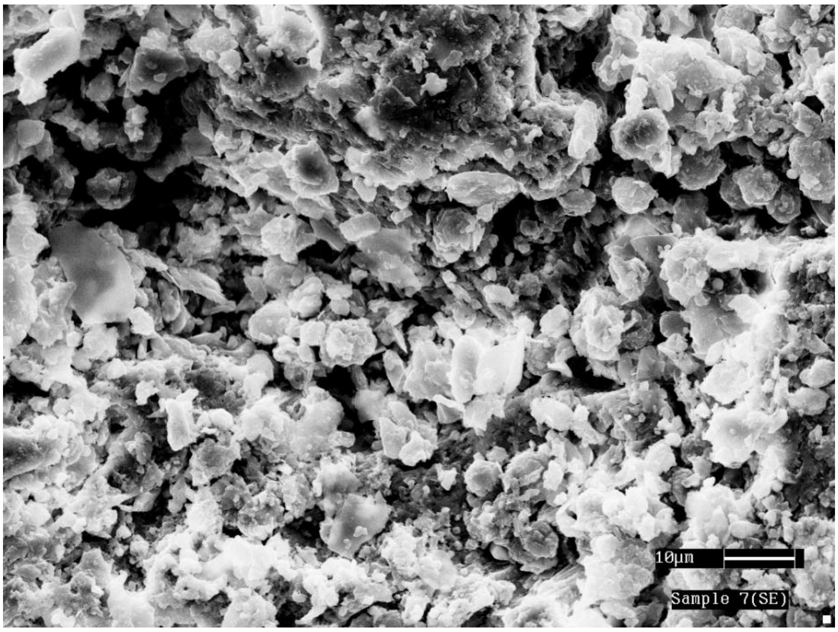


Fig. 7.17 – A typical micrograph of the original Marble.

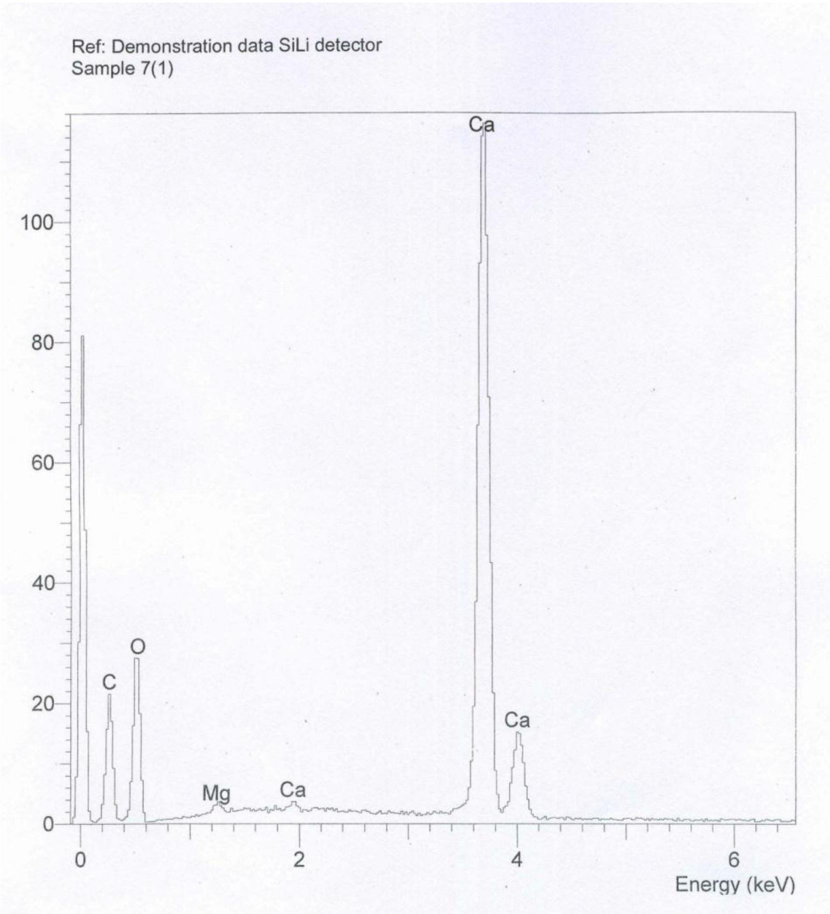


Fig. 7.18 – A typical spectrum diagram of the original Marble.

Table 7.7 – Typical EDX results of the original Marble.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 7 (1)

System resolution = 59 eV

Quantitative method: ZAF (6 iterations).
Analysed all elements and normalised results.

1 Peak possibly omitted: 6.36 keV

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Mg	K	MgO 01/12/93
Ca	K	Wollas 23/11/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	15.30	23.98
O	K	ED	51.09	60.11
Mg	K	ED	0.41	0.32
Ca	K	ED	33.20	15.59
Total			100.00	100.00

* = <2 Sigma

7.3.8 Sample 8 – Clean Marble

Fig. 7.19 shows a micrograph of Sample 8 and the other five micrographs are included in Figs. N.44 to N.48 in. Fig. 7.20 shows a typical spectrum diagram for Sample 8 and the other five diagrams are included in Figs. O.44 to O.48 in Appendix O. Table 7.8 lists a set of typical EDX results for Sample 8 and the other results are included in Tables P.44 to P.48 in Appendix P.

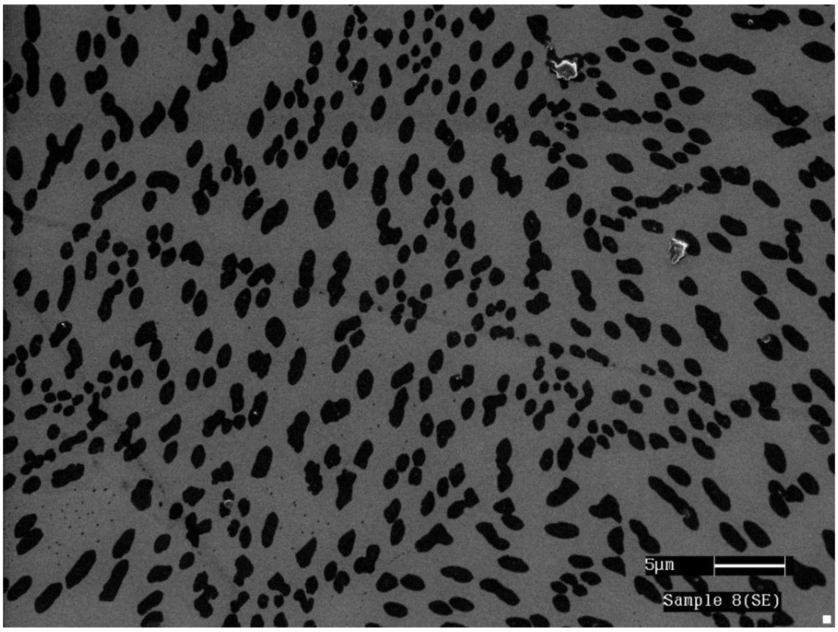


Fig. 7.19 – A typical micrograph of the clean Marble.

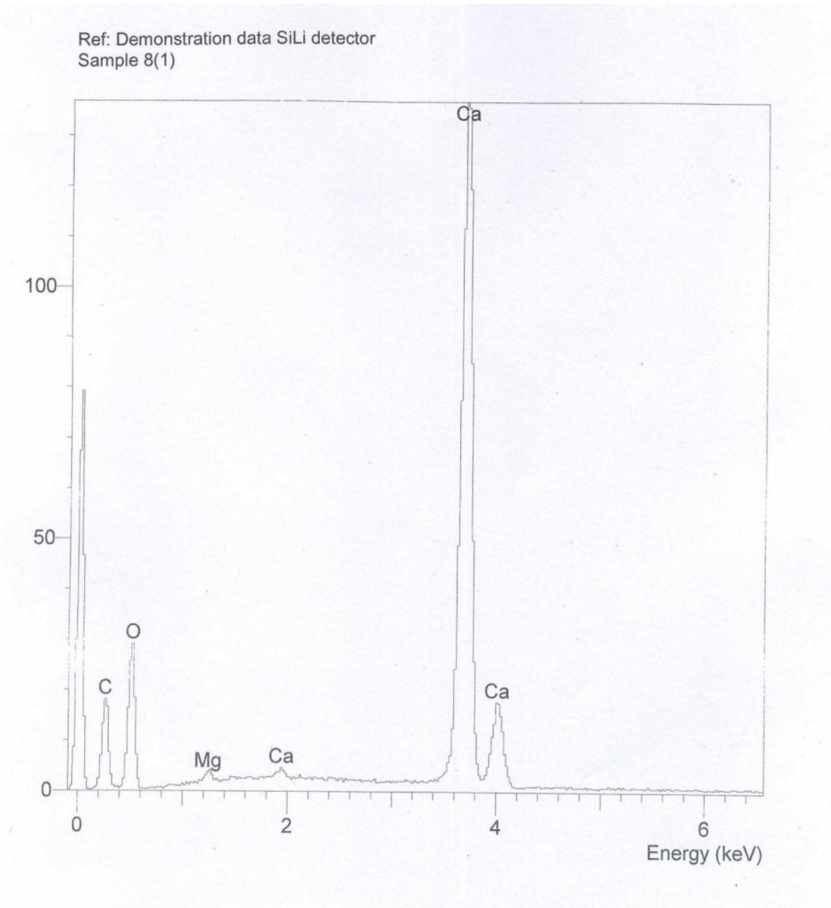


Fig. 7.20 – A typical spectrum diagram of the clean Marble.

Table 7.8 – Typical EDX results of the clean Marble.

SEMQuant results
Ref: Demonstration data SiLi detector
Spectrum label: Sample 8 (1)

System resolution = 59 eV

Quantitative method: ZAF (5 iterations).
Analysed all elements and normalised results.

Standards:

C	K	CaCO3 01/12/93
O	K	Quartz 01/12/93
Mg	K	MgO 01/12/93
Ca	K	Wollas 23/11/93

Elmt		Spect. Type	Element %	Atomic %
C	K	ED	12.71	20.67
O	K	ED	49.96	60.98
Mg	K	ED	0.49	0.39
Ca	K	ED	36.84	17.95
Total			100.00	100.00

* = <2 Sigma

7.4 Discussion

7.4.1 The EDX test results

The EDX tests were carried out on six points for each stone or brick sample and the test data on one point were expressed as the percentage quantities of the chemical elements. Tables 7.9 to 7.16 list all the EDX test data for the eight samples. The average value of each element is calculated and also listed in each table. It should be indicated that the data marked as * in the cells were excluded from analysis as they showed incomprehensively different trends from the majority.

Table 7.9 – EDX results for the original Yellow clay brick.

Original Yellow clay brick							
Cleaning stage	**0% clean**			**Unit**	**%**		
	Data on six sampling points for Sample 1						
Chemical element	**Sample 1-1**	**Sample 1-2***	**Sample 1-3**	**Sample 1-4**	**Sample 1-5**	**Sample 1-6***	**Average**
C	25.98	16.66	24.06	20.69	23.26	66.23	**23.50**
O	45.82	49.82	44.70	46.07	44.45	28.14	**45.26**
Na	0.71		0.42	0.28	0.13	0.52	**0.39**
Mg	0.62		0.31	0.62	0.64	0.48	**0.55**
Al	8.91		7.22	9.68	10.08	0.92	**8.97**
Si	13.47	33.53	19.39	17.73	15.09	1.76	**16.42**
S	0.11		0.10	0.08	0.05	0.17	**0.09**
Cl	0.31		0.29	0.18	0.11	0.29	**0.22**
K	1.43		1.24	1.44	0.99	0.06	**1.28**
Ca	0.33		0.23	0.78	0.29	0.52	**0.41**
Ti	0.23		0.67	0.31	0.53	0.33	**0.44**
Fe	2.08		1.37	2.14	4.37	0.49	**2.49**
P							
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Table 7.10 – EDX results for the clean Yellow clay brick.

Clean Yellow clay brick							
Cleaning stage	**100% clean**			**Unit**	**%**		
	Data on six sampling points for Sample 2						
Chemical element	**Sample 2-1**	**Sample 2-2***	**Sample 2-3***	**Sample 2-4**	**Sample 2-5**	**Sample 2-6**	**Average**
C	19.31	16.82	30.31	31.64	40.92	23.31	**28.80**
O	47.14	31.35	40.33	42.54	45.39	48.14	**45.80**
Na				0.15	0.12	0.14	**0.14**
Mg	0.46	0.24	1.37	0.39	0.33	0.56	**0.44**
Al	4.66	2.19	8.18	5.07	1.89	5.95	**4.39**
Si	24.14	5.47	11.62	13.9	5.9	12.55	**14.12**
S		11.98		0.2	0.46	0.19	**0.28**
Cl				0.12	0.34	0.08	**0.18**
K	1.28	0.68	1.87	0.86	0.56	1.01	**0.93**
Ca	0.65	29.75	0.88	2.21	1.87	4.96	**2.42**
Ti	0.67	0.12	0.23	0.66	0.21	0.35	**0.47**
Fe	1.69	1.39	5.21	2.27	1.56	2.62	**2.04**
P					0.45	0.14	**0.30**
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Table 7.11 – EDX results for the original Yellow sandstone.

Original Yellow sandstone							
Cleaning stage	**0% clean**			**Unit**	**%**		
	Data on six sampling points for Sample 3						
Chemical element	**Sample 3-1***	**Sample 3-2**	**Sample 3-3**	**Sample 3-4**	**Sample 3-5**	**Sample 3-6**	**Average**
C	40.73	20.65	13.71	19.56	22.68	20.54	**19.43**
O	43.13	49.16	59.26	57.02	53.10	53.72	**54.45**
Na							
Mg	0.20			0.17	0.23	0.19	**0.20**
Al	1.66	0.27	5.19	3.00	0.80	1.96	**2.24**
Si	10.86	29.92	21.10	17.16	21.96	17.76	**21.58**
S	0.24			0.16	0.10	1.21	**0.49**
Cl					0.03	0.04	**0.04**
K	0.20			1.34	0.12	0.58	**0.68**
Ca	0.26		0.75	0.51	0.48	2.81	**1.14**
Fe	2.14			1.08	0.49	1.20	**0.92**
Ti							
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Table 7.12 – EDX results for the clean Yellow sandstone.

Clean Yellow sandstone							
Cleaning stage	**100% clean**			**Unit**	**%**		
	Data on six sampling points for Sample 4						
Chemical element	**Sample 4-1***	**Sample 4-2***	**Sample 4-3**	**Sample 4-4**	**Sample 4-5**	**Sample 4-6**	**Average**
C	9.28	12.77	12.56	14.36	13.82	11.65	**13.10**
O	51.51	51.09	55.63	48.1	56.76	53.56	**53.51**
Na	0.56					0.25	**0.25**
Mg	0.73			0.05		0.2	**0.13**
Al	5.46		6.37	3.78	1.21	3.3	**3.67**
Si	5.20	36.14	18.78	29.38	26.3	24.2	**24.67**
S							
Cl							
K	0.15		6.66*	0.43	0.2	0.65	**0.43**
Ca	0.53			1.68	0.39	0.47	**0.85**
Fe	26.14			2.22	1.2	3.11	**2.18**
Ti					0.12	2.6	**1.36**
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Table 7.13 – EDX results for the original Limestone.

Original Limestone							
Cleaning stage	0% clean			Unit	%		
	Data on six sampling points for Sample 5						
Chemical element	**Sample 5-1**	**Sample 5-2***	**Sample 5-3**	**Sample 5-4**	**Sample 5-5**	**Sample 5-6**	**Average**
C	15.88	16.93	18.19	14.95	14.81	15.72	**15.91**
O	52.81	54.35	52.25	48.71	49.34	50.30	**50.68**
Na			0.38			0.19	**0.29**
Mg	0.22	0.24	0.29	0.18		0.27	**0.24**
Al		3.60	0.18	0.14		0.31	**0.21**
Si	0.19	5.05	0.73	0.22	0.22	1.27	**0.53**
S	0.16	1.81	0.26	0.23	0.15	0.26	**0.21**
Ca	30.74	17.06	27.71	35.56	35.49	31.55	**32.21**
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Table 7.14 – EDX results for the clean Limestone.

Clean Limestone							
Cleaning stage	100% clean			Unit	%		
	Data on six sampling points for Sample 5						
Chemical element	**Sample 6-1**	**Sample 6-2***	**Sample 6-3**	**Sample 6-4**	**Sample 6-5**	**Sample 6-6**	**Average**
C	12.45	15.88	13.97	12.44	13.2	11.94	**12.80**
O	49.08	29.62	49.3	51.19	47.65	52.36	**49.92**
Na							
Mg	0.41		0.26	0.21	0.15		**0.26**
Al							
Si							
S	0.23		0.26	0.16	0.14	0.25	**0.21**
Ca	37.83	54.50	36.21	35.99	38.86	35.45	**36.87**
Total	**100.00**	**100.00**	**100.00**	**99.99**	**100.00**	**100.00**	**100.00**

Table 7.15 – EDX results for the original Marble.

Original Marble							
Cleaning stage	**0% clean**			**Unit**	**%**		
	Data on six sampling points for Sample 7						
Chemical element	**Sample 7-1***	**Sample 7-2**	**Sample 7-3**	**Sample 7-4**	**Sample 7-5**	**Sample 7-6**	**Average**
C	15.30	20.31	31.36*	15.06	16.45	17.89	**17.43**
O	51.09	45.40	41.64*	47.70	49.54	50.86	**48.38**
Na		0.22	0.21	0.26	0.24	0.25	**0.24**
Mg	0.41	0.60	1.15	0.50	0.79	0.68	**0.74**
Al		0.78	0.56	0.84	1.56	1.19	**0.99**
Si		1.47	1.61	1.34	3.19	1.82	**1.89**
S		0.27	0.38	0.26	0.31	0.36	**0.32**
Cl		0.17	0.64	0.04	0.16	0.27	**0.26**
K			0.13	0.16	0.24	0.11	**0.16**
Ca	33.20	29.32	21.09	32.10	25.82	24.90	**26.65**
Fe		1.46	1.22	1.76	1.72	1.67	**1.57**
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

Table 7.16 – EDX results for the clean Marble.

Clean Marble							
Cleaning stage	**100% clean**			**Unit**	**%**		
	Data on six sampling points for Sample 8						
Chemical element	**Sample 8-1**	**Sample 8-2***	**Sample 8-3***	**Sample 8-4**	**Sample 8-5**	**Sample 8-6**	**Average**
C	12.71	18.28	29.52	12.57	12.55	12.95	**12.70**
O	49.96	46.41	1.84	51.88	51.46	51.76	**51.27**
Na		0.09	0.09				
Mg	0.49	1.87		0.45	0.55	0.46	**0.49**
Al		9.70				0.11	**0.11**
Si		16.61				0.16	**0.16**
S			35.72				
Cl							
K		6.53					
Ca	36.84	0.29	0.61	35.1	35.44	34.56	**35.49**
Fe			32.22				
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

7.4.2 Analysis of the EDX results

Figs. 7.21 to 7.24 illustrate the stacked column charts for all the masonry stones and clay bricks studied, which show the quantities of the chemical elements on the original and cleaned yellow clay brick samples. The increment or decrement of each element can be clearly identified by the 50% dividing line.

Fig. 7.21 shows the stacked column chart for the yellow clay brick, which indicates the quantities of the chemical elements on the original and clean samples. The main elements in the original clay brick were C, O, Si and Al at 23.50%, 45.26%, 16.42% and 8.97%, respectively. It also means that the main compounds in the clay brick were $CaCO_3$, SiO_2 and Al_2O_3, respectively. By viewing the 50% dividing line, it is found that C slightly increased to 28.80% after cleaning, while the Si and Al decreased to 14.12% and 4.39%. As the samples were coated with carbon, it is hard to analyse the changes of C. However, the decreases of Si and Al representing the Quartz (SiO_2) and Aluminium oxide (Al_2O_3) through the cleaning indicated that these two compounds were formed on the original yellow clay brick. As the stone façade had been exposed to the open air for such a long-time, Si and Al could be oxidised in the air with high probability. Similarly, the decreases of the rare chemical elements in the yellow clay brick such as Mg and Fe which represent the Magnesium oxide (MgO) and Iron disulphide (FeS_2) could be caused by polluting gases like O_3 and H_2S.

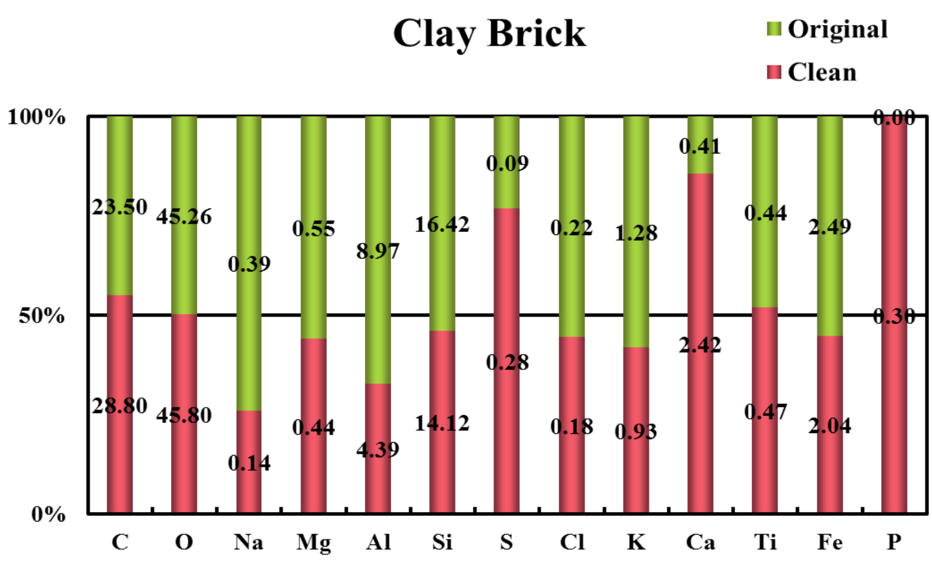


Fig. 7.21 – Chemical elements in percentages for the original and clean samples of the Yellow clay brick.

Fig. 7.22 is the stacked column chart for the yellow sandstone, which shows the quantities of the chemical elements on the original and clean samples. The main elements in the clean yellow sandstone were C, O and Si at 13.10%, 53.51% and 24.67%, respectively. It also means that the main compounds in the sandstone were $CaCO_3$ and SiO_2. By viewing the 50% dividing line, it is found that the main elements in the sandstone did not change much by the cleaning. However, some metallic elements such as Na, Al, Fe and Ti which represent Albite, Aluminium oxide (Al_2O_3), Iron disulfide (FeS_2) and Titanium (Ti) largely increased after cleaning, indicating that these elements were the original elements of the marble. The biological soiling on the stone surface such as bacteria which had the ability to largely dissolve a range of chemical components of the stone could lead to the loss of these compounds on the surface of the original stone. On the contrary, the decreases of Mg, S and Cl representing the Magnesium oxide (MgO), Iron disulfide (FeS_2) and Potassium chloride (KCl) through the cleaning indicated that these compounds were the naturally formed soiling on the façade of the yellow sandstone. Their formation was probably due to the reaction with the polluting gases such as O_3, SO_2 and H_2S in the atmosphere.

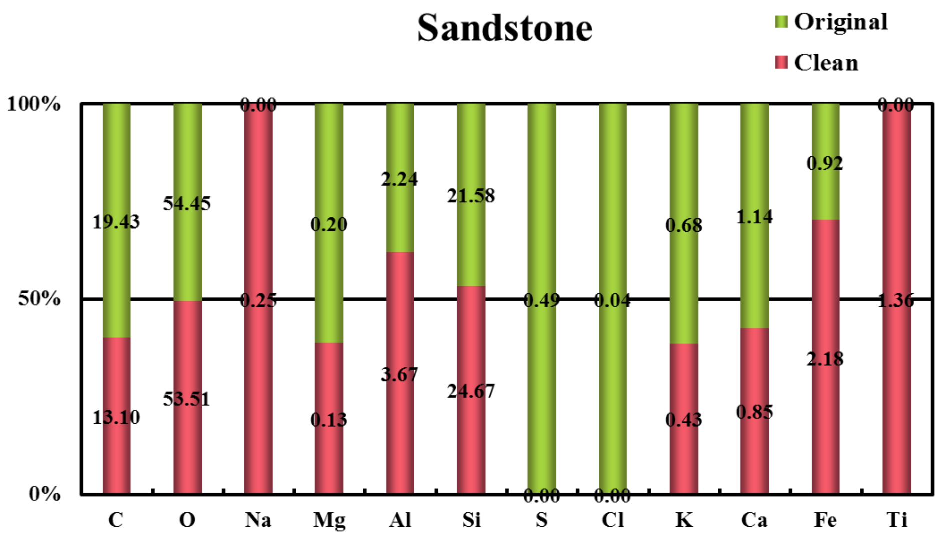


Fig. 7.22 – Chemical elements in percentages for the original and clean samples of the Yellow sandstone.

Fig. 7.23 is the stacked column chart for the Limestone, which shows the quantities of the chemical elements on the original and clean samples. The main elements in the clean limestone were C, O and Ca at 32.80%, 49.92% and 36.87%, respectively. It also means that the main chemical compounds in the sandstone were $CaCO_3$, SiO_2 and Wollas. By viewing the 50% dividing line, it is found that the main chemical elements in the limestone did not change much by the cleaning. However, some rare elements such as Na, Al and Si representing Albite, Aluminium oxide (Al_2O_3) and Quartz (SiO_2) disappeared after cleaning. This indicates that these compounds were not the original elements of the limestone.

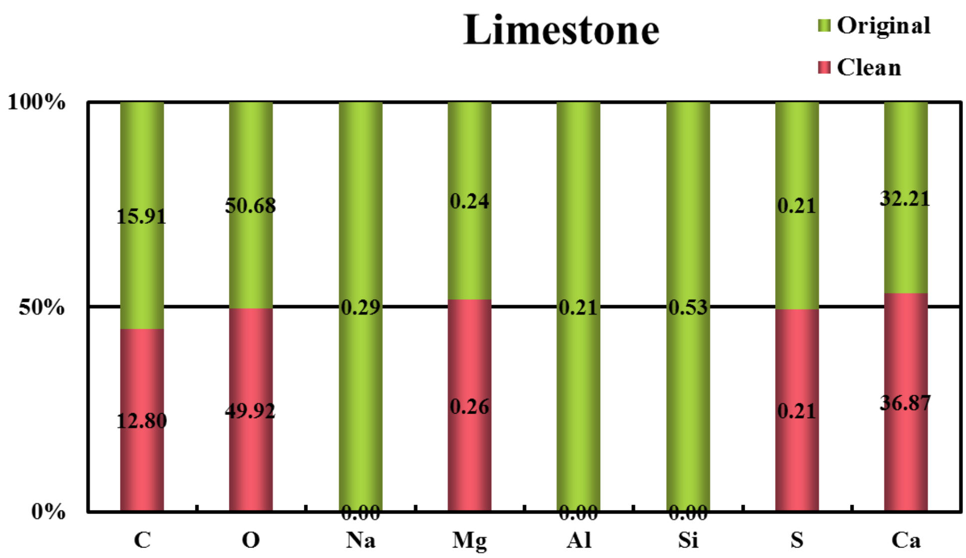


Fig. 7.23 – Chemical elements in percentages for the original and clean samples of the Limestone.

Finally, Fig. 7.24 shows the stacked column chart for the marble which indicates the quantities of the chemical elements on the original and clean samples. The main elements in the clean marble were C, O and Ca with 35.49%, 51.27% and 12.70%, respectively. It also means that the main chemical compounds in the marble were $CaCO_3$ and Wollas. By viewing the 50% dividing line, it is found that the rare compounds in the marble all largely decreased after cleaning, which indicates that the surface conditions of the original marble were not very good as large amounts of soiling formed on the surface. In addition, since the Mg, Al and Si still existed after cleaning, the clean marble likely contained small amounts of Magnesium oxide (MgO), Aluminium oxide (Al_2O_3) and Quartz (SiO_2).

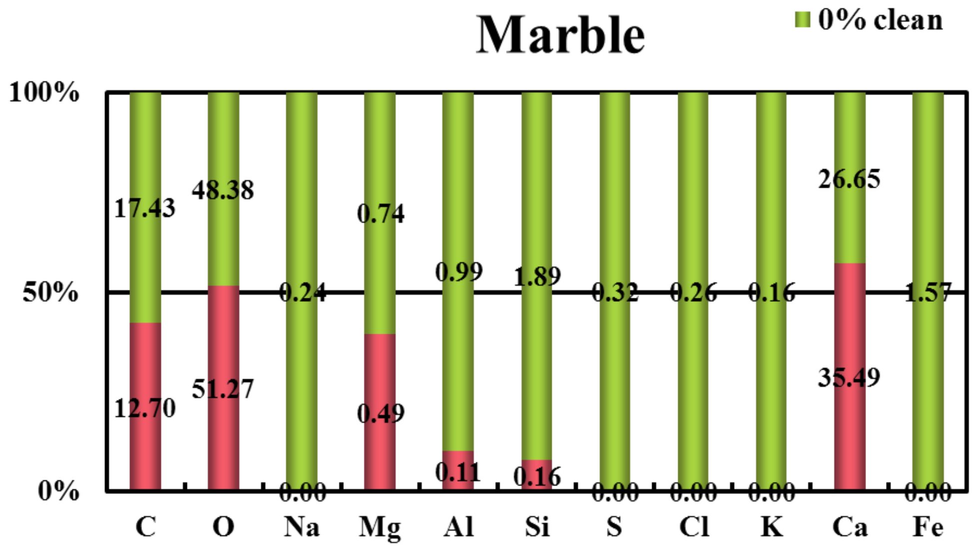


Fig. 7.24 – Chemical elements in percentages for the original and clean samples of the Marble.

7.5 Summary

This chapter has indicated the significance of applying the chemical analysis into exploring the formation and development of soling on masonry stones and clay bricks for historic buildings, and specified two chemical methods for this study including the Scanning Electron Microscope (SEM) and the Energy-Dispersive X-Ray Spectroscopy (EDX). The SEM method could help illustrate clear microscopic surface structures of the studied masonry stones and bricks at different cleaning stages, while the EDX technique could detect the chemical elements and compounds on the surfaces. This chapter has presented and analysed the detailed chemical test results on the carbon coated masonry stone and clay brick samples. This could nevertheless help qualitatively and quantitatively assess the soiling substances on the building façades and determine the efficient and effective ways to remove these soiling substances.

CHAPTER 8 CONCLUSIONS AND FUTURE SUGGESTIONS

8.1 Conclusions

8.1.1 General

This research aimed to circumvent the long lasting maintenance problem, cleaning of masonry buildings, which has become increasingly important to the conservation of historical masonry buildings and the maintenance of the city landscape for most of European countries and around the world. In this study, a comprehensive review has been firstly carried out on different types of pollutions to masonry stones and clay bricks and on their impacts to the buildings followed by an in-depth review on the history and recent development of the technologies for building cleaning. It has been confirmed that there is a need to explore the impacts of different cleaning techniques, to optimise the cleaning procedure and to access the outcomes. The significance of the research, aims, objectives and methodologies were presented.

For these purposes, a series of experimental investigations were conducted to explore the changes in physical and chemical characteristics of different types of masonry stones and clay bricks which are commonly used for construct masonry buildings. In this study, a total of eight different types of masonry stones and clay bricks were adopt to sustain the cleaning process, including red sandstone, yellow sandstone, limestone, marble, red clay brick, white clay brick, yellow clay brick and granite. Also three main types, seven sub-types of abrasives were selected for conducting the air abrasive cleaning, including coarse slag, medium slag, fine slag, coarse glass, medium glass, fine glass and natural abrasive.

The physical investigations included the sieve tests and impact tests on the abrasives for archiving the grading curves of these abrasives, the preliminary and advanced greyscale imaging analyses, the monitoring of thickness reductions of masonry stone and clay brick samples during the cleaning process, the Vickers hardness tests, the Charpy impact tests and the water absorption tests. The chemical investigations included the micro-graphing of the masonry stone and clay brick façades for assessing the features of the sample surfaces during the cleaning process and the analysis of the chemical elements and compounds on the corresponding surfaces before and after cleaning using the combined Scanning Electron Microscope (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDX) techniques. These investigations have all given a thorough understanding of the material, mechanical and chemical characteristics of the masonry stone and clay brick surfaces before, during and after the cleaning process and helped to select suitable abrasives for different types of masonry stones and clay bricks.

8.1.2 Physical testing on the abrasives

The impact tests and sieve tests on all seven abrasives confirmed that the particle size ranges of the abrasives provided by the suppliers ware fairly reliable. The abrasive with high bulk densities, e.g. slag or recycled glass abrasives, produced a smaller amount of fine particles after the impact tests than the abrasive with a lower bulk density, e.g. natural abrasive. However, after the impact tests, the particle size distribution curves moved slightly toward left because more fine particles were produced during the impact tests.

8.1.3 Greyscale image analysis and thickness reduction

In the preliminary greyscale imaging analysis, the cleaning degrees of the stone and brick samples, which were only cleaned with fine recycled glass, were assessed using the digital image analysis method by introducing a parameter, the greyscale for the masonry stone and clay brick surfaces, measured in a controlled lab environment. A lower greyscale, normally for a darker surface, corresponded to a more heavily polluted stone surface. It was observed that the greyscale continuously increased with the increasing cleaning time and tended to be stable when the surface became fully cleaned. In addition, a parameter the cleanness, defined as the ratio of the greyscale at certain cleaning stage to the greyscale when the stone was fully cleaned or called the relative greyscale, was introduced for assessing the effectiveness of the building cleaning. For a dirty surface, the cleanness was small; while for a fully cleaned surface, the cleanness was equal to one. A larger cleanness value corresponded to a better cleaned surface. The comparison of the cleanness values at different cleaning stages indicated that among all the studied masonry stones and clay bricks the original surface of the marble was extremely dirty, while the surface of the granite was the cleanest. This digital image analysis method together with applying the greyscale or cleanness was confirmed to be useful and efficient for quantitatively assessing the effectiveness of building cleaning. It could also provide detailed information of the pollutions on the façades of listed historic buildings so that the contractors can plan and optimise their cleaning procedures to achieve the best cleaning effect, minimise the impacts to the building and reduce the cost and time. This technique can also be used to estimate the maintenance cost for local authorities or the owners of the buildings.

Advanced greyscale imaging analysis by using the Adobe Photoshop software on the seven different types of masonry stones and clay bricks cleaned to different stages with all seven different abrasives further confirmed most of the findings obtained in the preliminary greyscale imaging analysis. However, the colours of the adopted abrasives should be considered because they may affect the final colours of the masonry stones or clay bricks cleaned. Also another factor should be paid attention to is the amount of dust that abrasives produce during the cleaning process. For example, the natural abrasive used in this could create more dust than the slag and glass abrasives, which can cause some healthy problems if the cleaning work is conducted in an unventilated area.

The thicknesses of the masonry stone and clay brick samples during the full cleaning process were continuously measured and the corresponding reductions were recorded and analysed. The larger thickness reduction a masonry stone or clay brick sample sustained, the cleaner and brighter the sample surface would be. Good relationships between the greyscale and the thickness reduction could be established. For most of the masonry stone and clay brick samples, monotonic increase trends between the two could be observed. However, the samples from the yellow clay brick and red sandstone samples possessed negative relationships between the greyscale and the thickness reduction, where the thickness kept decreasing accompanying with the decrease of the greyscale during the cleaning process. Nevertheless, both the greyscale imaging analysis and the thickness reduction measurement could be two highly useful methods for assessing the effectiveness of cleaning on masonry stones and clay bricks.

After the air abrasive cleaning was conducted, it can be observed that the abrasives with better cleaning results were those with smaller particle sizes, which were the medium and fine abrasives in this study. Compared with the medium and coarse abrasives, the coarse abrasives wore off more materials from the surfaces of the masonry stones and clay bricks, and also consumed longer cleaning times to archive the same cleaning effects. The analysis on the surface roughness of the masonry stones and clay bricks indicated more damages caused by using the coarse abrasives. This influencing factor should be carefully considered for future retention and conversation of masonry historic buildings.

8.1.4 Surface hardness and impact resistance

The surface hardness of all seven types of stones and bricks studied at different cleaning stages was assessed by conducting the Vickers hardness tests. A larger hardness value corresponded to a harder stone or brick surface. The hardness test results showed that the surface hardness continuously increased with the increasing cleaning time and would finally tend to be stable when the surface became fully cleaned. Most of the increasing trends of the surface hardness with the cleaning time could be approximately expressed using parabolic or bi-linear relationships or the mixes of both. The granite was found to be the hardest stone among all the masonry stones and clay bricks studied, and followed by the marble and limestone. However, there were no big differences in the surface hardness between the yellow clay brick, yellow sandstone, red sandstone, white clay brick and red clay brick. These results are valuable and important for optimising the cleaning procedure for a masonry building.

The impact resistances of seven types of masonry stones and clay bricks were obtained by conducting the Charpy impact tests. Granite showed the highest impact resistance among all the seven studied stones and bricks and was followed by marble, limestone, clay bricks and sandstones. The stones and bricks with higher impact resistances also had higher hardness values but lower water absorptions. In general, a masonry stone or clay brick with a higher impact resistance also possessed a higher hardness, but the variation trend between the masonry stones and clay bricks was not as large as the trend for the hardness.

8.1.5 Moisture content and water absorption

The moisture contents within the masonry stones and clay bricks and towards the surfaces of the stones and bricks plays an import role in selecting an abrasive to clean a masonry building. In this study, the water absorption capacities of the seven types of masonry stones and clay stones were also quantitatively determined. Two types of clay bricks showed the highest water absorptions, and the water absorptions for the limestone, yellow sandstone and red sandstone were also quite high. However, the water absorption of the marble and granite was found to be very low, which indicates that they could hardly absorb water. It was also observed that a larger water absorption capacity corresponded to a softer masonry stone or clay brick, while a smaller water absorption capacity corresponded to a harder stone or brick. Similar relationships of the water absorption with the impact resistance were also observed to those with the hardness.

8.1.6 Chemical testing

The chemical investigations conducted using the SEM and EDX techniques showed that the chemical substances on the masonry stone and clay brick surfaces largely varied with types of stones and bricks. Some chemical elements and compounds largely decreased and some increased during the building cleaning, but the chemical elements C and O always remained at large proportions of all the chemical elements within the stones and bricks. As the building façades were always exposed to the open environment for a long time, chemical reactions would occur, which could form various simple or multi chemical compounds on the stone or brick surfaces from the polluting gases in the air such as SO_2, H_2S, etc. This would lead to the formation of the soiling on the stone or brick surfaces. This study showed the way to detect such soiling using chemical analysis by monitoring the changes in chemical elements and compounds during the building cleaning.

8.1.7 Prospective impacts

Based on the analysis on all the testing data, it is possible to recommend a more suitable abrasive for each type of masonry stone and clay brick. For the granite and red clay brick, the abrasive that could produce the best performance should be medium glass, while for the limestone, marble and red sandstone, fine glass was more promising. For the yellow clay brick, fine slag could be the best option because it was less harmful, while for the yellow sandstone the natural abrasive was found to be more suitable.

Finally, when evaluating the test results from a more conservative point of view, it is worthwhile to note that in order to preserve the patina of the masonry stones and clay bricks for historic masonry buildings, the cleaning process should last over a shorter period for fully removing the soiling from building façades. It was impossible to assess whether granite façades had got patina or not because they had a polished surface. For the rest types of masonry stone and brick façades, only a few seconds may just be needed to archive a good balance between cleaning and conservation. For the limestone, for example, this balance was archived at cleaning stage four, and required for a period of only six seconds. For the marble and red clay brick, the relevant cleaning stage was stage five, and only a period of eight seconds was required to fully clean the samples. In the case of the red sandstone, the relevant cleaning stage was stage four, and the required time was only fifteen seconds. The yellow clay brick and yellow sandstone archived the aforementioned balance at stage two, and required only two and 10 seconds, respectively.

To sum up, it is clear that the experimental investigations accomplished in this study have produced a practical analysis of physical consequences of air abrasive cleaning on different types of masonry stones and clay bricks using different abrasives. Sensibly useful approaches for assessing the suitability and effectiveness of different abrasives on different types of masonry stones and clay bricks have been presented together with an estimation of the time duration the relevant cleaning process requires to produce a decent clean level without causing severe damage to the masonry stones or clay bricks. This study could be used in the future for assessing the suitability, in terms of time, thickness reduction and patina preservation, of air abrasive cleaning for the façades of historic masonry buildings under consideration.

A practically sensible selection of cleaning methods could largely influence the effectiveness, economy and future performance of restoration and conservation interventions of listed historic buildings.

8.2 Future Suggestions

In this study, extensive experimental investigations on evaluating building cleaning have been carried out, but there is still a lot of work for future, which is either planned to do but has not been carried out or has been done partially but could not be analysed and presented in this thesis due to the time restraints.

Here only the air abrasive cleaning method has been used for cleaning the studied masonry stones and clay bricks. There may be some other more effective cleaning methods other than the current method, and it is worthwhile to try other cleaning methods and do comparisons.

Seven abrasives have been selected for cleaning commonly used masonry stones and clay bricks. In practice, there are many other available abrasives for building cleaning, in particular recycled and natural materials rather than artificial materials. Their performances on different types of masonry stones and clay bricks should be investigated in similar ways as those in this study.

The surface hardness, impact resistance and water absorption capacity of the masonry stones and clay bricks are all largely influenced by their internal structures and compositions, e.g. porosity and pore size distribution of the stones and bricks. Hence it is important to investigate these microscopic properties of different types of masonry stones and clay bricks and explore their changes during building cleaning. Thus, relationships between these physical parameters can be well understood.

The present combined SEM and EDX chemical investigations were conducted on the carbon coated masonry stone and clay brick samples, it is interesting to conduct the similar tests on the samples coated with other materials to compare the variations in chemical elements and compounds due to different coating methods. Actually similar chemical investigations have been carried out on the gold coated stone and brick samples cleaned to different levels with fine recycled glass but the analysis could not been completed due to the time restraints. The chemical analysis on the gold coated samples can also solve the previous problem that it was hard to analyse the changes of chemical element carbon as the samples were all coated with carbon. The results will be further analysed and reported in the future.

In addition, since an inappropriate chemical cleaning method may cause great damage to the stone or brick façade, cleaning methods should be carefully selected according to the chemical characteristics on the surfaces of masonry stones and clay bricks. Therefore, the EMS and EDX can be utilised to detect the chemical elements and compounds on the stone or brick samples which have been cleaned by using different chemical cleaning methods. The decrease in quantity or the full loss of some chemical elements or compounds by comparing the chemical elements between the dirty and clean surfaces may indicate the damage or decay on building façades.

Moreover, current experimental work has been only carried out in the lab conditions. Large scale in-situ tests on real historic building should be an interesting application of the knowledge and technology developed in this study, Again the limitation of funding, manpower and time and the restriction of the current building regulations for listed historic masonry buildings have prevented this happen during the period of this study. However, this can be done in the future.

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Conservation and Repair of Historic Buildings

Fouad Khalaf[1], Humayun Reza[2] and Charles Fairfield[3]

This paper is dedicated to the memory of the late Dr Fouad Khalaf. His wisdom, knowledge, kindness, and contribution to academic life will be sadly missed.

ABSTRACT

Modern civilisations realised the importance of maintaining historical buildings to preserve them as good examples for future generations and also as a source of revenue through tourism. This investigation looks at the characteristics and origins of various types of stone used in the construction of historic buildings. The study also investigates different materials and techniques used in cleaning and repair of buildings and problems associated therewith. Tests were first carried out on various types of stone to determine properties such as porosity, water absorption and strength. A chemical analysis was carried out, under and on the surface, of the stones to determine the elements present in soiling. The information collected from all the tests was used to select the most appropriate materials and techniques used for in situ cleaning of a listed historic building.

KEYWORDS

Historic buildings, Stone masonry, Cleaning, Maintenance, Repair.

1 INTRODUCTION

One of the attractions of using stone in buildings is the wide variety of colours and textures available to the designer. There is a great variety of natural rocks, but not every rock can be used successfully in construction [Andrew *et al.* 1994, Hill and David 1995]. Some stones may be unaffected by centuries of exposure to the weather but others, if used in the wrong environment, may have to be replaced after a few years. Through time, and because of pollution and weathering, the external façades of buildings are affected: throughout the world stones have changed colour and texture. The cleaning of soiled building surfaces is not only necessary for aesthetic reasons but to ensure better preservation of these materials. Stone cleaning is a major activity for the construction industry, both in terms of financial outlay and effect on our built heritage. Removal of the soiling layer has been perceived by the general public and building owners as beneficial because of the simplistic notion that clean, bright façades reflect well on the urban environment in general and on the image of the building occupier in particular [Ashurst 1994].

Despite technical advances in the field of masonry cleaning, there are still a regrettable and unnecessary number of damaging mistakes made because of the lack of understanding of the type of stones used, the nature of the soiling and the materials and method used in cleaning. Standards and specifications do not provide answers or solutions to the cleaning of a building with a particular problem: each building's cleaning is unique due to the number of variables and unpredictable factors involved. Choosing the wrong material or method of cleaning could end up inflicting permanent damage to the building façade. Cleaning building façades is complex and the safe cleaning of buildings must be evaluated in detail before the process starts [Ashurst 1994, BRE 2000].

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2 STONES FOR BUILDINGS

Constraints inherent in stones limit their suitability for use in buildings. Igneous rocks may contain minerals which on exposure to the atmosphere may result in disintegration of the rock. Rising ground water with salt may cause spalling of some types of stones. Sedimentary rocks should be placed in a wall in such a way that the load is applied normal to the natural bedding planes. Metamorphic rocks may have harmful minerals which limit their use. The greatest restraint in the use of stone is that of the jointing. All rocks are naturally jointed and this controls the size of dimension stone that can be supplied by a quarry.

Even with their natural defects and constraints, stones will have durability other materials cannot match or provide. The identification of the type of stone is important when planning a new stone building in the vicinity of an existing one, or for repair and restoration work. The importance arises from matching materials for compatibility. Despite their great variety, relatively few types of stone are suitable for masonry construction. In addition to accessibility and ease of quarrying, the stone must satisfy the requirements of strength, hardness, workability, porosity, durability, and appearance. Some of the stones that satisfy these requirements are: granite, limestone, sandstone, marble, and slate. Key properties and factors affecting their use and selection are provided by Building Research Establishment Digest 420 [BRE 1997]

2.1 Granite

Granite is an intrusive igneous rock composed of crystals of quartz, potassium and sodium feldspars, biotite and muscovite micas. Colours vary depending on the amount and type of secondary minerals. The mineral present in the greatest quantity is feldspar. Granite is classified as possessing either fine, medium, or coarse-grained texture. Granites are well known for their durability and hard-wearing qualities in many types of environment. They are generally resistant to weathering and have high strength. The hardness of the stone lends itself to a finely polished surface finish but makes sawing and cutting very difficult.

2.2 Limestone

Limestone is a sedimentary rock, which is widely distributed throughout the Earth's crust. The rock is durable, easily cut, and readily worked. The durability is influenced by the porosity, more so than by the chemical composition, which for most limestones (except magnesian limestone) is broadly similar.

2.3 Sandstone

Sandstone is a sedimentary rock formed of sand or quartz grains cemented together by matrices of different compositions. The most common minerals are quartz, micas, feldspars and clays. Sandstones are classified according to their texture and nature of the cementing materials which largely governs their resistance to erosion. The cementing materials which are holding the sand grains together may be calcareous, dolomitic, siliceous or ferruginous. Sandstones in general are considered to have better resistance to chemicals in humid environments. They are available in a wide range of colours compared to limestone.

2.4 Slate

Slate is a metamorphic rock, formed from clay deposits which have been subjected to high pressure and heat over geological time. Thermal metamorphism produces material which is too weak to be used as building stone. The pressure on the other hand, not only hardens the clay, but realigns the flakes of mica and other minerals into planes of cleavage at right angles to the applied pressure. It is along these plains that the slate can easily be split into sheets. Slate is very susceptible to physical weathering. Exposed slate appears grey or grey-black although other colour varieties can exist.

2.5 Marble

Marble is a metamorphic rock formed by re-crystallisation of limestone or dolomite through some combination of heat and pressure; pure calcium carbonate yields a white marble, while the presence of other minerals gives a coloured or figured marble. Amongst all other stones, marble gives the widest variety of colours. The colours are due to impurities in the original sedimentary rock. Marble does not have the parallel structure possessed by many of the metamorphic rocks but has a compact or massive structure whose crystalline grains are so small that they cannot be distinguished except under a microscope. The low porosity and water absorption give marble a good resistance to weathering. However, marbles erode under acid rain and are affected by acidic gases.

3 TYPES OF SOILING

Soiling can be divided into two types: biological and non-biological. Stone façades are likely to have both present, either separately or combined. Soiling can cause stone decay: discoloration caused by soiling, affecting the aesthetics of the building, may not be causing physico-chemical damage.

3.1 Biological soiling

Biological soiling occurs when organisms and higher plant life forms (algae, bacteria, fungi, and lichens) grow on the masonry. These cause surface discoloration; some cause serious damage. Biological soiling needs: moisture, the correct temperature, nutrients, the correct pH, and light. Variations in any of these, outwith certain limits, may result in that organism's death. However, some micro-organisms can exist over a wide pH range; some bacteria will grow between $6 \leq pH \leq 9$; some fungi can tolerate $2 \leq pH \leq 11$ [RILEM 1988, Ashurst 1994].

3.1.1 Algae

Algae appear in a range of different colours (green, red, brown, or blue). The most common green algae colonise stones and turn black upon surface drying. They require light as they are photosynthetic. Algae prefer high moisture content surfaces and will grow on most damp substrates. They become darker in appearance as they collect more soot particles. While algae do not usually rely on the masonry substrate for food, organic acids they secrete can dissolve calcium carbonate in limestone, concrete, and mortar. Algae can also act on the substrate by cellular action within the masonry's pores. The moisture induced cellular swell-shrink cycle can have a mechanical influence on the stone and cause micro-cracking as reported by Verhoef [RILEM 1988].

3.1.2 Bacteria

Bacteria are organisms which are often recognised by the chemical and biological changes they cause [Ashurst 1994]. However, heavy deposits can exist in high concentrations with algae and fungi [Honeyborne 1990]. Some bacteria produce ammonia and other nitrogenous compounds; others are capable of oxidising ammonia to produce nitrous and nitric acids. In doing so they produce salts and mineral acids causing damage to the stone as well as promoting growth of other organisms through increased nitrogen availability [Winkler 1997].

3.1.3 Fungi

Fungi may appear in a range of colours (grey, green, black, and brown) often taking the form of furry spots or surface patches [Honeyborne 1990]. Fungi cannot produce their own food, so only appear on surfaces with organic food present. Fungi, although they produce organic acids while growing, do not cause serious damage to the stone. However, they disfigure and stain building façades and this would be reason enough for their removal.

3.1.4 Lichens

Lichens are a symbiotic intergrowth of algae and fungi. They may appear grey, green, orange, or yellow. They require light and mineral salts. Lichens do not like harmful urban environments and tend to be commonly found in rural areas. Lichens produce carbon dioxide which can react with calcium based substrates (limestone, lime render, some sandstones, and marble). Deposits below the surface (particularly in micro-porous stone) can restrict the ability of a stone to breathe leading to damage by surface spalling [Webster 1992].

3.2 Non-biological soiling

Non-biological soiling comprises airborne particulate matter deposited on the building façade such as soot, vehicle exhaust, and industrial emissions. Other non-biological soiling is due to soluble material from within the masonry drawn to the surface by evaporation. During this process mineralogical changes may take place within the stone and surface staining may result [Ashurst 1994].

3.2.1 Atmospheric constituents and pollutants

The atmosphere contains airborne particles which contaminate masonry. There are two key types of pollutants: naturally occurring particles (dust) and man-made pollutants (vehicle exhaust emissions, industrial chemical emissions, and soot). It can take as little as a year for a building exposed to the atmosphere to become soiled.

3.2.2 Aerosols

Aerosols can be both particulates and gaseous pollutants which are buoyant in air. The particulate matter of aerosols includes sulphates, chlorides, nitrates, ammonia, silicates, ions, soot, and hydrocarbons. By-products of fossil fuel combustion are also present and are among the finest constituents (particle diameter ≤ 0.1 µm) in the air. Their deposition on stone can be wet or dry, with dry being the most common.

3.2.3 Soot

Soot particles are more responsible for soiling of building façades than coarser particles. Their diameter ranges from 0.1 μm to 1 μm. The soiling is mainly due to dry deposition: wet soot deposition is of minor significance.

3.2.4 Particulates and other pollutants

Larger particles deposited on the building surface do not remain there very long. However when present, sulphates may create soiling by reacting with constituents within the stone, such as iron.

4 FULL-SCALE TESTING: PRESSURE WATER CLEANING

Pressure water cleaning is the most common method used to clean stone buildings. While it is a cheap and easily realisable method, when used on buildings unable to resist the pressure, it can be one of the most damaging methods. Pressure water cleaning was carried out on a sandstone wall situated beside a moderately busy road. The masonry had a wide variety of soiling present and was ideal to establish the effects of pressure water cleaning on a range of soiling types. The soiling included black gypsum soiling almost uniformly across the wall, the continuity of this is a result of its being situated close to the road and being more exposed to soiling than masonry walls situated further up or away from traffic. Algae, lichen, and vegetation were also present.

The equipment used was a pressure washer limited to 12 Nmm^{-2} with the working distance set to 300 mm: water was used at a lance pressure of 3.4 Nmm^{-2}. When cleaning over joints the lance should be aligned to ensure the water jet acting on the surface is perpendicular to the mortar joint. The risk of damaging the mortar is reduced as the severity of the cutting effect acting thereon is reduced [Campbell and Fairfield 2008]. The surface can be covered several times. If cleaning is not removing the soiling, avoid the temptation to reduce the working distance: the increased jetting force will give unreliable results as the relationship between cleansing power and working distance is non-linear. Covering the surface too many times can lead to its saturation. Notes should be taken on the effectiveness of the cleaning. Pre- and post-treatment photographs should be taken. These can be used to support notes taken on site, and give a visual impression of the extent of cleansing. To improve comparability of photographs, they should be taken from similar positions and in similar lighting conditions.

4.1 Results: pressure water cleaning

The pressure water cleaning was effective. Dirt and vegetation were removed; not all the lichens and embedded black gypsum were removed (Figs 1 to 4). Where the mortar was weak, pressure washing damaged it and the joints required re-pointing. This method was found to be cheap and effective in removing biological soiling.

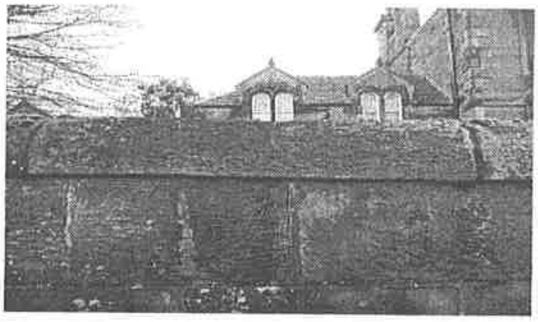

Figure 1. Algae and severe soiling on the external wall

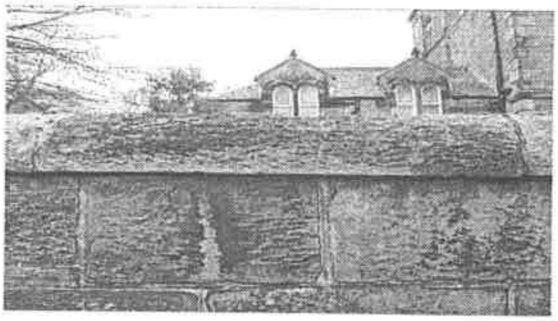

Figure 2. Algae removed: severe soiling remained

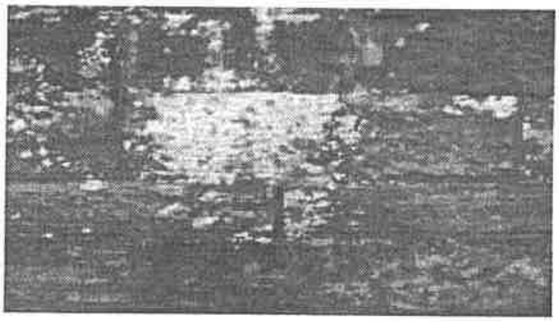

Figure 3. Lichens present on the wall before cleaning

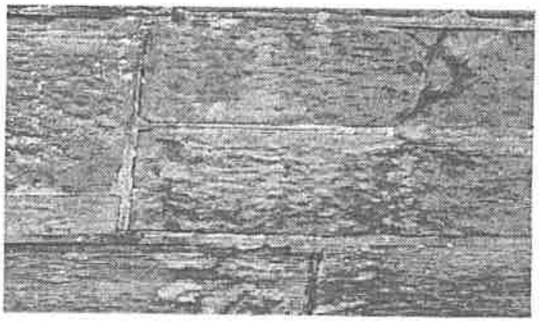

Figure 4. Traces of lichen remained after cleaning

4.2 Advantages and disadvantages: pressure water cleaning

Advantages:
- Quick removal of surface stains, loose surface debris, and biological soiling.
- May be used effectively in conjunction with chemical cleaning agents or abrasive materials.
- The amount of time spent scraping and scrubbing may be substantially reduced when appropriate rinsing pressures and water volumes are used.

Disadvantages:
- When used on its own, this method was generally not effective in removing severe staining.
- Very high water pressures and flow rates may have an abrasive effect and may damage the surface and increase masonry decay rates.
- Water-saturated masonry may take several weeks to dry thoroughly.
- Cleaning must be carried out when there is no threat of freezing temperatures.
- Excessive pressure can damage mortar joints and force water into the building's interior.
- Water runoff must be controlled to prevent intrusion into basement areas and surrounding properties.

5 FULL-SCALE TESTING: SANDBLASTING

The house cleaned was an occupied, listed, two storey sandstone masonry dwelling built in 1872. It was situated on a road and had trees and plant life around it. There were decorative features around the house such as three attractive balconies at the front of the building and two decorative pyramid-shaped sandstone windows. These pyramid-shaped windows had engravings showing fine architectural detail. The rear of the house comprised a massive wall with a number of windows placed therein and one bay window jutting out from the building. The masonry was solely sandstone and was in excellent condition. There was very little, if any decay, except for clearly visible soiling that had occurred on parts of the building. As the building was listed (although not in a conservation area) the owner needed permission to alter the façade's appearance.

The building had suffered general soiling by atmospheric pollutants, causing window sills and various features to become blackish in colour. The sills and bay window were the worst affected areas. The front of the building was on the roadside and was more susceptible to traffic pollution than the rear. The three balconies extending from the building were also more susceptible to rainfall and various airborne pollutants. Visual inspection showed that the three balconies were heavily soiled by various atmospheric pollutants such as soot and traffic fumes. The two pyramid windows were not as badly affected as the balconies but the decorative features on them were unclear from a distance because of this soiling.

The rear of the building was similar to the front in showing general soiling by atmospheric pollutants, causing the windows sills and other features to be rendered blackish in hue. At the rear there was a rain pipe, loose from the top near the roof which allowed the rainwater to leave staining down the full height of the façade. This caused drastic soiling which promoted the build-up of dense fungal and algal growths at the top of the rain pipe. The severity of fungal and algal contamination and allied staining decreased with distance down the façade.

5.1 Sandblasting: operational details

The following sandblasting equipment was used: water washer, air compressor (4.3 m^3/min), portable compressed air suction system, helmet with integral respirator, and a synthetic mineral abrasive available as either iron silicate or aluminium silicate with a grain size between 0.2 mm and 1.5 mm (JBlast Supa, supplied by Wolverhampton Abrasives Ltd). Scaffolding was erected to allow access to the full height of the façade. Before sandblasting started, windows and doors were covered with plastic sheeting, to prevent abrasive particles from damaging the windows and doors and entering the building. The operator was equipped with regulation personal protective equipment at all times. A small test patch was sandblasted to ascertain the correct air flow rate and abrasive content. Working top-down, rear to front of building, with a stand-off distance of *c*. 250 mm the operator sandblasted at a steady flow rate, trailing from left to right. On a wide open surface it was much easier for the operator to manoeuvre the gun and maintain the recommended 250 mm working distance. For less accessible regions, such as window sills, narrow strips between the bay window, and the balconies' architectural features, the pressure was greatly increased locally causing some areas to get more attention than others. A board was placed behind the balconies' architectural features to cause abrasive rebound and allow sandblasting of the otherwise inaccessible masonry. It is important to understand that a heavily soiled area does not need too much extra attention: if sandblasted for too long, damage can occur resulting in the stone acquiring an irreversibly burnt appearance.

It was particularly hard (even with an experienced operator) to cover the windows adequately: abrasive particles still managed to infiltrate the property necessitating the internal use of cloths around window frames as barriers. The sandblasting pot had to be filled periodically which slowed progress. Some blockages arose during sandblasting: these were resolved by adjusting the choke air valve and boosting airflow through the system to release the blockage. Blockages were caused by damp abrasive and accumulation of material. It may be the case that a water-repellent coating needs to be applied to the sandstone within 6 months of sandblasting to prevent a recurrence of the soiling. This is because sandblasting opens pores in the stones which make them more vulnerable to future attack. Expert consultation must be sought as water-repellent coatings are not universally recommended and with all such systems more harm than good may accrue if they are used unwisely.

5.2 Results: Sandblasting

During sandblasting, biological growths and some of the black soiling were removed; however, there were still large amounts of soiled material remaining encrusted in the masonry. The results of sandblasting are shown in Figs 5 to 10.

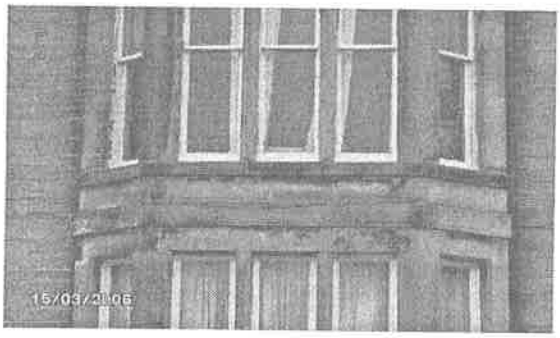

Figure 5. Soiled bay window

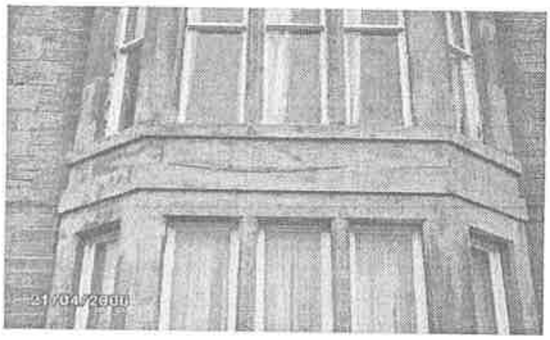

Figure 6. Sandblasted bay window

Figure 7. Soiled front balcony

Figure 8. Sandblasted front balcony

Figure 9. Soiled front window

Figure 10. Sandblasted front window

5.3 Advantages and disadvantages: sandblasting

Advantages:

- Effective at removing surface stains, loose surface debris, and biological soiling.
- Partially effective at removing black soiling from rough sandstones used in walls.
- More effective at removing black soiling from smooth and carved soft sandstones (*e.g.* on balconies, window sills and other features).
- Rapid operation.

Disadvantages:

- When used on its own, this method is not completely effective at removing severe staining.
- Experienced operatives are needed as over-sandblasting gives the stone an irreversibly burnt appearance.
- Sandblasting material consumables are expensive.
- Residual sandblasting material on green areas could harm surrounding vegetation.
- Difficulty covering doors and windows to prevent fines infiltrating the building or damaging glasswork.
- Sandblasting material should be completely dry to prevent blockages during cleaning.
- Periodic down-time required to refill the sandblasting pot and clear blockages.

6 CHEMICAL ANALYSIS

Energy dispersive X-ray analysis (EDXA) was used to give a detailed quantitative chemical analysis of the contaminated sandstone. EDXA was undertaken to determine which elements and hence compounds were contributing to the black soiling on the surface of the stones. A 20 mm _ 20 mm sandstone specimen was cut from the property and EDXA carried out on the surface and at 10 mm sub-surface. Thus a comparison between the chemicals present on the polluted surface and on the deeper, cleaner sandstone beneath was possible.

6.1 Results and discussion: EDX analysis

Figure 11 shows the typical EDXA results from both the surface (solid rendered plot) and 10 mm sub-surface (grey unshaded plot) analyses. As expected with sandstone the most dominant element present was silicon. The surface of the stone contained amounts of iron, carbon, and magnesium. The results suggested that the black coloured staining on the surface of the stone was non-biological and due to years of exposure to the environment, especially traffic and industrial airborne pollutants.

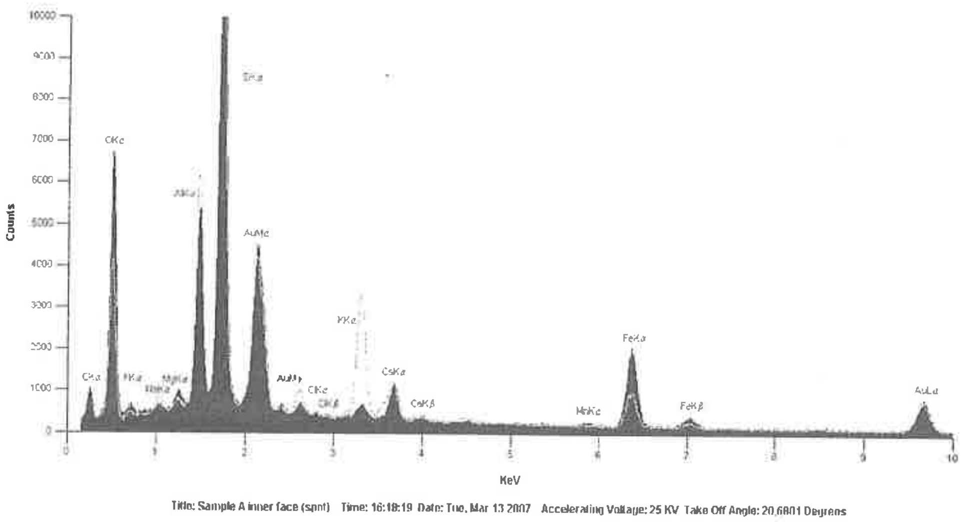

Figure 11. EDXA data from contaminated sandstone: surface (solid) and 10 mm sub-surface (grey)

Of interest, and as yet unexplained, is the potassium Kα transition observed in the sub-surface spot EDXA data at 3.3 keV which was barely present in the surface, more contaminated, sample. Also of note, is the presence of the contaminant elements in the sub-surface sample, albeit to a lesser extent, which would suggest prolonged exposure has allowed pollution to penetrate the sandstone to 10 mm depth.

6.2 Potential Future Analytical Developments

Linkage with other areas of research is mooted: microbiological and toxicological analyses of nanoparticles is an active field of work with potential collaborative effort applicable to stone masonry [Donaldson *et al.* 2005]. Computational fluid dynamics modelling to predict traffic pollution dispersal in urban environments [Addison *et al.* 1999] has been undertaken and is ripe for integration with the authors' field of research into its effects on masonry façades. High-pressure water jetting work on ceramic materials (initially applied to sewers by Fairfield [2008]) also overlaps with this topic: surface roughness profiling, scanning electron microscopy, and erosion damage rate predictions are all usefully transferable to this topic [Campbell 2008]. Recent problems in Edinburgh with sandstone decay [City of Edinburgh Council 2006] and the associated burden incumbent upon building surveyors, owners, the local authority, and engineering/building professions are bringing this research into context and indeed pushing it to the fore.

7. CONCLUSION

No single method proved to be the ideal cleaning method for the properties assessed as case studies here. Both water pressure washing and sandblasting have their advantages and disadvantages: these are evenly balanced in terms of both their number and technical implications. Future analysis is needed to verify the efficacy of each method at the microscopic level. Chemical methods of analysis are useful diagnostic tools for the classification of pollutant/contaminant types.

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PHYSICAL AND CHEMICAL CHARACTERISTICS OF MASONRY STONES DURING BUILDING CLEANING

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KEYWORDS: Masonry stones, cleanness, hardness, water absorption, chemical element, EDX, SEM.

ABSTRACT
This research focused on analysing and assessing the changes of the physical and chemical characteristics of the stone surface during the cleaning process by conducting various tests. Seven masonry stones were studied, including red sandstone, yellow sandstone, limestone, marble, white clay brick, yellow clay brick and granite. The physical testing included the evaluation of the cleaning degree, the Vickers hardness test, and measurements of water absorption. Using a digital imaging analysis, the greyscale and cleanness were introduced and determined to quantitatively assess the effectiveness of stone cleaning and proved to be useful and accurate. The cleanness analysis, hardness and water absorption tests showed that a stone with a higher cleaning degree always corresponded to a brighter and harder stone surface. The chemical investigations included the micrographs of the stone façade and analysis of the chemical elements and compounds on four of the stones before and after the cleaning using the Scanning Electron Microscope (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) techniques. In general, the physical and chemical properties were found to be largely affected by the cleaning degrees on the stone. The chemical test results showed that the chemical elements and compounds on the stone façade significantly varied after long exposures to the atmosphere, mainly due to the polluting gases and biological soiling.

INTRODUCTION

Historic buildings and monuments are precious finite asset and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The stone cleaning and restoration of old and historic buildings is a crucial strategy in maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations. Stone cleaning is one of the most noticeable changes a building can be subjected to, which can change its appearance, persona and environmental context (Ashurst, 1994a, 1994b; Historic Scotland, 1991, 1994; Verhoef, 1988). The stone cleaning and restoration of historic buildings has been conducted for decades in the United Kingdom due to the persistent investigations and research on physical and chemical characteristics of masonry stones for the buildings and the development of modern cleaning techniques. Millions of pounds have been spent every year on building cleaning and this is highly appraised by the public because of the significant effect on the appearance of the buildings and urban environment (Young et al, 2003; Khalaf et al, 2008). Before deciding the best method for cleaning a building preliminary investigations have to be conducted first on both physical and chemical characteristics of the surfaces of the masonry stones for the building.

In this study, the physical testing and analysis were conducted to accurately determine the hardness and water absorption and assess the efficiency on the surfaces of the masonry stones cleaned at four different stages, from dirty to clean. Seven masonry stones selected for physical testing included yellow sandstone, red sandstone, limestone, marble, white clay brick, yellow clay brick and granite. Meanwhile, the chemical analysis was also conducted to quantitatively assess the variations in chemical elements on the original dirty and fully cleaned surfaces of the masonry stones using the Scanning Electron Microscope (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDX) techniques. Four out of the seven masonry stones selected for the physical testing were adopted for chemical testing, including yellow clay brick, yellow sandstone, limestone and marble.

PREPARATION OF STONE SAMPLES

All seven types of stones were selected from those that had been used for masonry building and exposed to the open environmental conditions for decades with large amounts of heavy soiling and decay existing on the surfaces. The samples were cut into the required dimensions from the original masonry stones by using a diamond saw (Figure 1). Thereafter, the exposed surfaces of the stones were cleaned into different levels by using the abrasive cleaning method, sandblasting. Here an abrasive cleaning system selected included an air compressor, shot blasting cabinet and nozzle (Figure 2). Recycled fine glass with the particle size varying 125-1000 μm was selected for sandblasting cleaning (Figure 3). Figure 4 shows typical samples of seven selected masonry stones.

Figure 1: Cutting samples from original stones

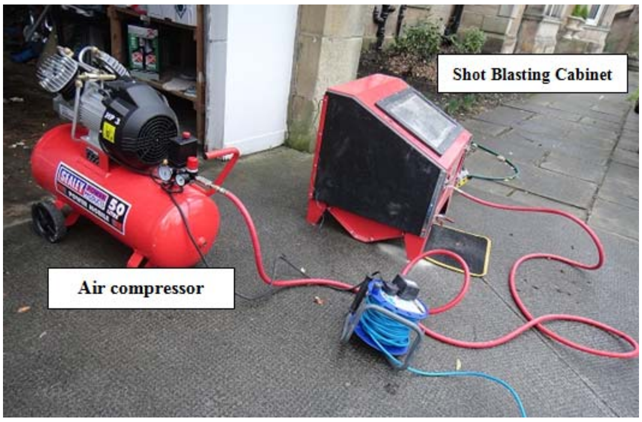

Figure 2: The abrasive cleaning system

Figure 3: Recycled fine glass

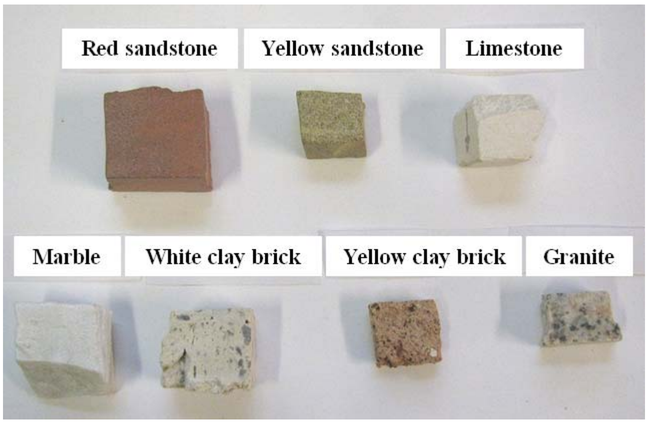

Figure 4: Typical masonry stone samples

During cleaning, the stone surfaces were gradually cleaned to four different levels by controlling the sandblasting time t from 0, 3, 6 and 10 sec for most stones, except the yellow clay brick and granite, with the cleaning degrees estimated as 0%, 30%, 60% and 100% (see Table 1). Granite had polished surface so only two stages were selected, fully dirty and fully clean. Figure 5 and 6 illustrate the red sandstone and limestone samples at different cleaning stages.

Table 1: Cleaning times in seconds for four cleaning stages

Cleaning degree	Yellow sandstone	Red sandstone	Limestone	Marble	White clay brick	Yellow clay brick	Granite
0%	0	0	0	0	0	0	0
30%	3	3	3	3	3	2	/
60%	6	6	6	6	6	4	/
100%	10	10	10	10	10	7	/

(a) *t* = 0 sec (b) *t* = 3 sec (c) *t* = 6 sec (d) *t* = 10 sec

Figure 5: Red sandstone samples at different cleaning stages

(a) *t* = 0 sec (b) *t* = 3 sec (c) *t* = 6 sec (d) *t* = 10 sec

Figure 6: Limestone samples at different cleaning stages

GREYSCALE AND CLEANNESS

To investigate the cleaning degrees of the surfaces of the stone samples, colour photos were taken first. A powerful lamp, used to create parallel lights, was fixed at 1.5 m above the samples. A Sony Cybershot DSC-T110 camera was used with the fixed 2.3 × optical zoom and distance of 0.5 m. All the colour photos taken were opened in the WORD files and converted to the greyscale digital images using the Photoshop software. These greyscale images were composed of shades of grey, varying from black at the weakest intensity to white at the strongest intensity. The corresponding greyscale levels could be read using Colourpad software. The greyscale (GS) is used to define the colour shades of the stone surface and ranges from 0 to 255 with 0 for pure black and 255 for pure white. An area of 1 cm^2 with a 10×10 grid including one hundred sampling points was placed on top of the greyscale photos and the GS values at the sampling points could be read in order to get the surface greyness of each stone sample by averaging these readings. Figs. 7 and 8 illustrate the sampling grids placed on the top of the greyscale photos of the red sandstone and limestone samples cleaned at different stages.

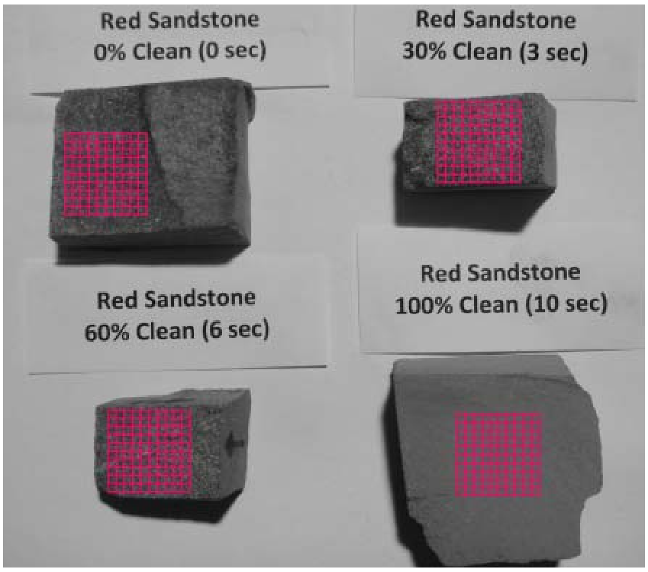

Figure 7: Grids on greyscale images of red sandstone

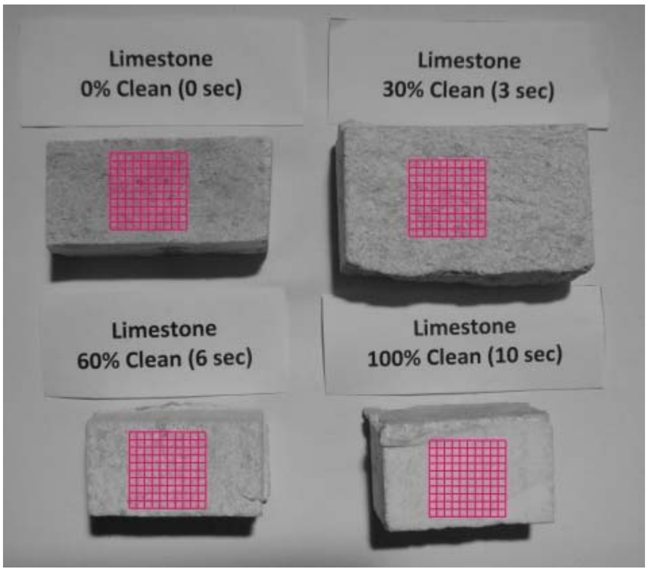

Figure 8: Grids on greyscale images of limestone

Figure 9 summarises the relationships between the greyscale and cleaning time for all seven types of masonry stones. It can be seen that the fully cleaned limestone had the brightest surface while the fully cleaned red sandstone had a darkest surface.

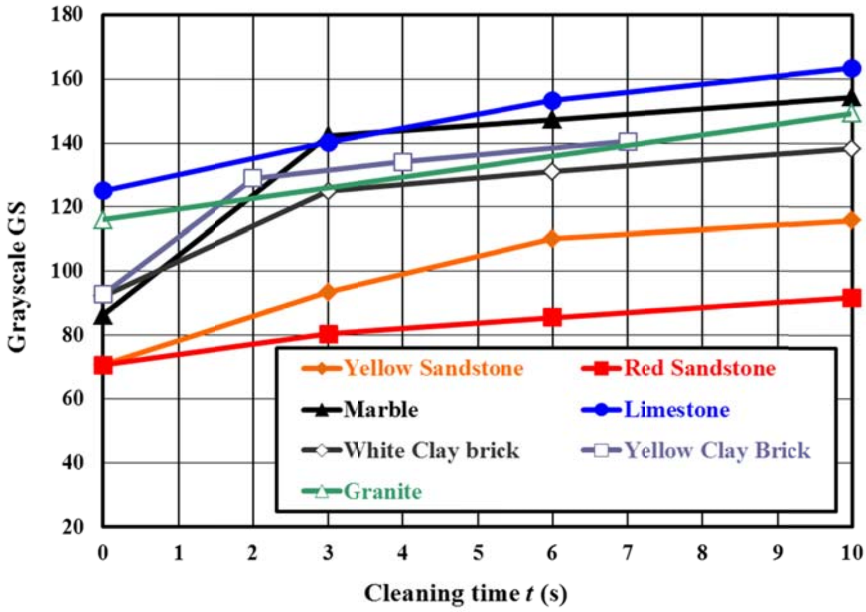

Figure 9: Greyscale versus cleaning time for various masonry stones

In general, the greyscale gradually increased with the increasing cleaning time but at a decrease rate and finally became stable when the stone surface was fully cleaned. These trends can be expressed using a parabolic or a bi-linear relationship. The differences in the greyscale between the original dirty and fully cleaned surfaces can be used to assess the dirty conditions on the stone surface. The larger the difference in greyscale, the dirtier the original stone surface. Marble had a largest difference of 68.3 and its original surface was the dirtiest. The differences in greyscale for yellow clay brick, white clay brick, yellow sandstone and limestone varied between 47.9 and 43.3 so they were relatively dirtier. The greyscale differences for granite and red sandstone were 33.3 and 21.2, respectively, which indicates that the original red sandstone was the least dirty.

In order to normalise the cleaning level for all types of the stones studied, a term of cleanness (CS) or the relative greyscale is introduced as follows:

$$\text{Cleanness (CS)} = \frac{\text{Greyscale at certain cleaning level}}{\text{Greyscale at fully cleaned level}} \qquad (1)$$

The cleanness value for a fully cleaned stone surface is defined as 1.0 and the cleanness for other cleaning levels are smaller than 1.0. Figure 10 summarises the relationships between the cleanness and cleaning time for all seven types of masonry stones. It can be seen that the cleanness had similar increasing trends with the cleaning time as the greyscale. The smaller the cleanness value, the dirtier the original dirty surface. It is obvious that the original surface of marble was the dirtiest, followed by yellow sandstone, yellow clay brick and white clay brick. Red sandstone still had the least dirty original surface, together with granite and limestone. These trends match those with respect to the greyscale, which indicates that the digital imaging analysis and the two proposed parameters can be used for assessing the building cleaning degree.

SURFACE HARDNESS OF MASONRY STONES

The surface hardness of the stone samples at different cleaning stages can be used for evaluating the changes in the surface strength during building cleaning. The Vickers hardness number H_V was adopted here and can be calculated from:

$$H_V = \frac{\text{Applied load (kg)}}{\text{Contact area of indenter (mm}^2\text{)}} = \frac{2P \sin \theta / 2}{d^2} \times 1000 = 1854.27 \frac{P}{d^2} \quad (2)$$

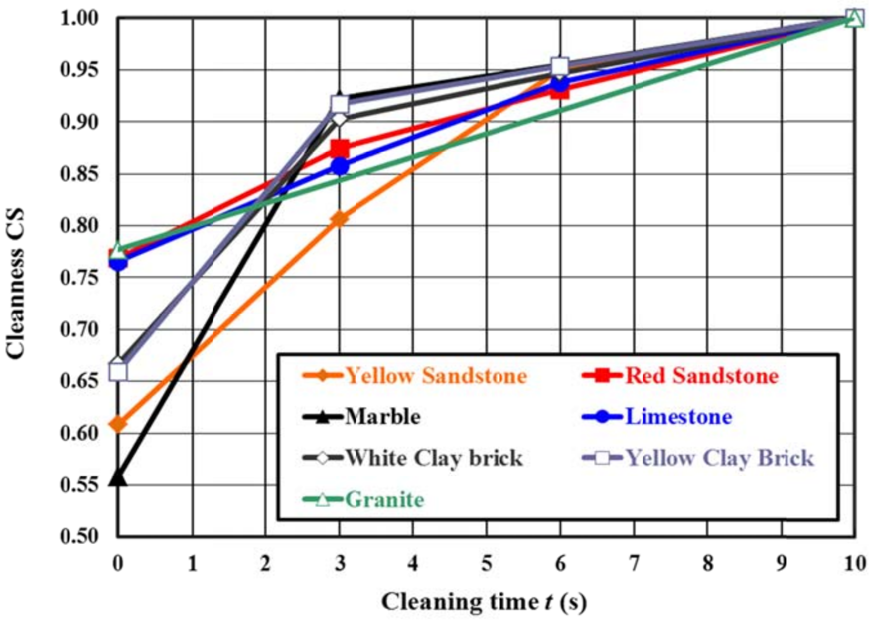

Figure 10: Cleanness versus cleaning time for various masonry stones

where

H_v Vickers Hardness Number (kg/mm^2)

P Applied load (g)

θ Angle between the opposite faces (136°)

d Diagonal of indentation (1 µm = 0.001 mm).

In the hardness testing, a stone sample was indented in the Vickers hardness instrument by a diamond indenter with a load P = 1000 g for 15 seconds (Figure 11). The pyramid shaped indenter had a square base diamond and an angle of 136° between opposite faces, as shown in Figure 12. After removing the load, a diamond indentation could be found on the stone surface using the microscope. Figure 13 shows that a diamond indentation had two diagonals, horizontal and vertical ones. The diagonal dimensions, d_H and d_V, were measured separately by attaching the two mark lines in the microscope to the edges of the indentation and then reading the values of d_H and d_V which were shown on the digital encoder. The two Vickers hardness numbers (H_V) corresponding to d_H and d_V could be obtained by checking against a Vickers hardness number table. The final value of H_V was the average of the two H_V results for the horizontal and vertical directions.

Figure 11: Vickers Hardness instrument

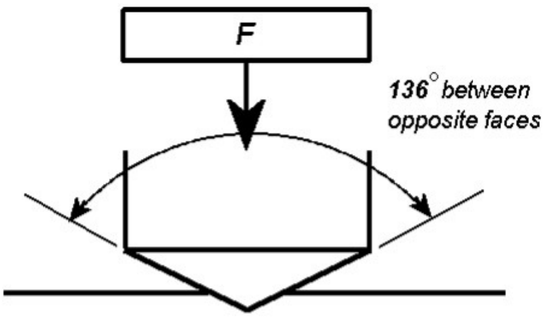

Figure 12: The pyramid shaped indenter

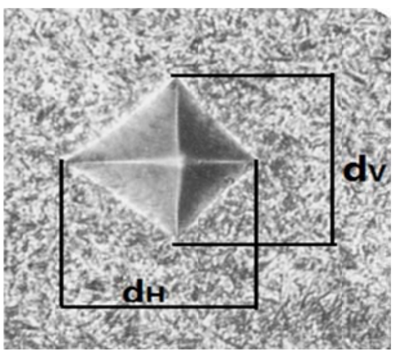

Figure 13: Diamond indentation on the stone surface

Figure 14 shows the increase trends of the surface hardness of the masonry stones with the increasing cleaning time but at a decrease rate. Similar trends could also be observed between the surface hardness and the cleanness. The granite had a hardest surface while the white clay brick had a softest surface.

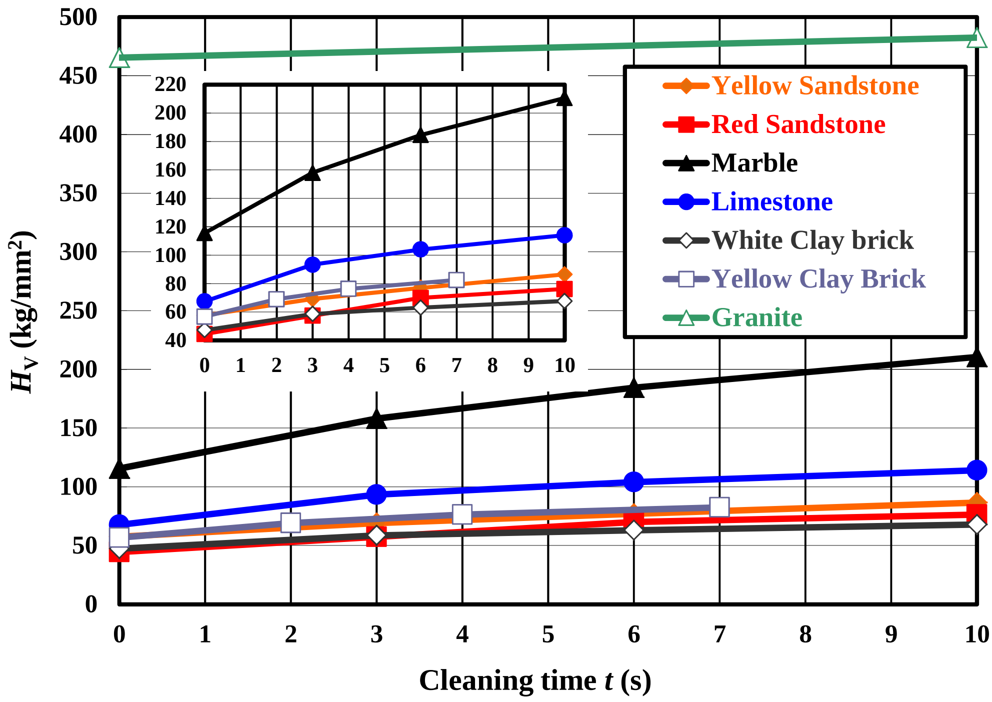

Figure 14: Vickers hardness number versus cleaning time for various types of masonry stones

WATER ABSORPTION

Water absorption, the quantity of water absorbed by a masonry stone when immersed in water for a stipulated period of time under the ambient atmospheric pressure, is another physical parameter which may largely influence the effectiveness of building cleaning. The water absorption testing was undertaken according to BS EN 13755 (BSI, 2008). The dried samples were placed in a tank after weighing, and then tap water at (20 ± 10)°C was added up to half the height of the stone samples. An hour later, tap water was added again until the level of the water reached three-quarter of the height of the samples. After another hour, tap water was added for a third time to overwhelm the samples completely. The samples were taken out of the tank after 48 hours, quickly wiped with a damp cloth and then weighed within 1 minute on a scale with an accuracy of 0.01 g. The result of the weighing was the weight of the saturated sample, $M_{\text{saturated}}$. The water absorption (WA) can be calculated from

$$\text{WA} = \frac{M_{\text{saturated}} - M_{\text{dried}}}{M_{\text{dried}}} \times 100\% \tag{3}$$

where

$M_{\text{saturated}}$ is the weight of the saturated sample

M_{dried} is the weight of the dried sample.

The water absorbing capacity of the seven types of stones was determined. Figure 15 illustrates that the two types of clay bricks showed the highest water absorptions among all the stones, at 13.09% and 8.66%, respectively. The water absorptions for the limestone, yellow sandstone and red sandstone were also quite high, at 5.40%, 5.09% and 2.96%, respectively. However, the marble and granite had absorbed little water, with the water absorptions of 0.32% and 0.23% only. It could also be observed that a larger value of water absorption corresponded to a softer masonry stone, while a smaller value of water absorption corresponded to a harder masonry stone.

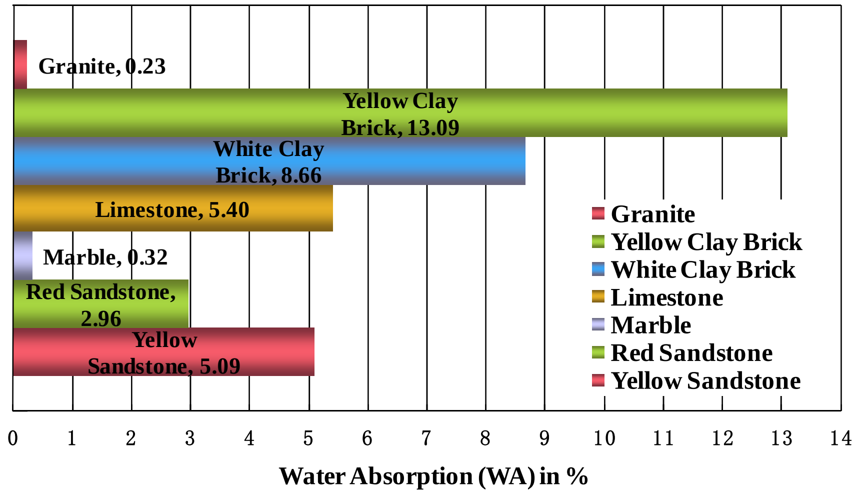

Figure 15: Water absorption for various types of masonry stones

CHEMICAL ANALYSIS

As the soiling and decay have the ability to affect the chemical substances on the stone surface, the chemical characteristics of the original dirty surface are largely different to the fully cleaned surface. In the cleaning process, the chemical substances on the stone surface continually change. Some elements and compounds may increase and some compounds may decrease or even disappear during building cleaning. The chemical analysis was conducted by using the instrument containing the Scanning Electron Microscope (SEM) and the Energy-Dispersive X-Ray Spectroscopy (EDX), as shown in Figure 16. The SEM was used to image a sample on a liquid crystal display (Figure 17) by scanning it with a beam of electrons in a raster scan pattern. It could produce the signals containing the information about the surface topography and composition of the sample by the interaction between the electrons and atoms. The EDX was used to analyse the chemical elements and compounds of the sample. EDX relies on the investigation of an interaction of some source of X-ray excitation with a sample. Its characterisation capabilities are due in large part to the fundamental principle that each element has a unique atomic structure allowing unique set of peaks on its X-ray spectrum. It would be possible to find out the elements on the different parts of the sample. The instrument used in this study was the Scanning Electron Microscope (SEM) LEO S 430 I, U.K., coupled with ISIS EDD detector from Oxford Instrument, U.K.

Figure 16: SEM and EDX instrument

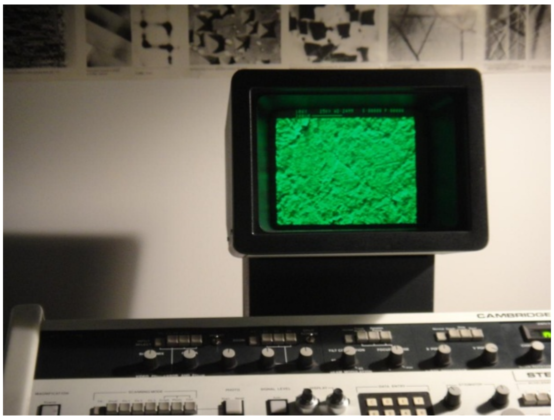

Figure 17: LCD for SEM

Sample preparation is a vital stage in the field of Electron Microscope. The insulation materials require a thin layer of conducting coating (~100 Å) to avoid charging. For the EDX in this study, carbon coating was adopted. The materials could also be observed at low primary energy, at which the coefficient for secondary emission was ~1 and the charge build-up was negligible. Entire sample preparation consisted of mounting the sample on a metallic platform via a conducting path.

Four out of seven types of masonry stones were tested:

- Yellow clay brick: Samples 1 (original dirty) and 2 (fully clean)
- Yellow sandstone: Samples 3 (original dirty) and 4 (fully clean)
- Limestone: Samples 5 (original dirty) and 6 (fully clean)
- Marble: Samples 7 (original dirty) and 8 (fully clean).

The surfaces of the clean samples were polished and cleaned in acetone. The original samples were rinsed in acetone. All the samples were dried under an IR lamp and coated with a thin layer of carbon to make them conductive. The samples were then mounted on the SEM stubs for the micro-structural and compositional analysis.

Six micrographs were recorded at different magnifications for each stone sample by using the SEM and six sampling points were selected for determining the chemical elements and compounds. Figure 18 shows a typical micrograph of the surface structures of the clean yellow clay brick with the corresponding spectrum diagram shown in Figure 19. Table 2 presents the percentage chemical elements and the corresponding compounds they formed.

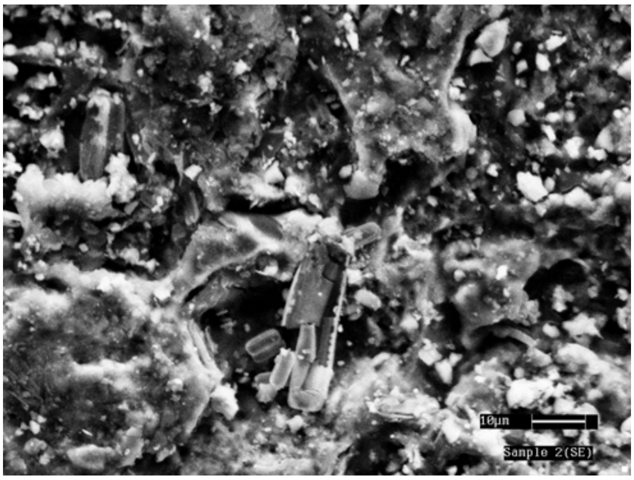

Figure 18: Micrograph for clean yellow clay brick

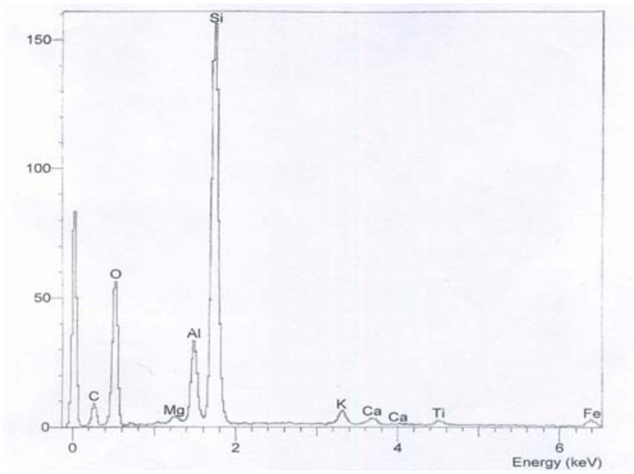

Figure 19: Spectrum diagram for clean yellow clay brick

Table 2: Typical EDX results for the clean yellow clay brick

SEMQuant results		Ref: Demonstration data SiLi detector		Spectrum label: Sample 2(1)	
System resolution = 61 eV		Quantitative method: ZAF (6 iterations)		Analysed all elements	
Element		Spectrum Type	Element (%)	Atomic (%)	Compound
C	K	ED	19.31	28.22	$CaCO_3$ 01/12/93
O	K	ED	47.14	51.70	Quartz 01/12/93
Mg	K	ED	0.46	0.33	MgO 01/12/93
Al	K	ED	4.66	3.03	Al_2O_3 23/11/93
Si	K	ED	24.14	15.08	Quartz 01/12/93
K	K	ED	1.28	0.58	MAD-10 02/12/93
Ca	K	ED	0.65	0.28	Wollas 23/11/93
Ti	K	ED	0.67	0.25	Ti 01/12/93
Fe	K	ED	1.69	0.53	Fe 01/12/93
Total			100.00	100.00	

Figure 20 shows the quantities of chemical elements on the original dirty and fully cleaned surfaces of the yellow clay brick samples. The main elements in the original yellow clay brick were C, O, Si and Al at 23.50%, 45.26%, 16.42% and 8.97%, respectively, which indicates that the main compounds in the yellow clay brick were $CaCO_3$, SiO_2 and Al_2O_3. By viewing the 50% dividing line, it can be seen that C slightly increased to 28.80% after cleaning while Si and Al decreased to 14.12% and 4.39%. As the samples were coated with carbon, it is hard to quantitatively analyse the changes of C. However, the decrease in Si and Al which represent Quartz (SiO_2) and Aluminium oxide (Al_2O_3) through the cleaning process indicates that these two compounds were formed in the original yellow clay brick. Similarly, the decrease of the rare elements in the yellow clay brick such as Mg and Fe which represent Magnesium oxide (MgO) and Iron disulfide (FeS_2) may be caused by polluting gases like O_3 and H_2S.

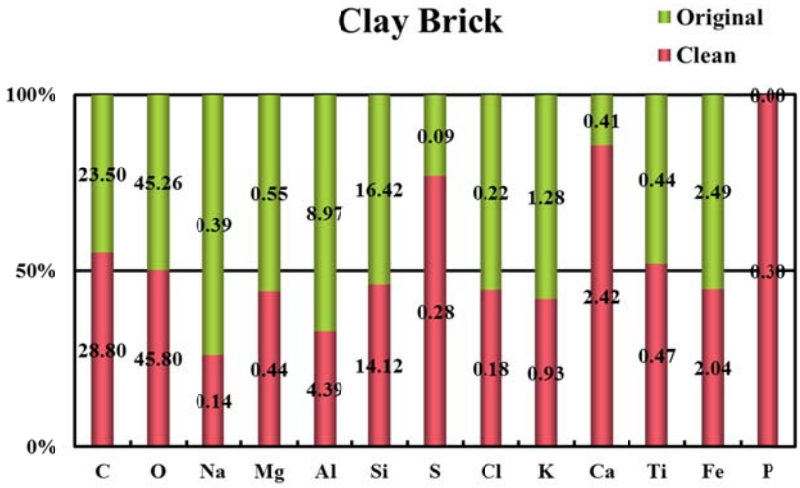

Figure 20: Chemical elements for the original dirty and fully clean yellow clay brick samples

Figure 21 shows the quantities of chemical elements on the original dirty and fully cleaned samples of the yellow sandstone. The main elements in the clean yellow sandstone were C, O and Si with 13.10%, 53.51% and 24.67%, respectively, and the corresponding compounds were $CaCO_3$ and SiO_2. By viewing the 50% dividing line, it can be seen that the main elements in the sandstone did not change much during cleaning. However, some metallic elements such as Na, Al, Fe and Ti which represent Albite, Aluminium oxide (Al_2O_3), Iron disulfide (FeS_2) and Titanium (Ti) largely increased after cleaning, which indicates that these elements were the original elements of the yellow sandstone. The biological soiling on the stone surface such as bacteria which has the ability to largely dissolve a range of components of the stone may lead to the loss of these compounds on the original stone. On the contrast, the decrease of Mg, S and Cl which represent Magnesium oxide (MgO), Iron disulfide (FeS_2) and Potassium chloride (KCl) through the cleaning indicates that these compounds were the naturally formed soiling on the façade of sandstone, probably due to the reactions with the polluting gases such as O_3, SO_2 and H_2S in the atmosphere.

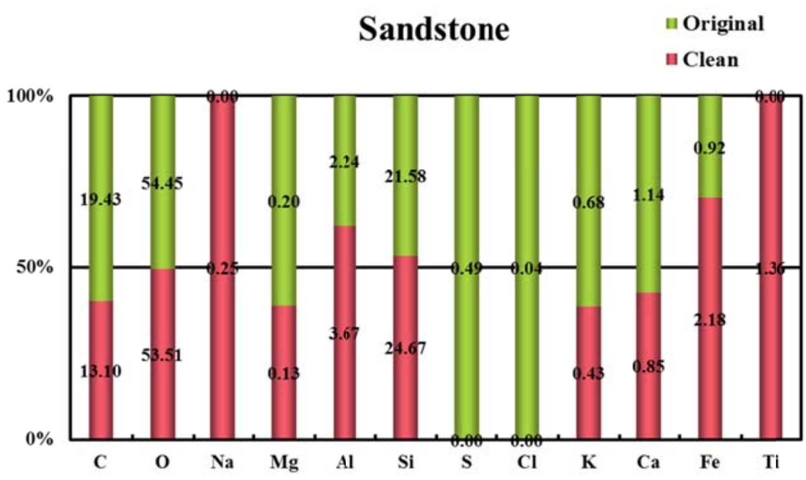

Figure 21: Chemical elements for the original dirty and fully clean yellow sandstone samples

Figure 22 shows the quantities of chemical elements on the original dirty and fully cleaned limestone samples. The main elements in the clean limestone were C, O and Ca with 12.80% 49.92%, and 36.87%, respectively, and the corresponding main compounds were $CaCO_3$, SiO_2 and Wollas. By viewing the 50% dividing line, it can be seen that the main elements in the limestone did not change largely by the cleaning. However, some rare elements such as Na, Al and Si which represent Albite, Aluminium oxide (Al_2O_3) and Quartz (SiO_2) disappeared after cleaning, which indicates that these compounds were not the original elements of the limestone but the dirty soiling.

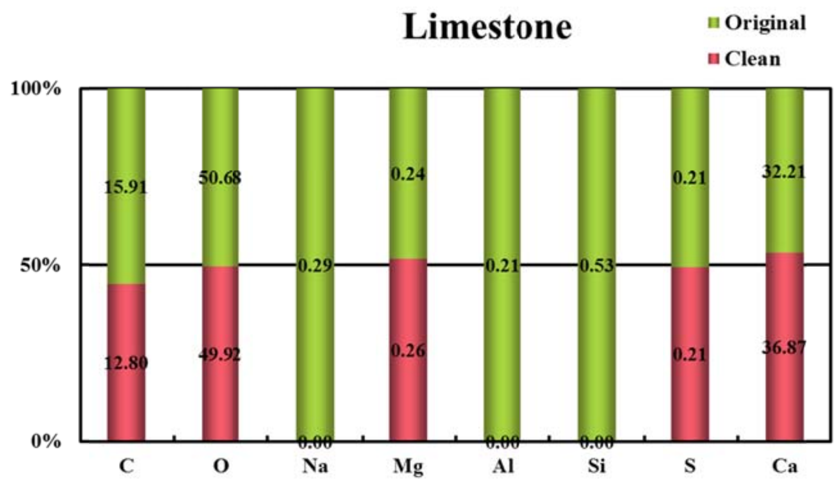

Figure 22: Chemical elements for the original dirty and fully clean limestone samples

Figure 23 shows the quantities of chemical elements on the original dirty and fully cleaned marble samples. The main elements in the clean marble were C, O and Ca with 12.70%, 51.27%and 35.49%, respectively, and the main compounds in the marble were $CaCO_3$ and Wollas. By viewing the 50% dividing line, it is found that the rare compounds in the marble were all largely decreased after cleaning, which indicates that the surface condition of the original marble was poor as large amounts of soiling formed on the surface. In addition, since Mg, Al and Si still existed after cleaning, the clean marble likely contained small amounts of Magnesium oxide (MgO), Aluminium oxide (Al_2O_3) and Quartz (SiO_2).

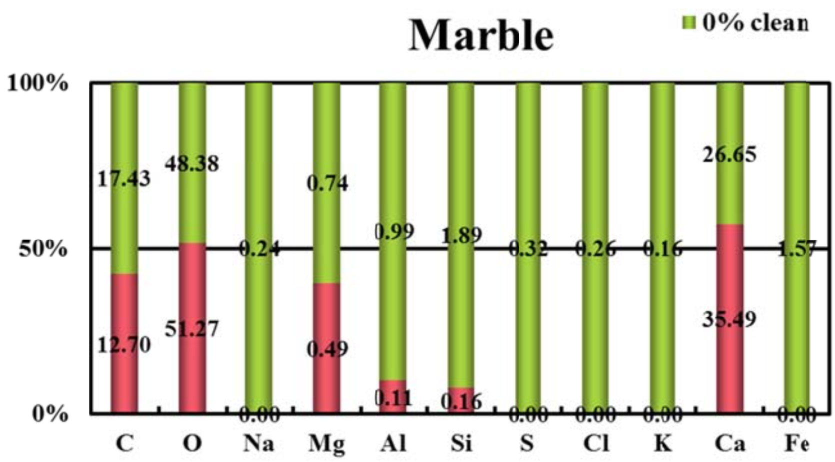

Figure 23: Chemical elements for the original dirty and fully clean marble samples

The test results showed that the chemical substances on the stone surface were quite different for different types of stones. Some chemical elements and compounds largely decreased or increased after cleaning, but the chemical elements C and O always remained at large proportions of all the chemical elements in the stones. As the stone façade was always exposed to the open environment for a long time, chemical reactions would occur, which would nevertheless form various chemical compounds or multi-components on the stone surface from the polluting gases in the air such as SO_2, H_2S, NH_3, O_3 and NO_X.

CONCLUSIONS

1. In this study, a series of tests were conducted to investigate the changes in physical and chemical characteristics of seven different types of masonry stones during the cleaning process, i.e. red sandstone, yellow sandstone, limestone, marble, white clay brick, yellow clay brick and granite. The physical investigations included the evaluation of cleaning degree, the Vickers hardness test, and measurements of water absorption. The chemical investigations included the micrographs of the stone façade and the analysis of the chemical elements and compounds on the stone façade before and after cleaning using the combined Scanning Electron Microscope (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDX) techniques.

2. The cleaning degrees of the samples were assessed by introducing a parameter, the greyscale, using the digital image analysis method. A lower greyscale corresponded to a dirtier stone surface. It was observed that the greyscale continuously increased with the increasing cleaning time and would finally stop when the surface became fully cleaned. In addition, another parameter, the cleanness which was defined as the ratio of the greyscale at certain cleaning stage to the one when the stone was fully cleaned or the relative greyscale, was introduced for assessing the effectiveness of the cleaning. For a dirty surface, the cleanness was small, while for a fully cleaned surface, the cleanness was equal to one. A larger cleanness value corresponded to a better cleaning level. The comparison of the cleanness values at different cleaning stages indicated that the original surface of the marble was extremely dirty while the surface of the granite was the cleanest among all the stones studied. This digital image analysis method together with applying the greyscale or cleanness was proved to be useful and efficient for quantitatively assessing the effectiveness of building cleaning.

3. The surface hardness of all seven types of stones studied at different cleaning levels was assessed by conducting the Vickers hardness tests. A larger hardness value corresponded to a harder stone surface. The harness test results showed that the surface hardness continuously increased with the increasing cleaning time and would finally become stable when the surface was fully cleaned. Most of the increasing trends of the surface hardness could be approximately expressed using bi-linear relationships. The granite was found to be the hardest stone among all the stones studied, and followed by the marble and limestone. However, there were no big differences in the surface hardness between the yellow clay brick, yellow sandstone, red sandstone and white clay brick.

4. The water absorbing capacity of the seven types of stones was also quantitatively determined. Two types of clay bricks showed the highest water absorptions, and water absorptions for the limestone, yellow sandstone and red sandstone were also quite high. However, the moisture absorption of the marble and granite was found to be very low, which indicates that they could hardly absorb water. It was also observed that a larger value of water absorption corresponded to a softer stone, while a smaller value of water absorption corresponded to a harder stone.

5. The chemical investigations by using the SEM and EDX techniques showed that the chemical substances on the stone surface were quite different for different types of stones. Some chemical elements and compounds largely decreased or increased after cleaning, but the chemical elements C and O always remained at large proportions of all the chemical elements in the stones. As the stone façade was always exposed to the open environment for a long time, chemical reactions would occur, which would also form various chemical compounds or multi-components on the stone surface from the polluting gases in the air such as SO_2, H_2S, NH_3, O_3 and NO_X. This may also lead to the formation of the soiling on the stone surface.

6. In summary, the investigations in this study indicated that the physical and chemical characteristics on the stone surfaces were all significantly influenced by the cleaning degrees. A stone with a higher cleaning degree always corresponded to a brighter and harder surface. Because an appropriate stone

cleaning method could not only improve the appearance of the building but also protect the stones from decay and damage, in this way, the present study could help to pave the way for selecting more appreciate, economical and effective methods of stone cleaning for existing listed masonry stone buildings.

ACKNOWLEDGEMENTS
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DIGITAL IMAGE PROCESSING OF WEATHERED STONE FOR DETERMINING THE OPTIMUM CLEANING LEVEL OF STONEWORK

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KEYWORDS: Building conservation; Stone cleaning; Image analysis; Stereovision.

ABSTRACT
In this study, the authors introduced a new image component sampling technique that can be used to evaluate level of cleaning of weathered masonry stone for historic buildings. The proposed technique is based on the Standard Pattern (SP). The images taken from different stages of cleaning are used to setup the SP and empirical model to predict the level of cleaning against the duration of cleaning. With the model and SP, Pollution Density Index (PDI) from the image of a building can be evaluated. An optimum cleaning duration can be calculated for each area base on PDI distribution on the surface of the building. The proposed method has been proved to be effective and easy to implement. It can be applied to different way of cleaning.

INTRODUCTION

Image processing is widely used in all kind of building conservation activities [1-3]. In this study, the authors introduced a new image component sampling methodology that can be used to evaluate level of cleaning of weathered masonry stone for historic buildings. The suggested technique is based on the image component analysis of the stone surface in a controlled testing environment for setting up Standard Pattern (SP). The images taken from different stages of cleaning are used to setup the SP and the image analysis results are employed to propose the empirical model to predict the level of cleaning against the duration of cleaning. With the model and SP, one can also predict the Pollution Density Index (PDI) from the image of a building by comparing each area of the image with the SP and then evaluate the PDI with the proposed model. With this PDI distribution on the surface of the building, an optimum cleaning duration can be calculated for each area. To evaluate the PDI distribution on a complicated building surface, the surface will be discretised into small planar areas for evaluation. In this study, the image processing is carried out on Adobe CS3 software package. The proposed method has been proved to be effective and easy to implement. It can be applied to different way of cleaning.

EQUIPMENT

To test the proposed method, recycle glass granulate was used to weathered sand stone samples as a trial test as the sand stone is one of the most commonly used materials for masonry building in Scotland and recycle glass is one the most environmental friendly materials. The test equipment used in this test includes an air compressor, enclosed cleaning chamber (Figure 1).

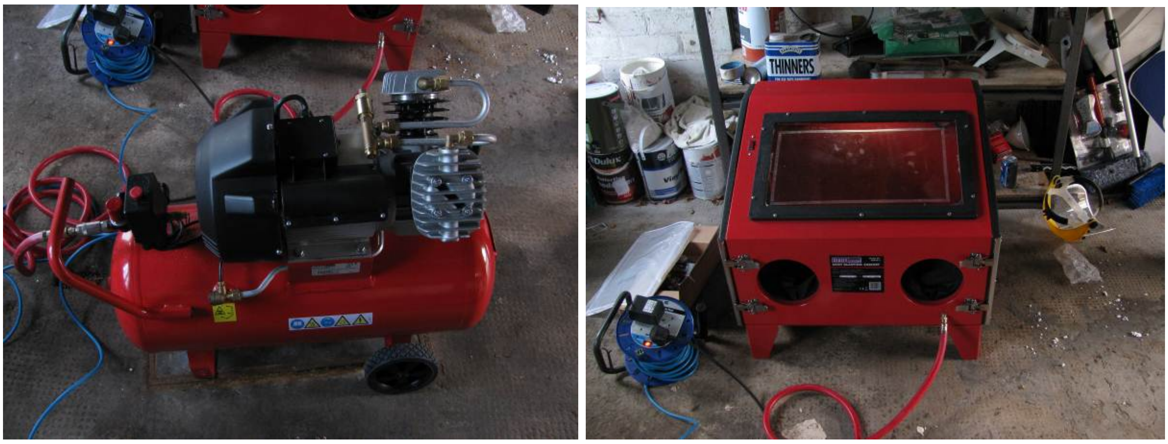

Figure 1: Air compressor and enclosed cleaning chamber

In order to photo the stone surface in a control environment, a wooden frame is design to make sure each photo was taken in same distance and same configuration. To keep the illumination of the sample surface in same condition, two LED flood illuminators are mount on top of the frame (Figure 2). The frame was kept in a dark environment when take the photos of samples at different stages of cleaning. The camera used in this test is Canon PowerShot 100s.

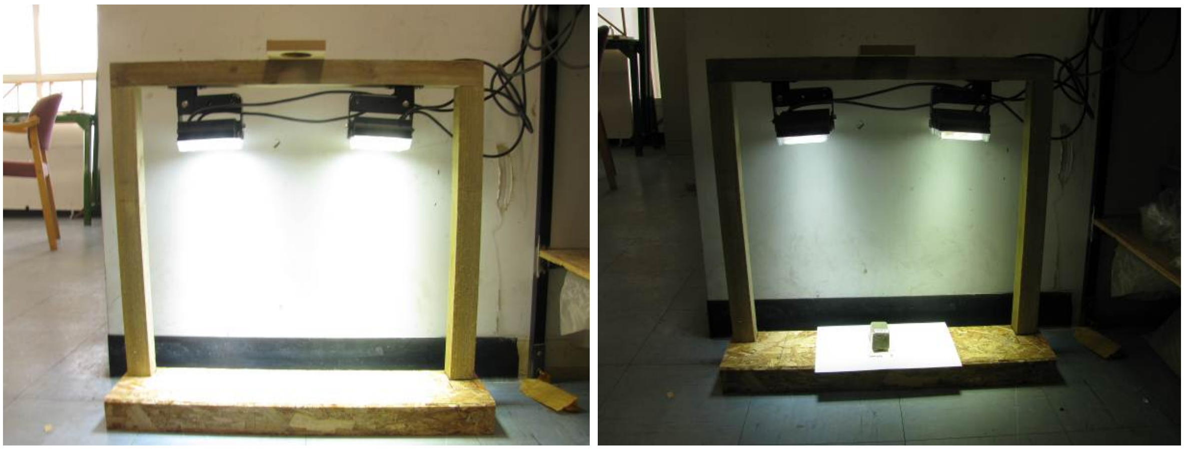

Figure 2: Frame for photo shooting

CALIBRATION

The calibration is the important step to provide the basic index for the new surface and polluted surface. In order to obtain a fresh surface, the sample stone is cut into the stone for 1-2cm to obtain a fresh surface, and the photo of this new surface is then photo and analysed to obtain the index for a new surface. The polluted external surface is also photo and analysed to obtain the index for the untreated surface. Both photos are taken under the frame mentioned above. A comparison of two photos is given in Figure 3. A screen shot of the data analysis with Adobe CS3 is also shown in Figure 4.

(a) Polluted (b) fresh

Figure 3: Polluted and fresh surfaces of sandstone

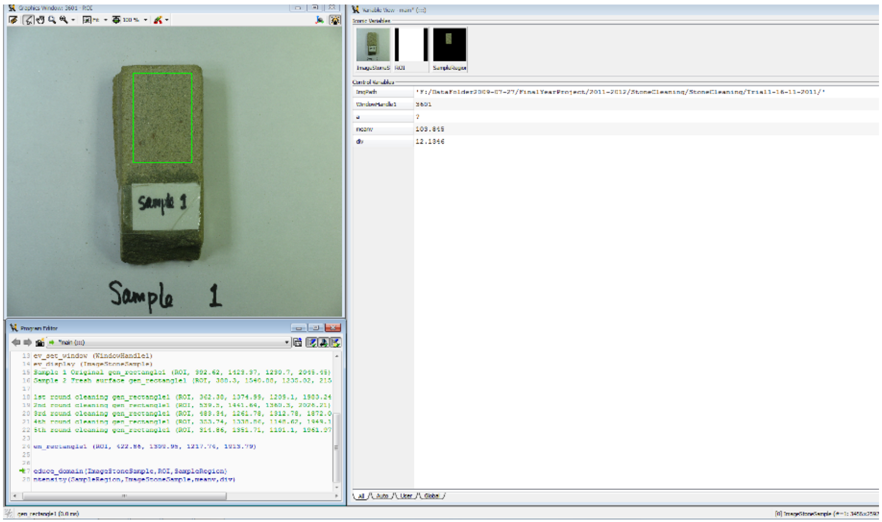

Figure 4: Screen shot of data analysis

TEST PROCEDURE

After calibration, the sample stones are put in the enclosed chamber to clean for a fix time in turn and then will be taken out to take the photos of the surface at different cleaning stage. After analysis the surface images, a level of cleaning can then be plot out against the time/stage of cleaning. The test result of sample 1 is shown in Table 1. The normalised cleanness value of the untreated surface is called the Pollution Density Index (PDI). The curve indicating different level of cleaning at each cleaning steps is shown in Figure 5. All the values tested are taken from 1000 sample points for each image. The cleanness of different stages C_i are calculated from the following formula

$$C_i = GV_f / GV_i$$

Where

GV_f is the grey value of fresh surface;

GV_i is the grey value of surface of corresponding round of cleaning

Table 1: Test result of sample 1

	Mean of Gray Scale	Std Div	Cleanness*
Dirty surface	62.47	10.43	1.68
1 round cleaning	79.99	14.07	1.31
2 round cleaning	87.19	13.38	1.20
3 round cleaning	93.70	12.62	1.12
4 round cleaning	98.25	12.38	1.07
5 round cleaning	103.85	12.13	1.01
Fresh surface	104.96	11.03	1.00

*Cleanness =Gray sale of (cleaned surface/fresh surface)

A typical normalised cleanness value in a 5-round cleaning test is show in Figure 5. A value of 1 indicated a fresh surface. From this curve, it can be seen that first and second round the cleaning is the most effective two steps. The later stages are less effective and will cause more abrasive damage to the surface.

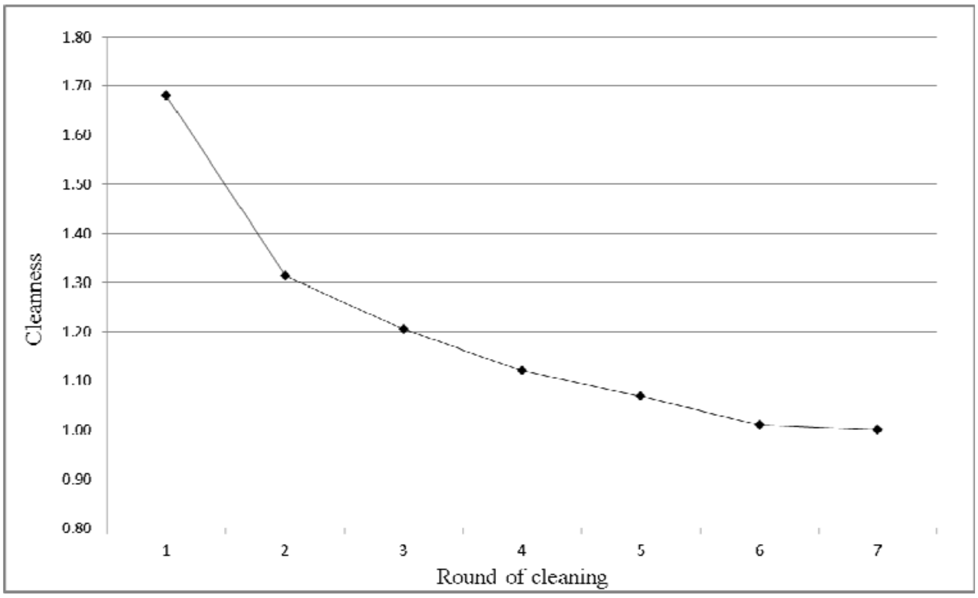

Figure 5: Levels of cleaning for Sample 1 at different cleaning stages

Same test procedure is repeated for 10 samples. Test result is shown in Figure 7. From the 10 sets of datum, a preliminary model to predict the level of cleanness after each round of cleaning is proposed as following:

$$y = \max(1.6236x^{-0.262}, 1.0)$$

where x is the number of round cleaned, y is the cleanness of the surface. Since the normalised cleanness of a fresh surface is 1.0, so in no case the value of the cleanness level of the cleaning surface should drop below 1.0. A set of images for sample 5 at different stages (Standard Pattern, SP) are shown in Figure 6. D indicates the surface before treatment. F indicates flesh surface and R1-5 indicates the treated surface after 1^{st} -5^{th} round of cleaning.

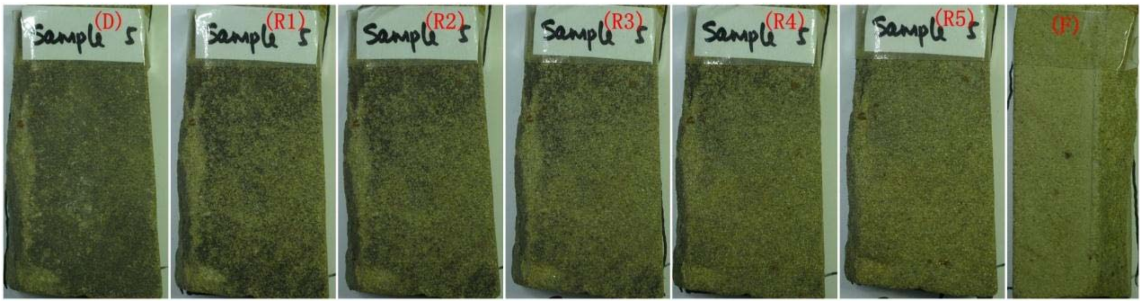

Figure 6: Images of sample 5 at different cleaning stages

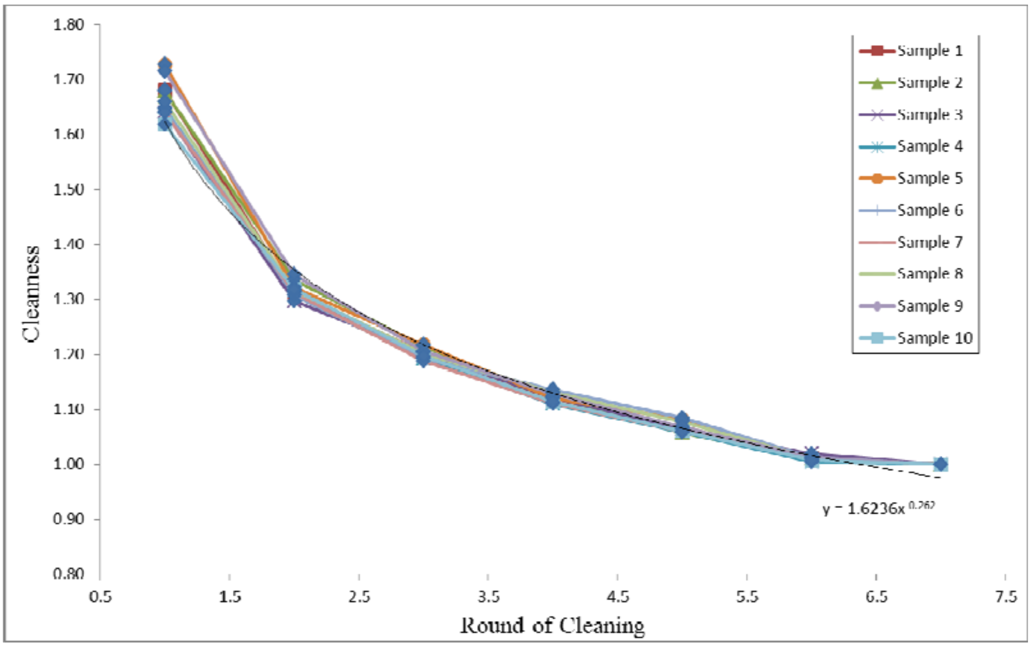

Figure 7: Sample 1-10 test result and empirical model of cleaning

With this empirical equation, the estimation of the cleaning duration and cost of a building surface can be predicted quantitatively. Thus, an optimum cleaning plan for a surface of the building can be followed up accordingly.

CONCLUSION

In this paper, the authors introduced a new image component sampling technique that can be used to evaluate level of cleaning of weathered masonry stone for historic buildings. The proposed technique is based on the Standard Pattern (SP). The images taken from different stages of cleaning are used to setup the SP and an empirical model to predict the level of cleaning is proposed based on the power function. With the proposed model and SP, Pollution Density Index (PDI) can be evaluated from a digital photo of a building. An optimum cleaning duration can be calculated for each area base on PDI distribution on the surface of the building. The proposed method has been proved to be effective and easy to implement. It can be applied to different way of cleaning.

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EVALUATION OF EFFICIENCY OF AIR ABRASIVE CLEANING ON OLD MASONRY BUILDINGS USING GREYSCALE IMAGING ANALYSIS

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KEYWORDS: Historic building, Masonry stone, Abrasive, Air abrasive cleaning, Greyscale, Cleanness.

ABSTRACT

The stone cleaning and restoration of historic buildings is a crucial strategy for maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations. In this study, advanced greyscale imaging analysis was conducted using Adobe Photoshop 6 on the surfaces of masonry stones, taken from old buildings, to accurately assess the efficiency of building cleaning. Five commonly used masonry stones for those buildings were selected, including granite, limestone, marble, yellow sandstone and red sandstone. Seven abrasives were adopted for air abrasive (sandblasting) cleaning, including steel plant by-product slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. Also the reductions in thickness were also monitored for assessing the cleaning efficiency. The cleaning degrees at different stages were evaluated using greyscale image photos, converted from original colour ones, together with reductions in thickness, where a lower greyscale value normally corresponded to a darker and dirtier surface and a higher greyscale value to a brighter and cleaner surface. In general, greyscale continuously increased with the cleaning time and tended to be stable when the surface became fully cleaned. Thickness reduction monotonically increased with the cleaning time, which could also be used to assess the cleaning efficiency in combination the cleaning time. The most efficient building cleaning case would be the one with the shortest cleaning time and smallest thickness reduction. The harder abrasives with smaller particles sizes were confirmed to be more effective, e.g. the medium or fine slag and glass in this study.

INTRODUCTION

Historic buildings which were normally built up with masonry stones are precious finite assets and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The cleaning and restoration of these historic buildings is a crucial strategy in maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations. Stone cleaning is one of the most noticeable changes a building can be subjected to. Stone cleaning has been dated back for over 40 years, peaking in the 1970s and 80s and growing into a multimillion pound industry (Laing & Urquhart, 1997; Ball et al, 2000; Ball, 2002; Feilden, 2003). At the time, the cleaning was inappropriately aggressive, causing damage to many building façades (Andrew et al, 1994; Ashurst, 1994a, 1994b; Verhoef, 1988; Young, 2002). Inappropriately selected methods of cleaning or right methods performed by unskilled operatives can lead to permanent damage to building façades. Fig. 1 shows a historic building in Edinburgh with original dirty and cleaned stonework façades.

In Scotland, natural masonry stones bricks as building materials were widely used in the built heritage, which hence led to large demands of stone cleaning (Webster et al, 1992; Young & MacLean, 1992; McMillan, 1999; Hyslop et al, 2006). In the 1960s, the cleaning of masonry buildings for aesthetic, commercial and sociological reasons became quite common. Transforming the black-soiled limestone building into a clean and bright structure became a kind of fashion, which was started in Paris and London and followed by many other places. When it turned to sandstone, however, more aggressive cleaning methods were required in order to remove the grime as the atmospheric pollutants attached to the surfaces of sandstone are quite different from those on the limestone surfaces. These excessively aggressive methods led to great damages to the stone surfaces, removing soiling as well as the stone surface, even the sharpness of building details. In the 1970s and 80s, the chemical method of stone cleaning was utilised, reducing the damage to the stone surface from abrasive cleaning method, and stone cleaning reached its peaks. However at that time, various cleaning methods still caused permanent damage to a building. As time goes by, people have now paid more attention to this and many studies on stone cleaning have been published (Verhoef, 1988; Urquhart, 1994; Cameron et al, 1997; Pryke, 1999, 2000; Murray et al, 2000; Brimblecombe, 2003; Young et al, 2003; Khalaf et al, 2008). Cleaning methods nowadays have become more finely tuned and less aggressive because new legislations have protected listed historic buildings and conservation areas from any detrimental treatments (Mynors, 1989, 2006).

(a) Original dirty stonework façade (b) Fully cleaned stonework façade

Fig. 1 A listed building in Edinburgh with original dirty and cleaned stonework.

There are four major types of cleaning methods: water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting). Water-based cleaning methods are not effective on sandstones, bricks or terracotta for removing soiling bound to these surfaces by insoluble compounds. Water cleaning can only remove algae but severe soiling may still be present (see Fig. 2). Using water washing techniques on masonry surfaces with high natural salts, such as sandstone and brick, can mobilise the salts and lead to efflorescence. Desalination of such surfaces after cleaning has, in rare cases, been carried out by water saturation followed by drying. Much research has been done on this aspect and useful methods have been proposed, e.g. poulticing technique (Verges-Belmin & Siedel, 2005; Petkovic et al, 2007; Lubelli & van Hees, 2010; Pel et al, 2010). Chemical cleaning methods are more effective because they work by the reaction between the cleaning agent, soiling and the masonry surface to which the soiling is attached (Pombo & Nicholson, 1998; Young, 1998; Young & Urquhart, 1998). The main problems with using chemical cleaning involve the extent and efforts of the retention of chemical agents and the possible mobilisation of salts within the stone. Another problem associated with chemical cleaning is the bleaching or staining of surfaces (see Figs. 3 and 4). Because chemical cleaning damage is irreversible, it should only be used with extensive pre-testing to ensure confidently that there will be no damage to the building façade. Mechanical cleaning removes soiling from the stone surface by physical forces, cutting or abrasion through hand-held implements or mechanised equipment. Abrasives can permanently damage the masonry as they do not differentiate between the dirt and the masonry stone. Brick, architectural terracotta, soft stone, detailed carvings and polished surfaces are especially susceptible to physical and aesthetic damage by abrasive methods. Increase in surface roughening is another consequence of mechanical cleaning. The most commonly used mechanical cleaning methods include dry brushing and surface rubbing, surface addressing, etc.

(a) Before cleaning: algae and severe soiling on the external wall

(b) After cleaning: algae removed but severe soiling still present

Fig. 2 A typical masonry stone wall before and after cleaning.

(a) On the upper storey external wall

(b) On the lower storey external wall

Fig. 3 Damages caused by chemical cleaning on the masonry stone walls.

Air abrasive cleaning (sandblasting) involves a stream of compressed air directing particles of abrasive materials onto the soiled masonry surfaces. Here, cleaning is accomplished by these particles dislodging the surface layer and the dirt adhering to it. The dislodging of the dirt deposits thus takes place by the breaking up, sometimes to a depth of several millimetres, the surface layer beneath the deposits. Both dry and wet blasting methods have similar effects on clean masonry façades. The abrasive cleaning does not differentiate between removing soiling and masonry, so the effect of jetting the abrasive material is controlled by the operator. When wrongly applied, it could have a long lasting damaging effect on the building façade. It is very time-consuming and expensive to use on historic masonry buildings. It is desirable for heavy soiling as long as it does not cause harm to the fragile and friable fabric of the building. Abrasive cleaning is a quick method and is therefore usually considered for large areas of metals or masonries which have few design features. The most commonly used system is the air pressure blast equipment. Typical nozzle pressures range from 0.02 kPa to 14.0 kPa. Compressed air is fed to a pressure pot containing the abrasive and the mixture travels along a hose to a blasting gun. An alternative system to the pressure pot is the venture system 'suction gun'. This is operated by a trigger which is easily controlled by an instant response to the operator requirement. Figs. 5 and 6 illustrate the balcony and wall around the windows of a listed sandstone building in Edinburgh before and after air abrasive cleaning with slag.

(a)

(b)

(c)

(d)

Fig. 4 Damages caused by chemical cleaning on the masonry stone surfaces.

(a)

(b)

Fig. 5 Masonry stone balcony before and after air abrasive cleaning with slag.

(a) (b)

Fig. 6 Masonry stone wall around the windows before and after air abrasive cleaning with slag.

Stone cleaning always has negative effects which are beyond the removal of superficial soiling. When carried out using inappropriate methods, aggressive cleaning can largely damage masonry stones. Many of the potential effects of inappropriate cleaning will be visible immediately or within a few weeks of cleaning. However, there may be longer-term consequences with respect to the aesthetic, functional and structural integrity of the stone. So far there are no consistent standards and parameters used for assessing the degree of building cleaning, and the efficiency of various cleaning methods is largely evaluated by visual inspections and mutual agreements. There is an urgent need to search for better physical parameters for such assessments. Previous investigations were largely focused on finding the substances of the soiling on the building façade and the methods to remove these substances. The information on the chemical compositions of the soiling and their changes during masonry cleaning is still limited. Meanwhile there is a lack of systematic monitoring and assessment on the changes in the physical and chemical characteristics of masonry stones during cleaning process even though such knowledge is significantly important for understanding and improving the efficiency of building cleaning. Greyscale imaging analysis can be used for such purpose, together with the monitoring the reduction in thickness during the cleaning.

To investigate the cleaning degrees of the stone surfaces, a digital imaging analysis method, greyscale imaging analysis, was used. The mechanism of this method is to determine the grey degree of greyscale digital images converted from normal colour photos for assessing the building cleaning effectiveness. This technique has been largely used in civil engineering fields, e.g. geotechnical analysis of aggregate particles (Kuo & Freeman, 1998; Rao & Tutumluer, 2000; Chandan et al, 2004), automatic road surface detection (Treash & Amaratunga, 2000; Ghanta et al, 2012), etc. Recently, applications of imaging analysis into assessing building cleaning have been reported (Thornbush & Viles, 2004; Kapsalas et al, 2007; Papadakis et al, 2010). The authors have tried to conduct preliminary digital imaging analysis using ColorPad by adopting two physical parameters (greyscale and cleanness) to quantitatively assess the effectiveness of stone cleaning and confirmed that it is a useful and accurate method (Reza et al, 2012; Reza 2014). However, collecting data by using ColorPad is very time consuming because it could only read the greyscale values point by point.

In this study, five types of masonry stones most commonly used for historic buildings were selected, including granite, limestone, marble, yellow sandstone and red sandstone. Also, three main types, seven sub-types, of abrasives were adopted for air abrasive cleaning, including slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. All seven abrasives were either industrial by-products or natural products which were environmentally sustainable. Thus, there would be a total of thirty-five combinations. Meanwhile the thickness reductions for all cases were measured. Thus, the efficiency of air abrasive (sandblasting) cleaning on various masonry stones using various abrasives could be extensively assessed, together with the thickness reductions.

PREPARATION OF MASONRY STONE EXAMPLES

(1) Stone Samples

All five types of masonry stones were selected from those used for masonry buildings and exposed to open environmental conditions for decades with large amounts of heavy soiling and decay existing on the façades. The samples were cut into the dimensions of 50 mm × 50 mm × 25 mm from the original masonry stones and bricks using a diamond saw (see Fig. 7). The exposed surfaces of the stone samples were then cleaned to different levels with each abrasive in turn. Here an abrasive cleaning system selected included an air compressor, shot blasting cabinet and nozzle (see Fig. 8). Fig. 9 shows all five types of masonry stone samples used for greyscale imaging analysis at different cleaning stages.

Fig. 7 Cutting samples from original stones

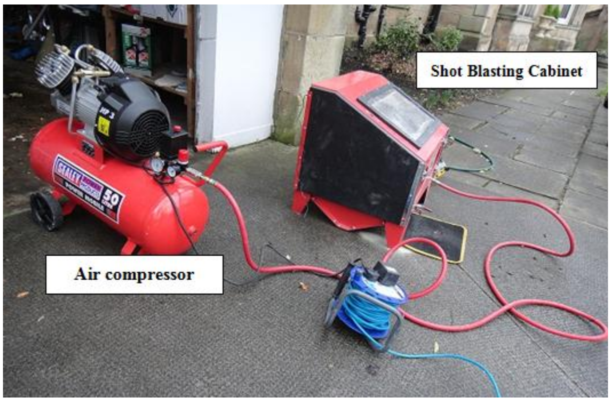
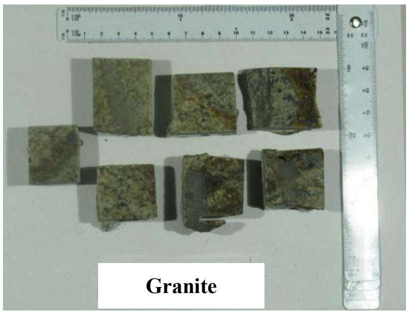
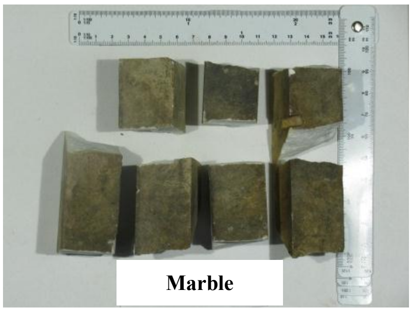


Fig. 8 The abrasive cleaning system



(a) Granite

(b) Limestone



(c) Marble

(d) Yellow sandstone

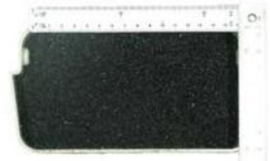
(e) Red sandstone

Fig. 9 Masonry stone samples for greyscale imaging analysis

(2) Abrasives for Air Abrasive (Sandblasting) Cleaning

Depending on the function of adopted abrasive materials, abrasive cleaning has different consequences. In this project, a total of seven types of abrasives have been adopted so as to provide a wide range of combinations: slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive, see Table 1.

Table 1 Abrasives used for sandblasting cleaning.

No	Abrasive	Sample	No	Abrasive	Sample
1	Coarse slag		4	Coarse glass	
2	Medium slag		5	Medium glass	
3	Fine slag		6	Fine glass	
			7	Natural abrasive	

Steel plant by-product slag abrasives are made from iron silicate, which forms an inert synthetic material. They do not produce chemical reactions when projected onto the stone so as to cause little dust. Glass abrasives are made from 100% recycled glass. They hold an angular shape, and produce little dust like slag. The fundamental physical properties of these two types of abrasive according to SCANGRIT (2004, 2010) are listed in Table 2. Natural abrasive, which is commercially named as *Granalla*, is a natural product composed of grains of coconut and almond shell. It has a slightly angular and polyhedral shape, giving a less satisfactory performance. The main physical properties of this abrasive are also illustrated in Table 2 (MPA, n.d.).

From the sieve tests, the fineness moduli (FM_{pre}) of all seven abrasives were obtained (CRD, 1980; Neville, 1995) and are also listed in Table 2, which shows that coarse recycled glass is the coarsest with FM = 6.37, natural abrasive is the finest with FM = 3.97, and the rest lie in-between with FM = 4.39 to 5.98. Slag abrasives are the heaviest and toughest and are followed by glass abrasives, with natural abrasive being the lightest and softest. Impact tests were also conducted on all seven abrasives (BSI, 2012), and the corresponding FM values (FM_{post}) were measured and listed in Table 2. In general, all FM values decreased after the impact tests due to finer particles produced during the tests. Natural abrasive sustained the largest drop in FM, followed by recycled glass abrasives; while slag abrasive sustained the least drop. This confirms that natural abrasive was the softest and slag abrasives were the hardest, with glass abrasives in-between. Fig. 10 illustrates the sieve test results, percentage passing rate versus sieve size, before the impact tests for all seven abrasives. Coarse glass was the coarsest abrasive, followed by medium glass and coarse slag, while natural abrasive was the finest abrasive, followed by fine glass and fine slag, with the rest in-between, the same as assessed using the fineness modulus.

Table 2 Physical properties of the abrasives used in this study.

No	Abrasive	Particle size (μm)	$FM_{pre/post}$	Mohs' scale hardness	Bulk density (g/cm^3)
1	Coarse slag	500 to 2000	5.22/5.13	7 to 8	1.7
2	Medium slag	200 to 1700	4.89/4.85		
3	Fine slag	200 to 850	4.56/4.39		
4	Coarse glass	1000 to 2000	6.37/6.08	5 to 6	1.3
5	Medium glass	500 to 1250	5.98/5.71		
6	Fine glass	200 to 500	4.39/4.02		
7	Natural	300	3.97/3.61	3	0.7 to 0.8

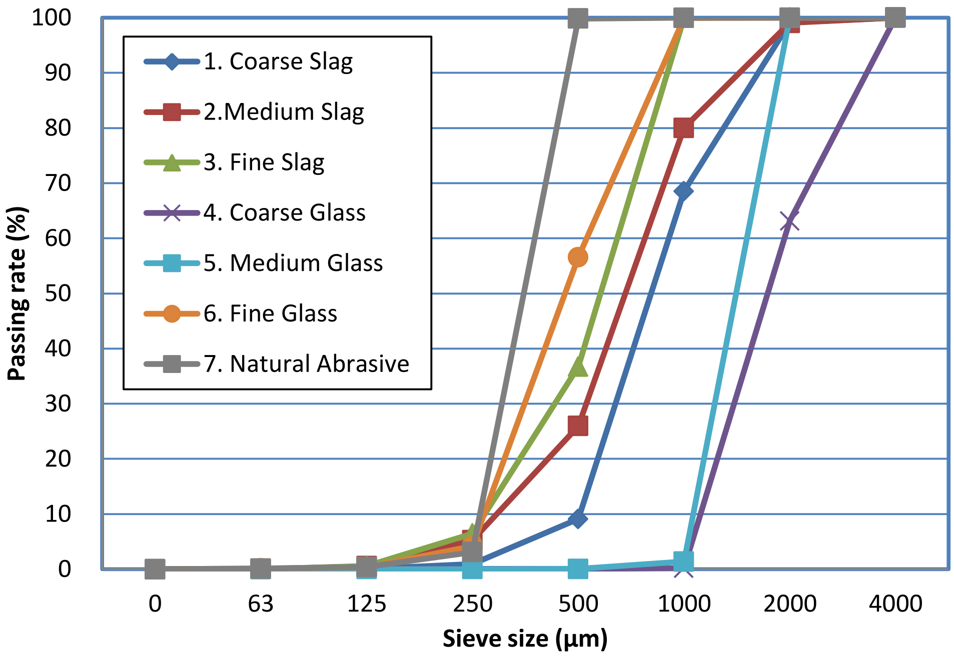


Fig. 10 Sieve test results before the impact tests for all abrasives.

DIGITAL GREYSCALE IMAGING ANALYSIS

In the preliminary digital greyscale imaging analysis (Zhang et al, 2014), all the photos were taken indoors under consistent illuminating conditions. However, during this analysis a problem was found. Because the environmental conditions during cleaning were inconsistent, inside a workshop but with the entrance door open, the images did not give unique levels of brightness. Although a frame was specially built to create constant luminosity conditions, the cleaning was conducted in the workshop lit by daylight, which affected the luminosity intensity of the images when they were taken, and also caused heterogeneous brightness. In order to solve this problem, firstly, all the images were treated using the software ColorPad (Fig. 11). This software identifies the RGB (red, green and blue) values of a selected area on the image. These values show the degree of combination of these three primary colours, each varying between 0 and 255, where 0 represents the darkest black colour and 255 represents the brightest white colour.

In order to quantitatively assess the colour changes of the stone samples, the background white paper is used as reference colour during the analysis. With the help of this software, the background brightness of all the images was adjusted, adjusting the red value at 200 as a reference point. Thereafter, these colour pictures were converted into greyscale images using Adobe Photoshop 6. The greyscale, like RGB, has a set of definition values, ranging from 0 to 255, as indicated in Fig. 12.

Since not all the samples had the same dimensions, their central areas of 2 cm × 2 cm were used for the greyscale imaging analysis. This standardisation of the area would allow all the images to be compared.

There would be four separate steps next. The original images were scaled and orientated. An area inside was selected by drawing a red frame on the image, which was then cropped. Finally, the cropped area was converted into the greyscale image. Fig. 13 shows a typical example of this procedure, which was then applied to all the images of 35 stone samples at different cleaning stages.

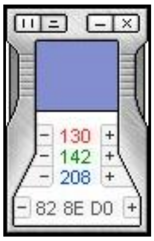
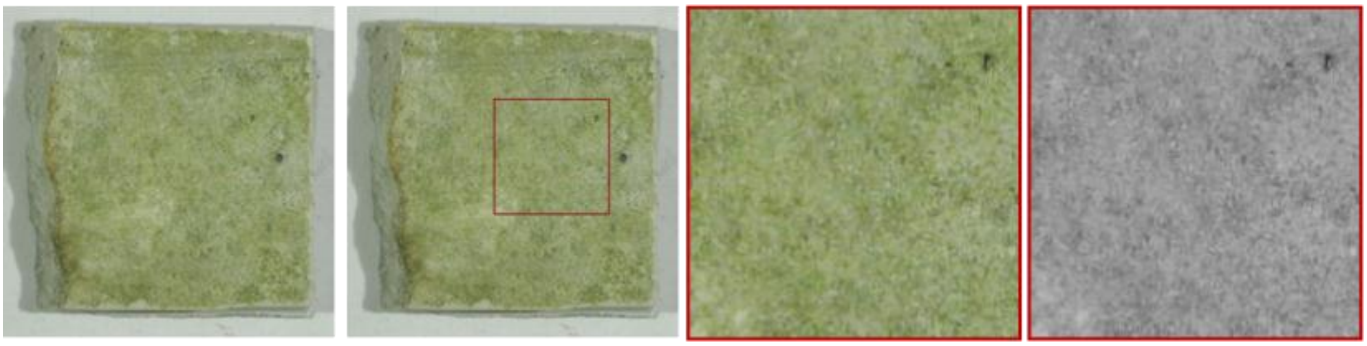


Fig. 11 ColorPad

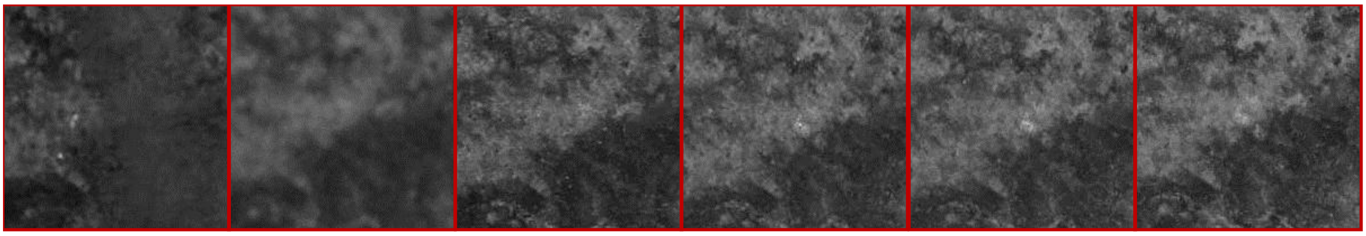
Fig. 12 Greyscale spectrum



(a) Colour photo (b) Selected area (c) Cropped selected area (d) Greyscale image

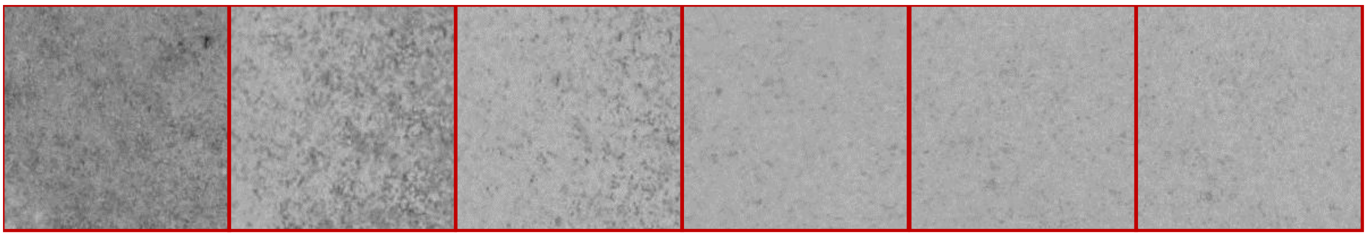
Fig. 13 Four steps for processing the image photos for limestone cleaned with fine slag.

Figs. 14 to 18 show the greyscale images of all masonry stone samples cleaned with either slag or glass abrasives at different cleaning stages, respectively. In these greyscale image photos, the first images show the original dirty surfaces and the last images show the fully cleaned surfaces. From each image the average greyscale value and standard deviation were obtained using Adobe Photoshop 6. All five sets of greyscale images indicate that the stone surfaces became gradually brighter with the progress of cleaning.



(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Cleaned

Fig. 14 Greyscale images of granite cleaned with fine glass at cleaning stages 1 to 6.



(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Cleaned

Fig. 15 Greyscale images of limestone cleaned with fine slag at cleaning stages 1 to 6.

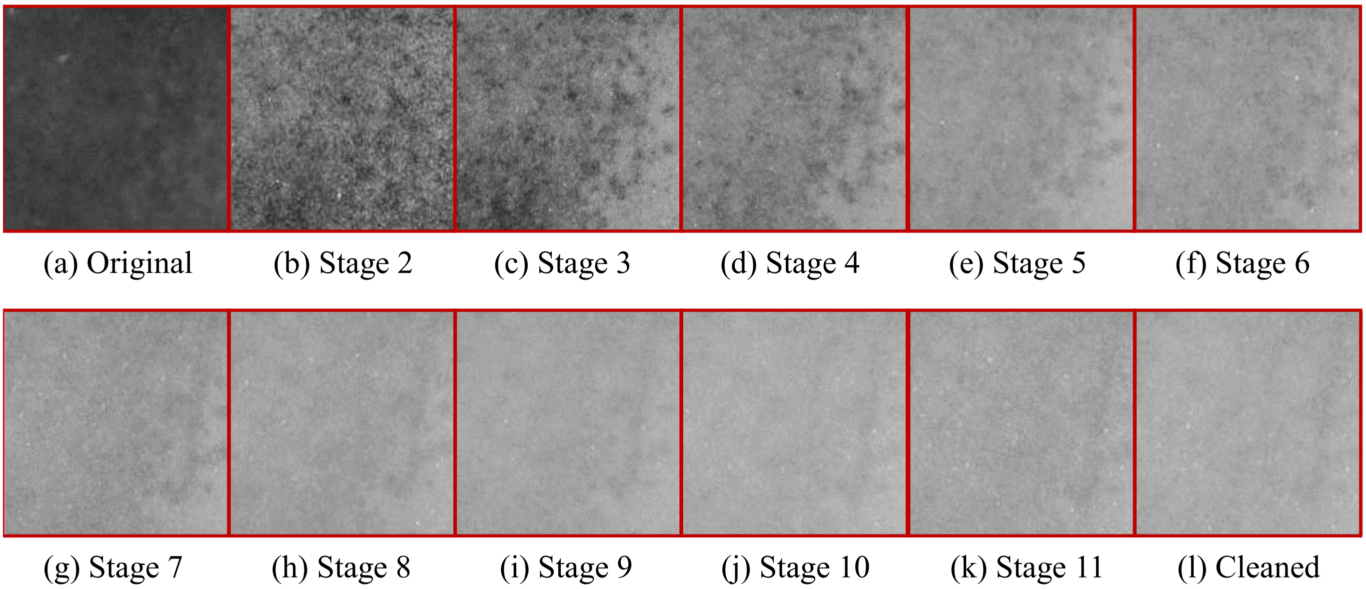


Fig. 16 Greyscale images of marble cleaned with fine glass at cleaning stages 1 to 12.

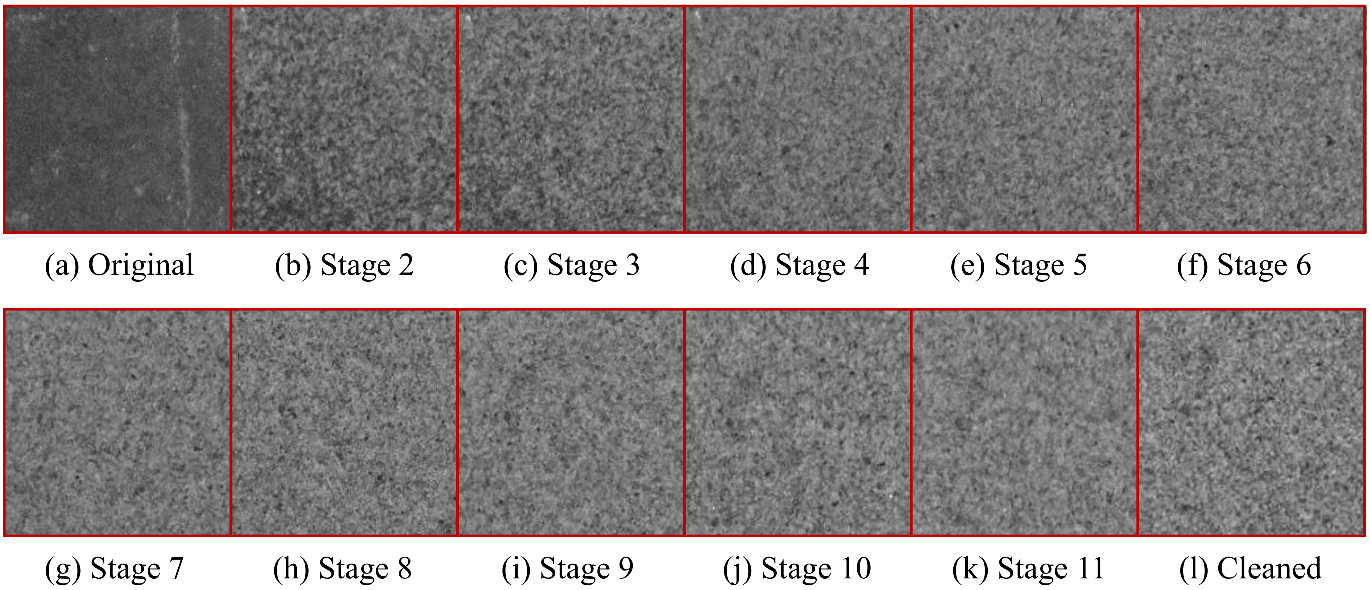
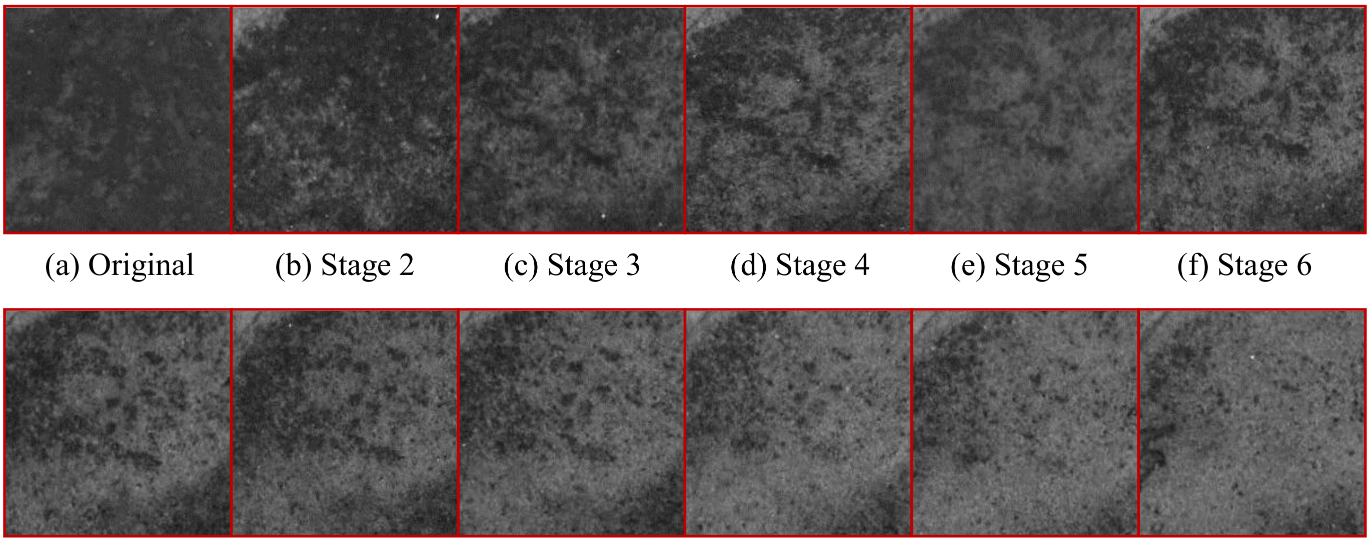


Fig. 17 Greyscale images of yellow sandstone cleaned with coarse slag at cleaning stages 1 to 12.

Figs. 19 to 23 show the relationships between the greyscale GS and the cleaning time t for the above mentioned five types of masonry stones. Fig. 19 illustrates that a parabola well reflects the increasing trend of greyscale with the cleaning time for granite cleaned with fine glass. The data and the parabola almost coincide since the R^2-value is equal to 0.964 which is very close to 1.0. Greyscale increased with the cleaning time from GS = 54.83 before cleaning at a decreasing rate and became stable at GS = 79.24 when the sample was fully cleaned after 10 seconds, up by 24.41 in GS or 44.5%. It seems that only 6 seconds corresponding to GS = 76.80 may be enough to largely clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was quite big, which indicates that the surface of the original granite was very dirty. Fig. 20 shows that a parabola can represent the increasing trend of greyscale with the cleaning time for limestone cleaned with fine slag. The data and the parabola almost coincide with R^2 = 0.965. Greyscale increased with the cleaning time from GS = 134.85 before cleaning at a decreasing rate and finally became stable at GS = 171.99 when the sample was fully cleaned after 10 seconds, up by 37.14 in GS or 27.5%. It seems that only 4 seconds corresponding to GS = 168.86 may be enough for almost fully cleaning this sample. The gap in greyscale values between the original dirty and fully cleaned states was not quite big, which indicates that the surface of the original granite was not very dirty.



(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Stage 6

(g) Stage 7 (h) Stage 8 (i) Stage 9 (j) Stage 10 (k) Stage 11 (l) Cleaned

Fig. 18 Greyscale images of red sandstone cleaned with fine glass at cleaning stages 1 to 12.

Fig. 21 shows that a parabola well reflects the increasing trend of greyscale with the cleaning time for marble cleaned with fine glass. The data and the parabola almost coincide with R^2 = 0.950. Greyscale increased with the cleaning time from GS = 68.09 before cleaning at a decreasing rate and finally became stable at GS = 172.81 when the sample was fully cleaned after 25 seconds, up by 104.72 in GS or 153.8%. It seems that it would take about 18 seconds, corresponding to GS = 171.85, to almost fully clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was huge, indicating that the surface of the original marble was extremely dirty. Fig. 22 illustrates that a parabola can represent the increasing trend of greyscale with the cleaning time for yellow sandstone cleaned with coarse slag, with R^2 = 0.827. Greyscale increased with the cleaning time from GS = 81.14 before cleaning at a decreasing rate and finally became stable at GS = 124.51 when the sample was fully cleaned after 180 seconds, up by 43.37 in GS or 53.5%. It seems that it would take about 100 seconds, corresponding to GS = 120.23, to almost fully clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was reasonably large, which indicates that the surface of the original yellow sandstone was quite dirty. Finally, Fig. 23 shows that a parabola well matches the increasing trend of greyscale with the cleaning time for red sandstone cleaned with fine glass. The data and the parabola almost coincide with R^2 = 0.959. Greyscale increased with the cleaning time from GS = 58.56 before cleaning at a decreasing rate and finally became stable at GS = 93.84 when the sample was fully cleaned after 80 seconds, up by 35.28 or 60.2%. It seems that 50 seconds, corresponding to GS = 90.94, may be enough for almost fully cleaning this sample. The gap in greyscale values between the original dirty and fully cleaned states was huge, indicating that the surface of the original red sandstone was very dirty.

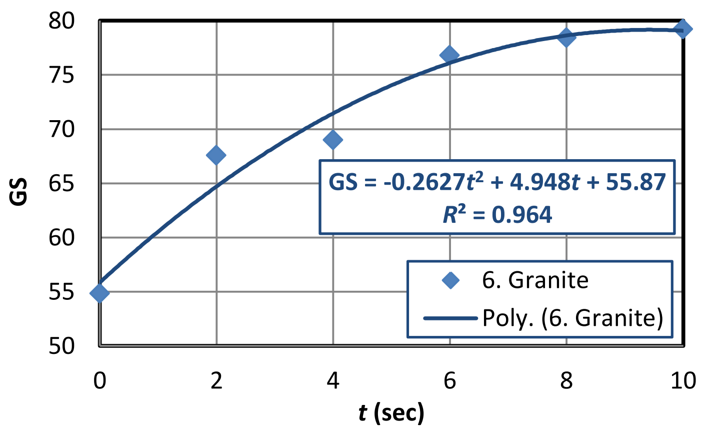


Fig. 19 Greyscale versus cleaning time for granite cleaned with fine glass.

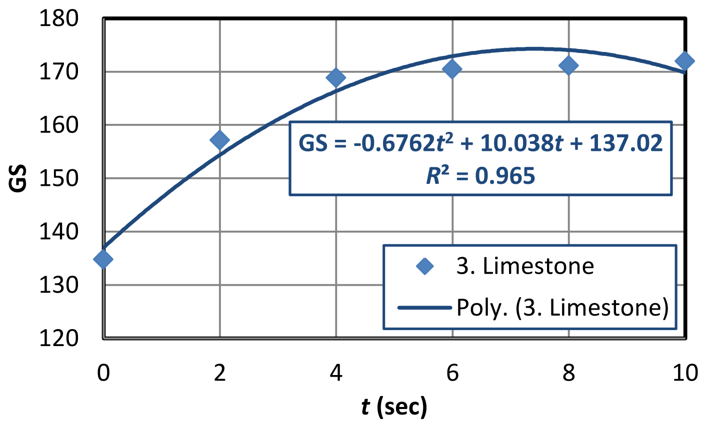


Fig. 20 Greyscale versus cleaning time for limestone cleaned with fine slag

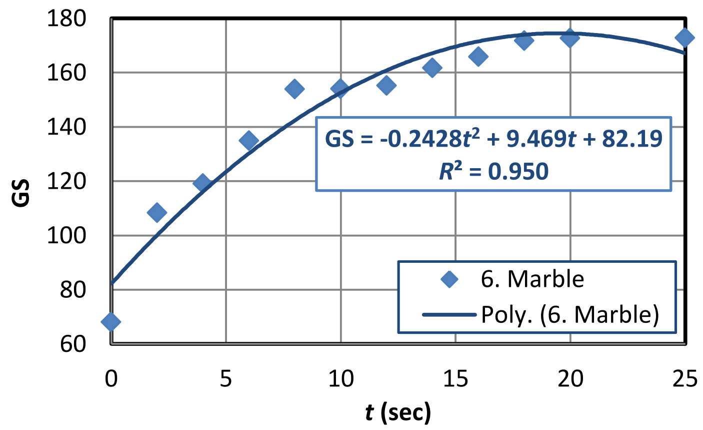


Fig. 21 Greyscale versus cleaning time for marble cleaned with fine glass.

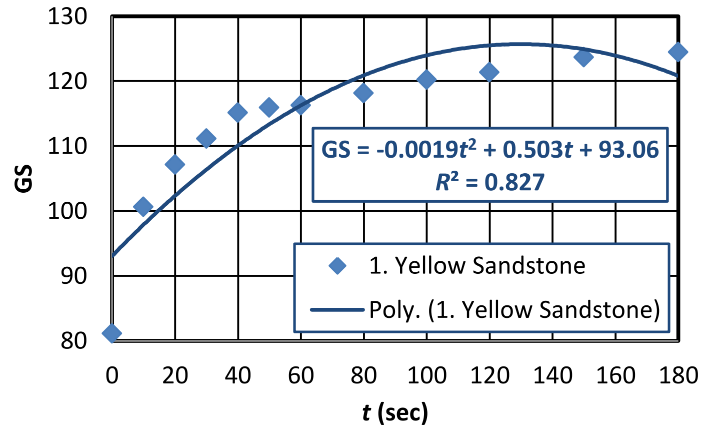


Fig. 22 Greyscale versus cleaning time for yellow sandstone cleaned with coarse slag.

Table 3 lists the total cleaning time t_{tot}, initial greyscale GS_{ini}, final greyscale GS_{fin}, change in greyscale ΔGS and total thickness deduction Δa for all types of masonry stones cleaned with seven different abrasives. The average values of the listed parameters except the total cleaning time, together with the corresponding standard deviations, are also listed in Table 3. For each type of stone, the initial greyscale values which represent the original dirty degree varied largely because the soiling states on the surfaces of the stone samples were different. For example, the greyscale for granite varied from 49.05 to 70.98, with an average of 60.18 and a standard deviation of 8.03, giving a smallest variation coefficient of 13.35%. On contrast, the greyscale for yellow sandstone varied from 53.50 to 97.12, with an average of 69.17 and a standard variation of 18.85, giving a largest variation coefficient of 27.25%. The variations in the original greyscale values for the rest stones lay in-between.

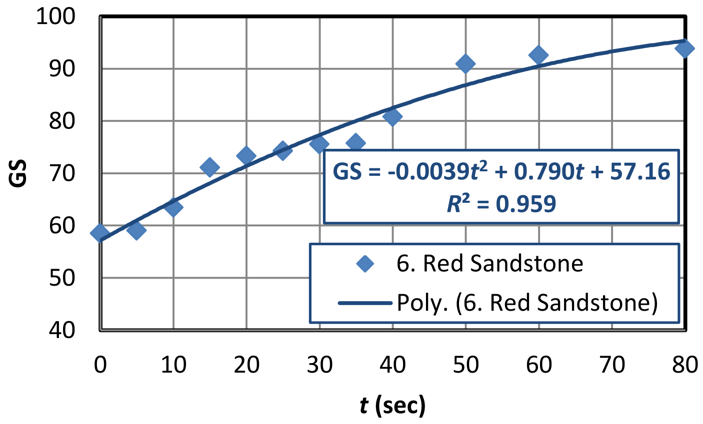


Fig. 23 Greyscale versus cleaning time for red sandstone cleaned with fine glass.

According to the final greyscale values from small to large, the original colours of the five masonry stones can be ranked, from dark to bright, as granite (GS = 75.23), red sandstone (GS = 95.46), yellow sandstone (GS = 115.64), limestone (GS = 166.29) and marble (GS = 167.98). This also indicates both marble and limestone were the brightest while the marble was the darkest, with the rest stones in-between. According to the percentage ratios of the greyscale changes to the final greyscale values, the dirty degrees of the five masonry stones can be ranked, from dirty to bright, as marble (58.32%), red sandstone (43.53%), yellow sandstone (40.19%), limestone (33.24%) and granite (20.01%). This indicates that the original marble had the dirtiest surface, followed by the red sandstone, yellow sandstone and limestone, while the original granite had the relatively cleanest surface. The final thickness reductions indicate that granite had a smallest average thickness loss of only 0.23 mm during the cleaning process, followed by limestone (Δa = 0.37 mm), marble (Δa = 0.49 mm), and yellow sandstone (Δa = 1.13 mm), while red sandstone had a largest average thickness loss of 1.54 mm. For each type of fully cleaned stone, a smaller thickness loss indicates a more effective cleaning process or a more suitable abrasive as well. For limestone, fine glass may be the most suitable abrasive with a thickness loss of 0.10 mm, followed by medium slag (Δa = 0.19 mm), fine slag (Δa = 0.26 mm) and natural abrasive (Δa = 0.30 mm), while medium glass can be regarded as the least effective abrasive with a thickness loss of 0.67 mm. For yellow sandstone, coarse glass may be the most suitable abrasive with a thickness loss of 0.58 mm, followed by coarse slag (Δa = 0.75 mm) and natural abrasive (Δa = 0.90 mm). The rest abrasives can be regarded as the less suitable or unsuitable ones. For red sandstone, fine glass may be the most suitable abrasive with a thickness reduction of 0.95 mm, followed by medium glass (Δa = 1.08 mm) and fine slag (Δa = 1.22 mm). The rest abrasives can be regarded as the less suitable or unsuitable ones.

The greyscale values obtained using a natural abrasive were largely affected by the nature of this abrasive. Natural abrasive is a very soft material, and is composed of coconut and almond shells. After impacting on stone surfaces it easily turns into dust. This impact would leave the stone surfaces lightly smudged with a brownish colour. As a result of this, the greyscale values measured were different from those on the samples cleaned with other abrasives, e.g. limestone, marble and yellow sandstone. The extreme case is that the greyscale for red sandstone decreased with the cleaning time, down by 21.10 or 38.93% when the sample was fully cleaned after 240 seconds.

By observing the statistical analysis on the greyscale results for the granite samples, it is clear that all the R^2 values were larger than 0.93. This indicates that the parabolic relationships between greyscale and cleaning time can well predict the trends. However, the final greyscale values were not very similar. This could be due to the fact that the surface of the granite samples was polished. Hence, it is suggested that the most suitable cleaning method for polished stone surfaces may be a manual cleaning, e.g. using a sponge or a brush and washing-up liquid, instead of air abrasive cleaning. Nevertheless, samples cleaned with three recycled glasses of different sizes produced similar final greyscale values, with the differences in greyscale between the initial and final cleaning stages ranging from 18 to 25.

Table 3 Summary of greyscale results before and after cleaning with final thickness reductions.

Stone	Abrasive	t_{tot} (sec)	GS_{ini}	GS_{fin}	ΔGS	Δa (mm)
Granite	Coarse slag	10	67.54	73.54	6.00	0.32
	Medium slag	10	53.14	60.84	7.70	0.17
	Fine slag	10	49.05	62.08	13.03	0.19
	Coarse glass	50	62.68	86.83	24.15	0.31
	Medium glass	10	70.98	89.59	18.61	0.15
	Fine glass	10	54.83	79.24	24.41	0.25
	Natural	50	63.03	74.46	11.43	0.21
	Average	/	60.18	75.23	15.05	0.23
	Standard deviation	/	8.03	11.11	7.49	0.07
Limestone	Coarse slag	30	96.11	171.65	75.54	0.41
	Medium slag	12	112.26	166.36	54.10	0.19
	Fine slag	10	134.85	171.99	37.14	0.26
	Coarse glass	140	117.79	176.83	59.04	0.64
	Medium glass	14	116.18	165.11	48.93	0.67
	Fine glass	10	74.94	160.53	85.59	0.10
	Natural	140	124.95	151.59	26.64	0.30
	Average	/	111.01	166.29	55.28	0.37
	Standard deviation	/	19.83	8.40	20.55	0.22
Marble	Coarse slag	45	61.32	166.94	105.62	0.53
	Medium slag	50	56.2	159.29	103.09	0.33
	Fine slag	35	83.18	172.33	89.15	0.52
	Coarse glass*	300	54.11	175.83	121.72	0.80
	Medium glass	25	79.85	170.31	90.46	0.40
	Fine glass	25	68.09	172.81	104.72	0.39
	Natural*	900	87.38	158.37	70.99	0.43
	Average	/	70.02	167.98	97.96	0.49
	Standard deviation	/	13.51	6.81	16.11	0.16
Yellow sandstone	Coarse slag	180	81.14	124.51	43.37	0.75
	Medium slag*	540	60.43	100.01	39.58	1.38
	Fine slag*	300	53.5	105.17	51.67	1.82
	Coarse glass	210	97.12	137.94	40.82	0.58
	Medium glass*	240	43.18	120.73	77.55	1.10
	Fine glass*	240	65.58	120.94	55.36	1.37
	Natural	120	83.22	100.19	16.97	0.90
	Average	/	69.17	115.64	46.47	1.13
	Standard deviation	/	18.85	14.27	18.40	0.43
Red sandstone	Coarse slag*	180	64.04	105.91	41.87	2.00
	Medium slag*	120	43.27	91.14	47.87	1.62
	Fine slag	60	49.49	89.87	40.38	1.22
	Coarse glass*	480	45.92	93.24	47.32	1.74
	Medium glass	80	62.15	98.75	36.60	1.08
	Fine glass	80	58.56	93.84	35.28	0.95
	Natural*	240	54.20	33.10**	-21.10**	2.15
	Average	/	53.95	95.46	41.55	1.54
	Standard deviation	/	8.05	5.96	5.26	0.46

* Abrasives were not recommended. ** The results were not included in the statistical analysis.

As the time required to fully clean a stone sample is another important practical consideration due to resultant labour costs, any abrasive material that took more than 210 seconds to clean a stone sample may not be regarded to be effective for that stone since it could not produce a desirable performance. It can be seen that all seven abrasives are suitable for granite and limestone, compared with marble for which only five abrasives were suitable and both coarse glass and natural abrasive are surely not suitable choices. Furthermore, for granite, limestone and marble, all three slags, medium glass and fine glass were more effective and economical. For yellow sandstone, only coarse slag, coarse glass and natural abrasive may be good options. Finally for red sandstone, only fine slag, medium glass and fine glass are suitable choices.

CONCLUSIONS

1. In this study, advanced greyscale imaging analysis was conducted using Adobe Photoshop 6 on the surface images of the masonry stones, taken from exiting old masonry buildings, to accurately assess changes in the colour component of the stone surface during cleaning and to eventually evaluate the cleaning effectiveness.

2. Five types of masonry stones most commonly used for old masonry buildings were selected, including granite, limestone, marble, yellow sandstone and red sandstone. Also, three main types, seven sub-types, of abrasives were adopted for the air abrasive (sandblasting) cleaning, including slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive.

3. From the results for all five types of masonry stones presented here, the cleaning degrees at different stages were evaluated using the greyscale images converted from the original colour photos, where a lower greyscale was related to a dirtier and darker surface and a higher greyscale to a cleaner and brighter surface. Relationships between cleaning degree (greyscale) and cleaning time were illustrated and represented with parabolic trend lines. In general, greyscale continuously increased with the cleaning time at a decreasing rate and tended to be stable when the stone surface became fully cleaned.

4. By considering both cleaning time and thickness reduction, any abrasives with longer cleaning times or bigger thickness losses for the same cleaning degree on one type of masonry stone would be regarded to be less suitable and uneconomical for that type of stone. In general, the abrasives with better cleaning performance were those industrial by-products with smaller particles sizes, i.e. medium or fine slag and recycled glass, because the coarse abrasives and natural abrasive would consume more cleaning times and possibly cause damages to masonry stone surface features.

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Assessment of air abrasive cleaning on masonry stones using greyscale imaging techniques

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ABSTRACT: In this study, advanced greyscale imaging analysis was conducted using the Adobe Photoshop 6 on the surfaces of masonry stones, taken from listed historic buildings, to accurately assess the effectiveness of building cleaning. Seven commonly used masonry stones and clay bricks for historic buildings were selected, together with seven abrasives adopted for air abrasive cleaning, e.g. copper slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. Here, only the results for granite, limestone and marble are presented. The cleaning degree at each stage was evaluated using greyscale images converted from original colour ones, where lower greyscale corresponded to dirtier surface and higher greyscale to brighter and cleaner surface. In general, greyscale continuously increased with the cleaning time and tended to be stable when the surface became fully cleaned. The abrasives with better performance were those with smaller particles sizes, i.e. the medium and fine abrasives.

1 INTRODUCTION

Masonry stones and clay bricks have been widely used for constructing historic buildings and monuments, which become grand assets for present and future generations. The cleaning and restoration of these historic masonry structures has become significantly important (Reza et al., 2008) and has been conducted for decades in the UK due to persistent investigations on physical and chemical characteristics of masonry stones and the development of modern cleaning techniques (Ashurst, 1994a, 1994b; Laing & Urquhart, 1997; Ball et al., 2000; Feilden, 2003; Young et al., 2003). Millions of Stirling pounds have been spent every year on building cleaning and this is highly appraised by the public because of the significant effect on the appearance of the buildings and urban environment.

Masonry stones in buildings considered for cleaning vary largely in type, surface texture and architectural style and suffer from different types of natural decay and even man-made pollutions. Cleaning methods are usually destructive and cause irreversible damage. The method of removing soiling from stone façade without affecting underlying stone and causing long term damage has not been devised yet. Physical cleaning methods such as grit blasting will lead to some abrasive damage to the stone façade. Chemical cleaning method may dissolve some stone components alone with the soiling and leave chemical residues in porous stones. Some effects may become apparent many years after and large scales of stone repair and replacement are needed to resolve the problem caused by the ill-cleaning in the past. There are four major types of cleaning methods: water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting). So far there are no consistent standards and parameters used for assessing the efficiency of various building cleaning methods, and this is largely evaluated by visual inspections and mutual agreements. There is an urgent need to search for better physical parameters for such assessments. Greyscale imaging analysis can be used for such purpose.

To investigate the cleaning degrees of the surfaces of the stone samples, a digital image analysis method, greyscale imaging analysis, was used. The mechanism of this method is to determine the grey degree of greyscale digital images converted from normal colour photos for assessing the building cleaning effectiveness. This technique has been largely used in civil engineering fields, e.g. geotechnical analysis of aggregate particles (Kuo & Freeman, 1998; Rao & Tutumluer, 2000; Chandan et al., 2004), automatic road surface detection (Treash & Amaratunga, 2000; Ghanta et al., 2012), etc. However, no much research has been reported on its use for assessing building cleaning. The authors tried to conduct preliminary digital imaging analysis using ColorPad by adopting two physical parameters (greyscale and cleanness) to quantitatively assess the effectiveness of stone cleaning and proved it is a useful and accurate method (Reza et al, 2012; Reza 2014). However, collecting data by using ColorPad is very time consuming because it could only read the greyscale values point by point.

In this study, seven types of masonry stones and clay bricks most commonly used for historic buildings were selected, including granite, limestone, marble, red sandstone, yellow sandstone, red clay brick and yellow clay brick. Also, three main types, seven sub-types, of abrasives were adopted for air abrasive cleaning, including copper slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. All seven abrasives were either industrial by-products or natural products which were environmentally sustainable. Thus, there would be a total of forty-nine combinations. In this paper, only the results for granite, limestone and marble are presented.

2 PREPARATION OF STONE SAMPLES

2.1 *Stone samples*

All seven types of masonry stones and bricks were selected from those used for masonry buildings and exposed to open environmental conditions for decades with large amounts of heavy soiling and decay existing on the façades. The samples were cut into the dimensions of 50 mm × 50 mm × 25 mm from the original masonry stones and bricks using a diamond saw (Fig. 1). The exposed surfaces of the stone samples were then cleaned to different levels using each abrasive in turn. Here an abrasive cleaning system selected included an air compressor, shot blasting cabinet and nozzle (Fig. 2). Figure 3 shows the granite, limestone and marble samples used for greyscale imaging analysis at different cleaning stages.

Figure 1. Cutting samples from original stones

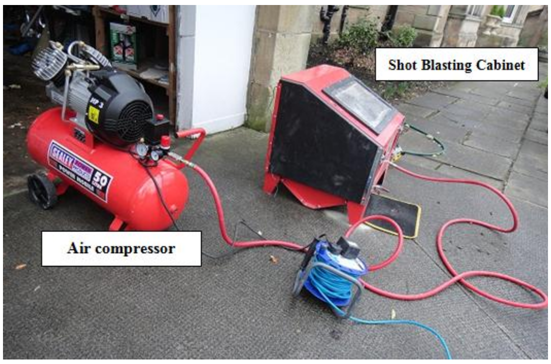


Figure 2. The abrasive cleaning system

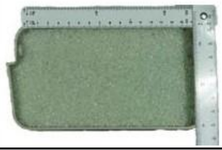
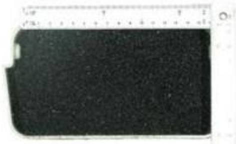
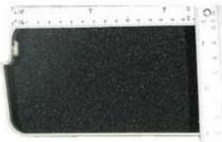
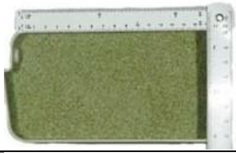
2.2 *Abrasives for sandblasting cleaning*

Depending on the function of adopted abrasive materials, abrasive cleaning has different consequences. In this project, a total of seven types of abrasives have been adopted so as to provide a wide range of combinations: copper slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive (see Table 1).

(a) Granite (b) Limestone (c) Marble

Figure 3. Masonry stone samples for greyscale imaging analysis

Table 1. Abrasives used in this study.

No	Abrasive	Sample	No	Abrasive	Sample
1	Coarse slag		4	Coarse glass	
2	Medium slag		5	Medium glass	
3	Fine slag		6	Fine glass	
			7	Natural abrasive	

Slag abrasives are made from iron silicate, which forms an inert synthetic material. They do not produce chemical reactions when projected onto the stone, and they produce little dust. Glass abrasives are made from 100% recycled glass. They hold an angular shape, and produce little dust like slag. The fundamental physical properties of these two types of abrasive according to SCANGRIT (2004, 2010) are listed in Table 2. Natural abrasive, which is commercially named as *Granalla*, is a natural product composed of grains of coconut and almond shell. It has a slightly angular and polyhedral shape, giving a less satisfactory performance. The main physical properties of this abrasive are also shown in Table 2 (MPA n.d.).

From the sieve tests, the fineness moduli (FMs) of all seven abrasives were obtained (CRD, 1980) and are also listed in Table 2, which shows that coarse recycled glass is the coarsest with FM = 6.37, natural abrasive is the finest with FM = 3.97, and the rest lie in-between with FM = 4.39 to 5.98. Slag abrasives are the heaviest and toughest and are followed by glass abrasives, with natural abrasive being the lightest and softest.

Table 2. Physical properties of the abrasives used in this study.

No	Abrasive	Particle size (μm)	FM	Mohs' scale hardness	Bulk density (g/cm^3)
1	Coarse slag	500 to 2000	5.22		
2	Medium slag	200 to 1700	4.89	7 to 8	1.7
3	Fine slag	200 to 850	4.56		
4	Coarse glass	1000 to 2000	6.37		
5	Medium glass	500 to 1250	5.98	5 to 6	1.3
6	Fine glass	200 to 500	4.39		
7	Natural	300	3.97	3	0.7 to 0.8

3 DIGITAL GREYSCALE IMAGING ANALYSIS

In the preliminary digital greyscale imaging analysis (Zhang et al., 2014), all the photos were taken indoors under consistent illuminating conditions. However, during this analysis a problem was found. Because the environmental conditions during cleaning were inconsistent, inside a workshop but with the entrance door open, the images did not give unique levels of brightness. Although a frame was specially built to create constant luminosity conditions, the cleaning was conducted in the workshop lit by daylight, which affected the luminosity intensity of the images when they were taken, and also caused heterogeneous brightness. In order to solve this problem, firstly, all the images were treated using the software ColorPad (Fig. 4). This software identifies the RGB (red, green and blue) values of a selected area on the image. These values show the degree of combination of these three primary colours, each varying between 0 and 255, where 0 represents the darkest black colour and 255 represents the brightest white colour. In order to quantitatively assess the colour changes of the stone samples, the background white paper is used as reference colour during the analysis. With the help of this software, the background brightness of all the images was adjusted, adjusting the red value at 200 as a reference point. Thereafter, these colour pictures were converted into greyscale images using Adobe Photoshop 6. The greyscale, like RGB, has a set of definition values, ranging from 0 to 255, as indicated in Figure 5.

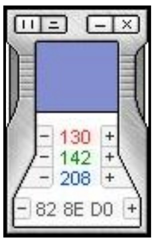


Figure 4. ColorPad

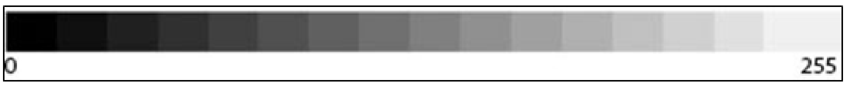
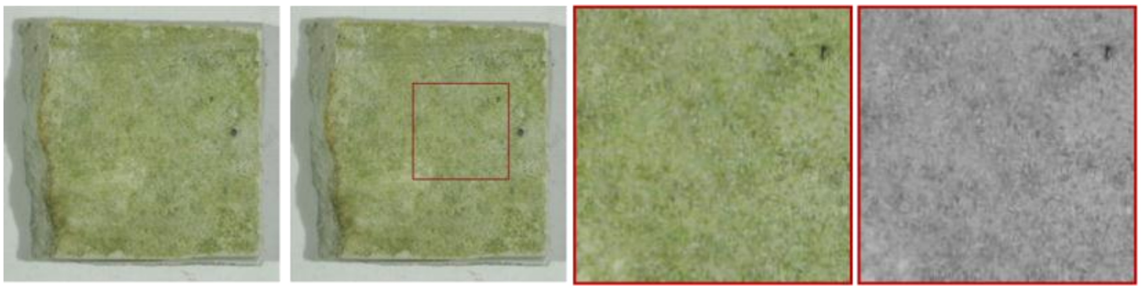


Figure 5. Greyscale spectrum

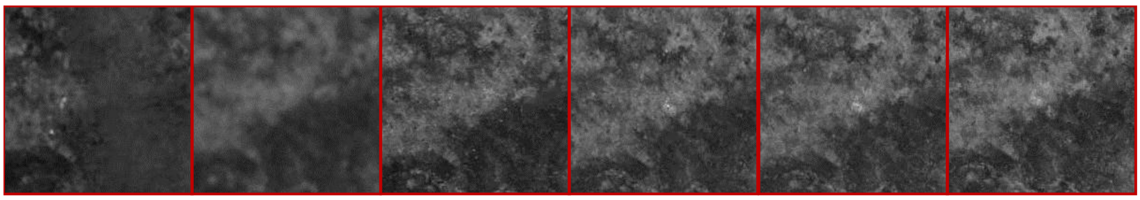
Since not all the samples had the same dimensions, their central areas of 2 cm × 2 cm were used for the greyscale imaging analysis. This standardisation of the area would allow all the images to be compared. There would be four separate steps next. The original images were scaled and orientated. An area inside was selected by drawing a red frame on the image, which was then cropped. Finally, the cropped area was converted into the greyscale image. Figure 6 shows a typical example of this procedure, which was then applied to all the images of 21 stone samples at different cleaning stages.

Figures 7 and 8 show the greyscale images of Granite and Limestone samples cleaned using fine glass and fine slag, at six cleaning stages, respectively. Figure 9 shows the greyscale images of Marble samples cleaned using fine glass, at twelve cleaning stages. The surface on the last image can be regarded as 100% clean. From each image the average greyscale value and standard deviation could be obtained using Adobe Photoshop 6. All three sets of greyscale images indicate that the stone surfaces became gradually brighter with the progress of cleaning.



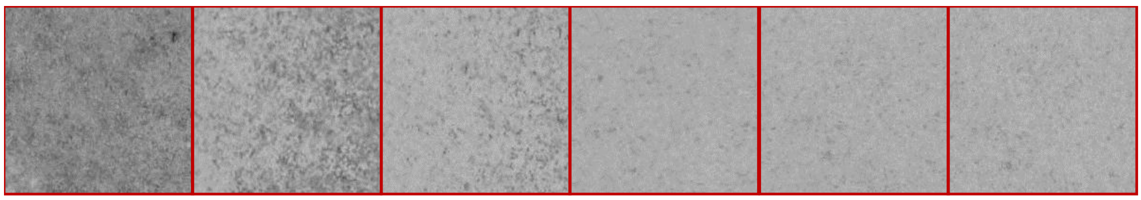
(a) Colour photo (b) Selected area (c) Selected area (d) Greyscale image

Figure 6. Four steps for processing the image photos for Limestone cleaned with fine slag



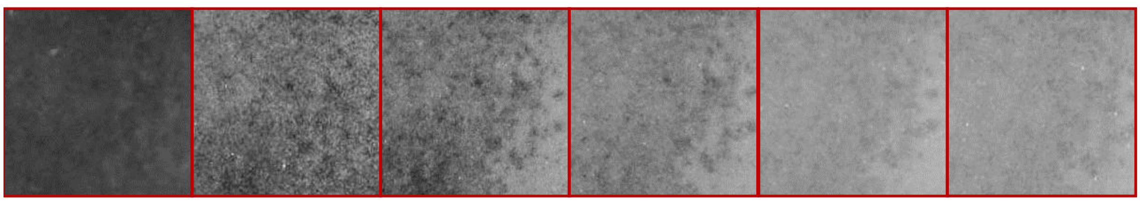
(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Cleaned

Figure 7. Greyscale images of Granite cleaned with fine glass at cleaning stages 1 to 6

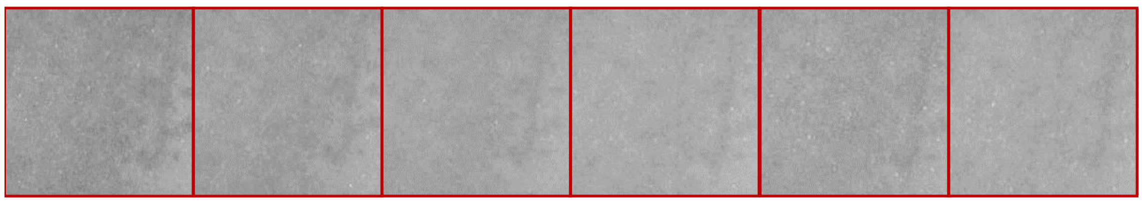


(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Cleaned

Figure 8. Greyscale images of Limestone cleaned with fine slag at cleaning stages 1 to 6



(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Stage 6



(g) Stage 7 (h) Stage 8 (i) Stage 9 (j) Stage 10 (k) Stage 11 (l) Cleaned

Figure 9. Greyscale images of Marble cleaned with fine glass at cleaning stages 1 to 12

Figures 10 to 12 show the relationships between the greyscale GS and the cleaning *t* for the above mentioned three masonry stones. Figure 10 illustrates that a parabola could well reflect the increasing trend for greyscale with cleaning time for Granite cleaned with fine glass. The data and the parabola almost coincide since the R^2-value is equal to 0.964 which is very close to 1.0. Greyscale increased with the increasing cleaning time from GS = 54.83 before cleaning at a decreasing rate and became stable at GS = 79.24 when it was fully cleaned after 10 seconds, up by 24.41 in GS or 44.5%. It seems that only 6 seconds corresponding to GS = 76.80 might be enough to largely clean this sample. As the gap in greyscale values between the original dirty and fully cleaned states was quite big, this indicates that the surface of the original granite was very dirty. Figure 11 illustrates that a parabola could reflect the increasing trend of greyscale with cleaning time for Limestone cleaned with fine slag. The data and the parabola almost coincide since the R^2-value is equal to 0.965. Greyscale increased with the increasing cleaning time from GS = 134.85 before cleaning at a decreasing rate and finally became stable at GS = 171.99 when it was fully cleaned after 10 seconds, up by 37.14 in GS or 27.5%. It seems that only 4 seconds corresponding to GS = 168.86 might be enough for almost fully cleaning this sample. As the gap in greyscale values between the original dirty and fully cleaned states was not quite big, this indicates that the surface of the original granite was not very dirty. Figure 12 illustrates that a parabola can also reflect the increasing trend for greyscale with cleaning time for Marble cleaned with fine glass. The data and the parabola almost coincide with R^2 = 0.950. Greyscale increased with the increasing cleaning time from GS = 68.09 before cleaning at a decreasing rate and finally became stable at GS = 172.81 when it was fully cleaned after 25 seconds, up by 104.72 in GS or 153.8%. It seems that it would take about 18 seconds, corresponding to GS = 171.85, to almost fully clean this sample. As the gap in greyscale values between the original dirty and fully cleaned states was huge, this indicates that the surface of the original marble was extremely dirty. The greyscale values at the final fully cleaned state indicate that both Limestone and Marble were almost the same bright but Granite was very dark. Based on the times spent on full cleaning, it can also be seen that the soiling on Marble was toughest to be removed, compared with that on Granite and Limestone.

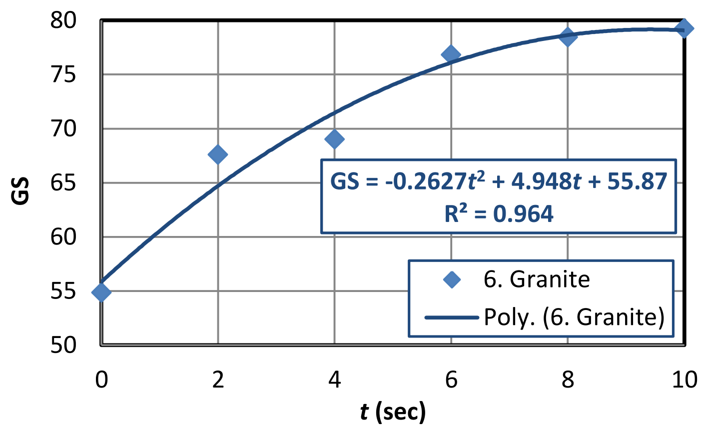


Figure 10. Greyscale versus cleaning time for Granite cleaned with fine glass

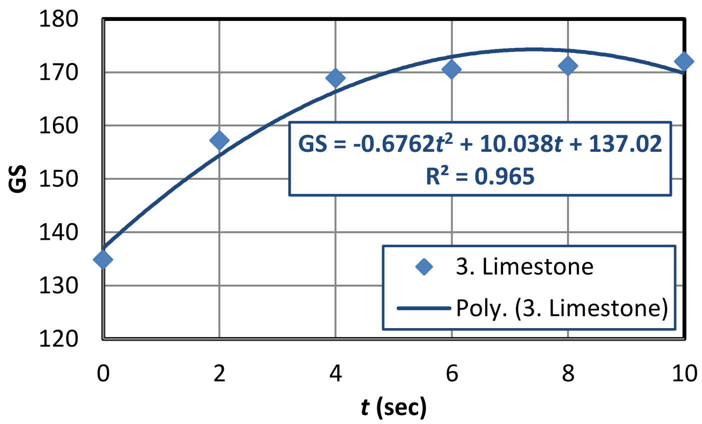


Figure 11. Greyscale versus cleaning time for Limestone cleaned with fine slag

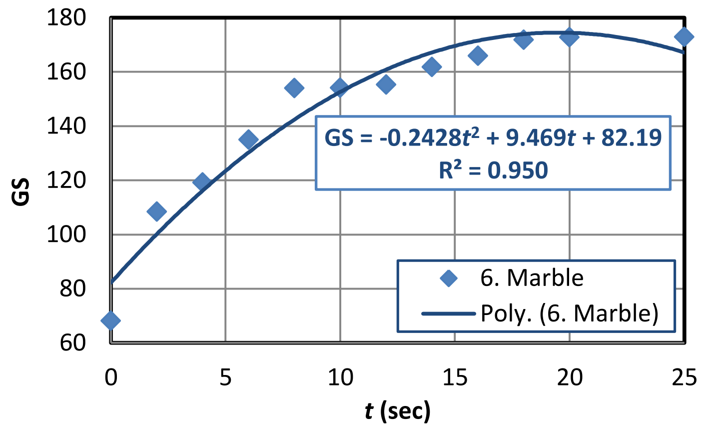


Figure 12. Greyscale versus cleaning time for Marble cleaned with fine glass

Table 3 lists the total cleaning time t_{tot}, initial greyscale GS_{ini}, final greyscale GS_{fin} and change in greyscale ΔGS for Granite, Limestone and Marble cleaned using seven different abrasives. The initial greyscale values varied largely for each type of stone because the soiling states on stone surfaces were different.

Table 3. Summary of greyscale results before and after cleaning.

Stone	Abrasive	t_{tot} (sec)	GS_{ini}	GS_{fin}	ΔGS
Granite	Coarse slag	10	67.54	73.54	6.00
	Medium slag	10	53.14	60.84	7.70
	Fine slag	10	49.05	62.08	13.03
	Coarse glass	50	62.68	86.83	24.15
	Medium glass	10	70.98	89.59	18.61
	Fine glass	10	54.83	79.24	24.41
	Natural	50	63.03	74.46	11.43
	Average	/	60.18	75.23	15.05
Limestone	Coarse slag	30	96.11	171.65	75.54
	Medium slag	12	112.26	166.36	54.10
	Fine slag	10	134.85	171.99	37.14
	Coarse glass	140	117.79	176.83	59.04
	Medium glass	14	116.18	165.11	48.93
	Fine glass	10	74.94	160.53	85.59
	Natural	140	124.95	151.59	26.64
	Average	/	111.01	166.29	55.28
Marble	Coarse slag	45	61.32	166.94	105.62
	Medium slag	50	56.2	159.29	103.09
	Fine slag	35	83.18	172.33	89.15
	Coarse glass	300*	54.11	175.83	121.72
	Medium glass	25	79.85	170.31	90.46
	Fine glass	25	68.09	172.81	104.72
	Natural	900*	87.38	158.37	70.99
	Average	/	70.02	167.98	97.96

* Abrasives were not suitable.

4 DISCUSSION

From Figure 3, the original colours for the same type of stone were different because biological crust non-uniformly deposited on the stone surfaces. For example, the limestone sample to be cleaned with fine slag was much brighter (GS = 134.85) than the limestone sample to be cleaned with fine glass (GS = 74.94). However, the greyscale values for each type of stone at the final cleaning stage were fairly similar for the majority of the samples. Typically, the final greyscale values for the Granite samples varied from 60.84 to 89.59, with an average of 75.23 and a standard deviation of 11.11. The final greyscale values for the Limestone samples varied from 151.59 to 176.83, with an average of 166.29 and a standard deviation of 8.40. The final greyscale values for the Marble samples varied from 158.37 to 175.83, with an average of 167.98 and a standard deviation of 6.81. The final greyscale values for Limestone and Marble were very close, 166.29 versus 167.98. However, the initial greyscale values and the changes in greyscale were largely different, 111.01 and 55.28 for Limestone and 70.02 and 97.96 for Marble, which confirms the original surface of Marble was much dirtier than that of Limestone.

The greyscale values obtained by using a natural abrasive were largely affected by the nature of this abrasive. Natural abrasive is a very soft material, and is composed of coconut and almond shells. After impacting on stone surfaces it easily turns into dust. This impact would leave the stone surfaces lightly smudged with a brownish colour. As a result of this, the greyscale values measured were different from those on the samples, e.g. Limestone and Marble, cleaned with other abrasives. This may not be true for Granite because its original colour was very dark.

By observing the statistical analysis on the greyscale results for the granite samples, it is clear that all the R^2 values were larger than 0.93 and some were very close to 1.0. Therefore, the parabolic relationships between greyscale and cleaning time may well predict the varying trends. However, the final greyscale values were not very similar. This could be due to the fact that the surface of the granite samples was polished. Hence, it is suggested that the most suitable cleaning method for polished stone surfaces may be a manual cleaning, e.g. using a sponge or a brush and washing-up liquid, instead of air abrasive cleaning. Nevertheless, samples cleaned with three recycled glasses of different sizes produced similar final greyscale values, with the differences in greyscale between the initial and final cleaning stages ranging from 18 to 25.

Finally, Table 3 also confirms the suitability of abrasive types for masonry stones. As the time required to fully clean each stone sample is an important practical consideration due to resultant labour costs, any abrasive material that took more than 210 seconds to clean a stone sample will not be considered being suitable for that stone since it could not produce a desirable performance. It can be seen that all seven abrasives are suitable for Granite and Limestone, compared with Marble for which only five abrasives were suitable. Furthermore, for Granite, all three slags, medium glass and fine glass were more economical. For Limestone, medium/fine slag and glass showed better performance. For Marble, medium and fine glass may be good options but surely coarse glass and natural abrasive are not suitable choices.

5 CONCLUSIONS

In this study, advanced greyscale imaging analysis was conducted using Adobe Photoshop 6 on the surface images of the masonry stones, taken from exiting listed historic buildings, to accurately assess changes in the colour component of the stone surface during cleaning and to eventually evaluate the cleaning effectiveness.

Seven types of masonry stones and clay bricks most commonly used for historic buildings were selected, including granite, limestone, marble, red sandstone, yellow sandstone, red clay brick, and yellow clay brick. Also, three main types, seven sub-types, of abrasives were adopted for the air abrasive cleaning, including copper slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive.

From the results for granite, limestone and marble presented here, the cleaning degrees at different stages were evaluated using the greyscale images converted from the original colour photos, where a lower greyscale was related to a dirtier surface and a higher greyscale to a brighter and cleaner surface. Relationships between cleaning degree (greyscale) and cleaning time were illustrated. In general, greyscale continuously increased with the increasing cleaning time and tended to be stable when the surface became fully cleaned. Any abrasives with longer cleaning times for the same cleaning degree on one type of masonry stone would be regarded to be less suitable for that type of stone. The abrasives with a better performance were those industrial by-products with smaller particles sizes, i.e. medium/fine slag and recycled glass, because the coarse abrasives and natural abrasive would consume more cleaning times.

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Investigations of Physical and Chemical Characteristics of Masonry Stones and Bricks during Building Cleaning: Part 1. Physical Testing

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Abstract: This series of study focused on analysing and assessing the changes of the physical and chemical characteristics of the surfaces of the masonrystones and bricks during the sandblasting cleaning process by conducting various physical and chemical tests. Seven masonry stones and bricks were adopted, including yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. The physical testing included evaluating the cleaning degree, determining the Vickers hardness, and detecting the water absorption. Using a digital imaging analysis method, the greyscale and cleanness were introduced to quantitatively assess the effectiveness of masonry building cleaning and confirmed to be useful and appropriate. The cleanness analysis, together with the hardness and water absorption tests showed that a masonry stone or a brick with a higher cleaning degree corresponded to a brighter and harder stone surface. In general, the physical properties were found to vary largely during the building cleaning.

Key words: Masonry stone and brick, sand blasting cleaning, greyscale, hardness, water absorption.

1. Introduction

Historic buildings and monuments are precious finite assets and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The stone cleaning and restoration of old and historic buildings is a crucial strategy in maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations. Stone cleaning is one of the most noticeable changes a building can be subjected to, which can change its appearance, persona and environmental context. A clean building can reflect well on the occupants. Stone cleaning has been dated back for over 40 years, peaking during the 1970s and 80s and growing into a multimillion pound industry [1-4]. At the time, the cleaning was inappropriately aggressive, causing damage to many building façades. Poorly or inappropriately selected methods of cleaning or the right methods performed by unskilled operatives can lead to permanent damage to building façades. The correct choice of repairing mortar for restoration work is also important to lengthen the life of stones and bricks in masonry buildings by stopping the damage due to stone decay.

A decision to clean or repair a historic building must be undertaken only if there is a strong reason to do so [5]. Preliminary investigations on both physical and chemical characteristics of the masonry stone or brick

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surfaces have to be carried out first before deciding on the best method of cleaning and the most appreciate type of mortar for repair to avoid any unnecessary damage to the building façades [6-9].

In Scotland, natural stones and bricks as building materials were widely used in the built heritage, which hence led to large demands of stone cleaning [10-12]. In the 1960s, the cleaning of masonry buildings for aesthetic, commercial and sociological reasons became quite common. At that time, transforming the black-soiled limestone building into a clean and bright structure became a kind of fashion, which was started in Paris and London and followed by many other places. When it turned to sandstone, however, more aggressive cleaning methods were required in order to remove the grime as the atmospheric pollutants attached to the surfaces of sandstone are quite different from those on the limestone surfaces. These excessively aggressive methods led to great damages on the stone surfaces, removing soiling as well as the stone surface with the sharpness of building details. During the 1970s and 80s, the chemical method of stone cleaning was utilised, reducing the damage to the stone surface from abrasive cleaning method, and stone cleaning reached its peaks. However at that time, various cleaning methods still caused permanent damage to a building. As time goes by, people have now paid more attention to this and many studies on stone cleaning have been published [8, 13-20]. Cleaning methods nowadays have become more finely tuned and less aggressive because new legislation has protected historic, listed buildings and conservation areas from any detrimental treatments [21, 22].

Masonry stones in buildings considered for cleaning vary largely in types, surface texture and architectural style and also suffer from different types of natural decay and even man-made pollutions. Cleaning methods are usually destructive and cause irreversible damage. The method of removing the soiling from the stone façade without affecting the underlying stone and causing long term damage has not been devised yet. It is discovered that physical cleaning methods such as grit blasting will lead to some abrasive damage to the stone façade. Chemical cleaning method may dissolve some stone components alone with the soiling and leave chemical residues in porous stones. Some effects may become apparent many years after and large scales of stone repair and replacement are needed to resolve the problem caused by the ill-cleaning in the past. There are four major types of cleaning methods: water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting).

When dirt is combined with gypsum ($CaSO_4$), a water soluble mineral cleaning method is usually used. It is more commonly used on calcareous surfaces such as limestone and marble. Water-based methods are not effective on sandstones, brick or terracotta for removing soiling which is bound to these surfaces by insoluble compounds. Using water washing techniques on masonry surfaces with high natural salts, such as sandstone and brick, can mobilise the salts and lead to efflorescence. Desalination of such surfaces after cleaning has, in rare cases, been carried out by water saturation followed by drying. Much research has been done on this aspect and useful methods have been proposed, e.g. poulticing technique [23-26]. Water cleaning can be further subdivided into the following categories: water jet spraying, intermittent nebulous spraying, water cleaning with pressure, steam cleaning, water cleaning with non-ionic soaps or detergents, etc., each having its own advantages and disadvantages.

Chemical cleaning methods are more effective because they work by the reaction between the cleaning agent, soiling and the masonry surface to which the soiling is attached [27-29]. Wide varieties of chemicals for cleaning masonry surfaces are available in the market, but there are two main types of chemical cleaners: acid and alkaline. The active ingredient of a cleaning agent can be a single component or a mixture and can vary largely in concentration and strength. More attention needs to be paid to selecting chemical agents, determining chemical staining, and applying chemicals to substrates. The main problems with using chemical cleaning involve the extent and efforts of the retention of chemical agents and the possible mobilisation of salts within the stone. Another problem associated with chemical cleaning is the bleaching or staining of surfaces. Chemical cleaning damage is irreversible and usually dramatic, so it should only be used with extensive pre-testing to ensure confidently that there is no damage to the building façade.

Mechanical cleaning removes soiling from the stone surface by physical forces, cutting or abrasion through hand-held implements or mechanised equipment. Abrasives can permanently damage the masonry as they do not differentiate between the dirt and the masonry stone or brick. How much material is removed depends on the masonry involved. Brick, architectural terra cotta, soft stone, detailed carvings and polished surfaces are especially susceptible to physical and aesthetic damage by abrasive cleaning methods. Increase in surface roughening is another consequence of mechanical cleaning. The most commonly used mechanical cleaning methods include dry brushing and surface rubbing, surface addressing, etc.

Air abrasive cleaning (sandblasting) involves a stream of compressed air directing particles of abrasive materials onto the soiled masonry surfaces. Here, cleaning is accomplished by these particles dislodging the surface layer and the dirt adhering to it. The dislodging of the dirt deposits thus takes place by the breaking up, sometimes to a depth of several millimetres, the surface layer beneath the deposits. Both dry and wet blasting methods have similar effects on clean masonry. The abrasive cleaning does not differentiate between removing soiling and masonry, so the effect of jetting the abrasive material is controlled by the operator. When wrongly applied, it could have a long-term damaging effect on the building façade. It is very time-consuming and expensive to use on historic buildings. It is desirable for heavy soiling as long as it does not cause harm to the fragile and friable fabric of the building. Abrasive cleaning is a quick method and is therefore usually considered for large areas of metals or masonries which have few design features. The most commonly used system is the air pressure blast equipment. Typical nozzle pressures range from 0.02 to 14.0 kPa. Compressed air is fed to a pressure pot containing the abrasive and the mixture travels along a hose to a blasting gun. An alternative system to the pressure pot is the venture system "suction gun". This is operated by a trigger which is easily controlled by an instant response to the operator requirement.

Stone cleaning always has negative effects which are beyond the removal of superficial soiling. When carried out using inappropriate methods, aggressive cleaning can largely damage stones or bricks. Many of the potential effects of inappropriate cleaning will be visible immediately after or within a few weeks of cleaning. However, there may be longer-term consequences with respect to the aesthetic, functional and structural integrity of the stone or brick. So far there are no consistent standards and parameters used for assessing the degree of building cleaning, and the efficiency of various cleaning methods is largely evaluated by visual inspections and mutual agreements. There is an urgent need to search for better physical parameters for such assessments. Previous investigations were largely focused on finding the substances of the soiling on the building façade and the methods to remove these substances. The information on the chemical compositions of the soiling and their changes during masonry cleaning is still limited. Meanwhile there is a lack of systematic monitoring and assessment on the changes in the physical and chemical characteristics of masonry stones and bricks during cleaning process even though such knowledge is significantly important for understanding and improving the efficiency of building cleaning.

In this series of study, physical and chemical characteristics of masonry stones and bricks subjected to progressive stages of cleaning were investigated for evaluating the effectiveness of building cleaning.

Physical tests included surface hardness tests and water absorption tests. The digital image analysis method based on the greyscale was used to quantitatively assess the degree of cleaning, or cleanness. Seven types of commonly used masonry stones and bricks were selected for physical tests, including yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. Some of these masonry samples were to be used for further chemical analysis. Thus, a complete evaluation procedure for building cleaning can be established.

2. Preparation of Stone Samples

Masonry stonesand brickswere selected from those for the 1860s-1870s listed buildings in the south west of the city of Edinburgh, which werepopularly used for local buildings [30] and exposed to the open environmental conditions for more than a century with large amounts of heavy soiling on the surfaces. A diamond saw was used to cut the masonry stones and bricks into small samples (Fig. 1). The exposed surfaces of the stones and bricks were cleaned into different levels using the abrasive sandblasting cleaning, and then they were cut into the required sizes for various physical and chemical tests. Here the abrasive cleaning system selected included an air compressor, a shot blasting cabinet and a blasting gun inside the cabinet (Fig. 2).

The abrasive particles used in the shot blasting cabinet are generally sand, slug, recycled glass particles and natural abrasives like coconut shells. To be environmentally friendly, recycled broken glass particles were used to clean the stone samples. Fig. 3shows three typical recycled abrasive glass particles for air abrasive cleaning. According to their particle sizeswhich varied between 125 and 1000 μm, the glass particles were classified as coarse, medium and fine glasses. Different finenesses of glass particles may largely affect the cleaning degree.

From the sieve tests, the values of the fineness modulus (FM) for these three categories were measured as 6.41, 5.98 and 4.20 for coarse, medium and fine glass particles, respectively [31]. Fig. 4 shows particle size distributions of the glass particles, which indicates that the difference in fineness between the coarse and medium glass particles was small. Preliminary tests were conducted on all three types of glass particles and fine glass was found to be the most effective abrasive material for building cleaning. In this study, the fine glass particles were hence adopted for cleaning the masonry stones and bricks.

During cleaning, the stone surfaces were gradually cleaned from fully dirty to further three different cleaning levels by controlling the sandblasting time *t* from 0 to 3, 6 and 10 s for most stones and bricks, except the yellow clay brick and granite, with the cleaning degrees estimated as 0%, 30%, 60% and 100% (Table 1).

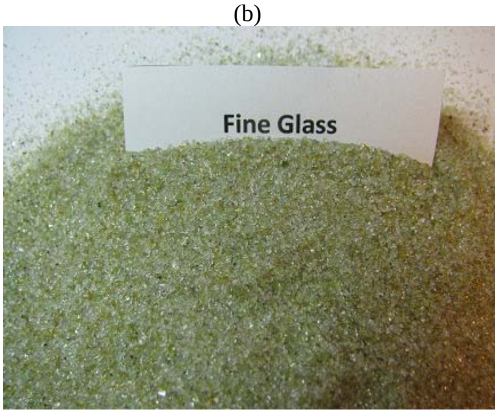
Granite had polished surface so only two stages were selected, fully dirty and fully clean. Figs. 5 to 11 show all seven types of stone and brick samples at different

Fig. 1 Samples cut from masonry stones and bricks using a diamond saw.

Fig. 2 The abrasive cleaning system.

(a)

(b)



(c)

Fig. 3 Recycled glass particles for air abrasive cleaning. (a) coarse glass; (b) medium glass and (c) fine glass.

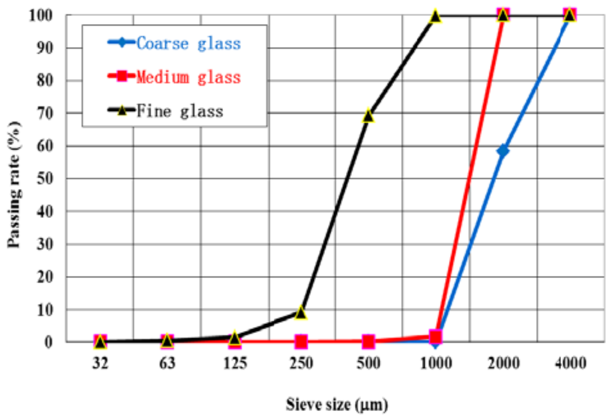
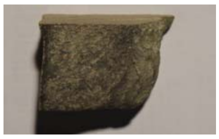


Fig. 4 Passing rates of glass particles.

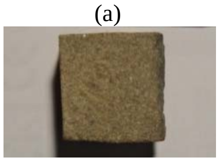
Table 1 Cleaning times for different cleaning stages.

Cleaning stage	I	II	III	IV
Yellow sandstone (s)	0	3	6	10
Red sandstone (s)	0	3	6	10
Limestone (s)	0	3	6	10
Marble (s)	0	3	6	10
Granite (s)	0	-	-	10
White clay brick (s)	0	3	6	10
Yellow clay brick (s)	0	2	4	7

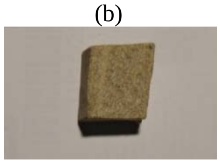


(a)

(b)

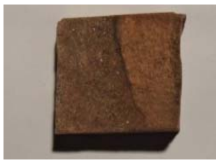


(c)



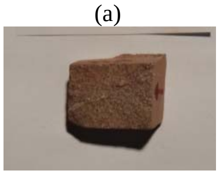
(d)

Fig. 5 Yellow sandstone samples at different cleaning stages: (a) t = 0 s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

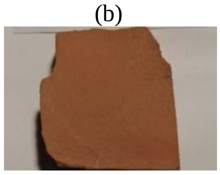


(a)

(b)



(c)



(d)

Fig. 6 Red sandstone samples at different cleaning stages: (a) t = 0 s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

cleaning stages. In general, the original dirty surfaces of stones and bricks were darker. With the progressof cleaning, these surfaces became brighter andshinier.

3. Digital Image Analysis—Greyscale and Cleanness

To explore the cleaning degrees of the surfaces ofthe masonry samples, a digital image analysis method, the greyscale method, was used. The mechanism of this method is to determine the grey degree of a grayscale digital image photo which is converted from a normal colour photo and to use it for assessing the cleaning degree. This technique has been largely used in civil

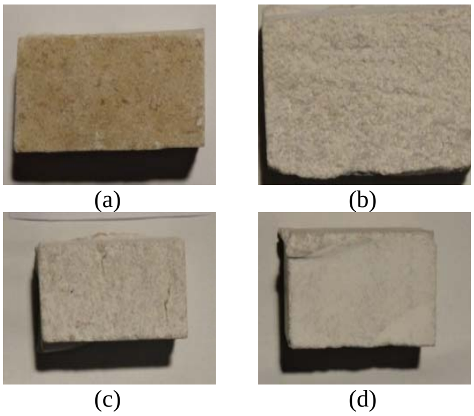


Fig. 7 Limestone samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

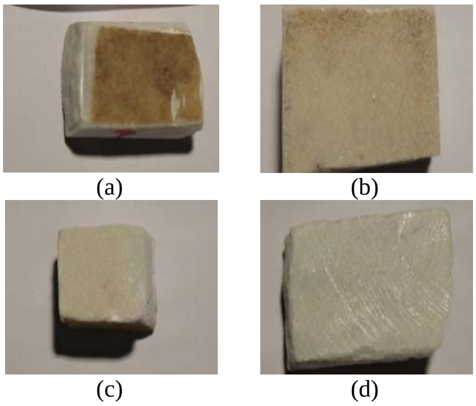


Fig. 8 Marble samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

Fig. 9 Granite samples at different cleaning stages: (a) *t* = 0 s and (b) *t* = 10 s.

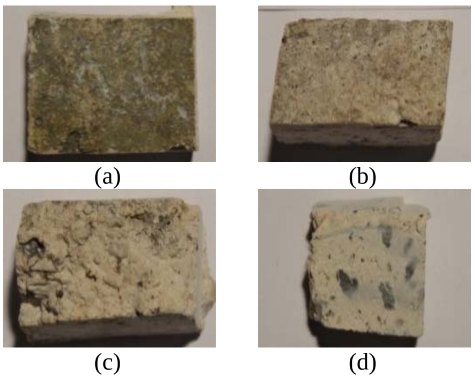


Fig. 10 White clay brick samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

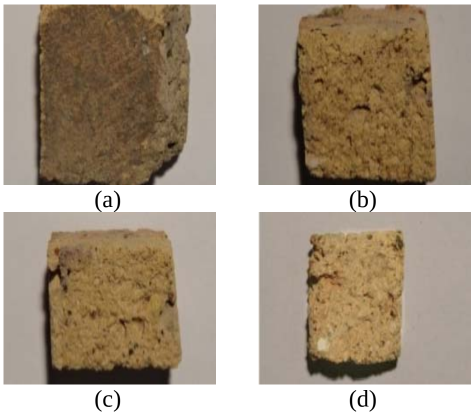


Fig. 11 Yellow clay brick samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

engineering, e.g. geotechnical analysis of aggregate particles [32-34], automatic road surface detection [35, 36], etc. However, no research is reported on its use for assessing building cleaning.

In this study, colour photos were taken indoors first. A powerful lamp, used to create parallel lights, was fixed at 1.5 m above the stone and brick samples. A Sony Cybershot DSC-T110 camera was used with the fixed 2.3 × optical zoom and at a distance of 0.5 m. All colour photos were then converted to the greyscale digital images using the Photoshop or the Microsoft WORD. These greyscale images were composed of shades of grey, scaling from 0 for pure black at the weakest intensity to 255 for pure white at the strongest intensity. Fig. 12 shows the grey level bars, and the greyscale levels which could be read using the Colorpad software are shown in Fig. 13.

3.1 Greyscale

The greyscale (GS) is used to define the colour shades of the stone or brick surfaces. An area of 1 cm^2 with a 10 × 10 grid including one hundredsampling points was placed on top of the greyscale photos and the GS values at the sampling points were read in order to obtain the surface greyness of each stone or brick sample and determined by averagingthese readings. Figs. 14 to 20 illustrate the grids placed on the top of the greyscale photos of all seven types of stone and brick samples cleaned to different levels.

Fig. 12 Grey level bars.

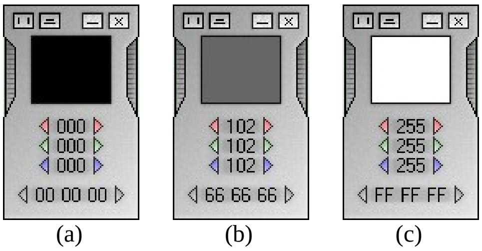


Fig. 13 Greyscale readings obtained using the Colorpad: (a) pure black; (b) grey and (c) pure white.

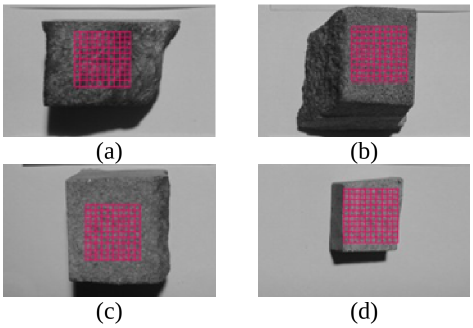


Fig. 14 Grids on the greyscale images of the yellow sandstone samples: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

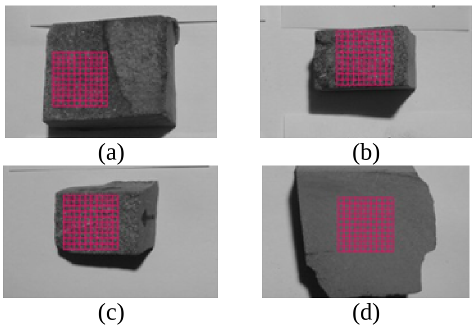


Fig. 15 Grids on the greyscale images of the red sandstone samples: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

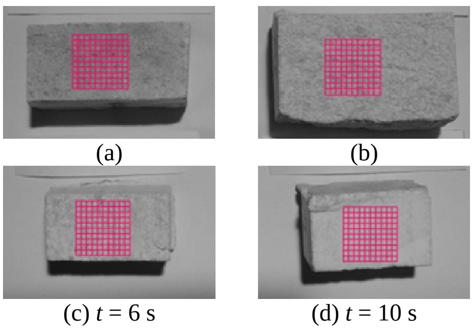


Fig. 16 Grids on the greyscale images of the limestone samples: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

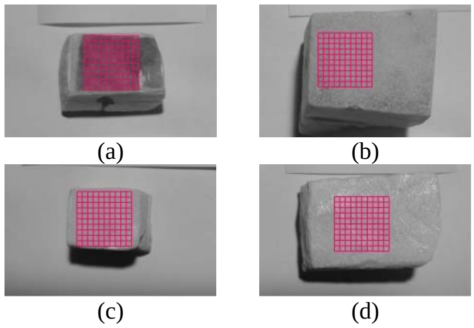


Fig. 17 Grids on the greyscale images of the marble samples: (a) *t* = 0 s (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

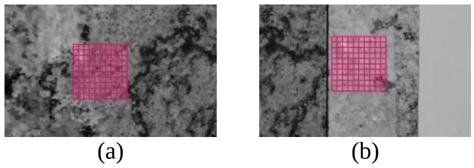


Fig. 18 Grids on the greyscale images of the granite samples: (a) *t* = 0 s and (b) fresh surface..

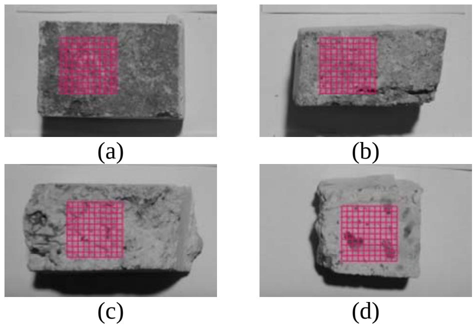


Fig. 19 Grids on the greyscale images of the white clay brick samples: (a) *t* = 0; s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

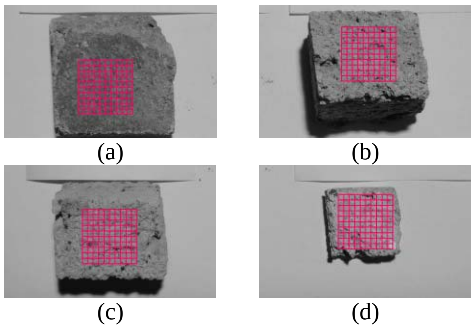


Fig. 20 Grids on the greyscale images of the yellow clay brick samples: (a) *t* = 0; s; (b) *t* = 2 s; (c) *t* = 4 s and (d) *t* = 7 s.

Table 2 lists the mean values of the greyscale for all seven types of stone and brick samples at different cleaning stages with the standard deviations in the round brackets. The differences in greyscale between

Table 2 Greyscale values for seven types of masonry stones and bricks at different cleaning stages.

Cleaning stage	Yellow sandstone	Red sandstone	Limestone	Marble	Granite	White clay brick	Yellow clay brick
I	70.44(13.83)	70.51 (9.05)	125.08 (7.47)	86.06 (6.75)	115.95 (16.61)	92.12 (12.69)	92.60 (9.60)
II	93.38 (9.22)	80.23 (11.62)	140.18 (7.41)	142.32 (5.05)	-	124.84 (10.17)	128.91 (9.69)
III	110.09 (7.62)	85.44 (8.02)	153.28 (5.66)	147.36 (3.55)	-	130.98 (13.95)	134.02 (8.24)
IV	115.81 (8.40)	91.74 (2.45)	163.37 (3.53)	154.32 (7.10)	149.18 (15.60)	138.26 (22.94)	140.53 (10.65)
Difference	45.37 [39.2%]	21.23 [23.1%]	38.29 [23.4%]	68.26 [44.2%]	33.23 [22.3%]	46.14 [33.4%]	47.93 [34.1%]

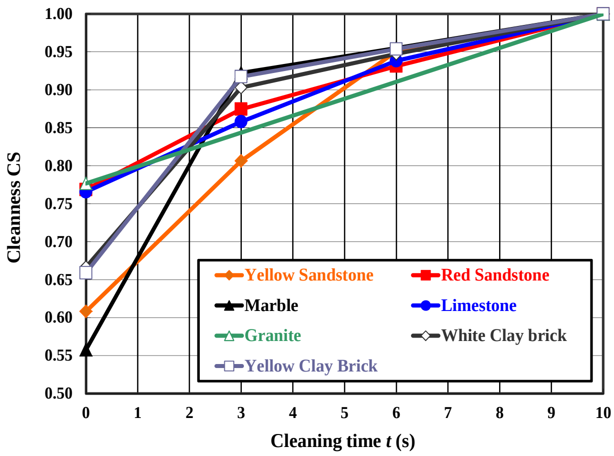


Fig. 21 Greyscale versus cleaning time for various masonry stones and bricks.

the original dirty surfacesand the fullycleaned surfaces are also included in the table, with the ratios of the greyscale values for the stone or brick surfaces cleaned at different stages to those for the fully cleaned surfaces in the square brackets.

Fig. 21 illustrates the relationships between the greyscale and cleaning time for all seven types of masonry stones and bricks.

A greater greyscale represents a cleaner surface. From Table 2, the overall greyscale varied from 70.44 for the uncleaned yellow sandstone to 163.37 for the fully cleaned limestone, which indicates that the former had the darkest surface while the latter had the brightest one. The standard deviation varied from the lowest 2.45 for the fully cleaned red sandstone to the highest 22.94 for the fully cleaned white clay brick, which indicates that the greyscale had the smallest variation for the former but the biggest variation for the latter. The coefficient of variation, the ratio of the standard deviation to the mean value, varied from 2.2% for the fully cleaned limestone to 19.6% for the fully dirty yellow sandstone, with most values below 15%, which indicates that the measured values possessed generally acceptable variations for construction practice.

In general, the greyscale gradually increased with the cleaning time but at a decrease rate and tended to be stable when the surface was fully cleaned. These trends can be expressed by a parabolic or bi-linear relationship. The differences in the greyscale between the original dirty and fully cleaned surfaces can be used to assess the dirty conditions on the stone or brick surface. The larger the difference in greyscale, the dirtier the original stone surface. Marble had a largest difference of 68.26 so its original surface was the dirtiest. The differences in greyscale for yellow clay brick, white clay brick, yellow sandstone and limestone varied from 47.93 to 38.29 so they were relatively dirtier. The greyscale differences for granite and red sandstone were only 33.23 and 21.22, respectively, which indicates that the original red sandstone was the least dirty.

3.2 Cleanness

In order to further quantitatively assess the cleaning level for all seven types of stones and bricks studied, the greyscale was normalised by introducing the cleanness (CS) or the relative greyscale as follows:

$$\textit{Cleanness (CS)} = \frac{\textit{Greyscale at certain cleaning level}}{\textit{Greyscale at fully cleaned level}} \quad (1)$$

The value of the cleanness for a fully cleaned stone or brick surface is defined as 1.0 and the cleanness forother cleaning levels are smaller than 1.0. Table 3 lists the calculated values of the cleanness for all seven types of stones and bricks at different cleaning stages,

Table 3 Cleanness for different types of masonry stones and bricks at four cleaning stages.

Cleaning stage	Yellow sandstone	Red sandstone	Limestone	Marble	Granite	White clay brick	Yellow clay brick
I	0.608	0.769	0.766	0.558	0.777	0.666	0.659
II	0.806	0.875	0.858	0.922	-	0.903	0.917
III	0.951	0.931	0.938	0.955	-	0.947	0.954
IV	1.000	1.000	1.000	1.000	1.000	1.000	1.000

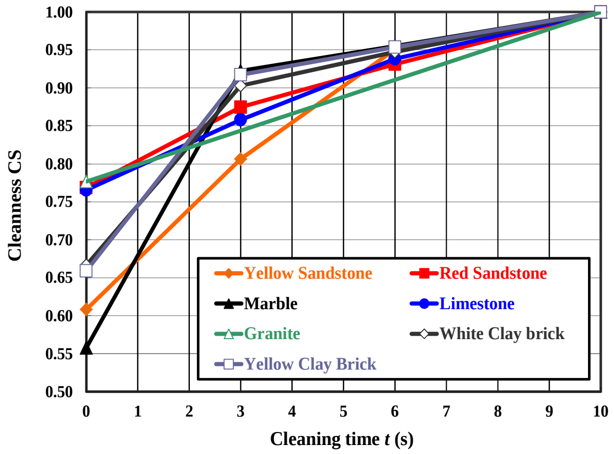


Fig. 22 Cleanness versus cleaning time for various masonry stones and bricks.

and Fig. 22 illustrates the corresponding relationships between the cleanness and cleaning time. It can be seen that the cleanness had the same increasing trends with the cleaning time as the greyscale. The smaller the value of the cleanness, the dirtier the original dirty stone surface. The cleanness value for dirty surfaces varied between 0.56 for marble and 0.78 for granite. It is obvious that the original surface of marble was the dirtiest, followed by yellow sandstone, yellow clay brick and white clay brick. Granite, red sandstone and limestone had the least dirty original surfaces. These trends generally match those with respect to the greyscale, which indicates that the digital imaging analysis and the two proposed parameters can be used for quantitatively assessing the cleaning degree.

4. Surface Hardness of Masonry Stones

The surface hardness of the stone and brick samples can be used for evaluating the changes in the surface strength during building cleaning. The Vickers hardness test, which was developed in the early 1920s, was adopted in this study because it is convenient to be carried out on small samples. This method was originally used for metallic material evaluation, quality control of manufacturing processes, and research and development efforts [37-39]. Later this method was applied to non-metallic materials, e.g. minerals, ceramic materials, stones and concrete materials [40-44].

The Vickers hardness number H_V was adopted here, which can be calculated from:

$$H_V = \frac{\mathit{Applied\ load}\ (\mathrm{kg})}{\mathit{Contact\ area\ of\ indenter}\ (\mathrm{mm}^2)} = \frac{2P\sin(\theta/2)}{d^2}\times 1000 = 1854.27\frac{P}{d^2} \quad (2)$$

where, H_v is the Vickers hardness number (kg/mm^2), P is the applied load (g), θ is the angle between the opposite faces (136°), d is the diagonal of indentation.

In the hardness testing, a stone sample was indented in the Vickers hardness instrument by using a diamond indenter with a load P = 1,000 g for 15 s (Fig. 23). The pyramid shaped indenter had a square base diamond with an angle of 136° between opposite faces, as shown in Fig. 24. After removing the load, a diamond indentation could be found on the stone surface using the microscope. Fig. 25 shows that a diamond indentation had two diagonals, horizontal and vertical ones. The two diagonal dimensions, d_H and d_V, were measured separately by aligning the two mark lines in the microscope to the edges of the indentation and then the values of d_H and d_V, which were shown on the digital encoder, were obtained. The two Vickers hardness numbers corresponding to d_H and d_V could be obtained by checking against the Vickers hardness number table [45]. The final value of H_V was the

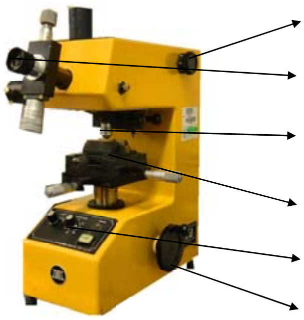


Fig. 23 Vickers hardness instrument.

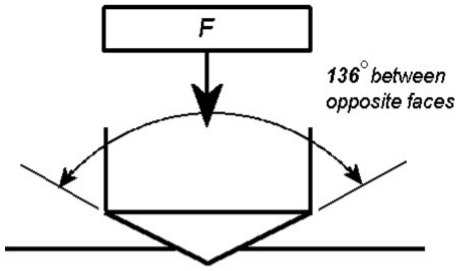


Fig. 24 The pyramid shaped indenter.

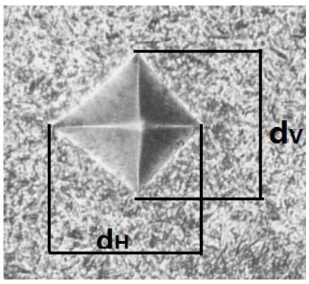


Fig. 25 Diamond indentation on the stone surface.

average of the two hardness results for the horizontal and vertical directions. One sample was selected for the Vickers hardness tests from each type of stone and brick. Three sampling points were taken on each stone sample.

Table 4 lists the mean values of the Vickers hardness numbers for all seven types of stone and brick samples at different cleaning stages, with the standard deviations in the round brackets. The higher the Vickers hardness number, the greater the stone surface strength. The measured values of the Vickers hardness number on the fully cleaned stone surfaces shows that granite was the hardest stone (H_V = 482.5 kg/mm^2), followed by marble with H_V = 210.5 kg/mm^2. White clay brick was the softest with H_V = 67.7 kg/mm^2 only, followed by red sandstone with H_V = 76.2 kg/mm^2. The rest of the stones lay in-between.

Table 4 also lists the differences in the Vickers harness numbers between the fully cleaned and original dirty stones, together with their relative ratios in percentage to the Vickers harness numbers for the fully cleaned surfaces in the square brackets. It can be seen that the soiling on the stone surface largely affected the surface hardness of the masonry stones. The Vickers hardness number for marble sustained a largest change and increased from 115.5 kg/mm^2 for the original dirty surface to 210.5 kg/mm^2 for the fully cleaned surface, which means that the soiling had decreased the surface hardness of marble by up to 95.0 kg/mm^2 or 45.13%. On contrast, the Vickers hardness number for granite had a smallest change and increased from 465.5 kg/mm^2 for the original dirty surface to 482.5 kg/mm^2 for the fully cleaned surface, which means that the soiling only decreased the surface hardness of granite by 17 kg/mm^2 or 3.52%. The influences of the soiling on the surface hardness for other stones and bricks varied from 30% to 40%.

Fig. 26 illustrates the Vickers hardness number against the cleaning time for all seven types of stones and bricks. A small figure is also inserted in Fig. 26 to give a clearer view of the trends for five stones with lower Vickers hardness numbers. In general, the Vickers hardness number for all stones and bricks

Table 4 Vickers hardness numbers for different types of stones and bricks at four cleaning stages.

Cleaning stage	Yellow sandstone	Red sandstone	Limestone	Marble	Granite	White clay brick	Yellow clay brick
I	57.6(1.4)	44.5 (1.5)	67.5(1.7)	115.5(3.8)	465.5(12.3)	47.3(0.7)	56.7(1.8)
II	69.2 (1.5)	57.4 (1.2)	93.3 (1.9)	158.0 (6.5)	-	58.6 (1.4)	69.0 (1.4)
III	77.0 (1.4)	69.9 (5.0)	104.0(5.0)	184.5 (6.0)	-	63.0 (1.5)	76.3 (1.4)
IV	86.5 (3.6)	76.2 (2.2)	114.0 (3.5)	210.5 (9.0)	482.5(23.3)	67.7 (1.5)	82.5 (1.9)
Difference	28.9 [33.4%]	31.7 [41.6%]	46.5 [40.8%]	95.0 [45.1%]	17.0 [3.5%]	20.4 [30.1%]	25.8 [31.3%]

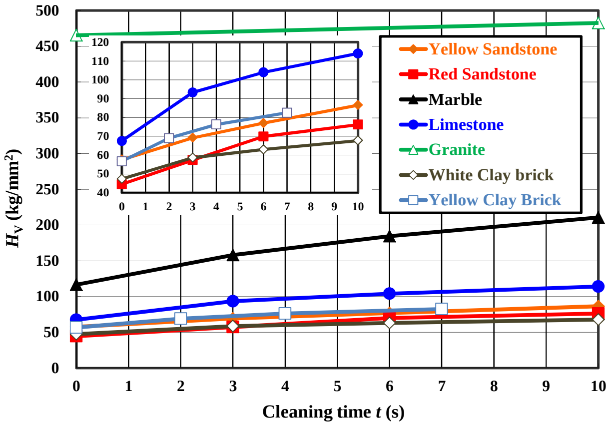


Fig. 26 Vickers hardness number versus cleaning time for various masonry stones and bricks.

gradually increased with the increasing cleaning time but at a decrease rate. These trends can be well expressed using parabolic relationships with high correlations.

Fig. 27 illustrates the Vickers hardness number against the cleanness for all stones and bricks. A small figure is inserted to help view more closely the trends for five masonry stones and bricks with lower Vickers hardness. In general, the Vickers hardness number for all stones and bricks monotonically increased with the increasing cleanness, and these trends can be expressed using linear or bilinear relationships. It is obvious that the original granite had the hardest and cleanest surface while the surface of the original marble was harder than any other stones except granite and was extremely dirty.

It should be mentioned that the hardness investigations can also help to select the most suitable abrasive materials for building cleaning. Too hard or too soft abrasives may not be beneficial for removing the soiling from the surface of a masonry stone or brick. Hard abrasives can effectively remove the soling but may damage the original masonry stone or brick surface. Soft abrasives may help preserve the building surface from damage caused by mechanical cleaningbut may not be able to effectively remove the soiling. Hence, there should be a balance in hardness between masonry stones/bricks, surface soling and abrasive materials. The current study can provide key information for masonry materials and soiling.

There are no available Vickers hardness values for the selected stones and bricks. Mineral Zone (46) reported the physical properties of typical natural stones, e.g., sandstone, limestone, marble and granite. Only the values of Mohs' hardness are given but they can be converted into the equivalent Vickers hardness values. Based on the mineral hardness conversion chart provided by CiDRA® Precision Services, LLC (47), the recommended Vickers hardness ranges are presented in Table 5 together with those on the fully cleaned surfaces in this study.

It can be seen that only the Vickers hardness value on the fully cleaned marble surface lay within the recommended range. The Vickers hardness values for limestone and granite were only half the average of the recommended ranges. For yellow and red sandstones,

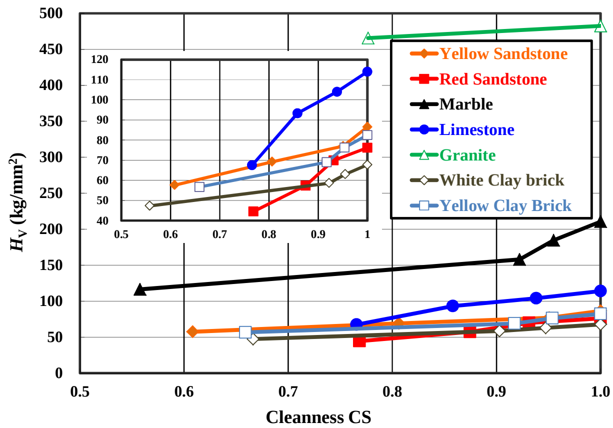


Fig. 27 Vickers hardness number versus cleanness for various masonry stones and bricks.

Table 5 Vickers hardness numbers for typical masonry stones.

Hardness	Yellow sandstone	Red sandstone	Limestone	Marble	Granite
Mohs (mm)	6.5-7	6.5-7	3-4	3-4	6-7
Vickers[1] (kg/mm^2)	982-1,161	982-1,161	157-315	157-315	817-1,161
Vickers[2] (kg/mm^2)	86.5	76.2	114.0	210.5	482.5

[1]Given by Mineral Zone (46); [2]Measured on the fully cleaned surface in this study.

the Vickers hardness values were even below 10% of the average of the recommended ranges. By remembering that all the recommended ranges of Vickers hardness are obtained on surfaces of fresh masonry stones, it can be claimed that all of these differences were due to environmental erosion and weathering over decades. Marble seems to be the most stable masonry stone and sustain the least damage, followed by limestone and granite. Yellow and red sandstones seem to be the worst ones which can be easily attacked by weathering and environmental erosion. On the other hand, this confirms again the importance of measuring the surface hardness of masonry stones and bricks during cleaning so as to help select appreciate types of abrasives for building cleaning because the hardness for a masonry stone is indeed not the same as that on the building surface. Otherwise large damage can happen from wrongly selecting abrasives.

5. Water Absorption

Water absorption is the quantity of water absorbed by a masonry stone or brick when fully immersed in water for a stipulated period of time under an ambient atmospheric pressure. It largely depends on the internal structure and porosity of a stone or a brick and can be closely related to the soiling deposited on the masonry surface. A stone or brick with loose structure and large porosity would attract moisture from rain, snow or other environmental conditions and lead to cracks, efflorescence, rust staining, wood rotting, wood rotting, paint peeling, darkening of masonry and spalling. Any masonry stone or brick with high porosity would absorb high moisture so as to attract biological soiling, such as fungus, mosses, lichens, etc. On the other hand, a masonry stone or brick with high water absorption capacity is often soft or less hard. Water absorption can thus be regarded as another physical parameter for assessing the hardness of masonry materials. Hence, it may be largely influential on the selection of cleaning abrasives, if air abrasive cleaning is adopted, and eventually on the effectiveness of building cleaning.

The water absorption testing was undertaken according to BS EN 13755 (48). The stone samples were put in an oven at a temperature of (70 ± 5) °C for 24 h until constant weights were obtained. The dried samples were placed in a tank after weighing, and then tap water at (20 ± 10) °C was added up to half the height of the stone samples. An hour later, tap water was added again until the level of the water reached three-quarter of the height of the samples. After another hour, tap water was added for a third time to submerge the samples completely. The samples were taken out of the tank after 48 h, quickly wiped with a damp cloth and then weighed within 1 minute on a scale with an accuracy of 0.01 g. A total of seven samples, one for each type of the masonry stones and bricks, were selected for the water absorption testing. All samples were cut from the original stones and bricks using a diamond saw and all the surfaces were fresh surfaces to void any effect of soiling. Fig. 28 shows all the stone and brick samples for the water absorption tests.

The water absorption (WA) of a masonry stone or brick can be calculated from

$$\mathrm{WA} = \frac{M_{\mathrm{saturated}} - M_{\mathrm{dried}}}{M_{\mathrm{dried}}} \times 100\% \qquad (3)$$

where, $M_{\mathrm{saturated}}$ is the weight of the sample fully saturated in the water, and M_{dried} is the weight of the sample fully dried in the oven.

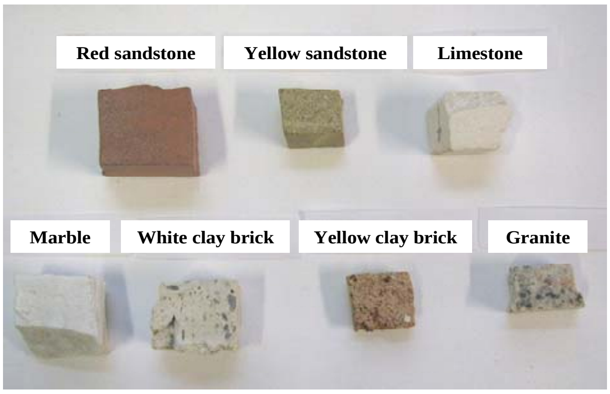


Fig. 28 Masonry stone and brick samples for water absorption tests.

Fig. 29 illustrates the measured values of the water absorption for all seven types of stones and bricks. Yellow and white clay bricks had the largest water absorptions among all the samples, with WA = 3.09% and 8.66%, respectively. Limestone, yellow sandstone and red sandstone also had relatively high water absorptions, with WA = 5.40%, 5.09% and 2.96%, respectively. On contrast, marble and granite absorbed little water so as to have the lowest water absorptions, with WA = 0.32% and 0.23%.

There are no available data of water absorption for clay bricks, but Mineral Zone [46] have suggested typical water absorption values for masonry stones, see Table 6. The water absorption values measured in this study are also listed in the table. It can be seen that the measured water absorption values for marble and granite lay within the recommended range, while the measured values for other three stones were far beyond the recommended range. For red sandstone, the water absorption was nearly three times as large as the recommended range, while for yellow sandstone and limestone, the water absorptions were five times as large as the recommended ranges. These differences were still due to decades' environmental erosion and weathering. Marble remained to be the most stable masonry stone, followed by granite. The rest stones were worse. This again confirms the importance of measuring the water absorption of masonry stones and bricks during cleaning so as to help select appreciate types of abrasives for building cleaning because the water absorption for a masonry stone or brick subjected to long term environmental erosion and weathering is indeed not the same as that for a fresh stone or brick on the building surface. Therefore, it can be said that the test for determining the water absorption for a stone or a brick is as equally important as the hardness test for building cleaning.

Fig. 30 shows the comparison between the water absorption and the Vickers hardness number for various types of stones and bricks. Two opposite trends can be clearly observed: the hardness approximately decreased while the corresponding water absorption continually increased. The water absorption of granite which had a hardest surface was the lowest. Similarly, yellow clay brick which was extremely soft had the highest water absorption. In general, greater water absorption likely corresponded to a softer stone or brick, while lower water absorption corresponded to a harder stone or brick.

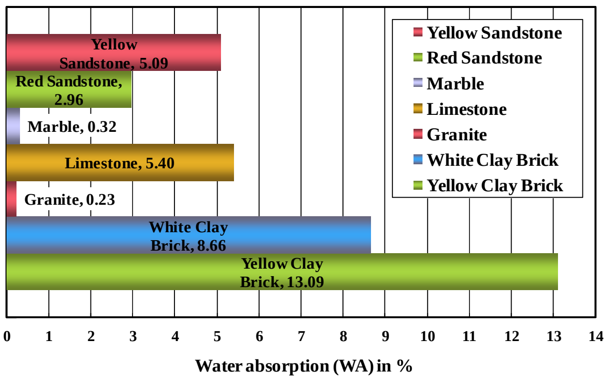


Fig. 29 Water absorption for various types of masonry stones and bricks.

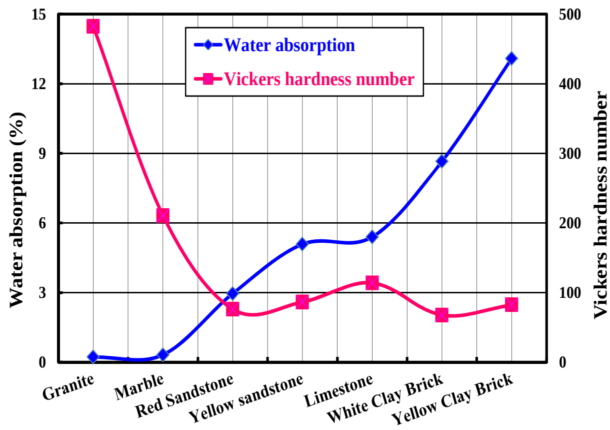


Fig. 30 Comparison between the water absorption and the Vickers hardness number for various types of masonry stones and bricks.

Table 6 Vickers hardness numbers for typical masonry stones.

Water absorption (%)	Yellow sandstone	Red sandstone	Limestone	Marble	Granite
Mineral Zone (46)	1.0-1.2	1.0-1.2	< 1	< 0.5	0.1-0.6
Current study	5.09	2.96	5.40	0.32	0.23

6. Conclusions

In this study, a series of tests were conducted to extensively investigate the changes in the physical and chemical characteristics of seven different types of popularly used masonry stones and bricks in Edinburgh during the cleaning process, i.e., yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. The physical investigations included evaluating the cleaning degree, determining the Vickers hardness, and detecting the water absorption.

The cleaning degrees of the masonry samples were assessed using the digital image analysis method by introducing a parameter, the greyscale. A lower greyscale corresponded to a dirtier stone surface. It was observed that the greyscale continuously increased with the increasing cleaning time and tended to be stable when the surface became fully cleaned. In addition, another parameter, the cleanness which was defined as the ratio of the greyscale at certain cleaning stage to the one when the stone was fully cleaned, or called as the relative greyscale, was introduced for assessing the effectiveness of the building cleaning. For a dirty surface, the cleanness was small, while for a fully cleaned surface, the cleanness was equal to one. A larger cleanness value corresponded to a better cleaned surface. The comparison of the cleanness values at different cleaning stages indicated that among all the stones and bricks studied the original surface of the marble was extremely dirty while the surface of the granite was the cleanest. This digital image analysis method together with applying the greyscale or cleanness was confirmed to be useful and efficient for quantitatively assessing the effectiveness of building cleaning.

However, it should be pointed out that the current work is only a preliminary study on the assessment of building cleaning using greyscale technique, and much work needs to be done to standardise the assessing process because there are many different types of stones in nature and artificial bricks, e.g., calibrating the benchmark for each type of masonry stone and brick for building construction. The cleanness of a masonry building façade need to be assessed objectively, e.g., use its fresh surface deeply inside a stoneor brick as the benchmark. In practice at the moment, the cleaning assessment is normally done in a more subjective way by considering relevant influencing factors, e.g. the satisfaction of the customers, the acceptance of the authorities, the limitation of the cost, etc. All of these affect the objective assessment of the cleaning work. Hence, a mutual balance between all influential factors is needed.

The surface hardness of all seven types of stones and bricks studied at different cleaning stages was assessed by conducting the Vickers hardness tests. A larger hardness value corresponded to a harder stone surface. The hardness test results showed that the surface hardness continuously increased with the increasing cleaning time but at a decrease rate. Most of the increasing trends of the surface hardness could be approximately expressed using parabolic or bi-linear relationships. Granite was found to be the hardest among all the stones and bricks studied, followed by marble and limestone. However, there were no big differences in the surface hardness between yellow clay brick, yellow sandstone, red sandstone and white clay brick. Also the comparison with the reported Vickers hardness values of the masonry stones studied confirmed that some stones had sustained large decay due to long term weathering and environmental erosion, in particular yellow sandstone, red sandstone and limestone.

The waterabsorbingcapacity of the seven types of stones and bricks was also quantitatively determined. Two types of clay bricks showed the highest water absorptions, and the water absorptions for limestone, yellow sandstone and red sandstone were also quite high. However, the moisture absorptions of marble and granite were found to be very low, which indicates that they could hardly absorb water. A larger value of water absorption corresponded to a softer stone or brick, while a smaller value of water absorption corresponded to a harder stone or brick. The current study on water absorption also confirmed that the yellow sandstone, red sandstone and limestone in this study had sustained severe environmental erosion and weathering.

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Investigations of Physical and Chemical Characteristics of Masonry Stones and Bricks during Building Cleaning: Part 2. Chemical Testing

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Abstract: This series of study focused on analysing and assessing the changes of the physical and chemical characteristics of the stone surfaces during the sandblasting cleaning process by conducting various physical and chemical tests. Seven masonry stones and bricks were adopted, including yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. The chemical investigations included the micrographing of the stone façade and the analysis of the chemical elements and compounds on four of the seven stones and bricks before and after the cleaning using the Scanning Electron Microscope (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) techniques. In general, the chemical properties were found to vary largely during the building cleaning. The chemical tests showed that the chemical elements and compounds on the stone façade significantly varied after long term exposures to the atmosphere, mainly due to the soiling on the building façade caused by environmental erosion and weathering.

Key words: Masonry stone and brick, sand blasting cleaning, chemical analysis, SEM, EDX.

1. Introduction

Masonry stones and bricks have been widely used for constructing historic buildings and monuments, which become grand assets for current and future generations. The cleaning and restoration of these old, historic stone and brick structures has also become significantly important accordingly. With the development of new building legislations and modern cleaning techniques in the past few decades, building cleaning nowadays has become a less aggressive practice and a more popular business [1-6]. In the United Kingdom, large demands of stone cleaning have occurred since [7-9]. Also, more attention has been paid to this and many studies on building cleaning have been published [10-18].

Frankly speaking, stone cleaning no matter how big care is taken always has negative effects beyond the removal of superficial soiling. When carried out using inappropriate methods, aggressive cleaning can largely damage stones. Many of the potential effects of inappropriate cleaning will be visible immediately after or within a few weeks of cleaning.

Hence, preliminary investigations on both physical and chemical characteristics of the masonry stone and brick surfaces are sometimes needed before deciding on the best cleaning method to avoid unnecessary damage to the buildings [10, 19-21]. However, so far there are no consistent standards and parameters used for assessing the degree of building cleaning, and the

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efficiency of various cleaning methods is largely assessed by visual inspections and mutual agreements. There is an urgent need to search for better physical parameters for such assessments. Previous studies were largely focused on finding the substances of the soiling on the building façade and the methods to remove these substances. The information on the chemical compositions of the soiling and their changes during masonry cleaning is still limited. Meanwhile there is a lack of systematic monitoring and assessment on the changes in the physical and chemical characteristics of masonry stones and bricks during cleaning process even though such knowledge is largely important for understanding and improving the efficiency of building cleaning.

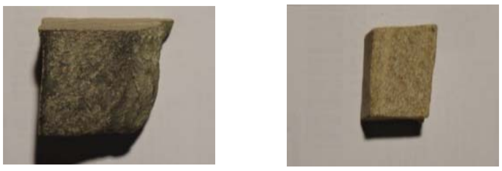
In this study, physical and chemical characteristics of masonry stones and bricks subjected to progressive stages of cleaning were investigated for evaluating the effectiveness of building cleaning. Part 1 of this study had reported the physical tests including digital image analysis method based on surface greyscale, hardness tests and water absorption tests [22]. Seven types of commonly used masonry stones and bricks selected for physical tests were yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. This second part of the work would report the chemical analysis carried out to quantitatively assess the variations of chemical elements on the original dirty and fully clean surfaces of the masonry stones and bricks using combined Scanning Electron Microscope (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) techniques to identify the chemical compositions of the soiling on the masonry surface. Four out of the seven masonry stones and bricks selected for the physical tests were adopted for the chemical analysis, including yellow clay brick, yellow sandstone, limestone and marble. Thus, a complete evaluation procedure for building cleaning can be established.

2. Preparation of Stone Samples

Masonry stones and bricks were selected from those for the 1860s-1870s listed buildings in the south west of the city of Edinburgh, which were popularly used for local buildings [23] and exposed to the open environmental conditions for more than a century with large amounts of heavy soiling deposited on the surfaces. A diamond saw was used to cut the masonry stones into small samples. The exposed surfaces of the stones and bricks were cleaned into different levels using the abrasive sandblasting cleaning with fine recycled glass particles, and then they were cut into the required sizes for various physical and chemical tests. Figs. 1 to 4 show the fully dirty and fully clean samples of yellow clay brick, yellow sandstone, limestone and marble for chemical analysis.

(a) (b)

Fig. 1 Yellow clay brick samples for SEM and EDX testing. (a) fully dirty sample and (b) fully clean sample.

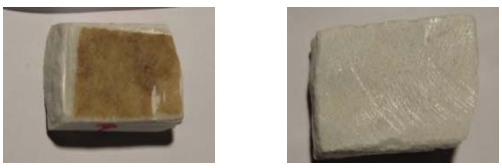


(a) (b)

Fig. 2 Yellow sandstone samples for SEM and EDX testing: (a) fully dirty sample and (b) fully dirty sample.

(a) (b)

Fig. 3 Limestone samples for SEM and EDX testing: (a) fully dirty sample and (b) fully dirty sample.



(a) (b)

Fig. 4 Marble samples for SEM and EDX testing: (a) fully dirty sample and (b) fully dirty sample.

3. Chemical Analysis

As the soiling and decay have the ability to affect the chemical substances on the stone or brick surface, the chemical characteristics of the original dirty surface are largely different to those on the fully clean surface. During the cleaning process, the chemical substances on the stone or brick surface continually change. Some chemical elements and compounds may increase and some elements and compounds may decrease or even disappear during building cleaning. This part of the work aimed to conduct quantitative chemical analysis on changes in chemical elements and compounds on the original dirty and fully cleaned (fresh) surfaces of masonry stones and bricks during cleaning process and to identify the chemical compositions and compounds of the soiling deposited on the stone and brick surfaces so as to find appropriate cleaning methods.

So far chemical analysis has been largely used for detecting the chemical compositions and compounds of the soiling remaining on masonry historic buildings and monuments after years' weathering, environment erosion and industrial pollutions [24, 25]. It is also largely used for assessing the performance of stone protection methods for conservations of historic buildings and monuments [26-29].

Most popularly used chemical analysis methods include SEM and EDX. The SEM technique is used to image a sample on a Liquid Crystal Display (LCD) by scanning it with a beam of electrons in a raster scan pattern. This will produce the signals containing the information about the surface topography and composition of the sample due to the interactions between the electrons and atoms. The EDX is used to analyse the chemical elements and compounds of the sample, based on an interaction of the source of X-ray excitation with a masonry sample. Its characterisation capabilities are largely due to the fundamental principle that each element has a unique atomic structure allowing a unique peak on its X-ray spectrum. It will be possible to detect the chemical elements on the different parts of the sample, and these elements can be related to certain chemical compounds.

In this study, the chemical analysis was conducted by using the instrument with the combined SEM and EDX, as shown in Fig. 5. The instrument used in this study was the SEM LEO S 430 I, UK, coupled with ISIS EDD detector from Oxford Instrument, UK.

Sample preparation is a vital stage for the testing using the Scanning Electron Microscope. Insulation materials are required to form a thin layer of conducting coating (~100 Å) to avoid charging. For the EDX in this study, carbon coating was adopted. The materials could be observed at low primary energy, at which the coefficient for secondary emission was ~1 and the charge build-up was negligible. The entire sample preparation included mounting the sample on a metallic platform via a conducting path.

Four adopted masonry stones and brick to be tested were numbered as:

- Yellow clay brick: Samples 1 (original dirty) and 2 (fully clean);
- Yellow sandstone: Samples 3 (original dirty) and 4 (fully clean);
- Limestone: Samples 5 (original dirty) and 6 (fully clean);
- Marble: Samples 7 (original dirty) and 8 (fully clean).

The surfaces of the fully clean samples were polished and cleaned using acetone. The original dirty samples were also gently rinsed using acetone. All the

Fig. 5 The SEM and EDX instrument.

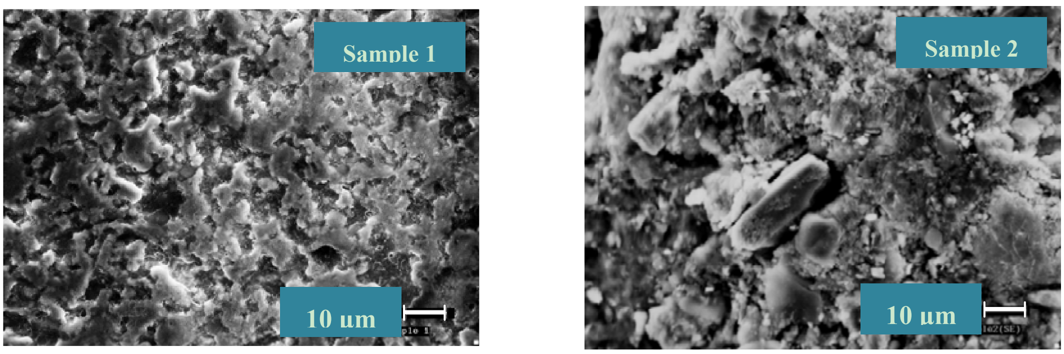
samples were dried under an IR lamp and coated with a thin layer of carbon to make the stone surfaces conductive. The samples were then mounted on the SEM stubs for the micro-structural and compositional analysis. Six micrographs were recorded at different magnifications for each sample by using the SEM and six sampling points were selected on each sample for detecting the chemical elements and compounds.

4. Yellow Clay Brick

Fig. 6 presents typical micrographs of the surface structures of the original dirty and fully clean yellow clay brick samples. Fig. 6a shows that the soling existed loosely on the dirty surface, and there were no obvious interactions between the particles. Fig. 6b shows that the fully clean surface was more crystalline and interactive. The numbers in the brackets represent the sampling points on the sample.

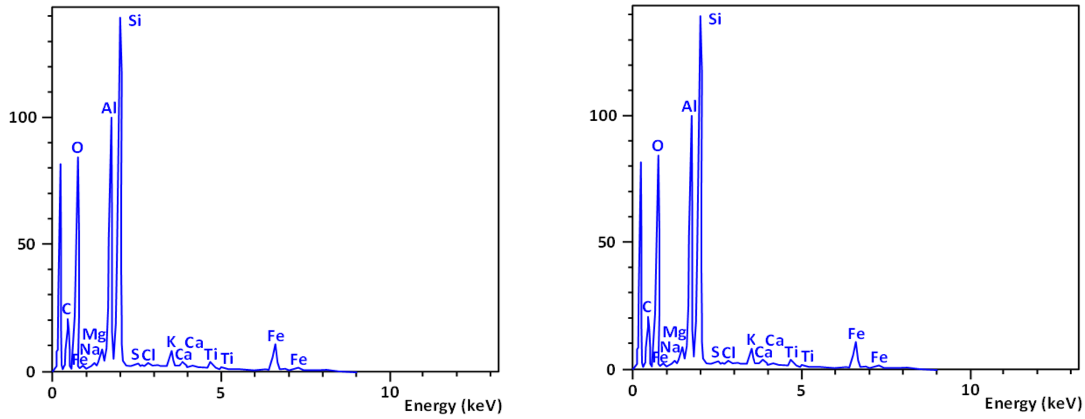
Fig. 7 shows typical chemical spectrum diagrams on the original dirty and fully clean surfaces of the yellow clay brick samples. Common chemical elements found to exist on both dirty and clean surfaces included C, O, Na, Mg, Al, Si, S, Cl, K, Ca, Ti and Fe, but the peak values were remarkably different for some elements, e.g. C, Al, Si, S, Ca and Fe, which indicates that the amounts of these elements varied during the cleaning process.

Table 1 lists the relative amounts of these thirteen detected chemical elements in percentage obtained by using the EDX for both original dirty and fully clean yellow clay brick samples. These values were the averages of six test results for each sample. The standard deviations (SD) for each chemical element are also included in the table. Compared with the average



(a) (b)

Fig. 6 Typical micrographs for the yellow clay brick samples. (a) Original dirty surface (Sample 1(6)) and (b) fully clean surface (Sample 2(5)).



(a) (b)

Fig. 7 Typical spectrum diagrams for the yellow clay brick samples. (a) Original dirty surface (Sample 1(5)) and (b) fully clean surface (Sample 2(4))

Table 1 EDX results for the yellow clay brick samples.

SEMQuant results			Ref: Demonstration data SiLi detector				Spectrum label: Samples 1&2
System resolution = 61 eV			Quantitative method: ZAF (6 iterations)				Analysed all elements
Element	Spectrum type		Element (%)				Chemical compound
			Dirty		Clean		
			Average	SD	Average	SD	
C	K	ED	23.50	2.19	28.80	9.58	$CaCO_3$ 01/12/93
O	K	ED	45.26	0.80	45.80	2.45	Quartz 01/12/93
Na	K	ED	0.39	0.25	0.14	0.02	Albite 02/12/93
Mg	K	ED	0.55	0.16	0.44	0.10	MgO 01/12/93
Al	K	ED	8.97	1.27	4.39	1.75	Al_2O_3 23/11/93
Si	K	ED	16.42	2.65	14.12	7.54	Quartz 01/12/93
P	K	ED			0.30	0.22	GaP 29/11/93
S	K	ED	0.09	0.03	0.28	0.15	FeS_2 01/12/93
Cl	K	ED	0.22	0.09	0.18	0.14	KCl 15/02/94
K	K	ED	1.28	0.21	0.93	0.30	MAD-10 02/12/93
Ca	K	ED	0.41	0.25	2.42	1.82	Wollas 23/11/93
Ti	K	ED	0.44	0.20	0.47	0.23	Ti 01/12/93
Fe	K	ED	2.49	1.30	2.04	0.22	Fe 01/12/93
Total			100.00		100.00		

values, the standard deviations were reasonably small so the average values can be regarded to represent the true relative quantities of chemical elements on the surfaces of the yellow clay brick in this study. Also based on these quantities together with the measured atomic weights, the possible chemical compounds could be indicated, see the last column of Table 1.

Fig. 8 shows the quantities of the chemical elements detected on the original dirty and fully clean surfaces of the yellow clay brick samples. The main chemical elements in the original yellow clay brick were C, O, Si and Al at 23.50%, 45.26%, 16.42% and 8.97%, respectively, which indicates that the main chemical compounds in the yellow clay brick were $CaCO_3$, SiO_2 and Al_2O_3. By viewing the 50% dividing line, it can also be seen that that C slightly increased to 28.80% after cleaning while Si and Al decreased to 14.12% and 4.39%. As the samples were coated with carbon, it is hard to quantitatively analyse the changes of C. However, the decrease in Si and Al which represent Quartz (SiO_2) and Aluminium oxide (Al_2O_3) through the cleaning process indicates that these two compounds were formed in the original yellow clay brick. Similarly, the decrease of the rare elements in the yellow clay brick such as Mg and Fe which represent Magnesium oxide (MgO) and Iron disulfide (FeS_2) may be caused by polluting gases like O_3 and H_2S.

Punmia et al. [30] claimed that the main chemical compositions in clay bricks included 50%-60% silica (SiO_2), 20%-30% alumina (Al_2O_3), 5-6% iron oxide (Fe_2O_3), 2%-5% lime (CaO) and magnesia (MgO) below 1%. The current results seemed indeed to match

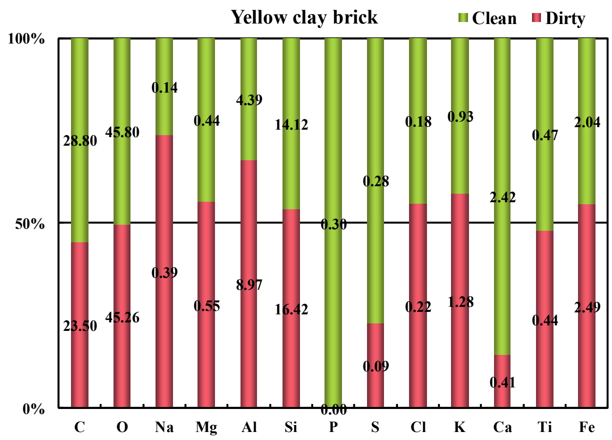


Fig. 8 Chemical elements on the surfaces of the original dirty and fully clean yellow clay brick samples.

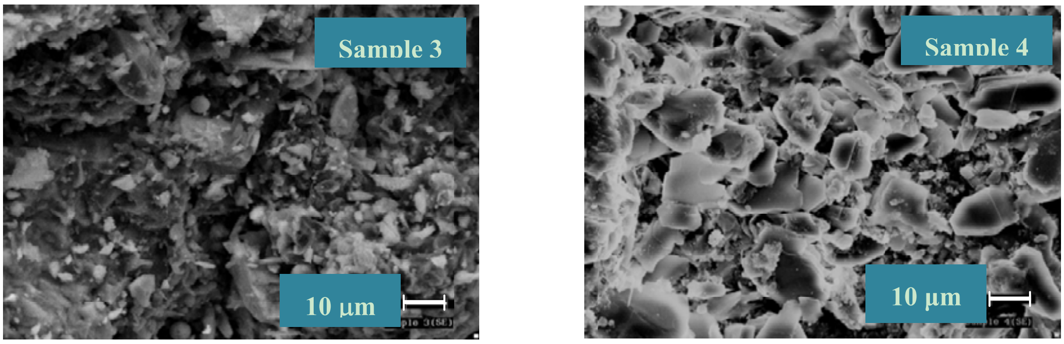
the reported distributions. For the yellow clay brick samples in this study, the detected extra chemical elements included Na, P, S, Cl, K, Ti and their compounds which existed in both the soiling and on the fully clean surface except P.

5. Yellow Sandstone

Fig. 9 presents typical micrographs of the surface structures of the original dirty and fully clean yellow sandstone samples. Fig. 9a shows that the soling still loosely existed on the surface of the dirty yellow sandstone, and there were no obvious interactions between the particles. Fig. 9b shows that the surface of the fully clean yellow sandstone was remarkably crystalline and orderly.

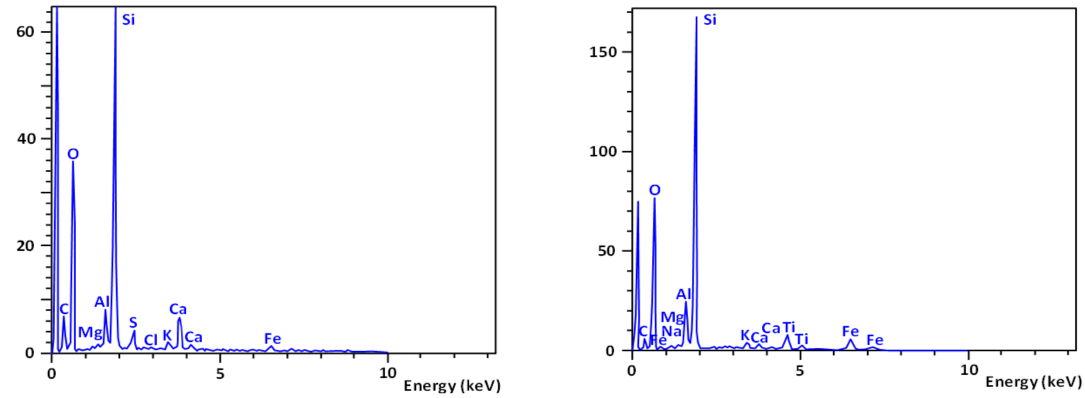
Fig. 10 illustrates typical chemical spectrum diagrams on the surfaces of the original dirty and fullyclean yellow sandstone samples. Common chemical elements observed on both dirty and clean surfaces included C, O, Mg, Al, Si, K, Ca and Fe, and the peak values were remarkably different for some elements, e.g. C, Al, K, S, Ca and Fe, which indicates that the amounts of these elements varied during the cleaning process. Si and Cl only existed on the original dirty surface while Na and Ti only existed on the fully clean surface.

Table 2 lists the relative amounts of these twelve detected chemical elements in percentage obtained by using the EDX for both original dirty and fully clean yellow sandstone samples. The standard deviations(SD) for each chemical element are also included in the table. Similarly, the standard deviations were reasonably small compared with the average values, so the average values can represent the true relative quantities of chemical elements on the surfaces of the yellow sandstone.



(a) (b)

Fig. 9 Typical micrographs for the yellow sandstone samples: (a) original dirty surface (Sample 3(4)) and (b) fully clean surface (Sample 4(5)).



(a) (b)

Fig. 10 Typical spectrum diagrams for the yellow sandstone sample: (a) original dirty surface (Sample 3(6)) and (b) fully clean surface (Sample 4(6)).

Table 2 EDX results for the yellow sandstone samples.

SEMQuant results			Ref: Demonstration data SiLi detector				Spectrum label: Samples 3&4
System resolution = 61 eV			Quantitative method: ZAF (6 iterations)				Analysed all elements
Element	Spectrum Type		Element (%)				Compound
			Dirty		Clean		
			Average	SD	Average	SD	
C	K	ED	19.43	3.39	13.10	1.22	$CaCO_3$ 01/12/93
O	K	ED	54.45	3.88	53.51	3.84	Quartz 01/12/93
Na	K	ED			0.25	0.05	Albite 02/12/93
Mg	K	ED	0.20	0.03	0.13	0.11	MgO 01/12/93
Al	K	ED	2.24	1.96	3.67	2.12	Al_2O_3 23/11/93
Si	K	ED	21.58	5.10	24.67	4.46	Quartz 01/12/93
S	K	ED	0.49	0.62			FeS_2 01/12/93
Cl	K	ED	0.04	0.01			KCl 15/02/94
K	K	ED	0.68	0.62	0.43	0.23	MAD-10 02/12/93
Ca	K	ED	1.14	1.12	0.85	0.72	Wollas 23/11/93
Ti	K	ED			1.36	1.75	Ti 01/12/93
Fe	K	ED	0.92	0.38	2.18	0.96	Fe 01/12/93
Total			100.00		100.00		

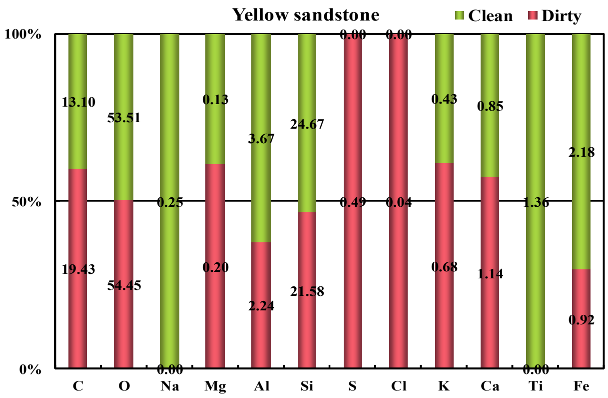


Fig. 11 Chemical elements on the surfaces of the original dirty and fully clean yellow sandstone samples.

Fig. 11 shows the quantities of the chemical elements detected on the original dirty and fully clean surfaces of the yellow sandstone samples. The mainelements in the clean yellow sandstone were C, O and Si at 13.10%, 53.51% and 24.67%, respectively, and the corresponding compounds were $CaCO_3$ and SiO_2. By viewing the 50% dividing line, it can also be seen that the main elements in the sandstone did not change much during cleaning.

However, some metallic elements such as Na, Al, Ti and Fe which represent Albite, Aluminium oxide (Al_2O_3), Titanium (Ti) and Iron disulfide (FeS_2) largely increased after cleaning, which indicates that these elements were the original elements of the yellow sandstone. The biological soiling on the stone surface such as bacteria which has the ability to largely dissolve a range of components of the stone may lead to the loss of these compounds on the original stone. On the contrast, the decrease of Mg, S and Cl which represent Magnesium oxide (MgO), Iron disulfide (FeS_2) and Potassium chloride (KCl) through the cleaning indicates that these compounds were the naturally formed soiling on the façade of sandstone, probably due to the reactions with the polluting gases such as O_3, SO_2 and H_2S in the atmosphere.

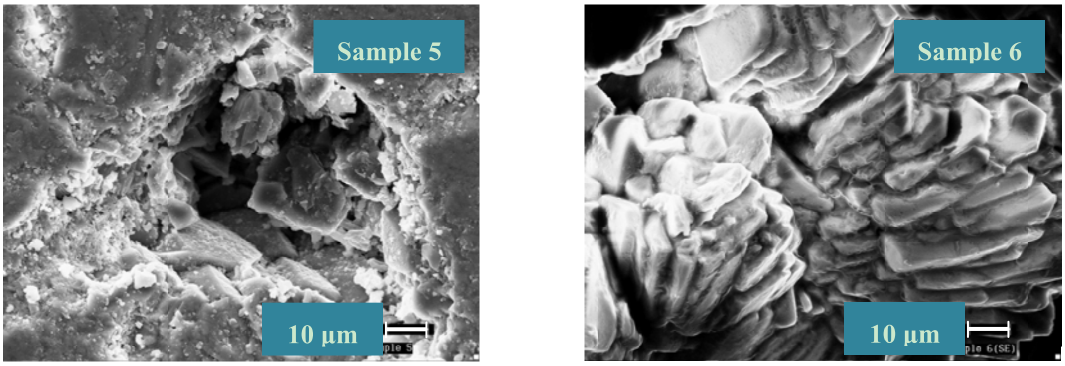
Mineral Zone [31] reported that the main chemical compositions in sandstone included 95%-97% silica (SiO_2), 1.0%-1.5% alumina (Al_2O_3), 0.5%-1.5% iron oxide (Fe_2O_3), soda (Na_2O) and potash (Kro) below 1%, lime (CaO), magnesia (MgO) and loss on ignition (LOI) below 0.5% each. The current results seemed to match the reported distributions. For the yellow sandstone samples in this study, the detected extra chemical elements included Na, S, Cl, K, Ti and their compounds, but only S and Cl existed in the soiling and Na and Ti only on the fully clean surface.

6. Limestone

Fig. 12 shows typical micrographs of the surface structures of the limestone samples. Fig. 12a shows that the soling on the surface of the dirty limestone was lightly crystalline with some defects. Fig. 12b shows that the surface of the fully clean limestone was more crystalline and orderly.

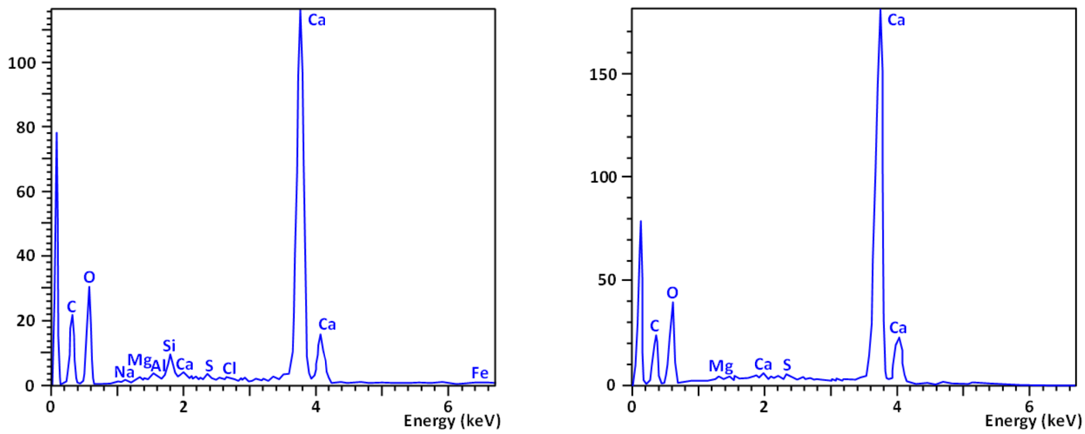
Fig. 13 illustrates typical chemical spectrum diagrams on the surfaces of the original dirty and fully clean limestone samples. Common chemical elements observed on both dirty and clean surfaces included C, O, Mg, Si and Ca, but the peak values were remarkably different for C and Ca, which indicates that the amounts of these two elements largely varied during the cleaning process. Na, Al and Si only existed on the original dirty surface.

Table 3 lists the relative amounts of the eight detected chemical elements by using the EDX for both original dirty and fully clean limestone samples. Fig. 14 shows the quantities of the chemical elements detected on the original dirty and fully clean surfaces of the limestone samples. The main chemical elements in the clean limestone were C, O and Ca at 12.80%, 49.92% and 36.87%, and the corresponding compounds were $CaCO_3$, SiO_2 and Wollas. By viewing the 50% dividing line, it can also be seen that the main elements in the limestone did not change largely during the cleaning. However, some rare elements such as Na, Al and Si which represent Albite, Aluminium oxide (Al_2O_3) and Quartz (SiO_2) disappeared after cleaning, which indicates that these compounds were not the original elements of the limestone but belonged to the dirty soiling.



(a) (b)

Fig. 12 Typical micrographs for the limestone samples. (a) Original dirty surface (Sample 5(2)) and Fully clean surface (Sample 6(4)).



(a) (b)

Fig. 13 Typical spectrum diagrams for the limestone samples. (a) Original dirty surface (Sample 5(6)) and (b) Fully clean surface (Sample 6(4)).

Table 3 EDX results for the limestone samples.

SEMQuant results			Ref: Demonstration data SiLi detector				Spectrum label: Samples 1&2
System resolution = 61 eV			Quantitative method: ZAF (6 iterations)				Analysed all elements
Element	Spectrum Type		Element (%)				Compound
			Dirty		Clean		
			Average	SD	Average	SD	
C	K	ED	15.91	1.36	12.80	0.79	$CaCO_3$ 01/12/93
O	K	ED	50.68	1.79	49.92	1.86	Quartz 01/12/93
Na	K	ED	0.29	0.13			Albite 02/12/93
Mg	K	ED	0.24	0.05	0.26	0.11	MgO 01/12/93
Al	K	ED	0.21	0.09			Al_2O_3 23/11/93
Si	K	ED	0.53	0.47			Quartz 01/12/93
S	K	ED	0.21	0.05	0.21	0.05	FeS_2 01/12/93
Ca	K	ED	32.21	3.35	36.87	1.42	Wollas 23/11/93
Total			100.00	100.00	100.00	100.00	

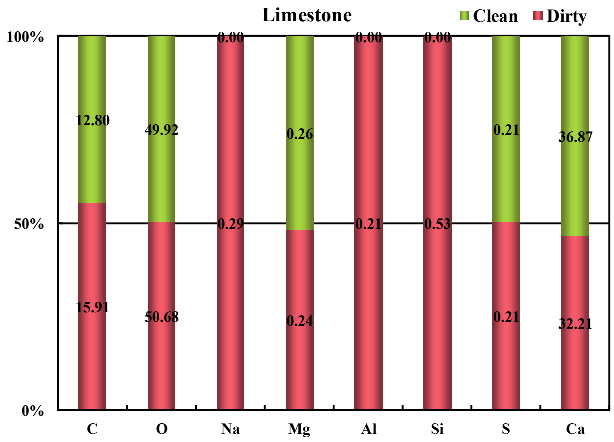


Fig. 14 Chemical elements on the surfaces of the original dirty and fully clean limestone samples.

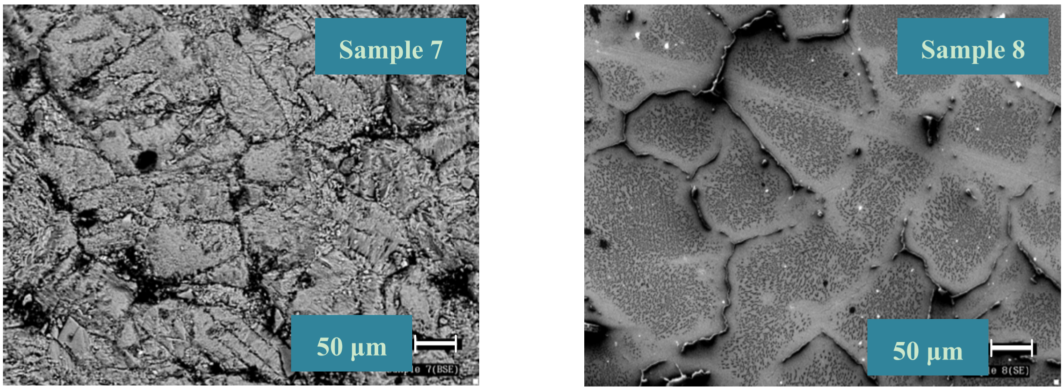
Mineral Zone [31] reported that the main chemical compositions in limestone included 15%-18% silica (SiO_2), 1%-1.5% iron oxide (FeO + Fe_2O_3), 38%-42% lime (CaO), 0.5%-3% magnesia (MgO), 1%-1.5% alumina (Al_2O_3), 1%-1.5% alkalies and 30-32% loss on ignition (LOI). For the limestone samples in this study, the detected amounts of lime (CaO) and magnesia (MgO) seemed to be reasonably within the reported range. Silica (SiO_2) and alumina (Al_2O_3) only appeared in the soiling on the original dirty surface but disappeared on the fully clean surface. Iron oxide (FeO + Fe_2O_3) did not appear on the fully clean surface at all. The extra chemical elements detected were Na, S and their compounds, and Na only appeared in the soiling on the original dirty surface but not on the fully cleaned surface.

7. Marble

Fig. 15 presents typical micrographs of the surface structures of the original dirty and fully clean marble samples. Fig. 15a shows that the soling on the surface of the dirty marble was rough and loose, while Fig. 15b shows that the surface of the fully clean marble was crystalline and orderly. Fig. 16 shows typical chemical spectrum diagrams on the surfaces of the original dirty and fully clean marble samples. Common chemical elements observed on both dirty and clean surfaces included C, O, Mg, Al, Si and Ca, but the peak values were remarkably different for C, O, Al, Si and Ca, which indicates that the amounts of these elements largely varied during the cleaning process. Na, S, Al, K and Fe only existed on the original dirty surface.

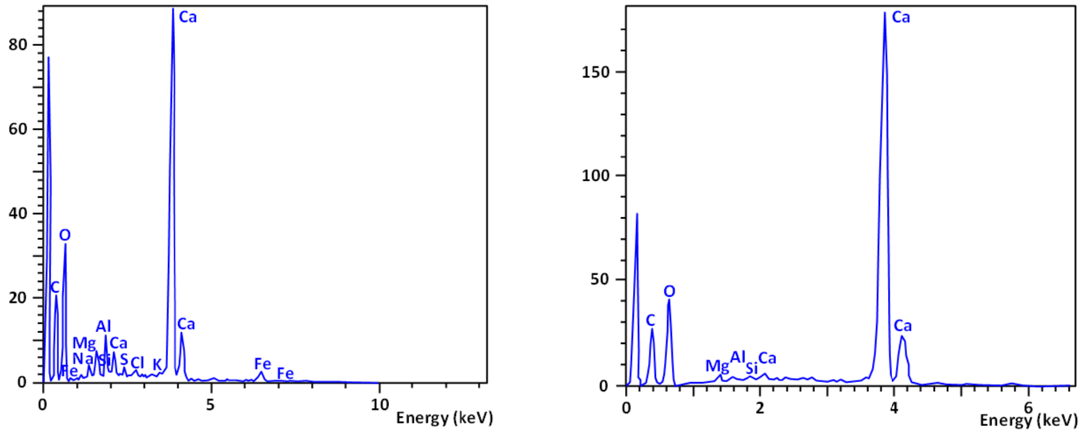
Table 4 lists the relative amounts of the eleven detected chemical elements in percentage by using the EDX for both original dirty and fully clean marble samples. Fig. 17 shows the quantities of the chemical elements detected on the original dirty and fully clean surfaces of the marble samples. The main elements in the clean marble were C, O and Ca at 12.70%, 51.27% and 35.49%, respectively, and the main compounds in the marble were $CaCO_3$ and Wollas.

It can also be seen that the rare compounds in the marble were all largely decreased after cleaning, which indicates that the surface condition of the original marble was poor as large amounts of soiling formed on



(a) (b)

Fig. 15 Typical micrographs for the marble samples. (a) Original dirty surface (Sample 7(3)) and (b) Fully clean surface (Sample 8(5))



(a) (b)

Fig. 16 Typical spectrum diagrams for the marble samples: (a) original dirty surface (Sample 7(6)) and (b) fully clean surface (Sample 8(6)).

Table 4 EDX results for the marble samples.

SEM Quant results				Ref: Demonstration data SiLi detector			Spectrum label: Samples 1&2
System resolution = 61 eV				Quantitative method: ZAF (6 iterations)			Analysed all elements
Element	Spectrum type			Element (%)			Compound
			Dirty		Clean		
			Average	SD	Average	SD	
C	K	ED	17.43	2.24	12.70	0.18	$CaCO_3$ 01/12/93
O	K	ED	48.38	2.37	51.27	0.89	Quartz 01/12/93
Na	K	ED	0.24	0.02			Albite 02/12/93
Mg	K	ED	0.74	0.25	0.49	0.05	MgO 01/12/93
Al	K	ED	0.99	0.39	0.11	0.02	Al_2O_3 23/11/93
Si	K	ED	1.89	0.75	0.16	0.03	Quartz 01/12/93
S	K	ED	0.32	0.05			FeS_2 01/12/93
Cl	K	ED	0.26	0.23			KCl 15/02/94
K	K	ED	0.16	0.06			MAD-10 02/12/93
Ca	K	ED	26.65	4.23	35.49	0.97	Wollas 23/11/93
Fe	K	ED	1.57	0.23			Fe 01/12/93
Total			100.00		100.00		

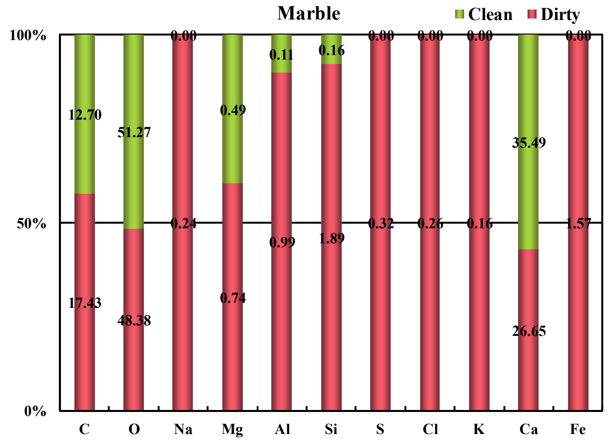


Fig. 17 Chemical elements on the surfaces of the original dirty and fully clean marble samples.

the surface. In addition, since Mg, Al and Si still existed after cleaning, the clean marble likely contained small amounts of Magnesium oxide (MgO), Aluminium oxide (Al_2O_3) and Quartz (SiO_2).

Mineral Zone [31] reported that the main chemical compositions in marble included 3%-30% silica (SiO_2, varying with variety), 1%-3% iron oxide (FeO + Fe_2O_3), 28%-32% lime (CaO), 20%-25% magnesia (MgO) and 20%-45% loss on ignition (LOI). For the marble samples in this study, the detected amounts of silica (SiO_2) and lime (CaO) seemed to be reasonably within the reported range. Iron oxide (FeO + Fe_2O_3) only appeared in the soiling but disappeared on the fully clean surface. The magnesia (MgO) was measured to be much lower than the reported range. The extra chemical elements detected were Na, Al, S, Cl, K and their compounds, but only Al stayed on the fully clean surface and the rest elements disappeared on the fully cleaned surface, which indicates they were part of the soiling.

The test results in this section showed that the chemical substances on the stone and brick surfaces were largely different for different types of stones and bricks. Some chemical elements and compounds largely decreased or increased after cleaning, but the chemical elements C and O always remained at large proportions of all the chemical elements in the stones and brick. The chemical elements and compounds that disappeared may be the main compositions of the soiling deposited on the stone and brick surfaces. As the masonry façade was always exposed to the open environment for a long time and even centuries, chemical reactions would occur, which would nevertheless form various chemical compounds or multi-components on the stone and brick surfaces from the polluting gases in the air.

8. Conclusions

In this study, a series of physical and chemical tests were conducted to extensively investigate the changes in the characteristics of seven different types of popularly used masonry stones and bricks in Edinburgh during the cleaning process, i.e., yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. The chemical analysis included micrographing the stone façade and detecting the chemical elements and compounds on the original dirty and fully clean stone and brick surfaces using the combined SEM and EDX techniques. This complete research work has contributed towards the building cleaning in at least three main aspects, i.e. systematic assessment of the physical and chemical characteristics of masonry stones and bricks during building cleaning, detection of the soiling deposited on the surfaces of masonry stones and bricks, and evaluation of cleaning effectiveness using grayscale imaging techniques [22].

The chemical investigations conducted using the SEM and EDX techniques showed that the chemical substances on the stone surface varied largely for different types of stones and bricks. Some chemical elements and compounds largely decreased or increased during the building cleaning, but the chemical elements C and O always remained at large proportions of all the chemical elements in the stones and bricks. As the stone façade was always exposed to the open environment for a long time, chemical reactions would occur, which could form various chemical compounds or multi-components on the stone or brick surface from the polluting gases in the air such as SO_2, H_2S, etc.. This would lead to the formation of the soiling on the stone surface. This study showed the way to detect such soiling using chemical analysis by monitor the changes in chemical elements and compounds during the building cleaning.

In summary, the investigations in this study indicated that the physical and chemical characteristics on the surfaces of masonry stones and bricks were all largely influenced by the building cleaning. For the types of stones and bricks assessed in this programme, a stone or brick with a higher cleaning degree always corresponded to a brighter and harder surface. An appropriate stone cleaning method could not only improve the appearance of the building but also protect the stones from quick decay and damage. However, further protection after building cleaning is still needed. Much effective research work has been done toward this aspect, e.g., using nanocomposites, polymer materials, etc.,as coating layers to protect the cleaned surfaces of historic buildings and monuments from further environmental erosion and weathering [26-29]. Meanwhile, the present study could help to pave the way for selecting more appreciate, economical and effective methods for cleaning existing listed masonry stone buildings. Further research is still under way on these issues and more results will be published later.

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