EVALUATION OF EFFICIENCY OF AIR ABRASIVE CLEANING ON OLD MASONRY BUILDINGS USING GREYSCALE IMAGING ANALYSIS

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KEYWORDS: Historic building, Masonry stone, Abrasive, Air abrasive cleaning, Greyscale, Cleanness.

ABSTRACT

The stone cleaning and restoration of historic buildings is a crucial strategy for maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations. In this study, advanced greyscale imaging analysis was conducted using Adobe Photoshop 6 on the surfaces of masonry stones, taken from old buildings, to accurately assess the efficiency of building cleaning. Five commonly used masonry stones for those buildings were selected, including granite, limestone, marble, yellow sandstone and red sandstone. Seven abrasives were adopted for air abrasive (sandblasting) cleaning, including steel plant by-product slag (coarse, medium and fine), recycled glass (coarse, medium and fine) and natural abrasive. Also the reductions in thickness were also monitored for assessing the cleaning efficiency. The cleaning degrees at different stages were evaluated using greyscale image photos, converted from original colour ones, together with reductions in thickness, where a lower greyscale value normally corresponded to a darker and dirtier surface and a higher greyscale value to a brighter and cleaner surface. In general, greyscale continuously increased with the cleaning time and tended to be stable when the surface became fully cleaned. Thickness reduction monotonically increased with the cleaning time, which could also be used to assess the cleaning efficiency in combination the cleaning time. The most efficient building cleaning case would be the one with the shortest cleaning time and smallest thickness reduction. The harder abrasives with smaller particles sizes were confirmed to be more effective, e.g. the medium or fine slag and glass in this study.

INTRODUCTION

Historic buildings which were normally built up with masonry stones are precious finite assets and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The cleaning and restoration of these historic buildings is a crucial strategy in maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations. Stone cleaning is one of the most noticeable changes a building can be subjected to. Stone cleaning has been dated back for over 40 years, peaking in the 1970s and 80s and growing into a multimillion pound industry (Laing & Urquhart, 1997; Ball et al, 2000; Ball, 2002; Feilden, 2003). At the time, the cleaning was inappropriately aggressive, causing damage to many building façades (Andrew et al, 1994; Ashurst, 1994a, 1994b; Verhoef, 1988; Young, 2002). Inappropriately selected methods of cleaning or right methods performed by unskilled operatives can lead to permanent damage to building façades. Fig. 1 shows a historic building in Edinburgh with original dirty and cleaned stonework façades.

In Scotland, natural masonry stones bricks as building materials were widely used in the built heritage, which hence led to large demands of stone cleaning (Webster et al, 1992; Young & MacLean, 1992; McMillan, 1999; Hyslop et al, 2006). In the 1960s, the cleaning of masonry buildings for aesthetic, commercial and sociological reasons became quite common. Transforming the black-soiled limestone building into a clean and bright structure became a kind of fashion, which was started in Paris and London and followed by many other places. When it turned to sandstone, however, more aggressive cleaning methods were required in order to remove the grime as the atmospheric pollutants attached to the surfaces of sandstone are quite different from those on the limestone surfaces. These excessively aggressive methods led to great damages to the stone surfaces, removing soiling as well as the stone surface, even the sharpness of building details. In the 1970s and 80s, the chemical method of stone cleaning was utilised, reducing the damage to the stone surface from abrasive cleaning method, and stone cleaning reached its peaks. However at that time, various cleaning methods still caused permanent damage to a building. As time goes by, people have now paid more attention to this and many studies on stone cleaning have been published (Verhoef, 1988; Urquhart, 1994; Cameron et al, 1997; Pryke, 1999, 2000; Murray et al, 2000; Brimblecombe, 2003; Young et al, 2003; Khalaf et al, 2008). Cleaning methods nowadays have become more finely tuned and less aggressive because new legislations have protected listed historic buildings and conservation areas from any detrimental treatments (Mynors, 1989, 2006).

(a) Original dirty stonework façade

(b) Fully cleaned stonework façade

Fig. 1 A listed building in Edinburgh with original dirty and cleaned stonework.

There are four major types of cleaning methods: water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting). Water-based cleaning methods are not effective on sandstones, bricks or terracotta for removing soiling bound to these surfaces by insoluble compounds. Water cleaning can only remove algae but severe soiling may still be present (see Fig. 2). Using water washing techniques on masonry surfaces with high natural salts, such as sandstone and brick, can mobilise the salts and lead to efflorescence. Desalination of such surfaces after cleaning has, in rare cases, been carried out by water saturation followed by drying. Much research has been done on this aspect and useful methods have been proposed, e.g. poulticing technique (Verges-Belmin & Siedel, 2005; Petkovic et al, 2007; Lubelli & van Hees, 2010; Pel et al, 2010). Chemical cleaning methods are more effective because they work by the reaction between the cleaning agent, soiling and the masonry surface to which the soiling is attached (Pombo & Nicholson, 1998; Young, 1998; Young & Urquhart, 1998). The main problems with using chemical cleaning involve the extent and efforts of the retention of chemical agents and the possible mobilisation of salts within the stone. Another problem associated with chemical cleaning is the bleaching or staining of surfaces (see Figs. 3 and 4). Because chemical cleaning damage is irreversible, it should only be used with extensive pre-testing to ensure confidently that there will be no damage to the building façade. Mechanical cleaning removes soiling from the stone surface by physical forces, cutting or abrasion through hand-held implements or mechanised equipment. Abrasives can permanently damage the masonry as they do not differentiate between the dirt and the masonry stone. Brick, architectural terracotta, soft stone, detailed carvings and polished surfaces are especially susceptible to physical and aesthetic damage by abrasive methods. Increase in surface roughening is another consequence of mechanical cleaning. The most commonly used mechanical cleaning methods include dry brushing and surface rubbing, surface addressing, etc.

(a) Before cleaning: algae and severe soiling on the external wall

(b) After cleaning: algae removed but severe soiling still present

Fig. 2 A typical masonry stone wall before and after cleaning.

(a) On the upper storey external wall

(b) On the lower storey external wall

Fig. 3 Damages caused by chemical cleaning on the masonry stone walls.

Air abrasive cleaning (sandblasting) involves a stream of compressed air directing particles of abrasive materials onto the soiled masonry surfaces. Here, cleaning is accomplished by these particles dislodging the surface layer and the dirt adhering to it. The dislodging of the dirt deposits thus takes place by the breaking up, sometimes to a depth of several millimetres, the surface layer beneath the deposits. Both dry and wet blasting methods have similar effects on clean masonry façades. The abrasive cleaning does not differentiate between removing soiling and masonry, so the effect of jetting the abrasive material is controlled by the operator. When wrongly applied, it could have a long lasting damaging effect on the building façade. It is very time-consuming and expensive to use on historic masonry buildings. It is desirable for heavy soiling as long as it does not cause harm to the fragile and friable fabric of the building. Abrasive cleaning is a quick method and is therefore usually considered for large areas of metals or masonries which have few design features. The most commonly used system is the air pressure blast equipment. Typical nozzle pressures range from 0.02 kPa to 14.0 kPa. Compressed air is fed to a pressure pot containing the abrasive and the mixture travels along a hose to a blasting gun. An alternative system to the pressure pot is the venture system „suction gun". This is operated by a trigger which is easily controlled by an instant response to the operator requirement. Figs. 5 and 6 illustrate the balcony and wall around the windows of a listed sandstone building in Edinburgh before and after air abrasive cleaning with slag.

(a)

(b)

(c)

(d)

Fig. 4 Damages caused by chemical cleaning on the masonry stone surfaces.

(a)

(b)

Fig. 5 Masonry stone balcony before and after air abrasive cleaning with slag.

(a) (b)

Fig. 6 Masonry stone wall around the windows before and after air abrasive cleaning with slag.

Stone cleaning always has negative effects which are beyond the removal of superficial soiling. When carried out using inappropriate methods, aggressive cleaning can largely damage masonry stones. Many of the potential effects of inappropriate cleaning will be visible immediately or within a few weeks of cleaning. However, there may be longer-term consequences with respect to the aesthetic, functional and structural integrity of the stone. So far there are no consistent standards and parameters used for assessing the degree of building cleaning, and the efficiency of various cleaning methods is largely evaluated by visual inspections and mutual agreements. There is an urgent need to search for better physical parameters for such assessments. Previous investigations were largely focused on finding the substances of the soiling on the building façade and the methods to remove these substances. The information on the chemical compositions of the soiling and their changes during masonry cleaning is still limited. Meanwhile there is a lack of systematic monitoring and assessment on the changes in the physical and chemical characteristics of masonry stones during cleaning process even though such knowledge is significantly important for understanding and improving the efficiency of building cleaning. Greyscale imaging analysis can be used for such purpose, together with the monitoring the reduction in thickness during the cleaning.

To investigate the cleaning degrees of the stone surfaces, a digital imaging analysis method, greyscale imaging analysis, was used. The mechanism of this method is to determine the grey degree of greyscale digital images converted from normal colour photos for assessing the building cleaning effectiveness. This technique has been largely used in civil engineering fields, e.g. geotechnical analysis of aggregate particles (Kuo & Freeman, 1998; Rao & Tutumluer, 2000; Chandan et al, 2004), automatic road surface detection (Treash & Amaratunga, 2000; Ghanta et al, 2012), etc. Recently, applications of imaging analysis into assessing building cleaning have been reported (Thornbush & Viles, 2004; Kapsalas et al, 2007; Papadakis et al, 2010). The authors have tried to conduct preliminary digital imaging analysis using ColorPad by adopting two physical parameters (greyscale and cleanness) to quantitatively assess the effectiveness of stone cleaning and confirmed that it is a useful and accurate method (Reza et al, 2012; Reza 2014). However, collecting data by using ColorPad is very time consuming because it could only read the greyscale values point by point.

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

PREPARATION OF MASONRY STONE EXAMPLES

(1) Stone Samples

All five types of masonry stones were selected from those used for masonry buildings and exposed to open environmental conditions for decades with large amounts of heavy soiling and decay existing on the façades. The samples were cut into the dimensions of 50 mm × 50 mm × 25 mm from the original masonry stones and bricks using a diamond saw (see Fig. 7). The exposed surfaces of the stone samples were then cleaned to different levels with each abrasive in turn. Here an abrasive cleaning system selected included an air compressor, shot blasting cabinet and nozzle (see Fig. 8). Fig. 9 shows all five types of masonry stone samples used for greyscale imaging analysis at different cleaning stages.

Fig. 7 Cutting samples from original stones

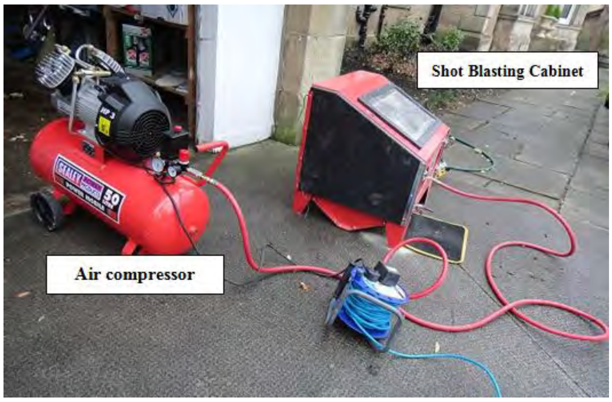
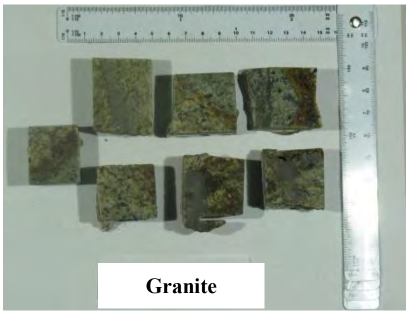
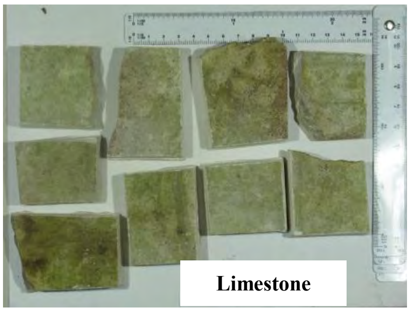


Fig. 8 The abrasive cleaning system



(a) Granite



(b) Limestone

(c) Marble

(d) Yellow sandstone

(e) Red sandstone

Fig. 9 Masonry stone samples for greyscale imaging analysis

(2) Abrasives for Air Abrasive (Sandblasting) Cleaning

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

Table 1 Abrasives used for sandblasting cleaning.

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

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

From the sieve tests, the fineness moduli (FM_{pre}) of all seven abrasives were obtained (CRD, 1980; Neville, 1995) and are also listed in Table 2, which shows that coarse recycled glass is the coarsest with FM = 6.37, natural abrasive is the finest with FM = 3.97, and the rest lie in-between with FM = 4.39 to 5.98. Slag abrasives are the heaviest and toughest and are followed by glass abrasives, with natural abrasive being the lightest and softest. Impact tests were also conducted on all seven abrasives (BSI, 2012), and the corresponding FM values (FM_{post}) were measured and listed in Table 2. In general, all FM values decreased after the impact tests due to finer particles produced during the tests. Natural abrasive sustained the largest drop in FM, followed by recycled glass abrasives; while slag abrasive sustained the least drop. This confirms that natural abrasive was the softest and slag abrasives were the hardest, with glass abrasives in-between. Fig. 10 illustrates the sieve test results, percentage passing rate versus sieve size, before the impact tests for all seven abrasives. Coarse glass was the coarsest abrasive, followed by medium glass and coarse slag, while natural abrasive was the finest abrasive, followed by fine glass and fine slag, with the rest in-between, the same as assessed using the fineness modulus.

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

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

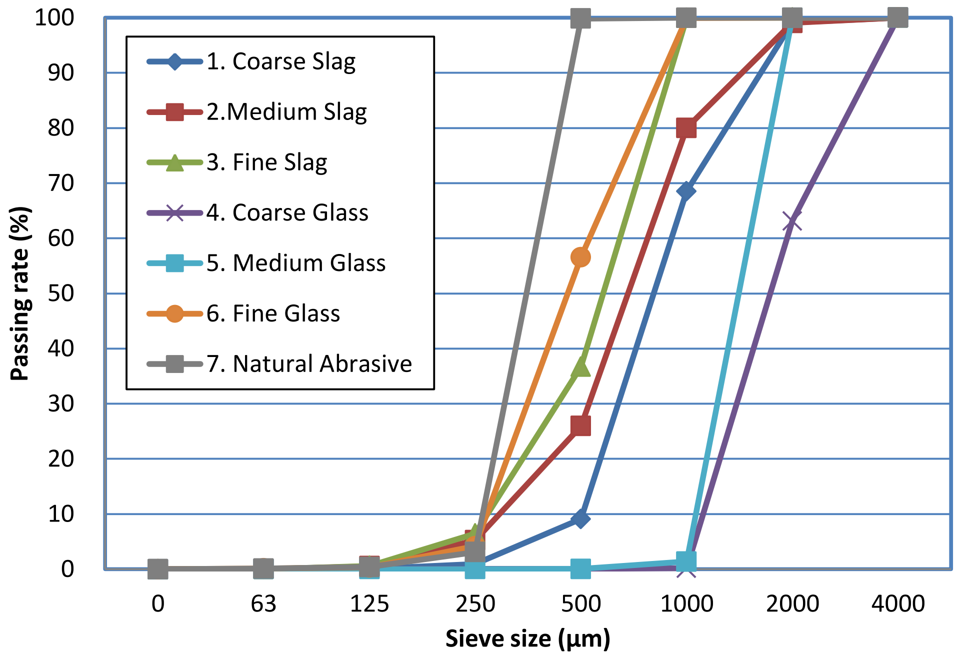


Fig. 10 Sieve test results before the impact tests for all abrasives.

DIGITAL GREYSCALE IMAGING ANALYSIS

In the preliminary digital greyscale imaging analysis (Zhang et al, 2014), all the photos were taken indoors under consistent illuminating conditions. However, during this analysis a problem was found. Because the environmental conditions during cleaning were inconsistent, inside a workshop but with the entrance door open, the images did not give unique levels of brightness. Although a frame was specially built to create constant luminosity conditions, the cleaning was conducted in the workshop lit by daylight, which affected the luminosity intensity of the images when they were taken, and also caused heterogeneous brightness. In order to solve this problem, firstly, all the images were treated using the software ColorPad (Fig. 11). This software identifies the RGB (red, green and blue) values of a selected area on the image. These values show the degree of combination of these three primary colours, each varying between 0 and 255, where 0 represents the darkest black colour and 255 represents the brightest white colour.

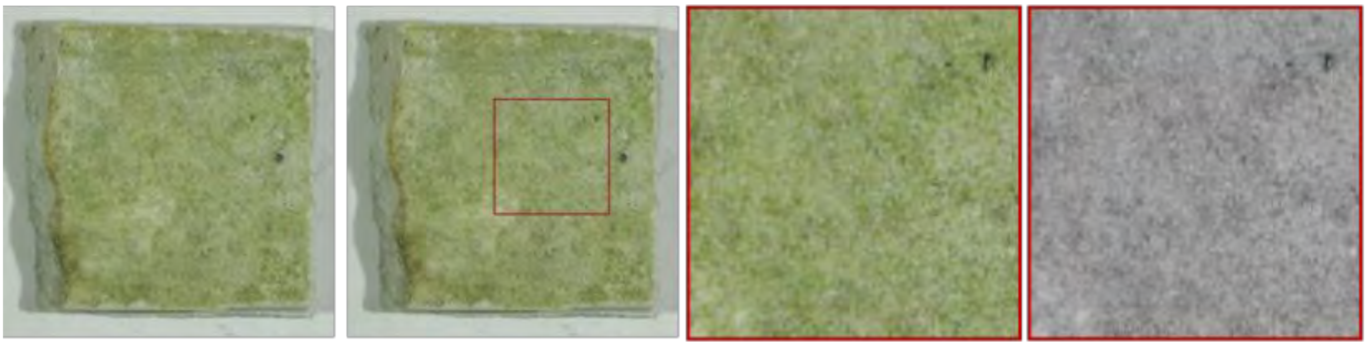
In order to quantitatively assess the colour changes of the stone samples, the background white paper is used as reference colour during the analysis. With the help of this software, the background brightness of all the images was adjusted, adjusting the red value at 200 as a reference point. Thereafter, these colour pictures were converted into greyscale images using Adobe Photoshop 6. The greyscale, like RGB, has a set of definition values, ranging from 0 to 255, as indicated in Fig. 12.

Since not all the samples had the same dimensions, their central areas of 2 cm × 2 cm were used for the greyscale imaging analysis. This standardisation of the area would allow all the images to be compared.

There would be four separate steps next. The original images were scaled and orientated. An area inside was selected by drawing a red frame on the image, which was then cropped. Finally, the cropped area was converted into the greyscale image. Fig. 13 shows a typical example of this procedure, which was then applied to all the images of 35 stone samples at different cleaning stages.

Fig. 11 ColorPad

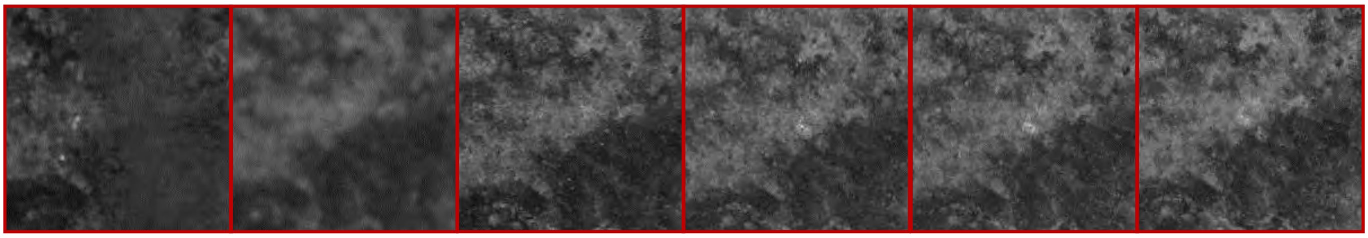
Fig. 12 Greyscale spectrum



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

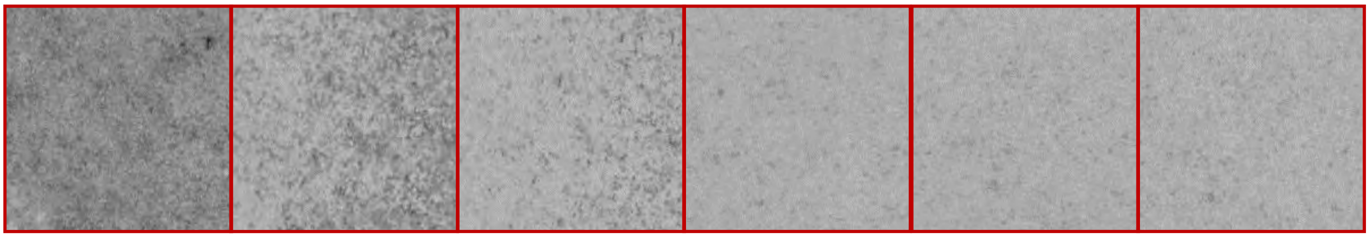
Fig. 13 Four steps for processing the image photos for limestone cleaned with fine slag.

Figs. 14 to 18 show the greyscale images of all masonry stone samples cleaned with either slag or glass abrasives at different cleaning stages, respectively. In these greyscale image photos, the first images show the original dirty surfaces and the last images show the fully cleaned surfaces. From each image the average greyscale value and standard deviation were obtained using Adobe Photoshop 6. All five sets of greyscale images indicate that the stone surfaces became gradually brighter with the progress of cleaning.



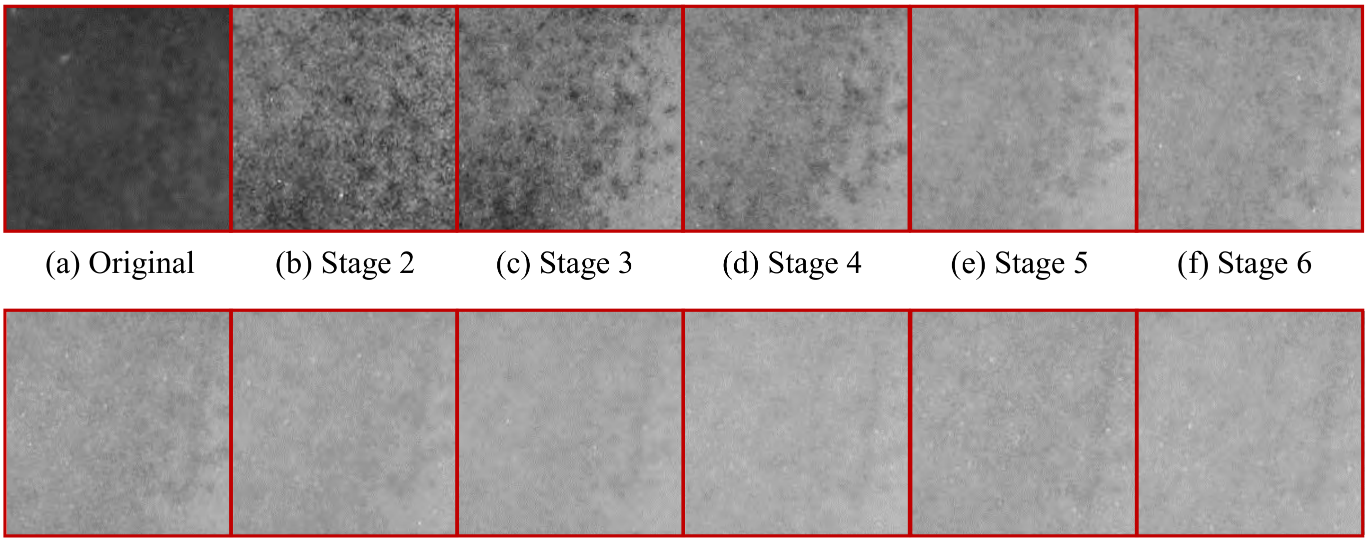
(a) Original (b) Stage 2 (c) Stage 3 (d) Stage 4 (e) Stage 5 (f) Cleaned

Fig. 14 Greyscale images of granite cleaned with fine glass at cleaning stages 1 to 6.



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

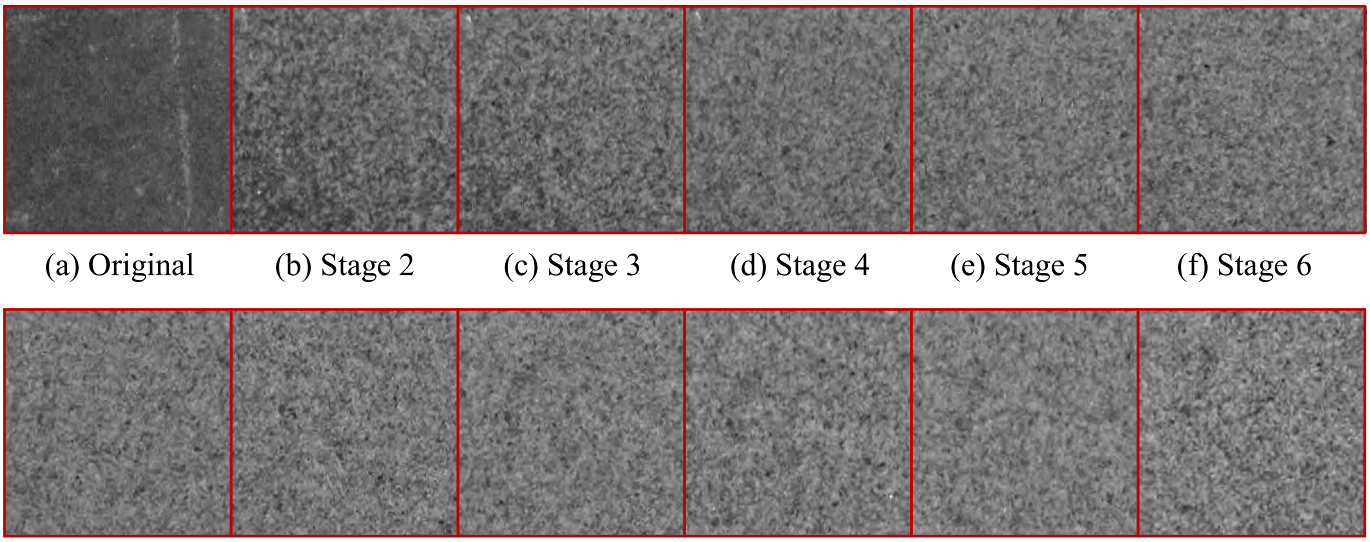
Fig. 15 Greyscale images of limestone cleaned with fine slag at cleaning stages 1 to 6.



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

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

Fig. 16 Greyscale images of marble cleaned with fine glass at cleaning stages 1 to 12.



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

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

Fig. 17 Greyscale images of yellow sandstone cleaned with coarse slag at cleaning stages 1 to 12.

Figs. 19 to 23 show the relationships between the greyscale GS and the cleaning time t for the above mentioned five types of masonry stones. Fig. 19 illustrates that a parabola well reflects the increasing trend of greyscale with the cleaning time for granite cleaned with fine glass. The data and the parabola almost coincide since the R^2-value is equal to 0.964 which is very close to 1.0. Greyscale increased with the cleaning time from GS = 54.83 before cleaning at a decreasing rate and became stable at GS = 79.24 when the sample was fully cleaned after 10 seconds, up by 24.41 in GS or 44.5%. It seems that only 6 seconds corresponding to GS = 76.80 may be enough to largely clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was quite big, which indicates that the surface of the original granite was very dirty. Fig. 20 shows that a parabola can represent the increasing trend of greyscale with the cleaning time for limestone cleaned with fine slag. The data and the parabola almost coincide with R^2 = 0.965. Greyscale increased with the cleaning time from GS = 134.85 before cleaning at a decreasing rate and finally became stable at GS = 171.99 when the sample was fully cleaned after 10 seconds, up by 37.14 in GS or 27.5%. It seems that only 4 seconds corresponding to GS = 168.86 may be enough for almost fully cleaning this sample. The gap in greyscale values between the original dirty and fully cleaned states was not quite big, which indicates that the surface of the original granite was not very dirty.

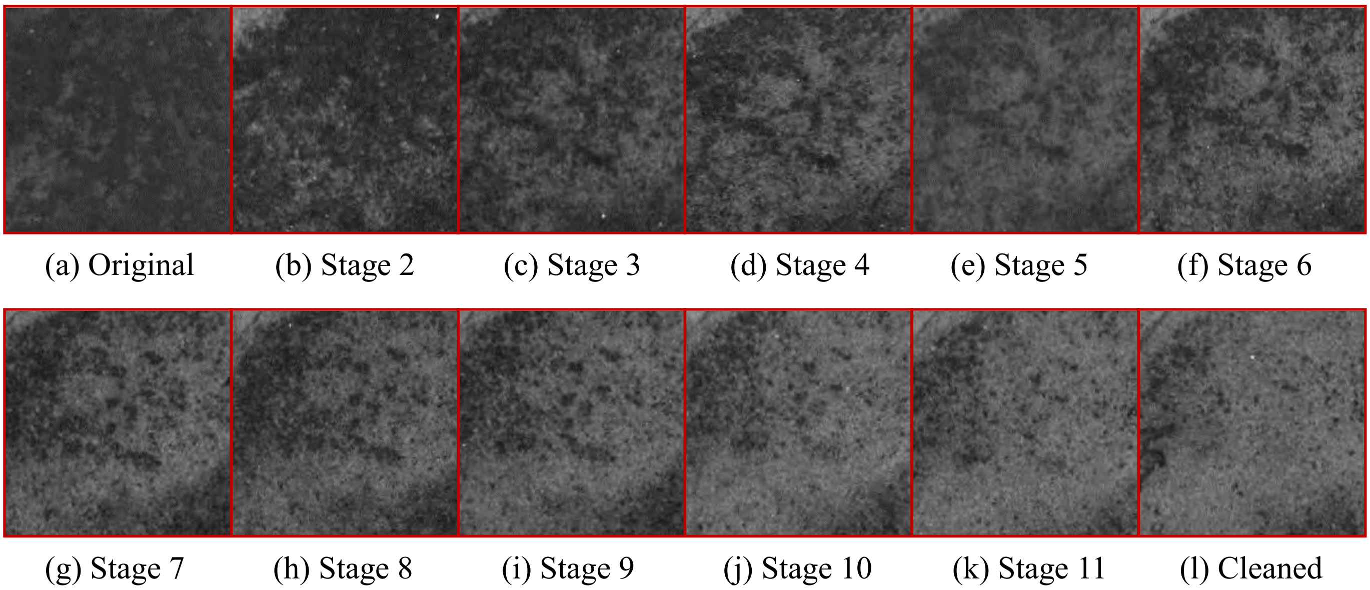


Fig. 18 Greyscale images of red sandstone cleaned with fine glass at cleaning stages 1 to 12.

Fig. 21 shows that a parabola well reflects the increasing trend of greyscale with the cleaning time for marble cleaned with fine glass. The data and the parabola almost coincide with R^2 = 0.950. Greyscale increased with the cleaning time from GS = 68.09 before cleaning at a decreasing rate and finally became stable at GS = 172.81 when the sample was fully cleaned after 25 seconds, up by 104.72 in GS or 153.8%. It seems that it would take about 18 seconds, corresponding to GS = 171.85, to almost fully clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was huge, indicating that the surface of the original marble was extremely dirty. Fig. 22 illustrates that a parabola can represent the increasing trend of greyscale with the cleaning time for yellow sandstone cleaned with coarse slag, with R^2 = 0.827. Greyscale increased with the cleaning time from GS = 81.14 before cleaning at a decreasing rate and finally became stable at GS = 124.51 when the sample was fully cleaned after 180 seconds, up by 43.37 in GS or 53.5%. It seems that it would take about 100 seconds, corresponding to GS = 120.23, to almost fully clean this sample. The gap in greyscale values between the original dirty and fully cleaned states was reasonably large, which indicates that the surface of the original yellow sandstone was quite dirty. Finally, Fig. 23 shows that a parabola well matches the increasing trend of greyscale with the cleaning time for red sandstone cleaned with fine glass. The data and the parabola almost coincide with R^2 = 0.959. Greyscale increased with the cleaning time from GS = 58.56 before cleaning at a decreasing rate and finally became stable at GS = 93.84 when the sample was fully cleaned after 80 seconds, up by 35.28 or 60.2%. It seems that 50 seconds, corresponding to GS = 90.94, may be enough for almost fully cleaning this sample. The gap in greyscale values between the original dirty and fully cleaned states was huge, indicating that the surface of the original red sandstone was very dirty.

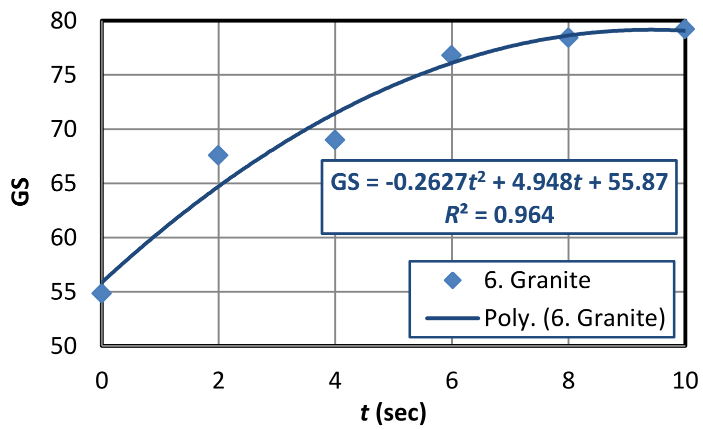


Fig. 19 Greyscale versus cleaning time for granite cleaned with fine glass.

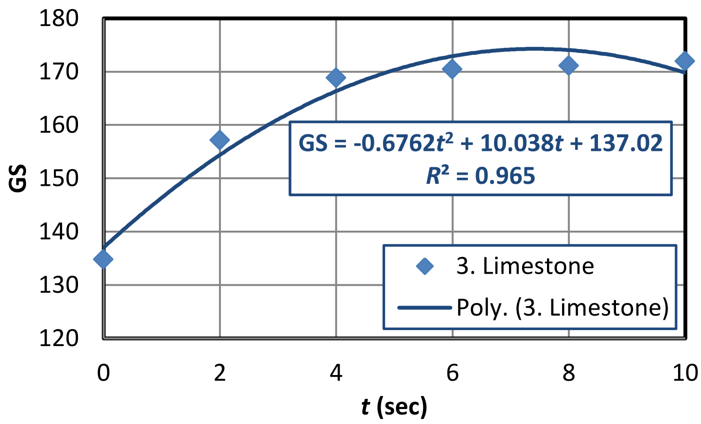


Fig. 20 Greyscale versus cleaning time for limestone cleaned with fine slag

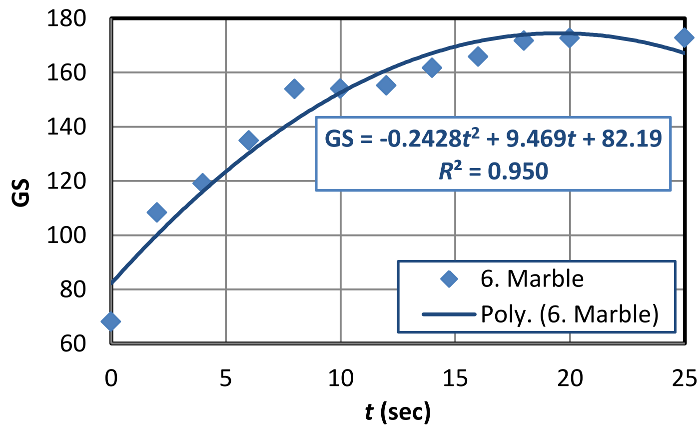


Fig. 21 Greyscale versus cleaning time for marble cleaned with fine glass.

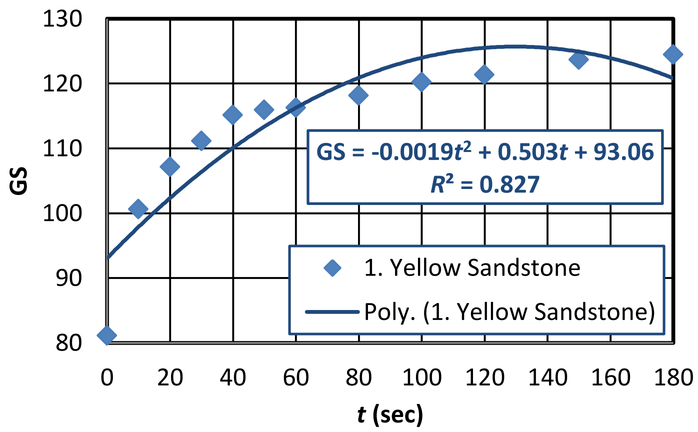


Fig. 22 Greyscale versus cleaning time for yellow sandstone cleaned with coarse slag.

Table 3 lists the total cleaning time t_{tot}, initial greyscale GS_{ini}, final greyscale GS_{fin}, change in greyscale ΔGS and total thickness deduction Δa for all types of masonry stones cleaned with seven different abrasives. The average values of the listed parameters except the total cleaning time, together with the corresponding standard deviations, are also listed in Table 3. For each type of stone, the initial greyscale values which represent the original dirty degree varied largely because the soiling states on the surfaces of the stone samples were different. For example, the greyscale for granite varied from 49.05 to 70.98, with an average of 60.18 and a standard deviation of 8.03, giving a smallest variation coefficient of 13.35%. On contrast, the greyscale for yellow sandstone varied from 53.50 to 97.12, with an average of 69.17 and a standard variation of 18.85, giving a largest variation coefficient of 27.25%. The variations in the original greyscale values for the rest stones lay in-between.

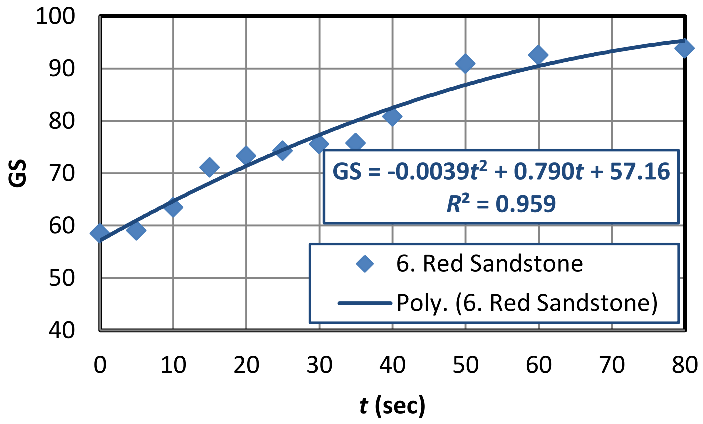


Fig. 23 Greyscale versus cleaning time for red sandstone cleaned with fine glass.

According to the final greyscale values from small to large, the original colours of the five masonry stones can be ranked, from dark to bright, as granite (GS = 75.23), red sandstone (GS = 95.46), yellow sandstone (GS = 115.64), limestone (GS = 166.29) and marble (GS = 167.98). This also indicates both marble and limestone were the brightest while the marble was the darkest, with the rest stones in-between. According to the percentage ratios of the greyscale changes to the final greyscale values, the dirty degrees of the five masonry stones can be ranked, from dirty to bright, as marble (58.32%), red sandstone (43.53%), yellow sandstone (40.19%), limestone (33.24%) and granite (20.01%). This indicates that the original marble had the dirtiest surface, followed by the red sandstone, yellow sandstone and limestone, while the original granite had the relatively cleanest surface. The final thickness reductions indicate that granite had a smallest average thickness loss of only 0.23 mm during the cleaning process, followed by limestone (Δa = 0.37 mm), marble (Δa = 0.49 mm), and yellow sandstone (Δa = 1.13 mm), while red sandstone had a largest average thickness loss of 1.54 mm. For each type of fully cleaned stone, a smaller thickness loss indicates a more effective cleaning process or a more suitable abrasive as well. For limestone, fine glass may be the most suitable abrasive with a thickness loss of 0.10 mm, followed by medium slag (Δa = 0.19 mm), fine slag (Δa = 0.26 mm) and natural abrasive (Δa = 0.30 mm), while medium glass can be regarded as the least effective abrasive with a thickness loss of 0.67 mm. For yellow sandstone, coarse glass may be the most suitable abrasive with a thickness loss of 0.58 mm, followed by coarse slag (Δa = 0.75 mm) and natural abrasive (Δa = 0.90 mm). The rest abrasives can be regarded as the less suitable or unsuitable ones. For red sandstone, fine glass may be the most suitable abrasive with a thickness reduction of 0.95 mm, followed by medium glass (Δa = 1.08 mm) and fine slag (Δa = 1.22 mm). The rest abrasives can be regarded as the less suitable or unsuitable ones.

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

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

Table 3 Summary of greyscale results before and after cleaning with final thickness reductions.

Stone	Abrasive	t_{tot} (sec)	GS_{ini}	GS_{fin}	ΔGS	Δa (mm)
Granite	Coarse slag	10	67.54	73.54	6.00	0.32
	Medium slag	10	53.14	60.84	7.70	0.17
	Fine slag	10	49.05	62.08	13.03	0.19
	Coarse glass	50	62.68	86.83	24.15	0.31
	Medium glass	10	70.98	89.59	18.61	0.15
	Fine glass	10	54.83	79.24	24.41	0.25
	Natural	50	63.03	74.46	11.43	0.21
	Average	/	60.18	75.23	15.05	0.23
	Standard deviation	/	8.03	11.11	7.49	0.07
Limestone	Coarse slag	30	96.11	171.65	75.54	0.41
	Medium slag	12	112.26	166.36	54.10	0.19
	Fine slag	10	134.85	171.99	37.14	0.26
	Coarse glass	140	117.79	176.83	59.04	0.64
	Medium glass	14	116.18	165.11	48.93	0.67
	Fine glass	10	74.94	160.53	85.59	0.10
	Natural	140	124.95	151.59	26.64	0.30
	Average	/	111.01	166.29	55.28	0.37
	Standard deviation	/	19.83	8.40	20.55	0.22
Marble	Coarse slag	45	61.32	166.94	105.62	0.53
	Medium slag	50	56.2	159.29	103.09	0.33
	Fine slag	35	83.18	172.33	89.15	0.52
	Coarse glass*	300	54.11	175.83	121.72	0.80
	Medium glass	25	79.85	170.31	90.46	0.40
	Fine glass	25	68.09	172.81	104.72	0.39
	Natural*	900	87.38	158.37	70.99	0.43
	Average	/	70.02	167.98	97.96	0.49
	Standard deviation	/	13.51	6.81	16.11	0.16
Yellow sandstone	Coarse slag	180	81.14	124.51	43.37	0.75
	Medium slag*	540	60.43	100.01	39.58	1.38
	Fine slag*	300	53.5	105.17	51.67	1.82
	Coarse glass	210	97.12	137.94	40.82	0.58
	Medium glass*	240	43.18	120.73	77.55	1.10
	Fine glass*	240	65.58	120.94	55.36	1.37
	Natural	120	83.22	100.19	16.97	0.90
	Average	/	69.17	115.64	46.47	1.13
	Standard deviation	/	18.85	14.27	18.40	0.43
Red sandstone	Coarse slag*	180	64.04	105.91	41.87	2.00
	Medium slag*	120	43.27	91.14	47.87	1.62
	Fine slag	60	49.49	89.87	40.38	1.22
	Coarse glass*	480	45.92	93.24	47.32	1.74
	Medium glass	80	62.15	98.75	36.60	1.08
	Fine glass	80	58.56	93.84	35.28	0.95
	Natural*	240	54.20	33.10**	-21.10**	2.15
	Average	/	53.95	95.46	41.55	1.54
	Standard deviation	/	8.05	5.96	5.26	0.46

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

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

CONCLUSIONS

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

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

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

4. By considering both cleaning time and thickness reduction, any abrasives with longer cleaning times or bigger thickness losses for the same cleaning degree on one type of masonry stone would be regarded to be less suitable and uneconomical for that type of stone. In general, the abrasives with better cleaning performance were those industrial by-products with smaller particles sizes, i.e. medium or fine slag and recycled glass, because the coarse abrasives and natural abrasive would consume more cleaning times and possibly cause damages to masonry stone surface features.

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