RECYCLING OF DEMOLISHED MASONRY RUBBLE

By

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DECLARATION

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In accordance with Napier University regulations governing the Degree of Doctor of Philosophy, the candidate submits this thesis as his own original research unless otherwise stated.

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ABSTRACT

The recycling of demolished masonry rubble as the coarse aggregate in new concrete represents an interesting possibility at a time when the cost of dumping such material is on the increase. With growing concerns over the environmental impact of aggregate extraction and the continued rise in aggregate demand in the UK, it is clear that the market is now there for recycled and secondary aggregates.

The present investigation consists of experimental and theoretical studies into the effects of using recycled aggregates to produce concrete instead of virgin aggregates. The aggregates used have been recycled from construction and demolition waste. The recycled aggregates were predominately made up of crushed bricks but the aggregates did contain impurities such as timber and mortar. New bricks were crushed to form an aggregate in order to investigate the properties of brick as a material without impurities.

The physical properties of the various aggregates were firstly examined and compared with granite aggregate, an aggregate proven in the production of good quality concrete. Concrete was then produced with the aggregates and all the physical and mechanical properties of the concretes were examined in some detail. The results showed that recycled masonry aggregates can be used successfully to produce concrete of an acceptable standard.

New test methods were presented in this investigation to determine brick porosity and water absorption. This involved the testing of broken brick fragments under vacuum, rather than the testing of whole brick units by 5hrs boiling or 24hrs submersion in cold water. The new test methods proved to be easy to perform and provided accurate results.

A new test method for estimating the strength of bricks was presented. This involved point-loading of masonry specimens to obtain strength index values. From the point-load results, equations were presented relating the strength index values of brick fragments to the compressive strength of whole brick units. This involved the

development of shape factors for different masonry specimens. The point-load test is easy to perform, presents a cheaper alternative to heavy compression machines and can be used on site to determine the suitability of recycled bricks as the aggregate in new concrete.

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Chapter 1

INTRODUCTION

Concrete is surely the most important civil engineering material used today. It is a strong, durable and very economic material which has been extensively used in the twentieth century to construct buildings, dams, roads and numerous other civil engineering structures. Concrete is produced by mixing cement, sand, coarse aggregate and water to produce a material which can be moulded into almost any shape.

The UK was once rich in natural sources of aggregate but many of these traditional sources have now been exhausted with the overworking of landbanks and increasing pressure from environmental groups and the public to preserve natural resources. This has meant that planning permissions for quarries are not being granted or renewed. Due to political and economic opposition, the production of sand and gravel by dredging is also no longer acceptable so it is becoming more and more important to find new aggregate sources as demand is unlikely to fall in the near future.

At the same time the number of readily accessible disposal sites around major cities in the world has decreased in recent years, with disposal volume and maximum sizes of waste being restricted. This has meant that the cost of dumping construction and demolition debris has increased substantially over recent years. This cost increase has been further fuelled in the UK with the introduction of a landfill tax in 1996 to tax the dumping of waste.

These environmental and economic factors are increasingly encouraging higher value utilisation of demolition and construction waste rather than simply landfilling the material. One way of addressing this issue is to recycle the material by crushing and grading it to produce aggregate for the production of concrete. This means that less waste material is dumped in landfill sites and the demand on natural aggregate sources is reduced so that the high quality natural aggregates can be preserved for high quality applications.

Recycling of construction and demolition rubble is not a new concept as several countries have been crushing waste to aggregate for a number of years but the aggregate used has mainly been used for sub-base material or as a capping layer. Britain has been slow to adopt recycling in the construction industry as the country has had substantial reserves of natural aggregates so recycling on a large scale has never really been economically viable.

There have been several barriers to recycling in the UK such as the lack of standards on the use of recycled materials, concern over the variability in composition of recycled aggregates, concern over the performance of recycled materials when used as aggregates and there has not been a big enough financial incentive to use recycled materials instead of primary aggregates, which can still be acquired relatively cheaply in this country as there is no government levy on primary aggregate extraction. Other barriers concern the actual processing of materials to produce recycled aggregates such as problems obtaining planning permission to recycle materials in urban areas. The reprocessing of construction and demolition waste can create noise, dust and increased road traffic which is not desirable in urban areas. However, to make recycling operations viable, the recycling plant must be located near to where the demolition and construction waste materials are arising, which is usually in urban areas.

There have been several investigations carried out into the possibilities of using crushed concrete and masonry rubble as the aggregate in new concrete. However, most of this work was carried out in the period immediately after the second world war using the demolished material which was available at that time. Only a small amount of work has been carried out using the types of brick and concrete which are commonly used in construction today and there is only limited knowledge on the subject in the UK. Use of recycled materials to produce concrete has mainly been restricted to the use of clean and uncontaminated crushed concrete which has been used successfully as the aggregate in new concrete.

The present investigation looks at the possibility of using crushed masonry rubble and demolition debris as aggregate in concrete. In order to study the effects of impurities on the properties of concrete, recycled aggregates and new crushed bricks were used.

Before any concrete was produced, a detailed examination of the properties of crushed recycled masonry rubble aggregates and new brick aggregates were carried out. The physical and mechanical properties of the recycled aggregates and the new brick aggregate were compared with the values obtained for the natural aggregate, granite. The ability of the recycled aggregates and the brick aggregates to comply with existing specifications for aggregates to be used in concrete, was also checked.

Tests were performed on fresh and hardened concrete and the performance of recycled aggregate concrete was compared to concrete produced with granite aggregate, an aggregate which was well proven in the production of good quality concrete. The effects of some impurities such as timber, rubber and mortar associated with recycled aggregates, on the properties of concrete were also investigated.

The study presented herein provides additional information to confirm, extend or adapt existing theory and procedures. The main objectives and scope of this study are outlined as follows:

1. To review current knowledge of recycling demolition and construction waste with respect to using it as the aggregate to produce concrete.

2. To review previous experience of recycling waste materials in this country and in other countries which have more sophisticated recycling techniques and technologies.

3. To identify any obstacles to recycling in this country, review the effects of the landfill tax on the economics of recycling and in general look at the advantages and disadvantages associated with the recycling of construction and demolition wastes.

4. To determine the physical and mechanical properties of recycled masonry aggregates and compare these values with aggregates which have been proven in the production of good quality concrete.

5. To develop an easy and portable new point-load test to determine the strength of small pieces of masonry rubble on site to check their suitability for use as the aggregate in concrete.

6. To examine the effects of impurities on the properties of new concrete by comparing the results of tests on concretes made with new crushed brick aggregate and recycled brick aggregate.

7. To develop a mix design which is suitable for recycled aggregates with acceptable levels of workability and an optimum water/cement ratio.

8. To study the physical and mechanical properties of concrete which has been produced with recycled aggregates and compare performance with concrete produced with a proven aggregate, granite.

The structure of the thesis can be summarised as follows:

Chapter 1 Introduction, scope and aim of the present investigation.

Chapter 2 Literature review of previous investigations into the recycling and reuse of demolished masonry rubble and the properties of concrete which has been produced with recycled aggregates.

Chapter 3 An experimental determination of physical and mechanical properties of the materials used elsewhere in the investigation to produce concrete.

Chapter 4 An experimental and theoretical investigation into the point-loading of masonry specimens in order to determine compressive strength.

Chapter 5 An experimental and theoretical investigation into the properties of concrete produced with new crushed brick as the coarse aggregate fraction.

Chapter 6 An experimental and theoretical investigation of the properties of concrete which has been produced with aggregates recycled from crushed demolition and construction waste.

Chapter 7 A general summary and conclusion with recommendations for further research.

Chapter 2
LITERATURE REVIEW

2.1 GENERAL

This chapter provides a review of previous work covering the use of demolition waste, especially crushed masonry, as the coarse aggregate in new concrete and the prospects of using such a material in modern construction. The review also includes information on recycling methods and the development of an easy and portable point-load test to estimate the strength of masonry specimens. The idea behind the point-load test was to use a simple and mobile piece of apparatus which can be used on site to assess the suitability of recycled masonry material for the use as aggregate in concrete.

Concrete buildings made with crushed brick have been known since early Roman times. An early example of this are the concrete channels of the Eiffel water supply to Cologne. In this structure the binder is a mixture of lime and crushed brick dust or other pozzolans of the time [1,2].

The first recorded mixing of crushed brick concrete with Portland cement was in Germany from 1860 for the manufacture of concrete products [2]. Systematic investigations have been carried out since 1928 on the effect of the cement content, water content and grading of crushed brick. Although, the first significant applications of crushed brick aggregate only date back to the use of rubble from buildings destroyed in the Second World War [2].

Broken brick along with burnt clay and earthenware were also used in the UK from the late 1800's, but even then their use was limited as engineers at the time recognised that the material did not have a high density [3].

In Germany during the reconstruction period immediately after the Second World War, it was necessary to satisfy an enormous demand for building materials and also necessary to remove the rubble from the destroyed cities. The quantity of this rubble in German towns was estimated at about 400 to 600 million cubic metres. By using this rubble it was possible not only to reduce site clearing costs, but also to fulfil the need for building materials.

In order to reuse the material, rubble recycling plants were set up in the then Federal Republic of Germany. These plants produced around 11.5 million cubic metres of crushed brick aggregate by the end of 1955, with which 175000 dwelling units were built [2]. By the end of 1956 statistics show, that about 85% of all building rubble in the Federal Republic of Germany had been cleared. This meant that there was no longer such a need for recycling demolished material [2].

Rubble was also recycled in the UK after the second world war, although to a lesser extent than in Germany. It applied more particularly to redundant defence structures which were mainly brick masonry constructions. These were used because they were very seldom rendered, hence there was hardly any presence of impurities as would be the case with other types of construction [4].

Although other parameters apply nowadays, as regards the composition of rubble and demolition and recycling technologies, the experience gained during the post war years remains useful and interesting particularly in connection with recycling of masonry rubble for use as aggregate for the production of new concrete.

According to Trevorrow et al [5] the UK has been left behind somewhat in the recycling business. A European Economic Community (EEC) report produced in the late 1970's predicted that the amount of demolished material produced would increase considerably in the following thirty years and examined the possibilities of recycling this material. Many countries like Belgium, West Germany and the Netherlands took notice of this and ploughed money into research. However, in the UK natural aggregates were readily available at very competitive prices, a situation that the aggregates industry predicted would continue for many years to come. For that reason the UK paid little interest to the EEC report. Later on the boom years of the 1980's fuelled vast economic expansion in the UK, but unfortunately this left us with the philosophy that waste generation was an acceptable by-product of growth and development.

2.2 RECYCLING PROSPECTS

Before investigating the use of recycled aggregate it is important to gauge whether or not there is a readily available supply of the material needed to produce the aggregate.

Forecasts have been made about the amount of rubble which will be available for recycling in the future. The annual concrete rubble production within the European Community is expected to reach 162 million tonnes in the year 2000, while that of brick rubble is expected to reach 52 million tonnes by the year 2000. These figures may be rather high due to the recession in the building market and hence only provide a rough estimate [2].

There are a number of options available for the management of demolition and construction wastes. These are shown in Figure 2.1.

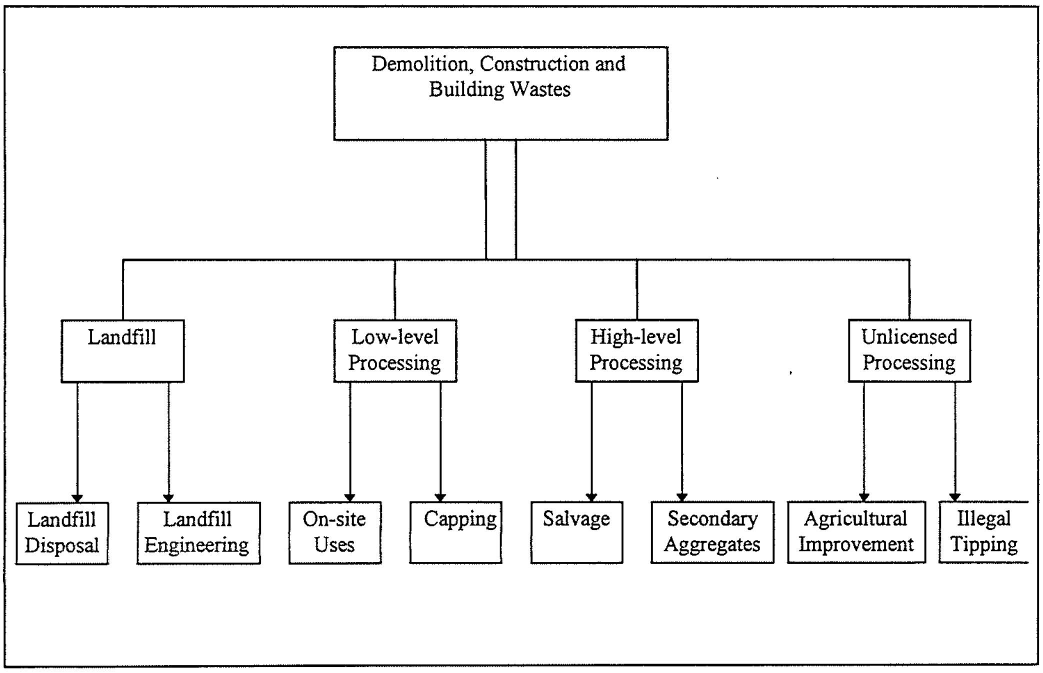


Figure 2.1 - Options for the management of demolition and construction waste

In the UK a study was carried out in 1991 by Ove Arup [6] into the amount of demolition and construction wastes which arise annually in the UK. They estimate that 70 million tonnes of demolition and construction waste arises annually in the UK. Of this amount some 44 million tonnes (63%) is recycled in some form or other. However, only 2.8 million tonnes (4%) is recycled to secondary aggregate; the majority of the material is recycled for low level uses on site or for use in landfill engineering. It is clear from this that there is some 26 million tonnes per annum which is not recycled in any useful form. The disposal routes for demolition and construction wastes are shown in Figure 2.2.

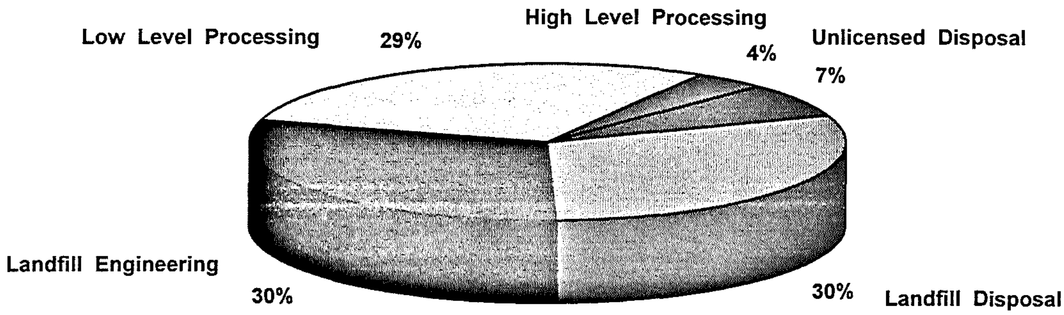


Figure 2.2 - Disposal routes for demolition and construction wastes

A survey of selected landfill operations carried out during Ove Arup's study, indicated that some 8 million tonnes of brick and concrete could be available for recycling annually in the UK if it were not deposited in landfill sites or used in landfill engineering. Of this amount, up to 4 million tonnes could be readily recycled as it is relatively clean and uncontaminated by other materials such as wood or metal. It is this material which could be most readily recycled as aggregate in new concrete. The remainder of the 8 million tonnes could be recycled if treated to separate components. There is also 7% of the total material which is disposed of to unlicensed sites. A proportion of this could be counted as recycled material and would no doubt contribute to the overall total.

From this it is possible to see that there is more than enough suitable material available in the UK to warrant recycling. Further advantages of recycling are that less primary aggregates are required hence conserving natural resources.

In 1988 Mulheron [7] split the available recycled material into 4 main categories. These 4 are as follows:

- Crushed demolition debris - Mixed crushed concrete and brick that has been screened and sorted to remove excessive contamination.

- Clean graded mixed debris - Crushed and graded concrete and brick with little or no contamination.

- Clean graded brick - Crushed and graded brick containing less than 5% of concrete or stone material and little or no contaminants.

- Clean graded concrete - Crushed and graded concrete containing less than 5% brick or stone material and little or no contaminants.

In 1994 a RILEM task force [8] on recycled aggregates made the recommendation that the classification of recycled aggregates be narrowed down into three main types:

- Type I - Aggregates which are implicitly understood to originate primarily from masonry rubble.

- Type II - Aggregates which are implicitly understood to originate primarily from concrete rubble.

- Type III - Aggregates which are implicitly understood to consist of a blend of recycled aggregates and natural aggregates.

Type III aggregates also have the following additional requirements

- The minimum content of natural aggregates is at least 80%.
- The maximum content of Type 1 aggregates is 10%.

These recommendations were made in order that government standards may be produced to promote and make easier the use of secondary aggregates in construction.

At present BS 6543 exists for the use of by-products and waste materials in building and civil engineering [9]. However, this standard only provides a very rough guide concerning the use of recycled construction and demolition waste as the aggregate in new concrete. It states that clean brick aggregates can be used to produce concrete of low strength but no other information is given concerning its production or performance.

According to O'Mahony [10] there is a large variation in material produced from different recycling operations. She believed this was because operators did not have standards to follow to produce acceptable recycled products. She stated that until this situation changed, consumer confidence would remain low.

2.3 DEMAND FOR AGGREGATE

It is important to look at whether there is a market for recycled aggregate and also a market for aggregate as a whole.

In the UK, national demand for aggregates has risen steadily since the Second World War [11]. This demand is chiefly influenced by booms in the construction and house building markets as well as government policies on road building. The UK consumption of crushed rock and sand in 1992 was 240 million tonnes obtained mainly by quarrying and dredging [2].

It was recognised in 1989 [12] that if the consumption of aggregate continued at the same rate, there would be a shortage of aggregate in many areas of the UK particularly the South East within a few years. The main problem was that many aggregate sources had been exhausted and planning approvals to develop new quarries were running at only about half the rate of extraction.

Road construction and maintenance account for about a third of the total aggregate demand every year, with new construction alone accounting for nearly 25% of the total demand. This demand is chiefly influenced by the Department of Environment, Transport and the Regions (DETR) who have overall control of local authority road building. Therefore it is central government which makes the demand for new road construction and subsequently aggregate demand.

Rose [13] reported that the water industry may play a major part in the demand for aggregate in the next few years. Since privatisation, investment by the water industry is set to increase from £1621M to £2557M. The British Aggregate Construction Materials Industries believe that this increase in spending will lead to an increase in aggregate demand from the water industry, having a considerable effect on the overall demand for aggregate. They are also worried that this increase may coincide with an increase in investment in the country's road building programme and an upswing in the house building market. Reeds [14] however disputes this, saying that there will only be a slight increase in aggregate demand over the next few years and the water industry will only have a small effect on the aggregate market.

MacNeil [15] suggested that the UK has enough suitable gravel and crushed rock to serve the market into the next decade. But if the demand increases at current levels, supplies are expected to run short within 20 years unless new aggregate sources are found. MacNeil believed that this gap between supply and demand could be filled by the use of secondary aggregates such as recycled demolition rubble and power station waste. If there is to be a swing to the use of secondary material the government must act now to encourage its use by restricting the supply of traditional aggregates.

2.4 OBSTACLES TO RECYCLING

In April 1994, the Department of the Environment released Mineral Planning Guideline 6, which commits the construction industry in the UK to a 100% increase in the use of secondary and recycled materials by the year 2006. The guideline suggests that this increase can be brought about by using secondary aggregates where they can replace primary aggregates technically, economically and environmentally. However, Carpenter [16] believed there is a price to pay for being eco-friendly. She suggested that potential users of secondary aggregates are put off by consumer tastes and over meticulous construction specifications. At present the cost of primary aggregates is still similar to that of secondary aggregates. Contractors are not likely to use secondary aggregates, with their variability in composition and properties, when an economical proven alternative is available.

Watson [17] stated in 1993 that the government needed to take tougher action if the use of secondary aggregates is to be encouraged. For this a number of options were available to the government: The price of virgin aggregates could be increased by more stringent controls on their extraction or by placing a levy on primary aggregates; a levy on mineral waste dumping could have been introduced - this has since been partly implemented by the introduction of the landfill tax but there is no different price banding for mineral waste; a change could have been made to road specifications to accommodate the use of secondary aggregates in place of primary aggregates, and development plan policies needed to be drawn up to preserve high grade materials for high grade applications. All this would have cleared up a lot of ambiguity surrounding the use of secondary material and allowed contractors to use the material with confidence.

Mclaughlin [18] cited overspecification as the main factor in the lack of use of secondary aggregates. He felt that designers were adopting a conservative approach as a result of concern regarding risk and liability. This is a view backed up by Rockliff [19] who reckoned good quality aggregates were being used in non-structural fill layers when instead they should have been used in asphalt or concrete. So if more use of secondary materials is to be made then the responsibility lies with clients and funding institutions and the designer, who should incorporate sustainability into the design [20].

There is also a complete lack of standards for the use and production of recycled materials and Chevin [21] believed that this meant that there was no incentive for demolition contractors to improve the quality of their product. In 1997, Dudgeon of the Highways Agency [22] admitted that many highway specifications were written around trusted recipes which could inhibit the scope for recycling in some instances. People involved in specifying materials for construction projects prefer to use materials with a proven performance and as a result many consultants in the UK will not risk specifying recycled materials. This reluctance to use secondary materials is often the result of a lack of well documented laboratory tests and field trials.

Road construction works account for approximately one third of the total aggregate consumption in the UK. The principal specification used for these works is the Specification for Highway Works (SHW) prepared by the Highways Agency. The common perception of the SHW was that it did not encourage the use of secondary and recycled aggregates. This was not entirely true so the Aggregates Advisory Service, set up by the Department of the Environment, published a digest document [23] to give guidance on where secondary and recycled aggregates can be used in highway works. Table 2.1 is taken from this document and shows where secondary and recycled aggregates may or may not be used in highway works.

It is possible to see from Table 2.1 that clean crushed concrete, containing a very low level of impurities can actually be used for a variety of applications. On the other hand, demolition waste which can contain high levels of impurities is only suitable for cement bound sub-base, embankment and fill and for a capping layer. Clean crushed masonry aggregate has not been considered but if clean crushed concrete can be used successfully for a variety of applications, it may be that if clean crushed masonry aggregate is separated from the demolition waste, it too could be considered for higher level applications including use as aggregate in pavement quality concrete. Table 2.1 shows where and where not, secondary materials can be used in highway works but the secondary aggregates must satisfy all the requirements in the specifications before being considered for use in highway works. Testing and monitoring of recycled aggregates is even more important than normal because there tends to be a higher level of variability in the composition of the material.

Table 2.1 - Current permitted UK applications of secondary aggregates for highway works (from Aggregates Advisory Service [23])

	USE						
Material	Cement bound sub-base	Embankment and Fill	Capping	Unbound sub-base	Cement-bound roadbase	Pavement quality concrete	Bitumen bound layers
Blast furnace slag	✓	✓	✓	✓	✓	✓	✓
China clay sand	✓	✓	✓	✓	✓	✓	✓
Crushed concrete	✓	✓	✓	✓	✓	✓	✖
Slate waste	✓	✓	✓	✓	✓	✓	✖
PFA	✓	✓	✓	✖	✓	✓	✖
Burnt colliery spoil	✓	✓	✓	✓	✖	✖	✖
Reclaimed bituminous material	✓	✓	✓	✖	✖	✖	✓
Spent oil shale	✓	✓	✓	✓	✖	✖	✖
Demolition wastes	✓	✓	✓	✖	✖	✖	✖
Furnace bottom ash	✓	✓	✓	✖	✖	✖	✖
Steel slag	✓	✖	✖	✓	✖	✖	✓
Unburnt colliery spoil	✓	✓	✖	✖	✖	✖	✖

Jakobsen [24] believed that one of the main difficulties with recycling demolished material is that the demolition works are not designed for materials recovery, giving mixed waste materials not suitable for any utilisation. Case studies have shown that with proper planning before demolition commencement, materials can be recycled more easily and more economically. The demolition of structures should really be considered during the planning stages before construction to ensure that relatively little waste is produced. Technical aspects of recycling should be considered during design, construction and building maintenance. This involves designing elements that are simple to dismantle and separate, limiting the use of bounded materials. A structure should be designed with several use options in addition to its initial use. This ensures that demolition in the early life of a building is not required. The current trend within the construction industry is to demolish old buildings and build new structures. Waste prevention oriented building designs need to include the potential for future uses. Opportunities to increase the potential future use of buildings include modular construction, elements for easy dismantling and open construction.

Webb [25] reported in 1991 that there was a great deal of debate going on between the British Aggregate Construction Materials Industries (BACMI), who represented the suppliers of primary aggregates, and the Department of Environment. The government wanted to put a levy on the use of primary aggregates in order to stimulate the use of secondary aggregates. This was to meet the governments forecasted aggregate demand of 421-490 million tonnes per annum by 2011. In 1991 only about 10% of the aggregates used were secondary aggregates, so it was the Conservative government's aim, at that time, to increase this figure by 2011 through taxes and levies. The BACMI and the Sand and Gravel Association (SAGA) felt that this was unfair and that the government was restricting the trade of the companies it represented.

Jenkinson [26] was of the opinion that most people advocate the principle of recycling. However, he suggested that the siting of waste and recycling facilities seemed to be fraught with difficulty, as was the granting of licences for mobile crushing plants. It seems that some government departments are encouraging recycling while others are stalling its development. The British Government Panel on Sustainable Development stated that "the use of recycled materials in all aspects of building will make an important contribution to reducing the sector's impact on the environment", but the industry in general feels that until other government departments work in harmony, progress in the use of recycled materials will be slow [27].

Sherwood [28] suggested that the main cause for concern was the environmental impact that aggregate extraction is having. He cited loss of mature countryside, visual intrusion, noise, dust, increased traffic and blasting vibration as the major problems associated with aggregate extraction. To stem these problems and meet aggregate demand, Sherwood suggested that more use should be made of waste and recycled materials such as china clay wastes, colliery spoil, power station wastes, asphalt road planings and construction and demolition wastes in road construction. It may be then that by reducing the amount of aggregate sources, through restrictions on planning permission, aggregate users will be forced to use secondary material.

However, Speare [29] reported that recycling also has its environmental problems. Aggregate extraction impacts are noise, dust, heavy vehicular traffic and despoliation of the landscape. Recycling plants also create noise, dust, vehicular traffic and visual intrusion and because the plants are often situated in urban locations, many more people are directly affected as a result.

As a result of the growing concern surrounding the use of secondary aggregates, the Building Research Establishment produced a report in 1995 for the Department of the Environment, concerning standards and specifications for the use of waste and recycled materials as aggregates [30]. In this report the authors recognise the fact that the current specifications hindered the use of secondary materials rather than promoting them.

More recently, Bland [31] of the Department of the Environment in 1997 announced the policy measures which were being undertaken to encourage reuse and recycling of waste products. These were namely:

- Increasing the cost of waste disposal.
- Increasing the relative price of primary aggregates.
- Developing specifications that do not preclude the use of recycled/secondary materials as aggregates.
- Encouraging and publicising demonstration projects.
- Funding research into the performance of recycled/secondary materials.

- Providing information on the opportunities for using alternative material as aggregates.
- Identifying suitable sites for recycling plants and good management practice.

Direct participation by government agencies was seen as the best way to lead by example and these opportunities included:

- Encouraging and accepting the use of recycled products in contract documents as alternatives to primary products.
- Setting a minimal requirement of recycled products (dependant on structure type) for public construction projects.
- Undertaking pilot projects with maximum use of recycled products and then publicising the results.

2.5 IMPLICATIONS OF THE LANDFILL TAX

Landfill tax was introduced in the UK on the 1st of October 1996. From this date anyone wishing to operate a landfill site was liable for accounting for the new tax to HM Customs and Excise.

The purpose of the new tax was to encourage business and consumers to produce less waste, to dispose of less waste in landfill sites and to recover value from more of the waste which is produced, for example through recycling.

The tax was introduced in 1996 at a rate of £2 per tonne for inactive waste and £7 per tonne for all other waste. The £7 per tonne figure rose to £10 per tonne in 1999 and this demonstrated the commitment of the government to continue the encouragement of recycling operations. Where a disposal for landfill contains both active and inactive materials, tax is payable at the higher rate for the whole load. The weight of waste to be disposed of is calculated by use of a weighbridge or by calculating the weight of the load on a volume basis. This means that an additional cost and time loss may be incurred to the disposer through the capital cost and operation of the weighbridge as well as the increased administrative burden. Unlike VAT, where intra-group transactions are disregarded for VAT purposes, movement of waste and landfill charges within the landfill tax group will still be subject to tax where the waste has been moved to another licensed site [32].

To encourage recycling and reuse, operators of landfill sites can apply to have part of their sites designated as tax free. This allows the operator to store waste that is to be sorted, recycled, reused or incinerated for a period of 12 months tax free.

In theory this should mean that recycled aggregates should become more readily available as more recycling operations will be created to avoid landfilling material which in turn should mean that recycled aggregates will become cheaper still.

Birch [33] believed that the landfill tax on its own was not enough to stimulate the use of recycled materials. He stated that without the markets to sell the additional materials into, the increase in recycling activity brought about by the landfill tax, would only be a temporary phenomenon.

An obvious problem with the landfill tax is that some of the less scrupulous operators will resort to fly-tipping in order to escape the levy. It is estimated that some 150,000 tonnes of waste material was dumped illegally in 1994, which cost the tax-payer more than £10 million to clean up. This figure has risen since the introduction of the tax and the Environment Agency found it necessary to introduce a 24 hour hotline for members of the public to report on possible fly-tipping [34].

The government in the Netherlands has a policy that re-use of construction and demolition waste must be increased to 90% by the year 2000. To achieve this value, they have taxed dumping in landfill at between £45 and £50 per tonne [35]. A landfill tax was introduced in Denmark and increased aggregate recycling from around 12% in 1985 to around 82% in 1993 [36]. One problem which occurred in the Netherlands after the introduction of landfill taxation was the dumping of large quantities of waste material on agricultural land which was exempt from the tax. This meant that waste recyclers could only charge modest amounts for accepting waste material, which meant that recycling was not receiving the financial boost which the landfill tax was meant to bring [37].

Hobbs [38] stated that the landfill tax was just one of the reasons why landfilling will become more expensive and less obtainable. His other reasons were that: existing landfill sites are being rapidly filled up; it is increasingly more difficult to establish new sites owing to restrictions on planning; new sites tend to be highly engineered with expensive gas and leachate collection systems, and aftercare responsibility has been introduced recently. This makes the site owner responsible for the site until the Waste Regulation Authority is satisfied that no pollution potential exists - this could be up to 50 years after site completion.

Since the introduction of the landfill tax, Murray [39] reported that the construction industry has started to make an attempt to minimise tax liabilities and reduce the amount of unwanted waste generated by projects. However, he reported that waste which would normally have gone to act as cover on biodegradable material at landfill sites, is now being used at exempt landfill sites where it is used for engineering features. Operators of mixed waste landfill sites rely on inert materials such as hardcore, soil and clay from construction sites for their site engineering. These materials are used to construct site roads, and to build the embankment walls of landfill 'cells', as well as for drainage and for cover and final capping. Construction companies are often given free or low cost tipping because of the value of the inert material to the landfill site engineer. If all inert materials were diverted to recycling operations, landfill sites would need to import hardcore material from elsewhere. This could raise landfill costs and would also cancel out some of the benefits of recycling construction and demolition waste. Another problem which has arisen, from the tax, is where to locate new recycling sites which are causing public concern because of pollution and increased lorry traffic.

A government review in 1998 [34] reported that since the introduction of the tax, there had been an increase in the re-use and recycling of wastes, although the exact effects of the tax were difficult to measure due to a lack of figures from before the introduction of the tax.

2.6 CONTAMINANTS IN RECYCLED AGGREGATE

One of the limiting factors on expanding the re-use and recycling of construction and demolition wastes is the need for predictable and consistent performance from the final product produced. One of the problems inherent in the use of recycled aggregates for manufacture of new concrete is the possibility of contaminants in the original debris passing into the new concrete and having detrimental effects on strength and durability. The following sections summarise the contaminants found in recycled aggregates.

2.6.1 Bitumen

The presence of asphalt in aggregates seriously reduces the strength of the concrete. Addition of 30% by volume of asphalt to recycled aggregate reduces the concrete compressive strength by approximately 30% [2]. From investigations [2] it was found that there was no obvious reasons why very stringent limits should be imposed upon the allowable contents of bituminous aggregate particles even though strength reductions are apparent.

2.6.2 Mortar

According to Sherwood [40] the fate of demolished brickwork is dependant on the type of bricks present and the type of mortar used. He stated that lime mortar can be easily removed from the surface of the bricks and this often leads to the recovery of strong whole bricks for the second-hand market. However, cement-containing mortar is much more difficult to remove than lime mortar so bricks that have this mortar adhered to it are usually crushed to aggregate. It is therefore inevitable that crushed masonry aggregate will have a considerable mortar content which should be taken into consideration.

2.6.3 Gypsum

Hansen [2] reviewed several systematic studies of the deleterious effects on recycled aggregate concrete of gypsum plaster in recycled aggregates due to sulphate expansion. From these studies it was concluded that stringent limits on gypsum content should be included in standard specifications for recycled aggregates. Recommendations suggest that sulphate resistant Portland cement should be used for the production of concrete where the recycled aggregate may be contaminated with gypsum.

2.6.4 Organic Matter

Many organic substances such as paper, wood, textile fabrics, joint seals and other polymeric materials are unstable in concrete when submitted to drying and wetting or freezing and thawing. Other types of organic substances, like paint may entrain large amounts of air in the concrete. It should be kept in mind that organic impurities are usually relatively light, which increases their content in concrete in terms of parts per volume.

2.6.5 Chlorides and Sulphates

The presence of chlorides, sulphates and other salts in recycled aggregates have little significant influence on the properties of plain concrete but in reinforced concrete they can give rise to corrosion of steel reinforcement. If sulphates are present in sufficient quantities they can react with cement compounds when concrete is produced. This reaction can cause excessive expansion and ultimately the deterioration of hardened concrete in damp conditions. Previous experience has found that crushed masonry aggregates have lower chloride and sulphate contents than crushed concrete aggregates [2].

2.6.6 Soils and Filler Materials

Demolished concrete and masonry is frequently contaminated by organic soil or clay. The clay is difficult to remove once incorporated in the material and clay minerals can be deleterious. The usual requirements for cleaning may be applied to specification, this is normally washing the waste over sieves with water.

2.6.7 Glass

Glass from windows can contaminate demolished material very easily, there are no values to which this contamination should be limited. Since plate glass has a similar density as concrete or aggregate, separation is very difficult. This is potentially dangerous as plate glass could take part in a alkali-silica reaction.

The specifications drawn up by a RILEM Task force on recycled aggregates [8] suggest maximum allowable values for impurities in recycled aggregate. These values are displayed in Table 2.2. In the table Type 1 aggregate is composed of 100% recycled brick, Type 2 is 100% recycled concrete and Type 3 is a blend of natural and recycled aggregates.

Table 2.2 - Classification of recycled coarse aggregates for concrete (from RILEM [8])

Mandatory requirements	**Type of aggregate**		
	Type 1	**Type 2**	**Type 3**
Min. dry particle density (kg/m^3)	1500	2000	2400
Max. water absorption (%)	20	10	3
Max. content of material with SSD<2200kg/m^3 (%)	-	10	10
Max. content of material with SSD<1800kg/m^3 (%)	10	1	1
Max. content of material with SSD<1000kg/m^3 (%)	1	0.5	0.5
Max. content of foreign materials (glass, bitumen, soft materials etc.)	5	1	1
Max. content of metals (%)	1	1	1
Max. content of organic material (%)	1	0.5	0.5
Max. content of filler (< 0.063mm) (%)	3	2	2
Max. content of sand (< 4mm) (%)	5	5	5
Max. content of sulphate (%)	1	1	1

SSD = Saturated surface dry density

2.7 RECYCLING PLANTS

The majority of recycling operations comprise of crushing and grading plant, either working on demolition sites or at fixed locations where delivered demolition and construction wastes are processed. At present they mainly produce crushed material for applications such as site fill and sub-base. Many operations are associated with other business enterprises and may be owned and operated by demolition, waste disposal or haulage contractors [6].

2.7.1 Layout

Plants for the production of recycled aggregates are quite similar to those that produce crushed aggregate from other sources. They incorporate various types of crushers, screens, transfer equipment and devices for the removal of foreign matter. The basic method for recycling waste is to crush the debris down to produce a granular product of given particle size. The degree of reprocessing carried out after this is determined by the level of contamination of the initial debris and the application for which the recycled material will be used. These include general bulk fill, base or fill in drainage projects, sub-base or surface material in road construction or new concrete. It has been found that for the recycling of Portland cement concrete specialised equipment such as pavement breakers and electromagnets for steel removal may be required [2]. However, all other equipment and procedures are those commonly used in the construction industry.

A number of different processes are possible for the crushing and sieving of demolition waste which mainly consists of concrete and masonry material. Figure 2.3 shows one of these processes. Installations working to one of these schemes are regarded as first generation processing plants. They are characterised by the fact that there are no facilities for the removal of any contaminants, with the possible exception of a magnet for the separation of reinforcing bars and other ferrous material. The most important step in the procedure is the crushing as this determines the particle size, grading and shape of the finished product.

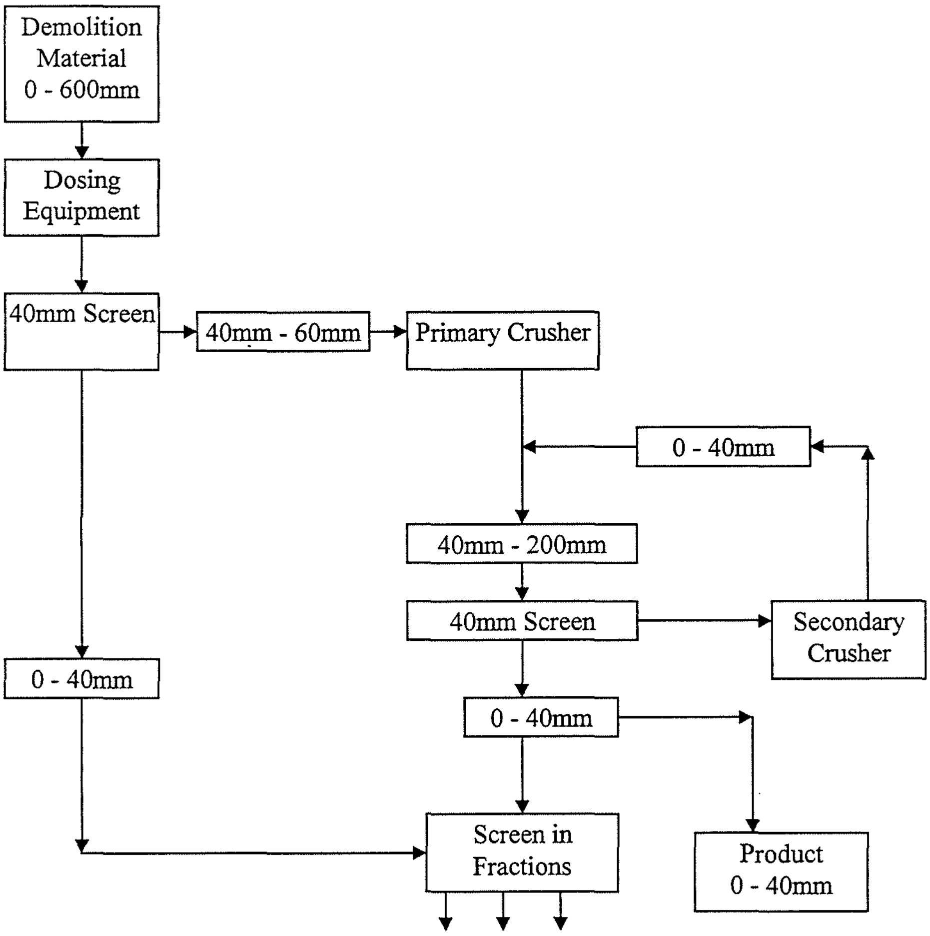


Figure 2.3 - Flow chart of a typical plant for the production of recycled aggregate

It is a fact that clean aggregate products cannot always be supplied from the demolition site. Demolished material often contains foreign matter such as metals, wood, hardboard, plastics and cladding etc. Based on the principle of first generation recycling plants, are second generation plants which have been adapted for small amounts of contaminants. These plants remove large pieces of foreign matter by manual or mechanical means before crushing. This is followed by cleaning the crushed product by means of wet or dry classification. The procedure for a second generation processing plant can be seen in Figure 2.4.

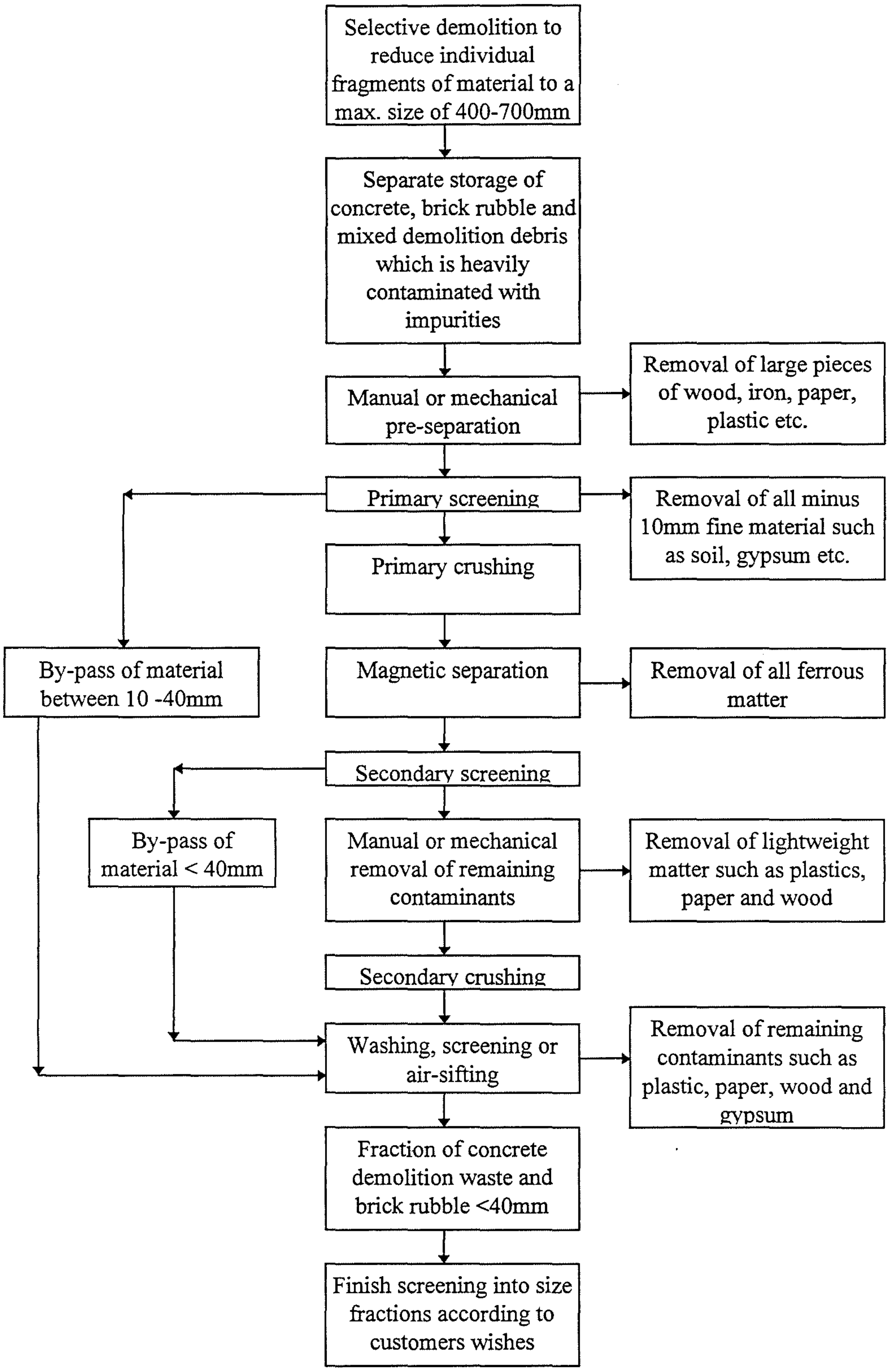


Figure 2.4 - Second generation processing for demolition waste

Recycled and processed aggregates made from mixed building rubble will usually contain less than 1% of impurities. This may be good enough for road construction purposes, but not necessarily acceptable for concrete aggregates.

In ideal future third generation plants, all demolished material should be supplied to the installation, processed and sold without the need to transport large quantities of residual matter to city dumps either from the demolition site or from the processing installation. This would be an ideal situation both from an environmental and an economic point of view. The first third generation recycling plant in the world where both rubble and wood wastes are processed is already operating in Rotterdam, the Netherlands [2].

2.7.2 Crushers

There are a number of different crushers such as jaw crushers, impact crushers, hammer mills and cone crushers which all operate on different principles, but the jaw crusher is used most exclusively in the UK [6].

2.7.3 Sorting Devices and Screens

In line with specifications for natural aggregate and crushed stone, recycled aggregate is required to be free from dirt, clay lumps, gypsum, asphalt, wood, paper, plastics, paint, textiles, lightweight concrete and other impurities.

The first stage in sorting the demolition debris is during the demolition process itself. By use of selective demolition methods, the contractor if given the incentive, can recover much of the material from the site relatively clean and uncontaminated. This could in theory save the contractor on disposal costs and potentially generate income through the sale of salvaged material. To achieve economic benefits, additional labour costs must be minimised by planning a source separation strategy and locating local processors that will purchase the material. In practice such orderly demolition procedures and separation techniques are not viable given the confinement of urban sites and the reality of time-penalty clauses. Once demolition has been completed and the debris taken to the recycling plant opportunities for sorting the debris are confined to selective stockpiling. This depends on the type of debris, degree of contamination and primary screening. This gives the plant operator the opportunity of dealing with oversize and undersize material separately.

According to Trankler [41] selective demolition techniques are essential if demolition waste is to be reprocessed into a desirable product. The author suggested that increases in the use of lightweight composite and insulating materials in buildings as well as chemical substances like coatings, seals, and bonding agents have meant that more care is needed when considering the material for re-processing.

In most recycling plants larger objects such as pieces of metal sheeting, wooden boards, beams, pieces of asphalt, loose reinforcing bars, sheets of paper, cloths and plastics are removed by hand before primary crushing. By passing the crushed materials over a set of scalping screens and washing all material below 10mm. Most of the dirt, gypsum, plaster and other fine impurities are eliminated after primary crushing. Self-cleaning magnets are strategically positioned over the conveyor belts to separate bits of reinforcing bars and other pieces of iron and steel from the stream of crushed aggregate.

In principle, fine-grained and lightweight contaminants can be removed from the rubble by air classification processes. The most frequently used of these techniques is dry-sifting, a process which can be carried out both horizontally and vertically. An important condition for obtaining a sufficient degree of separation is that the crushed product must be divided into four or five fractions when the product is of size between 0 and 40mm. Alternatively, lightweight contaminants can be separated from the heavier material by the use of directly applied water jets in combination with a float-sink technique. By the application of wet techniques, wood, hardboard, plastics and roofing felt as well as suspended sulphates and asbestos fibres can be effectively removed from the size range of 10-40mm. Sieving on a 10mm sieve screen prior to washing is recommended, because the 0-10mm fraction produces large quantities of sludge in the washing water [2,6].

2.7.4 Environmental Impact

Recycling of construction and demolition material presents both environmental advantages and disadvantages. The advantages are that it reuses substances and materials that would normally be classed as waste, reduces fuel use, reduces trucking and reduces the use of virgin aggregates. The disadvantages include the intrusion of trucks into areas where it may be undesirable, aesthetic concerns, potential of dust and noise pollution.

Operating of a crushing and screening plant is always accompanied by the generation of noise, vibrations and dust. Therefore, in the selection of plant location, environmental conditions of the surrounding area and legal requirements must be carefully studied and necessary counter measures taken.

The Town and Country Planning Acts state:

- Sites established for the purpose of waste disposal or recycling are developments which require planning permission.
- A major development may require the submission of an Environmental Impact Assessment when submitting a planning application.

And the Environmental Protection Act 1990 states:

- A waste disposal or recycling operation requires a Waste Management License issued by the Waste Regulatory Authority. Prior to 1st May 1994, this was dealt with under the Control of Pollution Act 1974.

- There is a Duty of Care which requires waste material to be correctly described, consigned and accounted for. Waste material has to be conveyed by a carrier licensed by a Waste Regulatory Authority with the use of consignment documentation.

- Crushing plant requires an Authorisation issued under The Environmental Protection (Prescribed Processes and Substances) Regulations 1991. Such Authorisations are issued by the Local Authority [6].

The simplest way to deal with noise is through distance. This can be said not to be a very practical means of noise pollution control in some urban areas, considering the typical noise level that is produced by a crushing and screening plant serviced by front-end loaders. Controlling the exterior noise produced by the machines is really dependent on the manufacturers of the machines. Although some improvements can be made by the operators, these include lining the hoppers of the primary crushers with rubber pads and placing mufflers on diesel engines. As for the noise produced by the recycling site the only remedy may be to construct acoustic screening or bunds from either the stockpiles of demolition waste or earth or a combination of the two. The noise level is usually monitored by local authorities, external consultants or health and safety officers.

Another problem that is created from the recycling plants is the contaminated run off to natural water courses. In earlier times demolition wastes were considered non-toxic wastes which could be disposed of at a city dump because they consisted almost entirely of mineral products. This is no longer true, since many building materials now contain components which are considered toxic from an environmental point of view, such as chlorinated carbon-hydrogens, phenols and heavy metals [2]. The operator must convince the authorities that there is no danger of pollution of ground water before he can sell his product. Although it must be remembered that roads have long been built with asphalt without giving rise to any problems, therefore it is hard to visualise why a small contamination of demolished concrete with asphalt should give any concern.

The last major problem which faces the operators of recycling plants is dust. The easiest control of this is water. Roads around the sites should be continuously watered as should stockpiles of crushed material. Fine mist water should be used at the crusher feed and screens. This spray must be very fine or the material will be too wet and the fine screens will blind. A wetting agent added to the water will give better dust control with less water.

It is possible to see that many environmental factors have to be taken into consideration when locating recycling plants. As well as these factors, the operator has to locate in close proximity to demolition arisings and to the market for processed materials. Taking this into account it is usually favourable for recycling plant operators to locate in large urban areas, where a continual flow of demolition material can be guaranteed rather than the spasmodic flow of material associated with more rural areas. The recycling site also has to be of considerable size to store large stockpiles of processed materials which have to be kept segregated and above all the plant has to be profitable due to the large initial capital cost of plant and equipment.

2.8 USING CRUSHED BRICK AS COARSE AGGREGATE IN CONCRETE

2.8.1 Introduction

There have been several investigations into the possibilities of using crushed brick as an aggregate in concrete. However, most of this work was carried out in the 1940s and 1950s using the type of bricks which were available at that time.

More recently, Akhtaruzzaman and Hasnat [42] carried out some research using well burnt brick as coarse aggregate in concrete. They found that it was possible to achieve concrete of high strength using crushed brick as the coarse aggregate. Their research was mainly concentrated on determining the mechanical properties of brick aggregate concrete, rather than the properties of the brick aggregate itself.

Khaloo [43] used crushed clinker bricks as the coarse aggregate in concrete. He reported only a 7% loss in concrete compressive strength compared with concrete made with natural aggregates. In contrast to this decrease in strength, there is a decrease in the unit weight of crushed brick concrete of 9.5%.

Only a small amount of work has been carried out using the types of brick which are commonly used in construction today and there is very limited knowledge on the subject in the UK. Much work has been carried out into the use of crushed concrete as the aggregate in new concrete. This is a similar aggregate to crushed brick in that it is a very porous material and problems arise when using it as an aggregate in concrete. It should be possible to apply many of the findings associated with the use of concrete aggregates in concrete production, to the use of clay brick as an aggregate in concrete.

2.8.2 Mix Design

Concrete mixes can be designed using crushed brick as the coarse aggregate in the same way as the design for proven aggregates. The only problem is that crushed brick aggregate is a very porous material and absorbs a large amount of the mixing water hence affecting workability. It is well known that apart from hard sintered clinkers, crushed brick and crushed rubble are highly absorbent aggregates and the higher the porosity of the parent bricks, the higher the absorption capacity of the aggregate.

According to Charisius et al [2], crushed brick must be completely saturated before being used in the manufacture of concrete. This is necessary to prevent the concrete from being "too thirsty". The absorption of crushed brick is estimated to be a value between 22 and 25% by weight in relation to the material in its dry state.

Test results [2] reveal that crushed brick becomes almost totally saturated with water after just 30 minutes submersion in water. Additional submersion for a further 24 hours produces only an increase of about 2% water absorption.

Khaloo [43] deemed pre-wetting of recycled clay brick aggregates to be unnecessary. He advocated mixing the coarse and fine aggregates along with the cement for 1-2 minutes before adding the mixing water. Then add the mixing water along with the amount of water that the aggregate absorbs for a period of 2 minutes and finally continue to mix for a further 3 minutes. Neville [44] does not recommend pre-wetting for any aggregate because the aggregate particles can become quickly coated with cement paste which prevents further ingress of water necessary for saturation. Consequently, the effective w/c ratio is higher than would be the case had full absorption of water by the aggregate been possible.

Barra de Oliveira and Vazquez [45] carried out a full study on the influence of retained moisture in aggregates from recycling on the properties of new hardened concrete. They produced concretes with recycled aggregates which were prepared to various moisture content conditions (dry, saturated and semi-saturated). They found that the moisture condition of the aggregates had little effect on the compressive strength of the final concrete but flexural strength was much lower for the concrete containing saturated aggregate. This finding is recognised by Neville [44] who reported that the moisture condition at the time of testing influenced the flexural strength. The main property affected by the aggregate moisture condition was found to be the concrete's resistance to freezing and thawing. The concretes containing dry and saturated aggregates were found to have a very low resistance to freezing and thawing while the concrete containing aggregate in the semi-saturated condition performed much better. It is thought that the semi-saturated aggregate led to the formation of a more solid and denser interface between the aggregate and cement paste, which in turn increased its resistance to freezing and thawing. It is clear from this research that if aggregates are to be soaked before use in concrete production, care must be taken to ensure that the aggregates are in a semi-saturated moisture condition and not a saturated condition.

Bairagi et al [46] worked on the development of a mix design procedure for recycled aggregate concrete. Their work involved the use of crushed concrete as the aggregate in new concrete but as the properties of crushed concrete and crushed brick aggregates are similar, the development of a mix design using crushed brick should also be similar to that of crushed concrete.

If crushed brick is to be used to produce concrete which is to be placed by pumping, some special considerations should be made [47]. As natural gravels are normally rounded and a wide range of sizes are available, they generally make better pump mixes than crushed rock aggregates. This is because crushed aggregates contain a proportion of dust which can cause high pipeline friction when pumped. This is a factor which must be addressed when using crushed brick aggregate which has a high proportion of dust.

Schulz [48] investigated the use of recycled rubble as the aggregate in new concrete. He reported that the water absorption is very significant for the mix design of concrete with recycled masonry rubble and in order to adjust the w/c ratio. For the mix design Schultz stipulated that the water content and the total water absorption of recycled masonry aggregate have to be known if the aggregate is not to be pre-soaked before use. However, evaluating the water addition on the basis of tested water absorption and water content is very difficult. Therefore Schultz, suggested that pre-soaking is the only sure way to assure the desired water-cement ratio is achieved and the desired workability levels are achieved.

It is generally accepted that crushed brick aggregate concretes can be made with all fresh concrete consistencies in the ranges from very stiff to plastic. Although it is also generally accepted that concretes containing recycled aggregates tend to be harsher and less workable than conventional aggregate mixes.

Hummel [2] reported that more favourable water contents and better workability of mixes can be achieved by using crushed brick and rubble sand, as opposed to using natural sand in the mixes. Possibly by using rubble sand another factor was introduced which may have an effect on the overall quality of the concrete. However, this rubble sand could easily be produced from the crushing of the bricks for use as coarse aggregate and hence presents an interesting way of manufacturing economical concrete.

Figure 2.5 shows the factors affecting the workability of fresh concrete. From this it is possible to see that the workability of a concrete mix can be improved in a number of ways. By prewetting crushed brick aggregate, acceptable workability levels can be achieved but this method is bad concrete practice and it is clear that something else is needed to improve workability.

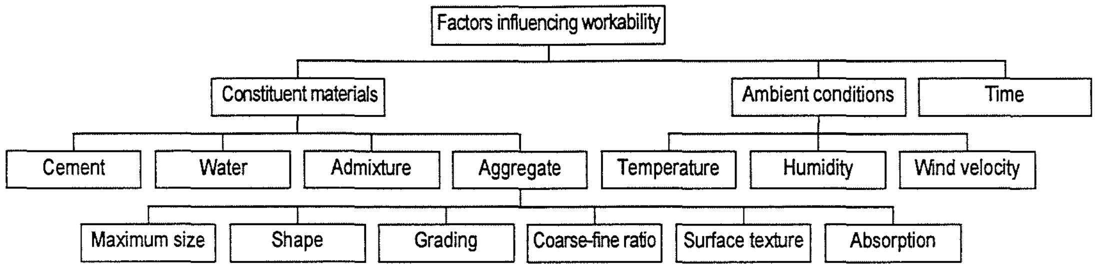


Figure 2.5 - Factors affecting workability of fresh concrete

According to de Vries [35] recycled aggregate is more angular in shape and has a higher water absorption so the total water requirement of the fresh concrete will be higher than fresh concrete made with gravel. He advised that moistening of the aggregate is possible at the storage bins. However, a disadvantage of doing this is the risk of local oversaturation. This in turn can cause problems in producing homogeneous mixes. de Vries proposed that a better solution is to add extra water in such amounts as to compensate for the absorption by the crushed aggregates, or better still, use only 20% recycled aggregate mixed in with virgin aggregates to avoid any workability problems. This is a view echoed by Kikuchi et al [49]. They used the similar aggregate, crushed concrete, and found that the deterioration in qualities of recycled aggregate concretes is proportional to the percentage of recycled aggregate used in the mix.

Mulheron and O'Mahony [50] compared the use of two recycled coarse aggregates, crushed concrete and mixed demolition debris containing crushed brick. They found that concrete containing crushed concrete as the coarse aggregate had a much lower workability than a control concrete containing a natural gravel as the coarse aggregate. While, the demolition debris derived aggregate produced concrete mixes of similar workability to the control. The authors attributed this to the fact that the individual particles in this aggregate were considerably rounder and less abrasive than the crushed concrete aggregate and concluded that it is the shape and texture of the aggregate particles which control the workability of the fresh concrete.

When using recycled aggregates, the dust content must be taken into account as it causes a reduction in workability [51]. If extra water has to be added to the mix to increase workability, then a loss of strength will be evident. If the reduction in strength is to be limited to around 5%, the maximum amount of dust which may be permitted ranges from 5% of the total aggregate content for low workability with a coarse grading, to 10% for low workability with a fine grading and to 20% for a mix having high workability with a fine grading.

Hansen and Narud [52] carried out trial mixes using crushed concrete as the coarse aggregate. Although this is a different aggregate to crushed brick, they are similar in that they are both porous aggregates and require more water during mixing. They reported that workability of recycled concretes decreases somewhat faster with time after mixing than the workability of mixes containing normal aggregates. This is a view echoed by Ravindrarajah [52] who reckoned that the use of different types of coarse aggregates has little influence on initial workability, but the decrease of workability with time is far greater when using porous aggregates. Hansen and Narud concluded that continued absorption of water by recycled coarse aggregate after mixing has little effect on the strength of recycled aggregate concrete. However, recycled aggregates always have a much higher coefficient of water absorption than natural aggregates, which could lead to practical difficulties in maintaining uniformity in the quality of concrete which is produced with recycled coarse aggregates.

Hansen [54] stated that the Department of the Environment Standard Mix Design Method could be used, with the following modifications to design concrete mixes containing recycled aggregates.

- When designing a concrete mix using recycled aggregate of variable quality, a higher standard deviation should be employed in order to determine a target mean strength on the basis of a required characteristic strength.

- When coarse recycled aggregate is used with natural sand, it may be assumed at the design stage that the free w/c ratio required for a certain compressive strength will be the same for recycled aggregate concrete as for conventional concrete. If trial mixes show that the compressive strength is lower than required, an adjustment of the w/c ratio should be made.

- For a recycled aggregate mix to achieve the same slump, the free water content will need to be approximately 10 litre/m^3 higher than for conventional concrete.

- If the free water content of a recycled aggregate concrete is increased, the cement content will also need to be higher to maintain the same w/c ratio.

- Trial mixes should be made to obtain the required workability, most suitable w/c ratio and the required strength.

The same author [2] reported that depending on the type and composition of crushed masonry aggregate, the cement requirement may be up to 20% higher than for normal concrete containing natural aggregates. If recycled masonry is used for the fine aggregate fraction as well as the coarse, then the cement content will be even higher. Figure 2.6 shows the relationship found by Hansen [2] between cement content and concrete compressive strength for crushed masonry aggregate.

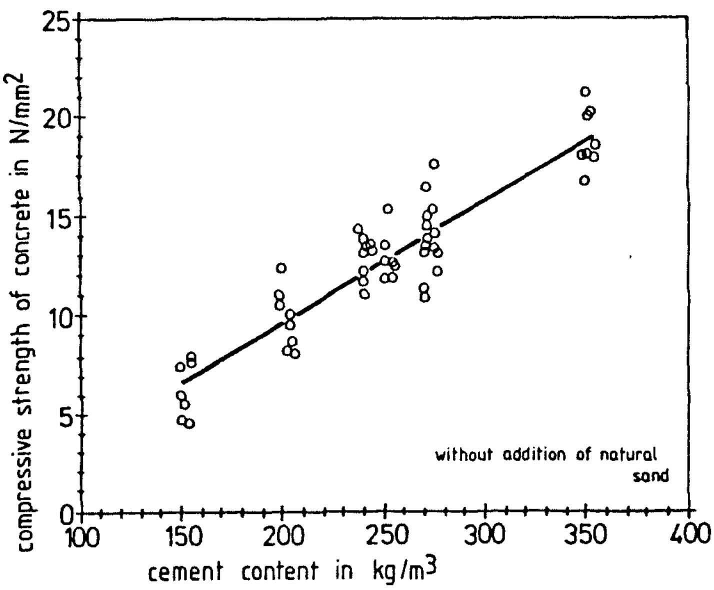


Figure 2.6 - Compressive strength of crushed brick concrete as a function of cement content (from Hansen [2])

2.8.3 Particle Strength

Hummel [2] carried out experiments into particle strength using aggregate from bricks of different strengths. He found that no relation existed between the strength of impact crushed material and that of the bricks. However, he did state that there was a relation between the particle strength and the final compressive strength of the concrete. It will be interesting to see whether or not this relationship still exists when modern bricks are tested.

2.8.4 Quality Control

Even when rubble was recycled from war damaged buildings, strict quality control measures were applied to rubble aggregates to prevent failures which could have brought recycled rubble materials into disrepute. The use of demolition and construction waste often means that the material arriving at the recycling plant is from multiple undocumented locations so careful control and frequent testing of the recycled products produced is vital [55].

One of the problems with using recycled brick aggregates from demolition sites according to Buck [56], is a risk that the sulphate content may be undesirably high. This is usually due to contamination with gypsum plaster so material should be properly screened before use as aggregate in concrete.

When recycling plants receive material from demolition sites, visual inspection of the material is the main, and sometimes only, method of quality control. The visual inspection can vary from looking at the load while still in the truck to tipping out the load and reloading it if it is found to be unsatisfactory. Some operators ask for source documents or may even choose to view the material at the demolition site before it is despatched.

In order to obtain good quality recycled aggregate from demolished material the contaminants should be removed before the material is crushed [57]. This is best done at the construction site itself, where contaminants such as wooden fixtures, plumbing and windows can be removed for separate recycling plants. After crushing, other contaminants such as wood, metal and plastic etc. can be picked out by hand along an exit conveyor belt or by a magnetic separator. Finally the material can be washed to remove dust and small particles of wood from the aggregate.

In 1985 the Association for Quality Control of Recycled Building Materials was established in the former Federal Republic of Germany. This association grants the manufacturers of recycled building materials the right to use a quality stamp of approval if their material is of an acceptable standard. At the moment these standards only exist for material which is to be used in road construction but maybe in the future this will be expanded to cover all applications [2].

Presently there exists standards in Britain covering the use of some waste products such as pulverised fuel ash, but at present no standards exist for the utilisation of waste concrete and masonry as aggregates in concrete. However, their use as an aggregate has been recognised as standards exist for the use of secondary aggregates as sub-base in road construction but no standard includes definitions of these products or the levels of acceptable contamination.

Quality control is introduced so that customer requirements are met and quality products are supplied. The customer demands materials which are to specification, are fit for purpose, consistent and at the right price. For recycled materials these requirements can be met through a quality management scheme, clear structure of control and also through testing of the finished products for certification. Without this type of quality control, producers will find it hard to sell their recycled products at a profitable price. However, quality control itself increases the cost of using recycled aggregates as quality control procedures have to be more intensive than the controls which have been used for natural aggregates. In particular, checking chloride and sulphate contents are not part of the normal daily routine of the concrete testing laboratory and extra bins/silos have to be provided at concrete batching plants for the segregated storage and treatment of recycled aggregates [35].

2.8.5 Crushing and Grading

In order to achieve the most desirable grading curves for concrete aggregate, a series of successive crushers must be used with the returning of any over size particles to the respective crusher. The best particle shape is usually achieved by primary crushing and then secondary crushing, but from an economic point of view, a single crushing process is usually most effective. Hammer and impact crushers are usually used for reducing the material to the required particle size in a single operation. According to Whitcher [58] primary crushing should reduce rubble to about 50mm pieces and on the way to the second crusher, electromagnets can be used to remove any metal impurities in the material. The second crusher is then used to reduce the material further to a particle size of about 14-20mm. Care should be taken when crushing brick material because more fines are produced during the crushing process than the crushing of concrete or primary aggregates [59]. These fines are not desirable because when they are included in concrete, they reduce the density of the concrete and hence its strength [4].

These crushing plants can be set up in central locations to receive material from the surrounding area. Although according to Servas [60] several operators find it more economical to move portable crushing plant to fixed dumping sites whenever sufficiently large stockpiles accumulate. However, mobile crushing plant is rarely sophisticated enough to remove all impurities so the material produced is usually used as site fill or for a capping layer.

A sieve analysis using a range of sieves is used to produce a grading curve for either individual aggregate fractions or their combinations. This is usually plotted on a logarithmic scale as the total amount of material passing a particular sieve versus sieve size. These curves can be used to monitor the size of the aggregates being used in concrete production. This is done so as to minimise the voids content within the concrete mix.

Grading curves do not take account of particle shape, but this according to Illston [61] does influence the voids content of the aggregate content. This is because more rounded particles will pack more efficiently with the addition of cement paste and will therefore have a lower voids content. When crushed brick aggregate has a fairly angular appearance compared to an aggregate such as crushed granite, the aggregate will not pack as efficiently.

According to Tavakoli and Soroushian [62], although using crushed concrete as coarse aggregate and not crushed brick, the mix proportions and the aggregate gradation have a significant effect on the strength of concrete produced.

When producing recycled aggregate by means of crushing and grading, a large percentage of recycled fines is produced. These recycled fines have been successfully used in the production of concrete blocks for beam and block flooring with only a small decrease in strength [63].

2.8.6 Porosity and Absorption

The porosity of aggregate, its permeability and absorption are very important factors in influencing such properties of aggregate as the bond between it and the cement paste, the resistance of concrete to freezing and thawing, as well as its chemical stability and resistance to abrasion. The specific gravity of aggregate also depends on its porosity and as a result the yield of concrete for a given weight of aggregate is affected. According to Murdock and Brook [64] it is often useful to determine the absorption of an aggregate after only a few minutes soaking, as this rate of absorption provides an indication to the reduction in workability between mixing and placing when the aggregate is used to produce concrete.

The pores contained within aggregate vary in size over a wide range. The largest pores can usually be seen easily under a microscope or even with the naked eye. The smallest pores are usually larger than the size of the gel pores contained in the cement paste. Some of the aggregate pores are contained entirely within the solid; others are open onto the surface of the aggregate particle. The cement paste is unable to penetrate the aggregate particle to any great depth due to its viscosity. However, water can easily penetrate these pores, the amount and rate of penetration depends on pore size, continuity and total volume. It is therefore important to look at porosity closely because this variable will affect how much water is required in a concrete mix.

The porosity of most common natural aggregates such as granite has been looked into but very little is known about the porosity of crushed brick aggregate except that it is a relatively high value.

2.8.7 Strength of Aggregate

In general, when producing concrete the objective is to use as much aggregate as possible as this material is far cheaper than the cement binder. This means that the maximum possible aggregate size should be used, with a continuous grading of particle sizes from fine sand up to the coarse aggregate. The grading of the aggregate is done so as to minimise the void content of the aggregate mixture and hence minimise the amount of cement paste required. Normally aggregate occupies between 70-80% of the total concrete volume so the strength of this aggregate is therefore very important to the final strength of concrete.

The compressive strength of concrete cannot exceed the strength of the major part of the aggregate contained therein, although it is very difficult to determine the strength of the individual particles. In fact aggregate strength characteristics usually have to be obtained by indirect tests, such as crushing strength of prepared rock samples, crushing value of bulk aggregate, impact test and performance studies of aggregate in concrete. The latter simply refers to previous experience of using such an aggregate in concrete or a trial use of the aggregate in a concrete mix known to have a certain strength with previously proven aggregates. If the aggregate under test leads to a lower final concrete compressive strength, and in particular if numerous aggregate particles have been fractured after the concrete has been crushed, then the strength of this aggregate must be lower than the aggregate for which the mix was initially designed for. In such a case the aggregate being tested must only then be used in concrete of a lower strength.

2.8.8 Classification of Crushed Brick Aggregate

Aggregates are usually obtained from natural sources, such as gravel deposits and crushed rocks or specifically manufactured for use in concrete. However, in this case it is proposed to use an aggregate, namely crushed brick aggregate, which has been specifically manufactured for another purpose. It is common practice to group the aggregates in terms of their density or specific gravity.

Many different types of natural materials have been employed in the production of concrete, including gravels, igneous rocks such as basalt and granite and the stronger sedimentary rocks such as limestone and sandstone. The mineral constituents are not of great importance, as long as the rock is of sufficient integrity and strength for use in concrete. All these rocks have a specific gravity in the range of about 2.55 - 2.75 [61], and will produce concretes with similar densities, usually in the range of about 2250 - 2450kg/m^3 depending on the mix proportions.

Where concrete of high density is required, for example in a nuclear reactor, heavyweight aggregates may be used such as barytes or steel shot. Concrete densities of up to 7000kg/m^3 can be achieved by using such aggregates.

Lightweight aggregates are used primarily to produce lower density concretes, which are advantageous in reducing the self weight of structures and have better thermal insulation than normal weight concrete [61]. The reduced specific gravity is achieved from a greater amount of air voids within the aggregate particles. The price to pay by using a lightweight aggregate is that there is normally an overall reduction in the concrete strength. The practical range for density of lightweight concrete is between about 300 and 1850kg/m^3.

Akhtaruzzaman and Hasnat [42] reported that concrete made with crushed brick as the coarse aggregate has a density between 2000 and 2080kg/m^3. This means that crushed brick cannot be classified as a normal weight aggregate or a lightweight aggregate as its value falls somewhere between the two.

2.9 PROPERTIES OF CRUSHED BRICK AGGREGATE CONCRETE

2.9.1 Compressive Strength of Brick Aggregate Concrete

Akhtaruzzaman and Hasnat [42] report concrete cube compressive strengths of between $22N/mm^2$ and $42N/mm^2$ at 28 days, for crushed clay brick aggregate concrete, with the w/c ratio being the main influence on strength. They produced concretes using crushed brick aggregates with water/cement ratios of between 0.54 and 0.88. These results compare favourably with Khaloo [43] who produced concrete of between $26N/mm^2$ and $41N/mm^2$ for different proportions of crushed brick aggregate.

Zakaria and Carbrera [65] produced concrete containing crushed brick as the coarse aggregate. They found that crushed brick aggregate concrete had a relatively lower strength at early ages than normal aggregate concrete. The authors attributed this characteristic to the higher water absorption of crushed brick aggregate compared with gravel which was used as the control aggregate. However, their investigation also found that crushed brick aggregate concrete had a relatively higher strength at later ages which they attributed to the pozzolanic effect of the finely ground portion of the brick aggregate.

2.9.2 Tensile and Flexural Strengths

Khaloo [43] found that there is an increase in tensile strength of around 2% in crushed brick aggregate concrete compared with concrete made with natural aggregates. They put this down to the rough surface of the crushed brick which provides a better bond between the concrete matrix and the coarse aggregate. They also reported a 15% increase in flexural strength which they also think is due to the improved bond between the cement paste and the coarse aggregate.

This can be compared with Hansen [2] who reported a 10% increase in tensile and flexural strengths when using crushed brick as the aggregate in concrete compared with normal aggregates. He also reported that flexural strength increased linearly as compressive strength increased when using crushed brick aggregate to produce concrete. This relationship for crushed brick aggregate concrete can be seen in Figure 2.7.

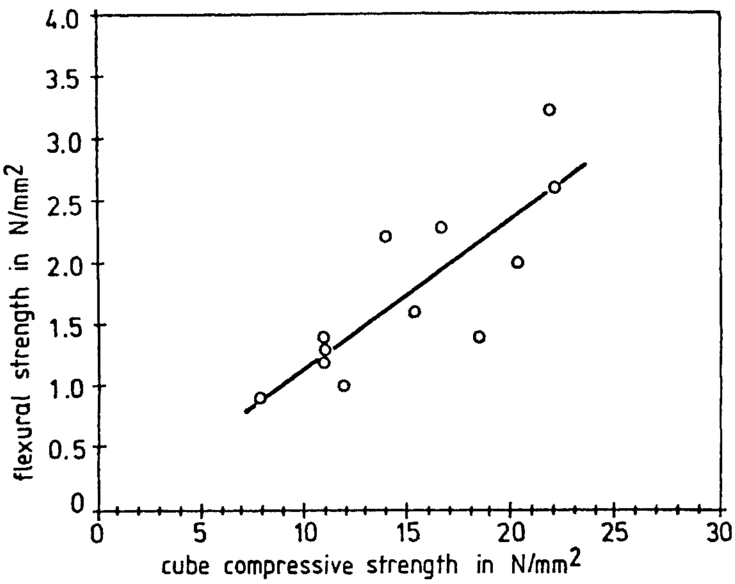


Figure 2.7 - Relationship between flexural strength and compressive strength for crushed brick aggregate concrete (from Hansen [2])

2.9.3 Bond of Aggregate

The bond between aggregate and the cement paste is an important factor in the strength of concrete. The bond can be defined as the interlocking of the aggregate and the paste owing to the roughness of the surface of the aggregate. A rougher surface, such as that of crushed aggregate particles, results in a better bond than when an aggregate with smooth surfaced particles is used. However, care should be taken when using a recycled aggregate to make sure that the dust content is not too high because this can effect the aggregate-cement paste bond [66].

The moduli of elasticity of the crushed brick aggregate particles and of the hardened cement paste do not differ much from each other. Consequently, no differential stresses between the two materials are induced, either by the applied load, or by thermal or hygrometric changes. Also, with aggregates like crushed brick, the water absorbed by the aggregate at the time of mixing becomes, with time, available for the hydration of the unhydrated remnants of cement. As this additional hydration occurs in the aggregate and cement paste interface zone, the bond between the aggregate and the matrix becomes stronger.

The determination of the quality of bond of aggregate is very difficult and no accepted test procedure exists. In general, when the bond is of good quality, a crushed concrete specimen should contain some aggregate particles which have been broken right through, in addition to the more numerous ones which have been plucked from their sockets. The bond using crushed brick aggregate may not be very good because when a brick is crushed, its particles tend to have fairly smooth surfaces. However, this may be counteracted by the fact that the brick aggregates are fairly angular, which leads to a larger aggregate particle surface area which can improve the bond quality.

2.9.4 Elasticity and Drying Shrinkage

The modulus of elasticity of crushed brick concrete is only between half and two-thirds that of normal concrete of the same strength [2,8]. This can be compared with values reported by Hansen and Boegh [67] who produced concrete with crushed concrete as the coarse aggregate. Their tests showed that the modulus of elasticity for concrete containing crushed concrete as the coarse aggregate, is up to 30% lower than that of normal concrete. This figure can even be lower according to Frondistou-Yannas [68] who reported a 40% reduction in the modulus of elasticity for recycled aggregate concrete with crushed concrete as the coarse aggregate. Also, results from these authors show that drying shrinkage and creep in concrete containing either concrete or masonry recycled aggregates is increased. These results show that the properties of crushed concrete and crushed brick aggregate concrete are similar although it is generally accepted that clean crushed concrete performs slightly better than crushed masonry when used as the coarse aggregate in concrete.

2.9.5 Structural Behaviour

Akhtaruzzaman and Hasnat [69] extended their research by looking at the structural behaviour of concrete made with crushed brick as the aggregate. Their investigation involved the testing of forty-eight reinforced concrete rectangular beams made with crushed brick as aggregate and containing no web reinforcement. The beams were tested under two-point loading to investigate shear and flexural strength with the only variables being concrete strength and shear span to effective depth ratio. Concrete beams containing natural aggregate were also tested so that the results could be compared.

The authors recorded a lower value of transitional span to effective depth ratio between diagonal tension failure and flexure failure for brick aggregate concrete beams. This indicates that the brick aggregate concrete beams have a higher shear strength compared to normal weight concrete beams produced with natural aggregate. They also reported that the difference between the shear strength of brick aggregate concrete beams and normal weight concrete beams is more pronounced when concrete strength is low. This increase in shear strength is due to the higher tensile strength of the material. The difference is about 15 to 35% depending on the concrete strength and the span to effective depth ratio. This crucially means that brick aggregate concrete beams will require less web reinforcement. This coupled with the added advantage of brick aggregate concrete beams having a lower unit weight, make it a suitable structural material with significant economic benefits.

The theoretical flexural strength was calculated using standard equations for normal weight concrete beams. When compared to the experimental results, the values obtained for brick aggregate concrete beams were in close proximity to the computed theoretical values. This means that when designing a brick aggregate concrete beam for flexural strength, the standard equations for normal weight concrete should be used as the relationship is the same.

2.9.6 Fire Resistance

In general, concrete is considered to have good properties in respect to fire resistance. The material is able to perform for a relatively high period of time and no toxic fumes are emitted when in contact with fire. Steel performs less well when subjected to fire so concrete is often used as a protective material. In a typical fire the temperature reaches about 500°C in about 10min and 950°C in 1hr so the concrete must be able to withstand rapid temperature rises as well as a high final temperature [70]. The rapid rise in temperature during a fire causes a build up of steam pressure in the concrete voids which can cause explosive spalling of the concrete surfaces. This usually occurs during the first 30min of exposure to heat. The concrete continues to degrade with the gradual separation of pieces caused by the formation of continuous fracture planes. During fires, temperatures of around 900°C are commonplace but only the outer layers of concrete members become drastically hot, the inner layers remain cooler hence protecting steel reinforcement.

Concrete strength is dependant on the cohesion of the cement paste, on its adhesion to the aggregate and on the properties of the aggregate itself. Many commonly used aggregates break down physically and/or chemically when heated to higher temperatures so the aggregate type is going to influence the ability of a concrete to withstand high temperatures.

Riley [71] reports that the factors influencing the penetration of heat into concrete relate to properties of the material itself at the onset of attack, coupled with changes in the physical and chemical composition of the concrete which result from the action of fire. The coefficient of thermal conductivity of concrete is largely dependant on the conductivity of its constituents, namely the cement paste and the aggregate. With an increase in temperature, the conductivity of concrete decreases as pore water is lost and the cement paste becomes dehydrated. As exposed concrete surfaces are heated these changes occur and an insulating layer of lower thermal conductivity is effectively produced. This layer acts as a refractory material and reduces the ingress of heat.

Khoury [72] reported elevated temperature tests on concrete containing crushed brick as the coarse aggregate. The tests revealed that concrete containing brick aggregate exhibited no loss in residual (i.e. after cooling) compressive strength for test temperatures up to 600°C, compared with Portland cement specimens and other common aggregates, which had revealed a significant loss in compressive strength for test temperatures above 300°C suggesting that the inclusion of the brick aggregate had an overall beneficial effect.

Newman [4] reported that crushed clay brick is one of the best aggregates for concrete which may have to resist fire and performs much better than similar concrete containing granite aggregate. The author found that crushed brick aggregate concrete lost only 22% of its strength when heated to 600°C, compared with a 77% loss in strength of the concrete containing the granite aggregate at the same temperature.

Brick aggregate is a thermally stable aggregate which is probably why it performs well when used as an aggregate in concrete subjected to high temperatures. In contrast, limestone aggregate is thermally unstable and when heated thermal expansion takes place which causes a considerable expansion and break-up of heated concrete when limestone is used as the aggregate. The expansion of individual and adjacent members can induce stresses capable of buckling reinforced members while at high temperatures. At these high temperatures, these stresses can cause cracking within the cement paste and around aggregate margins contributing to the overall break up of the material [71]. Other aggregates, such as carbonate decompose chemically when heated to high temperatures causing a weakening of the concrete structure.

Fire resistance of clay brickwork is an important characteristic since it has long been recognised that brickwork masonry is a very effective material for resisting and preventing the spread of fire. Its effectiveness in this role is largely due to the following characteristics : (i) a relatively high heat capacity; (ii) zero flammability and surface spread of flame; (iii) refractory properties which mean that it retains its strength and integrity up to very high temperatures approaching 1000°C in some cases. These properties mean that brick material does not catch fire itself, it inhibits spread of fire by conduction and radiation and is not easily breached by the fire. This means that when brick material is used as the aggregate in concrete, there should be no lowering of the concretes ability to resist fire.

Hansen [2] reported that crushed brick aggregate concrete had a very good fire resistance providing it could be kept dry. When wet, the internal steam pressure created in the case of fire can cause spalling of the recycled aggregate concrete. However, owing to the lower thermal conductivity of crushed masonry aggregate concrete compared with normal concrete, reinforced concretes are much better protected against early heating. This means that recycled masonry aggregate concrete keeps its structural integrity under fire for much longer than normal concrete.

2.9.7 Water Penetration and Absorption

The main agencies of deterioration of concretes require the presence and movement of water within the material itself. The measurement of well-defined material properties which describe the ability of a concrete to absorb and transmit water by capillarity is an important part of assessing the probable durability of a concrete [73]. Water is a necessary ingredient for the corrosion of embedded steel as it can carry chlorides and sulphates as well as other harmful ions. The presence of water can also cause freeze-thaw damage to concrete [74]. The surface skin of concrete is the first line of defence against the ingress of aggressive agents so tests have been developed to measure the quality of concrete at the near-surface zone [75].

The durability of concrete near an exposed surface is largely determined by the rate at which harmful agents can penetrate into the concrete. There are two parameters associated with concrete water absorption:

- The mass of water which is required to saturate the concrete - known as the effective porosity
- The rate of penetration - known as the sorptivity

According to Kelham [76] many concrete absorption tests have been developed but none of them can easily provide values for both parameters. The most useful test for absorption is the initial surface absorption test commonly known as the ISAT [77]. The test measures two absorption parameters combined, the rate of penetration and the effective porosity. The two absorption parameters can not be separated in this case because the volume of concrete saturated during the test is unknown. The test involves a water filled cap being sealed to the concrete surface, providing both a reservoir and a pressure head. The water flow into the concrete surface is measured at regular intervals up to a period of two hours.

The sorptivity is dependant on initial water content, temperature and fluid properties [78]. It is a material property which can be measured easily on its own by measurement of the capillary rise absorption rate.

Previous tests [2] have shown that water penetration depths are 50% higher in crushed brick aggregate concretes than normal aggregate concretes. This is an important factor because the penetration of the concrete cover by water containing chlorides can result in corrosion of the reinforcing bars [79]. Therefore, the cover to the reinforcement should be increased when using crushed brick aggregate concrete. Another important parameter in terms of durability is the permeability of the concrete. This is defined as the ease with which a fluid (liquid or gas) will pass through a porous medium, under the action of a pressure differential. According to Dhir [80], the permeability of concrete is most influenced by the w/c ratio and the type of curing that the concrete has been subjected to. Tests carried out by the author showed that permeability increases almost exponentially with increasing w/c ratio and adequate curing was just as important as a low w/c ratio if low permeability concrete was to be produced. Low permeability is desirable because low permeability concretes have better resistance to chlorides and abrasion [81].

Bamforth [82] reported that permeability of concrete reduces logarithmically as the compressive strength increases. The same relationship also exists between tensile splitting strength and permeability. The author stressed that durability of concrete cannot be inferred from a measurement of strength without a detailed knowledge of the curing history.

2.10 CONCRETE ADMIXTURES

2.10.1 Introduction

The use of admixtures can be traced back to the Romans [83] who used materials such as blood, milk and animal fat in their concrete mixes. It is thought that they used these substances to improve the concrete in its plastic state. Today admixtures, which are not an essential component of concrete, are commonly used in every day concrete practice as they offer many physical and economical advantages to the construction industry.

The use of admixtures will be investigated in the present study to try and improve the workability and quality of concrete containing crushed brick as the coarse aggregate.

2.10.2 Types of Admixture

The definition of an admixture is a chemical product which is added to the concrete mix in quantities no larger than 5% by mass of cement during mixing, for the purpose of achieving a specific modification, or modifications, to the normal properties of concrete [84].

These admixtures particularly benefit three key areas in which concrete is used: ready-mix concrete, precast bricks, blocks, tiles and pipes and factory produced mortars for extended on site use.

The admixtures themselves may be organic or inorganic in composition. The organic admixtures are usually produced from calcium, ammonium, magnesium and sodium lignosulphonates (these materials are often described as lignins and are by-products of the wood pulp industry commonly known as vinsol resins). Whereas, the inorganic admixtures are produced by mixing chemicals in the desired proportions [85].

Admixtures are commonly classified as seven types as follows:

- Water reducers
- Retarders
- Accelerators
- Water reducers and retarders
- Water reducers and accelerators
- High range water reducers or superplasticisers
- High range water reducers and retarders, or superplasticisers and retarders

To determine whether or not an admixture is required for a concrete mix, the criteria shown in Figure 2.8 should be considered during the mix design stage.

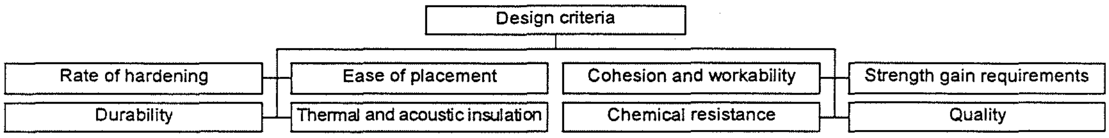


Figure 2.8 - Concrete design criteria

2.10.3 Advantages of Using Admixtures

Admixtures are advantageous in the production of normal concrete, reinforced concrete and concrete products such as precast concrete pipes [86]. The main advantage of admixtures is to improve the durability of concrete. Durability means the concrete's ability to withstand chemical attack, frost attack and continuous wetting and drying. The admixture usually used to improve frost attack is air entrainment.

Air entrainment is where bubbles are created in the concrete mix by adding a chemical solution to the mixing water. The entrained air bubbles are approximately 0.05 millimetres to 1.25 millimetres in diameter, some one thousand times larger than the capillary pores in the cement paste. Therefore, in air entrained cement paste, the capillaries are interrupted by a relatively large void as compared with normal cement paste. Because of surface tension effects these voids cannot fill with water from the capillaries, so under freezing conditions they behave as an "expansion chamber" to accommodate the ice formed. When the ice melts surface tension effects draw the water back into the capillary so that the air bubbles acts as a permanent safety valve, offering continued protection against frost damage [87].

The other major advantage of using admixtures in concrete production is that the workability of the concrete in its fresh state can be vastly improved. This property is improved by again using air entrainment. By the addition of an air entraining agent to the mixing water, a relatively stable network of small bubbles is created. These bubbles increase the spacing between the solids in the fresh mixture, which leads to increased cohesiveness as a result of increased viscosity and also a decrease in dilatancy [86]. The air bubbles also work in the same way as fine aggregate leading to a reduction in segregation of the constituent materials.

For high specification concrete mixes demanding more effective water use, a water reducing or plasticising admixture can be used. This admixture causes a significant reduction in water demand without affecting workability, with the additional advantage of improving early and ultimate strengths without additional cement. The admixture can also be used to increase workability so as to ease the placement of concrete in inaccessible locations [88]. This admixture can be used to improve the production of precast concrete, prestressed concrete and reinforced concrete.

If flowing concrete is required in inaccessible locations, in floor or pavement slabs or where very rapid placing is required, then a superplasticiser can be used. This is a more effective type of water reducing admixture with a reduction in the adverse side effects, but as a result is more costly. The admixture is particularly suitable for addition and redosing, if necessary, at point of placing to provide short term workability enhancement. This type of admixture is usually used in ready mixed concrete which is to be pumped into position or for precast concrete where there is an early strength requirement [89].

Forster [90] reported that the use of water reducing admixtures to lower the water content is effective in increasing strengths of concrete mixtures that contain recycled concrete as coarse aggregate. Similar research by Ravindrarajah and Tam [87] concluded that the quality of recycled aggregate concrete can be improved by using a water reducing admixture without affecting the workability of the concrete in its fresh state.

The setting time of concrete can be delayed using a retarding admixture which increases working times and reduces problems which can arise from delays in placing and compaction. Durability and compressive strength are also improved at all ages as well as a reduction in cohesion, which means placement of over cohesive mixtures is improved. This admixture is especially useful when concreting in hot weather, when the normal setting time is shortened by the higher ambient temperature [88] and can be used for prestressed concrete and reinforced concrete.

The setting time of concrete can also be accelerated using an admixture which accelerates stiffening and early hardening of the concrete. This allows early demoulding and faster mould turnaround as well as overcoming finishing delays, especially in cold weather. This sort of admixture is very useful for concrete repairs where a quick set is required or in winter where the normal setting times are increased due to the lower temperature [91].

2.10.4 Disadvantages of Using Admixtures

Admixtures, namely air entraining agents, can lead to a loss in compressive strength but this can usually be accounted for at the design stage. It is generally accepted that a five percent loss in strength will be incurred for every one percent increase in air content. However this loss in strength can be reduced as the addition of air usually allows for a reduction in water content as the air works as a plasticiser. Therefore, in practice a strength loss of 10-15% can be expected [89].

Problems often arise when using an air entraining admixture. This is because there are many factors which can affect the air entrainment obtained for a particular dosage of air entraining admixture. Sands of apparently the same grading may have significantly different effects on the level of air entrainment, depending on factors such as silt content, particle size distribution and particle shape. Where changes in sand source or content must be made, or where sand varies within the same source, a careful check must be made on the effects on air entrainment. Increased cement fineness or cement content will tend to decrease air content. Changes in cement source and type may also lead to changes in the admixture dosage required to obtain a particular air content. The presence of carbon or inorganic impurities may reduce the effectiveness of an air entrainer and require an increased dosage. This is a factor which would have to be taken into consideration when using recycled aggregates from demolition sites where impurities are commonplace. Temperature must also be taken into consideration when using an air entraining admixture. An increase in air temperature generally leads to a decrease in air content. Typically a rise from 10°C to

32°C may halve the level of air although it is not common to come across such a large temperature fluctuation. The last factor to take into consideration is the mixer type and transit time for the concrete which can decrease the air content of the concrete.

Another problem is that many of the admixtures available are not compatible with each other and if used may cause a reaction in the concrete and render it useless. Other admixtures have also been found to cause corrosion to reinforcement especially admixtures which contain chlorides.

Cost is a factor which should always be taken into consideration. The use of admixtures can be expensive but often this cost can be easily recovered if the admixture allows for a reduction in the cement content in the mix.

It may also be necessary to carry out trial mixes before using admixtures in order to determine the correct dosage of admixture to achieve the desired effect. Most admixtures come with recommended dosages, but if strange aggregates are used, trial mixes are required.

2.11 ECONOMICS OF RECYCLING

The economics of recycling is a very complex issue which has not been explored in depth. On one side of the equation, there is the cost of recycling demolished material which includes the cost of sorting, screening, crushing and transportation to the crushing plant as well as the cost of transportation to the place of use. On the other side, there is the cost of using primary aggregates. This includes the cost of extracting these aggregates either through quarrying or dredging and the cost of transporting the aggregates to their place of use. These cost factors are represented in Figures 2.9 and 2.10 for natural and recycled aggregates respectively.

There are however some hidden costs which are hard to put a price on. For primary aggregates, there is the environmental cost of obtaining the aggregates. This includes landscape scarring, noise, vibration, dust, visual intrusion and factors associated with the transportation of the end product. For recycled aggregates there is also noise, vibration, dust and visual intrusion of the recycling plant as well as the problems associated with transporting the material.

The economics of recycling are constantly changing usually due to government policies. The introduction of the landfill tax has been a big incentive to recycle and it may be that a levy on virgin aggregates will be the next measure to be imposed in the UK. The levy measure exists in other European countries such as Denmark [92].

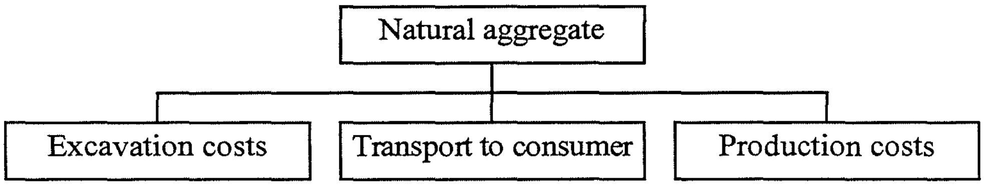


Figure 2.9 - Cost factors for natural aggregate

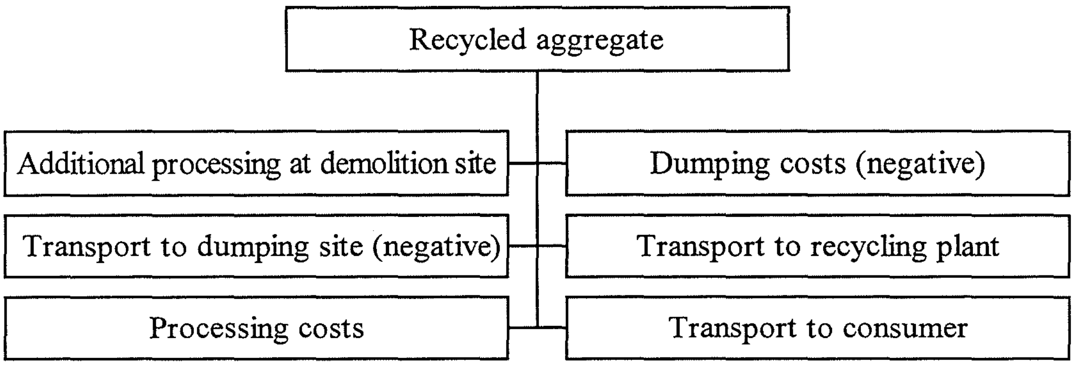


Figure 2.10 - Cost factors for recycled aggregate

If the waste is reused, the cost of dumping at the dumping site (including landfill tax) can be saved which is why this is a negative cost. It is difficult to assess the economics of recycling because variables like transport costs depend on factors such as distance [93]. There is also the cost that the recycled aggregates may not be of the same quality as natural aggregate and may not be able to perform as well when used as the aggregate in concrete. Desai [94] reported that, in general, it is unfair to expect waste materials such as crushed concrete or crushed brick to perform as well as normal aggregates when they are used to produce concrete with minimum changes made to existing concrete practice. He suggested that such waste materials should be considered initially for limited applications only, until further research is carried out. Nunes [95] stated that the use of secondary materials should be evaluated based on technical, economic and environmental factors.

It is possible to see that the economics of recycling are specific to the individual projects on which demolition and construction waste arise. Factors like programme restraints, location of recycling plant, location of landfill site and demand for recycled material all need to be taken into account for each project and recycling will only really be selected if it is the most economically viable option.

2.12 POINT LOADING OF MASONRY SPECIMENS

Before attempting to use crushed brick as the aggregate in concrete it is necessary to know the strength of the parent bricks. This is important as previous tests [2] have shown that the strength of the parent bricks will affect the strength of concrete produced with aggregate crushed from these bricks. This relationship between parent brick strength and concrete strength is illustrated in Figure 2.11.

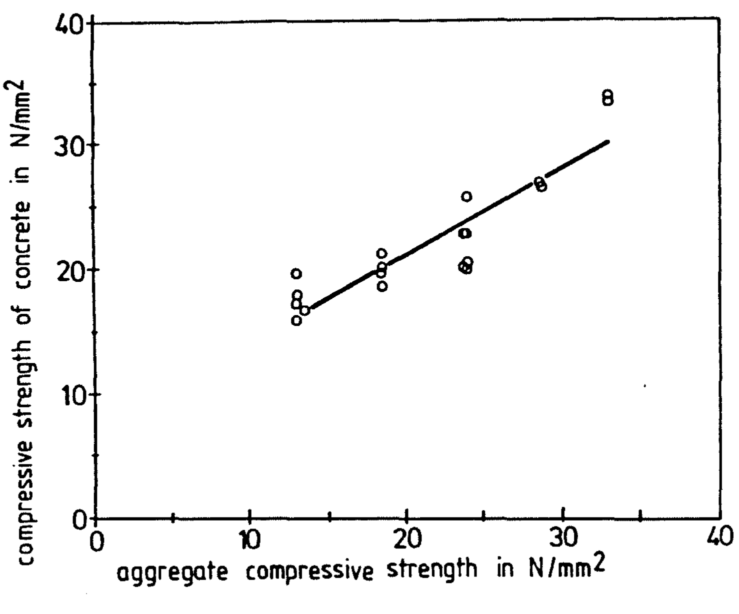


Figure 2.11 - Relationship between concrete strength and parent brick strength (from Hansen [2])

The present standard of assessing brick compressive strength is set out in BS 3921 [96], using large, heavy and very expensive crushing machines. A cheaper alternative is to use a simple point-load splitting machine. When applying basic theory, it is possible to study a relationship between the point-load strength of the specimen and its uniaxial compressive strength. The test uses portable equipment, the specimens require no machining and can take the shape of either specimens square in cross-section or irregular lumps. A single 'point-load strength index' can be obtained whatever the shape of the specimen, providing the shape is within proscribed limits and that a size and shape correction factor is made [97].

In point-load tests the critically stressed region lies in the interior of the specimen where surface irregularities have least effect. Strength can be expressed as the ratio of applied force to the square of the distance between platens, and provided that certain restrictions are placed on the shape and size of specimens the actual specimen geometry has little influence on the strength results. This means that types of point load test may be selected to suit the shapes of samples commonly available - typically either core samples or irregular lumps and for these tests no machining of specimens is required [98].

There are clearly advantages and disadvantages to the point-load test and the uniaxial compression test and these are outlined below.

Advantages of the point-load test:

- Smaller forces are needed so that a small and portable testing machine may be used.
- Specimens in the form of core or irregular lumps are used and require no machining.
- More tests may be made for the same cost and this allows for adequate sampling.
- Fragile or broken materials can be tested.
- Results show less scatter than those for uniaxial testing.
- Measurement of strength anisotropy is simplified.

Advantages of the uniaxial compression test:

- The testing procedure is better known and evaluated.
- Results are available for a wide variety of rock types and man-made materials, together with experience in linking.

This means that the quality of bricks being considered for recycling to crushed aggregate for concrete, could be assessed quickly, cheaply and on-site using whole bricks or bricks that have been partly broken up during demolition.

Research into the point-load strength test has been carried out since the early 1960's and the theory behind the point-load strength of rock specimens is well established. For purposes of examining its uniaxial compressive strength, bricks can be considered similar to rocks, as both are considered to be homogenous materials.

The point-load test is a simple and inexpensive test which can be carried out on site or in the laboratory. The test involves applying a point-load to the sample by means of a manually operated hydraulic jack. The sample is held between spherically truncated conical platens with a point of 5mm [98,99]. It has mainly been developed for the testing of rocks for classification and it was found that a correlation to within 20% existed between the point-load index and the uniaxial compressive strength [100]. Based on this, concrete cores have been tested and it has been found that a reasonable correlation exists between the point-load index, obtained from the point-load test on concrete cores, and the uniaxial compressive strength of the material [101,102,103].

The point-load test on irregular lumps, was developed in Russia, by Protodyakonov [98], to obtain a strength index using the following formula:

$$I_s = \frac{P}{V^{2/3}} \qquad \textbf{(Eqn. 2.1)}$$

In the formula, the strength index (I_S) is given as the rupture load (P) divided by the 2/3 power of the specimen volume (V). This gives an approximation of the cross-sectional area of the lump. The volume was determined using a sand-displacement technique. The international Bureau for Rock Mechanics incorporated the Protodyakonov test as a standard technique.

The test which was developed is an outgrowth of experiments with compression of irregular pieces of rock in which it was found that the shape and size effects were relatively small and could be accounted for and in which failure was usually by induced tension [104].

In Britain, the method was examined by Hobbs [98] with a view to classification of sedimentary rocks. His main criticism of the Russian method was that in laminated rocks the long axis of an irregular lump usually coincided with the plane of laminations, whereas the test requires it to be perpendicular. Specimen preparation is therefore difficult. He also expressed the view that strength measurements should not be restricted to a single orientation of the laminations, and that account should be taken of strength variations with the size of specimen. Hobbs used an alternative arrangement where irregular lumps, usually in the form of parallel-sided slabs that are easily obtained from sedimentary rocks, were compressed between flat plates, with the direction of compression perpendicular to the plane of laminations. Platen contact was therefore at several different points on the faces of the specimen. A strength index was obtained by dividing the rupture load by an average area perpendicular to the loading direction, this area was calculated as the ratio of the specimen mass to the product of specimen height and density.

Robins [105,106] used the point load test to estimate the compressive strength of concrete cores. He reported that a direct relationship existed between the point-load strength index and the compressive strength of the concrete. His investigation concluded that the length/diameter ratio of the samples should be greater than 1.2 otherwise strength results can be underestimated.

In France, the irregular lump test, devised by Protodyakonov was investigated by Diernat, Duffant and Maury [98]. They established that size, shape and orientation of the lump of rock affected test results. They demonstrated that for granite lumps the strength could be nearly double if the specimen were halved.

This was backed up by Bieniawski [107] who suggested that irregular lumps should be kept to a size of around 50mm and the depth to length ratio should be between 1.0 and 1.4 as illustrated in Figure 2.12.

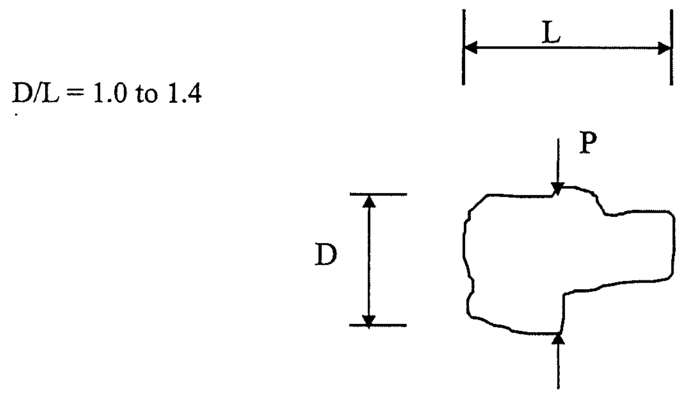


Figure 2.12 - Specimen constraints for irregular lump test

Hiramatsu and Oka [98] gave an alternative expression of strength index in terms of the ratio of the rupture load (P) to the square of the distance between platen contact points (D).

$$I_s = \frac{P}{D^2} \qquad \textbf{(Eqn. 2.2)}$$

The distance between the platens can be easily measured, but with Eqn. 2.1 the volume measurement using sand-displacement is inaccurate and difficult to measure. The authors showed that this formula gave a good approximation for irregular lumps and for other specimens.

In searching for a practical and reliable strength index test to estimate the compressive strength of bricks, the 'point-load strength tests' appeared suitable. This test was originally used to establish the tensile strength of rock materials. The test is now used to determine the point load strength index. Using the previous formula, the point-load can be applied to bricks, where the point-load tensile strength (I_S) is calculated from:

$$I_S = \frac{P}{D^2} \qquad \textbf{(Eqn. 2.2)}$$

where

P	=	the rupture load (N)
D	=	the distance between the two load platens (mm)

For bricks of different sizes compared to the normalised specimen, a shape factor (δ) can be applied to convert an irregular lump to a standard size. The implementation of the shape factor modifies Eqn. 2.2 into the Eqn 2.3.

$$I_S = \frac{\delta P}{D^2} \qquad \textbf{(Eqn. 2.3)}$$

An empirical relationship between the index and uniaxial compressive strength of brick material can be derived when a constant is introduced as a reasonable estimate by multiplying the index by (k). The modified formula is expressed as:

$$\sigma_C = k\,I_S \qquad \textbf{(Eqn. 2.4)}$$

The constant k can be found to assume different values depending on the material.

Chapter 3

MECHANICAL PROPERTIES OF MATERIALS USED IN INVESTIGATION

3.1 INTRODUCTION

The testing described in this chapter was performed in order to establish various properties of the eight different aggregate types used to produce concrete elsewhere in this investigation.

In order to investigate the use of different aggregate types as the aggregate in new concrete, it was first necessary to investigate the physical and mechanical properties of the aggregates themselves, as these properties will affect the properties of fresh and hardened concrete. The main aggregate properties influencing concrete properties are grading, strength, specific gravity, water absorption, porosity, shape, elasticity and surface characteristics. Results are presented in this chapter for grading of the aggregates, impact value, density, water absorption, porosity, tests on parent brick and impurities in recycled aggregate. The results have been compared with the limits set out in BS 882, "Aggregates from natural sources for concrete" [108].

Eight different types of coarse aggregate were used in this investigation. Five different crushed aggregates from new bricks, a recycled washed aggregate containing predominately masonry material, a recycled masonry aggregate and a proven natural granite aggregate. The reason for using crushed aggregate from new bricks was to investigate the effect of using clean crushed brick aggregates on the properties of concrete, rather than the effects of impurities which will be investigated by using the fully recycled aggregates. The granite aggregate was included in the experimental programme for comparison reasons.

This chapter presents the results of the experimental programme carried out to determine the physical and mechanical properties of all types of aggregate used in the investigation.

3.2 BRICK TESTING

The five types of new brick that were crushed to aggregate and used to produce new concrete are shown in Figure 3.1 and their dimensions are shown in Table 3.1. The Engineering B brick was only included for comparison and was not used as an aggregate to produce concrete. The reason for this was that the Engineering B brick was very strong and difficult to break up by hand to produce aggregate. Therefore, only a small amount of this brick type was broken up and tested so that comparisons could be made with the other types of aggregate used in the investigation.

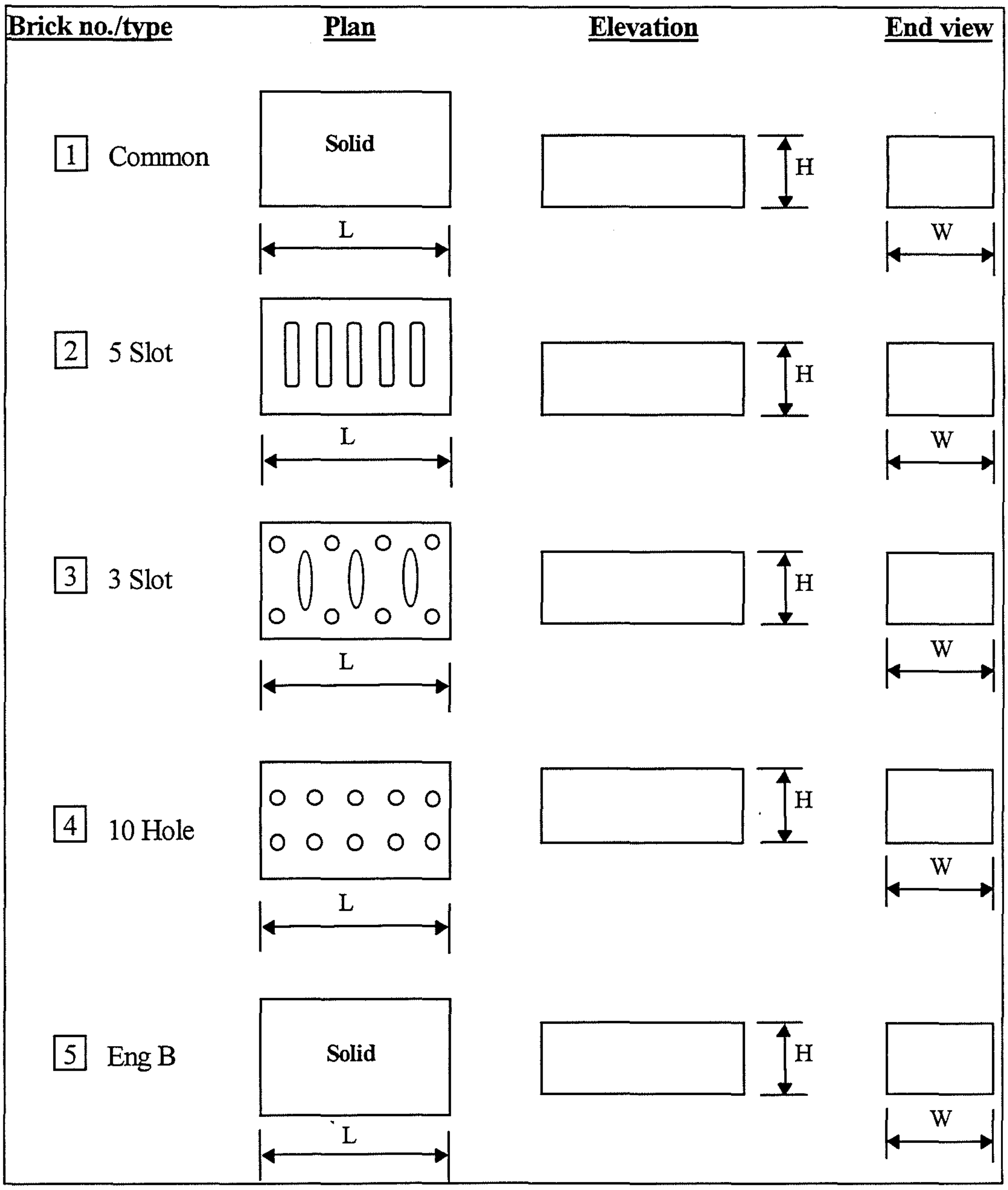


Figure 3.1 - Types of clay brick used in investigation

Table 3.1 - Dimensions of clay brick used

Brick no.	Length L (mm)	Height H (mm)	Width W (mm)	Diameter of holes (mm)	No. of holes	No. of slots	Width of slots (mm)	Length of slots (mm)
1	212	66	100	-	-	-	-	-
2	216	66	105	-	-	5	15	50
3	217	67	102	10	8	3	5 - 25	55
4	215	65	102	20	10	-	-	-
5	214	66	103	-	-	-	-	-

Before the new bricks were crushed down into a coarse aggregate, their compressive strength was required for comparison with the compressive strength of the concrete made with such bricks as the aggregate. To find the compressive strength of each brick type, tests were carried out in accordance with Appendix D of BS 3921 [96]. The only alteration made to the procedure was the number of each brick type tested. Instead of testing ten bricks, only five were tested. The brick compressive strength results are shown in Table 3.2.

Full bricks of each type were sawn into half bricks and tested to determine their compressive strength following the same procedure used for full bricks. This was done to provide more results to compare the physical and mechanical properties of the brick aggregates and new concrete with. The results for half-brick compressive-strength are given in Table 3.2.

Table 3.2 - Compressive strength of bricks used in investigation

Brick no.	Brick type	Full-brick compressive strength (N/mm^2)	C.V. (%)	Half-brick compressive strength (N/mm^2)	C.V. (%)
1	Common	39	6.6	43	3.2
2	5 Slot	53	5.8	65	7.3
3	3 Slot	68	5.2	79	9.0
4	10 Hole	81	3.3	84	7.3
5	Eng B	92	6.6	106	7.8

The results in Table 3.2 show that the different bricks used in this investigation represent a wide range of strength. The reason for using bricks of different strength was to study the effect of using the aggregate produced by crushing these bricks on the properties of new concrete.

3.3 AGGREGATE TESTING

3.3.1 Types of Aggregate used in Investigation

Three different kinds of crushed brick aggregate were used in the present investigation, these are as follows:

(A) New brick aggregate

The new brick aggregate was produced by breaking down whole new bricks. This was done by smashing up the bricks on a metal plate using a hammer. The large brick pieces were crushed again to smaller sizes and sieved until the grading of the aggregates complied with the grading limits set out in BS 882 for 20mm single sized aggregate (that is fractions passing the 20mm sieve but retained on 14, 10 and 5mm).

(B) Recycled washed aggregate

The 20mm recycled washed aggregate required no preparation as it was supplied as a 20mm single size aggregate from the recycling plant. This aggregate had been screened at the recycling plant to remove impurities but the material still contained a percentage of impurities such as timber, metal, glass, paper, rubber and mortar etc. They were not removed from the aggregate so that their effects on the characteristics of concrete could be monitored.

(C) Recycled masonry aggregate

The recycled masonry aggregate was produced by crushing larger masonry pieces supplied by the recycling plant as a 40-60mm aggregate. The crushed aggregate produced contained brick pieces from at least six different brick types. The only impurities present were pieces of mortar which were adhered to the bricks before crushing. When the bricks were crushed in the laboratory to a 20mm single sized aggregate, most of the mortar was reduced to dust and removed when sieved but some of the mortar still remains adhered to the aggregate particles.

(D) Granite aggregate

Natural crushed 20mm single sized granite aggregate, which had been successfully used before to produce good quality concrete, was used in the present investigation so that comparisons could be made with other aggregates.

To obtain a representative sample to carry out tests to determine the physical and mechanical properties, all aggregates were riffled in accordance with current British Standards [109]. Samples of the various aggregates were taken to carry out tests on impurities, grading, impact, relative density, water absorption and porosity.

3.3.2 Impurities in Recycled Washed Aggregate

A sample of the recycled washed aggregate was taken and the impurities were removed and weighed so that the percentages of individual impurities could be determined. The results of this analysis are shown in Table 3.3.

Table 3.3 - Percentages of impurities present in recycled washed aggregate

Impurity	Percentage by weight (%)
Paper	0.08
Plastic	0.11
Timber	0.12
Glass	0.45
Asphalt/felt	0.47
Metal	0.76
Ceramic	1.21
Total	3.2

From Table 3.3 it is possible to see that even after screening to remove metal and timber by magnets and flotation devices, some of this material still remains in the aggregate. There was also a percentage of mortar present in this aggregate but it was difficult to estimate the actual percentage because the mortar was mainly adhered to brick particles. With the addition of the mortar, the total percentage of impurities in Table 3.3 would probably be around 5%. The types and percentages of impurities in recycled aggregate are really dependant on the composition of the construction and demolition debris which has been processed. Sometimes the recycled materials contain a large percentage of plaster but in this case no plaster material was found but a large percentage of ceramic tile was present which is uncharacteristic of recycled material. It is evident that a standard is needed for recycled aggregates with maximum allowable values for named impurities which could be harmful when the material is used as an aggregate.

3.3.3 Sieve Analysis

A sieve analysis was carried out on all the coarse aggregates and fine concrete aggregate prior to their use in the experimental work. The appropriate nest of sieves used for each analysis was in accordance with the current British Standards for the grading of aggregate [110,111]. Table 3.4 displays the results of the sieve analysis for all the coarse aggregates used in the investigation, except for the Engineering B brick which was not used to produce concrete later in this investigation. The results of the sieve analysis for coarse aggregate were then compared with Table 3.5 to determine if the aggregates complied with the grading limits for 20mm single sized aggregates.

Table 3.4 - Sieve analysis results for all coarse aggregates

	Percentage by mass passing BS sieves for nominal sizes						
Sieve size (mm)	**1/Clay**	**2/Clay**	**3/Clay**	**4/Clay**	**6/Granite**	**7/Recycled washed**	**8/Recycled masonry**
37.5	-	-	-	-	100	-	-
20	100	100	100	100	95.0	100	100
14	25.9	23.5	18.0	18.0	24.4	44	22.8
10	5.6	5.7	3.0	4.0	2.5	12	5.0
5	1.5	0.6	0.5	1.0	0.4	5	0.5
2.36	0.4	0.3	0.5	0.5	0.3	3	0.2

Table 3.5 - Grading limits for coarse aggregate (from BS 882 [111])

Sieve size (mm)	Percentage by mass passing BS sieves for nominal sizes						
	Graded aggregate			Single-sized aggregate			
	40mm to 5mm	20mm to 5mm	14mm to 5mm	40mm	20mm	14mm	10mm
50	100	-	-	100	-	-	-
37.5	90-100	100	-	85-100	100	-	-
20	35-70	90-100	100	0-25	85-100	100	-
14	-	-	90-100	-	-	85-100	100
10	10-40	30-60	50-85	0-5	0-25	0-50	85-100
5	0-5	0-10	0-10	-	0-5	0-10	0-25
2.36	-	-	-	-	-	-	0-5

From Table 3.4 it is possible to see that all the aggregates tested had sieve analysis values which placed them within the limits for 20mm single sized aggregates from Table 3.5. This means that this variable was kept constant throughout the investigation so that the grading of different aggregates would not influence workability and strength when used in new concrete.

Natural fine concrete aggregate was used throughout the investigation. The results for the sieve analysis of the fine aggregate used are given in Table 3.6. and the grading limits for fine aggregate are shown in Table 3.7.

Table 3.6 - Sieve analysis of fine aggregate

Sieve size	Mass retained (g)	Mass passing (g)	% retained	Cumulative % passing	Cumulative % retained
10mm	0	349.7	0	100	0
5mm	0.9	348.8	0	100	0
2.36mm	42.3	306.5	12	88	12
1.18mm	84.8	221.7	24	64	36
600μm	108.7	113.0	31	33	67
300μm	65.6	47.4	19	14	86
150μm	36.1	11.3	10	4	96
Tray	11.3	0	4	0	100
Total	349.7				

Table 3.7 - Grading limits for fine aggregate (from BS 882 [111])

Sieve size	Percentage by mass passing BS sieve			
	Overall limits	Additional limits for grading		
		C	M	F
10mm	100	100	100	100
5mm	89-100	89-100	89-100	89-100
2.36mm	60-100	60-100	65-100	80-100
1.18mm	30-100	30-90	45-100	70-100
600μm	15-100	15-54	25-80	55-100
300μm	5-70	5-40	5-48	5-70
150μm	0-15	0-15	0-15	0-15

From Table 3.6 and Figure 3.2 it is possible to see that the fine concrete aggregate used during the experimental programme fitted into the limits set out in BS 882 [111] for a medium fine aggregate (Table 3.7).

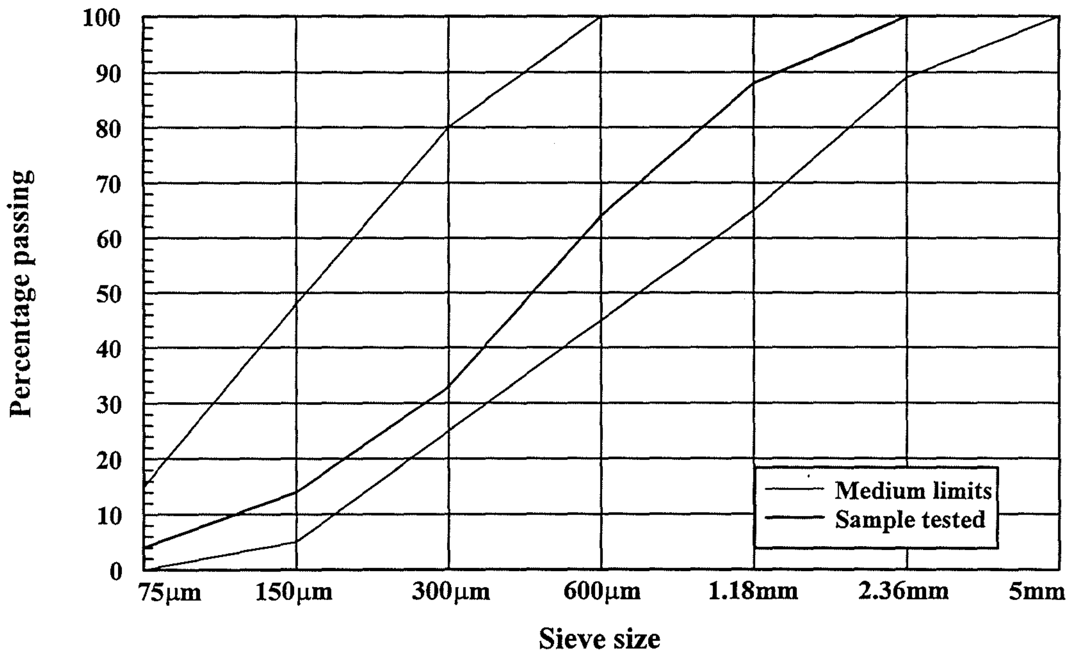


Figure 3.2 - Grading of fine concrete aggregate

3.3.4 Impact Value Test (IV)

The impact value gives a relative measure of the resistance of an aggregate to sudden shock or impact. In some aggregates this can differ from its resistance to a slowly applied compressive load. The impact value is found by dropping a standard hammer onto a sample of aggregate and measuring the weight of the fines resulting from the impact, therefore the lower the impact value, the tougher and stronger the aggregate.

The maximum allowable impact values for concrete aggregates given in BS 882 [111] are as follows:

- 25% when the aggregate is to be used for heavy duty concrete flooring
- 30% when the aggregate is to be used for pavement wearing surfaces
- 45% when the aggregate is to be used for other concretes

The impact values were calculated using the relevant British Standard [112] for the five different new brick aggregates, the granite aggregate and the two recycled aggregates. The results for the aggregate impact test are shown in Table 3.8.

Table 3.8 - Impact test results

Aggregate no./type	Impact value (%)
1/clay	31
2/clay	25
3/clay	19
4/clay	19
5/clay	14
6/granite	9
7/recycled washed	24
8/recycled masonry	33

Apart from brick aggregates No.1 and 8, the impact test results show that all other aggregates fall within the suitability limits for concrete which is to be used for heavy duty flooring and pavement wearing surfaces. Table 3.8 also shows that the recycled aggregates in general are not as strong as the clean crushed brick aggregates but this was expected due to the presence of impurities such as mortar. However, the results show that the recycled washed aggregate has an impact value of 24% which qualifies the aggregate to be used for heavy duty concrete flooring.

Figure 3.3 was plotted to show that a relationship exists between the compressive strength of parent half-brick and the impact value of the new brick aggregate. As the impact value of brick aggregate increases, the compressive strength of the parent brick decreases. This means that the impact test could be used to estimate the strength of brick units by testing brick lumps crushed from the parent brick. The results would also be useful to determine the suitability of recycled brick for use as the aggregate in new concrete.

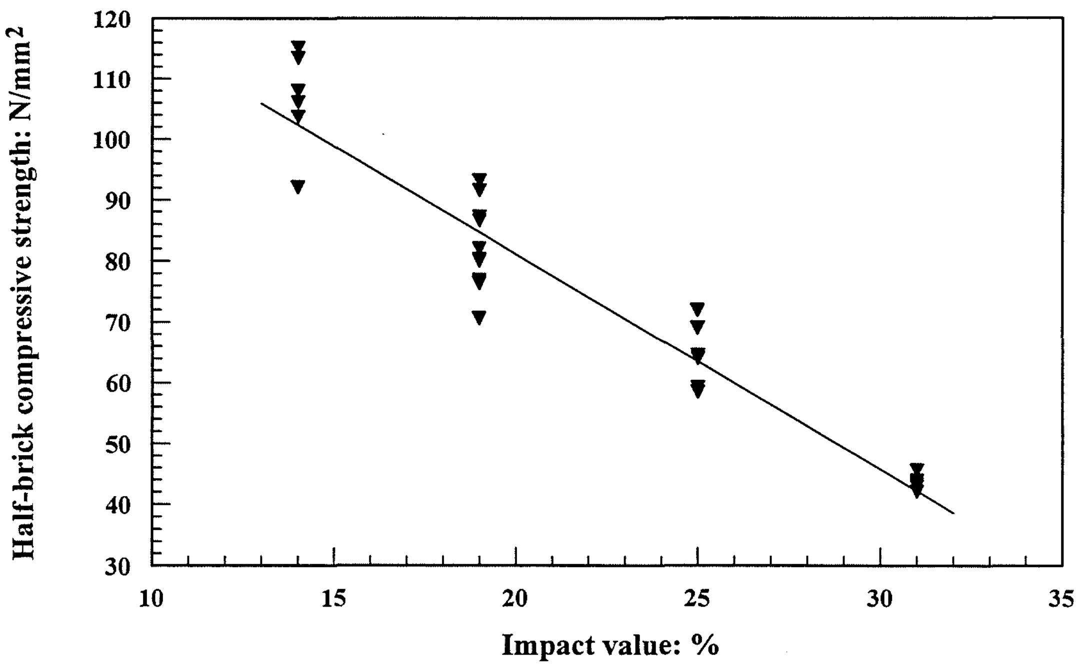


Figure 3.3 - Half-brick compressive strength versus impact value for new brick aggregate

The best fit equation for the relationship shown in Figure 3.3 is as follows:

$$f_{hb} = -3.54\ (IV) + 151.9 \qquad \textbf{(Eqn. 3.1)}$$

Where

f_{hb} = Half-brick compressive strength (N/mm^2)

IV = Impact value (%)

3.3.5 Relative Density (RD)

The relative densities of the brick aggregates and the granite aggregate were determined in accordance with BS 812 [113] using the gas jar method. This method involved the immersion of an aggregate sample in water for 24hrs in an air-tight vessel. The mass of the vessel containing the water and aggregate was weighed (Mass B) and the mass of the vessel containing only water was also recorded (Mass C). After the 24hrs immersion, the aggregate was removed from the water and placed on a dry cloth to remove excess water from the surface of the aggregate particles. The aggregate was weighed in this saturated surface-dry (SSD) condition (Mass A) and then placed in an oven at 105°C ± 5°C for 24hrs after that time the aggregate was again weighed (Mass B). The relative density was then calculated using Eqn. 3.2. The results of relative density for the aggregates used in this investigation are shown in Table 3.9.

$$\text{Relative density (RD)} = \frac{\text{Mass A}}{\text{Mass A - (Mass B - Mass C)}} \qquad \textbf{(Eqn. 3.2)}$$

Table 3.9 - Relative density results

Aggregate no./ type	Relative density (SSD)
1/clay	1.97
2/clay	2.22
3/clay	2.20
4/clay	2.25
5/clay	2.41
6/granite	2.85
7/recycled washed	2.18
8/recycled masonry	1.94

The results in Table 3.9 show that in general, as expected, the stronger bricks produced higher values of relative density. It is also possible to see that the new brick aggregates and recycled aggregates have a lower relative density than the granite aggregate. This means that if new brick aggregates or recycled aggregates are used in making concrete they should produce concrete of a lower density than granite aggregate. This is also due to the large amount of coarse aggregate used in producing concrete which usually accounts for between 60 and 70% of the concrete composition.

Figure 3.4 was plotted to show a linear relationship exists between the compressive strength of parent half-brick and the relative density of the new brick aggregate. As the relative density of the brick aggregate increases, the compressive strength of the half-brick increases. The relationship is very useful as it means that the strength of a brick could be estimated by determining the relative density of 20mm crushed brick aggregate. By taking the impact value and the relative density of a crushed brick sample together, it is possible to predict the strength of the parent brick fairly accurately. It is also possible by taking the two values together to determine the suitability of new or recycled brick for use as the aggregate in new concrete.

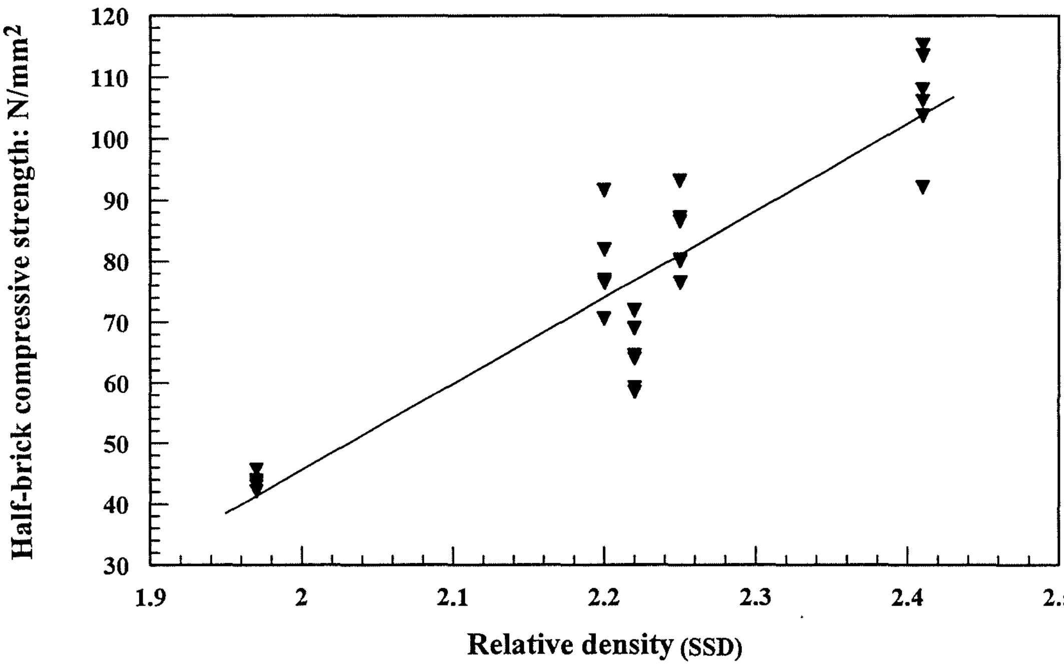


Figure 3.4 - Half-brick compressive strength versus relative density for new brick aggregate

The best fit equation for the relationship shown in Figure 3.4 is as follows:

$$f_{hb} = 142.2\,(RD) - 238.8 \qquad \textbf{(Eqn. 3.3)}$$

Where

RD = Relative density (SSD)

Figure 3.5 shows a relationship between the impact value of brick aggregate and its relative density. As the relative density increases, the impact value decreases at a linear rate. This means that tougher brick aggregates have a higher relative density.

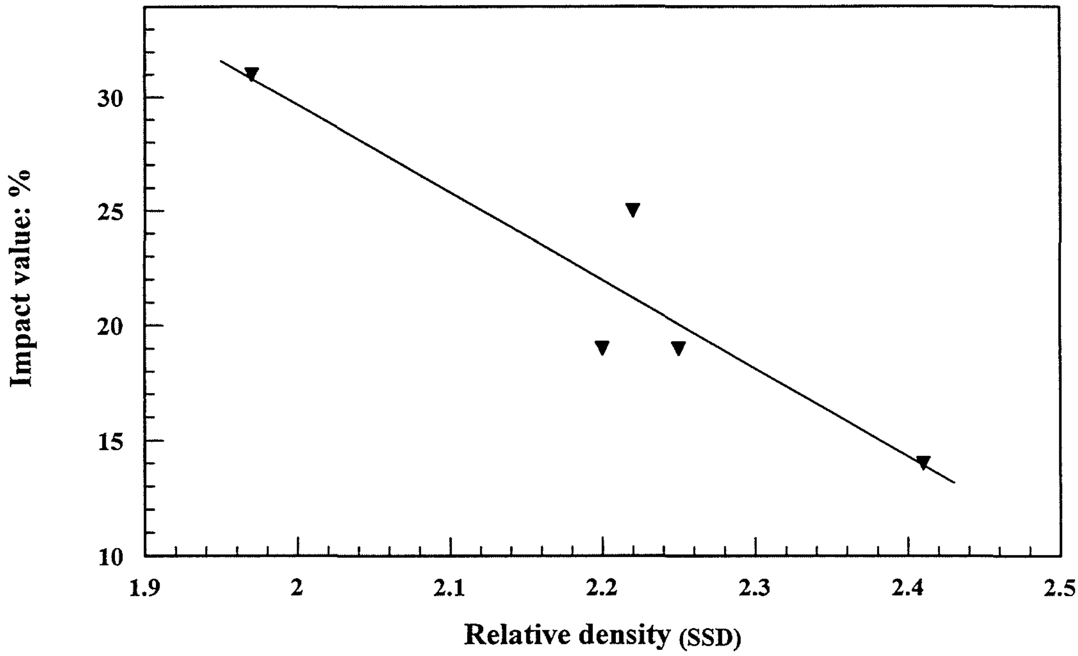


Figure 3.5 - Impact value versus relative density for new brick aggregate

The best fit equation for the relationship shown in Figure 3.5 is as follows:

$$IV = -38.4\,(RD) + 106.5 \qquad \textbf{(Eqn. 3.4)}$$

3.3.6 Water Absorption of Brick Units and Aggregates (WA)

Full bricks of each brick type were sampled and tested for water absorption in accordance with Appendix E of BS 3921 [114] using the 5hrs boiling method. In order that comparisons could be made, full bricks of each brick type were also tested for water absorption by 24hrs cold immersion. This allows the effects of the 5hrs boiling to be quantified.

Crushed brick aggregates from each brick type were mixed and riffled to achieve a representative sample. The 20mm brick lumps (passing 20mm but retained on 14mm sieve) were then tested for water absorption by the 5hrs boiling method in the same way as the full bricks. Samples of 20mm granite aggregate were also tested so that a comparison could be made with the brick aggregates.

During the present investigation the author discovered that the 5hrs boiling of 20mm lumps can easily be used as an alternative test to the BS 3921 test of boiling 10 full bricks. The author also found that the 5hrs boiling of 20mm brick lumps has several advantages to the BS 3921 test which will be discussed later in this chapter.

In order to standardise the 5hrs boiling test of brick lumps to be used for determining the water absorption of brick units, new brick aggregates and recycled brick aggregate, a full test procedure is outlined below:

<u>Procedure for new water absorption test by 5hrs boiling of brick lumps</u>

- Take five representative bricks from the pile. Brake up whole bricks to halves using a hammer. Discard one half and smash up the other half to lumps on a metal plate with the hammer. Mix and riffle the lumps of crushed brick to obtain a representative sample. Sieve the sample through 20mm and 14mm test sieves. Keep the fraction retained on the 14mm sieve for the water absorption test.
- Take a sample of at least 100g of the 20mm crushed brick lumps and dry in an oven at 105°C ± 5°C for 24hrs ± 0.5hrs. When cool weigh the sample to an accuracy of 0.1% (Mass A).
- Place the sample in a single layer in a tank of water immediately after weighing. Wire mesh or similar should be placed in the tank to allow water to freely circulate around the sample. Heat the water to boiling point in approximately 1hr, boil continuously for 5hrs and then allow the water to cool to room temperature by natural loss of heat for not less than 16hrs or more than 19hrs.
- Place the sample on a dry cloth and gently surface dry it with the cloth, transferring it to a second dry cloth when the first will remove no further moisture. Weigh the aggregate and record the mass (Mass B). Complete weighing of any one sample within 2mins after its removal from the water.
- Calculate the water absorption (WA), expressed as a percentage of the dry mass, using the following equation:

$$\text{Water absorption (WA)} = \frac{(\text{Mass B} - \text{Mass A})}{(\text{Mass A})} \times 100\% \qquad \textbf{(Eqn. 3.5)}$$

In order to measure the effects of the boiling on the lumps, samples of each brick type and the granite aggregate were tested for water absorption in accordance with BS 812: Part 109 [115]. This test is commonly used for natural concrete aggregate and involves the immersion of the sample in cold water for 24hrs in a sealed container. After oven drying, the water absorption was calculated as a percentage from the mass of water absorbed divided by the dry mass of the sample. The results for the 5hrs boiling and 24hrs immersion in cold water are given in Table 3.10.

Table 3.10 - Water absorption results

Agg. no.	Brick/aggregate type	Full-brick compressive strength (N/mm²)	Half-brick compressive strength (N/mm²)	Water absorption of brick units (%)		Water absorption of 20mm lumps (%)	
				5hrs Boil	24hrs Soak	5hrs Boil	24hrs Soak
1	Common	39	43	12.9	10.3	14.1	11.5
2	5 Slot	59	65	10.7	9.5	13.8	12.4
3	3 Slot	68	79	5.8	5.3	7.4	7.4
4	10 Hole	81	84	6.2	4.6	7.4	7.2
5	Eng B	92	106	6.0	5.2	6.3	6.2
6	Granite	-	-	-	-	2.63	2.55
7	Recycled washed	-	-	-	-	-	10.4
8	Recycled masonry	-	-	-	-	-	16.2

The results in Table 3.10 show that the 5hrs boiling of brick units gave higher water absorption values compared with 24hrs immersion in cold water. This suggests that the concept of boiling the bricks to expel air is effective. However, a much higher result was obtained for boiling 20mm brick lumps which suggests that the 5hrs boiling of brick units was not sufficient to expel all the air. As the brick lumps are much smaller, the air has a shorter distance and time to escape whereas in the whole brick unit, the air at the centre would find it more difficult to escape. Also by using brick lumps instead of whole bricks, there is no need to wipe the excess water from the brick perforations which improves the accuracy of the results.

Table 3.10 also shows that the two recycled aggregates have high water absorption values compared to the granite aggregate. The recycled masonry aggregate had a higher water absorption than all the other crushed brick aggregates, while the value for the recycled washed aggregate falls in the middle of the range of values for the various brick aggregates. The water absorption value for the recycled masonry aggregate is more than six times the value of the granite aggregate. Therefore if this aggregate is to be used to produce concrete, it would have to be in a saturated surface-dry (SSD) condition first to prevent problems with the concrete's workability.

The results in Table 3.10 suggest that the 5hrs boiling of 20mm brick lumps offers a simple and easy alternative test to the 5hrs boiling of 10 full bricks in accordance with BS 3921. The new test does not require a large and expensive boiling tank which uses a lot of electricity during the boiling of the 10 full bricks for 5hrs. The new test can be performed in the laboratory or on site using a small portable metal container and a metal mesh to lift the sample from the base of the container to allow the water to circulate around the lumps during boiling. The cold immersion of 20mm lumps in water for 24hrs also provides an accurate estimation of the water absorption of clay bricks and this test could be used as a works control test as it is easy to perform.

3.3.7 Porosity of Aggregate (P)

There is no test in BS 3921 [116] to measure the porosity of clay bricks. In rocks, porosity is defined as the volume of a rock's pore space expressed as a percentage of the rock's total volume. In bricks, the degree of porosity depends on the clay used to manufacture the brick, duration in kiln and temperature of firing.

A more consistent value for the porosity of brick material is desirable as porosity can influence how water is transported through the brick unit. The structure of the pores dictates the movement of water through the material, hence affecting the material's resistance to freezing and thawing and the movement of harmful chemicals contained within the absorbed water.

A value for the porosity of the various aggregates used in this investigation was calculated using a new test. The new test procedure was based on the British Standards for determining the porosity of materials [117,118,119] and insulating refractory products [120,121] and also on a test which was devised for determining the porosity of stone [122,123]. This variable is most conveniently measured by saturation of the stone by water under vacuum, although this method does not take into account any closed pores within the stone which cannot be accessed by water. A similar test procedure for acid-resisting bricks and tiles has been used in the past but the standard has been withdrawn [124].

The new test procedure presented in this chapter employs a similar method to the ones presented in the above standards to calculate the porosity of 20mm brick lumps. The suggested test is easy to perform with no need for a large vacuum bell jar. It is also more reliable if full brick units are tested because there is no need to wipe the excess water from the brick perforations. The apparatus used in the new test is shown in Figure 3.6.

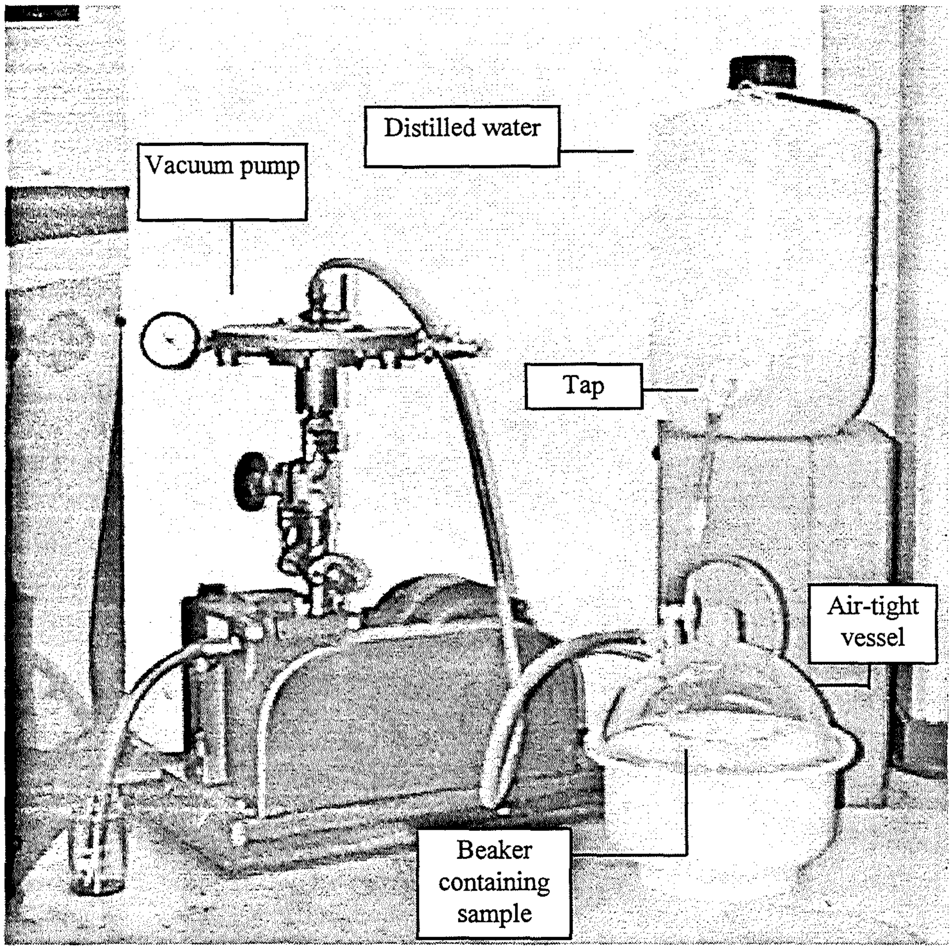


Figure 3.6 - Apparatus used in new porosity test

The procedure for the new test is summarised as follows:

<u>Procedure for new test to determine the porosity of brick aggregate</u>

- Take five representative bricks from the pile. Brake up whole bricks to halves using a hammer. Discard one half and smash up the other half to lumps on a metal plate with the hammer. Mix and riffle the lumps of crushed brick to obtain a representative sample. Sieve the sample through 20mm and 14mm test sieves. Keep the fraction retained on the 14mm sieve for the water porosity test.
- Take a sample of at least 100g of 20mm aggregate lumps (fraction passing 20mm sieve but retained on 14mm) and dry in an oven at 105°C ± 5°C for 24hrs ± 0.5hrs.
- Remove the sample from the oven and place in a desiccator for 30mins to cool. Weigh the sample and record mass (Mass A).

- Place sample in glass beaker and then place this inside a bell jar. The bell jar should be sealed with silicon to ensure it is totally airtight.
- Remove all air from the bell jar by using a vacuum pump operating at a pressure of 0.07bar. After 0.5hrs water is allowed into the beaker by means of a hose through the neck of the bell jar until the aggregate is fully covered with water.
- The vacuum pump can then be switched off and air may be allowed to re-enter the system. Remove the beaker and aggregate from the bell jar and leave the aggregate immersed in the water for at least 16hrs to allow all the pores within the aggregate to become filled with water.
- Place the aggregate on a dry cloth and gently surface dry it with the cloth, transferring it to a second dry cloth when the first will remove no further moisture. Weigh the aggregate and record the mass (Mass B).
- Weigh the surface-dry aggregate in water and record this mass (Mass C).
- The porosity is given by :

$$\text{Porosity (P)} = \frac{(\text{Mass B} - \text{Mass A})}{(\text{Mass B} - \text{Mass C})} \times 100\% \qquad \textbf{(Eqn. 3.6)}$$

This procedure was followed for each of the brick aggregates and also the granite aggregate so that a comparison could be made. The results are shown in Table 3.11.

Table 3.11 - Porosity results for aggregate from new test procedure

Aggregate no.	Brick/aggregate type	Porosity value (%)
1	Common	25.04
2	5 Slot	20.08
3	3 Slot	17.39
4	10 Hole	16.75
5	Eng B	14.85
6	Granite	6.15
7	Recycled washed	14.49
8	Recycled masonry	24.44

Table 3.11 shows that the new method proposed for testing brick porosity was proven to be effective, as the results from the water absorption test for lumps have backed up the porosity results. The new procedure is very effective at removing the trapped air from within the structure of the brick lumps. This is because the lumps are in an oven dry condition when the air is extracted meaning that there is no water to prevent the air escaping from within the particles. De-aired water is used when water is allowed to re-enter the system to make sure that no air is allowed to enter the pores of the brick lumps.

The results show that the new crushed brick aggregates are far more porous than the granite aggregate and the recycled aggregates also have a very high porosity. The recycled washed aggregate does not have as high a porosity as the rest of the brick aggregates. This was maybe due to the impurities in the aggregate having a lower porosity or possibly the pores in the aggregate particles were blocked with old mortar. The recycled masonry aggregate had a very high porosity and if this aggregate was to be used to produce concrete it would have to be pre-soaked first as it would absorb a large proportion of the mixing water.

Figure 3.7 was plotted to show that a linear relationship exists between the compressive strength of the half bricks and the porosity of 20mm lumps broken up from similar new brick units. The figure shows that the more porous bricks have a lower compressive strength compared to the bricks with a low porosity which have a higher strength.

The best fit equation for the relationship shown in Figure 3.7 is as follows:

$$f_{hb} = -7.4\,(P) + 210.6 \qquad \textbf{(Eqn. 3.7)}$$

Where

P = Porosity (%)

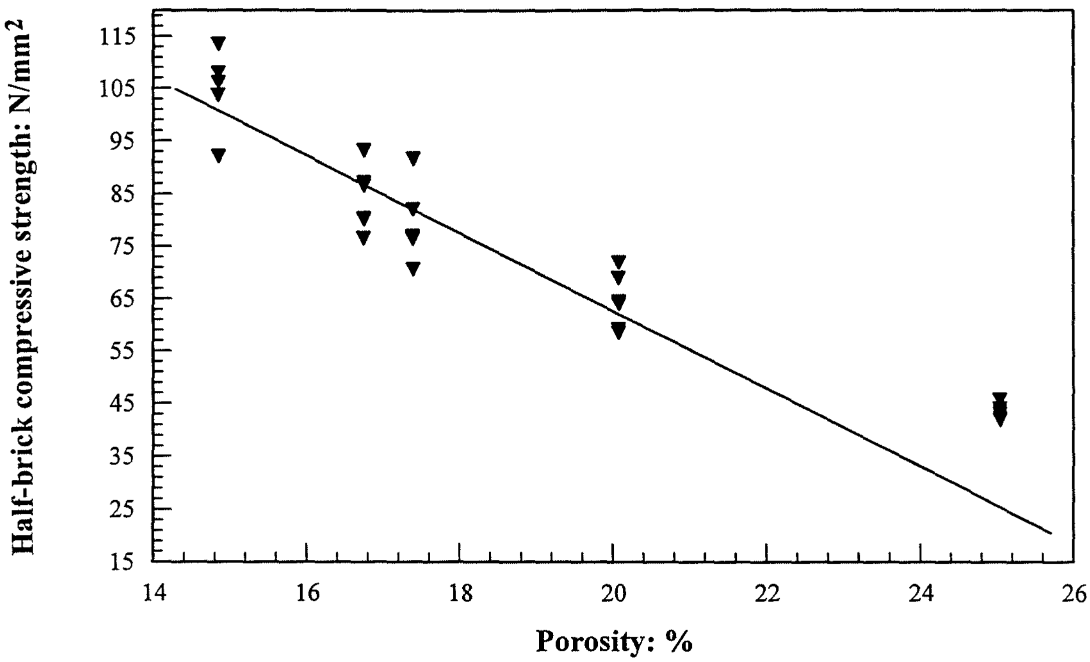


Figure 3.7 - Half-brick compressive strength versus porosity for new brick aggregate

Figure 3.8 shows a relationship between impact value and porosity for new brick aggregates.

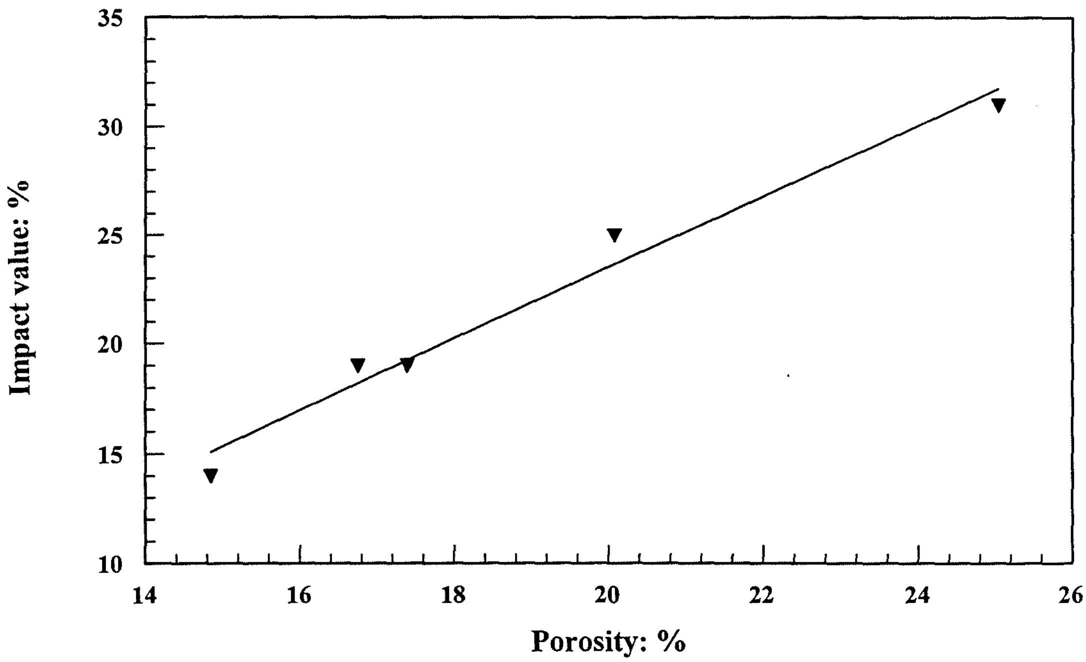


Figure 3.8 - Impact value versus porosity for new brick aggregates

The figure shows that as the aggregate porosity increases, the impact value of the aggregate also increases. This means that the porosity of a crushed brick aggregate can be estimated from the aggregate impact value or vice versa. This is useful because it is important to know whether or not an aggregate is porous when considering it for use as an aggregate in concrete.

The best fit equation for the relationship shown in Figure 3.8 is as follows:

$$IV = 1.6\,(P) - 9.2 \qquad \textbf{(Eqn. 3.8)}$$

Figure 3.9 shows a relationship between relative density and porosity for new brick aggregate. The figure shows that as the porosity of crushed brick aggregate increases, the relative density of the aggregate decreases. This means that as the relative density of a brick aggregate decreases, the volume of voids in the material increases causing a higher porosity value.

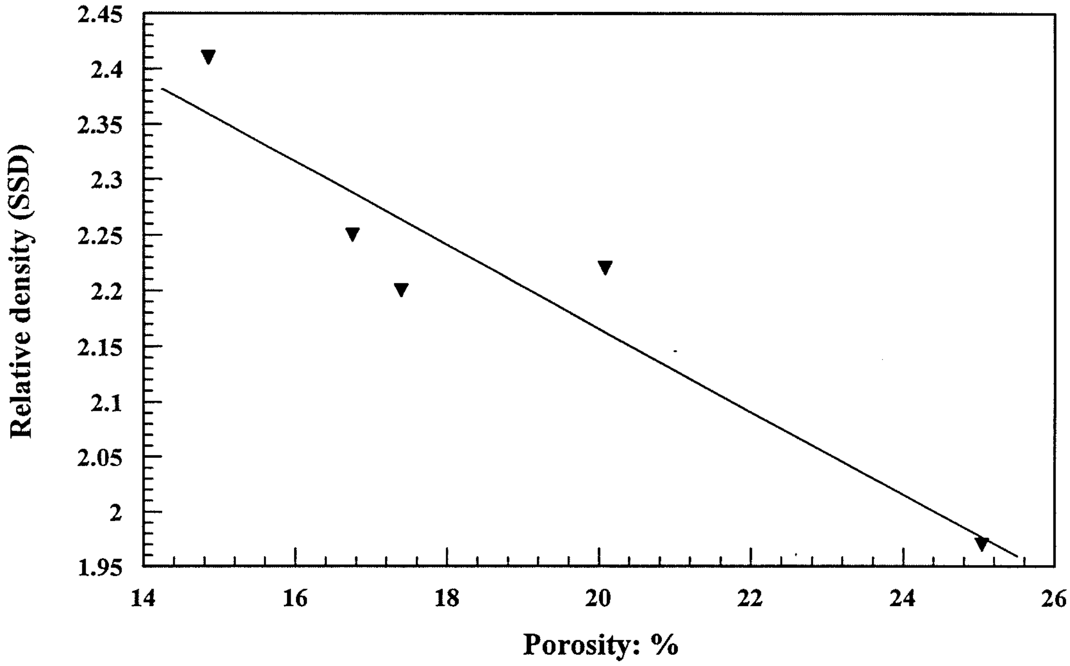


Figure 3.9 - Relative density versus porosity for new brick aggregates

The best fit equation for the relationship shown in Figure 3.9 is as follows:

$$RD = -0.04\,(P) + 2.92 \qquad \textbf{(Eqn. 3.9)}$$

3.4 CONCLUSIONS

The following conclusions can be made from the work presented in this chapter:

1. Even after crushing and screening to remove impurities, recycled aggregates still contain a small percentage of material which could be detrimental if the aggregate was used to produce concrete.

2. Apart from aggregates produced from common bricks and recycled masonry, the impact test results show that all other aggregates fall within the BS 882 suitability limits for concrete which is to be used for heavy duty flooring and pavement wearing surfaces.

3. A linear relationship exists between the compressive strength of the parent bricks and the impact value of aggregates produced from them. This relationship can be used to estimate the strength of new brick units and also to determine the suitability of recycled brick aggregate for use in new concrete.

4. The relative densities of the crushed brick aggregates and the recycled aggregates are considerably less than the density of the granite aggregate. This means that concrete made with these aggregates will have a lower density than concrete made with normal aggregates such as granite.

5. The results show that the 5hrs boiling on full size brick units, as recommended by BS 3921, under estimate the true value of water absorption of fired-clay bricks. This suggests that 5hrs boiling is not enough to expel the air from the brick pores.

6. The water absorption of clay bricks can be determined by 5hrs boiling of brick lumps which is easier to carry out and more reliable as no brick perforations have to be dried. This is a more economical test than boiling 10 whole bricks because a smaller water bath is required and less energy is consumed during the boiling process. The cold immersion of 20mm lumps in water for 24hrs

also provides an accurate estimation of the brick water absorption and this test could easily be used as a works control test.

7. No British Standard test currently exists for determining the porosity of bricks. However, the porosity of clay bricks can be found by testing brick lumps under vacuum in accordance with the new test procedure set out in this chapter. This test is reliable because the air is expelled from the material while in a bone dry state and there is no need to wipe excess water from the brick perforations which improves the accuracy of the results.

8. The two recycled aggregates have a higher porosity value than the crushed new brick aggregates and the granite aggregate. This means that these two aggregates will have a higher water demand when used as the aggregate in concrete.

9. The results show that a general relationship exists between brick compressive strength and porosity. The higher the porosity of brick units, the lower the compressive strength of the brick unit and vice versa.

10. When the results of the impact, relative density and porosity tests on brick lumps are combined, they provide a very good indication of the compressive strength of a new parent brick or a recycled brick unit. This can be used as an alternative test to the BS standard uniaxial compressive testing of 10 whole brick units.

CHAPTER 4

POINT-LOADING OF MASONRY SPECIMENS

4.1 INTRODUCTION

One of the main difficulties with recycling demolished materials is that the demolition works are not designed for materials recovery [24]. Bricks have similar uses although their mechanical and physical properties differ in terms of raw materials and the method of manufacture. Pre-sorting and screening of bricks by their strength before demolition, prevents the weaker bricks from mixing with bricks suitable for use as course aggregate in concrete. It is also important at any recycling plant to know the compressive strength of the original bricks before crushing the demolished masonry rubble into course aggregate. The compressive strength of the original brick is quite important as chapters later in this thesis proved its effect on the compressive strength of the new concrete produced with aggregate crushed from these bricks. If full bricks are available for testing, their characteristic compressive strength can be determined by crushing ten full sized bricks following the test procedure set out in Appendix D of BS 3921 [96]. This method involves the use of large, heavy and expensive laboratory testing machines. A portable test is needed so that pre-sorting of demolition rubble can take place on site to accept or reject material for recycling.

Previous chapters in this thesis present several methods (impact test, relative density, water absorption and porosity) to determine some of the mechanical and physical properties of brick aggregates. Most of these tests are performed in the laboratory which requires a source of electricity, accurate electronic balance, oven, water tank, vacuum pump, bell jar ... etc.

The main aim of this chapter therefore is to find an alternative test which is portable, accurate and easy to perform to assess the quality and suitability of demolished building rubble and crushed brick aggregates on site. It is also anticipated that the new test could be used` as an alternative test to determine the characteristic compressive strength of new brick units.

The test investigated in this chapter to achieve the above aim is known as the point-load test [98] which was developed and used for the testing and classification of natural rocks.

The point-load test was originally used to test standard sized core specimens but then further work developed a point-load test on irregular lumps. The test was developed in Russia by Protodyakonov [98] to obtain a strength index (I_s) using the following formula:

$$I_s = \frac{P}{V^{\frac{2}{3}}} \qquad \textbf{(Eqn. 4.1)}$$

Where

P	=	Rupture load (N)
V	=	Specimen volume (mm^3)

Further investigations [97,98,99] found that the size, shape and orientation of the specimen affected strength index values. Extensive testing developed a new equation (Eqn 4.2) in order to calculate the strength index value of rock specimens.

$$I_s = \frac{P}{D^2} \qquad \textbf{(Eqn. 4.2)}$$

Where

P	=	Rupture load (N)
D	=	Distance between loading platens (mm)

This chapter investigates the possibility of using Protodyakonov's apparatus to determine the characteristic strength of new or recycled bricks by means of splitting using a point-load. The investigation also studies the effect of changing the dimensions of a brick piece on the strength index (I_s). The results of the point-load testing were later used to find a relationship between the strength index of a reference standard unit (half-brick) and the different sized specimens. This is presented in the form of a shape factor (δ). From this a formula was derived relating the characteristic compressive strength of a half-brick to the shape factor and strength index of a brick piece.

From the formula it was possible to estimate the characteristic compressive strength of bricks without having to test ten whole bricks. This was possible by measuring the dimensions of small pieces of brick and testing them under point-load to derive their strength index. This provides an easy to perform and portable test for pre-sorting of demolition rubble on site to decide its suitability for recycling.

4.2 MATERIALS USED

4.2.1 Brick Units and Regular Pieces

To provide a wide range of results, Engineering brick Class A, Class B and a Common clay brick were used in the experimental programme. Table 4.1 shows the properties of these bricks as set out in BS 3921.

To determine the compressive strength of the brick units, the bricks were sawn in half and these half-bricks were tested to determine their compressive strength. This was done because the load required to cause failure in a whole brick of Engineering A type, exceeded the capacity of the testing machine. In order to study the effect of changing the dimensions of brick specimens on the values of strength index, full bricks from the different types were sawn to pieces of different height, width and length using a diamond tipped circular saw.

In the preparation of specimens prior to the uniaxial testing, the common clay brick had a double frog which was filled with mortar 1:1 (cement:sand by volume) to provide a uniform surface for a better contact with the machine steel platens.

Plywood was required to take up irregularities in the top and bottom face of the bricks during crushing to ensure no localised stress was created causing premature specimen failure. All half-bricks were prepared and tested in accordance with BS 3921.

Table 4.1 - Brick classification (BS 3921)

Class	Length (mm)	Height (mm)	Width (mm)	Compressive strength (N/mm^2)	Water absorption (%)
Engineering A	215	65	102.5	≥70	≤4.5
Engineering B	215	65	102.5	≥50	≤7.0
Common clay brick	215	65	102.5	≥5	No limit

4.2.2 New Irregular Brick Lumps

New brick lumps of irregular shape were produced from the point-load testing of regular shaped brick pieces. These were then tested under point-load.

4.2.3 Recycled Irregular Brick Lumps

Recycled brick lumps of two types were selected from a sample of recycled masonry aggregate which had been supplied straight from the recycling plant. These were tested under point-load to determine the strength index (I_s).

4.3 EQUIPMENT USED

4.3.1 Point-load Testing Machine

The point-load testing machine uses a high-pressure hydraulic ram with a small hydraulic hand-pump (Figure 4.1). The ram incorporates low friction seals to minimise inaccuracies in load measurement and also quick retraction to minimise delay between successive tests. The loading frame was designed to accept up to 100mm diameter rock specimens, so that it could be used with the most common sizes of rock core. This criteria satisfies the use of the machine for testing brick specimens. The capacity of the machine was limited to 50kN in order to keep the machine portable.

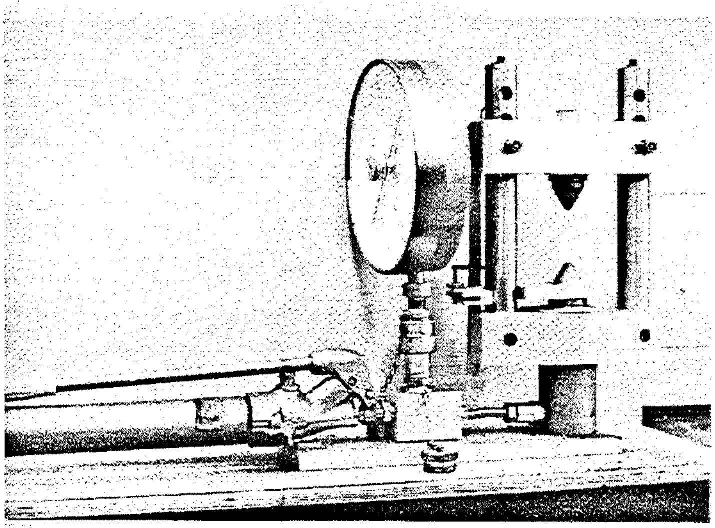


Figure 4.1 - Point-Load Testing Machine

4.3.2 Loading Platens

The cone shaped loading platens were standardised because changes in geometry of the cone gave differences in recorded strength values. From previous work [98], the radius of curvature and angle of the cone were selected as 5mm and 60° respectively. An illustration of the cone platen is shown in Figure 4.2.

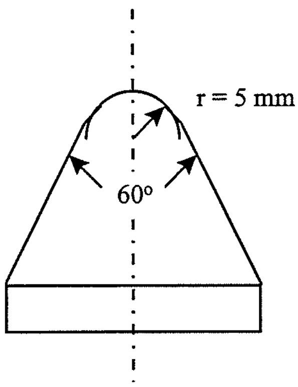


Figure 4.2 - Standard platen dimension for point-load testing

Platens were hardened to ensure that the contact surfaces would not be damaged by repeated testing. The alignment of the two cones could be checked by bringing the cones into contact before testing.

4.3.3 Load Measurement

Load was measured by monitoring the pressure in the jack. The ram incorporates low-friction seals, so the conversion from pressure to force is simple and accurate. Bourdon pressure gauges were calibrated to provide direct load readings in kN from an applied pressure by the hydraulic ram. A maximum pressure needle was necessary to provide the reading of the maximum failure load reliably.

4.3.4 Distance Measurement

A metal scale in millimetres was fixed to the crosshead of the testing machine to allow for the distance between the two conical platens to be determined. This distance corresponds to the height of the specimen (D) when initially loaded. A micrometer was also used to measure length and width of each loaded specimen before testing.

4.4 EXPERIMENTAL PROCEDURE AND TEST RESULTS

This part of the investigation describes the experimental procedures adopted to test and determine the failure load of samples of brick by point-load and by uniaxial compression.

4.4.1 Point-load Test

In the point-load test, brick specimens in the form of units, regular pieces or irregular lumps of brick were subjected to a load between two conically-shaped steel loading platens.

To carry out a test on brick units and regular pieces, brick specimens were inserted in the loading frame and the platens moved to make contact with the specimen. At this point the distance, D, was recorded using the metal scale fixed to the cross-head. A load was applied to the specimen on the flat surface using the hydraulic ram, and increased until failure of the specimen. The rupture load was recorded which represents the maximum failure load. At least three samples of each dimension were tested to establish an average result.

The point-load test was used to study the effect of changing specimen dimensions on the rupture load of the brick specimens. The test was carried out on the three types of brick used in this investigation. A first point-load test was carried out on specimens with varying height but constant length and width. Two sets of specimens with varying height, one length (214mm) and two different widths (102mm and 66mm) were tested. Results from the two sets tested are provided in Table 4.2.

A second investigation was carried out to study the effect of varying the sample width while keeping length (102mm) and height (33mm) constant. Results produced from this part of the investigation are also presented in Table 4.2.

The point-load test was also carried out on half-brick units of each brick type. This was done so that all the point-load results could be related to the half-brick result which was considered to be a reference unit. Results for the point-load test on half-bricks are again presented in Table 4.2.

The last column in Table 4.2 corresponds to a shape factor (δ) of the sample which is the ratio of the strength index of a reference brick to the strength index of a regular sample. This reference brick is taken as a half-brick, with point-load results given in Table 4.2. This factor is used to change the strength index (I_s) of regular pieces to the equivalent half-brick.

Further point-load tests were carried out on irregular brick lumps broken from the regular new brick pieces. An average of all dimensions for each specimen was measured and a load was applied at the centre of the specimen. The average test results on new irregular lumps are shown in figures later in this chapter. Tests were also carried out on two types of irregular recycled brick lumps and the results are presented in tables later in this chapter.

4.4.2 Uniaxial Compressive Strength Test

To correlate a relationship between brick strength index by point-load testing and brick compressive strength, bricks from the same batch were crushed. In the point-load test, a shape factor was used to convert or 'normalise' results to a half-brick so corresponding half-bricks were also used to determine the brick uniaxial compressive strength. The bricks were tested in accordance with Appendix D of BS 3921 [96], the only change was the testing of four half-brick samples instead of ten full bricks as specified in the British Standard test procedure. The results for the compressive strength of each type of half-brick are given in Table 4.3.

Table 4.2 - Point-load test results for new bricks

Specimen	Number of tests	Height D (mm)	Length L (mm)	Width W (mm)	Rupture load P (kN)	Strength index I_S (N/mm^2)	C.V. (%)	Shape factor δ
Engineering A brick: Changing height, fixing length (214mm) and width (102mm)								
1	3	16.5	213.5	102.0	13.0	47.8	4.0	0.25
2	3	30.3	212.7	101.7	24.3	26.5	2.2	0.46
3	3	46.0	213.0	102.0	35.0	16.5	1.4	0.73
4	3	65.0	215.0	102.0	51.0	12.1	1.0	1.00
Engineering B brick: Changing height, fixing length (214mm) and width (102mm)								
1	3	14.5	215.5	103.0	6.0	28.5	5.1	0.19
2	3	31.7	215.0	104.0	13.0	12.9	2.4	0.42
3	3	49.5	215.0	103.0	18.5	7.6	1.4	0.72
4	3	66.5	216.5	104.0	31.5	5.7	1.3	0.96
Common clay brick: Changing height, fixing length (214mm) and width (102mm)								
1	3	15.2	213.4	101.6	2.6	11.3	2.4	0.19
2	3	29.5	212.5	101.0	4.0	4.7	2.2	0.45
3	3	48.1	213.0	101.0	7.7	3.3	2.7	0.64
4	3	65.5	213.0	101.0	10.5	2.5	1.2	0.84
Engineering A brick: Changing height, fixing length (214mm) and width (66mm)								
1	3	22.7	213.3	64.3	14.0	27.2	2.2	0.44
2	3	33.0	213.0	64.5	22.1	20.3	1.8	0.60
3	3	48.0	213.0	64.5	30.0	13.0	1.1	0.93
4	3	77.0	213.0	64.5	42.0	7.1	0.6	1.70
Engineering B brick: Changing height, fixing length (214mm) and width (66mm)								
1	3	21.3	216.7	66.7	7.3	16.1	2.9	0.34
2	4	41.0	218.0	67.0	13.2	7.8	1.4	0.71
3	4	62.0	218.0	67.0	22.2	5.5	1.0	1.00
4	3	104.0	217.0	66.3	28.3	2.6	0.5	2.12
Common clay brick: Changing height, fixing length (214mm) and width (66mm)								
1	3	22.3	212.0	64.9	3.6	7.2	1.8	0.29
2	4	48.8	212.3	65.8	7.5	3.2	1.5	0.66
3	3	75.4	212.3	65.1	8.6	1.5	2.2	1.40
4	3	101.0	211.3	64.0	9.3	0.9	0.4	2.33
Engineering B Brick: Changing Width, fixing height (33mm) and length (102mm)								
1	4	30.0	104.5	26.5	7.0	7.78	1.4	0.70
2	4	31.8	104.5	50.0	9.3	9.20	1.7	0.59
3	4	31.3	104	74.3	11.3	11.5	2.1	0.47
4	4	32.0	104.0	107.8	12.8	12.5	2.3	0.44
Half-brick: Fixing height (66mm), length (107mm) and width (102mm)								
Brick A	3	65.0	107.5	102.0	51.0	12.1	1.0	1.00
Brick B	4	67.0	107.0	104.0	24.5	5.5	1.0	1.00
Common	3	65.5	102.0	101.0	9.0	2.1	1.0	1.00

Table 4.3 - Compressive strength test results

Specimen	Number of tests	Height D (mm)	Length L (mm)	Width W (mm)	Failure load (kN)	Compressive strength (N/mm^2)	C.V. (%)
Engineering A brick: Fixing height (66mm), length (107mm) and width (102mm)							
Half-brick	4	64.0	106.0	102.0	2175.0	201.2	3.4
Engineering B brick: Fixing height (66mm), length (107mm) and width (102mm)							
Half-brick	4	65.8	106.5	102.5	1149.5	105.3	2.8
Common clay brick: Fixing height (66mm), length (107mm) and width (102mm)							
Half-brick	4	64.5	105.0	99.8	252.6	24.1	2.3

4.5 DISCUSSION OF RESULTS

4.5.1 Point-loading of Masonry Specimens

(a) Modes of Failure of Point-load Specimens

When a point-load is applied to a brick specimen, the pattern of cracks is initiated first at the point of application and then progresses to the nearest sides due to the brittleness of the material making the clay brick. It is therefore necessary to examine the modes and patterns of failure under point-load for the tested specimens. In theory, the mode of failure for any brittle material under point-load would correspond towards the shortest length, i.e. the width of the specimen.

For full bricks of high strength (Classes A and B Engineering) the mode of failure under point-load shows some variation as shown in Figure 4.3. In the figure, brick No. 5 shows a typical theoretical failure, whilst brick No. 2 and brick No. 4 show the tensile cracks at an angle to the shortest distance (horizontal plane). Brick samples No. 1, No. 3, and No. 6 indicate similar diagonal cracks to specimens No. 2 and 4 but with a small single crack to one side along the width of the specimens. This single crack was believed to be created after the formation of the main diagonal crack which suggests that due to its late formation it does not have an effect on the value of rupture load. This means that the common mode of failure for a full brick unit was by a diagonal crack at an angle to the brick width (horizontal plane).

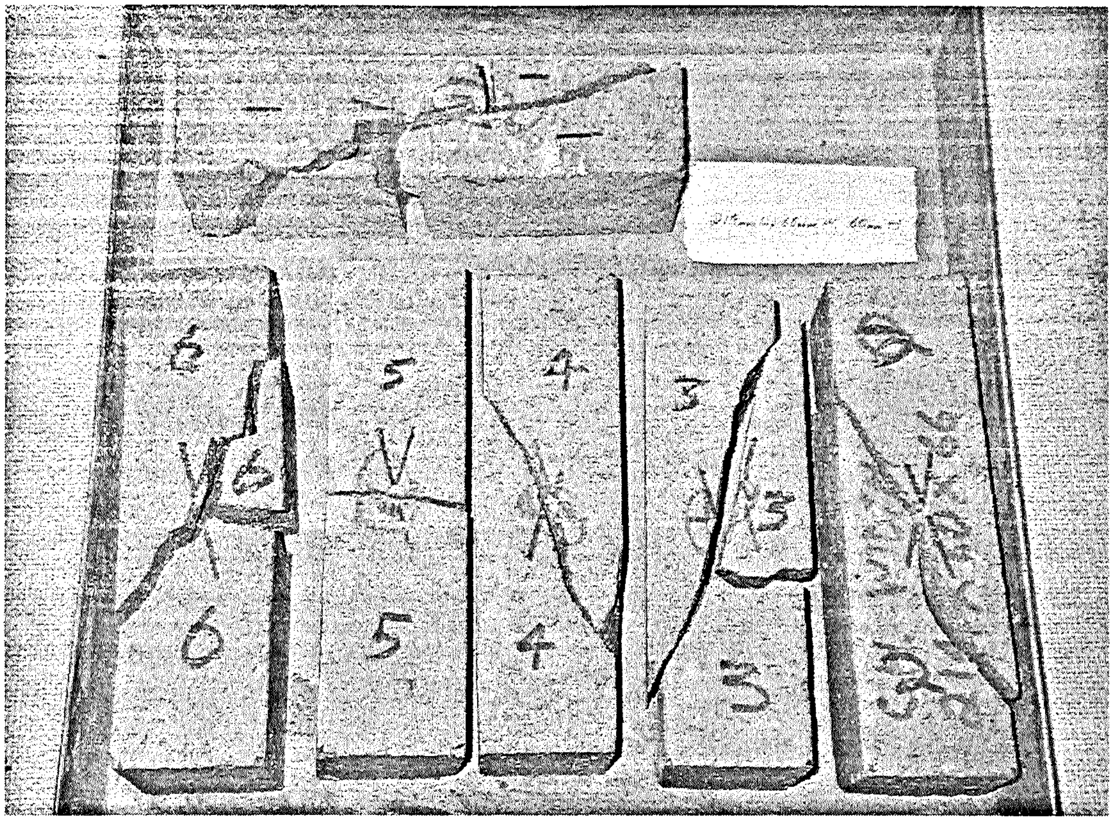


Figure 4.3 - Modes of failure in Engineering B brick (height = 66mm, length = 214mm and width = 60mm)

Full bricks of high strength (Classes A and B Engineering) and thinner sections showed similar modes of failure to the full-height units. The general mode was characterised by a single main diagonal crack, some accompanied by a small crack to one side of the specimens (Figs 4.4 and 4.5). This suggests that changing specimen height has no great influence on its mode of failure under point-load. This also suggests that the height of specimen selected for point-load testing should be limited by the capacity of the point-load testing machine and the distance between the cone loading platens (D). It is recommended that the maximum height of a specimen should be no more than the height of a brick (D = 66mm).

During testing it was noticed that the load dial gauges of the point-load testing machine were not very sensitive to low values of rupture load. This means that thin samples produce inaccurate and unreliable values of rupture load. The sensitivity of the point-load testing machine will be discussed in more details later in this chapter.

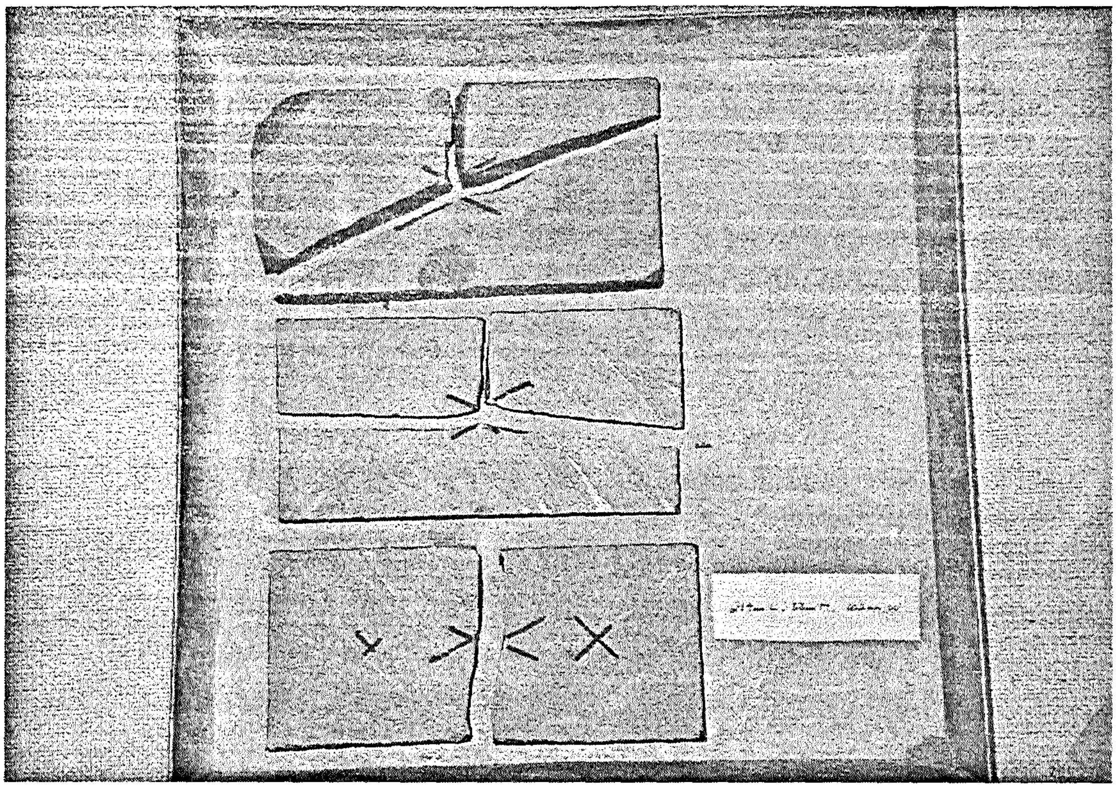


Figure 4.4 - Modes of failure in Engineering A brick (height = 33mm, length = 214mm and width = 102mm)

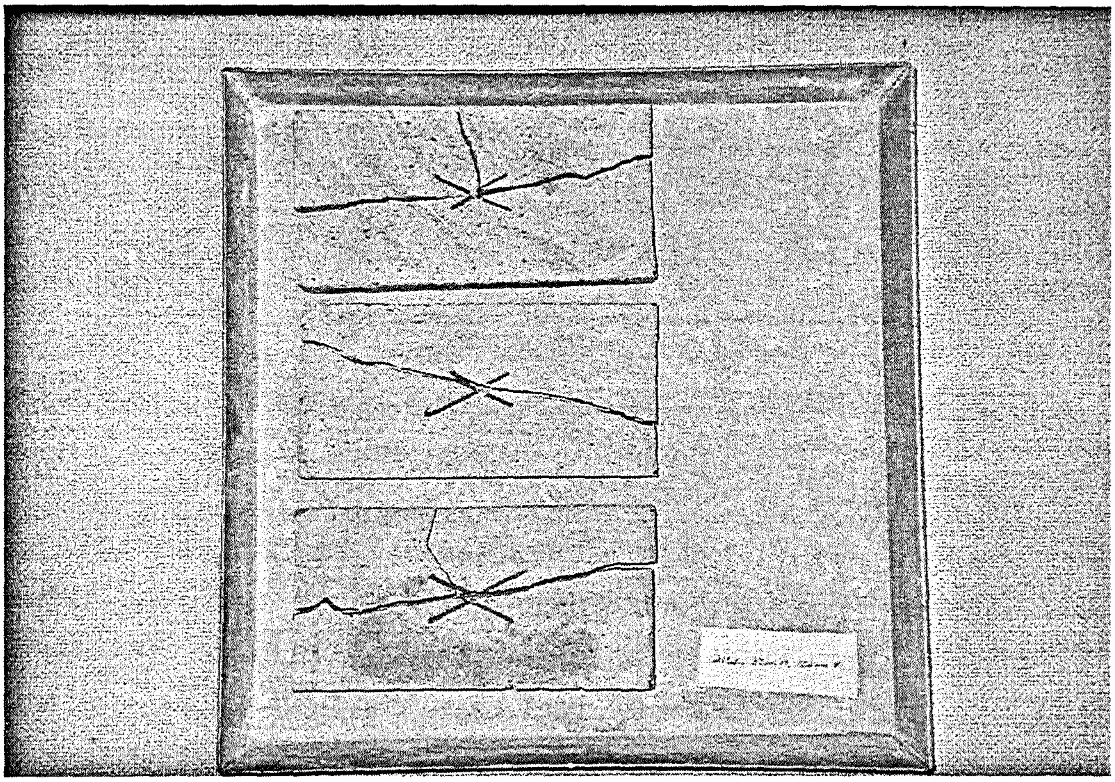


Figure 4.5 - Modes of failure in Engineering B brick (height = 33mm, length = 214mm and width = 102mm)

For common bricks of lower strength, the mode of failure for full brick units was by two cracks, one towards the shortest distance (specimen width) and the other along the length, as indicated by Figure 4.6. The mode of failure of common bricks was less brittle than the Engineering A and B bricks. This was because common bricks are usually fired at low temperatures so the interior of the brick is much softer than the exterior. This was clearly shown by the two distinct colourations when checked after failure. The smaller cracks in specimen No. 3 (Figure 4.6) were produced when the point-load was reapplied on one of the halves.

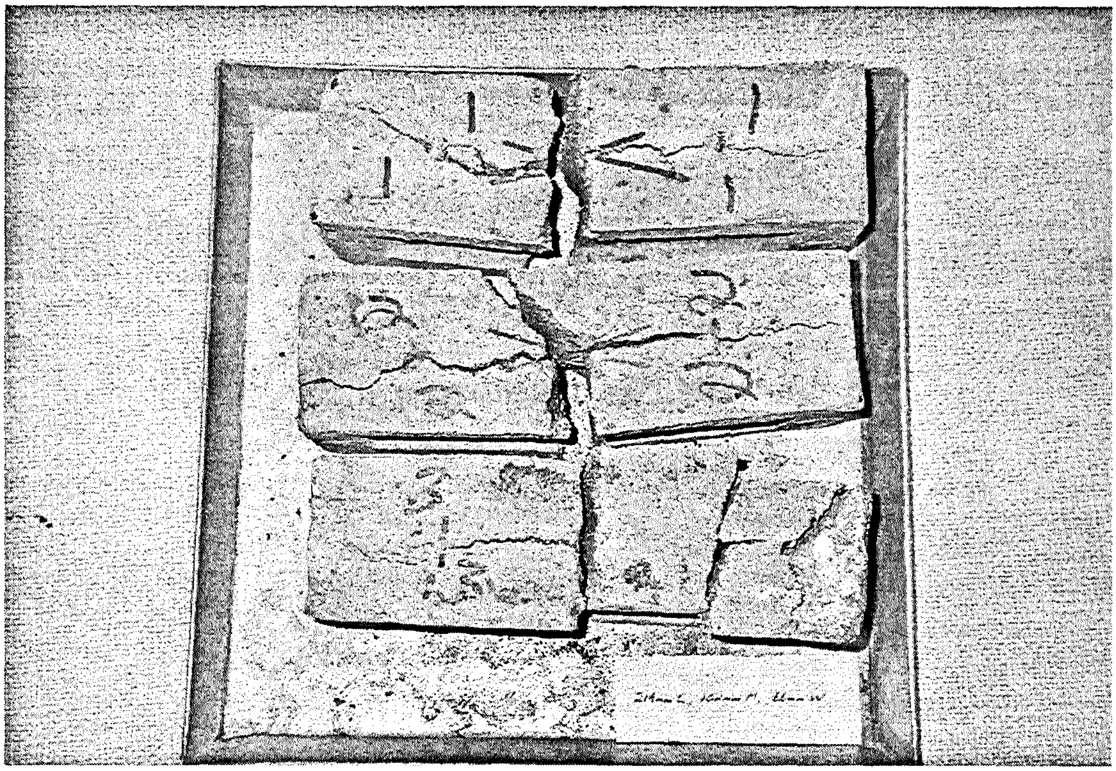


Figure 4.6 - Modes of failure in a common clay brick (height = 66mm, length = 214mm and width = 102mm)

In order to further investigate the effect of changing specimen shape on the mode of failure, samples with varying width (25, 50, 75 and 107mm) and fixed height and length were tested (Figure 4.7). By testing such samples it was possible to establish the extent of changing width on the mode of failure.

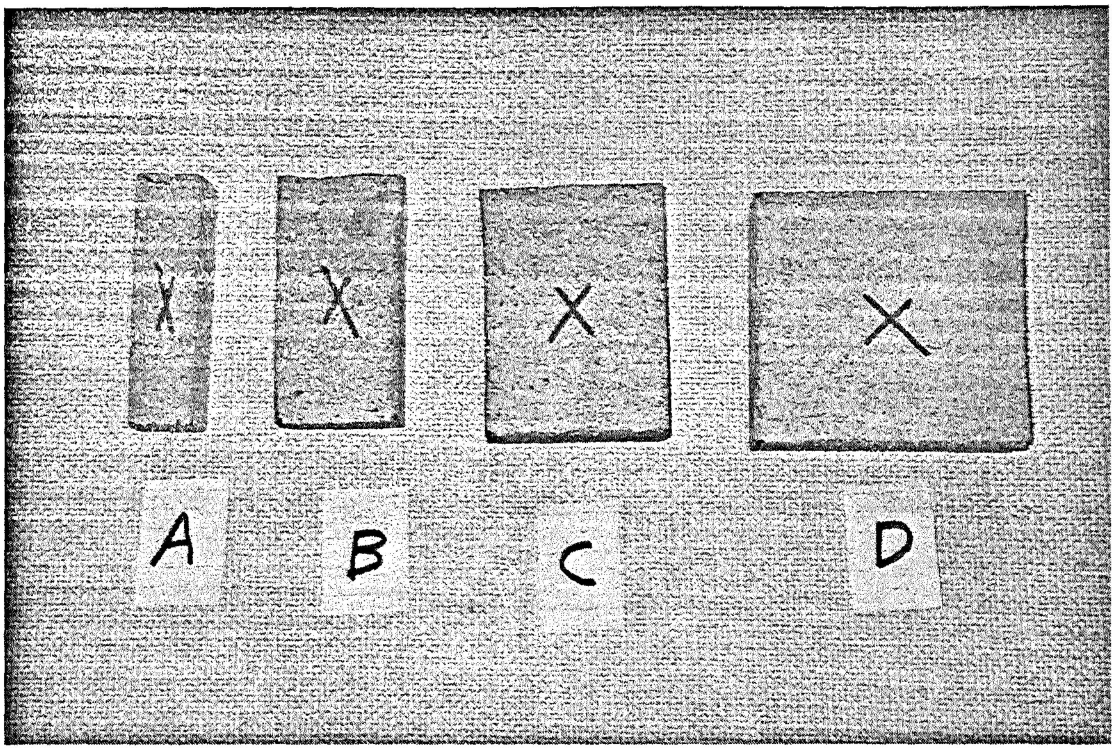


Figure 4.7 - Specimens of varying width
(fixed height = 33mm and length = 102mm)

Figure 4.8 shows a clear variation in the mode of failure between the different specimens tested. The figure shows that as the specimen width changes from 25mm to 107mm the direction of the major crack changes from a horizontal crack along the width to a diagonal crack. The mode of failure for the 50, 75, and 107mm wide specimens, in general, showed more occurrences of a diagonal crack than the narrow 25mm specimen. This diagonal crack, which was sometimes accompanied by a single crack towards one of the nearest faces, was similar to the one seen earlier in full-brick units of different heights. This suggests that the mode of failure for brick specimens with length/width ratio of 1 to 2 is similar to the mode of failure of full-brick units.

From past studies into the effect of changing the shape of rock core specimens, recommendations from various authors [97,107] concluded that the length of the specimen should be at least 1.5 to 2 times the diameter to gain the most desirable results.

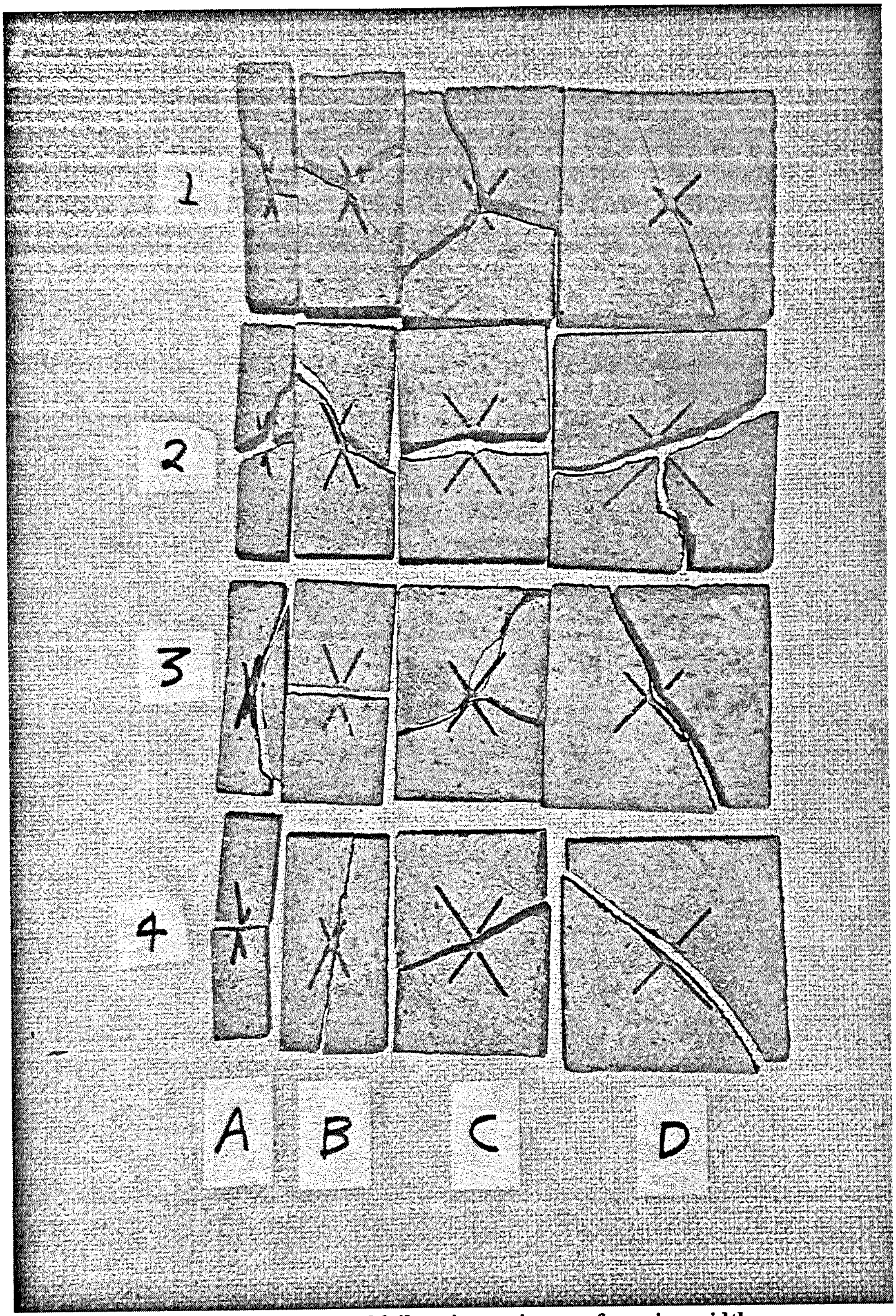


Figure 4.8 - Modes of failure in specimens of varying width (fixed height = 33mm and length = 102mm)

(b) Rupture Load of Point-Load Specimens

The point-load results in Table 4.2 show that the biggest factor influencing the rupture load is the height of a specimen. The rupture load is the maximum load the specimen can sustain before failing by splitting. Figure 4.9 shows the relationship between rupture load and height for the first set of specimens tested with variable height, fixed length of L = 214mm and width of W = 102mm.

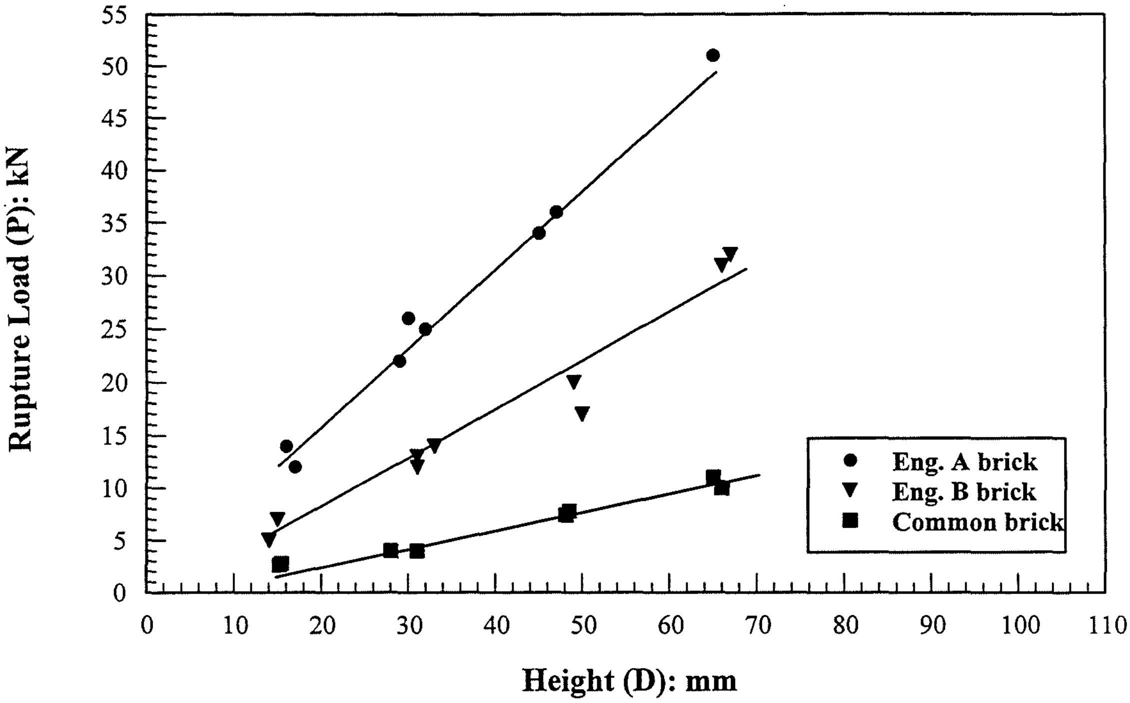


Figure 4.9 - Rupture load versus specimen height (fixed length = 214mm and width = 102 mm)

The figure shows that a linear relationship exists between rupture load and specimen height. As the height of specimen increases, the failure load increases and the gradient of the line increases with stronger brick. The best-fit line equations and correlation coefficients are displayed in Table 4.4. For the line equation P = a D + c, the constant was ignored as each line tends towards zero.

Table 4.4 - Best-fit equations and correlation coefficients for specimens of variable height, fixed length = 214mm and width = 102mm

Specimen	Equation of line *	Correlation coefficient
Engineering A brick	P = 0.760 D	0.995
Engineering B brick	P = 0.471 D	0.975
Common clay brick	P = 0.179 D	0.990

* P = Rupture load
* D = Specimen height or depth

A second set of specimens of the same brick types were tested with a variable height, fixed length L = 214mm and a narrow width of 66mm instead of 102mm. Similar to the first set of specimens, Figure 4.10 shows that a linear relationship still exists between rupture load and specimen height, with each line distinct according to brick strength. The line equations and correlation coefficients are listed in Table 4.5.

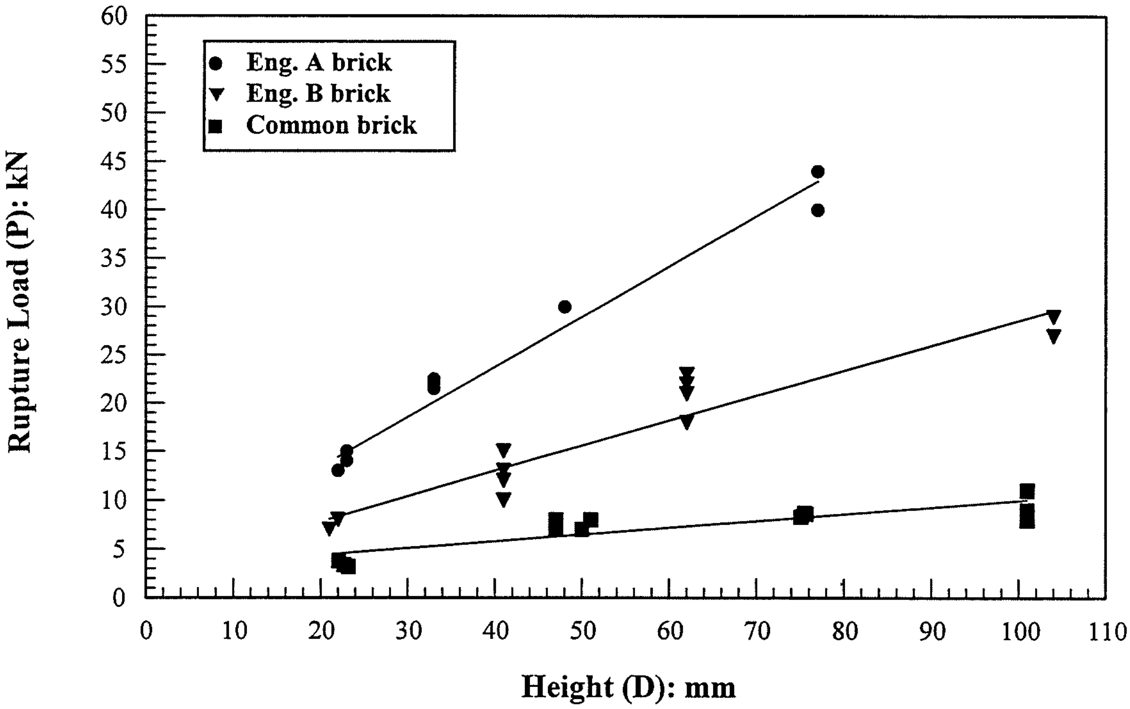


Figure 4.10 - Rupture load versus specimen height (fixed length = 214mm and width = 66 mm)

Table 4.5 - Best-fit equations and correlation coefficients for specimens of variable height, fixed length = 214mm and width = 66mm

Specimen	Equation of line *	Correlation coefficient
Engineering A brick	P = 0.520 D	0.989
Engineering B brick	P = 0.260 D	0.954
Common clay brick	P = 0.035 D	0.711

* P = Rupture load
* D = Specimen height or depth

In comparing the best-fit line equations in Tables 4.4 and 4.5 it was noticed that the line gradients for wider samples (W = 102mm), for almost all the types of brick tested, are higher than the narrow ones (W = 66mm). This is even more clear comparing Figures 4.9 and 4.10 which show that the wider samples of the same height and length, produced higher gradients or rupture loads than the narrow ones. For example, the rupture load for a 40mm high brick specimen from Figure 4.9 is approximately 35kN, whilst from Figure 4.10, a value of 25kN is obtained. This means that the width of sample has an affect on the failure load as well as the height of the sample.

To further investigate the effect of changing specimen width on the rupture load a third set of specimens was tested. Figure 4.11 was drawn for set number three (Engineering B brick) specimens with varying width, fixed height (D = 33mm) and length (L = 102mm).

As expected, the figure shows that as sample width increases, the rupture load increases. The figure also shows that sample width does not have as great an affect on the rupture load as sample height but the effects of sample width cannot be ignored.

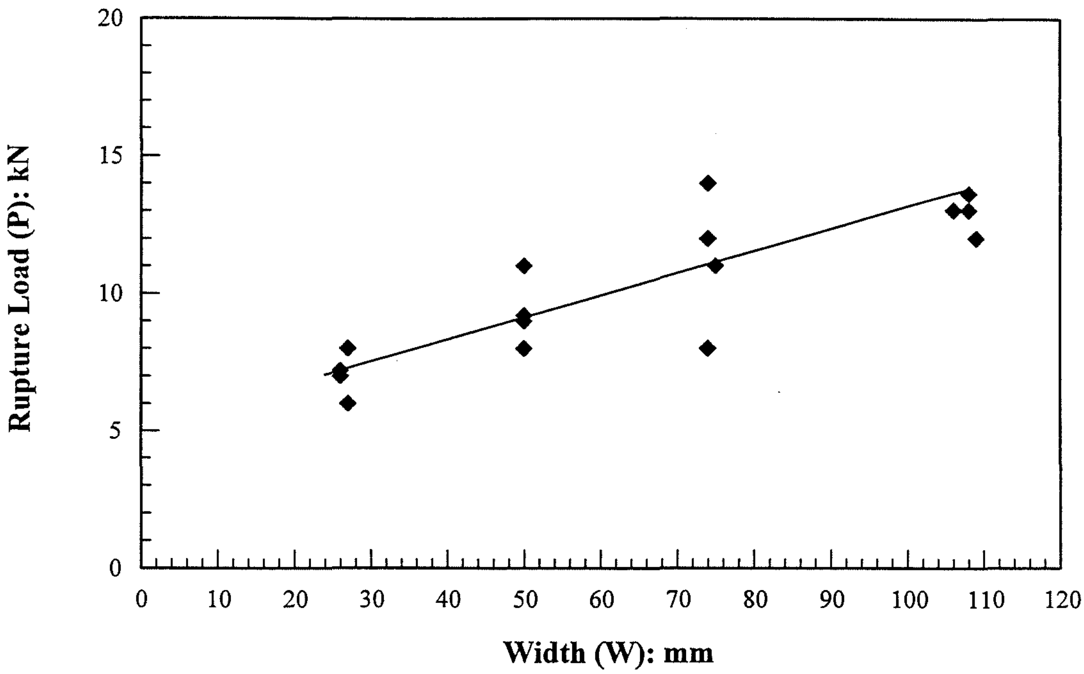


Figure 4.11 - Rupture load versus specimen width
(fixed height = 33mm and length = 102mm)

(c) Strength Index of Point-Load Specimens

The strength index (I_S) at failure is related to the rupture load (P) and the square of the distance between the conical platens (D) as follows:

$$I_S = \frac{P}{D^2} \qquad \textbf{(Eqn. 4.3)}$$

Under point-load the stresses normal to the failure plane were mostly tensile, but were accompanied by a concentrated local compressive stress in the direction of loading. This resulted in an indent in the specimen at the point of application near to the loading platens. In weaker specimens, this caused a reduction in height of the specimen and a reduced value of D. This reduction of height was only observed in the common clay bricks. The decrease in height was relatively small compared to the size of the specimen tested and deemed to have little effect on results. For the purpose of this investigation this factor was ignored.

Using Eqn. 4.3, relationships were produced relating the strength index to the height of specimens for the three brick types tested. Figure 4.12 shows the relationship between strength index and height for samples of variable height, fixed length (L = 214mm) and width (W = 102mm). The figure shows a clear difference in the values of the strength index (I_S) between the three different types of brick tested. The stronger brick (Engineering A brick) showed a sharp reduction in I_S with increase in height. On the other hand, the common clay brick showed a more gradual reduction as height increased. The figure also shows that as the descending curves reach height values of around D = 66mm, the values of I_S are almost constant and the differences between them for the three types of brick are small.

The results in Figure 4.12 suggest that the best height (D) for point-load testing to determine the strength index is between 30 and 66mm.

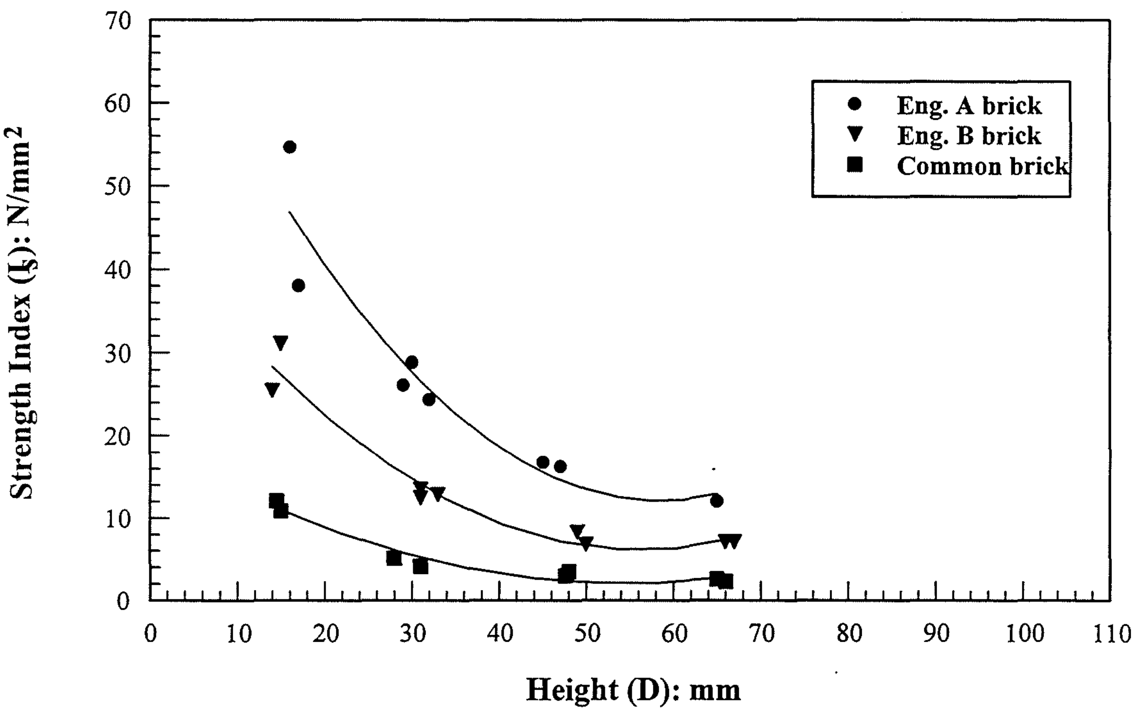


Figure 4.12 - Strength index versus specimen height
(fixed length = 214mm and width = 102mm)

Figure 4.13 shows the relationship for the second set of bricks with the same length (L = 214mm), variable heights (approximate range 20 to 100mm) and smaller width (W = 66mm) than the set tested before with W = 102mm (Figure 4.12). The figure shows that the reduction in the values of I_S as the height increases was less steep than the values presented in Figure 4.12. This suggests that wider samples of the same height and length produced higher I_S values. With samples of height above 66mm, the gradients of the line and strength index for all three brick types converge with similar results. This means that above D = 66mm it becomes more difficult to distinguish between bricks of different strength.

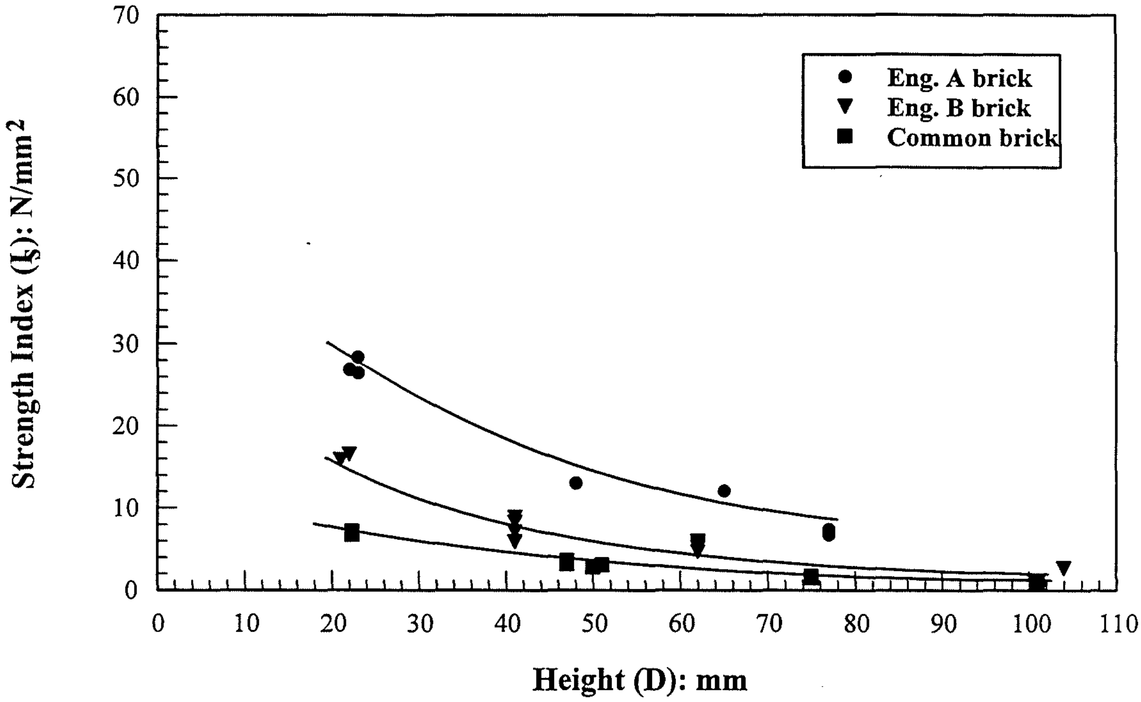


Figure 4.13 - Strength index versus specimen height (fixed length = 214mm and width = 66mm)

Figure 4.14 shows the relationship between strength index and width for samples with variable width, fixed height = 33mm and L = 102mm. The graph shows that as specimen width is increased, the strength index of the sample is also increased.

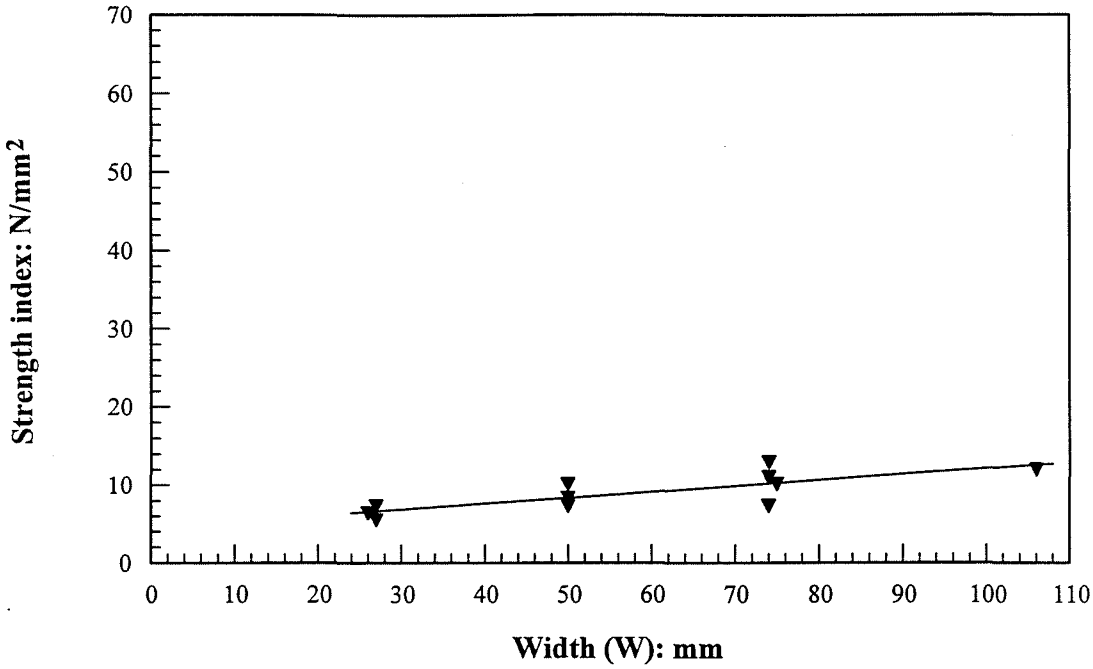


Figure 4.14 - Strength index versus specimen width (fixed height = 33mm and length = 102mm)

(d) Depth to Width Ratio (D/W)

From the graphs in the previous section, it was possible to see that both height and width govern the strength index of a point-load specimen.

To study the effects of specimen shape on test results, relationships were developed between the specimen strength index (Is) and height/width ratio (D/W). Figures 4.15, 4.16 and 4.17 show these relationships for the three sets of specimen tested.

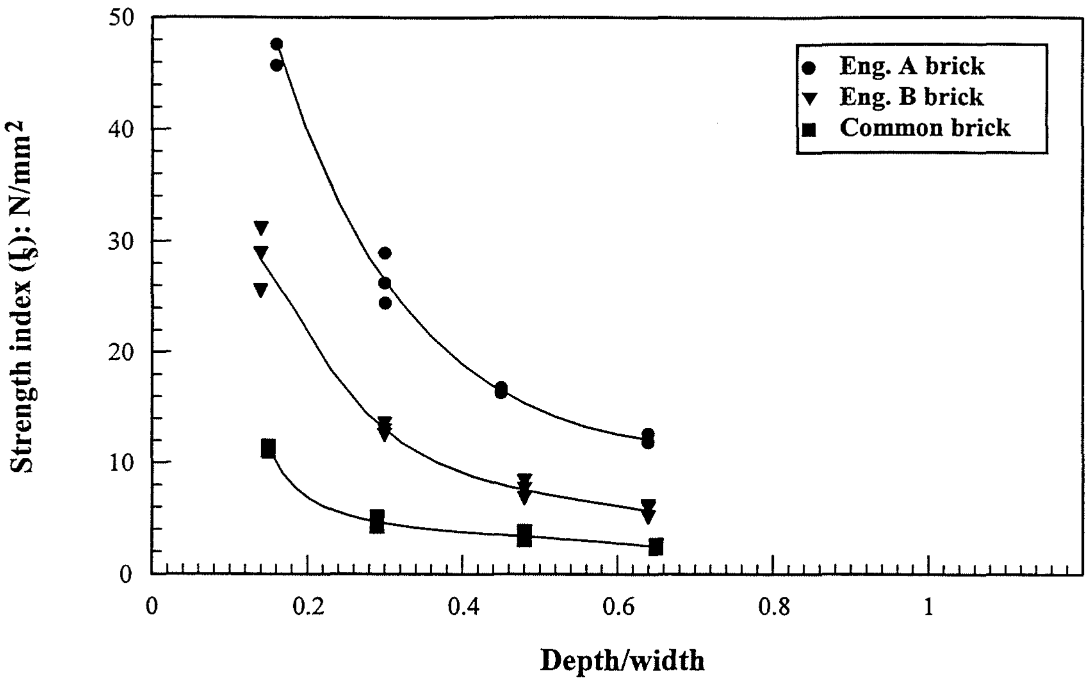


Figure 4.15 - Strength index versus depth/width ratio (fixed length = 214mm and width = 102mm)

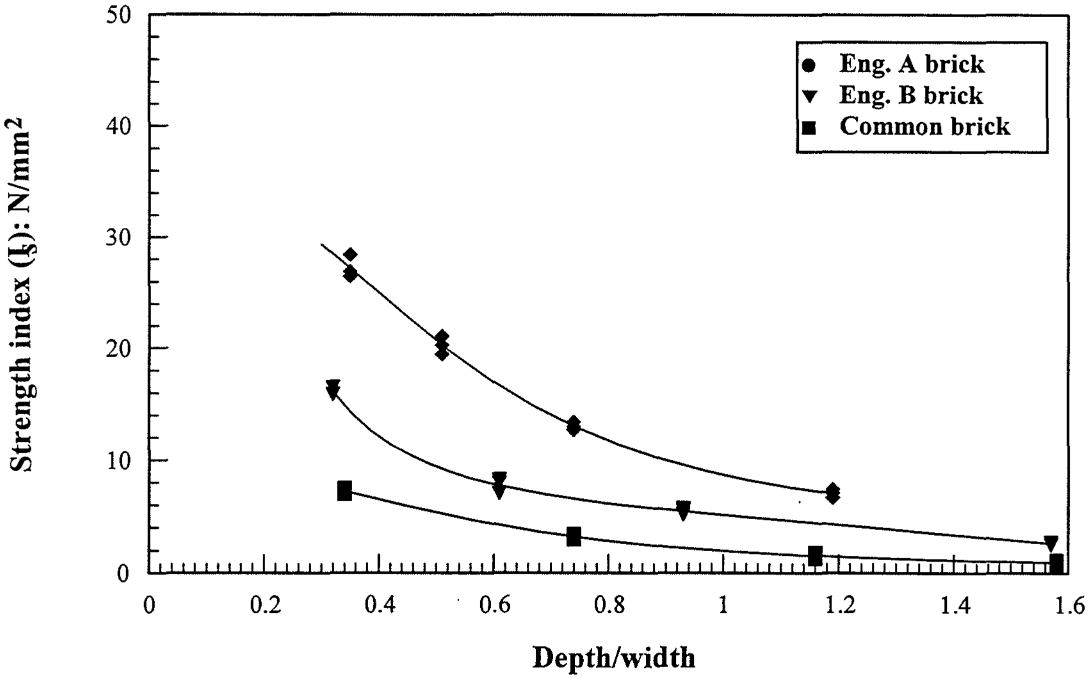


Figure 4.16 - Strength index versus depth/width ratio (fixed length = 214mm and width = 66mm)

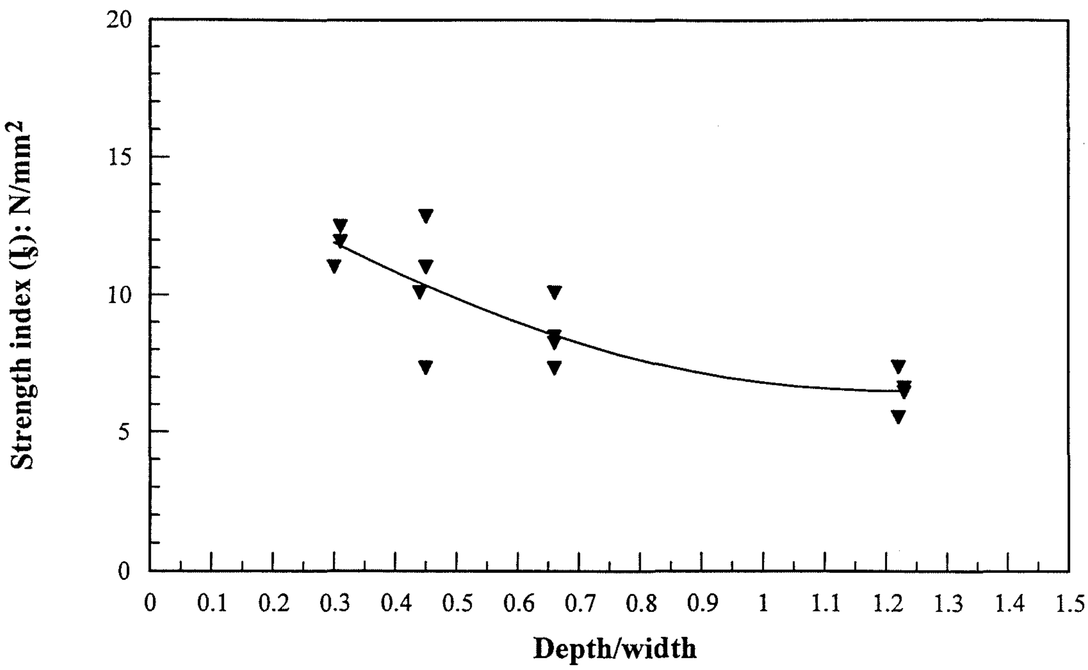


Figure 4.17 - Strength index versus depth/width ratio (fixed height = 33mm and length = 102mm)

The figures show that as the depth/width ratio (D/W) of a sample increases, the strength index decreases. These relationships are similar to the ones between specimen strength index and height presented in Figures 4.12, 4.13 and 4.14. From the above relationships, limits on the dimensions of samples suitable for point-load testing are as follows:

(i) Height (D) should be within these limits $30 \leq D \leq 65$mm.

(ii) Width (W) should be within these limits $30 \leq W \leq 102.5$mm.

(iii) Length (L) should be $L \geq W$.

(iv) Depth/width ratio (D/W) should be within these limits $0.3 \leq D/W \leq 0.63$.

These limits apply to brick units, regular and irregular new bricks and recycled brick lumps. Testing and results for irregular new bricks and recycled brick lumps are presented later in this chapter.

(e) Shape Factor (δ)

It is clear from the previous sections that the dimensions of a specimen have a major influence on its strength Index value. To account for the changes in dimensions, a shape factor (δ) was introduced to normalise the results of strength index to an equivalent standard unit. According to Khalaf and Hendry [125], a standard unit should be used which is of a convenient size and shape. The reference standard unit chosen in the present study was a half-brick of the same brick type as it was easily obtained from a full brick. The application of the shape factor would convert the value of I_S for a sample of any dimensions to an equivalent half-brick of the same brick type. The shape factor can be expressed mathematically in Eqn. 4.4 as:

$$\delta = \frac{I_S \text{ (half - brick)}}{I_S \text{ (sample)}} \qquad \textbf{(Eqn. 4.4)}$$

The next stage in the analysis was to find a relationship between the sample shape factor (δ) and its dimensions. Figure 4.18 was plotted to show the relationship between the shape factor and the depth/width ratio for sets No. 1 and 2 from Table 4.2. Set No. 1 has a width of 102mm and variable height whereas set No. 2 has a width of 66m and variable height.

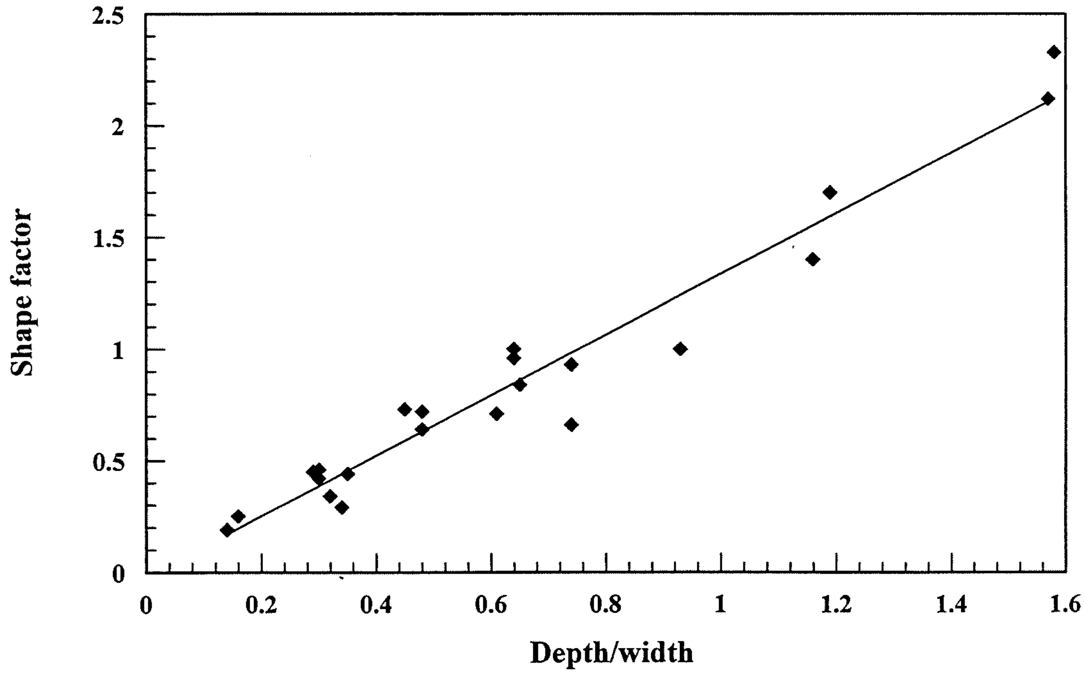


Figure 4.18 - Shape factor versus depth/width ratio

From the above figure the equation of the best-fit line passing through the results is given by the following formula:

$$\delta = 1.35\left(\frac{D}{W}\right) \qquad \textbf{(Eqn. 4.5)}$$

where

D = Sample depth or height (mm)

W = Sample width (mm)

By putting Eqn. 4.4 equal to Eqn. 4.5 and re-arranging:

$$I_{S\,(\text{sample})} = 0.74\left(\frac{W}{D}\right) I_{S\,(\text{half-brick})} \qquad \textbf{(Eqn. 4.6)}$$

or

$$I_{S\,(\text{half-brick})} = 1.35\left(\frac{D}{W}\right) I_{S\,(\text{sample})} \qquad \textbf{(Eqn. 4.7)}$$

Equation 4.7 can be used to normalise or convert the strength index of regular or irregular samples of brick to the strength index of an equivalent half-brick of the same type. Equation 4.6, on the other hand, can be used to compare the experimental results of strength index from Table 4.2 against the values predicted using the equation. This comparison is shown in Figure 4.19. In the figure the solid lines indicate experimental results and the dotted lines indicate theoretical values derived from Eqn. 4.6. The graph shows that the experimental and theoretical lines are very similar and this proves that Eqn. 4.6 can be used to predict the strength index values of regular or irregular pieces of brick samples.

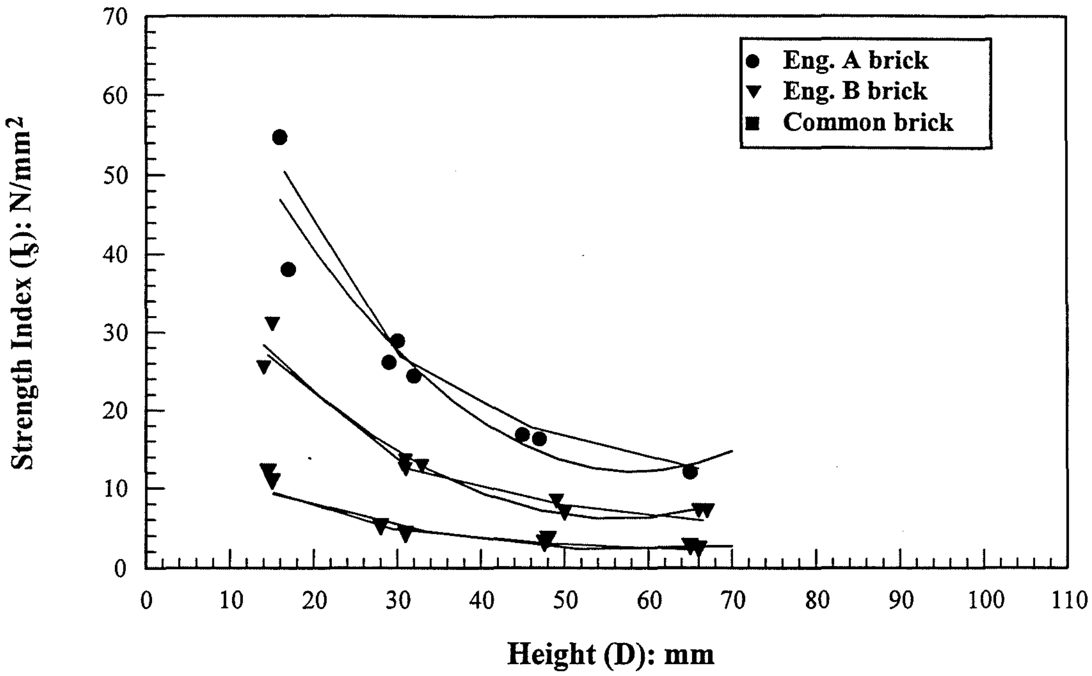


Figure 4.19 - Strength index versus height showing experimental and theoretical values for the three brick types used in the investigation

4.5.2 Compressive Strength Testing of Brick Units and Regular Brick Pieces

So far, a relationship has been established in Section 4.5.1 to normalise or convert the strength index of any regular shaped brick to the strength index of a standard half-brick using a shape factor. As clay bricks are usually classified by their compressive strength, a relationship to convert the strength index of a half-brick to its uniaxial compressive strength has many practical applications. The relationship can be used to determine the compressive strength of any new or old masonry unit indirectly by testing small pieces of brick using the point-load testing machine. This eliminates the need for heavy and expensive universal testing machines on site or in the laboratory. The relationship can also be used to find the compressive strength of demolished masonry rubble on site or in a recycling plant to decide on its suitability for crushing into coarse aggregate for use in new concrete.

To establish this important relationship, Figure 4.20 was plotted relating the strength index of half-bricks to their compressive strength for the three types of brick used in the investigation. The figure shows a good linear relationship between the two variables which can be represented as a best-fit line by Eqn. 4.8.

$$f_{b\,(\text{half-brick})} = 18 I_{S\,(\text{half-brick})} \qquad \textbf{(Eqn. 4.8)}$$

Where

f_b = Brick compressive strength

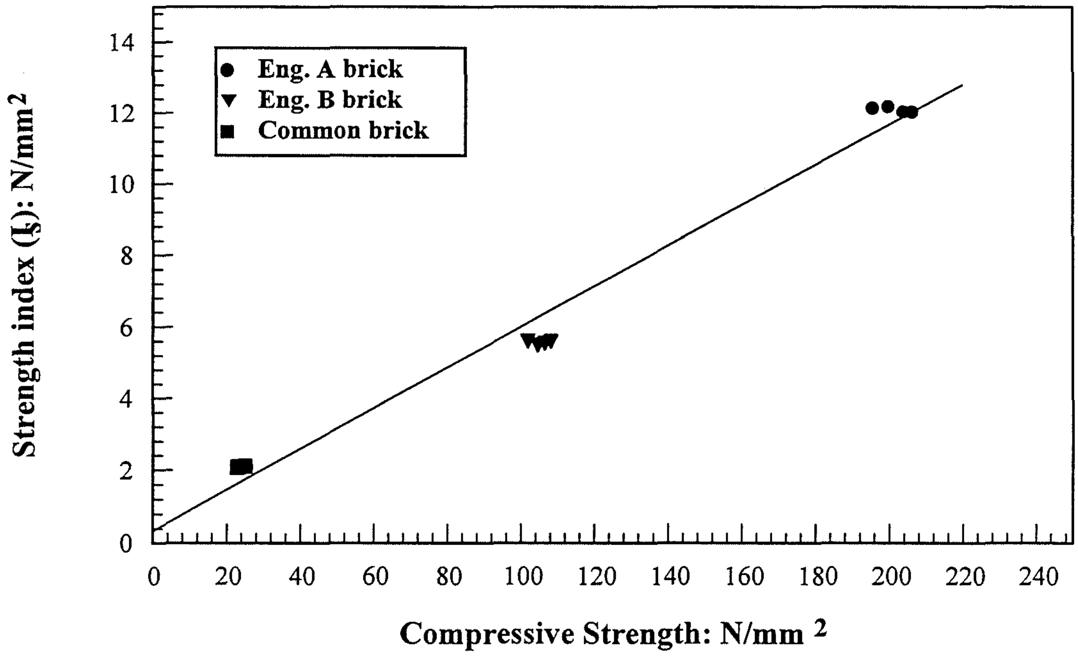


Figure 4.20 - Strength index versus compressive strength for half-bricks

Equation 4.8 can now be used to convert the strength index of a half-brick to its equivalent value of compressive strength. If the brick samples tested by the point-load testing machine are within the dimension constraints presented in Section 4.5.1 then Eqn. 4.8 or alternatively Figure 4.20 can be used to convert the values of strength index of any shape or size to an equivalent compressive strength. The conversion to compressive strength can be done if strength index values are derived from the following:

(i) Strength index from point-load test on full-bricks.

(ii) Strength index from point-load test on half-bricks.

(iii) Normalised values of strength index for half-bricks from point-load test on regular brick pieces derived using Eqn. 4.7.

(iv) Normalised values of strength index for half-bricks from point-load tests on irregular new brick lumps derived using Eqn. 4.7. The testing and results on irregular new brick lumps are presented and discussed later in this chapter.

(v) Normalised values of strength index for half-bricks from point-load test on recycled brick lumps derived using Eqn. 4.7. The testing and results on recycled brick lumps are presented and discussed later in this chapter.

The point-load test, used on rock cores, established a constant of 24. This value has been validated by various authors [97,102,107]. The rock cores tested included quartzite, sandstone, and dolomite which is a very dense material. The value of 18 is expected as brick is not as strong as the rocks mentioned above.

4.5.3 Point-load Testing of Irregular New Brick Lumps

The point-load test was carried out on irregular new brick lumps produced from the point-load testing of brick units and regular new brick pieces. With the point-load machine being small and easily portable, it is anticipated that the machine can be used in the laboratory or on site to test irregular new or recycled lumps of brick to determine their strength index and indirectly their compressive strengths. This eliminates the need for heavy and expensive universal testing machines usually used for determining the uniaxial compressive strength of brick units. In this section irregular lumps of different shape and size that were with-in the dimension limits or constraints given in Section 4.5.1 were tested using the point-load method to check the validity of the relationships derived earlier using brick units and regular new brick pieces. Figure 4.21 pictures various lumps of new brick which were used in this part of the investigation.

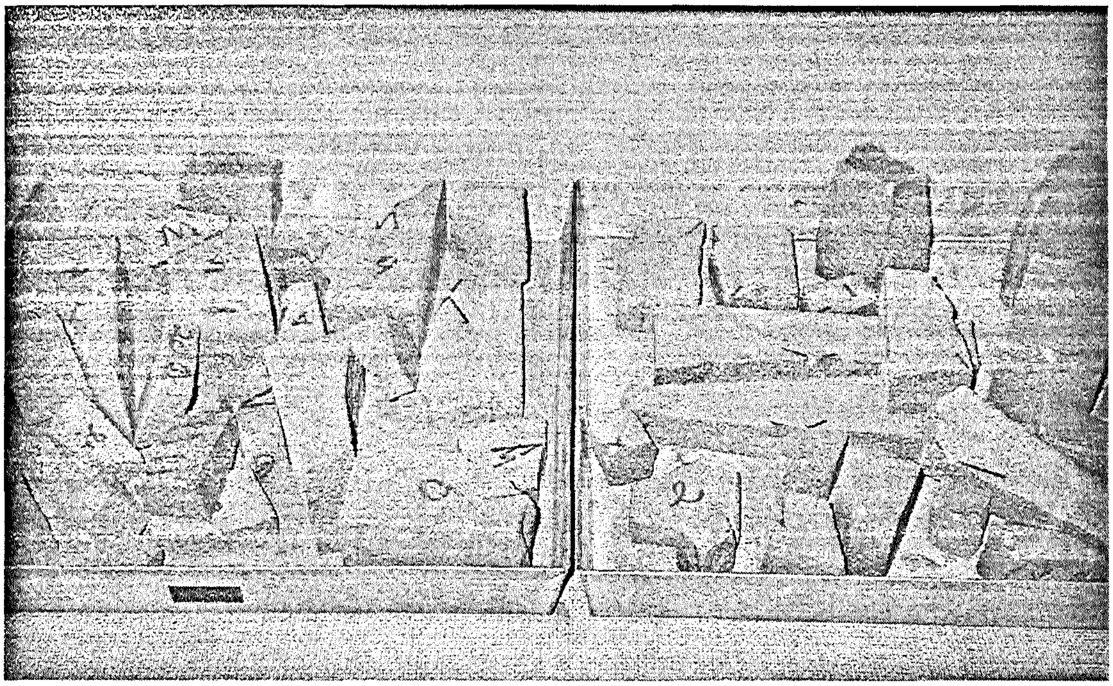


Figure 4.21 - Irregular new brick lumps

Several relationships were plotted to indicate that irregular specimens follow the same pattern of behaviour as the regular shaped specimens tested earlier in this chapter. The main aim of this section was to check or prove that Eqn. 4.6 can be used to predict successfully the values of strength index of irregular brick lumps. If proven, then Eqn. 4.7 can be used to normalise the values of strength index derived from tests on irregular shaped lumps to the strength index of half-bricks. This allows the conversion of the normalised values of strength index of half-bricks to the equivalent compressive strength using Eqn. 4.8 or Figure 4.20 (Section 4.5.1).

Figure 4.22 was plotted to show the relationship between specimen rupture load and height for irregular shaped specimens. The figure shows a similar trend to Figure 4.9 for regular pieces which shows that as the height of sample increases, rupture load increases and the gradient of the line increases with each stronger brick.

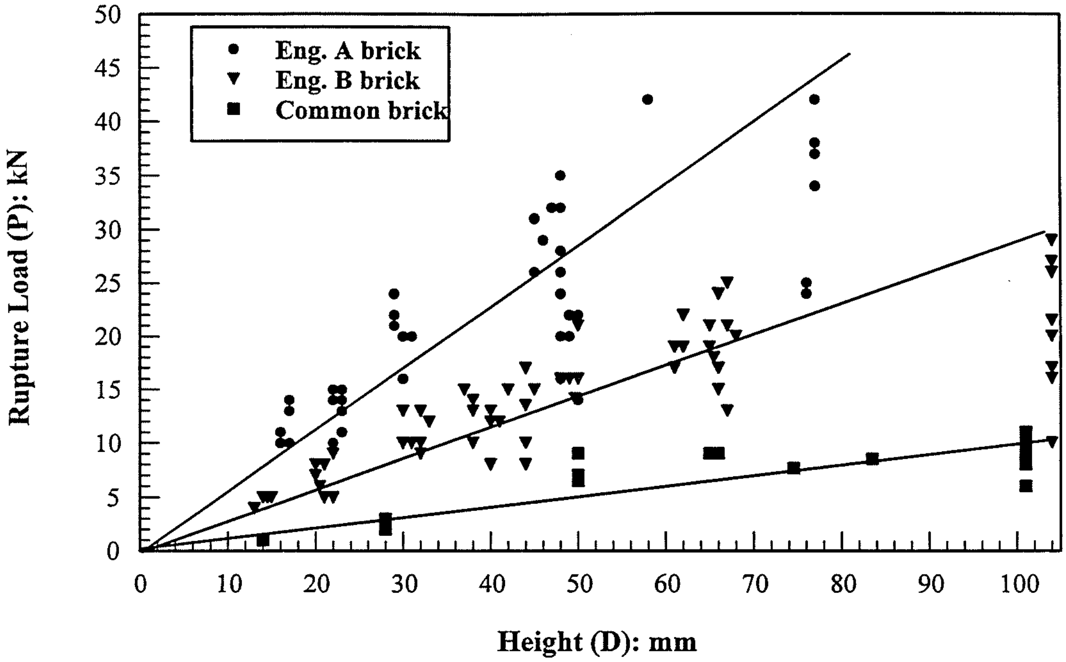


Figure 4.22 - Rupture load versus height for irregular shaped lumps

Figure 4.23 was plotted to show the relationship between strength index and height for irregular shaped lumps of all three brick types. As with the regular shaped specimens, as specimen height is increased, the strength index decreases. In Figure 4.23 the solid lines represent the experimental results obtained and the dotted lines represent the theoretical values predicted using Eqn. 4.6. The graph shows a good correlation between the theoretical values derived using Eqn. 4.6 and the experimental values. This suggests that irregular brick lumps of any shape or size behave in a similar manner under point-load as brick units and regular new brick pieces. This means that all the equations (Eqns 4.6, 4.7 and 4.8) derived earlier for brick units and regular pieces can be used for irregular shaped lumps. This allows the determination of compressive strength of half-brick units indirectly from point-load tests on irregular brick lumps as shown earlier in the chapter for regular pieces.

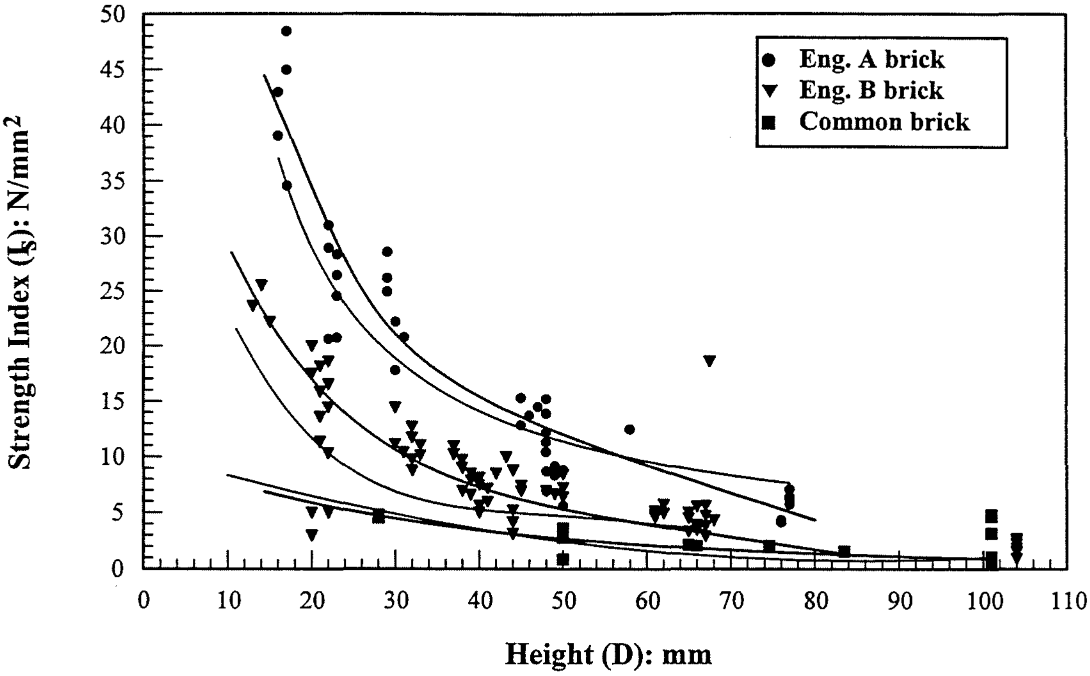


Figure 4.23 - Strength index versus height for irregular shaped lumps

4.5.4 Point-load Testing of Recycled Brick Lumps

This section attempts to determine the compressive strength of parent bricks indirectly from the results of point-load testing carried out on irregular shaped recycled brick pieces. Knowing the compressive strength of the parent bricks has the following advantages:

(i) Determining whether or not demolished building rubble is suitable for crushing into aggregates for use in new concrete.

(ii) Selection and sorting out of demolished building rubble on site before sending the materials to a recycling plant.

(iii) Allows the operator of a recycling plant to decide on whether or not the demolished building rubble arriving on lorries from unknown sources is suitable for recycling or not.

(iv) Helps the operator in sorting and storing the demolished building materials on site on the basis of their different engineering uses and applications.

For recycled bricks to be used as crushed aggregate in concrete it is quite important to estimate the compressive strength of the parent bricks because as shown in later chapters, the strength of the aggregate has a major influence on the strength of the new concrete.

Tables 4.6 and 4.7 present the point-load results from tests carried out on irregular shaped recycled brick pieces of two different types obtained from a recycling plant. Using Eqn. 4.7 the sample strength indexes were converted to the strength indexes of the equivalent half-bricks. Since the point-load test is easy to carry out, ten samples of each type were tested to determine the average values.

Table 4.6 – Point-load test results for Type 1 recycled brick lumps

Specimen	**Height D (mm)**	**Length L (mm)**	**Width W (mm)**	**Rupture load P (kN)**	**$I_{S\,(sample)}$ (N/mm^2)**	**Normalised $I_{S\,(half\text{-}brick)}$ (N/mm^2)**
1	29.0	85.9	58.9	4.9	5.8	3.9
2	31.0	68.7	34.1	2.9	3.0	3.7
3	26.0	92.0	37.8	2.7	4.0	3.7
4	23.0	46.8	37.2	2.3	4.3	3.6
5	21.0	72.6	37.9	2.2	5.0	3.7
6	23.0	53.8	40.5	2.3	4.3	3.3
7	24.0	57.0	33.7	2.1	3.6	3.5
8	14.0	63.7	28.2	1.0	5.1	3.4
9	29.0	55.0	29.8	2.2	2.6	3.4
10	33.0	64.2	54.2	4.5	4.1	3.4
Average normalise $I_{S\,(half\text{-}brick)}$						3.5

In Table 4.6 the average normalised strength index for a half-brick was found to be 3.5. This can be converted to a compressive strength of a half-brick by using Eqn. 4.8.

Compressive strength of half-brick

$(f_{b\,(half\text{-}brick)}) = 18 \times I_{S\,(half\text{-}brick)} = 18 \text{ x } 3.5 = 63\ N/mm^2$

Table 4.7 – Point-load test results for Type 2 recycled brick lumps

Specimen	Height (mm)	Length (mm)	Width (mm)	Rupture load P (kN)	$I_{S\ (sample)}$ (N/mm^2)	Normalised $I_{S\ (half\text{-}brick)}$ (N/mm^2)
1	50	103.4	57.4	5.3	2.1	2.5
2	50	64.9	59.2	5.5	2.2	2.5
3	85	97.3	61.6	11.1	1.5	2.8
4	36	94.4	36.2	2.5	1.9	2.6
5	31	107.8	44.5	2.4	2.5	2.4
6	16	50.0	44.8	1.7	6.6	3.2
7	36	94.5	75.3	5.1	3.9	2.5
8	41	47.2	64.7	4.5	2.7	2.3
9	38	93.2	47.9	4.3	3.0	3.2
10	34	69.8	59.7	4.5	3.9	3.0
Average normalise $I_{S\ (half\text{-}brick)}$						2.7

In Table 4.7 the average normalised strength index for a half-brick was found to be 2.7. This can be converted to a compressive strength of half-brick by using Eqn. 4.8.

Compressive strength of half-brick

$(f_{b\ (half\text{-}brick)}) = 18 \times I_{S\ (half\text{-}brick)} = 18 \times 2.7 = 48.6\ N/mm^2$

Overall, the method of establishing the uniaxial compressive strength of masonry specimens indirectly using the point-load is a new concept, with results showing a good correlation between strength index and uniaxial compressive strength. With such encouraging results, this method of determining the compressive strength by means of point-loading could be adapted for most brittle engineering materials.

4.6 CONCLUSIONS

As a result of point-load testing on different masonry specimens carried out in this part of the investigation the following conclusions have been reached.

1. The results show that the common mode of failure for full-brick units was by a diagonal crack at an angle to the brick width (horizontal plane). A clear similarity was also noticed between the mode of failure of full-brick units and brick specimens with length/width ratio of 1 to 2.

2. Changing specimen height has no great influence on its mode of failure under point-load. The height of specimens selected for point-load testing should be limited by the capacity of the point-load testing machine and the distance between the loading platens (D).

3. Sample width does not have as great an affect on the rupture load as sample height.

4. The limits and constraints on the dimensions of brick units, regular and irregular new bricks and recycled brick lumps suitable for point-load testing are as follows:

   (i) Height (D) should be within these limits $30 \leq D \leq 65$mm.
   (ii) Width (W) should be within these limits $30 \leq W \leq 102.5$mm.
   (iii) Length (L) should be $L \geq W$.
   (iv) Depth/width ratio (D/W) should be within these limits $0.3 \leq D/W \leq 0.63$.

5. A shape factor (δ) was introduced to normalise the results of strength index for a sample of any dimensions to an equivalent half-brick of the same brick type. The shape factor can be expressed mathematically as:

$$\delta = 1.35\left(\frac{D}{W}\right) \qquad \textbf{(Eqn. 4.5)}$$

6. Equation 4.7 was derived to normalise or convert the strength index of regular or irregular samples of brick to the strength index of an equivalent half-brick of the same type. The equation can be expressed mathematically as:

$$I_{S\,(half\text{-}brick)} = 1.35\left(\frac{D}{W}\right) I_{S\,(sample)} \qquad \textbf{(Eqn. 4.7)}$$

7. Equation 4.8 was derived to convert the strength index of a half-brick to a uniaxial compressive strength of a half-brick. The equation can be used to determine the compressive strength of any new or old masonry unit indirectly by tests on small pieces of brick using the point-load testing machine.

$$f_{b\,(half\text{-}brick)} = 18 I_{S\,(half\text{-}brick)} \qquad \textbf{(Eqn. 4.8)}$$

8. The results show that the use of the point-load machine is a feasible concept in determining the uniaxial compressive strength of new and old masonry bricks. The point-load testing machine is more convenient, cheaper, mobile and can be used on site or in the laboratory as an alternative means of determining compressive strength rather than heavy and expensive universal testing machines.

9. The point-load testing machine can be used to find the compressive strength of demolished masonry rubble on site or in a recycling plant. Knowing the compressive strength has the following advantages:

   (i) Determining whether or not demolished building rubble is suitable for crushing into aggregates for use in new concrete.

   (ii) Selection and sorting out of demolished building rubble on site before sending the materials to a recycling plant.

   (iii) Allows the operator of a recycling plant to decide on whether or not the demolished building rubble arriving on lorries from unknown sources is suitable for recycling or not.

(iv) Helps the operator in sorting and storing the demolished building materials on site on the basis of their different engineering uses and applications.

Chapter 5

USE OF CRUSHED NEW BRICK AGGREGATE IN THE PRODUCTION OF CONCRETE

5.1 INTRODUCTION

Clean crushed concrete aggregate has successfully been used to produce good quality concrete for a number of years [2,5,17,30,35,52,56,62,68]. However, the use of recycled masonry aggregate has mainly been limited to low level uses such as pipe bedding or site fill. This is mainly due to impurities in the material, lack of knowledge of its performance in concrete, lack of available standards on the use of recycled aggregates in concrete and high water absorption characteristics of recycled aggregates.

Some work has been carried out into the possibility of using crushed brick as an aggregate in concrete but most of the research dates back to just after the Second World War. Only a small amount of work has been carried out using the types of brick that are commonly used in construction today and there is little knowledge on the subject in the UK.

In order to investigate the effects of using recycled masonry aggregate with its impurities on the properties of fresh and hardened concrete, it was first necessary to use clean brick aggregates crushed from new bricks. The purpose of this chapter therefore is to investigate the physical and mechanical properties of concrete produced by using clean brick aggregates free from impurities as the coarse aggregate fraction. Results are presented for the compressive strength, density, splitting strength, flexural strength and fire resistance of various concrete mixes produced with different types of coarse aggregates crushed from new bricks. These results are compared to results obtained for concretes produced with granite as the coarse aggregate.

5.2 MATERIALS USED

5.2.1 Cement

Ordinary Portland cement of $42N/mm^2$ compressive strength was used during the experimental work. By using one type of cement the effect of varying the types of coarse aggregate in concrete can be investigated [126,127].

5.2.2 Fine Aggregate

A concrete fine aggregate of medium grading was used throughout all the experimental work so as to keep the fine aggregate variable constant. The results of the sieve analysis for the fine aggregate are presented in Table 3.6 and Figure 3.2 (Chapter 3).

5.2.3 New Clay Bricks

In Total, four types of new clay bricks with varying compressive strength were used to produce aggregates for this part of the investigation. The bricks used were of 215x102.5x65mm working sizes before crushing. The brick types used and their average compressive strengths are given in Table 5.1. Full details of tests on the brick units and the brick aggregates are presented in Chapter 3.

Table 5.1 - Clay brick types used in investigation

Aggregate no.	Brick type	Full-brick compressive strength, f_b (N/mm^2)	C.V. (%)
1	Common	39	6.6
2	5 Slot	53	5.8
3	3 Slot	68	5.2
4	10 Hole	81	3.3

5.2.4 Granite Aggregate

A 20mm single sized granite aggregate was used in this part of the investigation so that comparisons could be made with the new clay brick aggregates. The results of the sieve analysis and other tests on granite aggregate are given in Chapter 3.

5.2.5 Admixtures

An air entraining chemical admixture was used in this investigation in order to produce air entrained concrete with new brick aggregates.

A superplastising chemical admixture was used in this part of the investigation in order to study the effects of admixtures on the properties of fresh and hardened concrete.

5.2.6 Water

In accordance with British Standards, ordinary tap water suitable for human consumption was used in the production of concrete [128].

5.3 MIX DESIGN

Concrete mixes were designed for each of the four new brick aggregates and also for the granite aggregate. The concrete mix design method used was the one recommended by the Department of Environment "Design of Concrete Mixes" which is based on a report produced by the Building Research Establishment [129]. This was a mix design which had already been proven for the granite aggregate but the new brick aggregates would have to be pre-soaked before use as the mix design method is based on the aggregate being in a saturated surface-dry (SSD) condition.

Normal strength concrete mixes were first designed with a characteristic strength of f_c=30N/mm^2, a target mean strength of f_m=43N/mm^2 at 28 days and a w/c ratio of 0.55.

High strength concrete mixes were designed to determine if new brick aggregate could be used as the coarse aggregate in producing concrete of a higher strength. A new mix was designed with a characteristic strength f_c=50N/mm^2, a target mean strength f_m=63N/mm^2 and a w/c ratio of 0.4.

An air entrained mix was designed to incorporate 5% air into the concrete. This was done to check whether the concrete mix design method [129] can be used to design brick aggregate concrete mixes with air entrainment. It is also to study if entrainment of air would affect the workability and strength of crushed brick aggregate concrete. A mix was designed for three crushed brick aggregate concretes and also for a granite aggregate concrete in order that comparisons could be made.

In order to study the effects of varying the w/c ratio, the normal strength concrete mix design was used but the w/c ratio was only changed at the last stage to alter the mix proportions. The mix design was not altered at the design stage because this would have altered other variables such as cement content and fine aggregate content.

A normal strength mix design was modified to increase the workability limits from a slump of 10-30mm and Vebe of 6-12secs to 30-60mm and 3-6secs respectively. By specifying higher workability levels this had the effect of increasing the free water content at the design stage. The mix design was then modified further to raise the workability limits to 60-180mm and 0-3secs for the slump and Vebe time respectively. This mix was designed to investigate if crushed brick aggregate concrete could be produced without pre-wetting the brick aggregate before mixing.

A normal strength concrete mix design was used with the addition of a superplasticising chemical admixture to study the use of admixtures in brick aggregate concrete.

Table 5.2 shows a summary of the types of mixes which were designed for the present investigation. The types of aggregate used, target strengths, mean strengths and w/c ratios are given along with the workability limits.

Table 5.2 - Types of mixes designed for experimental programme

Mix no.	Mix type*	Agg. used	f_c (N/mm^2)	f_m (N/mm^2)	w/c ratio	Slump (mm)	Vebe (secs)
M1	Normal strength	Granite /brick	30	43	0.55	10-30	6-12
M2	High strength	Granite /brick	50	63	0.4	10-30	6-12
M3	Air entrained	Granite /brick	30	59	0.43	10-30	6-12
M4	Varying w/c ratio	Type 3 brick	30	43	0.55-0.7	10-30	6-12
M5	Increased workability	Type 3 brick	30	43	0.55	30-60	3-6
M6	No pre-wetting	Type 3 brick	30	43	0.55	60-180	0-3
M7	Admixtures	Granite /brick	30	43	0.55	10-30	6-12

* Mix designs can be viewed in Appendix A

5.4 EXPERIMENTAL PROGRAMME

5.4.1 General

The absorption of crushed new brick was found to be a value between 6.2 and 12.4% (Chapter 3, Table 3.10) by weight in relation to the material in its dry state. Since the concrete mix design method used is based on the aggregate being in a saturated surface-dry (SSD) condition, it was therefore necessary to saturate the crushed brick aggregates before mixing to prevent the concrete from becoming "too thirsty". This was done by submerging the aggregate in a bucket of water for a period of 30mins. Previous tests [2] have shown that 30mins is a practical length of time to soak the aggregate as additional submersion for a further 24hrs produces only an increase of about 2% water absorption. After submersion the aggregate was towel dried to remove any excess water which was on the surface of the material. The brick aggregate must be in its SSD state before mixing. This is very important as previous experience has shown that if excess water is present on the aggregate, it will produce a very "wet" mix. The workability of concrete was monitored using the slump and Vebe tests [130,131].

5.4.2 Normal and High Strength Concrete

In order to investigate the use of crushed masonry aggregate as the coarse aggregate in concrete, it was first necessary to produce a series of normal strength (M1) mixes using aggregates produced from crushed new bricks. This was done to investigate if the type of brick used has an influence on the physical and mechanical properties of the fresh and hardened concrete. The new bricks used were of varying compressive strength in order to determine whether or not this would have an affect on the strength of concrete produced from aggregate crushed from these bricks. New bricks were used and not ones which had been used in construction before. This was done so that the effects of impurities associated with recycled aggregates could be eliminated. It would have been impossible to accurately study the effects of the brick strength using old bricks because their strengths would all be different depending on where they had been used in construction and what conditions they had been exposed to. For this phase of the investigation a proven mix design was used so that the properties of the concretes produced with the new crushed brick aggregates could be compared to the properties of concrete produced with granite aggregate, which is a proven aggregate in the production of good quality concrete.

The next phase of the testing programme was to investigate if the new crushed brick aggregate could be used as the coarse aggregate in producing concrete of a higher strength. A new mix (M2) was designed with a characteristic mean strength f_c=50N/mm^2 and a target mean strength f_m=63N/mm^2 for aggregates crushed from three types of clay brick and one granite aggregate, to act as a control. Examples of these new high-strength mix designs can be viewed in Appendix A. The aim of producing high-strength concrete was to check if clay brick aggregates can be used in structural situations where a higher strength is required. It was hoped that the clay brick aggregate concretes could produce compressive strengths close to the target mean strength of f_m=63N/mm^2.

Each of the concrete mixes were made in accordance with current UK practice [129]. Each batch was of sufficient volume to produce nine 100mm cubes for crushing [132,133] at 7, 14 and 28 days (3 cubes for each). Ordinary Portland cement and a concrete fine aggregate were used and workability was measured using the slump and

Vebe tests [130,131]. The only difference in the mixing process was that prior to mixing the brick aggregates were soaked in water for a period of half an hour. The granite aggregate which was used as a control was not pre-soaked as it was already in a SSD condition prior to mixing.

The compressive strength and the density of the concrete made with the various aggregates was determined in accordance with the appropriate British Standards [134,135].

5.4.3 Air Entrained Concrete

In order to try and improve the workability of fresh concrete containing crushed brick aggregate, concrete (M3) was produced with 5% air entrained. It has become common everyday practice to entrain a percentage of air in concrete to improve its durability and in particular its resistance to frost attack. In order to check if the mix design method recommended by the Department of the Environment [129] for designing air entrained concrete mixes with normal aggregate can similarly be used to design concrete mixes containing crushed brick aggregate, a brick aggregate mix was produced with 5% air entrainment. The addition of air also improves the workability of concrete and makes it easier to compact, place and finish. Mixes were designed for three different types of brick aggregate and one granite aggregate as a control mix. The mixes were designed to entrain 5% air and a chemical admixture was used to achieve this. The admixture was added to the concrete's mixing water before it was added to the mix.

As before the crushed brick aggregates were pre-soaked before mixing commenced so as not to affect the workability of the fresh concrete. Ordinary Portland cement and medium graded fine aggregate were again used and workability was measured using the slump and Vebe tests [130,131]. Air content was monitored in accordance with the appropriate standard [136]. Nine 100mm concrete cubes were made [132] and cured in water for testing at 7, 14 and 28 days.

5.4.4 Concrete with Varying Water/Cement Ratio

In order to try and improve the workability of concrete made with crushed brick coarse aggregate, mixes (M4) were produced with various w/c ratios. The first mix was the normal strength mix with a w/c ratio of 0.55. Three other mixes were then prepared with w/c ratios of 0.6, 0.65 and 0.7 respectively. In the three new mixes, the values of w/c ratio were altered at the final stage of the mix design. This was done so that the effect of changing the w/c ratio on compressive strength could be monitored. If the ratio had been altered at the earlier stage in the mix design, then more cement would have been added to compensate for the loss of strength caused by adding more water. It was hoped that concrete could be produced with much higher workability levels than previously recorded, with a minimum loss of strength.

For this phase of the testing, only one brick type was selected so that this variable could be kept constant. The brick chosen was the red clay brick with three slots (Type 3) which is of a medium compressive strength and should hence give average results for all brick types. As before the crushed brick aggregate was pre-wetted for half an hour before mixing commenced. Ordinary Portland cement and natural fine aggregate were again used and workability was measured using the slump and Vebe tests. Nine 100mm concrete cubes were made for testing at 7, 14 and 28 days.

5.4.5 Increased Workability

Previously the mixes were all designed to produce concrete with a slump of 10-30mm and a Vebe time of 6-12secs. This produced concrete just inside the mentioned workability limits, making the concrete difficult to compact and finish. In order to increase the levels of workability, a new mix was designed (M5) with higher workability levels of 30-60mm slump and a Vebe time of 3-6secs. By re-designing the mix, the water content was increased to improve workability and the cement content was also increased to prevent any strength loss caused by the increase of water content. This means that the mix will be more expensive to produce as it contains more cement but it is essential that a mix has an acceptable level of workability.

The aggregate was again soaked in water so that it was in a saturated surface dry condition. The only brick aggregate used for this part of the investigation was Type 3 brick aggregate. Ordinary Portland cement and natural fine aggregate were used and workability was measured using the slump and Vebe tests. Nine 100mm concrete cubes were made for testing at 7, 14 and 28 days.

5.4.6 Concrete Without Pre-wetting Aggregate

Up until now, all the mixes carried out so far involved the pre-wetting of the crushed brick aggregate for 30mins before mixing. A new mix (M6) was designed for a slump of 60-180mm and a Vebe time of 0-3secs. This mix was made without pre-wetting the aggregate prior to mixing. It was anticipated that the mix would not produce workability levels as high as what had been designed for. Instead, the aggregate should soak up some of the mixing water but it was hoped that acceptable workability levels would still be reached.

For this stage in the investigation, the crushed clay brick obtained from the 3 slot clay parent brick (Type 3) was used. Ordinary Portland cement and a natural fine aggregate were again used and workability was measured using the slump and Vebe tests. Nine 100mm concrete cubes were made for testing at 7, 14 and 28 days.

5.4.7 Concrete with Admixtures

In order to improve workability a brick aggregate concrete mix (M7) was designed and produced with the addition of a superplastising admixture. The aggregate was not pre-soaked before mixing as it was hoped that the superplasticiser would improve the workability and allow the pre-soaking procedure to be omitted.

For this part of the investigation the Type 3 crushed brick aggregate was used. Workability was measured as before and again nine test cubes were produced for compressive strength testing at 7, 14 and 28 days.

5.4.8 Tensile Splitting Strength

The tensile splitting test involves the loading of concrete specimens as show in Figure 5.1 in accordance with BS 1881: Part 117 [137]. An increasing load was applied to the specimen continuously and without shock at a rate of 0.02 to 0.04N/(mm^2.s). This rate was maintained until failure and the failure load was recorded. From the failure load the tensile splitting strength f_{ct} was calculated using the formula:

$$f_{ct} = \frac{2F}{\pi \times l \times d} \qquad \textbf{(Eqn. 5.1)}$$

Where

f_{ct}	=	Tensile splitting strength (N/mm^2)
F	=	Failure load (N)
l	=	Length of specimen (mm)
d	=	Depth of specimen (mm)

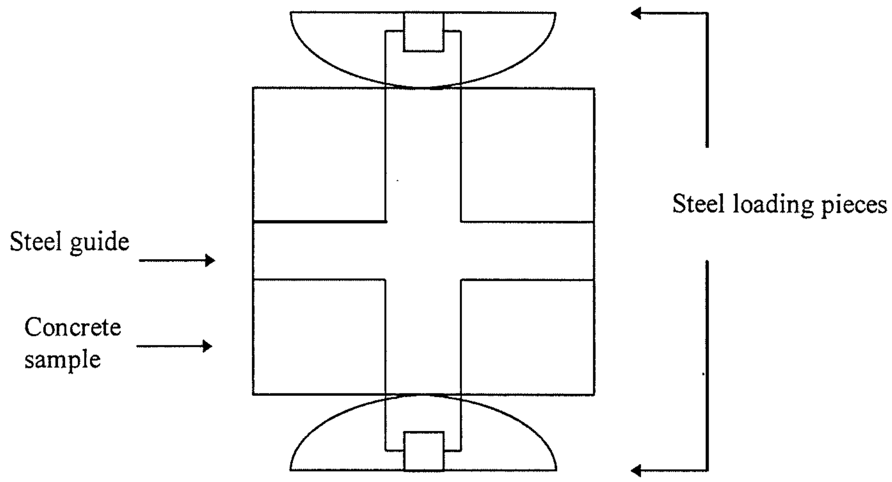


Figure 5.1 - Loading arrangement for tensile splitting strength

In order to determine the tensile splitting strength of brick aggregate concrete, a concrete mix (M1) was produced as before using crushed brick as the coarse aggregate using Type 4 parent brick. The brick aggregate was pre-wetted before use and a w/c ratio of 0.55 was used. Twelve sample cubes were taken and tested at 3, 7, 14 and 28 days for tensile splitting strength. Control concrete containing granite aggregate was also produced and tested in the same manner so that the performance of the brick aggregate could be asserted.

5.4.9 Flexural Strength

Flexural strength of hardened concrete was determined by testing a concrete beam using a two-point loading in accordance with BS 1881: Part 118 [138]. The loading arrangement to determine the flexural strength of concrete is shown in Figure 5.2. A load was applied without shock at a rate of 0.06 ± 0.04N/(mm^2.s) until failure occurred. The flexural strength f_{cf} was calculated using the formula:

$$f_{cf} = \frac{F \times l}{d_1 \times d_2^{\ 2}} \qquad \textbf{(Eqn. 5.2)}$$

Where

f_{cf}	=	Flexural strength (N/mm^2)
F	=	Failure load (N)
d_1 and d_2	=	Lateral dimensions (mm)
l	=	Distance between supporting rollers (mm)

In order to determine the flexural strength of brick aggregate concrete, beams of 400×100×100mm were produced using crushed new brick Type 4 (10 hole parent brick) as the coarse aggregate. As before a normal strength concrete mix (M1) was produced and the aggregate pre-soaked before use. The beams were produced in accordance with the appropriate British Standard [139] and a set of concrete beams containing granite aggregate was also produced so that comparison could be made. The beams were then cured in water for 28 days and tested wet to determine the flexural strength. After testing, the broken pieces of the concrete beams were cut to 100mm cubes and tested for compressive strength [140].

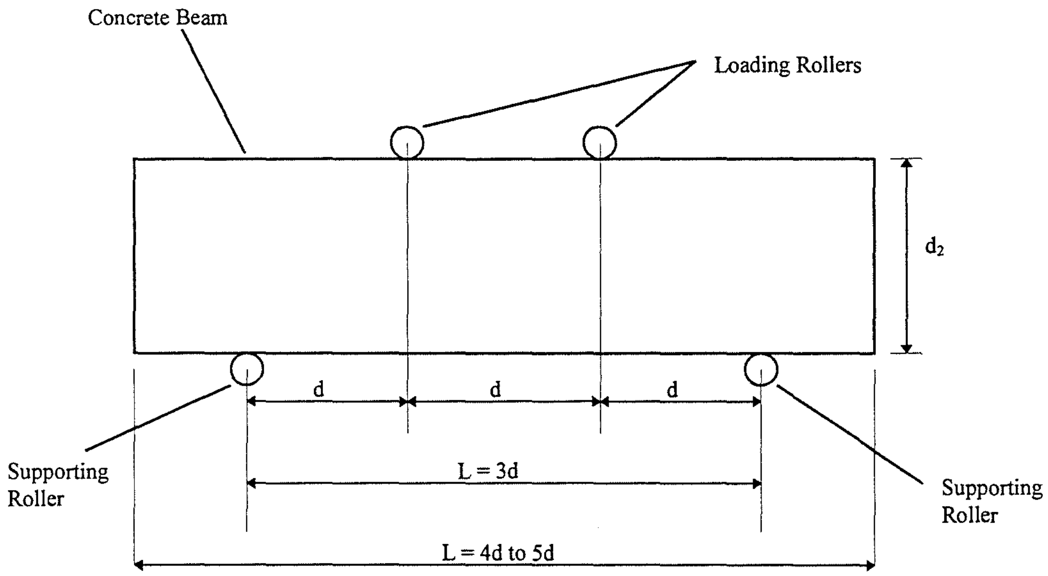


Figure 5.2 - Arrangement of loading test piece (two point loading)

The test beams used were 400mm in length and had a cross-sectional area of 100×100mm, which means that d=100mm in the above diagram.

5.4.10 Fire Resistance

One of the most important factors of concrete durability is the fire resistance of the material which must be taken into account when designing concrete structures [141]. This test determines the concretes ability to maintain compressive strength when exposed to extreme high temperatures.

Four concrete mixes were produced using crushed brick as the aggregate for two mixes and granite aggregate for the other two. For each aggregate, one ordinary (M1) and one air entrained mix (M3) were produced. Fifteen 100mm test cubes were taken from each mix for strength tests at different temperatures. Three cubes for each temperature were required from each different mix to test for compressive strength as well as three cubes which were crushed at room temperature to act as a control. The test cubes were placed in a kiln and subjected to designated temperatures of 200, 400, 600, and 800°C for a period of 2hrs. The cubes were tested hot within 15mins after removal from kiln for compressive strength.

Air entrained concrete was produced as well as the ordinary concrete to determine if the presence of entrained air affects the fire resistance of the concrete or not.

5.5 RESULTS AND DISCUSSION

5.5.1 Normal and High Strength Concrete

The average density, strength and workability results are presented in Table 5.3 for the two types of concrete mix produced (M1 and M2).

Table 5.3 - Properties of fresh and hardened concrete (M1 and M2)

Aggregate no./type	Concrete density (kg/m^3)	Compressive strength (N/mm^2)			C.V. (%)	Slump (mm)	Vebe (secs)
	28 Day	7 Day	14 Day	28 Day	28 Day		
M1 (Normal strength concrete)							
1(clay, f_b = 39N/mm^2)	2158	25.4	28.2	37.6	8.4	25	7
2(clay, f_b = 53N/mm^2)	2180	26.8	32.2	40.5	4.4	55	4
3(clay, f_b = 68N/mm^2)	2215	29.2	34.9	42.9	4.3	12	10
4(clay, f_b = 81N/mm^2)	2266	32.6	40.4	46.7	2.9	14	9
5/granite	2472	32.4	39.5	45.7	4.6	25	7
M2 (High strength concrete)							
1(clay, f_b=39N/mm^2)	2175	42.7	49.1	53.8	3.3	15	6
2(clay, f_b=53N/mm^2)	2208	46.8	51.6	59.2	3.8	23	6
3(clay, f_b=68N/mm^2)	2286	50.6	56.1	63.6	4.9	15	6
4(clay, f_b=81N/mm^2)	2307	49.4	60.0	66.7	5.3	20	7
5(Granite)	2558	49.0	60.6	66.8	8.5	18	7

*Density and strength results are the average of three cubes

From the results in Table 5.3 it is possible to see that most of the normal strength concretes (M1) had workability levels within the designed limits. However, the concrete mix containing the Type 2 brick aggregate exceeded the upper workability limit suggesting that this mix was too wet. This may have been caused by the presence of excess water on the aggregate particles before mixing. For high strength concrete mixes (M2) the slump and Vebe results were all within the designed workability limits. It was also observed that the high-strength concretes were more cohesive than the normal strength concretes. This may be due to the increase in cement content and the decrease in coarse aggregate content.

Overall the crushed brick aggregates produced normal strength concrete of an acceptable strength, with one of the aggregates producing concrete which was in excess of the target mean strength of $43N/mm^2$ at 28 days and also in excess of the concrete made with the granite aggregate. This is very encouraging and confirms that modern crushed bricks can be used in the production of high quality concrete. However, it is clear that some brick aggregates produce concrete which is stronger than others. Due to this fact, brick aggregates would have to be properly screened to decide the quality of the concrete they produce. This could be done by taking a sample of the aggregates and carrying out tests such as the impact, relative density or point load test on the brick lumps. From these tests it should be possible to determine the aggregates suitability for use in the production of concrete.

Research carried out in the 1940's [2] produced crushed brick aggregate concrete with a compressive strength of only between 15 and $25N/mm^2$, which is considerably lower than the strengths achieved in this investigation. The reason for this low strength is probably due to the fact that a weaker cement was used with a compressive strength of around $30N/mm^2$, compared with a cement strength of $42N/mm^2$ used in this investigation. Another reason could be that the types of brick used were not of the same quality as the ones used in this investigation and impurities could have been present in the brick aggregates which were detrimental to the concrete's strength.

From the results in Table 5.3 it is also possible to see that high strength concrete can be produced using crushed clay brick as the coarse aggregate. All three crushed clay brick aggregates produced concrete in excess of the characteristic compressive strength of $50N/mm^2$ at 28 days, with two of the aggregates producing concrete in excess of the target mean strength of $63N/mm^2$. The results of strength for brick aggregate concrete were in line with the strength values recorded for concrete containing granite aggregate.

Figure 5.3 shows the relationship between the compressive strength of the concrete cubes produced using the crushed brick aggregates and the compressive strength of the original brick units. Results are plotted for the normal strength concrete (M1) and the high strength concrete (M2).

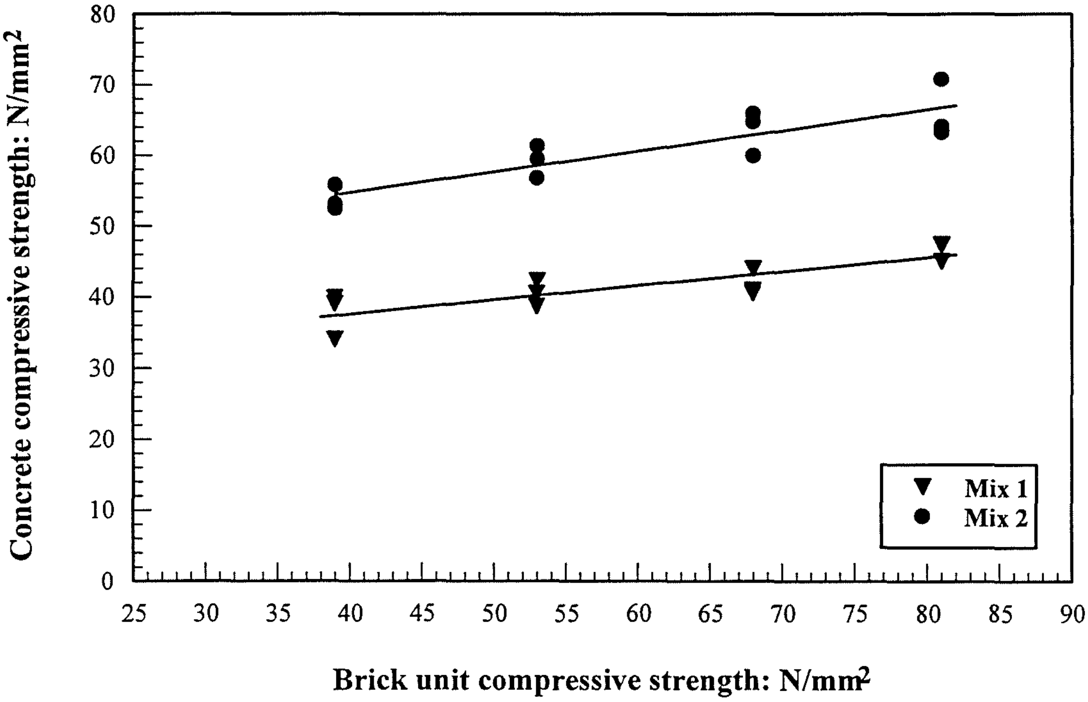


Figure 5.3 - Concrete compressive strength versus brick unit compressive strength

This graph suggests that the strength of brick aggregate concrete is influenced by the strength of the original brick. This means that it could be possible to take the strength of a brick and from that estimate the strength of concrete produced using the brick as the coarse aggregate. This would be very useful when using bricks recycled from demolished material. By determining the compressive strength of the recycled bricks, it would be possible to determine whether or not that particular brick type, in that particular condition, would be suitable for use as the coarse aggregate in new concrete.

Figure 5.4 shows the relationship between the compressive strength of concrete produced with Type 4 crushed brick aggregate and the age at testing. The figure shows that the (M1) and (M2) concretes gain strength at about the same rate as concrete made with proven aggregate (the curve was not drawn for clarity). This means that this characteristic of the concrete has not been altered by using crushed brick as the coarse aggregate and the same relation exists for both types of concrete.

The gain in strength with age is an important factor because it determines when the formwork can be stripped away from the concrete and in multi-storey construction, it is important that concrete can accept loads at early ages so that construction can continue without delay.

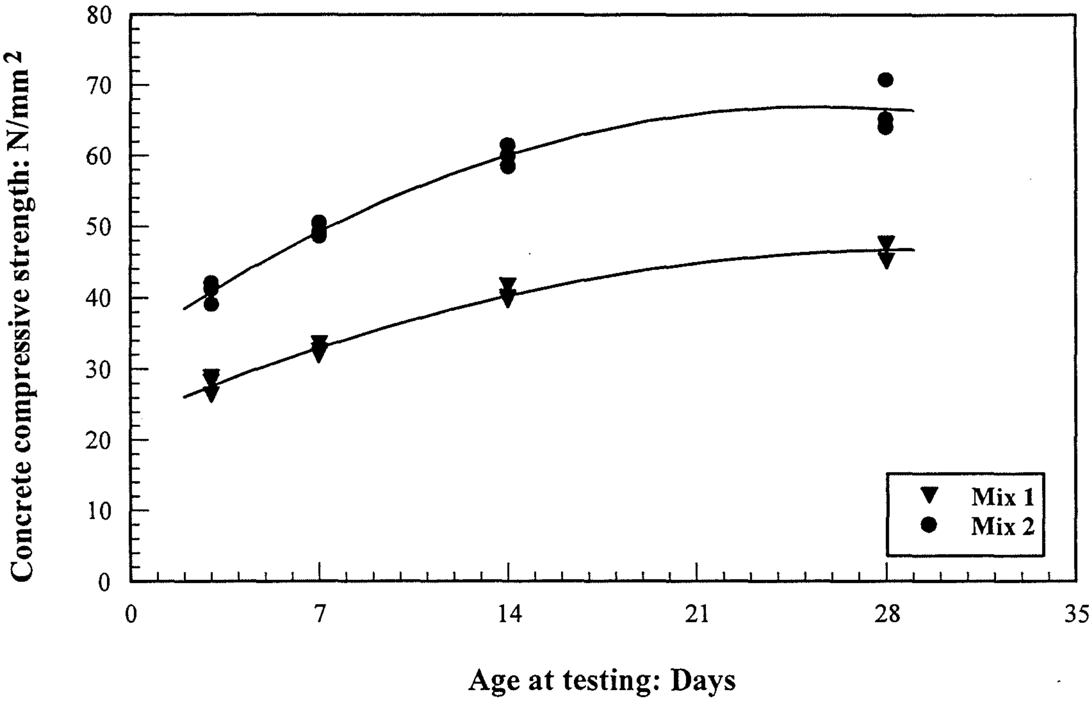


Figure 5.4 - Concrete compressive strength versus age at testing

By looking to the results of density in Table 5.3, it is clear that all the crushed brick aggregates have produced concrete with a lower density than the granite aggregate concrete. The concrete density is 8-13% less when crushed brick is used instead of granite aggregate to produce normal strength concrete. Similarly, when crushed brick was used to produce high strength concrete the concrete density was 10-15% less than the granite aggregate concrete with only a small loss in compressive strength. The density range of normal weight concrete is 2200 to 2600kg/m^3 so it is possible to see that most of the concretes produced with crushed brick have densities at the bottom or below this range. However, some of the crushed brick aggregates have produced concrete of a higher strength than the granite aggregate. This means that concrete made from crushed brick aggregate could be used where a concrete of low density is required and where self-weight is a problem. This is a big advantage because in concrete construction, self-weight represents a very large proportion of the total load on the structure. Therefore, by using a concrete of low self-weight, smaller sections can be used and consequently the size of foundations can be reduced representing a financial saving.

The values of concrete densities presented in Table 5.3 are slightly higher than the ones recorded by Akhtaruzzaman and Hasnat [42] who produced concrete made with crushed brick with a density between 2000 and 2080kg/m^3. Although the strength values of the concrete were much lower suggesting that the bricks used were of low compressive strength.

Figure 5.5 shows the relationship between concrete compressive strength at 28 days and concrete density for both the normal and high strength concretes. As expected an increase in concrete density leads to an increase in compressive strength which is the case for the present relationship and it is also the case in concrete made with normal aggregate.

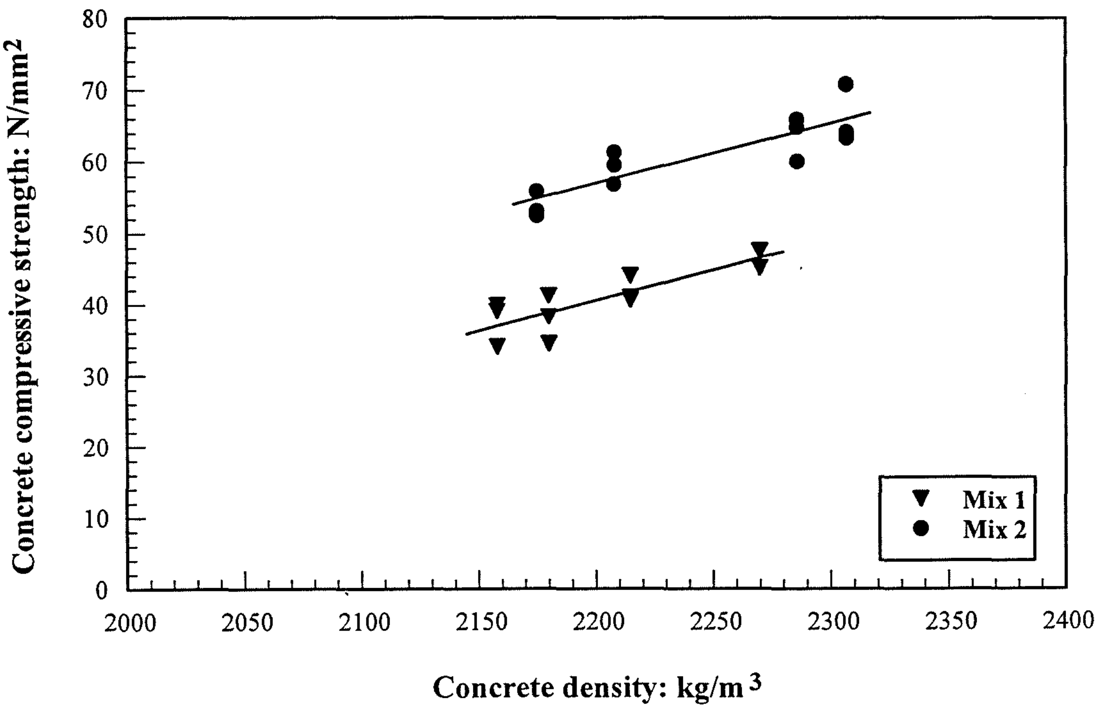


Figure 5.5 - Concrete compressive strength versus concrete density

After crushing, the concrete cubes made with the brick aggregate were examined closely. On inspection it was possible to see that many of the aggregate particles were broken right through while still being attached to the cement paste. This suggests that a good bond exists between brick aggregate particles and the cement paste even though some of the particles have a smooth surface. The reason for the good bond is that the brick aggregate particles are very angular which means that they have a large surface area to bond with the cement paste. This result is important as the bond between aggregate and cement paste is an important factor in the strength of concrete.

5.5.2 Air Entrained Concrete

The density, compressive strength, workability and air content results for the three types of brick aggregate and one granite aggregate concrete are presented in Table 5.4.

Table 5.4 - Results for air entrained concrete (M3)

Aggregate no./type	Concrete density* (kg/m^3)	Concrete compressive strength* (N/mm^2)			C.V. (%)	Slump (mm)	Vebe (secs)	Air content (%)
	28 Day	7 Day	14 Day	28 Day	28 Day			
1(clay, f_b=39N/mm^2)	2125	36.6	47.1	52.5	2.5	10	9	5.8
2(clay, f_b=68N/mm^2)	2214	39.3	44.2	58.4	5.3	15	8	5.8
3(clay, f_b=81N/mm^2)	2225	42.5	47.2	61.3	1.1	15	8	5.6
4/Granite	2482	41.3	46.6	60.0	4.1	12	11	5.1

*Density and strength results are the average of three cubes

The results in Table 5.4 show that air entrained concrete containing crushed brick aggregate can be successfully produced using the standard mix design method [128]. The compressive strengths achieved were close to the target strengths designed for and close to the strength achieved for the concrete produced with granite aggregate. The Type 3 brick aggregate (clay, f_b=81N/mm^2) concrete achieved a compressive strength which was 2% higher than the granite aggregate concrete. The density of the concrete produced was about the same as the normal concrete without air entrained but again the density was much lower than the control mix containing granite aggregate. The workability values achieved were all within the designed limits.

The strength results in Table 5.4 show that a relationship no longer exists between the original brick strength and the final concrete strength. All three types of brick aggregate used produced concrete of roughly the same compressive strength. Further testing would be required to determine if this was the case. The reason for this may be due to the combination of the high porosity of brick aggregates and the quantity of air entrained.

5.5.3 Concrete with Varying w/c Ratio

The density, compressive strength and workability results for the concretes produced with different w/c ratios are presented in Table 5.5.

Table 5.5 - Results for concrete with altered w/c ratio (M4)
(Type 3 brick aggregate, f_b=68N/mm^2)

w/c ratio	Concrete density* (kg/m^3)	Concrete compressive strength* (N/mm^2)			C.V. (%)	Slump (mm)	Vebe (secs)
	28 Day	7 Day	14 Day	28 Day			
0.55	2220	29.2	34.9	42.9	4.4	12	10
0.60	2227	20.6	26.3	31.7	1.8	40	5
0.65	2229	19.6	25.2	32.8	0.6	50	4
0.70	2209	13.0	18.9	22.7	1.3	170	2

*Density and strength results are the average of three cubes

The w/c ratio was increased in order to improve workability levels and to monitor the effects on compressive strength. By monitoring workability and strength it was then possible to determine the optimum w/c ratio which gives the strongest concrete with acceptable levels of workability. Table 5.5 shows that as the w/c ratio increases, the workability of the concrete improves considerably but it is also possible to see that the w/c ratio has little effect on the density of the concrete. Figure 5.6 on the other hand shows that as the w/c ratio increases, the compressive strength is reduced accordingly. The highest strength was recorded with a w/c ratio of 0.55. A mix with a w/c ratio of 0.5 was attempted but there was not enough water to compact the concrete in order to produce cubes. This means that the optimum w/c ratio for this mix using brick aggregate is 0.55. This result compares favourably with research carried out by Akhtaruzzaman and Hasnat [42] who reported an optimum w/c ratio of 0.54 for crushed brick aggregate concrete. The average 28 day strength of the concrete they produced was 42.2N/mm^2 which is also comparable with the result of 42.9N/mm^2 achieved in this investigation.

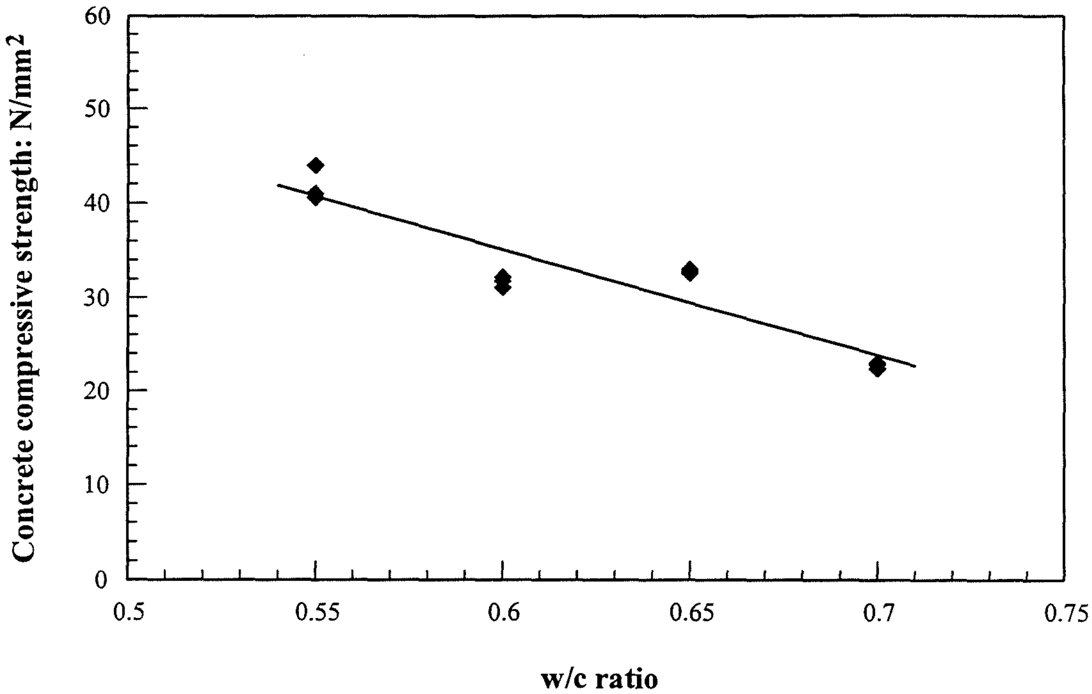


Figure 5.6 - Concrete compressive strength versus w/c ratio for Type 3 brick aggregate concrete

Figure 5.7 shows the relationship between the slump of concrete against the w/c ratio used in the concrete mixes. The graph shows that workability is increased rapidly as the w/c ratio is increased.

By looking at Figure 5.6 along with Figure 5.7, it is possible to see that if the w/c ratio is increased to 0.6 or 0.7, there is a rapid increase in the workability levels but only about a 25% loss in concrete compressive strength. This means that if high levels of workability are required, brick aggregate concrete can be produced with acceptable levels of workability and compressive strength which are acceptable for low grade concrete.

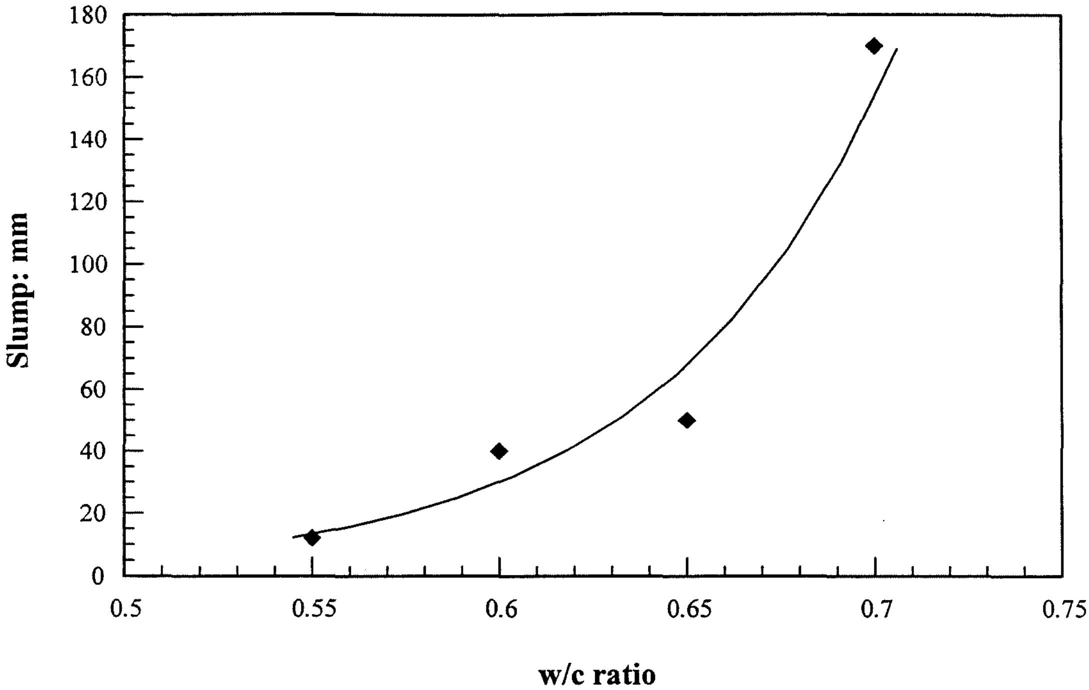


Figure 5.7 - Effect of increasing w/c ratio on concrete workability

5.5.4 Increased Workability

The density, compressive strength and workability results for the concrete mix design with higher workability (M5) are presented in Table 5.6 below.

Table 5.6 - Results for mix with higher workability (M5)
(Type 3 brick aggregate f_b=68N/mm^2)

Concrete density* (kg/m^3)			Concrete compressive strength* (N/mm^2)			C.V. (%)	Slump (mm)	Vebe (secs)
7 Day	14 Day	28 Day	7 Day	14 Day	28 Day	28 Day		
2247	2256	2252	28.2	36.1	41.6	5.3	30	6

*Density and strength results are the average of three cubes

It is possible to see from Table 5.6 that this mix produced much higher workability levels than before with the slump being raised from 12mm to 30mm but there was a drop in concrete compressive strength from 42.9 to 41.6N/mm^2 at 28 days. The results in Table 5.6 prove that crushed brick aggregate can be used to produce concrete with high levels of workability which makes it easy to compact and finish. The only disadvantage is the slightly higher cost of the concrete because the cement content has been increased by around 10% compared to the original normal mix (M1).

5.5.5 Mix without Pre-wetting Aggregate

The density, compressive strength and workability results for the concrete mix (M6) are presented in Table 5.7.

Table 5.7 - Results for concrete without aggregate pre-wetting (M6) (Type 3 brick aggregate f_b=68N/mm^2)

Concrete density* (kg/m^3)			Compressive strength* (N/mm^2)			C.V. (%)	Slump (mm)	Vebe (secs)
7 Day	14 Day	28 Day	7 Day	14 Day	28 Day	28 Day		
2262	2263	2266	35.1	38.1	43.8	7.5	10	9

*Density and strength results are the average of three cubes

Table 5.7 shows that concrete can be produced using crushed brick as the coarse aggregate without having to pre-wet the material before mixing. The slump designed for was 60-180mm but as expected due to the porous nature of the brick aggregate, a concrete with a slump of only 10mm was produced. The concrete gave a high compressive strength but the mix produced was very harsh and difficult to compact and finish. This suggests that pre-soaking of the aggregate is a better alternative than altering the mix design to increase the free water content. The density of the concrete which was produced was slightly higher than the values previously recorded for mixes with a lower designed workability due to the increase in cement content.

5.5.6 Concrete with Admixtures

The dosage of superplasticiser used, density, compressive strength and workability results for the concrete mix (M7) are presented in Table 5.8.

Table 5.8 - Results for concrete containing a superplasticiser (M7) (Type 3 brick aggregate f_b=68N/mm^2)

Dosage l/100kg cement	Density* (kg/m^3)			Compressive strength* (N/mm^2)			C.V. (%)	Slump (mm)	Vebe (secs)
	7 Day	14 Day	28 Day	7 Day	14 Day	28 Day	28 Day		
0	-	-	2270	32.6	40.4	46.7	2.9	14	9
2	2280	2289	2295	40.9	45.5	54.4	5.2	30	10
4	2307	2308	2313	40.0	48.2	56.1	4.7	70	2

*Density and strength results are the average of three cubes

The results in Table 5.8 show that the addition of a superplasticiser produced concrete with acceptable levels of workability. This was achieved without the need for pre-wetting. Compressive strength was increased by 16% for an admixture addition of 2/100kg of cement and by 20% for an admixture addition of 4/100kg of cement. These increases in strength compared with the concrete produced with pre-soaked aggregate were due to the fact that less water was present in the mix and the concrete was better compacted.

The concrete density was also increased each time the superplasticiser dosage was increased. This was due to a better compacted concrete as a result of the improvement in workability. This is clearly shown by the gradual increase in concrete density as the workability increases.

The only problem encountered with the mix was that the effect of the superplasticiser only lasted for about 15mins after that the concrete became difficult to work with. Again, this was a fairly expensive solution to the problem of aggregate pre-wetting but this has shown that, with the addition of a superplasticiser, concrete can be produced using aggregates of all moisture conditions including bone dry, with acceptable levels of workability. A cost analysis maybe needed to check the difference in cost between using a superplasticiser and aggregate pre-wetting.

It has been shown here that concrete can be produced without the need to pre-soak the coarse aggregate but the alternatives are slightly expensive although guarantee a concrete mix with higher workability. It is therefore recommended that the pre-wetting of the crushed brick aggregates is the best way of making sure that the desired workability for the concrete is reached and this procedure will be adopted for the rest of the experimental work.

5.5.7 Tensile Splitting Strength

The results for tensile splitting strength on concretes produced with Type 4 crushed brick aggregate and granite aggregate are shown in Table 5.9.

Table 5.9 - Tensile splitting strength of concrete cubes (M1)

Aggregate type	Tensile strength* (N/mm^2)				C.V. (%)
	3 Day	7 Day	14 Day	28 Day	28 Day
Granite	1.63	3.00	3.48	3.80	2.8
Crushed brick (f_b=81N/mm^2)	1.41	2.53	2.79	3.06	2.8

*Strength results are the average of three cubes

From Table 5.9 it is possible to see that at 28 days, there was a reduction in the tensile splitting strength of around 19% when using crushed brick as the coarse aggregate instead of granite. Other authors have reported increases in tensile splitting strength when using crushed brick compared with normal aggregate concretes. However, the type of natural aggregate used and the tensile splitting strength of the control normal aggregate concrete was not given so no conclusions can really be drawn.

5.5.8 Flexural Strength

The 28 day flexural strength results on concretes containing Type 4 brick aggregate and granite aggregate are given in Table 5.10.

Table 5.10 - Flexural strength of concrete beams (M1)

Aggregate type	28 Day flexural strength* (N/mm^2)	C.V. (%)	28 Day compressive strength (N/mm^2)	C.V. (%)
Granite	5.2	4.8	45.7	4.6
Crushed brick (f_b=81N/mm^2)	4.8	3.6	46.7	2.9

*Strength results are the average of three test beams

From the results it is possible to see that there was about an 8% reduction in flexural strength when crushed brick aggregate was used in place of granite as the coarse aggregate. The percentage reduction is not very high considering that the density of the crushed brick aggregate concrete is much lower than the granite aggregate concrete. This result can be compared with a 15% increase reported by Khaloo [43] and a 10% increase reported by Hansen [2]. However, without knowing the size and strength of the bricks they crushed for aggregate and the type of concrete they were comparing their results with, it is difficult to draw any conclusions from their results.

5.5.9 Fire Resistance

Results for the normal strength mixes (M1) and air entrained mixes (M3) for Type 4 new brick aggregate (f_b=81N/mm^2) and granite aggregate are shown in Table 5.11.

Table 5.11 - Strength results at different temperatures (Type 4 brick aggregate f_b=81N/mm^2)

Temperature (°C)	Compressive strength* brick aggregate concrete (N/mm^2)	C.V. (%)	Compressive strength* granite aggregate concrete (N/mm^2)	C.V. (%)
Normal strength concrete (M1)				
Room	40.3	0.7	40.7	3.3
200	36.4	4.1	30.4	2.3
400	40.2	5.5	37.6	2.3
600	27.3	6.5	24.2	10.6
800	15.0	6.2	13.7	1.5
Air entrained concrete (M3)				
Room	50.4	4.3	42.7	1.3
200	38.7	6.7	34.1	1.4
400	43.4	2.6	37.7	6.9
600	29.3	1.8	25.5	3.2
800	19.4	3.4	13.1	7.3

*Results are the average of three cubes

Figures 5.8 and 5.9 show the relationship between concrete compressive strength and temperature for ordinary and air entrained concretes respectively.

At 100° C, water within the concrete will begin to evaporate and continue to evaporate as the temperature rises causing the more tightly held water within the concrete structure to be driven off. If the concrete is initially saturated and has a relatively low permeability then the steam will not be able to escape quickly enough leading to a build up of pressure which then leads to cracking and spalling to the interior of the concrete.

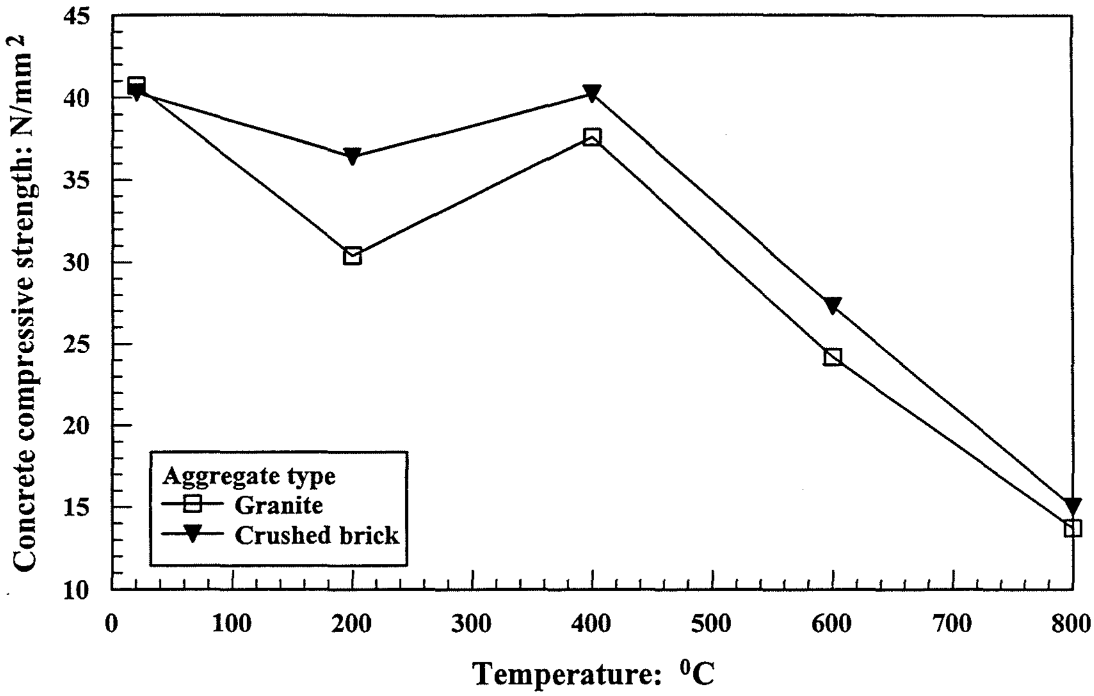


Figure 5.8 - Concrete compressive strength versus temperature for ordinary mix

Figure 5.8 shows that at approximately 200°C, both types of ordinary concrete lost their room temperature compressive strength. Although both show losses in strength, the concrete containing crushed brick clearly retains its strength better than the concrete containing granite aggregate. However, at 400°C both concretes have recovered some of their compressive strength. The gain in strength at 400°C was quite strange and maybe attributed to some hydration of the cement paste at this temperature which did not occur at lower temperatures. After 400°C the compressive strength drops off dramatically for both aggregate types. At 600°C there were visible changes in the appearance of the concrete cubes. There were surface cracks visible to the naked eye and the concrete had changed from grey to a much lighter colour for both aggregate types. At 800°C there were even more surface cracks and it was possible to see that the structure of the concrete had been affected considerably and the colour change was much more pronounced.

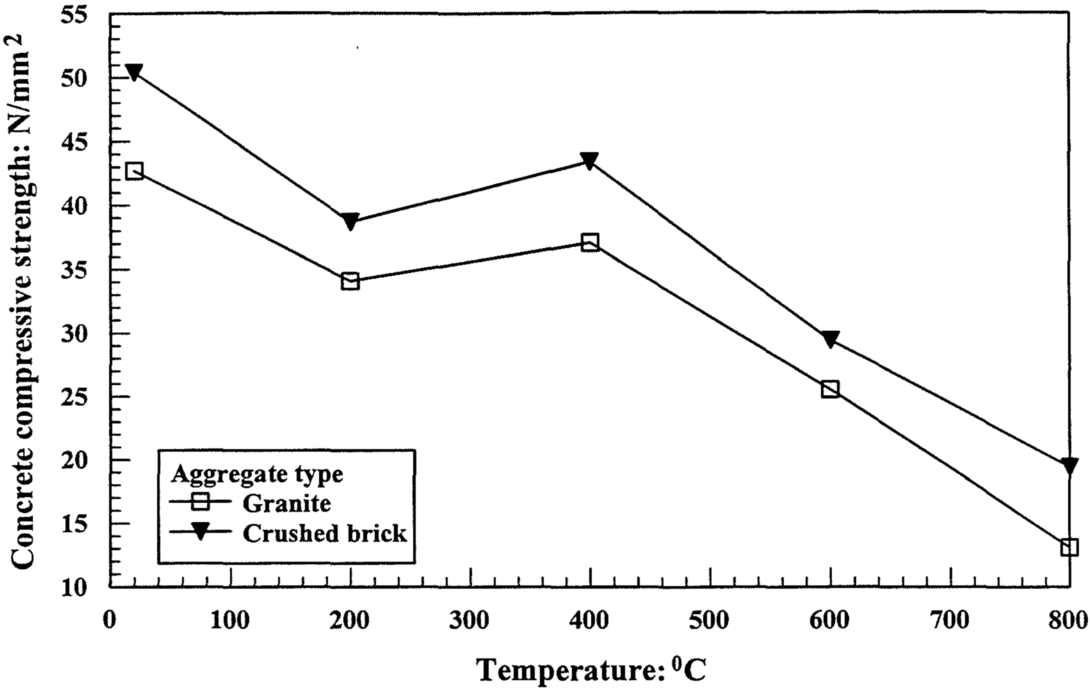


Figure 5.9 - Temperature versus compressive strength for air entrained mix

Figure 5.9 shows that the crushed brick air entrained concrete has a higher initial compressive strength than the granite concrete. When this was taken into account, it was possible to see that the two aggregate types perform equally as well when subjected to high temperatures. The results also show that as before at 400°C the strength of both concretes has recovered from an early loss in strength.

When comparing Figures 5.8 and 5.9, it is possible to see that the entrainment of air has little effect on the fire resistance of the concrete. This is backed up by the fact that the final concrete strengths at 800°C are almost the same for all concrete mixes meaning that the structure of the different concretes is broken up in the same way whether air is entrained or not. This means that crushed brick aggregate can be used in the production of good quality concrete which has a fire resistance better or at least as good as a proven aggregate, in this case granite.

It is difficult to compare the fire resistance performance of two different concretes when the initial strengths of the concrete are different. The best indicator of performance is to plot the compressive strength as a percentage of initial strength against temperature. Figures 5.10 and 5.11 plot this for the two ordinary mixes and for the two air entrained mixes respectively.

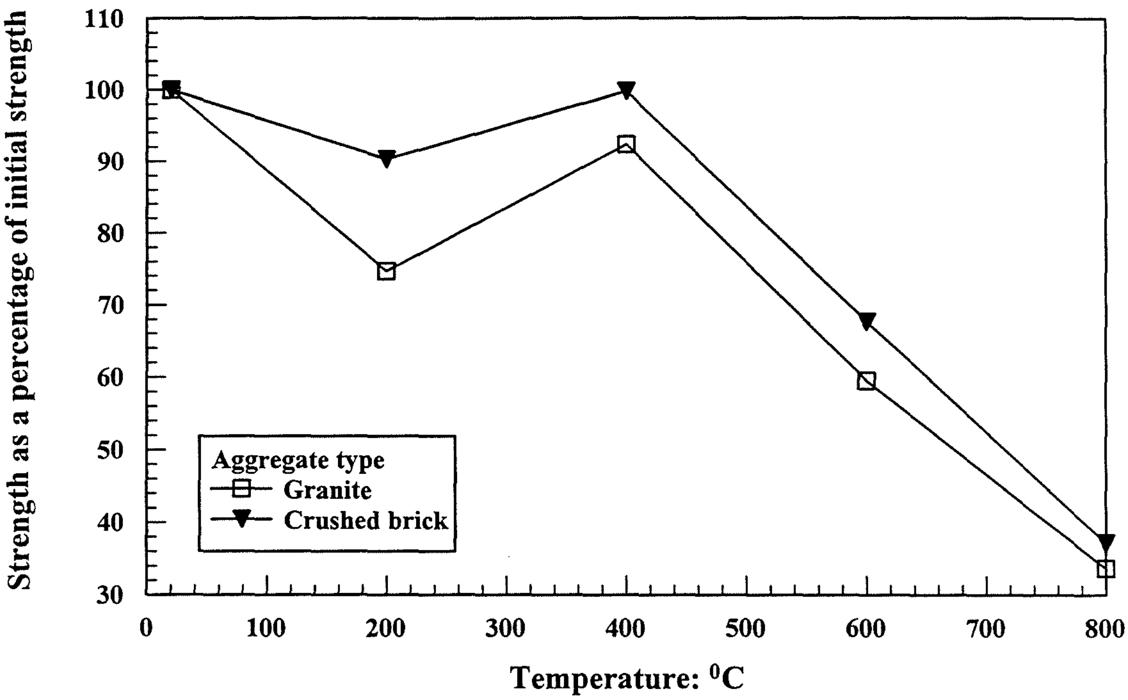


Figure 5.10 - Percentage reduction in strength versus temperature

From Figure 5.10 it is possible to see that the crushed brick aggregate concrete has maintained its strength better than the granite aggregate concrete at all temperatures. The figure shows that both types of concrete regain much of the strength at 400°C, which was lost in heating to 200°C. For the granite aggregate concrete, it regained in excess of 10% of its original strength at 400°C which had been lost at 200°C and for the crushed brick aggregate concrete, the strength regain was in excess of 7%. It is also possible to see that crushed brick aggregate concrete maintained 37% of its original strength after heating at 800°C for 2hrs. A figure of 50% at 800°C was reported by Newman [4] but no comparison can be made as no duration was given for the heating of samples.

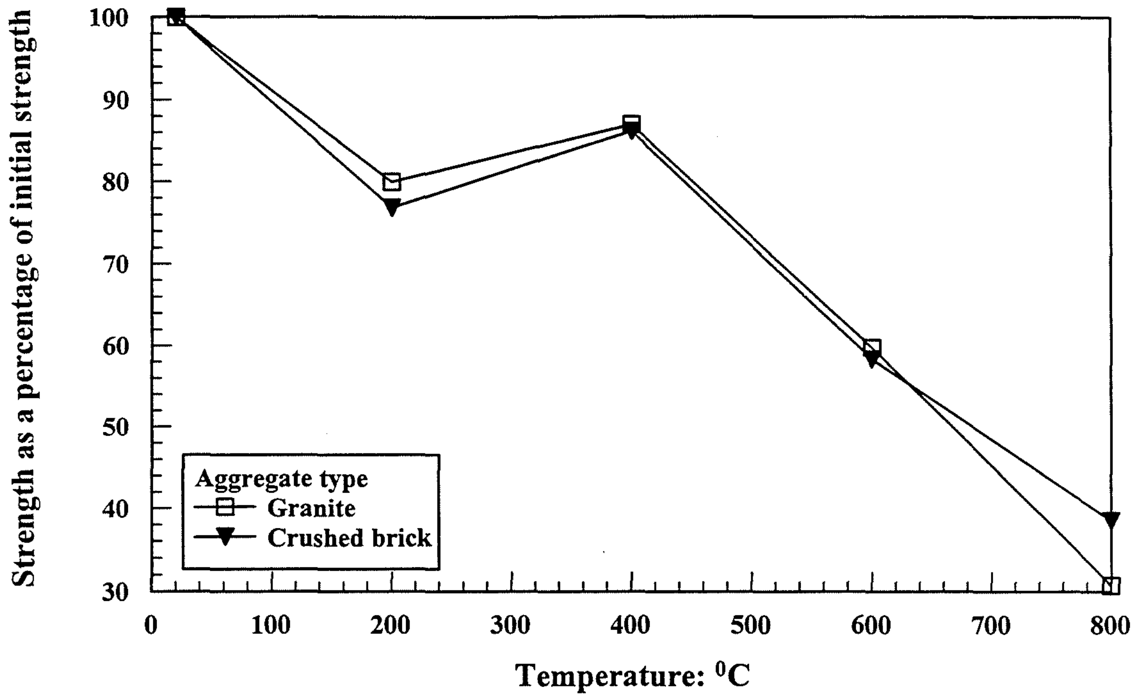


Figure 5.11 - Percentage reduction in strength versus temperature for air entrained concrete

From Figure 5.11 it is possible to see that both concrete types have performed very similarly up to a temperature of 600°C. Above this temperature the crushed brick aggregate concrete has maintained more of its strength than the granite aggregate concrete. The final strength of the crushed brick aggregate concrete was 38% of the original strength and the final strength of the granite aggregate concrete was 31% of the original strength. These percentages for air entrained concrete are comparable with the values of 37% and 34% obtained for the two ordinary concrete mixes. This proves that the addition of 5% air entrainment did not affect the concretes ability to resist extreme temperatures.

5.6 CONCLUSIONS

The following conclusions can be made from the work presented in this chapter:

1. The procedure for design of concrete mixes with normal aggregate can be used to design mixes using crushed brick aggregate. The only difference is the need for total submersion of crushed brick aggregates in water for 30mins before they can be used in concrete. However, care should be taken to make sure that the aggregate is totally surface dry before mixing.

2. Normal and high strength concrete can be designed and produced using new crushed brick as the coarse aggregate. The results show that some strengths exceed the design values and the strengths reached using granite aggregate. The compressive strength was even reached with a reduction in concrete density of between 8-15% compared to concrete produced with granite aggregate. This means that brick aggregate concrete is ideal for low density applications.

3. The stronger the original bricks, the stronger the compressive strength of the concrete made with aggregates produced by crushing these bricks. Similarly, the higher the density of the brick aggregate, the higher the concrete strength achieved.

4. Concrete made with crushed brick aggregate gains strength at the same rate as concrete made with granite aggregate.

5. A good bond can be achieved between the brick aggregates and the cement paste. This is because the brick aggregates are very angular which means they have a large surface area to bond with the paste.

6. Air-entrained concrete can be successfully produced using crushed brick aggregate. The compressive strengths achieved were close to the target strengths designed for and close to the strength achieved by the concrete produced with granite aggregate. Workability was improved slightly with the concrete relatively easy to compact and finish. The density of the air-entrained crushed brick aggregate concrete was again considerably lower than the concrete containing granite.

7. For crushed brick aggregate concrete, the optimum w/c ratio was found to be a value of 0.55, although if high workability is required then mixes can be made with w/c ratios of up to 0.7 but as expected this leads to a loss in compressive strength.

8. By designing for higher workability levels, concrete can be produced using pre-wetted crushed brick aggregate which is much easier to compact and finish. By altering the mix design, water and cement levels are increased this leads to the increase in workability without any loss in strength but more expense is involved because of the increase in cement content.

9. The pre-wetting of the crushed brick aggregate can be avoided by either designing a mix with very high workability levels or by adding a superplasticising admixture. Both methods produce concrete with an acceptable level of workability and compressive strengths are slightly higher. However, the effects of the superplasticiser only last for about 15mins, after which time the concrete becomes difficult to work with and chemical admixtures are quite expensive. By altering the mix design, the cement content is increased which means that any economical advantage of using such an aggregate would be negated. It is therefore suggested that pre-wetting is the best solution to the problem of such porous aggregates. In practice simple spraying of aggregate stockpiles with water can be carried out with minimum cost implications.

10. The tensile splitting strength of concrete produced with crushed brick aggregate was around 20% less than concrete made with granite aggregate. Similarly, concrete beams made with crushed brick aggregate were found to have an 8% reduction in flexural strength compared with the concrete produced with the granite aggregate.

11. The fire resistance of crushed brick aggregate concrete is better than granite aggregate when ordinary concrete is produced. Both concretes lose strength up to 200°C but then gain strength again up to 400°C. This maybe due to some form of hydration of the cement paste at this high temperature which accounts for an increase in strength which outweighs the detrimental effects of the high temperature. Above 400°C both concretes lost strength at a linear rate. It can be said that the two types of concrete containing the two aggregate types,

performed very similarly but the crushed brick aggregate concrete performed slightly better because brick is a thermally stable material.

12. On an average basis, the fire resistance of the two air entrained mixes are almost the same if taking into account, the fact that, the crushed brick aggregate concrete had a higher initial compressive strength than the granite aggregate concrete. At 200°C both concretes lose their strength at roughly the same rate and then regain it up to a temperature of 400°C. Again the reason for this increase in strength could be the hydration of the cement paste. Above a temperature of 400°C the strength of both concretes decreases at a linear rate as the structure of the concrete is broken up. The results suggest that both types of concrete react very similarly to extreme heat but because the crushed brick has a higher initial strength it has a slightly higher final strength as a result.

Chapter 6

USE OF RECYCLED AGGREGATE IN PRODUCTION OF CONCRETE

6.1 INTRODUCTION

Recycled aggregates have been used successfully for a number of years as sub-base and capping but their use as concreting aggregates has been very limited. This has been mainly due to concerns over impurities present in recycled aggregates and a lack of available standards concerning the use of recycled aggregates in the production of concrete. Recent innovations in recycling plant have meant that recycled aggregates have far fewer impurities present than a few years ago when demolition and construction waste was only roughly crushed. Recycling plants now have the facilities to crush waste material, grade it properly, remove dust and fine particles by washing and by proper screening it is possible to produce a material which is relatively uncontaminated. This means that material which was once only suitable for landfill can be processed to an aggregate which is suitable for producing concrete. However, before such an aggregate is accepted by industry, extensive testing of the material is required to assess its performance and reliability.

The testing described in this chapter was performed in order to establish the suitability of recycled crushed masonry material as the aggregate in new concrete. Two types of recycled aggregate were used during the testing. These two aggregate types were predominately made up of crushed masonry material obtained from crushing construction and demolition waste. The mechanical properties of these two aggregates were obtained and compared with the values obtained for clean crushed brick aggregates and the control aggregate, granite. Concrete was then produced in the laboratory and tested for density, compressive strength, tensile splitting strength and flexural strength. As recycled aggregates contain impurities, concrete containing various percentages of mortar, timber and rubber was produced to monitor the effects of these impurities on concrete strength and density.

6.2 MATERIALS USED

6.2.1 General

All the concrete mixes produced in this chapter were made with the same type of cement, water and fine aggregate as in Chapter 5.

6.2.2 Recycled Washed Aggregate

The recycled washed aggregate had been crushed, sieved to size and washed at the recycling plant in order to try and remove some of the impurities such as dirt, plaster, paper, rubber and pieces of timber. This aggregate was predominately made up of masonry material although a significant amount of impurities were still present such as pieces of concrete, mortar, paper, glass, rubber and small pieces of timber.

6.2.3 Recycled Masonry Aggregate

The recycled masonry aggregate was also obtained from the recycling plant and was almost entirely composed of pieces of broken brick in the size range of about 40-60mm. This material had been kept separate at the recycling plant because the plant operators try and keep masonry material out of sub-base material because it has high absorption characteristics. The aggregate was broken up further in the laboratory and sieved to a 20mm single sized aggregate. This aggregate was free of most impurities although a percentage of mortar was present which was adhered to the brick particles.

6.3 MIX DESIGN

Two types of concrete were designed as before in Chapter 5. Firstly a normal strength mix (M1) was designed (f_c=30N/mm^2 and f_m=43N/mm^2) with the two recycled aggregates. This mix had a w/c ratio of 0.55, a design slump of 10-30mm and natural fine aggregate was used as before. In order to assess the suitability of recycled aggregates to be used in concrete for load bearing elements, a second high-strength mix (M2) was designed (f_c=50N/mm^2 and f_m=63N/mm^2) with the two recycled aggregates. This mix had a w/c ratio of 0.4 and a design slump of 10-30mm.

6.4 EXPERIMENTAL PROCEDURE

6.4.1 Normal and High Strength Concrete

In order to investigate the use of recycled aggregates in the production of concrete, it was first necessary to produce a series of mixes using fully recycled aggregates obtained from the recycling plant. A normal strength concrete (M1) was first produced with the two recycled aggregates. The aggregates were not pre-wetted because they were already in a saturated surface-dry (SSD) condition. Nine sample cubes were made for density and compressive strength testing at 7, 14 and 28 days. High strength concrete (M2) was then produced with the two recycled aggregates. Sample cubes were again made for density and compressive strength testing. Workability for both mixes was monitored as before using the slump and Vebe tests. Results from Chapter 5 for concretes produced using crushed new brick and granite aggregate were used in this chapter to compare with the recycled aggregate concretes.

6.4.2 Tensile Splitting and Flexural Strength

Normal strength concrete (M1) was produced containing the two recycled aggregates and tested for tensile splitting strength and flexural strength in the same way as the new brick and granite aggregate concrete presented in Chapter 5. Three cubes were produced from each mix for tensile splitting at 28 days and three beams were produced for flexural strength testing at 28 days. Tensile splitting and flexural strength results of new brick aggregate concrete and granite aggregate concrete from Chapter 5 have been used in this chapter in order to compare with the recycled aggregate concretes.

6.4.3 Effects of Impurities

In order to investigate the effects of impurities on the properties of concrete, mortar, timber and rubber were included in concrete mixes, separately in varying percentages, to investigate what effect these impurities would have on density and compressive strength.

The brick type used for this investigation was Type 4 (10-hole) new brick, used earlier in the investigation, with a compressive strength of $81 N/mm^2$. The concrete produced was the normal strength concrete mix design (M1).

The impurities used were crushed mortar, timber and rubber. The mortar used was of 1:1/4:5 (cement: lime: sand) proportions by volume obtained from crushing previously built test walls which were more than 28 days old. The mortar was broken down and sieved to a 10mm single sized aggregate in the same manner as the brick aggregate. The timber and rubber were both cut into pieces of 20×20×10mm. OPC along with a fine concrete sand were used throughout this phase of the investigation. The impurities were added and mixed in to the brick aggregate before the concrete was mixed. As before the brick aggregates were pre-soaked along with the impurities for 30mins before the commencement of mixing and workability was monitored using the slump and Vebe tests.

Sufficient normal strength concrete (M1) was mixed to produce three 100mm cubes for 0, 10, 15, 25, 35% mortar, 0, 2, 5% timber and 0, 5, 10% rubber for density and compressive strength testing at 28 days.

6.4.4 Blending of Brick Aggregates

Recycled aggregates produced from demolished masonry material usually contain many brick types unless the processing of the material takes place at a particular demolition site using a mobile crusher. At fixed recycling plants, where demolition debris is brought in by truck from many different demolition sites, the material from one site can vary in quality in comparison with material from another site. This fact raises concerns over the variability in composition of recycled material and hence performance. In order to investigate this, six normal strength concrete mixes (M1) were produced blending different percentages (0,20,40,60,80 and 100%) of weak brick (Type 1, f_b=39N/mm^2) aggregate in with stronger brick aggregate (Type 4, f_b=81N/mm^2) to investigate the effects on density and compressive strength. Three cubes were produced for density and compressive strength testing at 28 days from each mix.

6.4.5 Initial Surface Absorption Test

The permeability of concrete is an important factor influencing the overall durability of concrete. Since permeability determines the relative ease with which concrete can become saturated with water, permeability has an important bearing on the vulnerability of concrete to frost damage and chemical attack. Furthermore in the case of reinforced concrete, the ingress of water containing soluble sulphate will result in the corrosion of the steel. Since this leads to an increase in the volume of the steel, cracking and spalling of the concrete cover may well follow. Ingress of moisture into concrete also affects its thermal insulation properties.

Since aggregate particles are enveloped by the cement paste, in fully compacted concrete it is the permeability of the cement paste that has the greatest effect on the permeability of the concrete. Although if the aggregate has a very low permeability its presence reduces the effective area over which flow can take place. Furthermore, since the flow path has to circumvent the aggregate particles, the effective path becomes considerably longer so that the effect of aggregate in reducing the permeability may be considerable [44].

One method of testing concrete permeability is the Initial Surface Absorption Test (ISAT) set out in BS 1881: Part 5 [73]. This test measures the rate of flow of water into concrete per unit area after a stated time interval and at a constant applied head and temperature. The test gives information about the outside skin of the concrete but the results can be used to obtain some indication of the overall concrete permeability. The apparatus used for the test can be viewed in Figures 6.1 and 6.2.

The test procedure involves attaching a plastic cap to the surface of the concrete so that it is water-tight and air-tight. The cap has an inlet tube connected to a reservoir of water and an outlet tube connected to a capillary tube which has a numerical scale attached so that readings may be taken. The inlet pipe has a tap to control the flow of water into the cap. At the start of the test, water is allowed to enter into the cap and out of the outlet tubing until no more air escapes and care should be taken to keep the reservoir replenished to maintain a constant head of water. The system is filled with water and when a reading is to be taken the inlet pipe is closed off so that water is prevented from entering the cap and when water starts to flow along the capillary tube the time is noted. After a period of 1min, water is allowed back into the system and the capillary tube is consequently refilled. Readings are taken after 10mins, 30mins, 1hr and 2hrs.

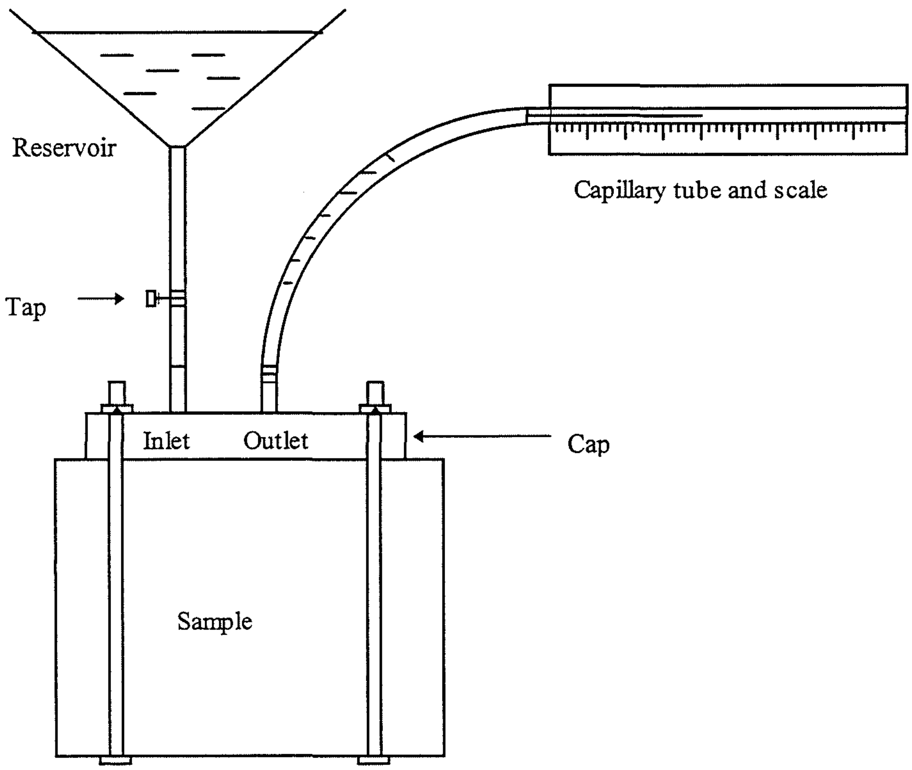
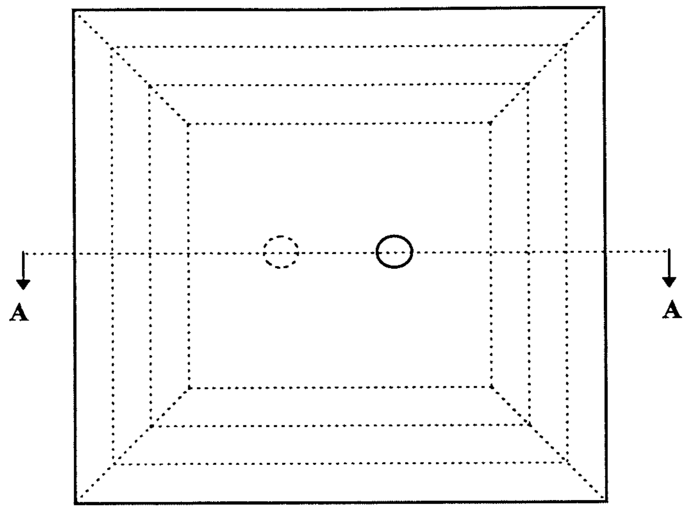


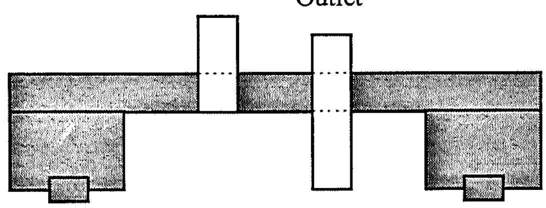
Figure 6.1 - Full ISAT assembly, excluding stands, clamps, etc

In order to study the effects of aggregate type on concrete permeability, normal strength concrete mixes (M1) were produced containing the four aggregate types (recycled washed, recycled masonry, new brick and granite aggregates). The ISAT was carried out on two, 150mm sample cubes which were taken from each mix.

The concrete cubes were cured in water for a period of 26 days and then placed in an oven at 105°C for a period of 48hrs. After oven drying, the samples were placed in a cooling cabinet and remained there until the temperature in the cabinet fell to within 2°C of the temperature in the room.



Plan view



Section A-A

Figure 6.2 - Typical cap suitable for clamping to concrete surface

6.5 RESULTS AND DISCUSSION

6.5.1 Normal and High Strength Concrete

Table 6.1 shows the density, compressive strength and workability results obtained for concrete produced with the two different recycled aggregate types. Results for the concrete containing the 10 hole new brick aggregate (f_b=81N/mm^2), the new common clay brick (f_b=39N/mm^2) and the granite aggregate have also been included so that comparisons can be made.

Table 6.1 - Results for normal and high strength concrete

Aggregate type	Concrete density* (kg/m^3)	Concrete compressive strength* (N/mm^2)			C.V. (%)	Slump (mm)	Vebe (secs)
		7 Day	14 Day	28 Day	28 Day		
Normal strength concrete (M1)							
Recycled washed	2221	21.6	26.2	33.0	5.7	22	10
Recycled masonry	2140	30.3	35.4	39.2	4.8	18	10
Common brick	2158	25.4	28.2	37.6	8.4	25	7
10 Hole brick	2266	32.6	40.4	46.7	2.9	21	7
Granite	2472	32.4	39.5	45.7	4.6	23	8
High strength concrete (M2)							
Recycled washed	2228	33.5	38.5	40.6	3.1	30	6
Recycled masonry	2162	36.8	41.3	44.8	6.4	25	7
Common brick	2175	42.7	49.1	53.8	3.3	15	6
10 Hole brick	2307	49.4	62.6	66.1	5.3	18	9
Granite	2558	49.0	60.6	66.8	8.5	25	6

*Density and strength results are the average of three cubes

From Table 6.1 it is possible to see that when using recycled aggregates there was a reduction in concrete compressive strength, compared with using granite or 10 hole new brick aggregate for the normal strength concrete (M1). The recycled washed aggregate had a compressive strength which was 35% lower than the concrete containing the granite aggregate and 29% less than the concrete containing the 10 hole new brick aggregate at 28 days. Similarly the concrete containing recycled masonry aggregate had a compressive strength which was 22% lower than the granite aggregate concrete and 16% lower than the 10 hole new brick aggregate concrete at 28 days. However, the recycled masonry aggregate concrete did have a compressive strength which was 4% higher than the concrete containing the new common brick aggregate. The recycled masonry aggregate concrete was also 16% stronger than the concrete containing the recycled washed aggregate which was surprising as it had a lower unit density. For the concrete containing the recycled washed aggregate the target compressive strength designed for was 43N/mm^2 at 28 days and the characteristic strength at 28 days was $30N/mm^2$. It is possible to see that the concrete containing recycled washed aggregate did not reach its target strength but did exceed its characteristic strength at 28 days. The reason for this low strength compared with the other recycled aggregate concrete was probably due to the presence of impurities in the recycled washed aggregate which could have caused points of weakness in the concrete.

Table 6.1 also shows that by using the Department of Environment concrete mix design method and a standard concrete mixing procedure, concrete containing recycled aggregates can be produced with an acceptable workability. It was observed that the recycled aggregates produced more cohesive mixes than the new brick aggregates and were not prone to segregation when compacted. This is probably because the recycled aggregate particles were more rounded due to the mechanical crusher used, than the new brick aggregate particles which were crushed by hand.

Table 6.1 also shows that the high strength concretes (M2) produced with recycled washed aggregate had a compressive strength which was around 39% lower than the concretes containing the granite aggregate and new 10 hole brick aggregate at 28 days. Similarly the concrete containing recycled masonry aggregate had a compressive strength which was around 33% lower than the two control concretes at 28 days. However, the recycled masonry aggregate concrete was 9% stronger than the concrete containing the recycled washed aggregate.

In general, the results for the ordinary and high-strength concrete mixes show that it is possible to produce new concrete by using recycled demolition waste as the coarse aggregate. However, these recycled aggregates have not produced concrete with as high a strength as the concretes containing 10 hole new brick and granite aggregates, which means that the recycled material should probably be screened for contaminants before being used in concrete. The cement content should also be increased by about 5-10% to achieve the same strength as concrete containing the natural granite aggregate.

The densities of the concrete made with 10 hole new brick and granite aggregate are higher than that of the concrete made with the recycled aggregates. The concrete containing the recycled washed aggregate has a density which is 11% less than the concrete containing the granite aggregate and 2% less than the new 10 hole brick aggregate concrete. Similarly concrete produced with the recycled masonry aggregate had a density 15% less than the granite aggregate concrete, 6% less than the new 10 hole brick aggregate concrete and 4% less than the concrete containing the other recycled aggregate. The decrease in density for the two recycled aggregates as expected has also resulted in a decrease in strength, although the strength achieved would be suitable for some construction purposes especially where a low density concrete is required.

Figure 6.3 shows the relationship between the concrete compressive strength and age at testing for the normal strength concrete mix (M1) for the five types of aggregate used in the present investigation.

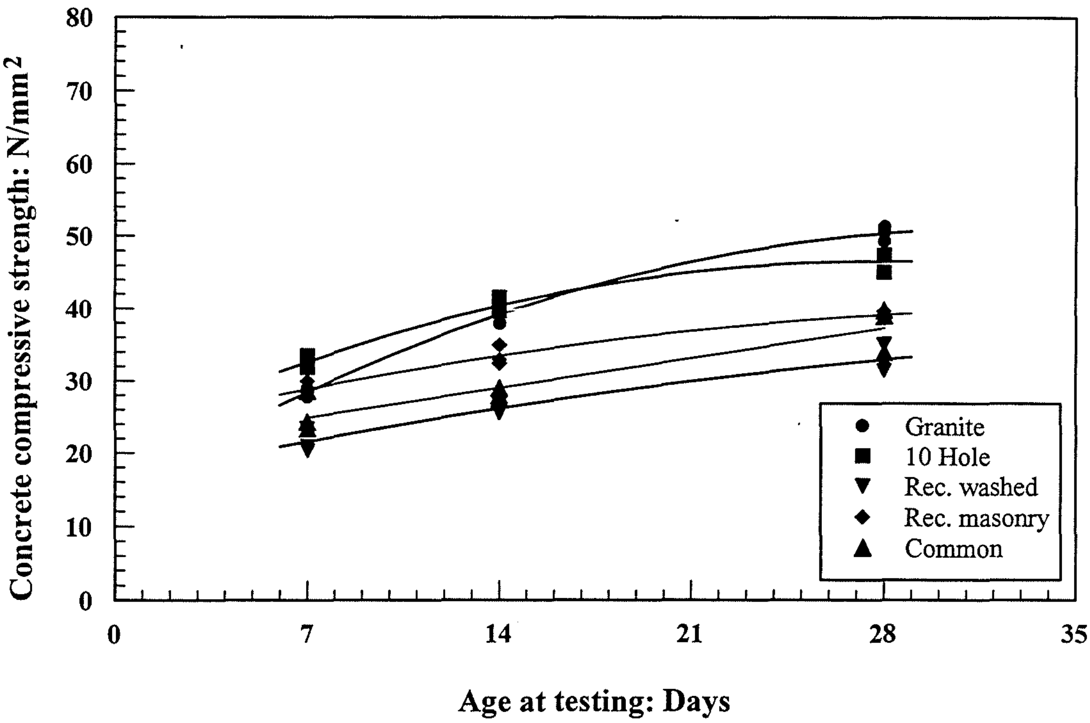


Figure 6.3 - Concrete compressive strength versus age at testing for all types of aggregate

The figure shows that the concretes produced with each type of aggregate managed to reach and exceed the designed characteristic compressive strength of 30N/mm^2 at 28 days.

The strength of the 10 hole new brick aggregate is greater than that of the granite aggregate at 7 days which are both greater than the concrete produced using the two types of recycled aggregate produced from demolition and construction waste. The 10 hole brick aggregate concrete showed a greater strength after 18 days of curing than the companion granite concrete. At this point the granite aggregate concrete gained more strength and at the age of 28 days shows a higher compressive strength than the 10 hole brick aggregate concrete. The concrete with the recycled demolition waste aggregate showed a lower strength at 7 days than the other 10 hole and granite aggregates, although this was expected due to the amount of contaminants that were present in the material. At 28 days the strength was considerably lower than the granite and 10 hole brick aggregate concrete respectively. However, the compressive strength at 28 days did manage to exceed the designed characteristic strength of 30N/mm^2.

6.5.2 Tensile Splitting and Flexural Strength

Table 6.2 shows the results for tensile splitting and flexural strength for the two recycled aggregates. Again the results for the two types of new brick aggregate concrete and the granite aggregate concrete have been included for comparison.

Table 6.2 - Tensile splitting and flexural strength results

Aggregate type	Strength test results			
	Tensile (N/mm^2)	C.V. (%)	Flexural (N/mm^2)	C.V. (%)
Recycled washed	2.29	6.4	3.6	2.8
Recycled masonry	2.78	11.5	3.9	3.0
Common new brick	2.51	3.1	3.8	3.5
10 Hole new brick	3.06	2.8	4.8	3.6
Granite	3.80	2.8	5.2	4.9

From Table 6.2 it is possible to see that the recycled aggregates have produced concrete which has lower tensile and flexural strengths than the concretes produced with the 10 hole new brick and granite aggregates. The concrete containing the recycled washed aggregate had a tensile splitting strength which was almost 40% less than the granite aggregate concrete and 25% less than the concrete containing the 10 hole new brick aggregate. The recycled masonry aggregate concrete performed significantly better than the concrete containing the other recycled aggregate. It had a tensile splitting strength which was only 9% less than the 10 hole brick aggregate concrete and 27% less than the granite aggregate concrete. The recycled masonry aggregate concrete had a tensile strength which was around 10% greater than the concrete containing the common brick aggregate.

Flexural strength was also reduced when recycled aggregates were used instead of 10 hole new brick aggregate or granite aggregate. The concrete containing the recycled washed aggregate had a flexural strength which was 31% less than the granite aggregate concrete and 25% less than the 10 hole brick aggregate concrete. Again the recycled masonry aggregate performed better than the other recycled aggregate producing a flexural strength which was 8% greater than the recycled washed aggregate concrete, 3% greater than the common brick aggregate concrete, 19% less than the 10 hole new brick aggregate concrete and 25% less than the granite aggregate concrete.

From these strength results it is possible to see that the recycled masonry aggregate, although relatively uncontaminated with impurities, performs less well than the 10 hole new crushed brick aggregate but does however, perform better than the recycled washed aggregate and the new common brick aggregate. Therefore bricks which have previously been used for construction purposes perform less well when crushed and used as the coarse aggregate compared with the 10 hole new brick aggregate. This may be because the recycled aggregate is made up of bricks of different strength or that with age, the structure of the bricks has been weakened.

The results obtained show that there are many relationships involving the aggregate's impact value, which is a measure of its toughness and other aggregate and concrete physical and mechanical properties. Table 6.3 shows the impact, water absorption and porosity results for all the aggregates used in this chapter.

Table 6.3 - Impact, water absorption and porosity results for aggregates used

Aggregate type	Impact value (%)	Water absorption (%)	Porosity (%)
Recycled washed	24	10.4	14.49
Recycled masonry	33	16.2	24.44
Common new brick	31	11.5	25.04
10 Hole new brick	19	7.2	16.75
Granite	9	2.55	6.15

Figure 6.4 shows the relationship between aggregate water absorption and the impact values of the different aggregates. As water absorption increases, the aggregate impact value also increases i.e. the tougher the aggregate, the less water it absorbs. Looking at the impact value for the granite aggregate, it can be seen that it is much tougher and absorbs less water than the other two aggregates.

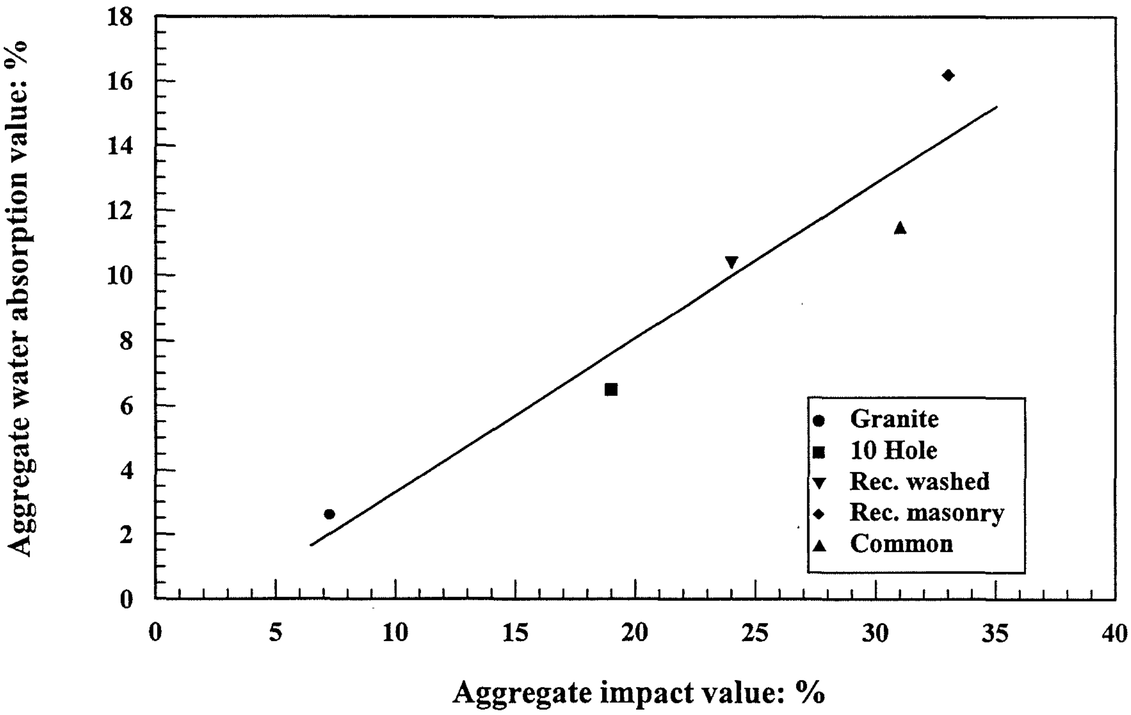


Figure 6.4 - Aggregate water absorption versus aggregate impact value

Figure 6.5 shows the relationship between aggregate porosity and aggregate impact value.

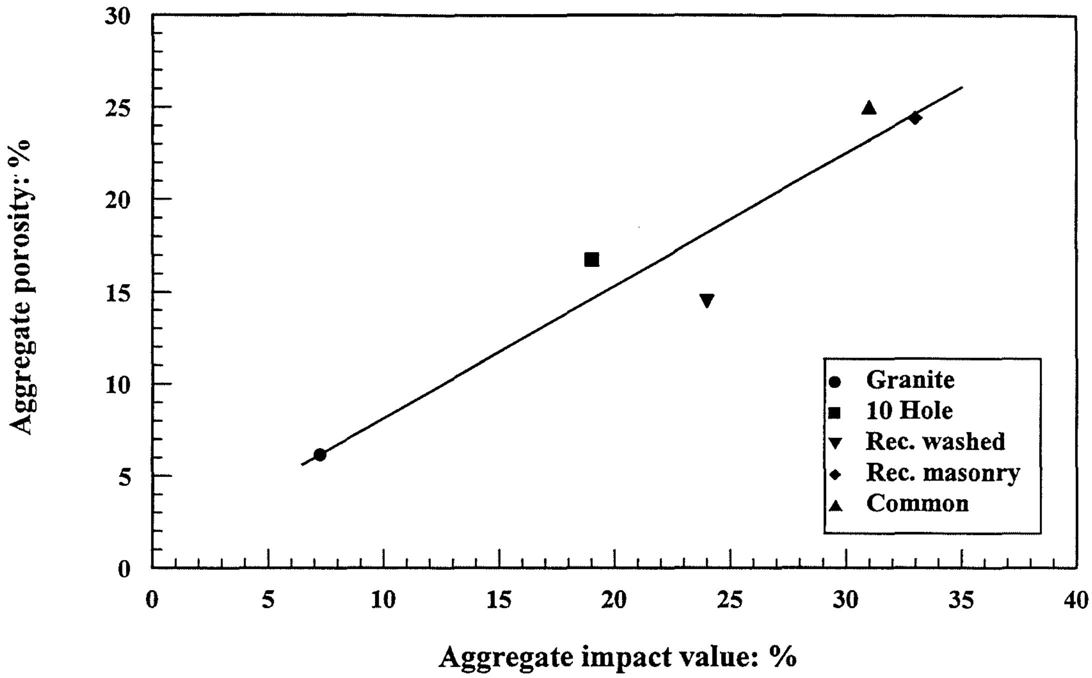


Figure 6.5 - Aggregate porosity versus aggregate impact value

The figure shows that as aggregate impact value increases, the aggregate porosity increases at a linear rate. This means that in general, the more porous aggregates are not as strong as the less porous aggregates. This is because a high porosity value indicates that the aggregate has a large proportion of voids which weakens the structure of the material as indicated by the high impact values recorded.

Figure 6.6 shows a linear relationship between the aggregate relative density and the aggregate impact value. The figure shows that as the impact value increases, the relative density decreases. Therefore, the denser the material the tougher it is. This means that it is possible to estimate the strength of an aggregate from its relative density.

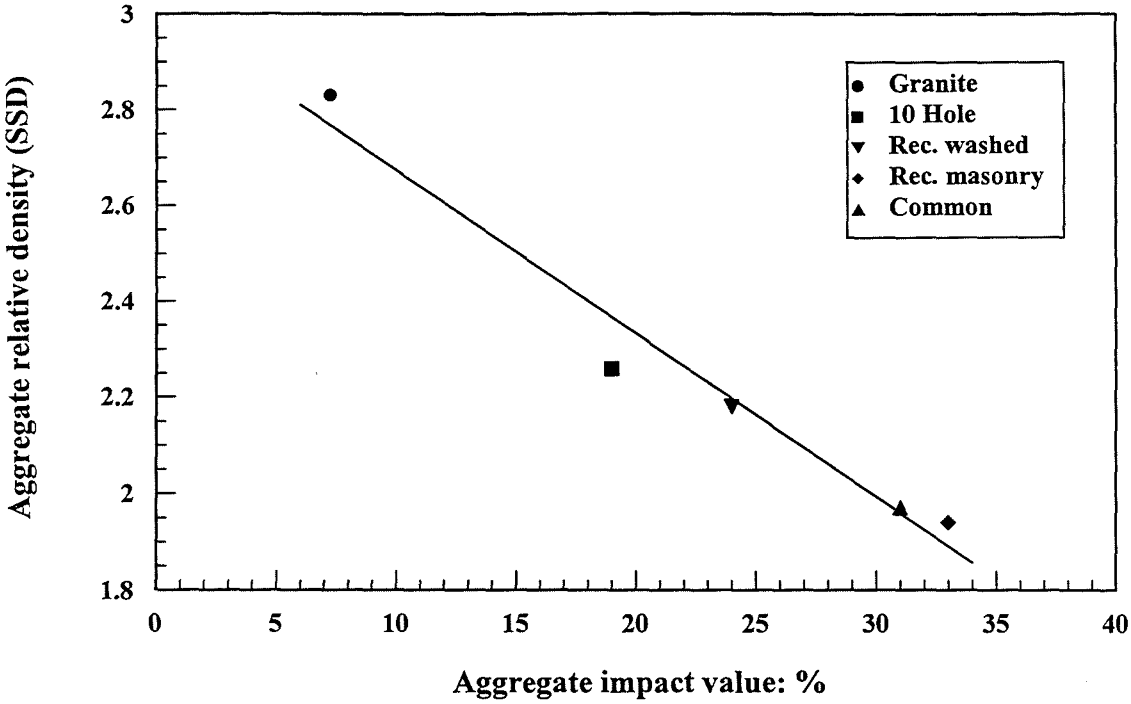


Figure 6.6 - Aggregate relative density versus aggregate impact value

The impact value was also plotted against the compressive, tensile and flexural strengths of the concrete at 28 days. Shown in Figures 6.7, 6.8, and 6.9 respectively.

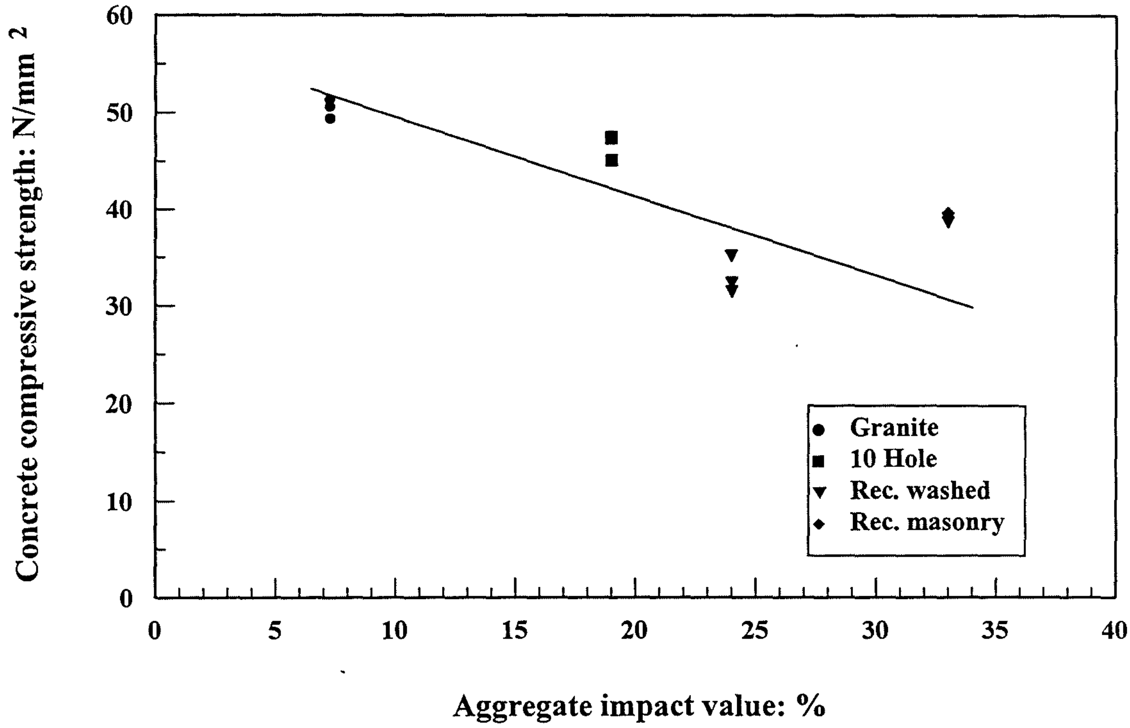


Figure 6.7 - Concrete compressive strength versus aggregate impact value

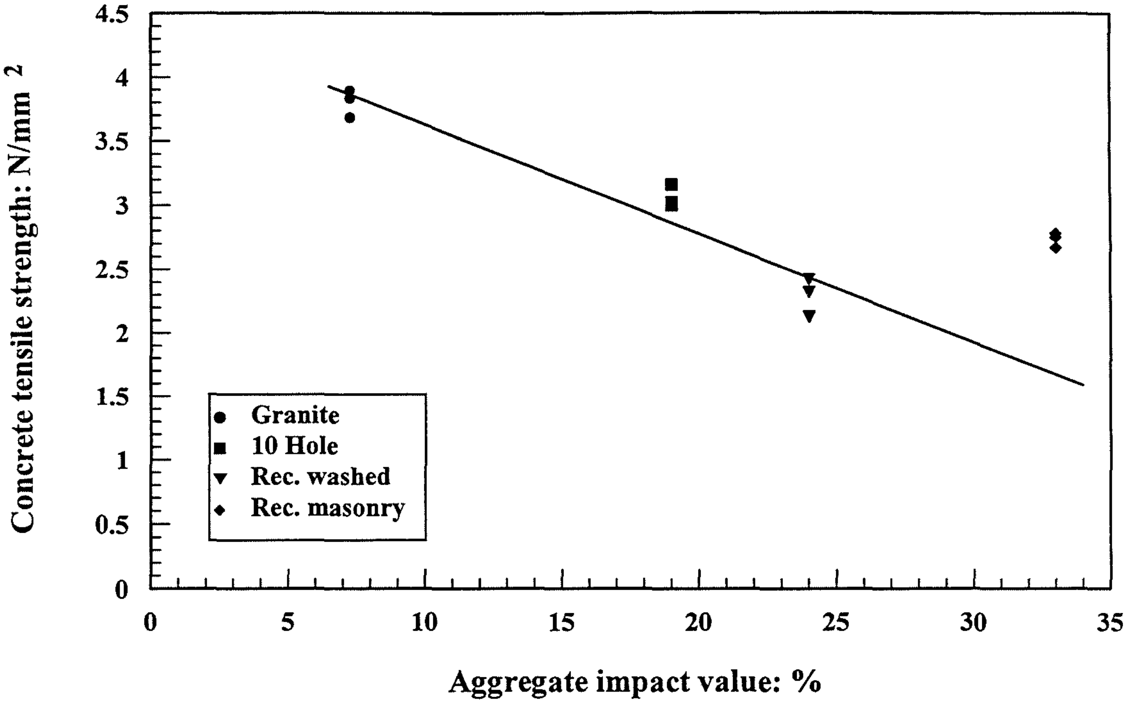


Figure 6.8 - Concrete tensile strength versus aggregate impact value

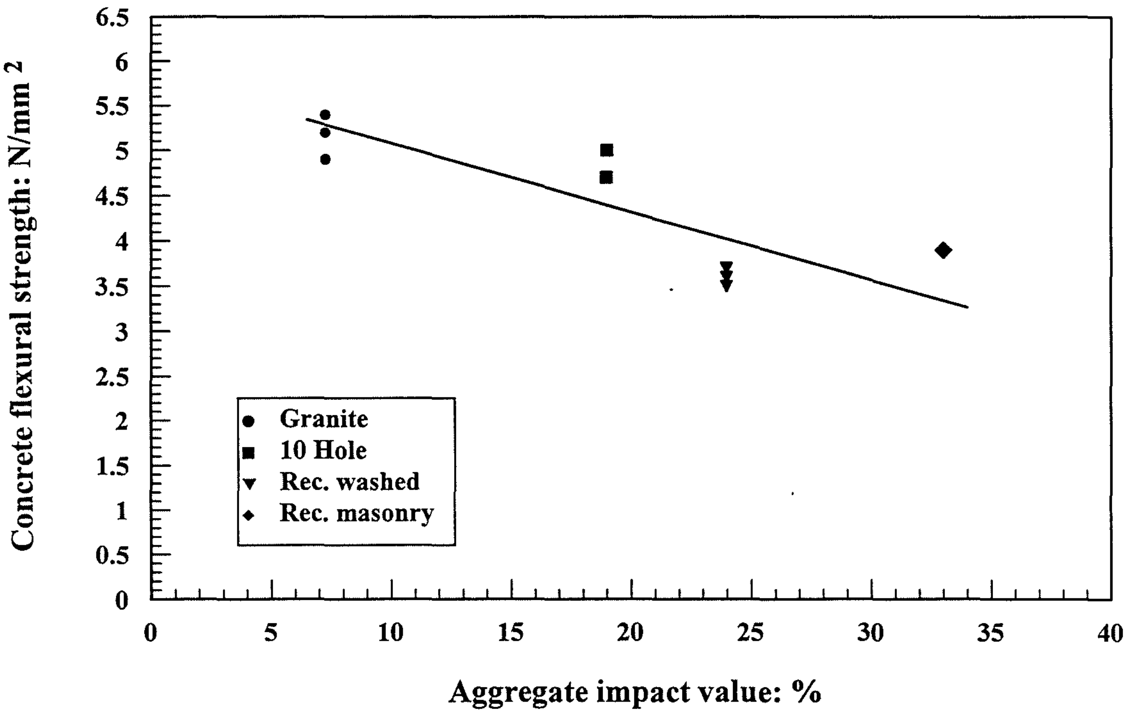


Figure 6.9 - Concrete flexural strength versus aggregate impact value

It is clear from these graphs that the impact value can help determine the strength of new concrete. As can be seen from each of the three graphs as the impact value increases the compressive, tensile splitting and flexural strengths of concrete decreases. Therefore the tougher the aggregate the lower the impact value, the better the strength, density and the final quality of concrete.

Figure 6.10 shows the relationship between the compressive strength of concrete and the aggregate relative density for the five types of aggregate used in this investigation. The relationship shows that the denser the aggregate, the stronger the concrete. This could prove very useful when using recycled demolition waste as an aggregate in concrete. As the concrete's final strength could be estimated by simply determining the aggregates relative density first.

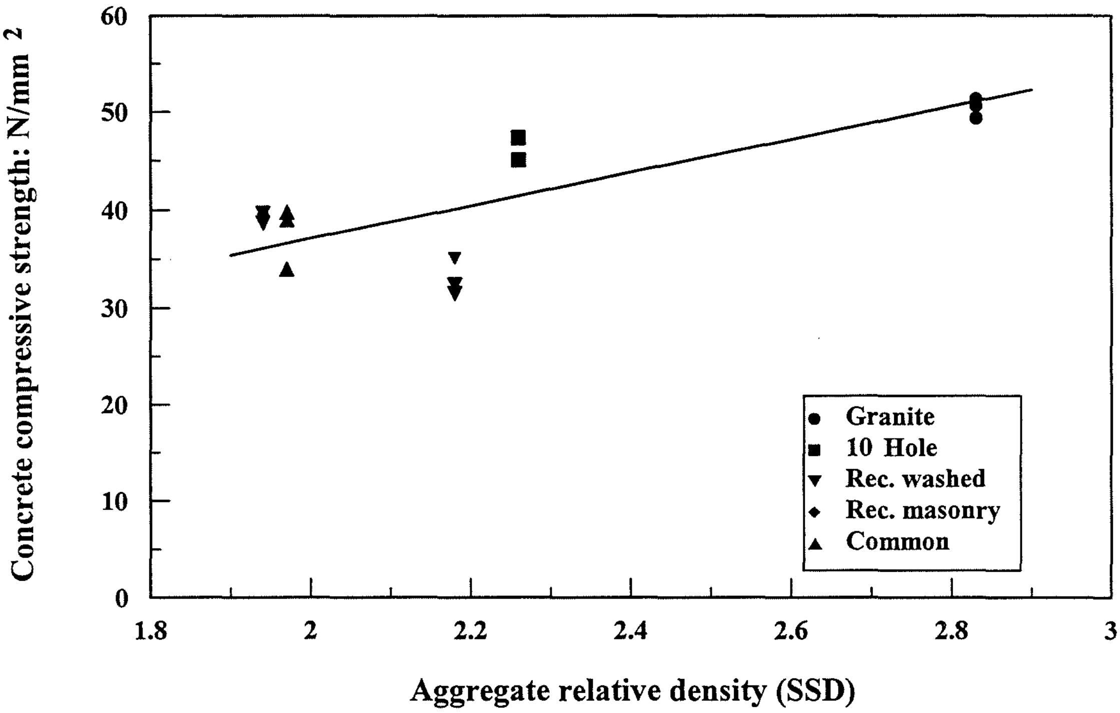


Figure 6.10 - Concrete compressive strength versus aggregate relative density

Overall the recycled demolition waste aggregate produced concrete of an acceptable strength, although it was not as high as the granite or 10 hole new brick aggregate concrete. The results of strength did exceed the designed characteristic strength. This is encouraging and confirms that recycled material can be used in the production of concrete and would particularly be useful for solving problems with the self-weight of structures. In cases where strength is required from the recycled demolition waste aggregate, adjustments can be made to the mix design to produce the concrete required for the particular job. However, it is clear that it does have a lower strength.

Therefore it is essential that future generation recycling plants ensure that the material is supplied to the customer without the need to check for impurities or worry about the problems of concrete with a low compressive strength. Before producing the concrete, simple tests such as the impact or water absorption test could be used to determine if the aggregate is going to produce concrete suitable enough for its purpose. Although the specific gravity of the demolished material is low when compared to granite and new brick, the strength achieved at 28 days is acceptable.

6.5.3 Bond between Aggregate and Cement Paste

After testing for strength, the concrete cubes and beams with the recycled demolition waste aggregate were closely inspected. On examination it was possible to see that the particles within the concrete were broken through while still being attached to the cement paste. This suggests that a good bond was formed between the aggregate and the cement paste.

6.5.4 Effects of Impurities

Table 6.4 shows the density and compressive strength results for the normal strength concretes (M1) produced with different percentages of impurities.

Table 6.4 - Density and compressive strength results for normal strength concrete (M1)

Percentage impurity	Concrete density at 28 days* (kg/m^3)	Concrete compressive strength at 28 days* (N/mm^2)	C.V. (%)
0%	2270	46.7	2.9
10% Mortar	2275	44.5	2.5
15% Mortar	2238	35.1	2.2
25% Mortar	2240	32.0	3.9
35% Mortar	2219	22.4	2.5
2% Timber	2198	34.2	6.4
5% Timber	2072	28.4	13.2
5% Rubber	2228	27.3	5.8
10% Rubber	2216	22.3	8.0

* Results are the average of four test samples

The workability of each concrete mix was monitored using the slump and Vebe tests and all the concrete mixes produced had workability levels which fell within the M1 design limits. It was however noticed that when the mix containing the 5% timber was compacted, some of the timber pieces rose to the top of the concrete which made it difficult to get a finish on the surface of the concrete.

Figure 6.11 shows the relationship between concrete density and the percentage of mortar present in the concrete mix.

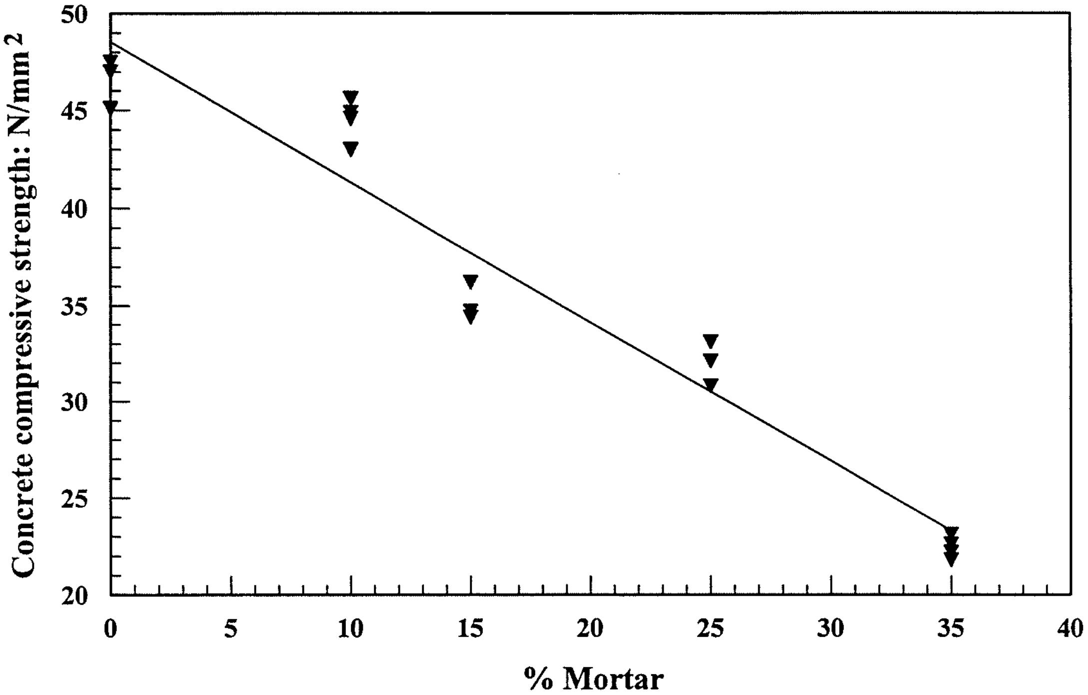


Figure 6.11 - Concrete compressive strength versus percentage of mortar

Figure 6.11 shows that the greater the percentage of mortar in the mix, the lower the compressive strength of the concrete produced. In the mix design, the target mean strength was specified at 43N/mm^2. From the graph it is possible to see that for 0% mortar, the compressive strength is well above the target strength value specified. It remains above this value until the percentage of mortar included in the mix reaches a value of approximately 10%. At 10% mortar, there is only a 4.7% loss in concrete compressive strength but at 15% mortar, the compressive strength has fallen by 25% and at 35% mortar, the compressive strength has fallen by 52%. Therefore no more than 10% mortar should be permitted in a concreting aggregate in order to maintain target strengths.

Figure 6.12 shows the relationship between the concrete density and the percentage of mortar present in the mix.

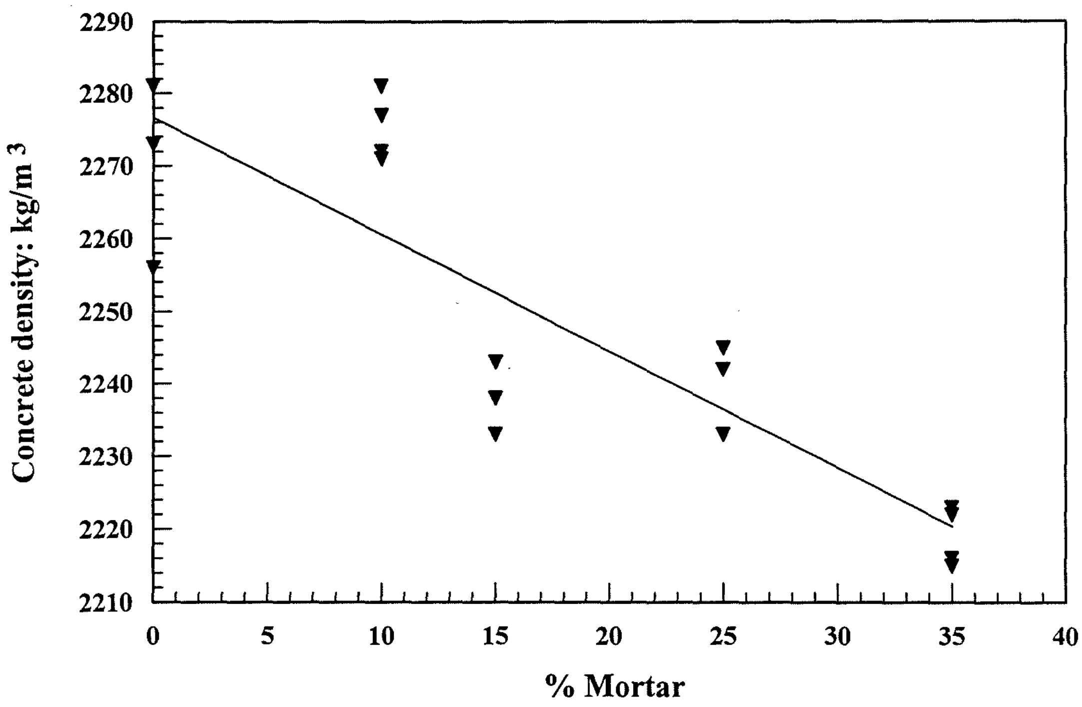


Figure 6.12 - Concrete density versus percentage of mortar

Figure 6.12 shows that as the percentage of mortar is increased, the density of the concrete produced is decreased. This is due to the mortar having a lower relative density than the crushed brick and the relative density of aggregate influences the density of concrete produced with such an aggregate. It is possible to see that at 10% mortar, the loss in density is still relatively small so as long as the percentage of mortar present is limited to 10% there should not be a large loss in concrete density.

Figure 6.13 shows the relationship between concrete compressive strength and the percentage of timber present in the mix.

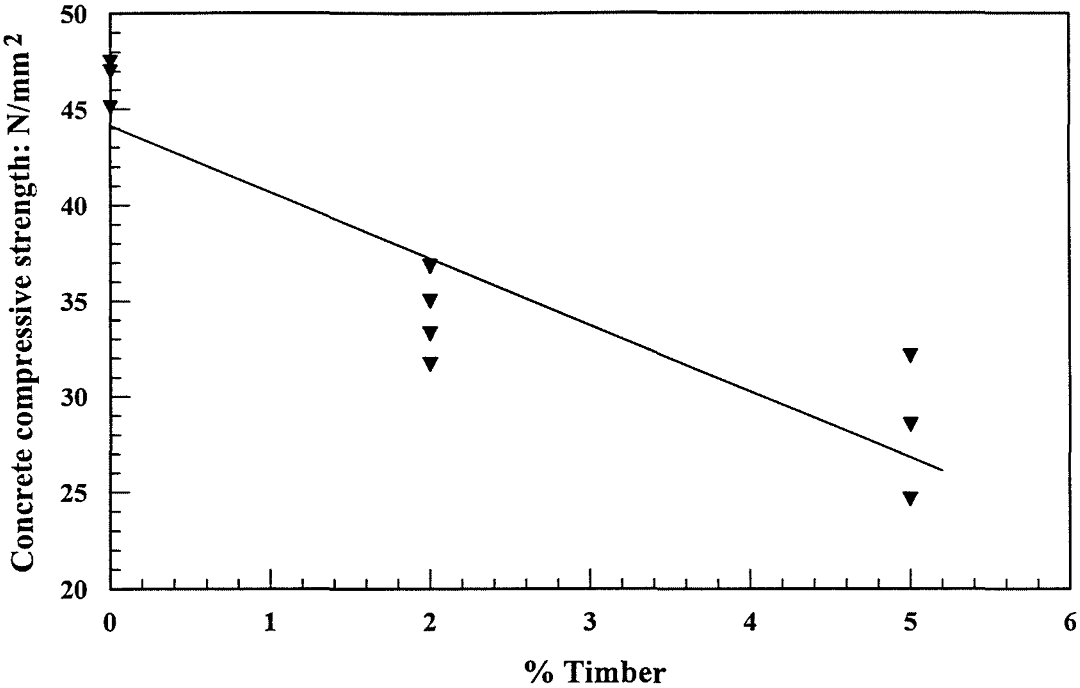


Figure 6.13 - Concrete compressive strength versus percentage of timber

The figure shows that the greater the percentage of timber present in the mix, the lower the compressive strength of the concrete. It is possible to see that when only 2% timber is added to the mix, it causes a loss of around 27% in concrete compressive strength so it can be concluded that timber is a very detrimental impurity, which should be removed from material which is to be used as aggregate in concrete.

Figure 6.14 shows the relationship between the concrete density and the percentage of timber present in the mix.

The figure shows that a relationship exists between the density of concrete and the percentage of timber present in the mix. As expected, the figure shows that the timber present in the mix has the effect of decreasing the concrete's density as the timber pieces have a lower relative density than the brick aggregate particles.

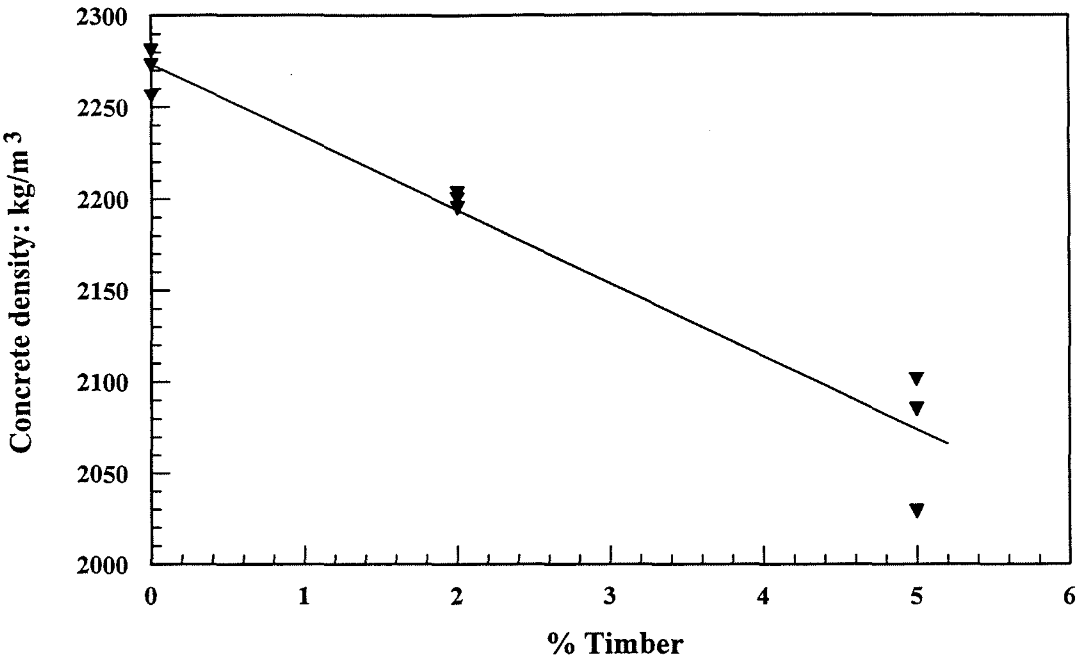


Figure 6.14 - Concrete density versus percentage of timber

Figure 6.15 shows a relationship between the compressive strength of concrete and the percentage of rubber present in the concrete mix.

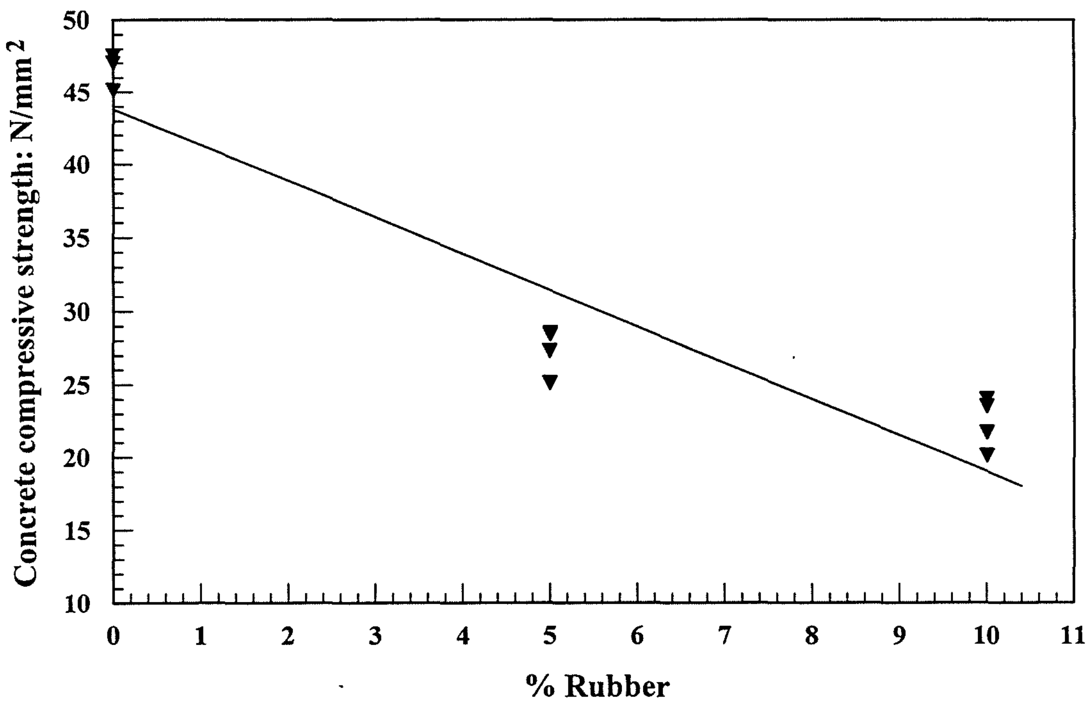


Figure 6.15 - Concrete compressive strength versus percentage of rubber

The figure shows that as the percentage of rubber increases, the concrete compressive strength decreases and on inspection of the concrete after crushing it is possible to see that the rubber creates definite points of weakness and poor bond within the concrete structure. From the graph, it is possible to see that when 5% rubber is included in the mix, there is a 42% loss in concrete compressive strength.

Figure 6.16 shows a relationship between the density of concrete and the percentage of rubber present in the mix.

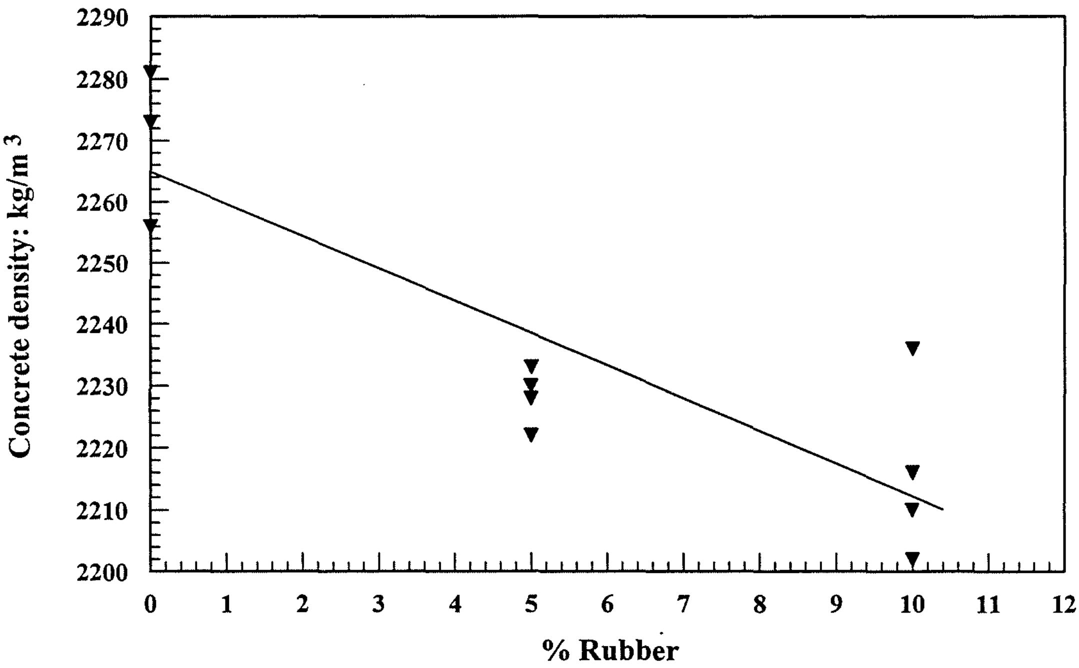


Figure 6.16 - Concrete density versus percentage of rubber

The figure shows that the rubber present in the mix has the effect of decreasing the concrete's density. It can be concluded that rubber is also a very detrimental impurity which causes large reductions in strength and density when present in concrete.

6.5.5 Blending of Brick Aggregates

The results obtained for 28 day compressive strength and density are displayed in Table 6.5 for the six (M1) concrete mixes which were produced.

Table 6.5 - Density and compressive strength results for normal strength concrete (M1) with blended aggregates

Percentage of weak brick (%)	28 Day density (kg/m^3)	28 Day concrete compressive strength* (N/mm^2)	C.V. (%)
0	2270	46.7	2.9
20	2253	45.8	1.4
40	2229	43.1	2.7
60	2206	43.1	2.6
80	2184	40.9	1.5
100	2158	37.6	8.4

*Results are the average of three cubes

Figure 6.17 shows the relationship between the concrete compressive strength and the percentage of weak brick present in the concrete mix.

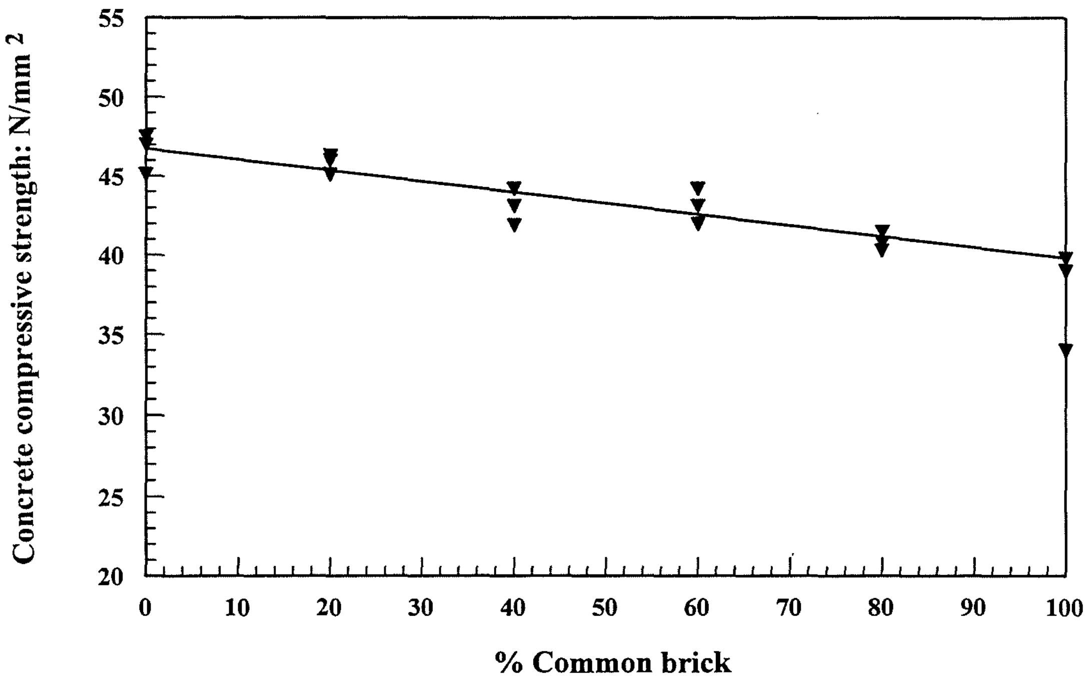


Figure 6.17 - Concrete compressive strength versus percentage of weak brick

From Figure 6.17 it is possible to see that a linear relationship exists between the compressive strength of concrete and the percentage of weaker brick aggregate present. As expected the greater the percentage of weak brick included in the mix, the weaker the concrete produced.

This means that if recycled crushed brick is to be used as the aggregate to produce concrete, care must be taken at the recycling plant to monitor what type of bricks are being included for recycling as weak bricks can lower the concrete strength by up to about 10%.

Figure 6.18 shows the relationship between the concrete density and the percentage of weak brick present in the concrete mix.

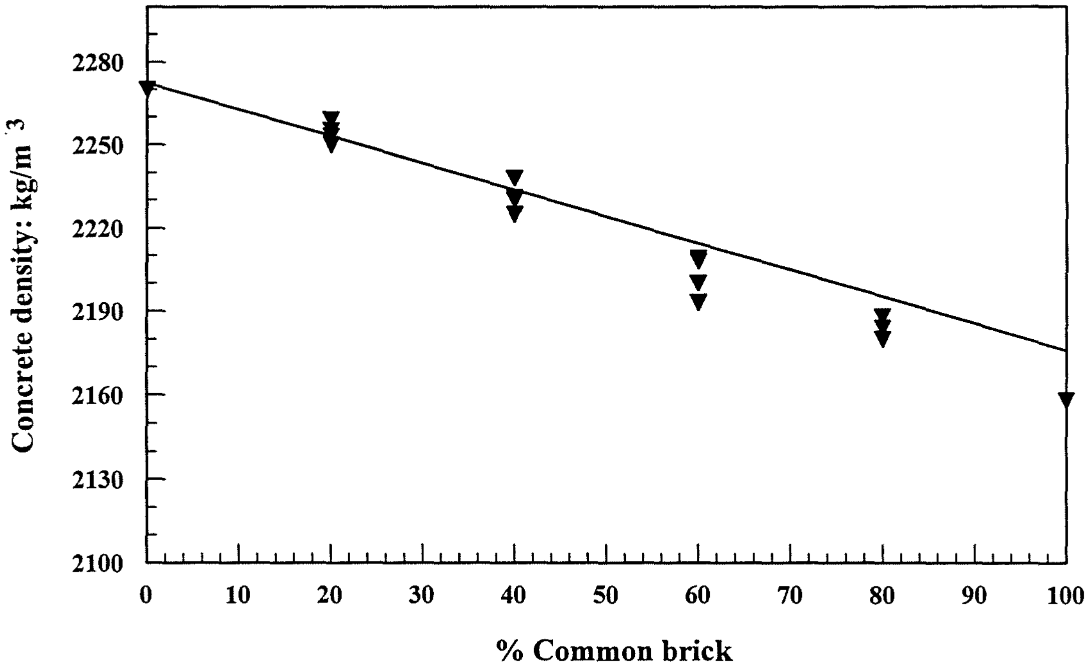


Figure 6.18 - Concrete density versus percentage of common brick

From Figure 6.18 it is possible to see that the effect on concrete density, by including percentages of weak brick, is more pronounced than the effects on compressive strength. As expected as the percentage of weak brick is increased, the concrete density reduces linearly.

At 50% weak brick, there is a decrease in density of 2% and a decrease in compressive strength of 7%. Similarly at 100% weak brick, there is a decrease in density of 5% and a decrease in compressive strength of around 20%. This means that when brick aggregates are blended together, a saving can be made in concrete density for only a small strength loss. A small percentage saving in concrete density can represent a significant cost saving as self weight of the concrete is reduced and so is the cost of the materials required to produce the concrete.

6.5.6 Initial Surface Absorption Test (ISAT)

The initial surface absorption results for the normal strength concretes (M1) produced with the four different aggregates are shown in Table 6.6.

Table 6.6 - Initial surface absorption results for normal strength concrete (M1)

Time (mins)	Initial surface absorption ($ml/m^2/sec$)			
	Recycled washed	Recycled masonry	10 Hole new brick	Granite
10	0.180	0.316	0.190	0.145
15	0.129	0.260	0.161	0.119
20	0.117	0.227	0.142	0.102
30	0.087	0.184	0.121	0.088
40	0.079	0.163	0.109	0.077
50	0.072	0.148	0.100	0.072
60	0.067	0.138	0.092	0.061
90	0.059	0.112	0.080	0.052

From Table 6.6 it is possible to see that the granite aggregate concrete absorbs the least water in the standard time, while the concrete containing the recycled masonry aggregate absorbs the most. Figure 6.19 plots initial surface absorption against time for each of the four concrete types.

From Figure 6.19 it is possible to see that all four of the concrete types have a similar relationship between time and initial surface absorption. The graph shows that the initial surface absorption of all concretes containing brick aggregate is higher than concrete containing granite aggregate. It is also possible to see that the concrete containing recycled masonry has the highest initial surface absorption value compared with the other three concrete types. This suggests that this aggregate has a higher porosity than the other three aggregate types. This is confirmed by the next figure.

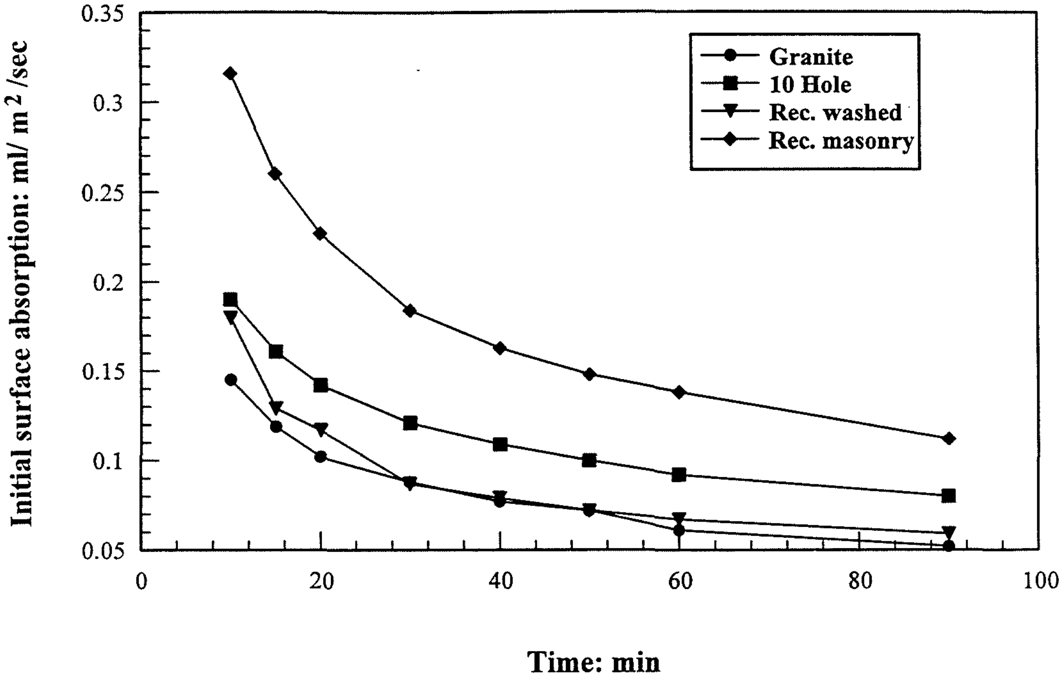


Figure 6.19 - Initial surface absorption of concrete against time

Figure 6.20 shows the relationship between the initial surface absorption value at 10mins for concretes produced with the four aggregates and the porosity of the aggregates used.

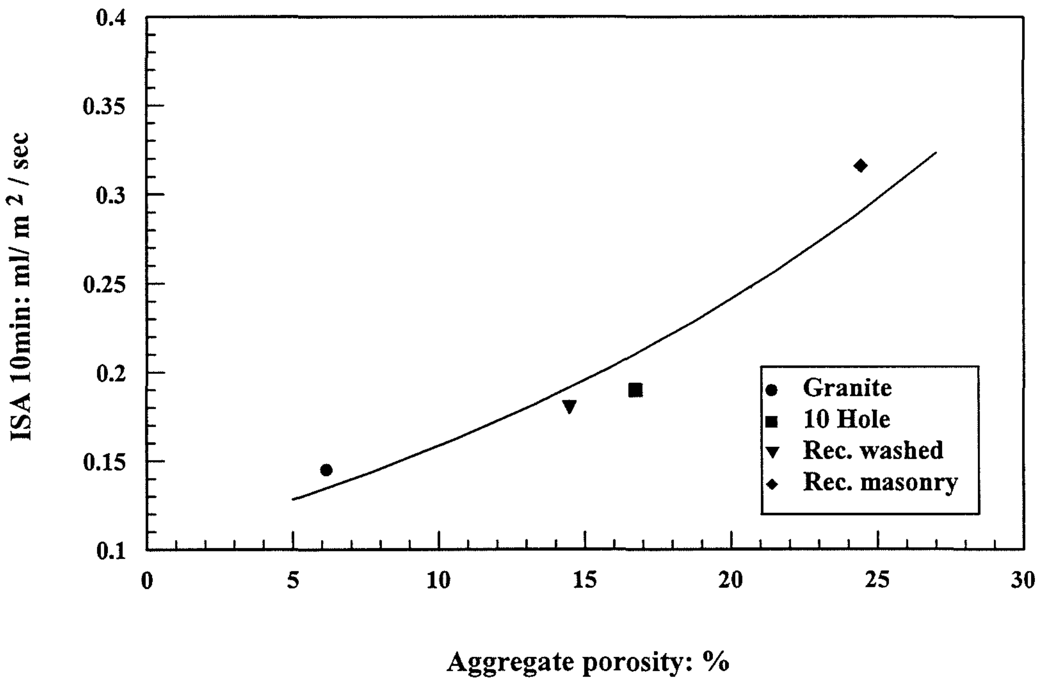


Figure 6.20 - Aggregate porosity versus ISA 10min for each concrete type

It is clear from Figure 6.20 that the higher the aggregate porosity, the higher the initial surface absorption of concrete. The figure also confirms that the main reason for the high initial surface absorption of concrete containing recycled masonry aggregate is the high porosity of this type of aggregate. This means that it could be possible to predict the initial surface absorption characteristics of concrete from the porosity of the aggregate which was used to produce the concrete.

Figure 6.21 shows the relationship between the water absorption of aggregates and the initial surface absorption, after 10mins, for concrete produced with these aggregates. As expected the greater the water absorption of the aggregates, the higher the initial surface absorption rate of concrete produced with these aggregates.

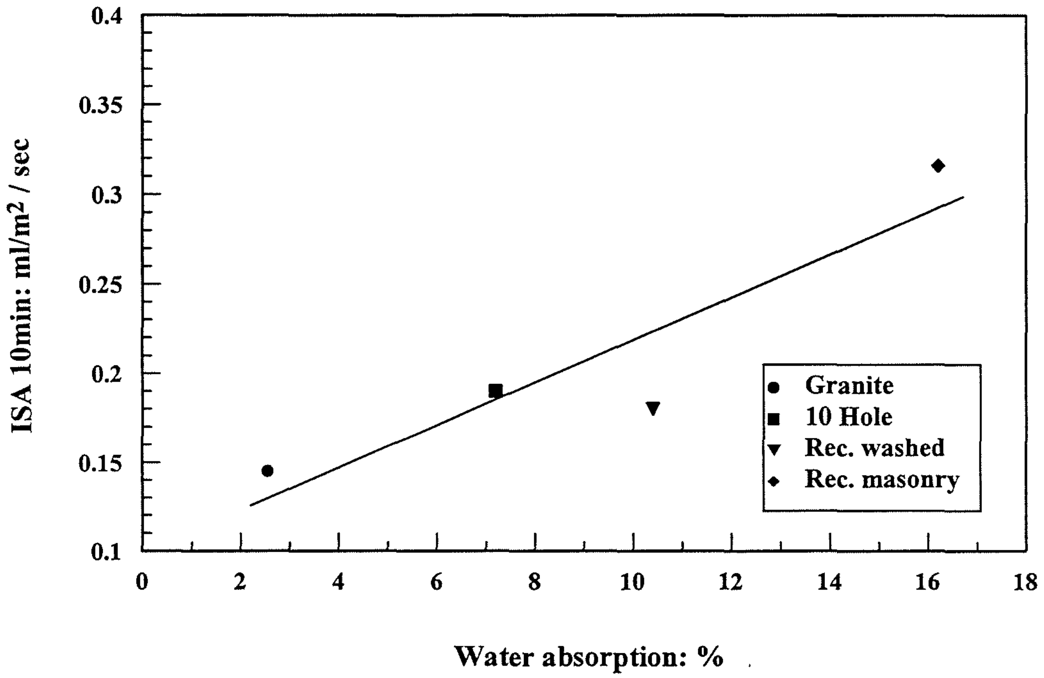


Figure 6.21 - Concrete ISA 10min versus aggregate water absorption

Figure 6.22 shows that a linear relationship exists between concrete initial surface absorption and aggregate impact value for the four aggregate types.

The graph shows that as impact value increases, initial surface absorption after 10mins also increases. This means that tougher aggregates with a low impact value produce concrete with a lower initial surface absorption.

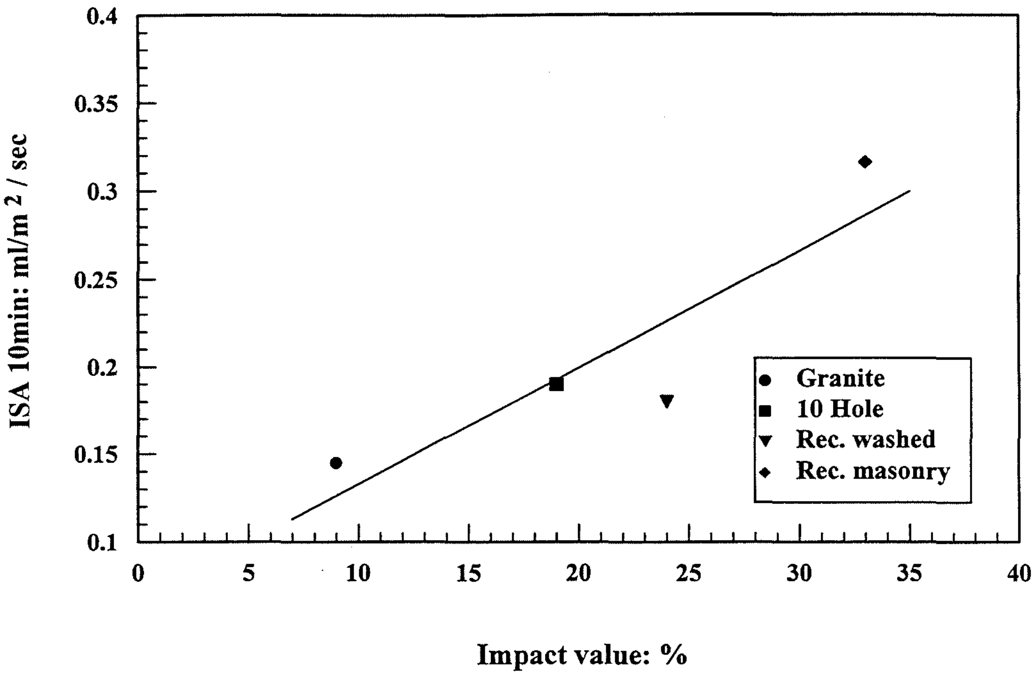


Figure 6.22 - Concrete ISA 10min versus aggregate impact value

Figure 6.23 shows that a relationship exists between initial surface absorption at 10mins and the density of the concrete for the four different aggregate types. It is possible to see, that in general, as concrete density increases, initial surface absorption of the concrete decreases.

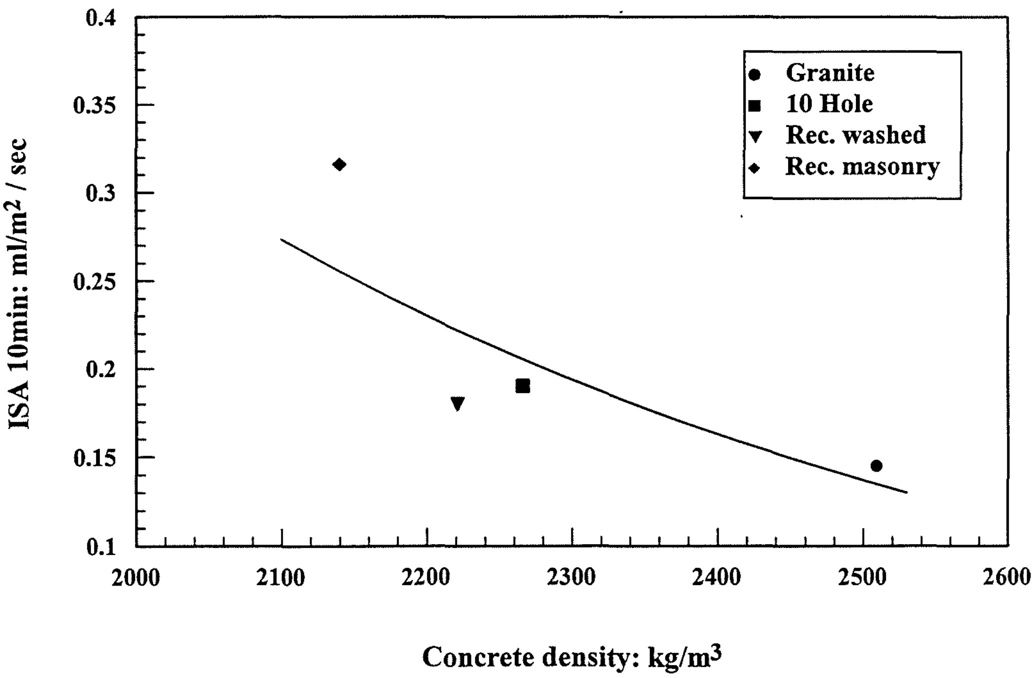


Figure 6.23 - Concrete ISA 10min versus concrete density

6.6 CONCLUSIONS

From the laboratory testing carried out in this chapter it is possible to make the following conclusions about the use of recycled aggregates in the production of new concrete:

1. It is possible to use the same mix design procedure for recycled aggregates as it is for concrete with normal aggregate, such as granite. However, it is important that the recycled aggregate is in a saturated surface-dry (SSD) moisture condition before the commencement of mixing because recycled masonry aggregates have a high rate of water absorption. Recycled aggregates should be assessed for moisture condition before use in concrete and if necessary the aggregate stockpiles should be sprayed with water to get the aggregate into a saturated surface-dry condition.

2. The concretes produced with recycled aggregates did not reach the designed target compressive strengths. The concretes containing the recycled washed aggregate and recycled masonry aggregate obtained strength values exceeding the characteristic design strength of $30N/mm^2$ at 28 days. The strength achieved was short of the designed target mean strength of $43N/mm^2$ but these concretes would still have been strong enough for low level applications.

3. The recycled aggregates produced concrete with a lower density than concrete produced with new crushed brick or granite aggregates. The concretes containing the recycled washed and recycled masonry aggregates had a density which was 11-15% less than the granite aggregate concrete. This means that recycled aggregate concrete would be ideal for applications where self-weight is a problem.

4. Concrete containing the recycled washed aggregate had a tensile splitting strength which was almost 40% less than the granite aggregate concrete and 25% less than the 10 hole new brick aggregate concrete. The concrete containing the recycled masonry aggregate performed better with a tensile splitting strength which was only 9% less than the 10 hole new brick aggregate

concrete. This suggests that the impurities in the recycled washed aggregate cause some losses in tensile splitting strength.

5. Flexural strength was also reduced when recycled aggregates were used to produce concrete. The concrete with recycled washed aggregate had a flexural strength which was 31% less than the granite aggregate concrete and 25% less than the concrete containing crushed 10 hole new brick aggregate. Similarly, the concrete produced with the recycled masonry aggregate had a flexural strength which was 25% less than the granite aggregate concrete, 19% less than the 10 hole new brick aggregate concrete but 8% greater than the concrete containing the recycled washed aggregate.

6. Concrete produced with recycled aggregates gains strength at about the same rate as concrete produced with proven aggregates. This means that recycled aggregate concrete would require no special curing measures.

7. It was found that a good bond existed between the aggregate particles and the cement paste for the new brick and recycled aggregate concretes.

8. The presence of impurities in the recycled aggregates have the effect of lowering the compressive strength and density of the concrete. It is also evident, from tested specimens that impurities cause points of weakness in the concrete.

9. In order to produce concreting aggregates from recycled demolition waste the technology at the recycling plants will have to be sophisticated enough to remove all kinds of contaminants, as only a small percentage of impurities can be detrimental to concrete strength and density.

10. The strength of concrete is related to the impact value of the aggregate used to produce the concrete. This means that the aggregate impact test could be used to determine an aggregates suitability for use in the production of concrete.

11. It was found that if weak bricks were blended with stronger bricks to produce an aggregate for concrete, concrete compressive strength was reduced proportionally to the percentage of weak brick included. The density of the concrete also decreased proportionally to the percentage of weak brick included.

12. Concrete containing recycled washed material or recycled masonry material, has a higher initial surface absorption (ISA) rate than concrete containing granite aggregate. The initial surface absorption rate of concrete is related to the porosity of the aggregate used. The results show that the higher the porosity of the aggregate, the higher the initial surface absorption rate of the concrete.

13. A linear relationship was found between concrete initial surface absorption and aggregate water absorption. As expected aggregates with high water absorption characteristics produce concretes with high initial surface absorption values.

14. The initial surface absorption values of concrete produced with each aggregate type were found to be related to the impact values of the four aggregate types used in this part of the investigation. It was found that the higher the aggregate impact value, the higher the initial surface absorption of the concrete produced with the aggregate.

Chapter 7

SUMMARY AND CONCLUSIONS

7.1 GENERAL SUMMARY

This thesis presents a comprehensive study into the possibilities of using crushed new brick and recycled masonry aggregates as the aggregate in new concrete. The experimental results presented in this thesis prove that concrete can be successfully produced using recycled aggregates which have been produced from demolition and construction waste. Concrete produced with these aggregates does not perform as well as concretes produced with natural aggregates in terms of strength. However, the concrete still has a strength which would make it suitable for some applications with the added benefit that density values are much lower making it suitable in situations where self-weight is a problem.

Chapter 2 presents a comprehensive literature review on the possibilities of using brick and recycled aggregates as the coarse aggregate in new concrete. Recycling prospects, methods and technologies are investigated along with a review on using crushed brick and concrete as the aggregates in new concrete. Also presented is a review of the work carried out into the point-load test in order to estimate compressive strength.

An experimental study of the properties of new brick, recycled and granite aggregates used in the investigation has been reported in Chapter 3.

Chapter 4 presents the results of the experimental and theoretical investigation carried out into the point-loading of masonry specimens. Equations are presented to convert point-load values into compressive strength values so that brick strengths can be estimated from small irregular shaped specimens.

Chapter 5 is devoted to the experimental and theoretical investigation into the use of new brick aggregates as the coarse aggregate in concrete. Results are presented for concrete density, compressive strength, tensile splitting strength, flexural strength and fire resistance. The results for the new brick aggregate concretes are compared with results obtained for concrete containing granite aggregate.

Chapter 6 presents the results of the experimental and theoretical investigation into the use of recycled masonry aggregates as the coarse aggregate in new concrete. Results are presented for concrete which has been produced with two different types of recycled aggregate. The effects of impurities associated with recycled aggregates are investigated and the initial surface absorption of recycled aggregate concrete is also investigated. The results are all compared to the results obtained for concretes containing new brick and granite aggregates.

7.2 CONCLUSIONS

1. Apart from aggregates produced from common bricks and recycled masonry, the impact test results show that all other aggregates fall within the BS 882 suitability limits for concrete which is to be used for heavy duty flooring and pavement wearing surfaces.

2. The relative densities of the crushed brick aggregates and the recycled aggregates are considerably less than the density of the granite aggregate. This means that when these aggregates are used to produce concrete, the density of the concrete will be much lower as the aggregate density has a large influence on the concrete density.

3. A new test method was devised in order to determine the porosity of clay bricks by testing brick lumps under vacuum. The test could be used for testing all aggregate types and gives an indication of the water requirement of the aggregate, when it is used to produce concrete. Through the testing of the brick lumps it was found that the higher the porosity, the lower the compressive strength of the brick units of the same type.

4. The two recycled aggregates have a higher porosity value than the crushed new brick aggregates and the granite aggregate. This means that these two

aggregates will have a higher water demand when used as the aggregate in concrete.

5. Testing revealed that the results produced by 5hr boiling on full size brick units, as recommended by BS 3921, under-estimate the true value of water absorption of fired-clay bricks. This suggested that 5hr boiling is not enough to expel the air from the brick pores. To obtain a more accurate value for brick water absorption, a new test procedure was presented, involving the boiling of brick lumps which was easier to carry out and more reliable than the boiling of whole bricks. The new test was also more economic than the boiling of whole bricks as a smaller water bath was required and less energy was consumed during the boiling process.

6. The point-load testing on masonry specimens revealed that limits and constraints had to be placed on the dimensions of brick units, regular and irregular new bricks and recycled brick lumps as follows:

   (i) Height (D) should be within these limits $30 \leq D \leq 65$mm.
   (ii) Width (W) should be within these limits $30 \leq W \leq 102.5$mm.
   (iii) Length (L) should be $L \geq W$.
   (iv) Depth/width ratio (D/W) should be within these limits $0.3 \leq D/W \leq 0.63$.

7. A shape factor (δ) for point-load testing of masonry specimens was introduced to normalise the results of strength index for a sample of any dimensions to an equivalent half-brick of the same brick type. The shape factor can be expressed mathematically as:

$$\delta = 1.35\left(\frac{D}{W}\right) \qquad \textbf{(Eqn. 7.1)}$$

8. Equation 7.2 was derived to normalise or convert the strength index, from point-load testing, of regular or irregular samples of brick to the strength index of an equivalent half-brick of the same type.

$$I_{S\,(half\text{-}brick)} = 1.35\left(\frac{D}{W}\right) I_{S\,(sample)} \qquad \textbf{(Eqn. 7.2)}$$

9. Equation 7.3 was derived to convert the strength index, from point-load testing, of a half-brick to a uniaxial compressive strength of a half-brick. The equation can be used to determine the compressive strength of any new or old masonry unit indirectly by tests on small pieces of brick using the point-load testing machine.

$$f_{b\,(half\text{-}brick)} = 18\ I_{S\,(half\text{-}brick)} \qquad \textbf{(Eqn. 7.3)}$$

10. The results show that the use of the point-load machine is a feasible concept in determining the uniaxial compressive strength of new and old masonry bricks. The point-load testing machine is more convenient, cheaper, mobile and can be used on site or in the laboratory as an alternative means of determining compressive strength rather than heavy and expensive universal testing machines.

11. The point-load testing machine can be used to find the compressive strength of demolished masonry rubble on site or in a recycling plant. By knowing the compressive strength it is possible to determine whether or not demolition rubble is suitable for crushing to aggregate for use in new concrete. Demolished material could be sorted on site by strength classification before the material is sent to the recycling plant and if compressive strength is known, different recycled materials can be processed and stored for different applications depending on the strength required.

12. When using crushed brick aggregate as the coarse aggregate in concrete, the strength of the original bricks that the aggregate has been crushed from, will influence the strength of the concrete. The stronger the original bricks, the stronger the concrete produced with that particular brick aggregate type.

13. Concrete containing new brick or recycled aggregates can be produced with acceptable levels of workability using the standard mix design method

recommended by the Department of the Environment. No alterations have to be made to the mix design as long as the aggregate is in a saturated and surface dry condition before the commencement of mixing.

14. Normal and high strength concrete can be designed and produced using new crushed brick as the coarse aggregate. The results show that some compressive strengths exceed the design values and the strengths reached using granite aggregate. Concrete produced with crushed new brick aggregate had a tensile splitting strength which was 19% less than the concrete produced with granite aggregate. For the same concrete, there was also a reduction in flexural strength of 8% compared with the granite aggregate concrete.

15. All the concretes produced with new brick aggregates had densities which were lower than the granite aggregate concrete. Similarly, concrete containing recycled aggregates was found to have a lower density than concrete produced with the normal aggregate, granite. The concrete produced with the recycled washed aggregate had a density which was 11% less than the granite aggregate concrete and 2% less than the concrete containing the 10 hole new brick aggregate. The concrete produced with the recycled masonry aggregate had a density which was lower still; 15% less than the granite aggregate concrete, 6% less than the 10 hole new brick aggregate concrete and 4% less than the concrete containing the recycled washed aggregate. The use of recycled materials could be considered during planning stages by defining uses for recycled aggregate concrete in building design such as in areas with low pressure requirements or where self weight is a problem.

16. The concretes produced with recycled aggregates did not reach their designed target compressive strengths of $43N/mm^2$ at 28 days. The concretes containing the recycled washed aggregate and recycled masonry aggregate obtained compressive strength values at 28 days of $33.0N/mm^2$ and $39.2N/mm^2$ respectively. These values were up to 35% lower than the concrete containing the granite aggregate but the concrete produced was still of acceptable strength for many civil engineering applications.

17. By examination of broken test specimens it was found that a good bond existed between the new brick aggregates and the cement paste. This was probably because the brick aggregates were very angular which means they had a large surface area to bond with the paste. The recycled aggregates also achieved a good bond between the cement paste.

18. A relationship was established between the strength of concrete and the impact value of the aggregate which was used to produce the concrete. This means that the aggregate impact test could be used to determine an aggregates suitability for use in the production of concrete. The recycled aggregate impact values also fell within the prescribed limits for use in concrete production.

19. It was found, that in general, concretes containing recycled aggregates had lower tensile splitting strengths than concretes produced with granite or new brick aggregates. The recycled washed aggregate had a tensile splitting strength which was almost 40% less than the granite aggregate concrete and 25% less than the 10 hole new brick aggregate concrete. The concrete containing the recycled masonry aggregate performed better with a tensile splitting strength which was only 9% less than the 10 hole new brick aggregate concrete. This suggests that the impurities in the recycled washed aggregate cause significant losses in tensile splitting strength.

20. Flexural strength was also reduced when recycled aggregates were used to produce concrete. The concrete with recycled washed aggregate had a flexural strength which was 31% less than the granite aggregate concrete and 25% less than the concrete containing crushed new brick. Similarly, the concrete produced with the recycled masonry aggregate had a flexural strength which was 25% less than the granite aggregate concrete, 19% less than the new brick aggregate concrete but 8% greater than the concrete containing the recycled washed aggregate.

21. Air-entrained concrete can be successfully produced using crushed brick aggregate. The compressive strengths achieved were close to the target strengths designed for and close to the strength achieved by the concrete produced with granite aggregate. Workability was improved slightly with the concrete relatively easy to compact and finish. The density of the air-entrained crushed brick aggregate concrete was again considerably lower than the concrete containing granite.

22. The pre-wetting of crushed brick aggregates, to get them into a SSD condition, can be avoided by either designing a mix with very high workability levels or by adding a superplasticising admixture. Both methods produce concrete with an acceptable level of workability and compressive strengths are slightly higher. However, the effects of the superplasticiser only last for about 15mins, after which time the concrete becomes difficult to work with and chemical admixtures are quite expensive. By altering the mix design, the cement content is increased which means that any economical advantage of using such an aggregate would be negated. It is therefore suggested that pre-wetting is the best solution to the problem of such porous aggregates. In practice simple spraying of aggregate stockpiles with water can be carried out with minimum cost implications.

23. The fire resistance of crushed brick aggregate concrete is as good as the fire resistance of granite aggregate concrete if not better. The entrainment of air into the concrete had little affect on the fire resistance of concrete.

24. Recycled aggregate concrete containing recycled washed material or recycled masonry material, has a higher initial surface absorption rate than concrete containing granite aggregate or new brick aggregate. The initial surface absorption rate of concrete was also found to be related to the porosity of the aggregate used to produce the concrete. The higher the porosity of the aggregate, the higher the initial surface absorption rate of the concrete will be. Therefore, it is possible to predict the initial surface absorption rate of concrete from the porosity of the aggregate used to produce it.

25. The presence of impurities in the recycled aggregates had the effect of lowering the density of the concrete and lowering its compressive strength. It was also possible to see, from tested specimens, that impurities cause points of weakness in the concrete. The recycled washed aggregate had a higher level of impurities than the recycled masonry aggregate so more points of weakness were created, resulting in a much lower compressive strength.

26. It was found that if weak bricks were blended with stronger bricks to produce an aggregate for concrete, concrete compressive strength was reduced proportionally to the percentage of weak brick included. The density of the concrete also decreased proportionally to the percentage of weak brick included.

27. From the laboratory testing it was possible to see that some brick types, when crushed and used as the aggregate in concrete, perform better than others. It is therefore important when dealing with recycled masonry rubble to screen the material properly to maintain some sort of quality control. When considering using recycled masonry material as the aggregate in concrete, it would be advisable to carry out trial mixes to determine the quality of the material.

28. Standards on the use of recycled aggregates as the aggregate in concrete are urgently required to promote the safe use of recycled aggregates and the production of recycled aggregate concrete.

7.3 SUGGESTIONS FOR FURTHER RESEARCH

Further research and case studies will be required in order to produce standards for the use of recycled aggregates in the production of concrete. Until a standard becomes available, the use of recycled aggregates in concrete will be restricted to low level applications such as non load-bearing concrete or concrete that is to be used for fill.

The durability of recycled aggregate concrete could be investigated further by testing concrete specimens for resistance to frost attack. This would involve subjecting concrete samples to alternate freezing and thawing for a specified number of cycles and then assessing the concrete for visible damage and testing the concrete for loss in strength. By comparing the recycled aggregates performance with concrete produced with proven natural aggregates it will be possible to assess the frost resistance of recycled aggregate concrete.

The resistance of recycled aggregate concrete to sulphate attack could be determined by storing concrete in a solution of sodium or magnesium sulphate. By subjecting the concrete samples to alternate wetting and drying, the damage owing to the crystallisation of salts is accelerated. The effects of the exposure to these salts can then be quantified by testing the concrete's modulus of elasticity, its expansion and loss in weight.

Further work is required to investigate the shrinkage and creep of recycled aggregate concrete. It has been suggested that the cement content should be increased when producing concrete with recycled aggregates to prevent any loss in strength. The larger the amount of hydrated cement paste in concrete, the higher the shrinkage is expected to be so by increasing the cement content in recycled aggregate concrete may increase shrinkage considerably. Recycled aggregate also has a lower modulus of elasticity than natural aggregates meaning that it cannot restrain shrinkage as well as natural aggregates. This may cause shrinkage cracks so long term testing is required to determine the level of shrinkage associated with recycled aggregate concrete, before it is considered for use in structural situations.

Further research and in particular case studies and trials are required in order to investigate the overall performance of recycled aggregate concrete. The modulus of elasticity, stiffness, damping and dynamic properties of recycled aggregate concrete all need to be investigated. These trials could also be used to quantify the performance of recycled aggregates financially as well as on a material performance basis.

Further investigation into the use of the point-load test to determine the compressive strength of materials is required. The investigation could be extended to look at the point-load testing of concrete cubes, cores and irregular shaped pieces to study the properties of the material to see if the relationship between point-load and uniaxial compressive strength exists. If so the point-load test could be used as a simple site test to aid in the estimation of strength for various civil engineering materials.

The results which were obtained from the point load testing of masonry specimens should be investigated further using Finite Element Analysis (FEA) to study the experimental modes of failure, stress distribution and confirm the experimental results.

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Appendix A

Mix Designs Used in Experimental Work

Design 1 - Mix design for ordinary concrete produced

Concrete mix design form **Job title** Granite Aggregate (Control Mix)

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm²; N/mm²
	1.4	Target mean strength	C2	30 + 13 = 43 N/mm²
	1.5	Cement type	Specified	OPC/~~SRPC/RHPC~~
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/ ~~uncrushed~~ Crushed/~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.55 } Use the lower value 0.55
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.60
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	190 kg/m³
3	3.1	Cement content	C3	190 ÷ 0.55 = 345 kg/m³
	3.2	*Maximum cement content*	*Specified*	kg/m³
	3.3	*Minimum cement content*	*Specified*	300 kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 — 345 kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.70 ~~known~~/ assumed
	4.2	Concrete density	Fig 5	2440 kg/m³
	4.3	Total aggregate content	C4	2440 - 345 - 190 = 1905 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	40 %
	5.3	Fine aggregate content	C5	1905 x 0.40 = 762 kg/m³
	5.4	Coarse aggregate content		1905 - 762 = 1143 kg/m³

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	345	190	762		1143	
per trial mix of 0.01 m³	3.45	1.90	7.62		11.43	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 2 - Example of Modified Design For Brick Aggregate

Concrete mix design form **Job title** Type 3 Aggregate (3 Slot Clay Brick)

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm²; N/mm²
	1.4	Target mean strength	C2	30 + 13 = 43 N/mm²
	1.5	Cement type	Specified	OPC/~~SRPC/ RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/ ~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.55 } Use the lower value 0.55
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.60
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	190 kg/m³
3	3.1	Cement content	C3	190 ÷ 0.55 = 345 kg/m³
	3.2	*Maximum cement content*	*Specified*	kg/m³
	3.3	*Minimum cement content*	*Specified*	300 kg/m³
				use 3.1 if ≤ 3.2; use 3.3 if > 3.1 — 345 kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.45 known/ ~~assumed~~
	4.2	Concrete density	Fig 5	2265 kg/m³
	4.3	Total aggregate content	C4	2265 - 345 - 190 = 1735 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	40 %
	5.3	Fine aggregate content	C5	1730 x 0.40 = 692 kg/m³
	5.4	Coarse aggregate content	C5	1730 - 692 = 1038 kg/m³

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	345	190	692		1038	
per trial mix of 0.01 m³	3.45	1.90	6.92		10.38	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 3 - High-Strength Concrete Mix

Concrete mix design form **Job title** Control Mix (Granite Aggregate)

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	50 N/mm² at 28 days
				Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm²
				N/mm²
	1.4	Target mean strength	C2	50 + 13 = 63 N/mm²
	1.5	Cement type	Specified	OPC/~~SRPC/ RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.4 } Use the lower value 0.4
	1.8	*Maximum free-water/cement ratio*	*Specified*	
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	190 kg/m³
3	3.1	Cement content	C3	190 ÷ 0.4 = 475 kg/m³
	3.2	*Maximum cement content*	*Specified*	kg/m³
	3.3	*Minimum cement content*	*Specified*	300 kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 475 kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.7 ~~known~~/ assumed
	4.2	Concrete density	Fig 5	2440 kg/m³
	4.3	Total aggregate content	C4	2440 - 475 - 190 = 1775 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	37 %
	5.3	Fine aggregate content	C5	1775 x 0.37 = 657 kg/m³
	5.4	Coarse aggregate content	C5	1775 - 657 = 1118 kg/m³

Quantities		Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)		475	190	657		1118	
per trial mix of	0.01 m³	4.75	1.90	6.57		11.18	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 4 - High-Strength Brick Aggregate Concrete

Concrete mix design form | **Job title**: 10 Hole Red Clay Brick

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	50 N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm²; N/mm²
	1.4	Target mean strength	C2	50 + 13 = 63 N/mm²
	1.5	Cement type	Specified	OPC/~~SRPC~~/~~RHPC~~
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/ ~~uncrushed~~ Crushed/~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.4 } Use the lower value 0.4
	1.8	*Maximum free-water/cement ratio*	*Specified*	
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	190 kg/m³
3	3.1	Cement content	C3	190 ÷ 0.4 = 475 kg/m³
	3.2	*Maximum cement content*	*Specified*	kg/m³
	3.3	*Minimum cement content*	*Specified*	300 kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 — 475 kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.48 known/ ~~assumed~~
	4.2	Concrete density	Fig 5	2280 kg/m³
	4.3	Total aggregate content	C4	2280 - 475 - 190 = 1615 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	37 %
	5.3	Fine aggregate content	C5	1615 x 0.37 = 598 kg/m³
	5.4	Coarse aggregate content	C5	1615 - 598 = 1017 kg/m³

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	475	190	598		1017	
per trial mix of 0.01 m³	4.75	1.9	5.98		10.17	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 5 - Air Entrained Concrete Mix

Concrete mix design form for air-entrained concrete **Job title** Control Mix (Granite Aggregate)

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm²; N/mm²
	1.4	Target mean strength	C2 & Para 8.1*	30 + 13 = 43 N/mm²
	*1.4.1	Air content		5 %
	*1.4.2	Modified target mean strength		43 ÷ (1- 0.055 x 5) = 59 N/mm²
	1.5	Cement type	Specified	OPC/ ~~SRPC/ RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/ ~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.43 } Use the lower value 0.43
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.6
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3 & Para 8.2*	170 kg/m³
3	3.1	Cement content	C3	170 ÷ 0.43 = 395 kg/m³
	3.2	*Maximum cement content*	*Specified*	kg/m³
	3.3	*Minimum cement content*	*Specified*	300 kg/m³
				use 3.1 if ≤ 3.2; use 3.3 if > 3.1: 395 kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.7 ~~known~~/ assumed
	4.2	Concrete density	Fig 5 & Para 8.3*	2460 - (10 x 5 x 2.7) = 2325 kg/m³
	4.3	Total aggregate content	C4	2325 - 395 - 170 = 1760 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	38 %
	5.3	Fine aggregate content	C5	1760 x 0.38 = 669 kg/m³
	5.4	Coarse aggregate content	C5	1760 - 669 = 1091 kg/m³

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	395	170	669		1091	
per trial mix of 0.0105 m³	4.15	1.79	7.02		11.46	

Items in italics are optional limiting values that may be specified (see Section 7)

*Modifications for air entrainment

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 6 - Air-Entrained Brick Aggregate Concrete

Concrete mix design form for air-entrained concrete **Job title** 10 Hole Red Clay Brick

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm^2 at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm^2 or no data 8 N/mm^2
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm^2; N/mm^2
	1.4	Target mean strength	C2 & Para 8.1*	30 + 13 = 43 N/mm^2
	*1.4.1	Air content		5 %
	*1.4.2	Modified target mean strength		43 ÷ (1- 0.055 x 5) = 59 N/mm^2
	1.5	Cement type	Specified	OPC/ ~~SRPC/ RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/ ~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.43 } Use the lower value 0.43
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.6
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3 & Para 8.2*	170 kg/m^3
3	3.1	Cement content	C3	170 ÷ 0.43 = 395 kg/m^3
	3.2	*Maximum cement content*	*Specified*	kg/m^3
	3.3	*Minimum cement content*	*Specified*	300 kg/m^3
				use 3.1 if ≤ 3.2; use 3.3 if > 3.1 → 395 kg/m^3
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.48 known/ ~~assumed~~
	4.2	Concrete density	Fig 5 & Para 8.3*	2300 - (10 x 5 x 2.48) = 2176 kg/m^3
	4.3	Total aggregate content	C4	2176 - 395 - 170 = 1611 kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	38 %
	5.3	Fine aggregate content	C5	1611 x 0.38 = 612 kg/m^3
	5.4	Coarse aggregate content	C5	1611 - 612 = 999 kg/m^3

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	395	170	612		999	
per trial mix of 0.01 m^3	3.95	1.70	6.12		9.99	

Items in italics are optional limiting values that may be specified (see Section 7)

*Modifications for air entrainment

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 7 - Mix With Increased Slump

Concrete mix design form **Job title** 3 Slot Clay Brick (Increased Slump)

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm^2 at 28 days
				Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm^2 or no data 8 N/mm^2
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm^2
				N/mm^2
	1.4	Target mean strength	C2	30 + 13 = 43 N/mm^2
	1.5	Cement type	Specified	OPC/~~SRPC/ RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.55
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.60 } Use the lower value $\boxed{0.55}$
2	2.1	Slump or Vebe time	Specified	Slump 30 - 60 mm or Vebe time 3 - 6 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	$\boxed{210}$ kg/m^3
3	3.1	Cement content	C3	210 ÷ 0.55 = 382 kg/m^3
	3.2	*Maximum cement content*	*Specified*	kg/m^3
	3.3	*Minimum cement content*	*Specified*	300 kg/m^3
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 $\boxed{382}$ kg/m^3
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.45 known/ ~~assumed~~
	4.2	Concrete density	Fig 5	2240 kg/m^3
	4.3	Total aggregate content	C4	2240 - 382 - 210 = 1648 kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	43 %
	5.3	Fine aggregate content	C5	1648 x 0.43 = $\boxed{709}$ kg/m^3
	5.4	Coarse aggregate content	C5	1648 - 709 = $\boxed{939}$ kg/m^3

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	382	210	709		939	
per trial mix of 0.011 m^3	4.2	2.31	7.09		9.39	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 8 - Mix Without Pre-wetting Aggregate

Concrete mix design form | **Job title**: 3 Slot Brick (Increased Slump) / No Prewetting of Aggregate

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm²; N/mm²
	1.4	Target mean strength	C2	30 + 13 = 43 N/mm²
	1.5	Cement type	Specified	OPC/~~SRPC/ RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.55 } Use the lower value 0.55
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.60
2	2.1	Slump or Vebe time	Specified	Slump 60 - 180 mm or Vebe time 0 - 3 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	225 kg/m³
3	3.1	Cement content	C3	225 ÷ 0.55 = 409 kg/m³
	3.2	*Maximum cement content*	*Specified*	kg/m³
	3.3	*Minimum cement content*	*Specified*	kg/m³
				use 3.1 if ≤ 3.2; use 3.3 if > 3.1 — 409 kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.45 known/ ~~assumed~~
	4.2	Concrete density	Fig 5	2380 kg/m³
	4.3	Total aggregate content	C4	2155 - 409 - 225 = 1746 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	48 %
	5.3	Fine aggregate content	C5	1746 x 0.48 = 838 kg/m³
	5.4	Coarse aggregate content	C5	1746 - 838 = 908 kg/m³

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	409	225	838		908	
per trial mix of 0.011 m³	4.5	2.48	8.38		9.08	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).

OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.

Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 9 - Mix Design for Recycled Washed Aggregate

Concrete mix design form — Job title: Recycled Washed Aggregate

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm²; N/mm²
	1.4	Target mean strength	C2	30 + 13 = 43 N/mm²
	1.5	Cement type	Specified	OPC/~~SRPC/RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.55 } Use the lower value $\boxed{0.55}$
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.60
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	$\boxed{190}$ kg/m³
3	3.1	Cement content	C3	190 ÷ 0.55 = 345 kg/m³
	3.2	*Maximum cement content*	*Specified*	kg/m³
	3.3	*Minimum cement content*	*Specified*	300 kg/m³
				use 3.1 if ≤ 3.2; use 3.3 if > 3.1 — $\boxed{345}$ kg/m³
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.18 known/ ~~assumed~~
	4.2	Concrete density	Fig 5	2100 kg/m³
	4.3	Total aggregate content	C4	2100 - 345 - 190 = 1565 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	40 %
	5.3	Fine aggregate content	C5	1565 x 0.40 = $\boxed{626}$ kg/m³
	5.4	Coarse aggregate content	C5	1565 - 626 = $\boxed{939}$ kg/m³

Quantities	Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	345	190	626		939	
per trial mix of 0.02 m³	6.9	3.8	12.52		18.78	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

Design 10 - Recycled Masonry Aggregate

Concrete mix design form | Job title: Recycled Masonry Aggregate

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	30 N/mm^2 at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig. 3	N/mm^2 or no data 8 N/mm^2
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 x 8 = 13 N/mm^2; N/mm^2
	1.4	Target mean strength	C2	30 + 13 = 43 N/mm^2
	1.5	Cement type	Specified	OPC/~~SRPC/RHPC~~
	1.6	Aggregate type: coarse		Crushed/ ~~uncrushed~~
		Aggregate type: fine		Crushed/~~uncrushed~~
	1.7	Free-water/cement ratio	Table 2, Fig. 4	0.55 } Use the lower value 0.55
	1.8	*Maximum free-water/cement ratio*	*Specified*	0.60
2	2.1	Slump or Vebe time	Specified	Slump 10 - 30 mm or Vebe time 6 - 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	190 kg/m^3
3	3.1	Cement content	C3	190 ÷ 0.55 = 345 kg/m^3
	3.2	*Maximum cement content*	*Specified*	kg/m^3
	3.3	*Minimum cement content*	*Specified*	300 kg/m^3
				use 3.1 if ≤ 3.2; use 3.3 if > 3.1: 345 kg/m^3
	3.4	Modified free-water/cement ratio		
4	4.1	Relative density of aggregate (SSD)		1.94 known/ ~~assumed~~
	4.2	Concrete density	Fig 5	1920 kg/m^3
	4.3	Total aggregate content	C4	1920 - 345 - 190 = 1385 kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	33 %
	5.2	Proportion of fine aggregate	Fig. 6	40 %
	5.3	Fine aggregate content	C5	1385 x 0.40 = 554 kg/m^3
	5.4	Coarse aggregate content		1385 - 554 = 831 kg/m^3

Quantities		Cement (kg)	Water (kg or L)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)		345	190	554		831	
per trial mix of	0.02 m^3	6.9	3.8	11.08		16.62	

Items in italics are optional limiting values that may be specified (see Section 7)

1 N/mm2 = 1 MB/m2 = 1 MPa (see footnote to Section 3).
OPC = ordinary Portland cement; SRPC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement.
Relative density = specific gravity (see footnote to Para 5.4). SSD = based on a saturated surface-dry basis

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