Assessment of air abrasive cleaning on masonry stones using greyscale imaging techniques

H. Reza
Edinburgh Napier University, Edinburgh, UK

B. Zhang
Glasgow Caledonian University, Glasgow, UK

M. Hernandez Montoya & N. Gupta
Edinburgh Napier University, Edinburgh, UK

ABSTRACT: In this study, advanced greyscale imaging analysis was conducted using the Adobe Photoshop 6 on the surfaces of masonry stones, taken from listed historic buildings, to accurately assess the effectiveness of building cleaning. Seven commonly used masonry stones and clay bricks for historic buildings were selected, together with seven abrasives adopted for air abrasive cleaning, e.g. copper slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. Here, only the results for granite, limestone and marble are presented. The cleaning degree at each stage was evaluated using greyscale images converted from original colour ones, where lower greyscale corresponded to dirtier surface and higher greyscale to brighter and cleaner surface. In general, greyscale continuously increased with the cleaning time and tended to be stable when the surface became fully cleaned. The abrasives with better performance were those with smaller particles sizes, i.e. the medium and fine abrasives.

1 INTRODUCTION

Masonry stones and clay bricks have been widely used for constructing historic buildings and monuments, which become grand assets for present and future generations. The cleaning and restoration of these historic masonry structures has become significantly important (Reza et al., 2008) and has been conducted for decades in the UK due to persistent investigations on physical and chemical characteristics of masonry stones and the development of modern cleaning techniques (Ashurst, 1994a, 1994b; Laing & Urquhart, 1997; Ball et al., 2000; Feilden, 2003; Young et al., 2003). Millions of Stirling pounds have been spent every year on building cleaning and this is highly appraised by the public because of the significant effect on the appearance of the buildings and urban environment.

Masonry stones in buildings considered for cleaning vary largely in type, surface texture and architectural style and suffer from different types of natural decay and even man-made pollutions. Cleaning methods are usually destructive and cause irreversible damage. The method of removing soiling from stone façade without affecting underlying stone and causing long term damage has not been devised yet. Physical cleaning methods such as grit blasting will lead to some abrasive damage to the stone façade. Chemical cleaning method may dissolve some stone components alone with the soiling and leave chemical residues in porous stones. Some effects may become apparent many years after and large scales of stone repair and replacement are needed to resolve the problem caused by the ill-cleaning in the past. There are four major types of cleaning methods: water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting). So far there are no consistent standards and parameters used for assessing the efficiency of various building cleaning methods, and this is largely evaluated by visual inspections and mutual agreements. There is an urgent need to search for better physical parameters for such assessments. Greyscale imaging analysis can be used for such purpose.

To investigate the cleaning degrees of the surfaces of the stone samples, a digital image analysis method, greyscale imaging analysis, was used. The mechanism of this method is to determine the grey degree of greyscale digital images converted from normal colour photos for assessing the building cleaning effectiveness. This technique has been largely used in civil engineering fields, e.g. geotechnical analysis of aggregate particles (Kuo & Freeman, 1998; Rao & Tutumluer, 2000; Chandan et al., 2004), automatic road surface detection (Treash & Amaratunga, 2000; Ghanta et al., 2012), etc. However, no much research has been reported on its use for assessing building cleaning. The authors tried to conduct preliminary digital imaging analysis using ColorPad by adopting two physical parameters (greyscale and cleanness) to quantitatively assess the effectiveness of stone cleaning and proved it is a useful and accurate method (Reza et al, 2012; Reza 2014). However, collecting data by using ColorPad is very time consuming because it could only read the greyscale values point by point.

In this study, seven types of masonry stones and clay bricks most commonly used for historic buildings were selected, including granite, limestone, marble, red sandstone, yellow sandstone, red clay brick and yellow clay brick. Also, three main types, seven sub-types, of abrasives were adopted for air abrasive cleaning, including copper slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. All seven abrasives were either industrial by-products or natural products which were environmentally sustainable. Thus, there would be a total of forty-nine combinations. In this paper, only the results for granite, limestone and marble are presented.

2 PREPARATION OF STONE SAMPLES

2.1 *Stone samples*

All seven types of masonry stones and bricks were selected from those used for masonry buildings and exposed to open environmental conditions for decades with large amounts of heavy soiling and decay existing on the façades. The samples were cut into the dimensions of 50 mm × 50 mm × 25 mm from the original masonry stones and bricks using a diamond saw (Fig. 1). The exposed surfaces of the stone samples were then cleaned to different levels using each abrasive in turn. Here an abrasive cleaning system selected included an air compressor, shot blasting cabinet and nozzle (Fig. 2). Figure 3 shows the granite, limestone and marble samples used for greyscale imaging analysis at different cleaning stages.

Figure 1. Cutting samples from original stones

Figure 2. The abrasive cleaning system

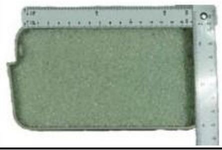
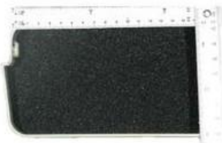
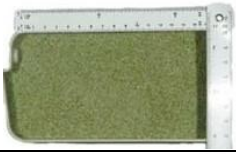
2.2 *Abrasives for sandblasting cleaning*

Depending on the function of adopted abrasive materials, abrasive cleaning has different consequences. In this project, a total of seven types of abrasives have been adopted so as to provide a wide range of combinations: copper slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive (see Table 1).

(a) Granite (b) Limestone (c) Marble

Figure 3. Masonry stone samples for greyscale imaging analysis

Table 1. Abrasives used in this study.

No	Abrasive	Sample	No	Abrasive	Sample
1	Coarse slag		4	Coarse glass	
2	Medium slag		5	Medium glass	
3	Fine slag		6	Fine glass	
			7	Natural abrasive	

Slag abrasives are made from iron silicate, which forms an inert synthetic material. They do not produce chemical reactions when projected onto the stone, and they produce little dust. Glass abrasives are made from 100% recycled glass. They hold an angular shape, and produce little dust like slag. The fundamental physical properties of these two types of abrasive according to SCANGRIT (2004, 2010) are listed in Table 2. Natural abrasive, which is commercially named as *Granalla*, is a natural product composed of grains of coconut and almond shell. It has a slightly angular and polyhedral shape, giving a less satisfactory performance. The main physical properties of this abrasive are also shown in Table 2 (MPA n.d.).

From the sieve tests, the fineness moduli (FMs) of all seven abrasives were obtained (CRD, 1980) and are also listed in Table 2, which shows that coarse recycled glass is the coarsest with FM = 6.37, natural abrasive is the finest with FM = 3.97, and the rest lie in-between with FM = 4.39 to 5.98. Slag abrasives are the heaviest and toughest and are followed by glass abrasives, with natural abrasive being the lightest and softest.

Table 2. Physical properties of the abrasives used in this study.

No	Abrasive	Particle size (μm)	FM	Mohs' scale hardness	Bulk density (g/cm^3)
1	Coarse slag	500 to 2000	5.22	7 to 8	1.7
2	Medium slag	200 to 1700	4.89		
3	Fine slag	200 to 850	4.56		
4	Coarse glass	1000 to 2000	6.37	5 to 6	1.3
5	Medium glass	500 to 1250	5.98		
6	Fine glass	200 to 500	4.39		
7	Natural	300	3.97	3	0.7 to 0.8

3 DIGITAL GREYSCALE IMAGING ANALYSIS

In the preliminary digital greyscale imaging analysis (Zhang et al., 2014), all the photos were taken indoors under consistent illuminating conditions. However, during this analysis a problem was found. Because the environmental conditions during cleaning were inconsistent, inside a workshop but with the entrance door open, the images did not give unique levels of brightness. Although a frame was specially built to create constant luminosity conditions, the cleaning was conducted in the workshop lit by daylight, which affected the luminosity intensity of the images when they were taken, and also caused heterogeneous brightness. In order to solve this problem, firstly, all the images were treated using the software ColorPad (Fig. 4). This software identifies the RGB (red, green and blue) values of a selected area on the image. These values show the degree of combination of these three primary colours, each varying between 0 and 255, where 0 represents the darkest black colour and 255 represents the brightest white colour. In order to quantitatively assess the colour changes of the stone samples, the background white paper is used as reference colour during the analysis. With the help of this software, the background brightness of all the images was adjusted, adjusting the red value at 200 as a reference point. Thereafter, these colour pictures were converted into greyscale images using Adobe Photoshop 6. The greyscale, like RGB, has a set of definition values, ranging from 0 to 255, as indicated in Figure 5.

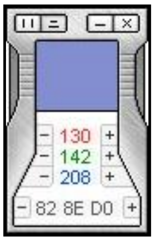


Figure 4. ColorPad

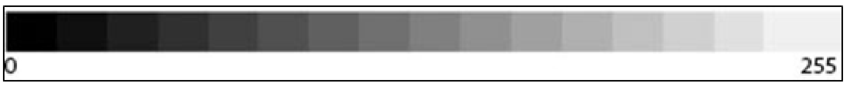
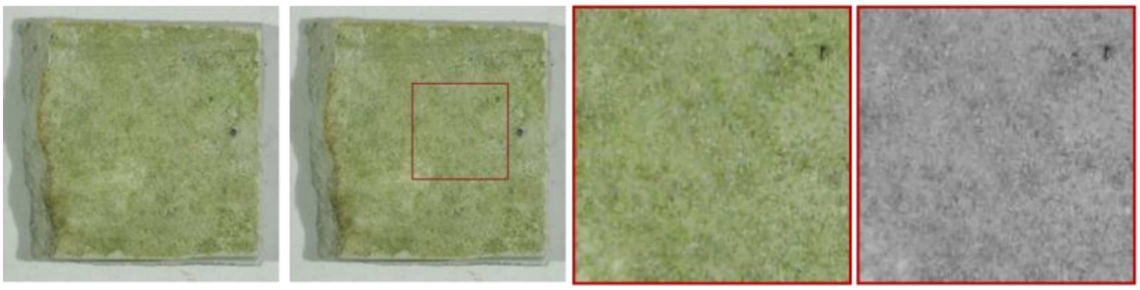


Figure 5. Greyscale spectrum

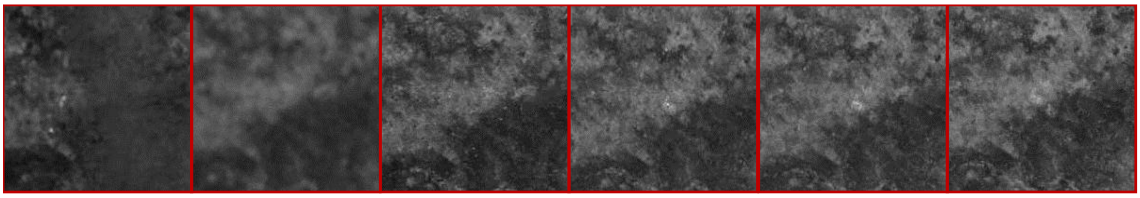
Since not all the samples had the same dimensions, their central areas of 2 cm × 2 cm were used for the greyscale imaging analysis. This standardisation of the area would allow all the images to be compared. There would be four separate steps next. The original images were scaled and orientated. An area inside was selected by drawing a red frame on the image, which was then cropped. Finally, the cropped area was converted into the greyscale image. Figure 6 shows a typical example of this procedure, which was then applied to all the images of 21 stone samples at different cleaning stages.

Figures 7 and 8 show the greyscale images of Granite and Limestone samples cleaned using fine glass and fine slag, at six cleaning stages, respectively. Figure 9 shows the greyscale images of Marble samples cleaned using fine glass, at twelve cleaning stages. The surface on the last image can be regarded as 100% clean. From each image the average greyscale value and standard deviation could be obtained using Adobe Photoshop 6. All three sets of greyscale images indicate that the stone surfaces became gradually brighter with the progress of cleaning.



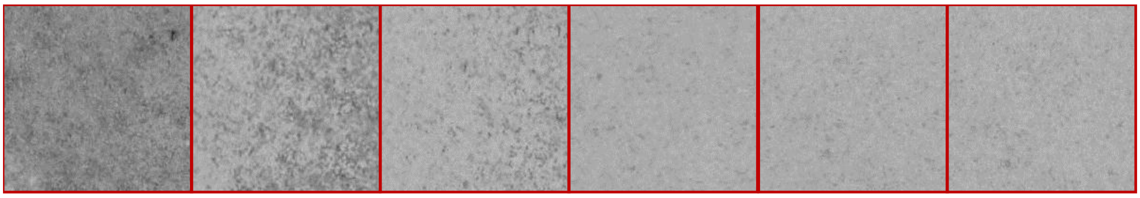
(a) Colour photo (b) Selected area (c) Selected area (d) Greyscale image

Figure 6. Four steps for processing the image photos for Limestone cleaned with fine slag



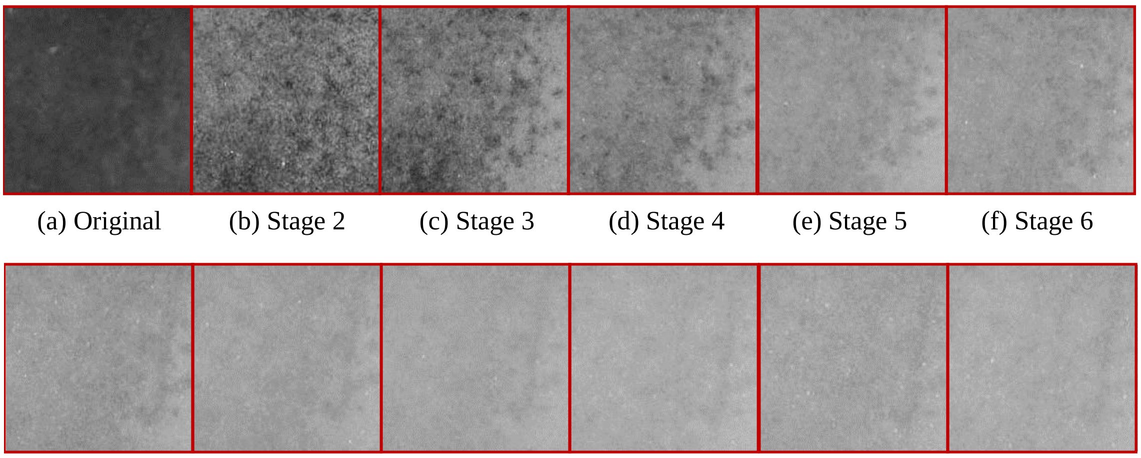
(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Cleaned

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



(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Cleaned

Figure 8. Greyscale images of Limestone cleaned with fine slag at cleaning stages 1 to 6



(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Stage 6

(g) Stage 7 (h) Stage 8 (i) Stage 9 (j) Stage 10 (k) Stage 11 (l) Cleaned

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

Figures 10 to 12 show the relationships between the greyscale GS and the cleaning *t* for the above mentioned three masonry stones. Figure 10 illustrates that a parabola could well reflect the increasing trend for greyscale with cleaning time for Granite cleaned with fine glass. The data and the parabola almost coincide since the R^2-value is equal to 0.964 which is very close to 1.0. Greyscale increased with the increasing cleaning time from GS = 54.83 before cleaning at a decreasing rate and became stable at GS = 79.24 when it was fully cleaned after 10 seconds, up by 24.41 in GS or 44.5%. It seems that only 6 seconds corresponding to GS = 76.80 might be enough to largely clean this sample. As the gap in greyscale values between the original dirty and fully cleaned states was quite big, this indicates that the surface of the original granite was very dirty. Figure 11 illustrates that a parabola could reflect the increasing trend of greyscale with cleaning time for Limestone cleaned with fine slag. The data and the parabola almost coincide since the R^2-value is equal to 0.965. Greyscale increased with the increasing cleaning time from GS = 134.85 before cleaning at a decreasing rate and finally became stable at GS = 171.99 when it was fully cleaned after 10 seconds, up by 37.14 in GS or 27.5%. It seems that only 4 seconds corresponding to GS = 168.86 might be enough for almost fully cleaning this sample. As the gap in greyscale values between the original dirty and fully cleaned states was not quite big, this indicates that the surface of the original granite was not very dirty. Figure 12 illustrates that a parabola can also reflect the increasing trend for greyscale with cleaning time for Marble cleaned with fine glass. The data and the parabola almost coincide with R^2 = 0.950. Greyscale increased with the increasing cleaning time from GS = 68.09 before cleaning at a decreasing rate and finally became stable at GS = 172.81 when it was fully cleaned after 25 seconds, up by 104.72 in GS or 153.8%. It seems that it would take about 18 seconds, corresponding to GS = 171.85, to almost fully clean this sample. As the gap in greyscale values between the original dirty and fully cleaned states was huge, this indicates that the surface of the original marble was extremely dirty. The greyscale values at the final fully cleaned state indicate that both Limestone and Marble were almost the same bright but Granite was very dark. Based on the times spent on full cleaning, it can also be seen that the soiling on Marble was toughest to be removed, compared with that on Granite and Limestone.

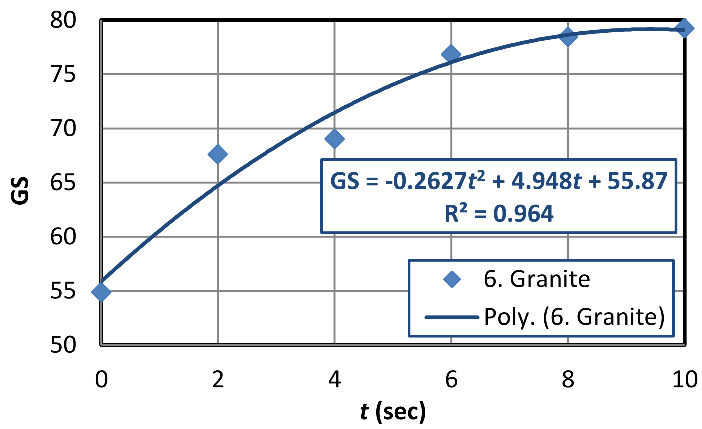


Figure 10. Greyscale versus cleaning time for Granite cleaned with fine glass

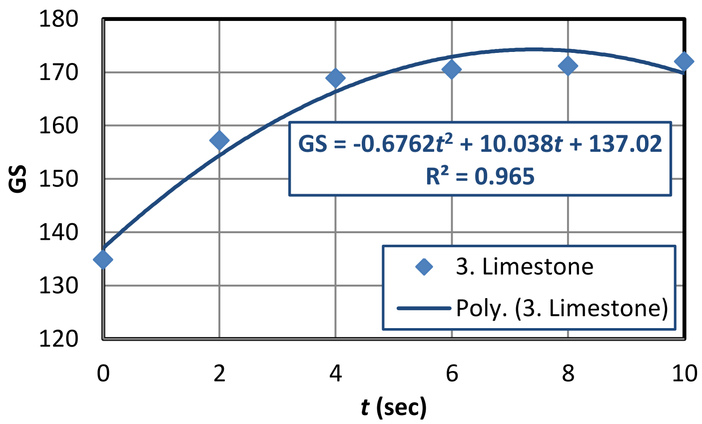


Figure 11. Greyscale versus cleaning time for Limestone cleaned with fine slag

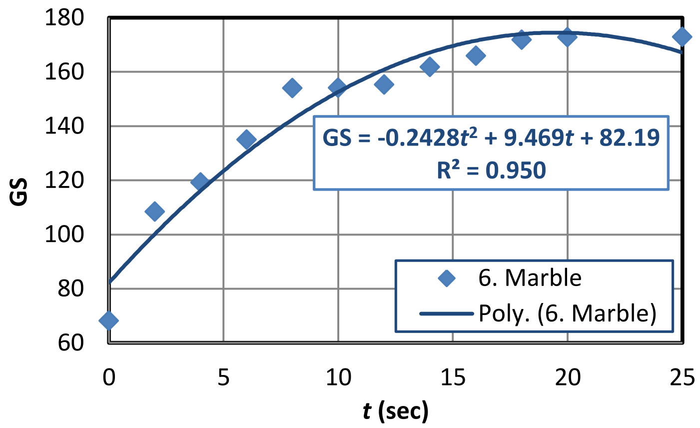


Figure 12. Greyscale versus cleaning time for Marble cleaned with fine glass

Table 3 lists the total cleaning time t_{tot}, initial greyscale GS_{ini}, final greyscale GS_{fin} and change in greyscale ΔGS for Granite, Limestone and Marble cleaned using seven different abrasives. The initial greyscale values varied largely for each type of stone because the soiling states on stone surfaces were different.

Table 3. Summary of greyscale results before and after cleaning.

Stone	Abrasive	t_{tot} (sec)	GS_{ini}	GS_{fin}	ΔGS
Granite	Coarse slag	10	67.54	73.54	6.00
	Medium slag	10	53.14	60.84	7.70
	Fine slag	10	49.05	62.08	13.03
	Coarse glass	50	62.68	86.83	24.15
	Medium glass	10	70.98	89.59	18.61
	Fine glass	10	54.83	79.24	24.41
	Natural	50	63.03	74.46	11.43
	Average	/	60.18	75.23	15.05
Limestone	Coarse slag	30	96.11	171.65	75.54
	Medium slag	12	112.26	166.36	54.10
	Fine slag	10	134.85	171.99	37.14
	Coarse glass	140	117.79	176.83	59.04
	Medium glass	14	116.18	165.11	48.93
	Fine glass	10	74.94	160.53	85.59
	Natural	140	124.95	151.59	26.64
	Average	/	111.01	166.29	55.28
Marble	Coarse slag	45	61.32	166.94	105.62
	Medium slag	50	56.2	159.29	103.09
	Fine slag	35	83.18	172.33	89.15
	Coarse glass	300*	54.11	175.83	121.72
	Medium glass	25	79.85	170.31	90.46
	Fine glass	25	68.09	172.81	104.72
	Natural	900*	87.38	158.37	70.99
	Average	/	70.02	167.98	97.96

* Abrasives were not suitable.

4 DISCUSSION

From Figure 3, the original colours for the same type of stone were different because biological crust non-uniformly deposited on the stone surfaces. For example, the limestone sample to be cleaned with fine slag was much brighter (GS = 134.85) than the limestone sample to be cleaned with fine glass (GS = 74.94). However, the greyscale values for each type of stone at the final cleaning stage were fairly similar for the majority of the samples. Typically, the final greyscale values for the Granite samples varied from 60.84 to 89.59, with an average of 75.23 and a standard deviation of 11.11. The final greyscale values for the Limestone samples varied from 151.59 to 176.83, with an average of 166.29 and a standard deviation of 8.40. The final greyscale values for the Marble samples varied from 158.37 to 175.83, with an average of 167.98 and a standard deviation of 6.81. The final greyscale values for Limestone and Marble were very close, 166.29 versus 167.98. However, the initial greyscale values and the changes in greyscale were largely different, 111.01 and 55.28 for Limestone and 70.02 and 97.96 for Marble, which confirms the original surface of Marble was much dirtier than that of Limestone.

The greyscale values obtained by using a natural abrasive were largely affected by the nature of this abrasive. Natural abrasive is a very soft material, and is composed of coconut and almond shells. After impacting on stone surfaces it easily turns into dust. This impact would leave the stone surfaces lightly smudged with a brownish colour. As a result of this, the greyscale values measured were different from those on the samples, e.g. Limestone and Marble, cleaned with other abrasives. This may not be true for Granite because its original colour was very dark.

By observing the statistical analysis on the greyscale results for the granite samples, it is clear that all the R^2 values were larger than 0.93 and some were very close to 1.0. Therefore, the parabolic relationships between greyscale and cleaning time may well predict the varying trends. However, the final greyscale values were not very similar. This could be due to the fact that the surface of the granite samples was polished. Hence, it is suggested that the most suitable cleaning method for polished stone surfaces may be a manual cleaning, e.g. using a sponge or a brush and washing-up liquid, instead of air abrasive cleaning. Nevertheless, samples cleaned with three recycled glasses of different sizes produced similar final greyscale values, with the differences in greyscale between the initial and final cleaning stages ranging from 18 to 25.

Finally, Table 3 also confirms the suitability of abrasive types for masonry stones. As the time required to fully clean each stone sample is an important practical consideration due to resultant labour costs, any abrasive material that took more than 210 seconds to clean a stone sample will not be considered being suitable for that stone since it could not produce a desirable performance. It can be seen that all seven abrasives are suitable for Granite and Limestone, compared with Marble for which only five abrasives were suitable. Furthermore, for Granite, all three slags, medium glass and fine glass were more economical. For Limestone, medium/fine slag and glass showed better performance. For Marble, medium and fine glass may be good options but surely coarse glass and natural abrasive are not suitable choices.

5 CONCLUSIONS

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

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

From the results for granite, limestone and marble presented here, the cleaning degrees at different stages were evaluated using the greyscale images converted from the original colour photos, where a lower greyscale was related to a dirtier surface and a higher greyscale to a brighter and cleaner surface. Relationships between cleaning degree (greyscale) and cleaning time were illustrated. In general, greyscale continuously increased with the increasing cleaning time and tended to be stable when the surface became fully cleaned. Any abrasives with longer cleaning times for the same cleaning degree on one type of masonry stone would be regarded to be less suitable for that type of stone. The abrasives with a better performance were those industrial by-products with smaller particles sizes, i.e. medium/fine slag and recycled glass, because the coarse abrasives and natural abrasive would consume more cleaning times.

REFERENCES

Ashurst, N. 1994a. *Cleaning Historic Buildings: Substrates Soiling and Investigation*, *Vol.1*. London: Donhead.

Ashurst, N. 1994b. *Cleaning Historic Buildings: Substrates Soiling and Investigation*, *Vol.2*. London: Donhead.

Ball, J., Laing, R.A. & Young, M.E. 2000. Stonecleaning: comparing perceptions with physical and financial implications. *Journal of Architectural Conservation* 6(2): 47-62.

Chandan, C., Sivakumar, K., Masad, E. & Fletcher, T. 2004. Application of imaging techniques to geometry analysis of aggregate particles. *Journal of Computing in Civil Engineering* 18(1): 75-82. ASCE.

CRD. 1980. *Method of Calculation of the Fineness Modulus of Aggregate*, *No.1*. http://www.wbdg.org/ccb/ARMYCOE/COESTDS/crd_c104.pdf. Accessed in February 2013.

Feilden, B.M. 2003. *Conservation of Historic Buildings* (3rd Ed). Oxford: Architectural Press.

Ghanta, S., Birken, R. & Dy, J. 2012. Automatic road surface defect detection from grayscale images. *Proc. SPIE 8347, Nondestructive Characterization for Composite Materials*, *Aerospace Engineering, Civil Infrastructure, and Homeland Security 2012*, San Diego, California.

Kuo, C.-Y. & Freeman, R.B. 1998. Image analysis evaluation of aggregates for asphalt concrete mixtures. *Transportation Research Record* 1615: 65-71. Washington DC: Transportation Research Board.

Laing, R.A. & Urquhart, D.C.M. 1997. Stone cleaning and its effect on property market selling price. *Journal of Property Research* 14: 329-336.

MPA (n.d.) *Granalla Vegetal Aval*, http://www.mpa.es/3023/v3_00ver_productos.php?params=b3023a1097a1923a0310900. Accessed in February 2013.

Rao, C. & Tutumluer, E. 2000. A new image analysis approach for determination of volume of aggregates. *Transportation Research Record* 1721: 73-80. Washington DC: Transportation Research Board.

Reza, H., Khalaf, F. & Fairfield, C.A. 2008. Conservation and repair of historical buildings. *Proc. 8th Int. Sem. Struct. Masonry*: 541-575. Istanbul, Turkey.

Reza, H., Zhang, B. & Gupta, N. 2012. Physical and chemical characteristics of masonry stones during building cleaning. *International Conference on Structural Faults and Repairs 2012*. Edinburgh, Scotland.

Reza, H. 2014. *Cleaning and Restoring Old Masonry Buildings — Investigations of Physical and Chemical Characteristics of Masonry Stones and Clay Bricks during Cleaning*, *PhD Thesis*. Edinburgh Napier University, Edinburgh, UK.

SCANGRIT. 2004. *Glassia Technical Data Sheet*. http://www.scangrit.co.uk/?page_id=73. Accessed in February 2013.

SCANGRIT. 2010. *Iron Silicate Technical Data Sheet*. http://www.scangrit.co.uk/wp-content/uploads/2011/03/Iron-Silicate-Safety-Data-April-2010.pdf. Accessed in February 2013.

Treash, K. & Amaratunga, K. 2000. Automatic road detection in grayscale aerial images. *Journal of Computing in Civil Engineering* 14(1); 60-69. ASCE.

Young, M.E., Ball, J., Laing, R., Cordiner, P. & Hulls, J. 2003. *The Consequences of Past Stonecleaning Intervention on Future Policy and Resources*. Edinburgh: Historical Scotland.

Zhang, B., Reza, H., Gu, S. & Gupta, G. 2014. Investigations of physical and chemical characteristics of masonry stones and bricks during building cleaning — Part 1 Physical testing. *Journal of Physical Science and Applications* (in press).