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Assessment of Efficiency of Air Abrasive Cleaning on Masonry Stones and Bricks Using Greyscale Imaging Analysis

Humayun Reza, Binsheng Zhang and Naren Gupta

***Abstract* — Advanced greyscale imaging analysis was conducted using Adobe Photoshop 6 on the surfaces of masonry stones and clay bricks, taken from old buildings, to accurately assess the efficiency of building cleaning. Five commonly used masonry stones and clay bricks for those buildings were selected, and seven abrasives were adopted for air abrasive (sandblasting) cleaning. Also the reductions in thickness were continuously monitored for assessing the cleaning efficiency. The cleaning degree at different stages was assessed using greyscale image photos, converted from original colour ones, together with reductions in thickness. In general, greyscale continuously increased with the cleaning time and tended to be stable when the surface became fully cleaned. Thickness reduction monotonically increased with the cleaning time. The most efficient building cleaning case would be the one with the shortest cleaning time and smallest thickness reduction. The harder abrasives with smaller particles sizes were confirmed to be more effective.**

***Keywords* — historic building, masonry stones and bricks, air abrasive cleaning, greyscale, cleanness**

I. Introduction

Masonry stones and clay bricks have been largely used to construct historic buildings which nowadays become precious finite assets and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The cleaning and restoration of these historic buildings is a crucial strategy in maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations.

Humayun Reza
School of Engineering and the Built Environment
Edinburgh Napier University
United Kingdom

Binsheng Zhang
School of Engineering and Built Environment
Glasgow Caledonian University
United Kingdom

Naren Gupta
School of Engineering and the Built Environment
Edinburgh Napier University
United Kingdom

Stone cleaning is one of the most noticeable changes a building can be subjected to. Stone cleaning has been dated back for over 40 years, peaking in the 1970s and 80s and growing into a multimillion pound business [1-3]. In the early times, the cleaning was inappropriately aggressive, causing damage to many building façades. Inappropriately selected methods of cleaning or right methods performed by unskilled operatives can lead to permanent damage to building façades.

In Scotland, natural masonry stones and clay bricks were widely used as building materials in the built heritage, which hence led to large demands of stone cleaning [4,5]. Since the 1960s, people have paid more attention to cleaning methods and many studies on stone cleaning have been published [6-8]. Cleaning methods nowadays have become more finely tuned and less aggressive because new legislations have protected listed historic buildings and conservation areas from any detrimental treatments [9].

Air abrasive cleaning (sandblasting) involves a stream of compressed air directing particles of abrasive materials onto the soiled masonry surfaces. Here, cleaning is accomplished by these particles dislodging the surface layer and the dirt adhering to it. The dislodging of the dirt deposits thus takes place by the breaking up, sometimes to a depth of several millimetres, the surface layer beneath the deposits. Both dry and wet blasting methods have similar effects on cleaning masonry façades. The abrasive cleaning does not differentiate between removing soiling and masonry, and the effect of jetting the abrasive material is controlled by the operator. When wrongly applied, it could have a long lasting damaging effect on the building façade. Abrasive cleaning is a quick method and is therefore usually considered for large areas of metals or masonries which have few design features. The most commonly used system is the air pressure blast equipment. Typical nozzle pressures range from 0.02 kPa to 14.0 kPa.

So far there are no consistent standards and parameters used for assessing the degree of building cleaning, and the efficiency of various cleaning methods is largely evaluated by visual inspections and mutual agreements. There is an urgent need to search for more appropriate physical parameters for such assessments. Previous investigations were largely focused on finding the substances of the soiling on the building façade and the methods to remove these substances. Greyscale imaging analysis can be used for such purpose, together with the monitoring the reduction in thickness during the cleaning.

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To study the cleaning degrees of the masonry surfaces, a digital imaging analysis method, greyscale imaging analysis, was used. The mechanism of this method is to determine the grey degree of greyscale digital images converted from colour photos for assessing building cleaning effectiveness. This technique has been largely used in civil engineering fields, e.g. geotechnical analysis of aggregate particles [11,12], automatic road surface detection [13], etc. Recently, applications of imaging analysis into assessing building cleaning have been reported [14,15]. The authors tried to conduct preliminary digital imaging analysis using ColorPad by adopting two physical parameters (greyscale and cleanness) to assess the effectiveness of stone cleaning and confirmed that it is a useful and accurate method [16,17]. However, collecting data by using ColorPad is very time consuming because the greyscale values were read point by point.

In this study, five types of masonry stones and clay bricks most commonly used for historic buildings were selected, including granite, yellow sandstone, red sandstone, yellow clay brick and red clay brick. Also, three main types, seven sub-types, of abrasives were adopted for air abrasive cleaning, including slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. All seven abrasives were either industrial by-products or natural products which were environmentally sustainable. Thus, there would be a total of thirty-five combinations of cleaning cases. Meanwhile the thickness reductions for all cases were measured. Thus, the efficiency of air abrasive cleaning on masonry stones and clay bricks could be largely assessed.

II. Preparing Masonry Samples

A. *Masonry Stone and Brick Samples*

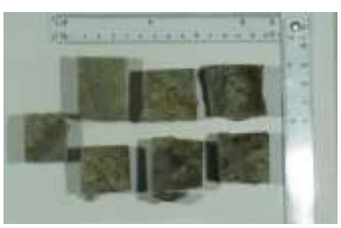
All five masonry stones and clay bricks were selected from those for masonry buildings and exposed to environmental conditions for decades with large amounts of soiling and decay on the façades. The samples were cut into the sizes of 50 mm × 50 mm × 25 mm from the original masonry stones and bricks using a diamond saw (see Fig. 1). The exposed surfaces of the samples were then cleaned to different degrees with each abrasive in turn. The cleaning system included an air compressor, shot blasting cabinet and nozzle (see Fig. 2). Fig. 3 shows all five masonry stone and clay brick samples.

B. *Abrasives for Air Abrasive Cleaning*

In this project, a total of seven types of abrasives have been adopted so as to provide a wide range of combinations: slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive, see Table I. Steel plant by-product slag abrasives are made from iron silicate, which forms an inert synthetic material and does not produce chemical reactions. Glass abrasives are made from 100% recycled glass and also produce little dust like slag. The fundamental physical properties of these two types of abrasive according to SCANGRIT [18,19] are listed in Table II. Natural abrasive is a natural product composed of grains of coconut and almond shell [20].

Figure 1. Cutting samples from original stones and bricks.

Figure 2. The abrasive cleaning system.



(a) Granite

(b) Yellow sandstone

(c) Red sandstone

(d) Yellow clay brick

(e) Red clay brick

Figure 3. Masonry stone and clay brick samples for greyscale imaging analysis.

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TABLE I. ABRASIVES USED FOR AIR APPRASIVE (SANDBLASTING) CLEANING.

 1. Coarse slag	 2. Medium slag	 3. Fine slag	 4. Coarse glass
 5. Medium glass	 6. Fine glass	 7. Natural abrasive	

TABLE II. PHYSICAL PROPERTIES OF THE ABRASIVES USED IN THIS STUDY.

No	Abrasive	Particle size (μm)	FM_{pre}	FM_{post}	ΔFM	Mohs' scale hardness	Bulk density (g/cm^3)
1	Coarse slag	500 - 2000	5.22	5.13	0.09	7 to 8	1.7
2	Medium slag	200 - 1700	4.89	4.85	0.04		
3	Fine slag	200 - 850	4.56	4.39	0.17		
4	Coarse glass	1000 - 2000	6.37	6.08	0.29	5 to 6	1.3
5	Medium glass	500 - 1250	5.98	5.71	0.27		
6	Fine glass	200 - 500	4.39	4.02	0.37		
7	Natural	300	3.97	3.61	0.36	3	0.7 to 0.8

From the sieve tests, the fineness moduli (FM_{pre}) of all seven abrasives were obtained [21,22] and are also listed in Table II, which shows that coarse recycled glass is the coarsest with FM = 6.37, natural abrasive is the finest with FM = 3.97, and the rest lie in-between with FM varying from 4.39 to 5.98. Impact tests were also conducted on all seven abrasives [23], and the corresponding FM values (FM_{post}) were measured and are listed in Table II. In general, all FM values decreased after the impact tests due to more fine particles produced during the tests. Natural abrasive sustained the largest drop in FM, followed by recycled glass abrasives; while slag abrasives sustained the least drop. This confirms that natural abrasive was the softest and slag abrasives were the hardest, with glass abrasives in-between. Coarse glass was the coarsest abrasive, followed by medium glass and coarse slag, while natural abrasive was the finest abrasive, followed by fine glass and fine slag, with the rest in-between, the same as assessed using the fineness modulus.

III. Digital Greyscale Imaging Analysis

In the preliminary digital greyscale imaging analysis [24], all the photos were taken indoors under consistent illuminating conditions. As the environmental conditions during cleaning were inconsistent, inside a workshop but with the entrance door open, the images did not give unique levels of brightness. Although a frame was specially built to create constant luminosity conditions, the cleaning was conducted in the workshop lit by daylight, which affected the luminosity intensity of the images, causing heterogeneous brightness. To solve this problem, firstly, all the images were treated using the software ColorPad (Fig. 4). It identifies the RGB (red, green and blue) values of a selected point on the image, which show the combination degree of these three primary colours, each varying from 0 to 255, where 0 indicates the darkest pure black colour and 255 indicates the brightest pure white colour.

In order to quantitatively assess the colour changes of the stone and brick samples, the background white paper was used as reference for the analysis. Using ColorPad, the background brightness of all the images was adjusted, setting the red value at 200 as a reference. Thereafter, these colour pictures were converted into greyscale images using Adobe Photoshop 6. The greyscale, like RGB, has a set of definition values, ranging from 0 to 255, as indicated in Fig. 5.

Figure 4. ColorPad.

Figure 5. Greyscale spectrum.

Since not all the samples had the same dimensions, their central areas of 20 mm × 20 mm were used for the greyscale imaging analysis. This standardisation of the area would allow all the images to be compared. There would be four separate

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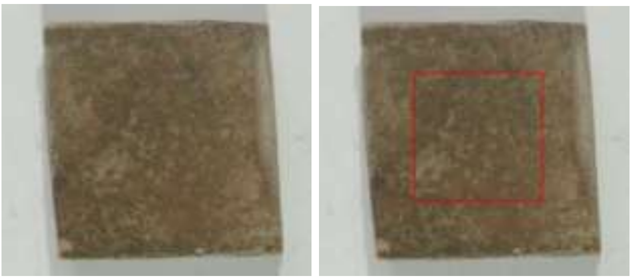
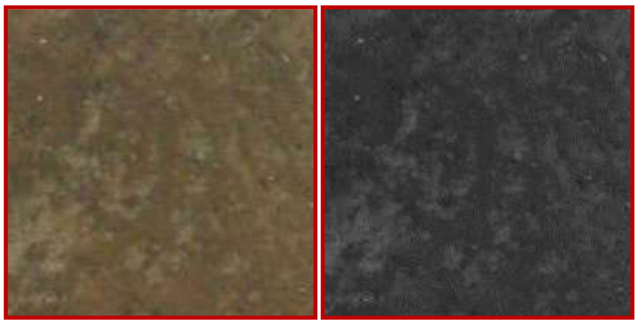
steps next. The original images were scaled and orientated. An area inside was selected by drawing a red frame on the image, which was then cropped. Finally, the cropped area was converted into the greyscale image. Fig. 6 shows a typical example of this procedure, which was then applied to all the images of 35 stone samples at different cleaning stages.



(a) Scaling and orientating a sample (b) Selecting an area

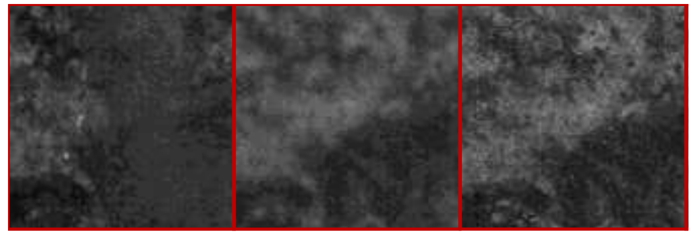


(c) Showing the selected area (d) Converting to the greyscale

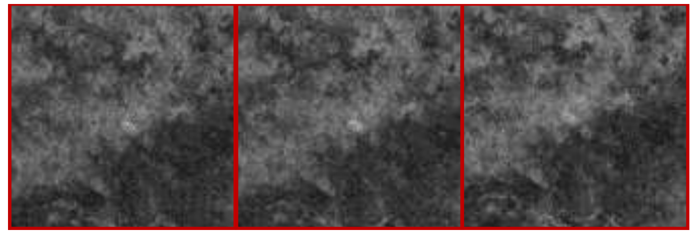
Figure 6. Four steps for processing an image photo for red sandstone. cleaned with fine glass.

Figs. 7 to 11 show the greyscale images of all masonry stone and brick samples cleaned with slag or glass abrasives at different cleaning stages. In these photos, the first images show the original dirty surfaces and the last photos show the fully cleaned surfaces. From each image the average greyscale value and standard deviation were obtained using Adobe Photoshop 6. All five sets of greyscale images indicate that the masonry surfaces became gradually brighter with cleaning except yellow clay brick which sustained reverse trends.

Figs. 12 to 16 show the relationships between the greyscale GS and the cleaning time *t* for the five masonry stones and clay bricks. Fig. 12 indicates that a parabola well reflects the increasing trend of greyscale with the cleaning time for granite cleaned with fine glass. The data and the parabola almost coincide since the R^2-value is equal to 0.964 which is very close to 1.0. Greyscale increased with the cleaning time from GS = 54.83 before cleaning at a decreasing rate and became stable at GS = 79.24 when the sample was fully cleaned after 10 seconds, up by 24.41 in GS or 44.5%. It seems that only 6 seconds corresponding to GS = 76.80 may be enough to largely clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was quite big, which indicates that the surface of the original granite was very dirty.

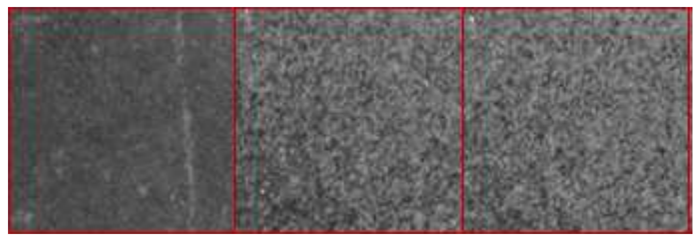


(a) Original (b) Stage 2 (c) Stage 3

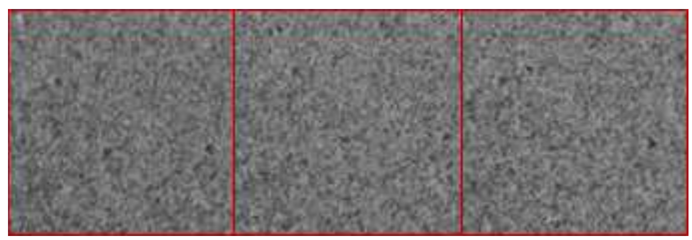


(d) Stage 4 (e) Stage 5 (f) Cleaned

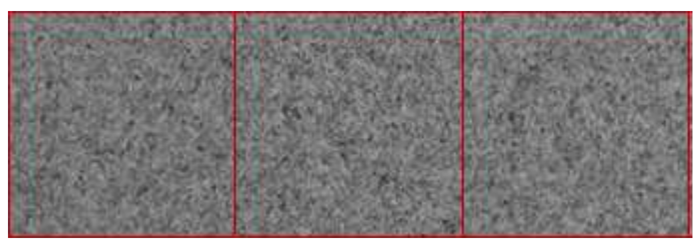
Figure 7. Greyscale images of granite cleaned with fine glass at cleaning stages 1 to 6.



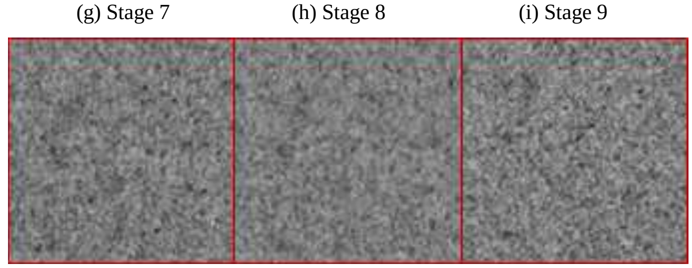
(a) Original (b) Stage 2 (c) Stage 3



(d) Stage 4 (e) Stage 5 (f) Stage 6



(g) Stage 7 (h) Stage 8 (i) Stage 9



(j) Stage 10 (k) Stage 11 (l) Cleaned

Figure 8. Greyscale images of yellow sandstone cleaned with coarse slag at cleaning stages 1 to 12.

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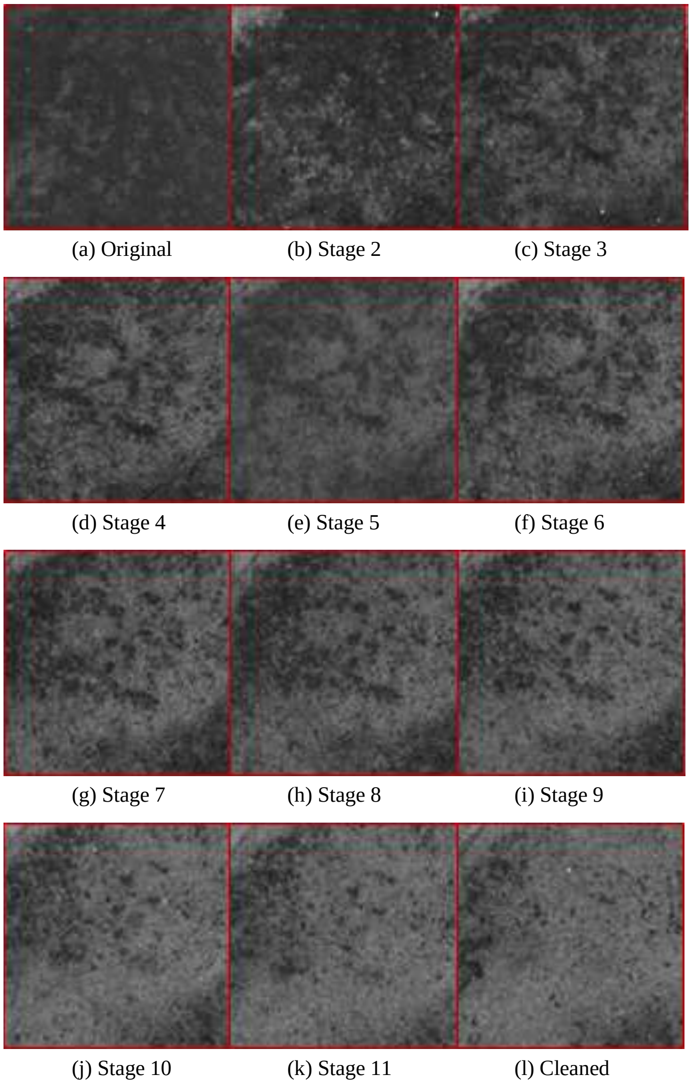

Figure 9. Greyscale images of red sandstone cleaned with fine glass at cleaning stages 1 to 12.

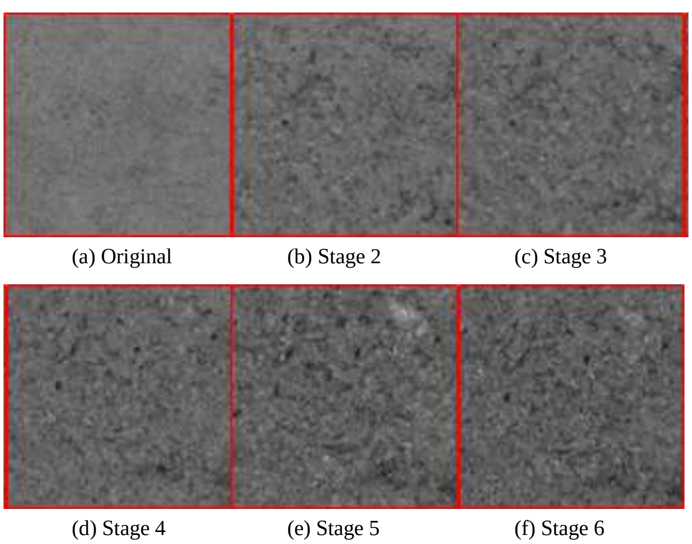

Figure 10. Greyscale images of yellow clay brick cleaned with medium glass at cleaning stages 1 to 6.

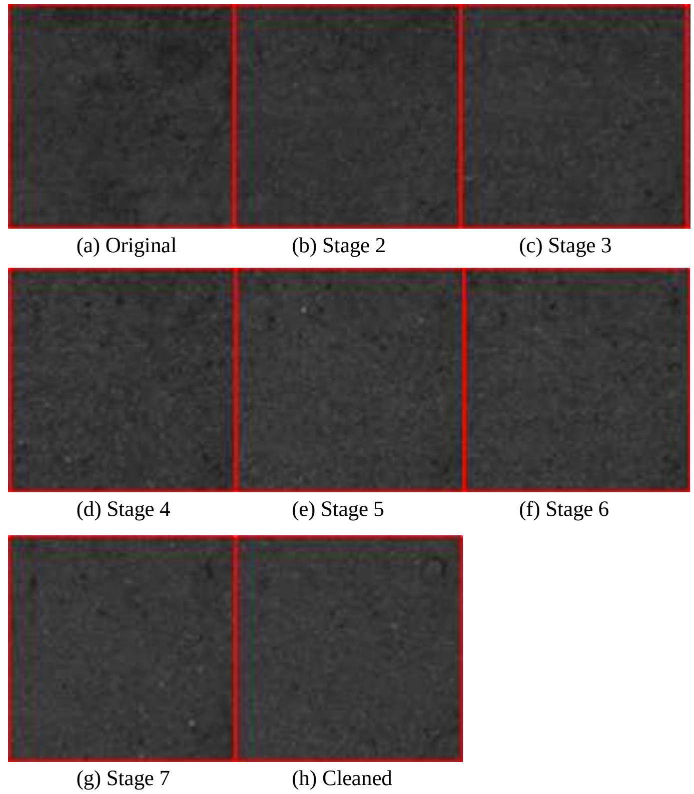

Figure 11. Greyscale images of red clay brick cleaned with medium glass at cleaning stages 1 to 8.

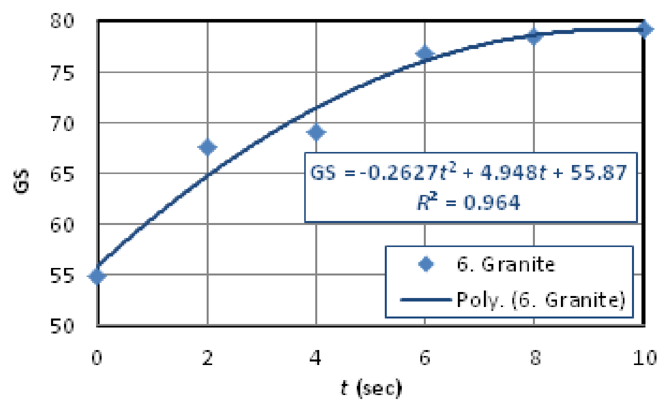

Figure 12. Greyscale versus cleaning time for granite cleaned with fine glass.

Fig. 13 shows that a parabola can represent the increasing trend of greyscale with the cleaning time for yellow sandstone cleaned with coarse slag, with R^2 = 0.827. Greyscale increased with the cleaning time from GS = 81.14 before cleaning at a decreasing rate and finally became stable at GS = 124.51 when the sample was fully cleaned after 180 seconds, up by 43.37 in GS or 53.5%. It seems that it would take about 100 seconds, for GS = 120.23, to almost fully clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was reasonably large, which indicates that the surface of the original yellow sandstone was quite dirty.

Fig. 14 shows that a parabola well matches the increasing trend of greyscale with the cleaning time for red sandstone cleaned with fine glass. The data and the parabola almost

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coincide with R^2 = 0.959. Greyscale increased with the cleaning time from GS = 58.56 before cleaning at a decreasing rate and finally became stable at GS = 93.84 when the sample was fully cleaned after 80 seconds, up by 35.28 or 60.2%. It seems that 50 seconds, corresponding to GS = 90.94, may be enough for almost fully cleaning this sample. The gap in greyscale values between the original dirty and fully cleaned states was huge, indicating that the surface of the original red sandstone was very dirty.

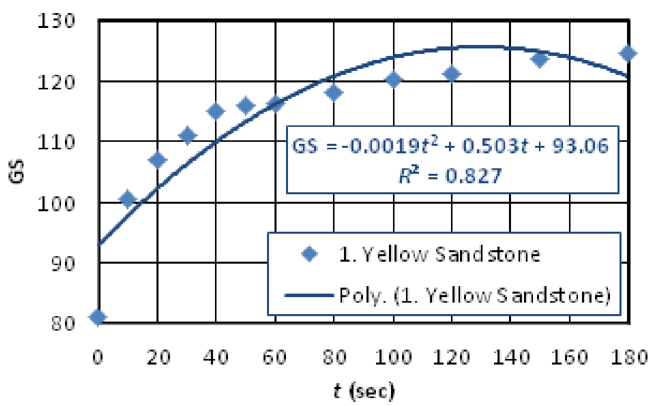

Figure 13. Greyscale versus cleaning time for yellow sandstone cleaned with coarse slag.

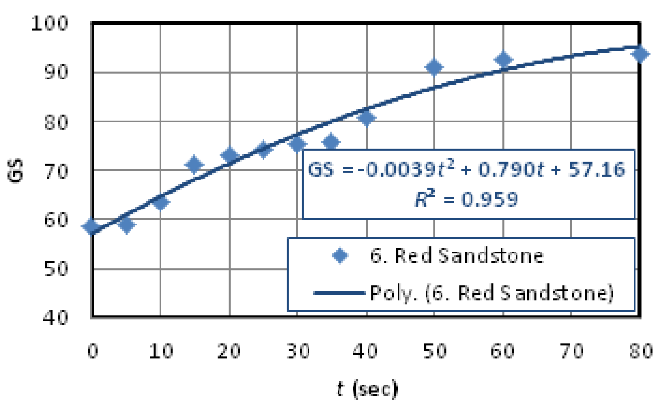

Figure 14. Greyscale versus cleaning time for red sandstone cleaned with fine glass.

Fig. 15 shows that a parabola can represent the reverse decreasing trend of greyscale with the cleaning time for yellow clay brick cleaned with medium glass. The data and the parabola almost coincide with R^2 = 0.958. Greyscale decreased with the cleaning time from GS = 114.60 before cleaning at a decreasing rate and finally became stable at GS = 94.96 when the sample was fully cleaned after 10 seconds, down by 19.24 in GS or 16.8%. It seems that only 6 seconds corresponding to GS = 98.36 may be enough for almost fully cleaning this sample. The gap in greyscale values between the original dirty and fully cleaned states was not quite big, which indicates that the surface of the original yellow clay brick was not very dirty.

Finally, Fig. 16 shows that a parabola well reflects the increasing trend of greyscale with the cleaning time for red clay brick cleaned with medium glass as well. The data and the parabola almost coincide with R^2 = 0.987. Greyscale increased with the cleaning time from GS = 50.74 before cleaning at a decreasing rate and finally became stable at GS = 58.38 when the sample was fully cleaned after 14 seconds, up by 7.64 in GS or 15.1%. It seems that it would take about 10 seconds, corresponding to GS = 57.33, to almost fully clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was also small, indicating that the surface of the original red clay brick was not very dirty.

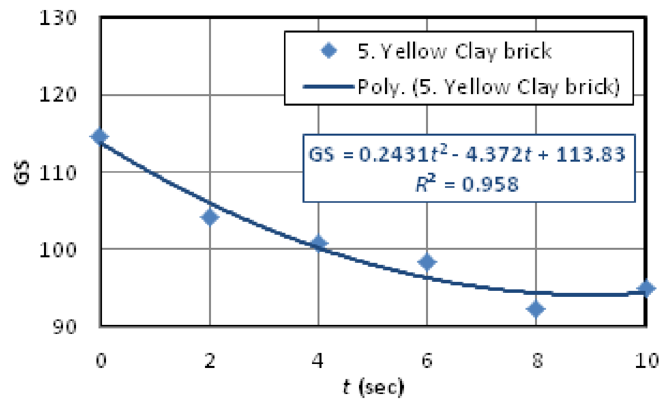

Figure 15. Greyscale versus cleaning time for yellow clay brick cleaned with medium glass.

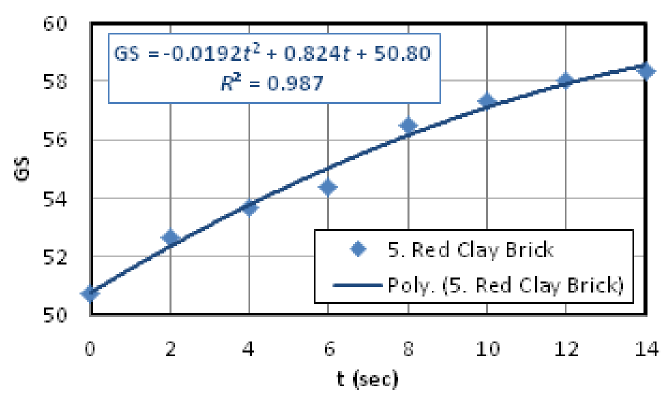

Figure 16. Greyscale versus cleaning time for red clay brick cleaned with medium glass.

Table III lists the total cleaning time t_{tot}, initial greyscale GS_{ini}, final greyscale GS_{fin}, change in greyscale ΔGS and total thickness deduction Δa for all masonry stones and clay bricks cleaned with seven different abrasives. The average values of the listed parameters except the total cleaning time, together with the corresponding standard deviations, are also listed in Table III. For each stone or brick, the initial greyscale values which represent the original dirty degree varied largely because the soiling states on the surfaces of the stone samples were different. For example, the greyscale for yellow clay brick varied from 114.60 to 125.05, with an average of 121.63 and a standard deviation of 3.47, giving a smallest variation coefficient of 2.85%. On contrast, the greyscale for yellow sandstone varied from 53.50 to 97.12, with an average of 69.17 and a standard variation of 18.85, giving a largest variation coefficient of 27.25%. The variations in the original greyscale values for the rest stones and bricks lay in-between.

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TABLE III. SUMMARY OF GREYSCALE RESULTS BEFORE AND AFTER CLEANING WITH FINAL THICKNESS REDUCTIONS.

Stone/brick	Abrasive	t_{tot} (sec)	GS_{ini}	GS_{fin}	ΔGS	Δa (mm)
Granite	Coarse slag	10	67.54	73.54	6.00	0.32
	Medium slag	10	53.14	60.84	7.70	0.17
	Fine slag	10	49.05	62.08	13.03	0.19
	Coarse glass	50	62.68	86.83	24.15	0.31
	Medium glass	10	70.98	89.59	18.61	0.15
	Fine glass	10	54.83	79.24	24.41	0.25
	Natural	50	63.03	74.46	11.43	0.21
	Average	/	60.18	75.23	15.05	0.23
	Standard deviation	/	8.03	11.11	7.49	0.07
Yellow sandstone	Coarse slag	180	81.14	124.51	43.37	0.75
	Medium slag*	540	60.43	100.01	39.58	1.38
	Fine slag*	300	53.5	105.17	51.67	1.82
	Coarse glass	210	97.12	137.94	40.82	0.58
	Medium glass*	240	43.18	120.73	77.55	1.10
	Fine glass*	240	65.58	120.94	55.36	1.37
	Natural	120	83.22	100.19	16.97	0.90
	Average	/	69.17	115.64	46.47	1.13
	Standard deviation	/	18.85	14.27	18.40	0.43
Red sandstone	Coarse slag*	180	64.04	105.91	41.87	2.00
	Medium slag*	120	43.27	91.14	47.87	1.62
	Fine slag	60	49.49	89.87	40.38	1.22
	Coarse glass*	480	45.92	93.24	47.32	1.74
	Medium glass	80	62.15	98.75	36.60	1.08
	Fine glass	80	58.56	93.84	35.28	0.95
	Natural*	240	54.20	33.10**	-21.10**	2.15
	Average	/	53.95	95.46	41.55	1.54
	Standard deviation	/	8.05	5.96	5.26	0.46
Yellow clay brick	Coarse slag*	10	121.12	95.73	-25.39	0.66
	Medium slag	10	120.90	88.78	-32.12	0.23
	Fine slag	10	122.84	82.20	-40.64	0.19
	Coarse glass*	100	124.55	101.09	-23.46	0.86
	Medium glass	10	114.60	94.96	-19.24	0.25
	Fine glass	10	125.05	88.84	-36.21	0.27
	Natural	12	122.37	80.04	-42.33	0.29
	Average	/	121.63	90.23	-31.34	0.39
	Standard deviation	/	3.47	7.56	-8.90	0.26
Red clay brick	Coarse slag*	35	55.10	70.84	15.74	1.48
	Medium slag*	35	45.03	63.41	18.38	1.27
	Fine slag	20	48.48	58.47	9.99	0.42
	Coarse glass*	420	48.80	58.10	9.30	0.60
	Medium glass	14	50.74	58.38	7.64	0.35
	Fine glass	10	64.66	71.80	7.14	0.47
	Natural*	900	36.99	50.87	13.88	1.23
	Average	/	49.97	61.70	11.72	0.83
	Standard deviation	/	8.56	7.53	4.31	0.48

* Abrasives were not recommended. ** The results were not included in the statistical analysis.

According to the final greyscale values from small to large, the original colours of the five masonry stones and clay bricks can be ranked, from dark to bright, as red clay brick (GS = 61.70), granite (GS = 75.23), yellow clay brick (GS = 90.23), red sandstone (GS = 95.46) and yellow sandstone (GS = 115.64). This also indicates that yellow sandstone was the brightest while the red clay brick was the darkest, with the rest lying in-between. According to the percentage ratios of the greyscale changes to the final greyscale values, the dirty degrees of the five masonry stones can be ranked, from dirty to bright, as red sandstone (43.53%), yellow sandstone (40.19%), yellow clay brick (34.73%), granite (20.01%) and

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red clay brick (19.00%). This indicates that the original red sandstone had the dirtiest surface, followed by the yellow sandstone and limestone, while the original granite and red clay brick had the relatively cleanest surfaces.

The final thickness reductions indicate that granite had a smallest average thickness loss of only 0.23 mm during the cleaning process, followed by yellow clay brick (Δa = 0.39 mm), red clay brick (Δa = 0.83 mm), and yellow sandstone (Δa = 1.13 mm), while red sandstone had a largest average thickness loss of 1.54 mm. For each type of fully cleaned stone and brick, a smaller thickness loss indicates a more effective cleaning process or a more suitable abrasive as well. All seven abrasives used in this study may be all suitable for cleaning granite. For yellow sandstone, coarse glass may be the most suitable abrasive with a thickness loss of 0.58 mm, followed by coarse slag (Δa = 0.75 mm) and natural abrasive (Δa = 0.90 mm). The rest abrasives can be regarded as the less suitable or unsuitable ones. For red sandstone, fine glass may be the most suitable abrasive with a thickness reduction of 0.95 mm, followed by medium glass (Δa = 1.08 mm) and fine slag (Δa = 1.22 mm). The rest abrasives can be regarded as the less suitable or unsuitable ones. For yellow clay brick, five medium and fine abrasives including natural abrasive may be the suitable abrasives with thickness losses between 0.19 mm and 0.29 mm, while coarse slag and coarse glass can be regarded as the less effective ones with thickness losses of 0.66 mm and 0.86 mm respectively. Finally for red clay brick, fine slag, medium glass and fine glass may be the more suitable abrasives with thickness losses of 0.42 mm, 0.35 mm and 0.47 mm respectively, while the rest abrasives can be regarded as the less effective ones.

The greyscale values obtained using a natural abrasive were largely affected by the nature of this abrasive. Natural abrasive is a very soft material, and is composed of coconut and almond shells. After impacting on stone and brick surfaces it easily turns into dust. This impact would leave the masonry surfaces lightly smudged with a brownish colour. As a result of this, the greyscale values measured were different from those on the masonry samples cleaned with other abrasives, e.g. granite, yellow sandstone, yellow clay brick and red clay brick. The extreme case is that the greyscale for red sandstone decreased with the cleaning time, down by 21.10 or 38.93% when the sample was fully cleaned after 240 seconds.

By observing the statistical analysis on the greyscale results for the granite samples, it is clear that all the R^2 values were larger than 0.93. This indicates that the parabolic relationships between greyscale and cleaning time can well predict the trends. However, the final greyscale values were not very similar. This could be due to the fact that the surface of the granite samples was polished. Hence, it is suggested that the most suitable cleaning method for polished stone surfaces may be a manual cleaning, e.g. using a sponge or a brush and washing-up liquid, instead of air abrasive cleaning. Nevertheless, samples cleaned with three recycled glasses of different sizes produced similar final greyscale values, with the differences in greyscale between the initial and final cleaning stages ranging from 18 to 25.

As the time needed to fully clean a stone or brick sample is another important practical consideration due to resultant labour costs, any abrasive material that took more than 210 seconds to clean a stone or brick sample may be regarded to be ineffective for that stone or brick since it could not produce a desirable performance. It can be seen that all seven abrasives are suitable for granite, compared with yellow clay brick for which only five abrasives were suitable and both coarse glass and natural abrasive are surely not suitable choices. Furthermore, for granite and yellow clay brick, medium and fine slag or glass were more effective and economical. For yellow sandstone, only coarse slag, coarse glass and natural abrasive may be good options. Finally for red sandstone and red clay brick, only fine slag, medium glass and fine glass are suitable choices.

IV. Conclusions

In this study, advanced greyscale imaging analysis was conducted using Adobe Photoshop 6 on the surface images of the masonry stones and clay bricks, taken from exiting old masonry buildings, to accurately assess changes in the colour component of the masonry surface during cleaning and to eventually evaluate the cleaning effectiveness.

Five types of masonry stones and clay bricks most commonly used for old masonry buildings were selected, including granite, yellow sandstone, red sandstone, yellow clay brick and red clay brick. Also, three main types, seven sub-types, of abrasives were adopted for the air abrasive (sandblasting) cleaning, including slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive.

From the results for all five types of masonry stones and clay bricks presented here, the cleaning degrees at different stages were evaluated using the greyscale images converted from the original colour photos, where a lower greyscale was normally related to a dirtier and darker surface and a higher greyscale to a cleaner and brighter surface except yellow clay brick. Relationships between cleaning degree (greyscale) and cleaning time were illustrated and represented with parabolic trend lines. In general, greyscale continuously increased with the cleaning time at a decreasing rate and tended to be stable when the masonry surface became fully cleaned. However, greyscale for yellow clay brick followed reverse decreasing trends with the cleaning time but also tended to be stable when the brick surface became fully cleaned.

By considering both cleaning time and thickness reduction, any abrasives with longer cleaning times or bigger thickness losses for the same cleaning degree on a type of masonry stone or clay brick would be regarded to be less suitable and uneconomical for that type of stone or brick. In general, the abrasives with better cleaning performance were those industrial by-products or recycled products with smaller

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particles sizes, i.e. medium and fine slag or recycled glass, because the coarse abrasives and natural abrasive would consume more cleaning times and possibly cause damages to masonry surface features.

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Dr. Humayun Reza:

In this study, five masonry stones and clay bricks most commonly used for historic buildings, including granite, yellow and red sandstones, and yellow and red clay bricks, were selected and air-abrasively cleaned with seven different abrasives.

Dr. Binsheng Zhang:

Greyscale imaging analysis using Adobe Photoshop 6 on the surface images of the masonry stones and clay bricks can accurately assess changes in the colour of the masonry surface during cleaning and to evaluate the cleaning effectiveness.

Professor Naren Gupta:

Considering cleaning time and thickness reduction, the abrasives with better cleaning performance were, in general, those industrial by-products or recycled products with smaller particles sizes, i.e. medium and fine slag or recycled glass.

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