Journal of Physical Science and Application 4 (4) (2014) 207-222

Investigations of Physical and Chemical Characteristics of Masonry Stones and Bricks during Building Cleaning: Part 1. Physical Testing

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Received: October 22, 2013 / Accepted: November 25, 2013 / Published: April 15, 2014.

Abstract: This series of study focused on analysing and assessing the changes of the physical and chemical characteristics of the surfaces of the masonrystones and bricks during the sandblasting cleaning process by conducting various physical and chemical tests. Seven masonry stones and bricks were adopted, including yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. The physical testing included evaluating the cleaning degree, determining the Vickers hardness, and detecting the water absorption. Using a digital imaging analysis method, the greyscale and cleanness were introduced to quantitatively assess the effectiveness of masonry building cleaning and confirmed to be useful and appropriate. The cleanness analysis, together with the hardness and water absorption tests showed that a masonry stone or a brick with a higher cleaning degree corresponded to a brighter and harder stone surface. In general, the physical properties were found to vary largely during the building cleaning.

Key words: Masonry stone and brick, sand blasting cleaning, greyscale, hardness, water absorption.

1. Introduction

Historic buildings and monuments are precious finite assets and powerful reminders for future generations of the work and way of life of earlier cultures and civilisations. The stone cleaning and restoration of old and historic buildings is a crucial strategy in maintaining the aesthetic appearance, integrity and quality of the fine art, construction method and architecture of previous civilisations. Stone cleaning is one of the most noticeable changes a building can be subjected to, which can change its appearance, persona and environmental context. A clean building can reflect well on the occupants. Stone cleaning has been dated back for over 40 years, peaking during the 1970s and 80s and growing into a multimillion pound industry [1-4]. At the time, the cleaning was inappropriately aggressive, causing damage to many building façades. Poorly or inappropriately selected methods of cleaning or the right methods performed by unskilled operatives can lead to permanent damage to building façades. The correct choice of repairing mortar for restoration work is also important to lengthen the life of stones and bricks in masonry buildings by stopping the damage due to stone decay.

A decision to clean or repair a historic building must be undertaken only if there is a strong reason to do so [5]. Preliminary investigations on both physical and chemical characteristics of the masonry stone or brick

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surfaces have to be carried out first before deciding on the best method of cleaning and the most appreciate type of mortar for repair to avoid any unnecessary damage to the building façades [6-9].

In Scotland, natural stones and bricks as building materials were widely used in the built heritage, which hence led to large demands of stone cleaning [10-12]. In the 1960s, the cleaning of masonry buildings for aesthetic, commercial and sociological reasons became quite common. At that time, transforming the black-soiled limestone building into a clean and bright structure became a kind of fashion, which was started in Paris and London and followed by many other places. When it turned to sandstone, however, more aggressive cleaning methods were required in order to remove the grime as the atmospheric pollutants attached to the surfaces of sandstone are quite different from those on the limestone surfaces. These excessively aggressive methods led to great damages on the stone surfaces, removing soiling as well as the stone surface with the sharpness of building details. During the 1970s and 80s, the chemical method of stone cleaning was utilised, reducing the damage to the stone surface from abrasive cleaning method, and stone cleaning reached its peaks. However at that time, various cleaning methods still caused permanent damage to a building. As time goes by, people have now paid more attention to this and many studies on stone cleaning have been published [8, 13-20]. Cleaning methods nowadays have become more finely tuned and less aggressive because new legislation has protected historic, listed buildings and conservation areas from any detrimental treatments [21, 22].

Masonry stones in buildings considered for cleaning vary largely in types, surface texture and architectural style and also suffer from different types of natural decay and even man-made pollutions. Cleaning methods are usually destructive and cause irreversible damage. The method of removing the soiling from the stone façade without affecting the underlying stone and causing long term damage has not been devised yet. It is discovered that physical cleaning methods such as grit blasting will lead to some abrasive damage to the stone façade. Chemical cleaning method may dissolve some stone components alone with the soiling and leave chemical residues in porous stones. Some effects may become apparent many years after and large scales of stone repair and replacement are needed to resolve the problem caused by the ill-cleaning in the past. There are four major types of cleaning methods: water cleaning, chemical cleaning, mechanical cleaning and air abrasive cleaning (sandblasting).

When dirt is combined with gypsum ($CaSO_4$), a water soluble mineral cleaning method is usually used. It is more commonly used on calcareous surfaces such as limestone and marble. Water-based methods are not effective on sandstones, brick or terracotta for removing soiling which is bound to these surfaces by insoluble compounds. Using water washing techniques on masonry surfaces with high natural salts, such as sandstone and brick, can mobilise the salts and lead to efflorescence. Desalination of such surfaces after cleaning has, in rare cases, been carried out by water saturation followed by drying. Much research has been done on this aspect and useful methods have been proposed, e.g. poulticing technique [23-26]. Water cleaning can be further subdivided into the following categories: water jet spraying, intermittent nebulous spraying, water cleaning with pressure, steam cleaning, water cleaning with non-ionic soaps or detergents, etc., each having its own advantages and disadvantages.

Chemical cleaning methods are more effective because they work by the reaction between the cleaning agent, soiling and the masonry surface to which the soiling is attached [27-29]. Wide varieties of chemicals for cleaning masonry surfaces are available in the market, but there are two main types of chemical cleaners: acid and alkaline. The active ingredient of a cleaning agent can be a single component or a mixture and can vary largely in concentration and strength. More attention needs to be paid to selecting chemical agents, determining chemical staining, and applying chemicals to substrates. The main problems with using chemical cleaning involve the extent and efforts of the retention of chemical agents and the possible mobilisation of salts within the stone. Another problem associated with chemical cleaning is the bleaching or staining of surfaces. Chemical cleaning damage is irreversible and usually dramatic, so it should only be used with extensive pre-testing to ensure confidently that there is no damage to the building façade.

Mechanical cleaning removes soiling from the stone surface by physical forces, cutting or abrasion through hand-held implements or mechanised equipment. Abrasives can permanently damage the masonry as they do not differentiate between the dirt and the masonry stone or brick. How much material is removed depends on the masonry involved. Brick, architectural terra cotta, soft stone, detailed carvings and polished surfaces are especially susceptible to physical and aesthetic damage by abrasive cleaning methods. Increase in surface roughening is another consequence of mechanical cleaning. The most commonly used mechanical cleaning methods include dry brushing and surface rubbing, surface addressing, etc.

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

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

In this series of study, physical and chemical characteristics of masonry stones and bricks subjected to progressive stages of cleaning were investigated for evaluating the effectiveness of building cleaning.

Physical tests included surface hardness tests and water absorption tests. The digital image analysis method based on the greyscale was used to quantitatively assess the degree of cleaning, or cleanness. Seven types of commonly used masonry stones and bricks were selected for physical tests, including yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. Some of these masonry samples were to be used for further chemical analysis. Thus, a complete evaluation procedure for building cleaning can be established.

2. Preparation of Stone Samples

Masonry stonesand brickswere selected from those for the 1860s-1870s listed buildings in the south west of the city of Edinburgh, which werepopularly used for local buildings [30] and exposed to the open environmental conditions for more than a century with large amounts of heavy soiling on the surfaces. A diamond saw was used to cut the masonry stones and bricks into small samples (Fig. 1). The exposed surfaces of the stones and bricks were cleaned into different levels using the abrasive sandblasting cleaning, and then they were cut into the required sizes for various physical and chemical tests. Here the abrasive cleaning system selected included an air compressor, a shot blasting cabinet and a blasting gun inside the cabinet (Fig. 2).

The abrasive particles used in the shot blasting cabinet are generally sand, slug, recycled glass particles and natural abrasives like coconut shells. To be environmentally friendly, recycled broken glass particles were used to clean the stone samples. Fig. 3shows three typical recycled abrasive glass particles for air abrasive cleaning. According to their particle sizeswhich varied between 125 and 1000 μm, the glass particles were classified as coarse, medium and fine glasses. Different finenesses of glass particles may largely affect the cleaning degree.

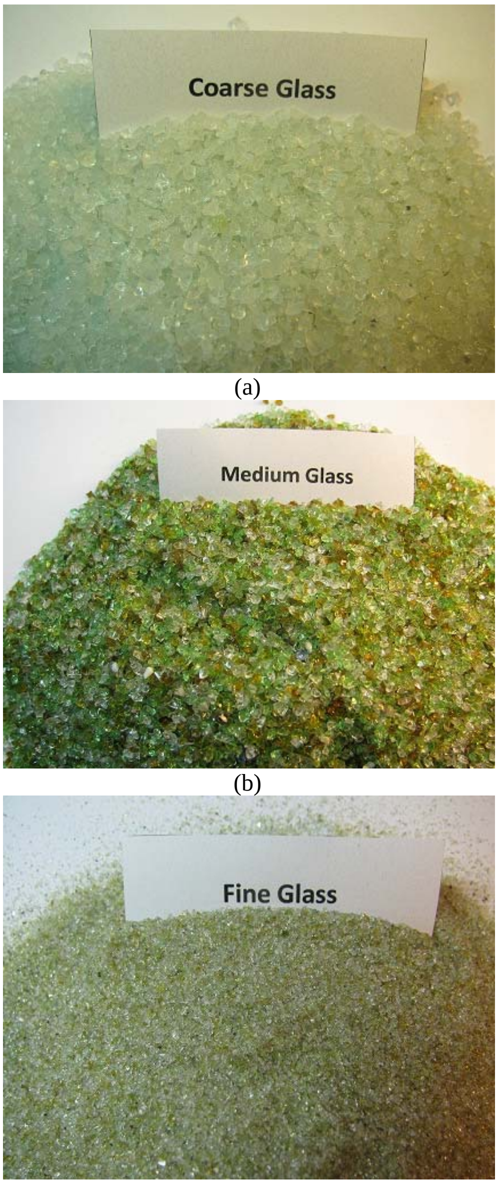
From the sieve tests, the values of the fineness modulus (FM) for these three categories were measured as 6.41, 5.98 and 4.20 for coarse, medium and fine glass particles, respectively [31]. Fig. 4 shows particle size distributions of the glass particles, which indicates that the difference in fineness between the coarse and medium glass particles was small. Preliminary tests were conducted on all three types of glass particles and fine glass was found to be the most effective abrasive material for building cleaning. In this study, the fine glass particles were hence adopted for cleaning the masonry stones and bricks.

During cleaning, the stone surfaces were gradually cleaned from fully dirty to further three different cleaning levels by controlling the sandblasting time *t* from 0 to 3, 6 and 10 s for most stones and bricks, except the yellow clay brick and granite, with the cleaning degrees estimated as 0%, 30%, 60% and 100% (Table 1).

Granite had polished surface so only two stages were selected, fully dirty and fully clean. Figs. 5 to 11 show all seven types of stone and brick samples at different

Fig. 1 Samples cut from masonry stones and bricks using a diamond saw.

Fig. 2 The abrasive cleaning system.



(a) (b) (c)

Fig. 3 Recycled glass particles for air abrasive cleaning. (a) coarse glass; (b) medium glass and (c) fine glass.

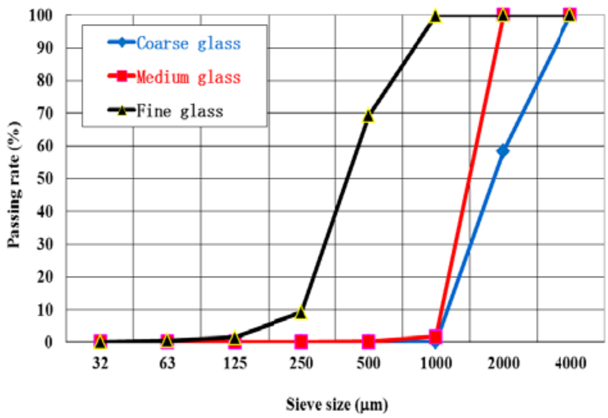
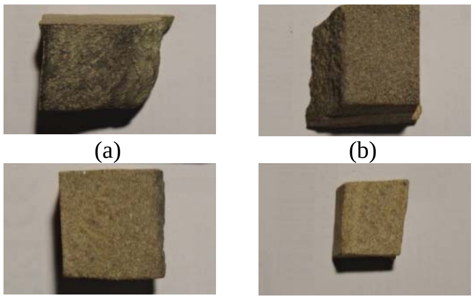


Fig. 4 Passing rates of glass particles.

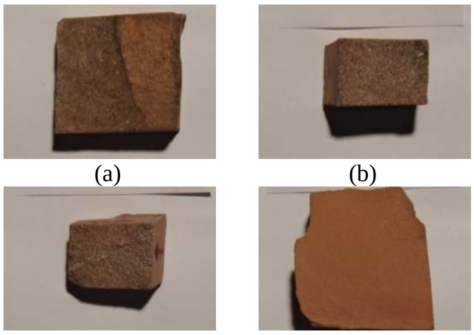
Table 1 Cleaning times for different cleaning stages.

Cleaning stage	I	II	III	IV
Yellow sandstone (s)	0	3	6	10
Red sandstone (s)	0	3	6	10
Limestone (s)	0	3	6	10
Marble (s)	0	3	6	10
Granite (s)	0	-	-	10
White clay brick (s)	0	3	6	10
Yellow clay brick (s)	0	2	4	7



(a) (b) (c) (d)

Fig. 5 Yellow sandstone samples at different cleaning stages: (a) t = 0 s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.



(a) (b) (c) (d)

Fig. 6 Red sandstone samples at different cleaning stages: (a) t = 0 s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

cleaning stages. In general, the original dirty surfaces of stones and bricks were darker. With the progressof cleaning, these surfaces became brighter andshinier.

3. Digital Image Analysis—Greyscale and Cleanness

To explore the cleaning degrees of the surfaces ofthe masonry samples, a digital image analysis method, the greyscale method, was used. The mechanism of this method is to determine the grey degree of a grayscale digital image photo which is converted from a normal colour photo and to use it for assessing the cleaning degree. This technique has been largely used in civil

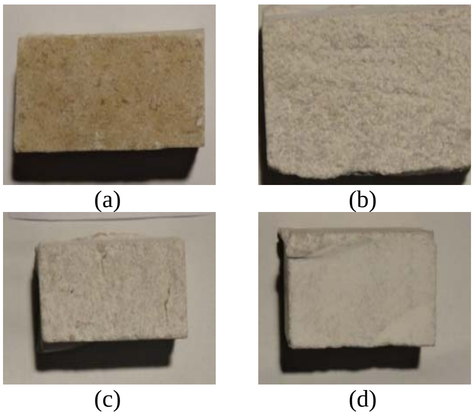


Fig. 7 Limestone samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

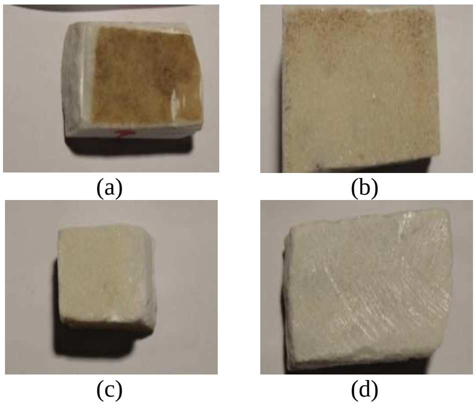


Fig. 8 Marble samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

Fig. 9 Granite samples at different cleaning stages: (a) *t* = 0 s and (b) *t* = 10 s.

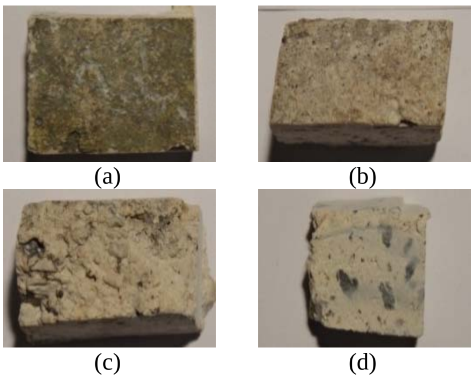


Fig. 10 White clay brick samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

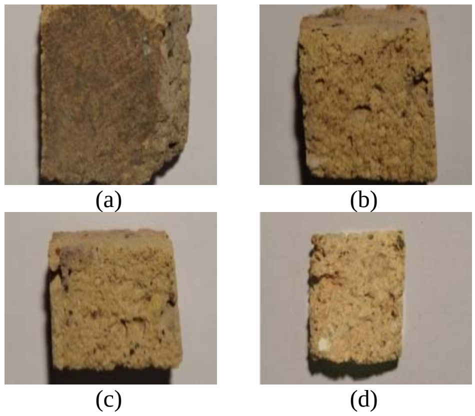


Fig. 11 Yellow clay brick samples at different cleaning stages: (a) *t* = 0 s; (b) *t* = 3 s; (c) *t* = 6 s and (d) *t* = 10 s.

engineering, e.g. geotechnical analysis of aggregate particles [32-34], automatic road surface detection [35, 36], etc. However, no research is reported on its use for assessing building cleaning.

In this study, colour photos were taken indoors first. A powerful lamp, used to create parallel lights, was fixed at 1.5 m above the stone and brick samples. A Sony Cybershot DSC-T110 camera was used with the fixed 2.3 × optical zoom and at a distance of 0.5 m. All colour photos were then converted to the greyscale digital images using the Photoshop or the Microsoft WORD. These greyscale images were composed of shades of grey, scaling from 0 for pure black at the weakest intensity to 255 for pure white at the strongest intensity. Fig. 12 shows the grey level bars, and the greyscale levels which could be read using the Colorpad software are shown in Fig. 13.

3.1 Greyscale

The greyscale (GS) is used to define the colour shades of the stone or brick surfaces. An area of 1 cm^2 with a 10 × 10 grid including one hundredsampling points was placed on top of the greyscale photos and the GS values at the sampling points were read in order to obtain the surface greyness of each stone or brick sample and determined by averagingthese readings. Figs. 14 to 20 illustrate the grids placed on the top of the greyscale photos of all seven types of stone and brick samples cleaned to different levels.

Fig. 12 Grey level bars.

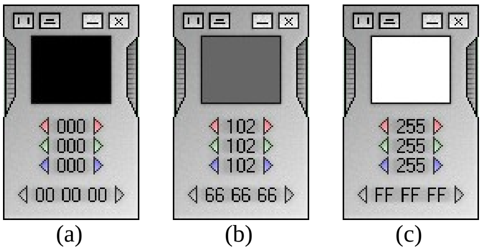


Fig. 13 Greyscale readings obtained using the Colorpad: (a) pure black; (b) grey and (c) pure white.

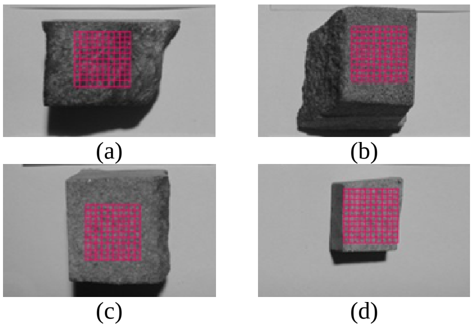


Fig. 14 Grids on the greyscale images of the yellow sandstone samples: (a) t = 0 s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

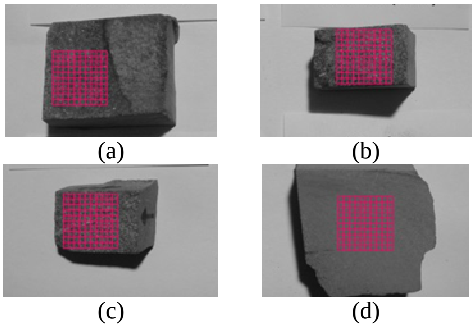


Fig. 15 Grids on the greyscale images of the red sandstone samples: (a) t = 0 s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

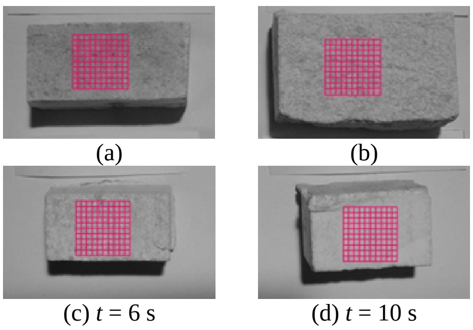


Fig. 16 Grids on the greyscale images of the limestone samples: (a) t = 0 s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

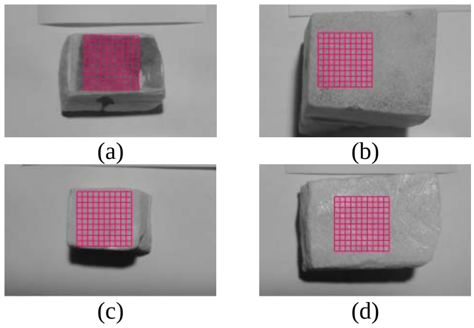


Fig. 17 Grids on the greyscale images of the marble samples: (a) t = 0 s (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

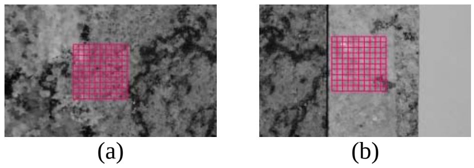


Fig. 18 Grids on the greyscale images of the granite samples: (a) t = 0 s and (b) fresh surface..

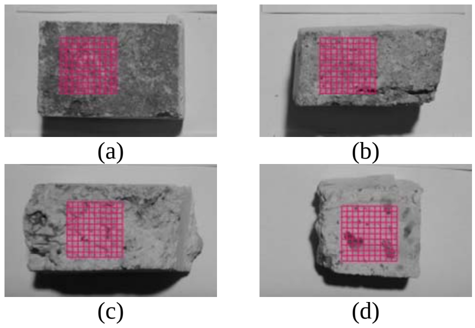


Fig. 19 Grids on the greyscale images of the white clay brick samples: (a) t = 0; s; (b) t = 3 s; (c) t = 6 s and (d) t = 10 s.

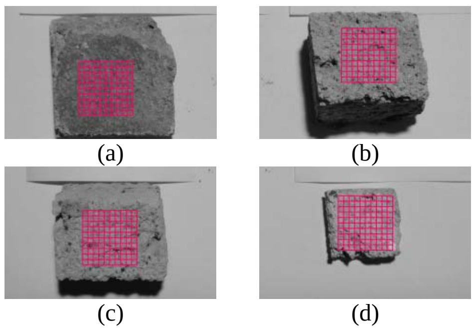


Fig. 20 Grids on the greyscale images of the yellow clay brick samples: (a) t = 0; s; (b) t = 2 s; (c) t = 4 s and (d) t = 7 s.

Table 2 lists the mean values of the greyscale for all seven types of stone and brick samples at different cleaning stages with the standard deviations in the round brackets. The differences in greyscale between

Table 2 Greyscale values for seven types of masonry stones and bricks at different cleaning stages.

Cleaning stage	Yellow sandstone	Red sandstone	Limestone	Marble	Granite	White clay brick	Yellow clay brick
I	70.44(13.83)	70.51 (9.05)	125.08 (7.47)	86.06 (6.75)	115.95 (16.61)	92.12 (12.69)	92.60 (9.60)
II	93.38 (9.22)	80.23 (11.62)	140.18 (7.41)	142.32 (5.05)	-	124.84 (10.17)	128.91 (9.69)
III	110.09 (7.62)	85.44 (8.02)	153.28 (5.66)	147.36 (3.55)	-	130.98 (13.95)	134.02 (8.24)
IV	115.81 (8.40)	91.74 (2.45)	163.37 (3.53)	154.32 (7.10)	149.18 (15.60)	138.26 (22.94)	140.53 (10.65)
Difference	45.37 [39.2%]	21.23 [23.1%]	38.29 [23.4%]	68.26 [44.2%]	33.23 [22.3%]	46.14 [33.4%]	47.93 [34.1%]

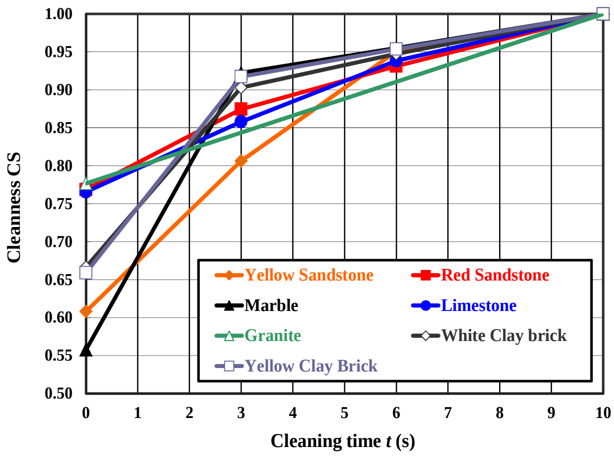


Fig. 21 Greyscale versus cleaning time for various masonry stones and bricks.

the original dirty surfacesand the fullycleaned surfaces are also included in the table, with the ratios of the greyscale values for the stone or brick surfaces cleaned at different stages to those for the fully cleaned surfaces in the square brackets.

Fig. 21 illustrates the relationships between the greyscale and cleaning time for all seven types of masonry stones and bricks.

A greater greyscale represents a cleaner surface. From Table 2, the overall greyscale varied from 70.44 for the uncleaned yellow sandstone to 163.37 for the fully cleaned limestone, which indicates that the former had the darkest surface while the latter had the brightest one. The standard deviation varied from the lowest 2.45 for the fully cleaned red sandstone to the highest 22.94 for the fully cleaned white clay brick, which indicates that the greyscale had the smallest variation for the former but the biggest variation for the latter. The coefficient of variation, the ratio of the standard deviation to the mean value, varied from 2.2% for the fully cleaned limestone to 19.6% for the fully dirty yellow sandstone, with most values below 15%, which indicates that the measured values possessed generally acceptable variations for construction practice.

In general, the greyscale gradually increased with the cleaning time but at a decrease rate and tended to be stable when the surface was fully cleaned. These trends can be expressed by a parabolic or bi-linear relationship. The differences in the greyscale between the original dirty and fully cleaned surfaces can be used to assess the dirty conditions on the stone or brick surface. The larger the difference in greyscale, the dirtier the original stone surface. Marble had a largest difference of 68.26 so its original surface was the dirtiest. The differences in greyscale for yellow clay brick, white clay brick, yellow sandstone and limestone varied from 47.93 to 38.29 so they were relatively dirtier. The greyscale differences for granite and red sandstone were only 33.23 and 21.22, respectively, which indicates that the original red sandstone was the least dirty.

3.2 Cleanness

In order to further quantitatively assess the cleaning level for all seven types of stones and bricks studied, the greyscale was normalised by introducing the cleanness (CS) or the relative greyscale as follows:

$$\textit{Cleanness}\ (\mathrm{CS}) = \frac{\textit{Greyscale at certain cleaning level}}{\textit{Greyscale at fully cleaned level}} \quad (1)$$

The value of the cleanness for a fully cleaned stone or brick surface is defined as 1.0 and the cleanness forother cleaning levels are smaller than 1.0. Table 3 lists the calculated values of the cleanness for all seven types of stones and bricks at different cleaning stages,

Table 3 Cleanness for different types of masonry stones and bricks at four cleaning stages.

Cleaning stage	Yellow sandstone	Red sandstone	Limestone	Marble	Granite	White clay brick	Yellow clay brick
I	0.608	0.769	0.766	0.558	0.777	0.666	0.659
II	0.806	0.875	0.858	0.922	-	0.903	0.917
III	0.951	0.931	0.938	0.955	-	0.947	0.954
IV	1.000	1.000	1.000	1.000	1.000	1.000	1.000

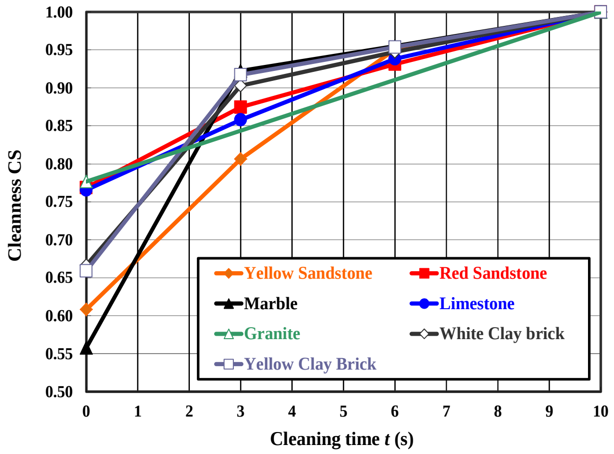


Fig. 22 Cleanness versus cleaning time for various masonry stones and bricks.

and Fig. 22 illustrates the corresponding relationships between the cleanness and cleaning time. It can be seen that the cleanness had the same increasing trends with the cleaning time as the greyscale. The smaller the value of the cleanness, the dirtier the original dirty stone surface. The cleanness value for dirty surfaces varied between 0.56 for marble and 0.78 for granite. It is obvious that the original surface of marble was the dirtiest, followed by yellow sandstone, yellow clay brick and white clay brick. Granite, red sandstone and limestone had the least dirty original surfaces. These trends generally match those with respect to the greyscale, which indicates that the digital imaging analysis and the two proposed parameters can be used for quantitatively assessing the cleaning degree.

4. Surface Hardness of Masonry Stones

The surface hardness of the stone and brick samples can be used for evaluating the changes in the surface strength during building cleaning. The Vickers hardness test, which was developed in the early 1920s, was adopted in this study because it is convenient to be carried out on small samples. This method was originally used for metallic material evaluation, quality control of manufacturing processes, and research and development efforts [37-39]. Later this method was applied to non-metallic materials, e.g. minerals, ceramic materials, stones and concrete materials [40-44].

The Vickers hardness number H_V was adopted here, which can be calculated from:

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

where, H_v is the Vickers hardness number (kg/mm^2), P is the applied load (g), θ is the angle between the opposite faces (136°), d is the diagonal of indentation.

In the hardness testing, a stone sample was indented in the Vickers hardness instrument by using a diamond indenter with a load P = 1,000 g for 15 s (Fig. 23). The pyramid shaped indenter had a square base diamond with an angle of 136° between opposite faces, as shown in Fig. 24. After removing the load, a diamond indentation could be found on the stone surface using the microscope. Fig. 25 shows that a diamond indentation had two diagonals, horizontal and vertical ones. The two diagonal dimensions, d_H and d_V, were measured separately by aligning the two mark lines in the microscope to the edges of the indentation and then the values of d_H and d_V, which were shown on the digital encoder, were obtained. The two Vickers hardness numbers corresponding to d_H and d_V could be obtained by checking against the Vickers hardness number table [45]. The final value of H_V was the

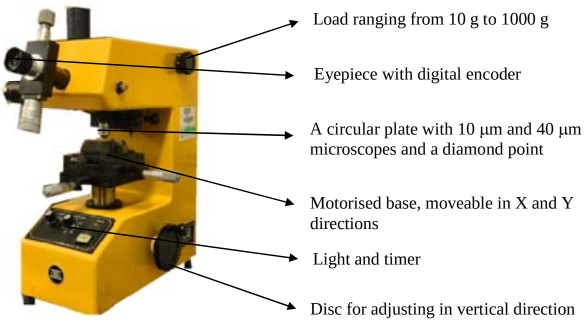


Fig. 23 Vickers hardness instrument.

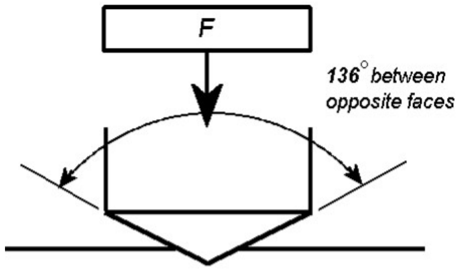


Fig. 24 The pyramid shaped indenter.

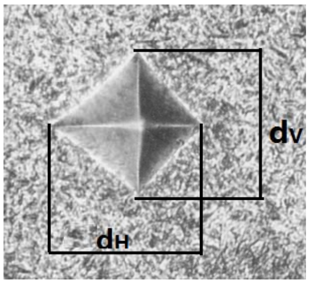


Fig. 25 Diamond indentation on the stone surface.

average of the two hardness results for the horizontal and vertical directions. One sample was selected for the Vickers hardness tests from each type of stone and brick. Three sampling points were taken on each stone sample.

Table 4 lists the mean values of the Vickers hardness numbers for all seven types of stone and brick samples at different cleaning stages, with the standard deviations in the round brackets. The higher the Vickers hardness number, the greater the stone surface strength. The measured values of the Vickers hardness number on the fully cleaned stone surfaces shows that granite was the hardest stone (H_V = 482.5 kg/mm^2), followed by marble with H_V = 210.5 kg/mm^2. White clay brick was the softest with H_V = 67.7 kg/mm^2 only, followed by red sandstone with H_V = 76.2 kg/mm^2. The rest of the stones lay in-between.

Table 4 also lists the differences in the Vickers harness numbers between the fully cleaned and original dirty stones, together with their relative ratios in percentage to the Vickers harness numbers for the fully cleaned surfaces in the square brackets. It can be seen that the soiling on the stone surface largely affected the surface hardness of the masonry stones. The Vickers hardness number for marble sustained a largest change and increased from 115.5 kg/mm^2 for the original dirty surface to 210.5 kg/mm^2 for the fully cleaned surface, which means that the soiling had decreased the surface hardness of marble by up to 95.0 kg/mm^2 or 45.13%. On contrast, the Vickers hardness number for granite had a smallest change and increased from 465.5 kg/mm^2 for the original dirty surface to 482.5 kg/mm^2 for the fully cleaned surface, which means that the soiling only decreased the surface hardness of granite by 17 kg/mm^2 or 3.52%. The influences of the soiling on the surface hardness for other stones and bricks varied from 30% to 40%.

Fig. 26 illustrates the Vickers hardness number against the cleaning time for all seven types of stones and bricks. A small figure is also inserted in Fig. 26 to give a clearer view of the trends for five stones with lower Vickers hardness numbers. In general, the Vickers hardness number for all stones and bricks

Table 4 Vickers hardness numbers for different types of stones and bricks at four cleaning stages.

Cleaning stage	Yellow sandstone	Red sandstone	Limestone	Marble	Granite	White clay brick	Yellow clay brick
I	57.6(1.4)	44.5 (1.5)	67.5(1.7)	115.5(3.8)	465.5(12.3)	47.3(0.7)	56.7(1.8)
II	69.2 (1.5)	57.4 (1.2)	93.3 (1.9)	158.0 (6.5)	-	58.6 (1.4)	69.0 (1.4)
III	77.0 (1.4)	69.9 (5.0)	104.0(5.0)	184.5 (6.0)	-	63.0 (1.5)	76.3 (1.4)
IV	86.5 (3.6)	76.2 (2.2)	114.0 (3.5)	210.5 (9.0)	482.5(23.3)	67.7 (1.5)	82.5 (1.9)
Difference	28.9 [33.4%]	31.7 [41.6%]	46.5 [40.8%]	95.0 [45.1%]	17.0 [3.5%]	20.4 [30.1%]	25.8 [31.3%]

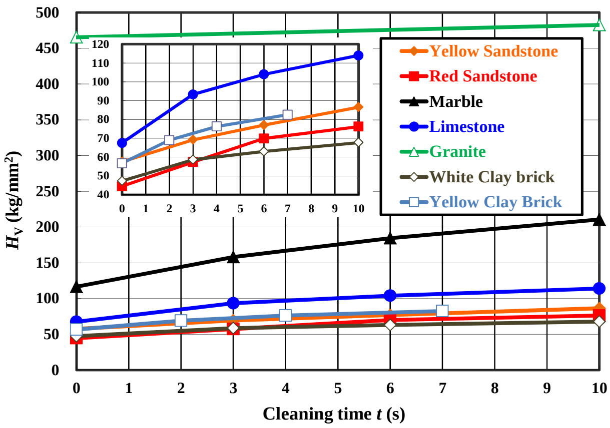


Fig. 26 Vickers hardness number versus cleaning time for various masonry stones and bricks.

gradually increased with the increasing cleaning time but at a decrease rate. These trends can be well expressed using parabolic relationships with high correlations.

Fig. 27 illustrates the Vickers hardness number against the cleanness for all stones and bricks. A small figure is inserted to help view more closely the trends for five masonry stones and bricks with lower Vickers hardness. In general, the Vickers hardness number for all stones and bricks monotonically increased with the increasing cleanness, and these trends can be expressed using linear or bilinear relationships. It is obvious that the original granite had the hardest and cleanest surface while the surface of the original marble was harder than any other stones except granite and was extremely dirty.

It should be mentioned that the hardness investigations can also help to select the most suitable abrasive materials for building cleaning. Too hard or too soft abrasives may not be beneficial for removing the soiling from the surface of a masonry stone or brick. Hard abrasives can effectively remove the soling but may damage the original masonry stone or brick surface. Soft abrasives may help preserve the building surface from damage caused by mechanical cleaningbut may not be able to effectively remove the soiling. Hence, there should be a balance in hardness between masonry stones/bricks, surface soling and abrasive materials. The current study can provide key information for masonry materials and soiling.

There are no available Vickers hardness values for the selected stones and bricks. Mineral Zone (46) reported the physical properties of typical natural stones, e.g., sandstone, limestone, marble and granite. Only the values of Mohs' hardness are given but they can be converted into the equivalent Vickers hardness values. Based on the mineral hardness conversion chart provided by CiDRA® Precision Services, LLC (47), the recommended Vickers hardness ranges are presented in Table 5 together with those on the fully cleaned surfaces in this study.

It can be seen that only the Vickers hardness value on the fully cleaned marble surface lay within the recommended range. The Vickers hardness values for limestone and granite were only half the average of the recommended ranges. For yellow and red sandstones,

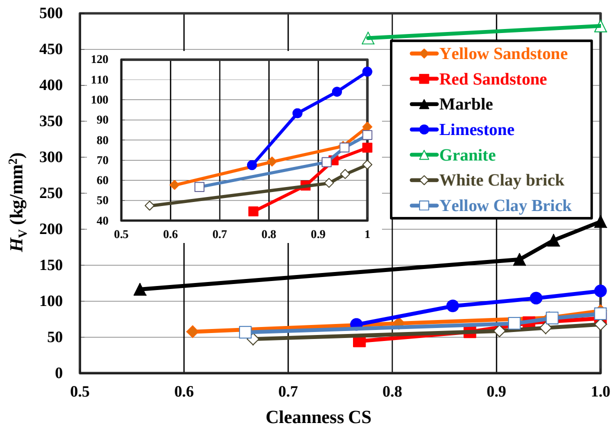


Fig. 27 Vickers hardness number versus cleanness for various masonry stones and bricks.

Table 5 Vickers hardness numbers for typical masonry stones.

Hardness	Yellow sandstone	Red sandstone	Limestone	Marble	Granite
Mohs (mm)	6.5-7	6.5-7	3-4	3-4	6-7
Vickers[1] (kg/mm^2)	982-1,161	982-1,161	157-315	157-315	817-1,161
Vickers[2] (kg/mm^2)	86.5	76.2	114.0	210.5	482.5

[1]Given by Mineral Zone (46); [2]Measured on the fully cleaned surface in this study.

the Vickers hardness values were even below 10% of the average of the recommended ranges. By remembering that all the recommended ranges of Vickers hardness are obtained on surfaces of fresh masonry stones, it can be claimed that all of these differences were due to environmental erosion and weathering over decades. Marble seems to be the most stable masonry stone and sustain the least damage, followed by limestone and granite. Yellow and red sandstones seem to be the worst ones which can be easily attacked by weathering and environmental erosion. On the other hand, this confirms again the importance of measuring the surface hardness of masonry stones and bricks during cleaning so as to help select appreciate types of abrasives for building cleaning because the hardness for a masonry stone is indeed not the same as that on the building surface. Otherwise large damage can happen from wrongly selecting abrasives.

5. Water Absorption

Water absorption is the quantity of water absorbed by a masonry stone or brick when fully immersed in water for a stipulated period of time under an ambient atmospheric pressure. It largely depends on the internal structure and porosity of a stone or a brick and can be closely related to the soiling deposited on the masonry surface. A stone or brick with loose structure and large porosity would attract moisture from rain, snow or other environmental conditions and lead to cracks, efflorescence, rust staining, wood rotting, wood rotting, paint peeling, darkening of masonry and spalling. Any masonry stone or brick with high porosity would absorb high moisture so as to attract biological soiling, such as fungus, mosses, lichens, etc. On the other hand, a masonry stone or brick with high water absorption capacity is often soft or less hard. Water absorption can thus be regarded as another physical parameter for assessing the hardness of masonry materials. Hence, it may be largely influential on the selection of cleaning abrasives, if air abrasive cleaning is adopted, and eventually on the effectiveness of building cleaning.

The water absorption testing was undertaken according to BS EN 13755 (48). The stone samples were put in an oven at a temperature of (70 ± 5) °C for 24 h until constant weights were obtained. The dried samples were placed in a tank after weighing, and then tap water at (20 ± 10) °C was added up to half the height of the stone samples. An hour later, tap water was added again until the level of the water reached three-quarter of the height of the samples. After another hour, tap water was added for a third time to submerge the samples completely. The samples were taken out of the tank after 48 h, quickly wiped with a damp cloth and then weighed within 1 minute on a scale with an accuracy of 0.01 g. A total of seven samples, one for each type of the masonry stones and bricks, were selected for the water absorption testing. All samples were cut from the original stones and bricks using a diamond saw and all the surfaces were fresh surfaces to void any effect of soiling. Fig. 28 shows all the stone and brick samples for the water absorption tests.

The water absorption (WA) of a masonry stone or brick can be calculated from

$$\mathrm{WA} = \frac{M_{\mathrm{saturated}} - M_{\mathrm{dried}}}{M_{\mathrm{dried}}} \times 100\% \qquad (3)$$

where, $M_{\mathrm{saturated}}$ is the weight of the sample fully saturated in the water, and M_{dried} is the weight of the sample fully dried in the oven.

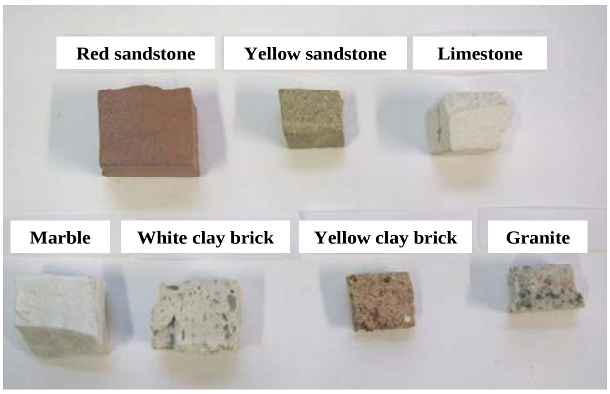


Fig. 28 Masonry stone and brick samples for water absorption tests.

Fig. 29 illustrates the measured values of the water absorption for all seven types of stones and bricks. Yellow and white clay bricks had the largest water absorptions among all the samples, with WA = 3.09% and 8.66%, respectively. Limestone, yellow sandstone and red sandstone also had relatively high water absorptions, with WA = 5.40%, 5.09% and 2.96%, respectively. On contrast, marble and granite absorbed little water so as to have the lowest water absorptions, with WA = 0.32% and 0.23%.

There are no available data of water absorption for clay bricks, but Mineral Zone [46] have suggested typical water absorption values for masonry stones, see Table 6. The water absorption values measured in this study are also listed in the table. It can be seen that the measured water absorption values for marble and granite lay within the recommended range, while the measured values for other three stones were far beyond the recommended range. For red sandstone, the water absorption was nearly three times as large as the recommended range, while for yellow sandstone and limestone, the water absorptions were five times as large as the recommended ranges. These differences were still due to decades' environmental erosion and weathering. Marble remained to be the most stable masonry stone, followed by granite. The rest stones were worse. This again confirms the importance of measuring the water absorption of masonry stones and bricks during cleaning so as to help select appreciate types of abrasives for building cleaning because the water absorption for a masonry stone or brick subjected to long term environmental erosion and weathering is indeed not the same as that for a fresh stone or brick on the building surface. Therefore, it can be said that the test for determining the water absorption for a stone or a brick is as equally important as the hardness test for building cleaning.

Fig. 30 shows the comparison between the water absorption and the Vickers hardness number for various types of stones and bricks. Two opposite trends can be clearly observed: the hardness approximately decreased while the corresponding water absorption continually increased. The water absorption of granite which had a hardest surface was the lowest. Similarly, yellow clay brick which was extremely soft had the highest water absorption. In general, greater water absorption likely corresponded to a softer stone or brick, while lower water absorption corresponded to a harder stone or brick.

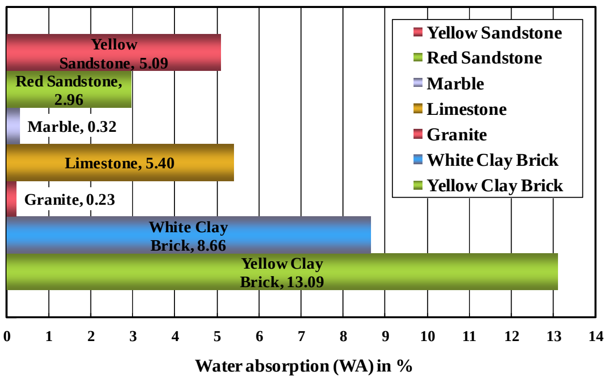


Fig. 29 Water absorption for various types of masonry stones and bricks.

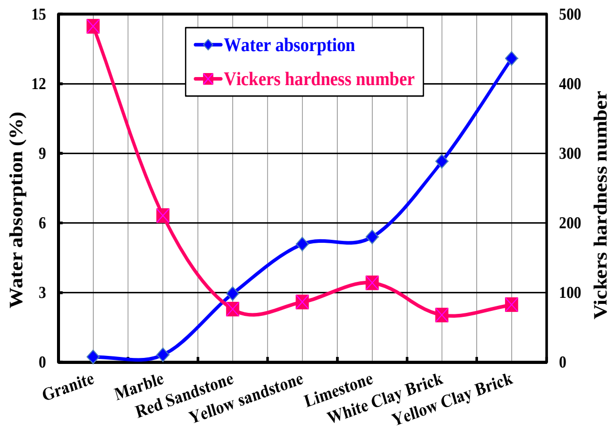


Fig. 30 Comparison between the water absorption and the Vickers hardness number for various types of masonry stones and bricks.

Table 6 Vickers hardness numbers for typical masonry stones.

Water absorption (%)	Yellow sandstone	Red sandstone	Limestone	Marble	Granite
Mineral Zone (46)	1.0-1.2	1.0-1.2	< 1	< 0.5	0.1-0.6
Current study	5.09	2.96	5.40	0.32	0.23

6. Conclusions

In this study, a series of tests were conducted to extensively investigate the changes in the physical and chemical characteristics of seven different types of popularly used masonry stones and bricks in Edinburgh during the cleaning process, i.e., yellow sandstone, red sandstone, limestone, marble, granite, white clay brick and yellow clay brick. The physical investigations included evaluating the cleaning degree, determining the Vickers hardness, and detecting the water absorption.

The cleaning degrees of the masonry samples were assessed using the digital image analysis method by introducing a parameter, the greyscale. A lower greyscale corresponded to a dirtier stone surface. It was observed that the greyscale continuously increased with the increasing cleaning time and tended to be stable when the surface became fully cleaned. In addition, another parameter, the cleanness which was defined as the ratio of the greyscale at certain cleaning stage to the one when the stone was fully cleaned, or called as the relative greyscale, was introduced for assessing the effectiveness of the building cleaning. For a dirty surface, the cleanness was small, while for a fully cleaned surface, the cleanness was equal to one. A larger cleanness value corresponded to a better cleaned surface. The comparison of the cleanness values at different cleaning stages indicated that among all the stones and bricks studied the original surface of the marble was extremely dirty while the surface of the granite was the cleanest. This digital image analysis method together with applying the greyscale or cleanness was confirmed to be useful and efficient for quantitatively assessing the effectiveness of building cleaning.

However, it should be pointed out that the current work is only a preliminary study on the assessment of building cleaning using greyscale technique, and much work needs to be done to standardise the assessing process because there are many different types of stones in nature and artificial bricks, e.g., calibrating the benchmark for each type of masonry stone and brick for building construction. The cleanness of a masonry building façade need to be assessed objectively, e.g., use its fresh surface deeply inside a stoneor brick as the benchmark. In practice at the moment, the cleaning assessment is normally done in a more subjective way by considering relevant influencing factors, e.g. the satisfaction of the customers, the acceptance of the authorities, the limitation of the cost, etc. All of these affect the objective assessment of the cleaning work. Hence, a mutual balance between all influential factors is needed.

The surface hardness of all seven types of stones and bricks studied at different cleaning stages was assessed by conducting the Vickers hardness tests. A larger hardness value corresponded to a harder stone surface. The hardness test results showed that the surface hardness continuously increased with the increasing cleaning time but at a decrease rate. Most of the increasing trends of the surface hardness could be approximately expressed using parabolic or bi-linear relationships. Granite was found to be the hardest among all the stones and bricks studied, followed by marble and limestone. However, there were no big differences in the surface hardness between yellow clay brick, yellow sandstone, red sandstone and white clay brick. Also the comparison with the reported Vickers hardness values of the masonry stones studied confirmed that some stones had sustained large decay due to long term weathering and environmental erosion, in particular yellow sandstone, red sandstone and limestone.

The waterabsorbingcapacity of the seven types of stones and bricks was also quantitatively determined. Two types of clay bricks showed the highest water absorptions, and the water absorptions for limestone, yellow sandstone and red sandstone were also quite high. However, the moisture absorptions of marble and granite were found to be very low, which indicates that they could hardly absorb water. A larger value of water absorption corresponded to a softer stone or brick, while a smaller value of water absorption corresponded to a harder stone or brick. The current study on water absorption also confirmed that the yellow sandstone, red sandstone and limestone in this study had sustained severe environmental erosion and weathering.

Acknowledgments

Ms. Lynn Chalmers at Edinburgh Napier University who largely helped conduct the hardness tests is greatly appreciated.

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