

# MEASURING SURFACE ROUGHNESS ON STONE: BACK TO BASICS

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**Summary**—*Stylus profilometry, reflected-light image analysis and visual/tactile evaluation were tested as techniques for assessing roughness of abrasive-blasted stone. Measurement of microdrop water absorption time was also tested as a complementary technique. Instrumental techniques showed significant shortcomings when measuring surfaces of roughness similar to most weathered stone, as well as flame-finished surfaces comparable to tooled stone. Tactile comparison of surfaces was found to be a more practical and cost-effective technique. On historic masonry structures, however, soiling and uneven weathering limit the usefulness of roughness as a property to be measured in evaluating cleaning techniques.*

## Introduction

Damage induced by cleaning on historic masonry structures has been assessed by many techniques, which are comprehensively reviewed in an excellent recent publication [1]. These techniques measure physical properties, such as roughness, surface recession, water (or water vapor) transfer, color and hardness, or identify deleterious products of chemical cleaning, such as soluble salts. No studies are known, however, that test the accuracy and applicability of these methods.

The purpose of the present study was to systematically test methods that measure surface roughness, although one method for assessing water transfer was also tested as a complementary technique. Roughness-measuring techniques have been used to assess damage in laboratory evaluations of cleaning and consolidation materials [2–6]. Measurement of surface recession was excluded from study because recession reflects losses greater than are normally acceptable for cleaning of historic masonry structures. It is more appropriate for determining weathering rates of rocks and durability of building stones or for quantifying damage from air pollutants [7]. Moreover, recession-measuring techniques often cannot be used on historic structures; for example, a technique that uses metal points set into the stone to create a reference plane is unsuitable [8]. Chemical cleaning was not considered, in order to produce a study of manageable size, and measurement of color and hardness was excluded because changes would be insignificant for unweathered masonry materials.

## Experimental

Measurements were made of nine different masonry

surfaces that had been blasted at several pressures with five abrasives. Testing was carried out in two phases: during the first phase a small number of samples was measured with many techniques; while during the second phase many more samples were measured with only a few techniques, those found to be the most promising and available during the first phase. The concentration here is on results produced during the second phase, but the experimental protocol is described for both phases since selected data are presented from both.

### *Sample materials*

For the first phase, three single pieces of different masonry materials available in the laboratory served as samples: polished marble, limestone and brick. The second phase used eight samples each of polished marble, sawn marble, sawn limestone, sawn sandstone, polished granite, flame-finished granite, glazed tile and quarry tile; the total number of samples was 64. Discussion here will focus principally on marble, limestone and sandstone samples because these materials showed the largest differences in roughness after surfaces were blasted.

Polished white marble (Carrara Gioia) was purchased in the form of tiles, and the back sides of the tiles served as samples of sawn marble. Indiana (Salem) limestone was obtained from the stoneyard of Washington National Cathedral; irregularities in sawing permitted some samples to be characterized as rough sawn and others as smooth sawn. Indiana limestone is a light-colored, fine-grained building stone that has been widely used throughout the United States. Red-colored Seneca Creek (Maryland) sandstone was cut from an ashlar block recently removed from the mid nineteenth-century Smithsonian 'Castle' to permit handicapped access to the building. It showed few signs of weathering,

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however, and samples were cut perpendicular to the weathered surface. Irregularities in sawing also permitted samples to be characterized as rough or smooth sawn. Seneca Creek sandstone, from the Triassic formation, has a ferruginous binder. Polished and flame-finished tiles of red granite from North Dakota, glazed tiles and quarry tiles were obtained commercially.

### *Sample preparation*

For the first phase, the three samples were roughened using S.S. White abrasive powders and air abrasive equipment in the laboratory; hence, results for these samples are designated 'lab blasted'. One area on each served as the control, and two other areas were blasted respectively with glass shot (#9, 44 $\mu$ m average diameter) and alumina (#3, 50 $\mu$ m average diameter). Each area measured at least 5cm on a side, and areas not being blasted were protected with plastic tape. The pressure gauge read 60psi (400kPa), and the pencil-type nozzle with an aperture measuring 0.46mm (0.018in) was held approximately 2cm from the masonry surfaces.

For the second phase, half of each of 64 masonry squares was blasted in the field while the other half served as a control for direct comparison with the blasted surface. Each masonry square measured about 15  $\times$  15cm; hence, individual test areas measured 7.5  $\times$  15cm. Controls were protected during blasting with an adhesive rubber layer used in the tombstone business to protect surrounding areas when inscriptions are engraved by sandblasting. Blasting was performed by an experienced operator with each of four abrasives at two different pressures, producing eight different surfaces for each masonry type.

Abrasives representing a range of hardness were selected to produce both the gamut of roughness and different kinds of damage. Powdered walnut shells (between 60 and 200 ASTM mesh sieves or 74–250 $\mu$ m particle size) were selected because they were expected to produce minimal damage and might polish the stone, although they are rarely used on stone except to remove loose paint, e.g., during the 1980 cleaning of the Old Courthouse in St Louis, Missouri. Water blasting was expected to be more aggressive, especially at high pressure, and it was included because of the ubiquity of pressurized water washing equipment and its common use for rinsing after chemical cleaning. Glass shot (passing a 270 sieve or <53 $\mu$ m particle size) was chosen because it was expected to produce intermediate roughness. Glass powder has been used with the JOS® system, although larger particle sizes (mostly >250 $\mu$ m) have been reported [9]. Black Beauty 2040 (90% between 20 and 40 mesh sieves or 425–850 $\mu$ m

particle size) was selected because it was expected to produce marked damage on softer stones and has been recommended for removal of hard deposits on granite [10]. Black Beauty is a glassy slag produced by power plants, often used as a substitute for sand because it does not cause silicosis.

Blasting was done simultaneously across each suite of eight samples. The spray measured 2–4cm in diameter at the surface of the stone depending on the abrasive, and adjacent passes overlapped slightly. A Lindsay 35 sandblasting unit was used with the abrasive powders, and the 0.8cm (5/16in) nozzle was held at an angle of about 75° from the horizontal samples. Pressure upstream from the nozzle was maintained at about 350kPa (50psi), designated LP for 'low pressure', and 700kPa (100psi), designated HP for 'high pressure'. Water blasting was done with Hydroteck equipment using a nozzle tip of 25°; flow rate was 19 liters per minute (5.5 gallons per minute). Pressures upstream from the nozzle were 7000kPa (1000psi) and 14,000kPa (2000psi), designated LP and HP respectively.

### *Replica preparation*

Silicone rubber replicas were made of all samples for reflected-light image analysis (RLIA) because variations in stone color and translucency would otherwise bias results. Testing during the first phase showed that white silicone rubber replicas were so reflective that there was insufficient distribution of RLIA data, and the white replicas produced erroneous results when roughness measurements were made with a laser. Red silicone rubber (Dow Corning 3120 and standard cure catalyst #1) replicas gave better results, and therefore they were prepared for RLIA tests in the second phase. Molds were made after all other surface measurements had been completed since silicone rubber residues might prejudice results for other tests.

The silicone rubber was poured onto each stone sample using Plasticine to hold the liquid rubber on the surface. To de-air the silicone rubber, a vacuum was drawn and released approximately 10 times. The silicone rubber was allowed to cure for 24 hours and removed from the surface. Replicas made for the first phase had proved too variable in thickness to compare results between samples: thus, for the second phase, care was taken to apply a constant amount of silicone rubber to each sample, and the normal 10:1 w/w ratio of silicone rubber to catalyst was doubled to improve levelling. Nevertheless, differences in thickness of the replicas could still be measured. Satisfactory uniformity of thickness was finally achieved by applying silicone rubber caulk to the reverse side of each silicone rubber mold and clamping the ensemble between

heavy Plexiglas sheets separated by 0.5cm (3/16in) spacers.

A release coating (Acryloid B-72) was applied to samples prior to replication during the first phase, but brushstrokes left from its application were visible in replicas made of polished marble surfaces. As a result, use of a release coating was eliminated for samples in the second phase since staining by the silicone rubber was not an issue (as it would be for stone artifacts). Unfortunately, the silicone rubber adhered tenaciously to uncoated sandstone. After it had been removed by dissolution with Silicone Dissolving Solution, sandstone samples were coated with a 2% solution of Acryloid B-72 in 1:1 acetone: ethanol. Replicas were re-made and removed without any problem.

Description of replica preparation has been detailed partly to show that making accurate replicas is not a trivial matter. Furthermore, light-colored stones became distinctly red after the replicas were made, indicating both that replicas had lost detail and that potentially undesirable residues had been left in the stone. Therefore large-scale replication cannot be recommended as a general practice although replicas may be useful for documentation of surfaces left by cleaning tests in the field, as they can be conveniently examined with a microscope and photographed in a laboratory [1].

### *Techniques*

During the first phase, stylus profilometry, laser triangulation profilometry and reflected-light image analysis were used to measure all samples, but only a few results will be presented here since samples were limited, and most results have already been published [11]. Laser results for the first phase are briefly discussed in the section on stylus profilometry because the same parameter was measured with both techniques; unfortunately cost precluded use of the laser to measure the larger number of samples produced during the second phase. White light interferometry imaging was also tested on a few samples, but was successful only on relatively smooth surfaces and would have been prohibitively expensive for use on many samples. Thermographic imaging of the surface of a uniformly heated sample by an infrared camera did not prove successful, apparently because of interference by the crystallography or mineralogy of the sample [12].

Techniques selected for testing on the 64 blasted and 64 control samples during the second phase include those described below as well as gloss measurement. The latter technique had proved effective in quantifying chemical dissolution of polished marble during an earlier study [13], but testing during the second phase showed that it could be applied

only on surfaces that had some polish, i.e., polished marble, polished granite, and glazed tile samples. Gloss measurement results are not presented here, but data did show that even slight changes correlated well with stylus profilometry data [12].

### *Stylus profilometry*

Stylus profilometry measurements are made by an instrument with a metal stylus (needle) that traverses a line. Developed and widely used for measuring surface roughness of metals, the technique has been employed on stone, although one study noted that data did not prove useful [2]. Roughness average ( $R_a$ ) is the primary statistical parameter used by metrologists to present results, defined as the arithmetic average of the absolute values of the measured heights from the mean surface taken within an evaluation area. Sometimes roughness is given as  $R_q$ , the root mean square (rms) parameter corresponding to  $R_a$ .

A relatively inexpensive (about US\$5000) field model instrument, the Surtronic 3+, was used to measure average roughness ( $R_a$ ) of all samples. It has a diamond stylus with a  $5\mu\text{m}$  tip radius and a 6mm-radius red ruby skid, against which the vertical position of the stylus is measured by means of a piezo-electric transducer. The maximum traverse length of the stylus is 25mm, and the gauge (vertical) range for measurements was  $100\mu\text{m}$ . Measurements were made in different areas on each sample: a minimum of five if results were consistent, but an average of 10 (and as many as 15) if results were inconsistent. The instrument was calibrated against a metal standard before each sample was measured and checked every five measurements if there were more than five. Data were analyzed with the instrument's software (ST3PLUS), and the  $R_a$  measurements were averaged.

For proper statistics, data are analyzed by stylus profilometers in multiple cutoff lengths (also referred to as sampling lengths), with five considered the minimum for each calculation. Specification of cutoff length is mandated by the American Society of Mechanical Engineers, and longer cutoff lengths are recommended as roughness increases [14, 15]. Data presented here were analyzed in cutoff lengths of 8mm, recommended when  $R_a$  exceeds  $10\mu\text{m}$ . Since the actual traverse length of the instrument did not allow travel of five times the cutoff length, however, results calculated by the software may not be as precise as for an instrument that has full capability.

### *Reflected-light image analysis (RLIA)*

Reflected-light image analysis is a term that we coined to describe computer-analyzed measurement

of raking light reflected from sample surfaces. To our knowledge, it is the first time that this technique has been applied to stone surfaces, although computers have been used to assess texture by analyzing brightness of light microscope and scanning electron microscope images on metal surfaces, calibrated by direct measurement of roughness [16]. Cross-sections of stone, however, have been studied with image analysis to determine the fractal properties of porosity [17, 18] and measure roughness [19].

The image of each replica surface was acquired by a 1.3cm ( $\frac{1}{2}$ in) single-chip RGB camera (World Video Automaticam) with a Nikon 55mm Micro Nikkor lens set at f4. The ensemble was mounted on a fixed stand, its optical axis perpendicular to the sample surface. The light source was a Fostec 21V 150W tungsten halogen EJA lamp; the iris diaphragm was open, and the rheostat was set at 60%. Light was distributed through two 5cm (2in) fiber optic line generators set at fixed angles ( $24^\circ$ ) that evenly illuminated the sample area. Shutter speed was 1/1000sec. Using a Leica image analysis workstation, an area measuring  $5.25\text{cm}^2$  was captured in monochrome in a frame of  $538 \times 394$  pixels (211,972 total); each pixel corresponded to  $2.5\mu\text{m}^2$ .

At least three measurements were made on each blasted and control area, and samples were rotated between measurements to cancel directional effects. Data were plotted, the X-axis representing gray values from 0 (black) to 255 (white) and the Y-axis representing the pixel count. 'Maximum pixel count' was the average of the three measurements.

#### *Microdrop water absorption testing*

Microdrop water absorption testing, which measures the absorption time of a fixed quantity of water, was used to complement other measurements of surface roughness. The test may be a valid indicator of damage to stone since water is the principal agent of deterioration, and it has the advantage that it can be done with minimal and inexpensive equipment. A modified version of a test developed by other researchers was used [20, 21]. Samples were stored in a stable environment ( $21^\circ\text{C}$  and 45% RH) for more than 10 days before measurement, drop size was  $10 \pm 2\mu\text{l}$ , and dropping distance was 2.5cm. At least five measurements were made on each sample and averaged. Polished stones were not measured after preliminary testing showed that times were in the same range as for water drops on glass, which disappeared by evaporation after an average of 32 minutes.

#### *Visual and tactile evaluation*

Tactile and visual evaluations might be overlooked

for assessing roughness, but it has been observed that they can be surprisingly effective [1, 22, 23]. Three examiners evaluated the 64 blasted surfaces visually and by touch. These were compared to control areas and rated according to verbalized criteria like 'slight', 'moderate' and 'significant' changes in roughness, as well as the presence or absence of a step at the interface between blasted and control areas.

Later on, six blindfolded examiners selected smaller sets of marble, limestone and sandstone samples that serve as 'standards' for presentation of data in this paper. These were chosen by tactile comparison between samples of each material, and the intention was to represent the broadest possible range of roughness with distinctly different samples. Samples were ranked with the number '1' assigned to the smoothest surface and progressively higher numbers to rougher surfaces. Although most samples were chosen from those produced during the second phase, some samples blasted in the laboratory during the first phase were included because they had intermediate roughness not produced in the second phase.

### **Results and discussion**

The second phase generated a large quantity of data [12]. Much of it proved repetitive, however, because only small changes occurred on walnut-shell- and water-blasted samples, and significant changes were limited to samples blasted with Black Beauty. Moreover, an equipment problem resulted in repetition of blasting that produced an anomalous result for samples blasted with glass shot at low pressure: surfaces were clearly rougher than those blasted at twice the pressure. Finally, all instrumental techniques had difficulty measuring the roughest surfaces or produced data that did not reflect obvious changes that had occurred.

In order to facilitate comparison of results for the different measuring techniques, the smaller sets of samples were selected by touch to serve as standards for each of the three stone types, as described in the previous section. Measurements made on these standards by stylus profilometry, reflected-light image analysis and microdrop water absorption testing are presented in Tables 1 through 3 and described below.

#### *Stylus profilometry*

Average roughness measured by the stylus profilometer invariably increased in the same order as the standards chosen by tactile comparison. This is most clearly reflected by data for marble because the instrument was able to measure all samples

Table 1 Marble samples ranked by touch in order of increasing roughness and measured by stylus profilometry, microdrop water absorption testing, and reflected-light image analysis (RLIA)\*

Marble surface	Touch	Stylus $R_a$ [ $\mu\text{m}$ ]	Microdrop (minutes)	RLIA Max. pixels (thousands)
Polished control	1	0.85 (0.4)	—	8.6 (0.1)
Sawn control	2	6.5 (0.7)	21.1 (1.7)	5.7 (0.5)
Sawn, glass shot (LP)	3	13.8 (2.1)	5.6 (0.8)	5.5 (1.0)
Polished, Black Beauty (LP)	4	17.0 (1.4)	3.5 (0.7)	3.8 (0.09)
Polished, Black Beauty (HP)	5	29.2 (2.3)	1.8 (0.4)	3.4 (0.04)

\*Standard deviations are given in italics between parentheses.

Table 2 Limestone samples ranked by touch in order of increasing roughness and measured by stylus profilometry, microdrop water absorption testing, and reflected-light image analysis (RLIA)\*

Limestone surface	Touch	Stylus $R_a$ [ $\mu\text{m}$ ]	Microdrop (minutes)	RLIA Max. pixels (thousands)
Smooth-sawn control	1	17.3 (3.3)	2.8 (0.6)	3.5 (0.2)
Rough-sawn control	2	24.7 (3.9)	1.6 (0.4)	2.9 (0.3)
Glass shot (LP)	3	37.2 (5.7)	0.04 (0.02)	2.2 (0.1)
Water (HP)	3	39.4 (3.7)	0.12 (0.1)	2.7 (0.3)
Glass bead (lab blasted)	4	46.0 (3.7)	—	—
Alumina (lab blasted)	4	46.8 (4.0)	—	—
Black Beauty (LP)	5	51.8 (7.8)†	0.027 (0.003)	2.1 (0.07)
Black Beauty (HP)	6	52.7 (6.1)‡	0.030 (0.003)	1.9 (0.03)

\*Standard deviations are given in italics between parentheses.

One third (†) and one half (‡) the measurements 'over range' of the instrument.

Table 3 Sandstone samples ranked by touch in order of increasing roughness and measured by stylus profilometry, microdrop water absorption testing, and reflected-light image analysis (RLIA)\*

Sandstone surface	Touch	Stylus $R_a$ [ $\mu\text{m}$ ]	Microdrop (minutes)	RLIA Max. pixels (thousands)
Smooth-sawn control	1	28.6 (2.8)	0.15 (0.07)	2.1 (0.1)
Rough-sawn control	2	29.8 (1.8)	0.15 (0.07)	1.9 (0.1)
Glass shot (LP)	3	38.5 (2.5)	0.025 (0.003)	1.6 (0.03)
Black Beauty (LP)	4	40.1 (6.6)	0.030 (0.005)	1.9 (0.02)
Black Beauty (HP)	5	61.7 (6.1)†	0.023 (0.003)	1.9 (0.03)

\*Standard deviations are given in italics between parentheses.

†Half the measurements 'over range' for the instrument.

without difficulty (Table 1). When the roughest limestone and sandstone samples were measured, the instrument often read 'over range', apparently because the gauge range of the Surtronic 3+ was insufficient (Tables 2 and 3). Flame-finished granite could not be measured at all by the Surtronic 3+ because its macro-roughness is too great. It should also be noted that although the equipment appears easy to operate, experience was found to be necessary to produce good results, particularly with respect to the Surtronic 3+ software.

Measurement with a more expensive research stylus profilometer (in the range of US\$50,000) might be effective in measuring rougher stones, because the electronics and hardware allow measurement of higher gauge ranges. Nevertheless, inconsistent data published for abrasive-blasted sandstone measured by such an instrument (a Form Talysurf) raise doubts about the applicability of the technique on stone [3].

A significant problem may be lack of increase in average roughness when stone becomes more eroded. After limestone samples were blasted with the mildly abrasive glass shot, for example, increases in  $R_a$  were measured (Table 2), and these measurements may be correlated with visibly deeper pits around grains than on control samples, apparently produced by removal of the soft matrix which binds grains together. After blasting limestone samples with the most aggressive abrasive (Black Beauty) at two different pressures, however,  $R_a$  values were almost the same although there was a much greater step (surface recession) between control and blasted areas in the case of the sample blasted at higher pressure. More widely spaced irregularities of texture, known as waviness, were also observed on the sample blasted with Black Beauty at higher pressure, but measurement of waviness is precluded by the skid on the Surtronic 3+. In a similar fashion, only the soft matrix which binds the grains of hard sedimentary stone together is reportedly removed during the initial stages of weathering, and increases in  $R_a$  are measured [7, 24]. After decades outdoors, however, surfaces of weathered stones are found to maintain constant roughness as grains are dislodged, although they may recede significantly.

There may also be a fundamental problem with using stylus profilometers on stone. The morphology of stone is quite different from the machined metal surfaces for which the instrumentation was developed, and the stylus did not appear to measure the stone samples' deep pits, which are generally absent from such metal surfaces. Moreover, computation of the average roughness parameter ( $R_a$ ) uses mathematical functions developed for measuring metal surfaces that, for instance, assume

Gaussian distribution of peak heights around a mean line, and these functions may not correctly characterize the different types of surface roughness found on stone.

Average roughness ( $R_a$ ) can also be calculated by measuring the reflectance of a laser beam [5, 25], and data produced during the first phase generally correlated well with stylus profilometry data for replicas of the same surfaces [11]. Laser measurements also tended to confirm that stylus data analyzed at cutoff lengths recommended by metrologists were more accurate. Laser triangulation profilometry should provide better measurements than stylus profilometry since data for more points are averaged and a laser can 'read' significant depth and height of peaks. For most masonry, however, replicas are necessary to prevent interference of color, and equipment costs start around US\$25,000.

#### *Reflected-light image analysis (RLIA)*

RLIA plots follow a predictable pattern with changes in roughness produced by blasting the smoothest samples, exemplified here by polished marble (Figure 1) but also shown for polished granite and glazed tile. Replicas of the polished surfaces produced narrowly distributed plots. As the smooth surfaces lost polish by blasting with mild abrasives, plots became relatively symmetrical bell-shaped curves. With increased roughness produced by more aggressive blasting, peaks broadened and lost height. Plots for limestone and sandstone surfaces showed less change after blasting and smaller differ-

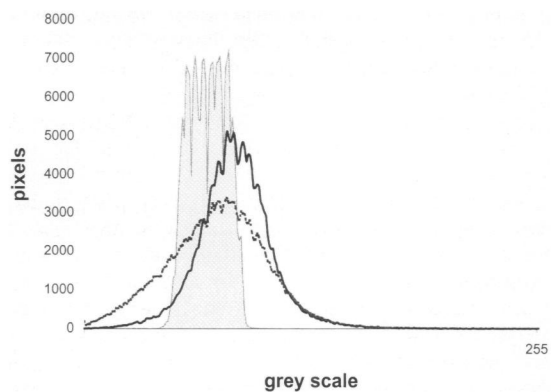


Figure 1 Reflected-light image analysis of replicas of marble samples representing the range of roughness. The plot for a polished surface is indicated by hatching; a sawn surface, by the upper trace; and a surface blasted with Black Beauty at high pressure, by the lower trace.

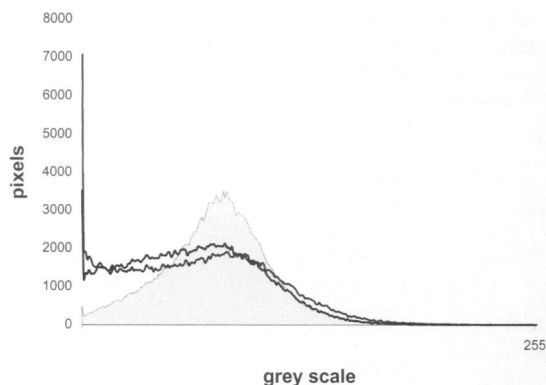


Figure 2 Reflected-light image analysis of replicas of limestone samples representing the range of roughness. The plot for a sawn surface is indicated by hatching; a surface blasted with glass shot at low pressure, by the upper trace; and a surface blasted with Black Beauty at high pressure, by the lower trace.

ences between blasted samples. Replicas of smooth-sawn limestone surfaces produced symmetrical bell-shaped curves before blasting (Figure 2). After surfaces were roughened by blasting, plots flattened and pixel counts increased to the left of the peak (dark side of the spectrum), forming 'plateaus'. Although significant differences are apparent in digital images of blasted samples of limestone (Figure 3), only small differences can be observed between plots. Replicas of the relatively rough surfaces of sawn sandstone samples produced broad plots that are slightly asymmetrical (Figure 4). After blasting, higher pixel count plateaus again formed in the dark portion of spectra, but change was even less than for limestone samples, and differences between plots for blasted surfaces even smaller.

Significant further information may be derived by image analysis, but for this experiment the only parameter measured by the image analysis program that correlated in any consistent way with changes in roughness of marble and limestone measured by other techniques was the 'maximum pixel count' (Tables 1 and 2). This mostly decreased as roughness increased according to tactile comparison and stylus profilometry. Increased roughness of sandstone measured by other techniques, however, did not correlate with 'maximum pixel count' (Table 3).

Because a larger area can be analyzed than by other techniques, image analysis has the potential to provide a more representative indication of surface texture. To measure the same area that had been analyzed by the computer with a Surtronic 3+, for example, would require hundreds of 2.5cm-long scans. Moreover, the larger area might take

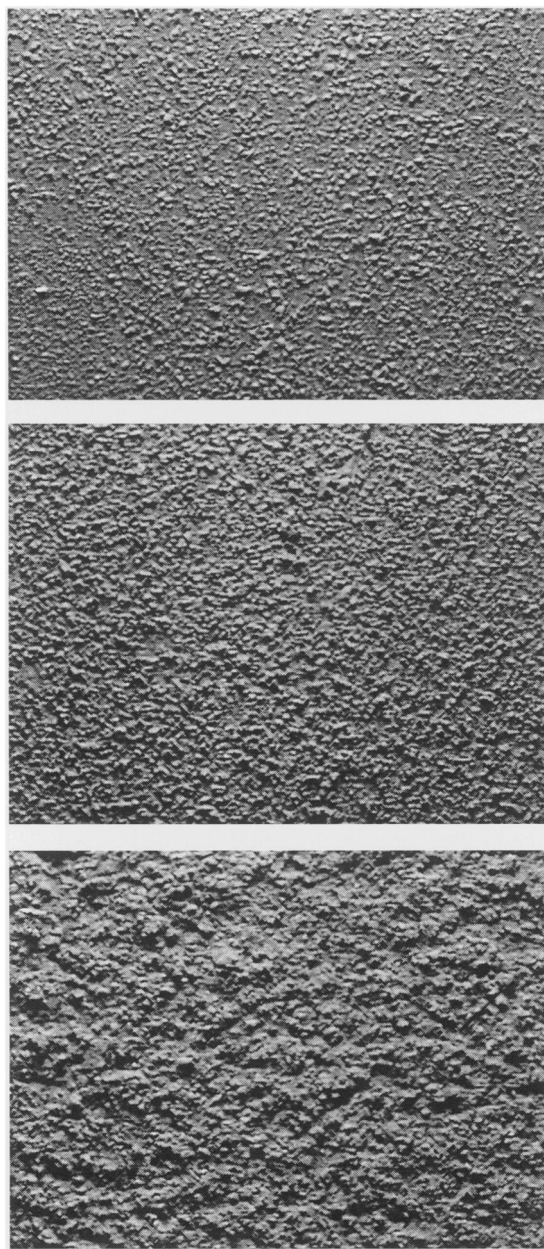


Figure 3 Digital images of limestone replicas analyzed in Figure 2: a sawn surface (top), a surface blasted with glass shot at low pressure (center), and a surface blasted with Black Beauty at high pressure (bottom). Imaged areas measured approximately  $2 \times 2.5\text{cm}$ .

into account any waviness introduced by non-uniform blasting. Our technique did not produce useful results for rougher surfaces, however, and more

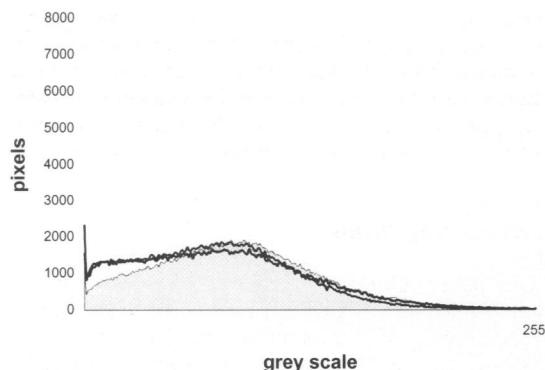


Figure 4 Reflected-light image analysis of sandstone samples representing the range of roughness. The plot for a sawn surface is indicated by hatching; a surface blasted with glass shot at low pressure, by the lower trace; and a surface blasted with Black Beauty at high pressure, by the upper trace.

testing is required. Image analysis equipment is currently in the US\$10,000 range and is becoming increasingly common in many laboratories.

#### *Microdrop water absorption testing*

The time of water absorption should decrease with increased surface roughness, and faster water absorption often correlated well with increased roughness measured by other techniques (Tables 1 through 3). Data showed, however, that there was little variation in time after a certain roughness had been reached. For example, water absorption was similar for sandstone blasted with glass shot and Black Beauty at both pressures, although profilometry and touch evaluation showed significant differences in roughness (Table 3).

Sandstone samples blasted with walnut shells had anomalous results, showing longer water absorption times [1.3 (0.2) minutes for low pressure blasting and 1.5 (0.4) minutes for high pressure blasting] than control samples [0.15 (0.7) minutes]. This is attributed to burnishing of the sandstone binder by the abrasive. Deposition of oil by the walnut shells was also considered as a possible explanation, but the same phenomenon was not found on limestone samples. Flame-finished granite also showed slower water absorption after blasting with all abrasives, suggesting that surfaces of the samples had been so altered by the flame-finishing process that they were smoothed even by harsh abrasives such as Black Beauty.

The test proved relatively easy and inexpensive to administer in the laboratory. Results confirmed that it may be useful as a complement to other test

methods although it would be difficult to use in the field.

#### *Visual and tactile evaluation*

Perception of change for the 64 samples evaluated visually and by touch appeared to be excellent when results were compared to data for other tests [12]. Observed differences in surfaces were often noted more frequently than tactile differences, but re-examination of samples indicated that visual observations were influenced by slight color changes that reflected removal of superficial surface accretions rather than loss of stone. Increased roughness was invariably felt when other tests showed significant change in roughness, and it was concluded that touch is more reliable than visual evaluation. Thus, the selection of standards presented in Tables 1 through 3 was made by touch. It should also be noted that there were some discrepancies in evaluations of samples when changes in roughness were rated according to verbalized criteria, whereas consensus was easily achieved when samples were ranked by comparison to each other in order of increasing roughness.

The fact that data for other techniques shown in Tables 1 through 3 generally follow the same trends as touch evaluation indicates the validity of the tactile method. The technique also has the advantage that it was effective over the entire range of roughness. Assessment could be improved by using a standard set of samples with a systematic increase in roughness for comparison against blasted samples, just as the ASTM surface profile comparator is used for metals [26].

#### *Applicability in the field*

It should go without saying that degraded stone of any type is far more susceptible to damage than the unweathered samples tested during our study. Hence, extrapolation of results should not be made to surfaces of historic masonry. For example, water blasting had only small effects on test samples, while weathered tombstones may be easily damaged when blasted at similar pressures [27].

Except for tactile comparison, laboratory techniques tested in our study have many limitations for use in assessing cleaning methods on stone buildings or sculpture. They cannot be used directly in the field, and destructive sampling or replication of surfaces would be required for measurements to be made in the laboratory. Furthermore, in most cases stone that requires cleaning is already relatively rough, and in those instances the techniques would not be very reliable, as shown by test results for rougher surfaces. Moreover, as was demonstrated by the failure of the stylus profilometer to



measure test samples of the highly irregular flame-finished granite, techniques can often be used only on smoothly finished ashlar, thereby excluding tooled or rusticated stones from measurement.

The usefulness of roughness measurement in the field is also limited by characteristics of stone that requires cleaning. The roughness of a dirty stone surface before cleaning is necessarily unknown, and it usually increases after cleaning even when no stone is removed because surface accretions tend to smooth surfaces by filling pores. Hence, if one wanted to compare results for several cleaning techniques, one would be limited to comparing areas only estimated to have the same roughness and dirtiness. An even more significant problem is that condition of stone tends to vary considerably over the surface of a weathered building or sculpture. Thus, stones in different states of deterioration and dirtiness cannot be cleaned using exactly the same blasting parameters if losses are to be minimal and the result is to be a visually even surface. Difficult-to-control factors such as dwell time and malfunctioning of equipment may also be significant for producing damage, as was illustrated by the increased roughness produced by low-pressure glass shot-blasting during our experiment. Hence, judgment and sensitivity on the part of the person doing the cleaning are critical and cannot be replaced by even the best specifications.

## Conclusion

Results of testing showed that touch evaluation was the most successful method of evaluating roughness over a wide range of stone surfaces. Along similar lines, experts at a recent Dahlem Workshop advised lowering the accuracy of measurement for assessment of surface roughness in connection with cleaning [28]. Instrumental techniques were not satisfactory for comparing damage on abrasive-blasted stone when surface roughness was high, i.e., in the same range as most weathered stone. More sophisticated techniques such as laser profilometry or image analysis might be used in laboratory situations, but in the field they would not make sense when such a simple technique as touch evaluation can bridge the range of surface texture found on stone, including both roughness and waviness. For increased accuracy, a set of standard roughness samples for each stone should be used for comparison. Touch evaluation can also be particularly effective across the boundary of a test-cleaned area.

Nevertheless, given the variations in condition and dirtiness of weathered stone, measurement of roughness can only provide limited, complementary information for evaluation of damage induced by

cleaning. Moreover, cleaning by a well-trained craftsman or professional stone conservator who makes adjustments according to variations in condition is superior to tightly specified cleaning parameters, particularly when a valuable masonry structure or stone sculpture is the object of treatment.

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## Suppliers of materials

Acryloid B-72: Rohm and Haas, 100 Independence Mall West, Philadelphia, PA 19106, USA.  
Black Beauty: Reed Minerals, 1011 Mumma Road, Wormleysburg, PA 17043, USA.  
Carrara marble, glazed tiles and quarry tiles: Morris Tile Distributors, 2525 Kenilworth Avenue, Tuxedo, MD 20781, USA.  
Glass shot (MS-XL): Cataphote, 1001 Underwood Drive, Flowood, MS 39208, USA.  
Granite: Hilgartner Natural Stone Company, 7007 Wisconsin Avenue, Chevy Chase, MD 20815, USA.

Leica Q500MC: Leica Cambridge Ltd, Clifton Road, Cambridge CB1 3QH, England.  
 Silicone Dissolving Solution: AMTEX Chemical Company, 890 Fern Hill Road, West Chester, PA 19380, USA.  
 Silicone RTV rubber: Dow Corning, PO Box 995, Midland, MI 48686, USA.  
 Surtronic 3+ profilometer: Rank Taylor Hobson Inc., 2100 Golf Road, Rolling Meadows, IL 60008, USA.  
 Walnut shells (Shelblast AD 10.5 B Nutshell): Agrashell, 4560 East 26th Street, Los Angeles, CA 90040, USA.  
 S.S. White Airbrasive Unit (Model-K) and abrasive powders: S.S. White Technologies, 151 Old New Brunswick Road, Piscataway, New Jersey, USA.

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**Résumé**—Afin de mesurer la rugosité de la pierre nettoyée par jet abrasif, on a testé plusieurs techniques: la profilométrie par palpeur mécanique, l'analyse d'image par réflexion, et l'évaluation visuelle et tactile. Des mesures du temps d'absorption de microgouttes ont également été effectuées à titre complémentaire. Les techniques instrumentales ont montré des rapprochements significatifs entre les mesures de surfaces de rugosités voisines sur des pierres très altérées, ainsi que sur des surfaces de pierres travaillées et finies à la flamme. La comparaison tactile des surfaces s'est révélée être la technique la plus pratique et la moins coûteuse. Cependant, sur des enduits historiques, les salissures et les irrégularités superficielles dues au vieillissement limitent le choix de la rugosité comme indicateur de la qualité des techniques de nettoyage.

**Zusammenfassung**—Die Möglichkeiten der sensorischen Oberflächenabtastung und der Lichreflexuntersuchung kamen zusammen mit einer visuellen und taktilen Beurteilung bei der Bewertung der Oberflächenrauheit von strahlbehandelten Steinen zum Einsatz. Ergänzend wurde die Absorptionszeit von Mikrowassertropfen gemessen. Die mit instrumentellen Techniken durchgeführten Messungen zeigten signifikante Fehler bei bestimmten Gesteinsoberflächen. Der Tast-Vergleich von Oberflächenstrukturen stellt dagegen eine praktische und kostengünstige Untersuchungsmöglichkeit dar. Auf historischem Mauerwerk begrenzen jedoch Verschmutzungen und ungleichmäßige Bewitterung den Nutzen, die Oberflächenbeschaffenheit als Meßgröße bei der Bewertung von Reinigungstechniken einzusetzen.

**Resumen**—Con el fin de evaluar la aspereza o tosquedad de la piedra dañada o tratada por abrasión se ensayaron técnicas como la perfilometría de aguja, análisis de la imagen por luz reflejada y evaluación visual/táctil. También fue probado el tiempo de absorción de agua por microgota como técnica complementaria. Las técnicas instrumentales mostraron limitaciones significativas cuando se midieron superficies de asperezas similares en piedra envejecida naturalmente por agentes ambientales y por el paso del tiempo, así como en superficies similares de piedra trabajada con herramientas. La comparación táctil de las superficies se mostró como un medio más práctico así como una técnica efectiva e interesante en relación al coste. En las estructuras de cantería histórica, sin embargo, los depósitos de suciedad y el envejecimiento irregular por el medio ambiente limitan la utilidad de la aspereza como propiedad a ser medida al evaluar técnicas de limpieza.