MEASURING SURFACE ROUGHNESS: THREE TECHNIQUES

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SUMMARY
This preliminary study compared three techniques to determine their range of applicability for measurement of surface roughness of stone: stylus profilometry; laser triangulation profilometry; and reflected light image analysis, a technique new to stone conservation. Samples of three materials were measured, representing a range of finishes from high polish (marble) to medium roughness (brick paver) to rough (sawn limestone). To measure changes in roughness from cleaning, one third of each sample was blasted with glass beads and another third with aluminum oxide. Laser triangulation profilometry and reflected light image analysis required that replicas of the surface be made for accurate measurement. Red silicone rubber replicas gave the best results, allowing comparison of roughness between materials with differently colored surfaces. The paper analyzes data, compares the results of the different techniques, and discusses their limits of applicability.

1 INTRODUCTION

The present study stems from an earlier experiment in which changes in surface roughness after cleaning polished marble were successfully measured using reflectometry [1]. The question then arose as to what methods could effectively be used to measure cleaning changes on masonry materials having rougher surfaces, which cannot be measured with reflectometry. A secondary consideration was to find a method that could be used in the field. A survey of the stone conservation literature found only one text that considered the accuracy and applicability of available methods, but focussed principally on physical measurement instruments like stylus profilometers and depth gauges [2]. Most articles described use of a single technique to measure damage during cleaning or artificial aging experiments.

For this preliminary study, three techniques were selected for comparison. Stylus profilometry, developed and widely used for measuring surface roughness of metals, has been most frequently used in measuring roughness of stone [3-5], but little information is given in the stone conservation literature beyond the name of the instrument used. Recently laser triangulation profilometry has been used for measuring damage to brick, even in the field [6]. Also referred to as laser profilography or laser surface profilometry, the technique has begun to be applied to measure minute changes resulting from cleaning of other artist's materials [7]. Reflected light image analysis is new to stone conservation, although image analysis has a long history of use for measuring texture [8]. It had been hoped that a line profilometer in conjunction with a stereomicroscope [9,10] could be used for our experiments but the equipment and software were not commercially available.

2 EXPERIMENTAL

Stylus profilometry, laser triangulation profilometry, and reflected light image analysis were used to measure roughness of polished marble, sawn limestone, and a brick paver. Each sample was divided into three sections: one served as a control, the second was blasted with glass beads, and the third, with alumina powder. Silicone rubber replicas were also made of all the samples.

2.1 Sample Materials

The Carrara marble sample (15cm x 15cm square, approximately 1cm thick) was cut from a commercial tile. The Indiana limestone sample was a 5cm thick prism with a 6cm x 23cm top sawn surface. The red brick paver was approximately 20cm x 10cm x 5cm. Both the narrow and wide (bedding) faces of the brick were blasted, but because the wide face had deep pits, measurements were made on the narrow face.

2.2 Sample Preparation

The blasting of the samples was carried out in the laboratory using a pencil micro-abrader (S.S. White Airbrasive Unit Model-K). The glass beads were S.S. White abrasive powder #9 (44mm in average diameter), and the alumina powder was S.S. White abrasive powder #3 (50mm in average diameter). Unblasted areas were protected with plastic tape during blasting. The tip of the nozzle (f = 0.018") was held about 3/4" from the surface, with a flow rate of the abrasive powder approximately 10g/min at 60psi. The blasting was carried out by scanning first in horizontal and then vertical rows using a circular motion, attempting to achieve an even-looking surface. Blasting the polished marble with glass beads required extra passes to produce this surface.

2.3 Replica Preparation

Silicone rubber replicas of the masonry materials were made for laser triangulation profilometry and reflected light image analysis because color variations of the masonry would bias results for those techniques. Initial measurements on white silicone rubber replicas showed the white color to be too reflective for good results. Red silicone rubber replicas were subsequently prepared and used successfully.

Surfaces to be replicated were first brush-coated with a 5% w/v solution of Acryloid B-72 (Röhm & Haas) in acetone to avoid adherence of the silicone rubber to the stone, as well as staining. The replicas were made with Dow Corning silicone rubber (3110 RTV for the white and 3120 RTV for the red) with standard cure catalyst #1 in a 10:1 w/w ratio. The silicone rubber was poured onto the stone surface, which had been framed with a plasticine "dam" to hold the liquid, and a vacuum was drawn on the silicone rubber. The vacuum was drawn approximately ten times. The silicone rubber cured for 24 hours and was removed from the surface of the stone. Small amounts of silicone rubber could be seen afterwards at low magnification in the interstices of the limestone, but replication of all the surfaces was generally excellent.

The replica of the marble tile even reproduced brushstrokes of the Acryloid B-72, particularly for the polished control. Hence the surface was cleaned with toluene to remove the acrylic coating, and a second replica was made. Subsequent experimentation showed that a more dilute solution (2%), which would reduce the possibility of brush strokes, effectively prevented staining. If staining were not an issue, successful replication of a number of uncoated stone materials later showed coating to be unnecessary for release in most cases; however, silicone rubber did adhere tenaciously to sandstone.

The set-up for reflected light image analysis required replicas of uniform thickness. These proved difficult to realize for the relatively viscous 3120 silicone rubber using the standard dilution. Better levelling was achieved by using a 20:1 w/w ratio, but differences in thickness could still be measured. These were finally eliminated by applying silicone rubber caulk to the reverses of the replicas and placing them between heavy Plexiglas sheets clamped together with 3/16" spacers in between.
Experiments were also made with a methylmethacrylate reproduction material (Facsimile made by Flexbar), recommended by metrologists for field replication of materials to be measured with a laboratory stylus profilometer. However, replication of the masonry surfaces appeared poor compared to the silicone rubber. Moreover, variable coloration of the replica, visible at low magnification, precluded use of the material for laser triangulation profilometry and reflected light image analysis. Producing a hard positive cast of the silicone rubber replica remains a possibility.

3 RESULTS

3.1 Stylus profilometry

The samples were measured with a relatively inexpensive field model Surtronic 3+ profilometer (Rank Taylor Hobson Ltd). It has a diamond stylus with a 5mm tip radius and a 6mm radius red ruby skid. The maximum traverse length is 25mm, and the maximum gauge (vertical) range is 500mm. The resolution is 1mm for horizontal measurements and 10nm for vertical. The instrument is calibrated against a standard by the operator. It is computer operated, and data were analyzed through the ST3PLUS program.

Roughness average (Ra) is the primary statistical parameter of several used by metrologists to describe surface texture. It is defined as the arithmetic average of the absolute values of the profile height deviations recorded within the evaluation length and measured from the mean line:

$$R_a = (1/L)\ ð_0^L \_\ y(x)\_dx$$

where y(x) is the surface profile, sampled by a set of N points y_i over the length L.

The Ra may change significantly depending on the cut-off or sampling length (Lc). The upper limit for Lc on the Surtronic 3+ is 2.5mm. However, the software can recalculate the Ra using an Lc of 8mm. This longer sampling length is recommended for surfaces with an Ra over 10mm [11,12].

Table I shows average roughnesses obtained at the 2.5mm sampling length and recalculated for an 8mm sampling length. Data were averaged from at least five measurements but in most instances 10 or 15 were used. The apparatus was unable to "read" the rougher surfaces; in these cases, the average presented in the table is artificially low. Furthermore, even when the machine gave a roughness measurement, it is likely that the tip "skidded" over the surface without measuring deeper pits.

3.2 Laser triangulation profilometry (LTP)

A custom-made laser triangulation profilometer was used to measure the surface profile of the samples as well as both white and red silicone rubber replicas. This consisted of an Aromat laser distance sensor (LM200 RAC) mounted on an X-Y translation stage. A computer with an analog to digital board was used to digitize the laser distance sensor's signal, control the stage positioning, and process the surface profile.

The laser distance sensor projects a beam of light perpendicularly to the specimen surface. Its light source is a low power (<1.9mW) laser diode (red, 670nm). The sensor triangulates the surface position by imaging the laser spot with an adjacent lens to a position sensitive detector. The device calibration is tested by translating it towards a stationary surface using a precision stage.

The results are expressed in Ra (mm), averaged for three areas on each sample (Table II). Each area (1 cm^2) was scanned in ten lines which contained 5 blocks of 40 reading points each, thus totalling 2000 reading points per cm^2. Each point is equivalent to $50mm^2$. The reproducibility of each area was excellent. Since the standard deviations calculated for the average roughness of each area overlapped, results were subjected to an analysis of variance which confirmed that real differences existed between the means of each area.

Even a cursory examination of the data shows some wide variations in results between the masonry surfaces and their replicas. In the case of marble, artificially high measurements can be attributed to the relative transparency of the stone. Light returning to the displacement sensor from below the surface of the marble exaggerated the signal. The LTP signal accuracy is also adversely affected when measuring highly reflective surfaces, such as polished marble. Mirror-like surfaces scatter very little light in directions other than the direct reflection; therefore, a small amount of light is collected by the sensor's lens, resulting in a noisier signal. In the case of the limestone, measurements would have been affected by the occasional presence of quartz grains and traces of iron oxides. By contrast, similar results for the red replica of the brick and the brick surface reflect the fact that they are similar in color and confirm that the silicone rubber reproduces the brick surface accurately.

Comparison of measurements for the white and red silicone rubber replicas of the same surface shows that the white replicas "appear" smoother. This erroneous result is because the area around the laser spot on the white silicone rubber tended to glow (the laser spot "bloomed"). The sensor's effective footprint was resultantly much larger and therefore averaged or smoothed the surface features. The red silicone rubber demonstrated none of this effect.

3.3 Reflected light image analysis (RLIA)

Reflected light image analysis reduces three-dimensional information to two-dimensional representation, measuring texture indirectly. It was carried out on the white and red silicone rubber replicas with a video microscope, assembled with a 55 mm Micro-Nikkor lens (set at f4) and a single 1/2" RGB chip camera (World Video Automaticam). These were mounted on a fixed stand with its optical axis perpendicular to the sample surface. The light source was a Fostec fiber optic 21V 150 W tungsten halogen EJA lamp, controlled by rheostat (set at 60%) and with the iris diaphragm open, distributed through two 2" fiber optic line generators. These were set at a fixed angle (24°), illuminating the sample with even raking light. Shutter speed was 1/1000 sec. The image analysis workstation was a Leica Quantimet 500.

An area of $5.43cm^2$ was captured in monochrome in a frame of 538 x 394 pixels (211,972 total); each pixel corresponded to $2500mm^2$. The distribution of pixels on a grey scale which ranged from 0 (black) to 256 (white) was presented in a histogram. The value of the highest bar was indicated on the pixel (y) axis. At least three different areas were randomly selected and measured on each sample. The values for the three areas measured on each sample were similar.

Reproducibility of results proved to be predicated on a fixed set-up and the use of replicas of the same substance and uniform thickness. When the lighting conditions, color of the sample, its reflectivity, or degree of tilt from the optical axis was changed, the shape and position of the peak in the histogram changed. Figure 1 shows the difference in the peak's shape and position between a white and red silicone rubber replica of the same surface (note that the y axes of all the histograms are on different scales, indicated by the number of pixels for the highest bar). Figure 2 shows differences for the same red replica examined at two different light intensities. Figure 3 shows the effect that changes in tilt can introduce, representing measurements made on a slightly wedge-shaped replica that was rotated.

The shape and position of peaks in the histograms provide qualitative measures of surface texture, although uncertainties remain regarding interpretation. For the polished marble surface, the peak of the histogram appears as a high block of reflected light (Figure 4a). As the surface roughens, the block becomes a relatively symmetrical bell-shaped peak (Figure 4b,c). With increasing roughness, the peak broadens while losing height, illustrated by the brick sample (Figure 5). On the limestone, a spike is present at the dark end of the grey scale, which can be attributed to deep shadows cast by its rough surface; this spike increases and the central peak flattens after blasting (Figure 6).

The intention was to find a single parameter for surface texture with which comparisons could be made between samples. The number of pixels of the highest bar in the peak towards the center of the histogram, averaged from at least three different areas on each sample, can be inversely correlated with roughness, giving a quantitative measure (Table III). However, this measure does not encompass all the information provided by RLIA, and several parameters may be necessary for good characterization. More experimental work is required.

4 DISCUSSION

In reviewing results for the different techniques, distinctions can be made between control and blasted areas, which were clearly rougher for all samples. By contrast, little difference was apparent between surfaces of the same samples blasted with glass beads and with alumina.

Average roughnesses obtained with the stylus profilometer and LTP can be compared in Table IV. Polished surfaces, exemplified by the polished marble sample, are better characterized by the stylus profilometer, given the difficulties described above for LTP. These are reflected in an order of magnitude difference in the values. However, from a practical standpoint, one rarely finds outdoor stonework which requires cleaning and has any degree of polish, with the possible exception of granite.

The stylus profilometer produced less satisfactory results for rougher surfaces, such as those of blasted limestone. It requires a longer cut-off length to approach values obtained with LTP, and a longer gauge length is required to measure deep pits. Only an expensive laboratory model profilometer could measure these types of surfaces, and field measurement would then require use of hard replicas or removal of a core. Finally, stylus profilometers were developed for measuring the roughness of metals, which are not porous, i.e., not having deep holes. Therefore, computation of the average roughness parameter (Ra) may not adequately characterize the surface roughness of masonry materials. Other parameters such as skewness, a measure of the asymmetry of the profile about the mean line, may be necessary for making this relevant to stone.

LTP appeared to be more reliable than the stylus profilometer for rougher surfaces. Although data have a wide spread, the average is taken from far more points. LTP, through appropriate image analysis systems, can also produce line profiles and three-dimensional representations of the surface.

RLIA is a promising technique, particularly because it can rapidly measure large surface areas, but the full potential and limits of applicability have yet to be determined. Results cannot be compared directly with the two other methods in the absence of an Ra for the RLIA, although an Ra might be calculated from a line profile that the computer software can produce. Calibration of the system would be required, which would contribute as well to comparison between laboratories. RLIA can also produce an image of the surface, and the image analysis system can easily process data, e.g., subtracting a control from a blasted sample.

The purpose of this study was to compare measurement techniques, not to compare damage from different cleaning techniques. Nevertheless, preliminary evidence suggests that roughness measurements are not sufficient to evaluate damage induced through cleaning. Similar roughnesses, as those produced by blasting with glass beads and alumina, do not necessarily reflect equal damage done to the surface at a microscopic level. Nor do roughness measurements indicate the amount of material removed.

5 CONCLUSION

In this preliminary study none of the three techniques was found to be entirely satisfactory for measuring roughness of the three masonry materials. In nearly all cases the techniques require use of replicas or destructive sampling if field measurement is desired. All require expensive instrumentation and skilled operators for good results. However, the newest technique for measurement of stone, reflected light image analysis, shows promise and will be explored further.

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Table I. Average roughness measured with a stylus profilometer at an evaluation length of 25mm and cut-off length of 2.5mm, also given as recalculated at a cut-off length of 8mm. Standard deviations are given in parentheses.

Sample	Roughness Ra (mm) @ Lc 2.5mm	@ Lc 8mm
Marble/polished	0.74 (±0.38)	0.85 (±0.43)
Marble/glass beads	7.01 (±0.62)	7.85 (±0.78)
Marble/alumina	5.45 (±0.94)	7.8 (±1.5)
Limestone/sawn	30.4 (±3.7)	36.3 (±4.5)
Limestone/glass beads	38.6 (±2.2)*	46.0 (±3.1)
Limestone/alumina	38.1 (±2.9)*	46.8 (±4.0)
Brick	12.1 (±1.3)	21.8 ±1.4)
Brick/glass beads	16.4 (±1.8)	26.6 (±7.3)
Brick/alumina	17.9 (±4.7)	26.5 (±7.4)

* Instrument failed to read some points because of roughness.

Table II Average roughness measured with LTP on masonry surfaces, white and red silicone rubber replicas. Standard deviations are given in parentheses.

Sample	Roughness Ra (mm) Masonry	White replica	Red replica
Marble/polished	50 (±11)	2.5 (±0.5)	5.5 (±1.0)
Marble/glass beads	42 (±10)	5.1 (±1.4)	7.1 (±1.5)
Marble/alumina	35 (±8)	3.5 (±0.8)	6.2 (±1.2)
Limestone/sawn	18 (±9)	13 (±5)	24 (±13)
Limestone/gl. beads	26 (±11)	20 (±10)	44 (±20)
Limestone/alumina	30 (±12)	21 (±8)	50 (±24)
Brick	9 (±3)	7 (±3)	9 (±3)
Brick/glass beads	11 (±5)	8 (±4)	12 (±7)
Brick/alumina	12 (±6)	9 (±3)	12 (±4)

Table III Total pixels for the highest bar towards the center of the histogram, measured by RLIA on the red silicone rubber replicas. Standard deviations are given in parentheses.

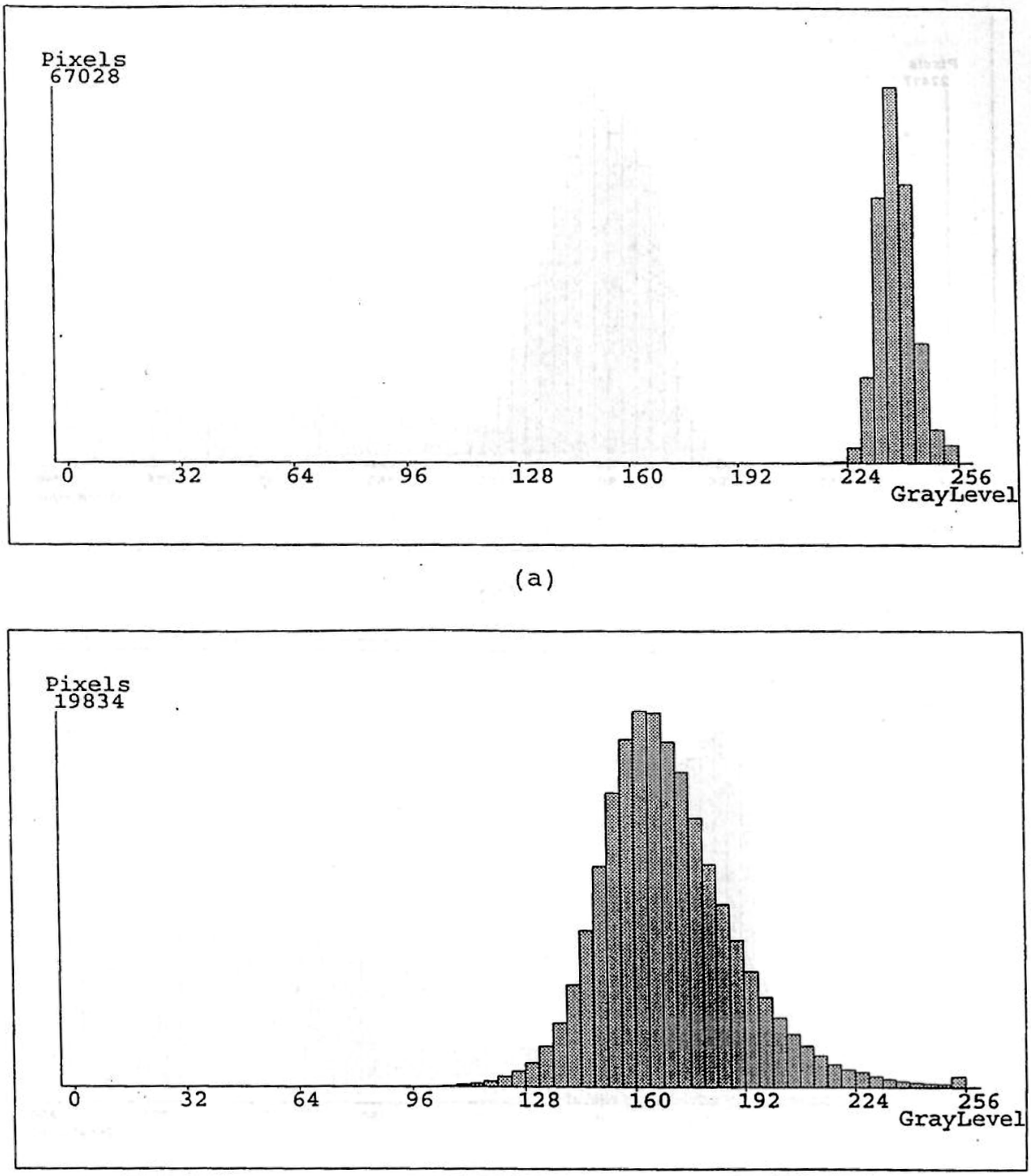
Sample	total pixels (in thousands)
Marble/polished	25 (±1)
Marble/glass beads	21 (±10)
Marble/alumina	23 (±8)
Limestone/sawn	8.7 (±0.4)
Limestone/glass beads	6.0 (±0.2)*
Limestone/alumina	5.3 (±0.2)*
Brick	20 (±1)
Brick/glass beads	18 (±7)
Brick/alumina	13 (±11)

* Indicates a spike at the black end of the histogram.

Table IV Average roughness measured with the stylus profilometer and LTP on red silicone rubber replicas of the same surfaces. Standard deviations are given in parentheses.

Sample	Roughness Ra [mm]		
	Stylus		LTP
	@ Lc 2.5mm	@ Lc 8mm	
Marble/polished	0.74 (±0.38)	0.85 (±0.43)	5.5 (±1.1)
Marble/glass beads	7.01 (±0.62)	7.85 (±0.78)	7.1 (±1.5)
Marble/alumina	5.45 (±0.94)	7.8 (±1.5)	6.2 (±1.2)
Limestone/sawn	30.4 (±3.7)	36.3 (±4.5)	24 (±13)
Limestone/glass beads	38.6 (±2.2)*	46.0 (±3.1)	44 (±20)
Limestone/alumina	38.1 (±2.9)*	46.8 (±4.0)	50 (±24)
Brick	12.1 (±1.3)	21.8 (±1.4)	9 (±3)
Brick/glass beads	16.4 (±1.8)	26.6 (±7.3)	12 (±7)
Brick/alumina	17.9 (±4.7)	26.5 (±7.4)	12 (±4)

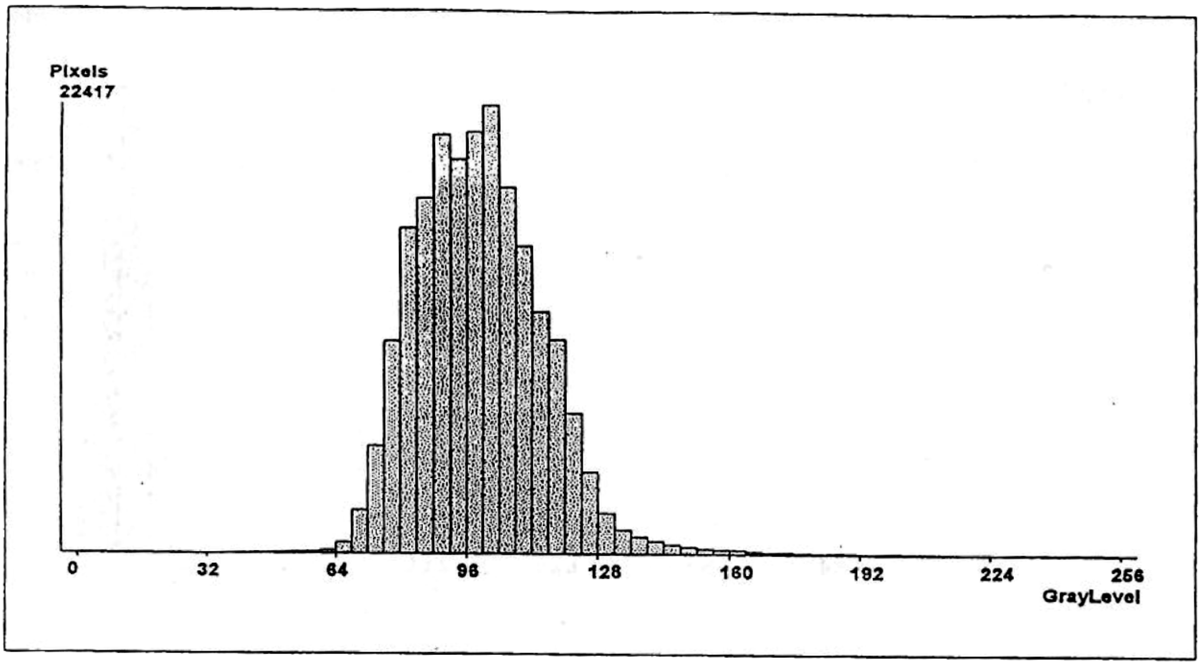
* Instrument failed to read some points because of roughness.



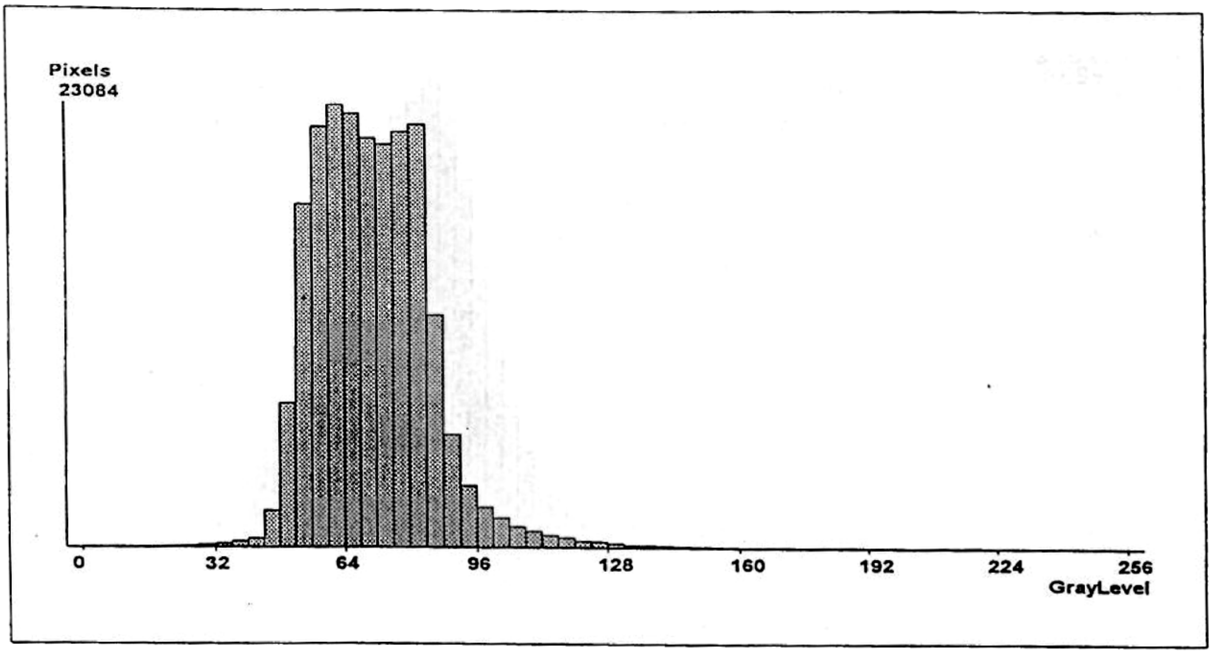
(a)

(b)

Figure 1. RLIA histograms for replicas of a marble surface blasted with glass beads, made of (a) white silicone rubber and (b) red silicone rubber

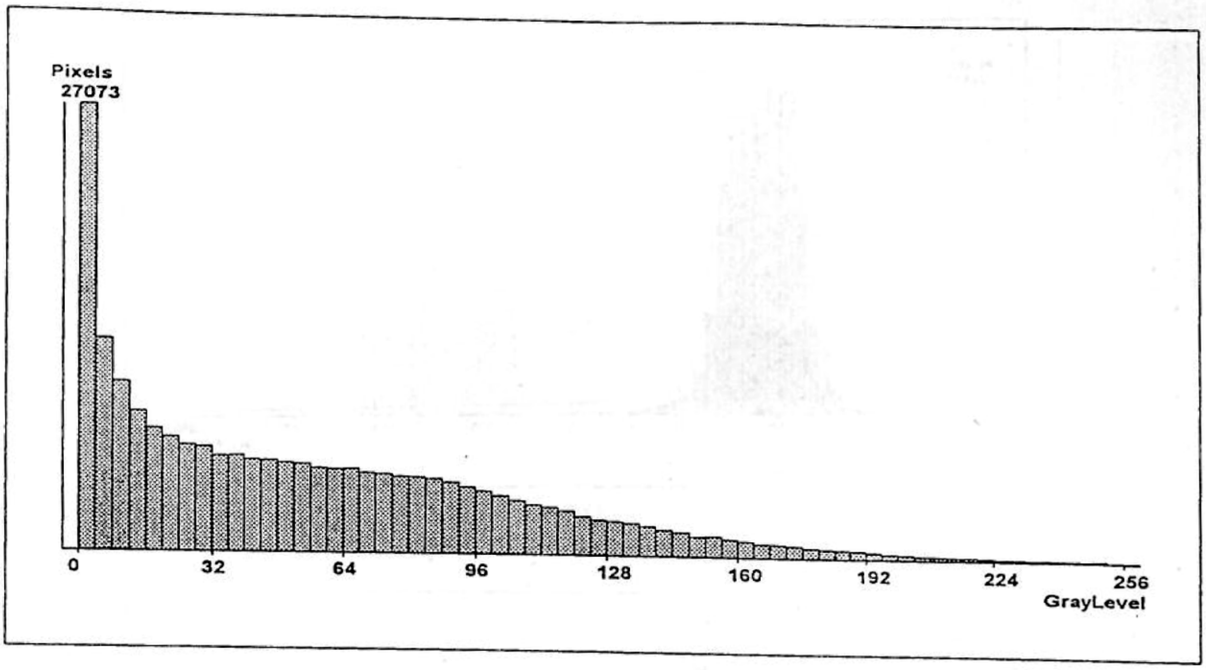


(a)



(b)

Figure 2. RLIA histograms for red silicone rubber replicas of a polished marble surface measured at different light intensities: (a) higher and (b) lower



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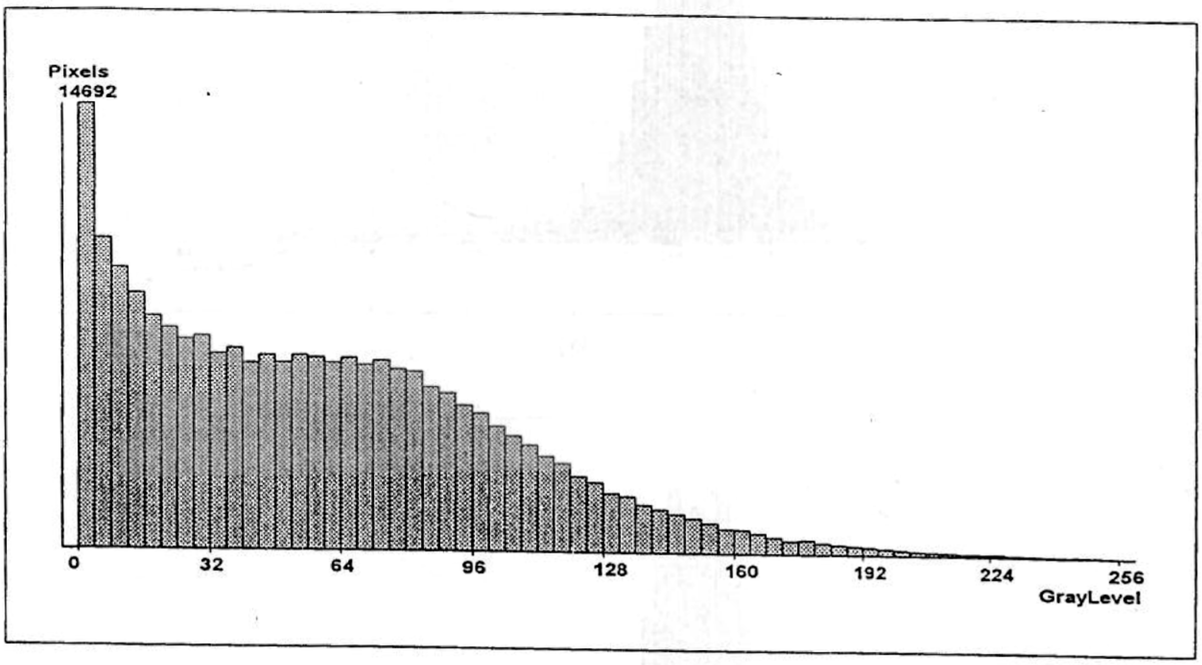
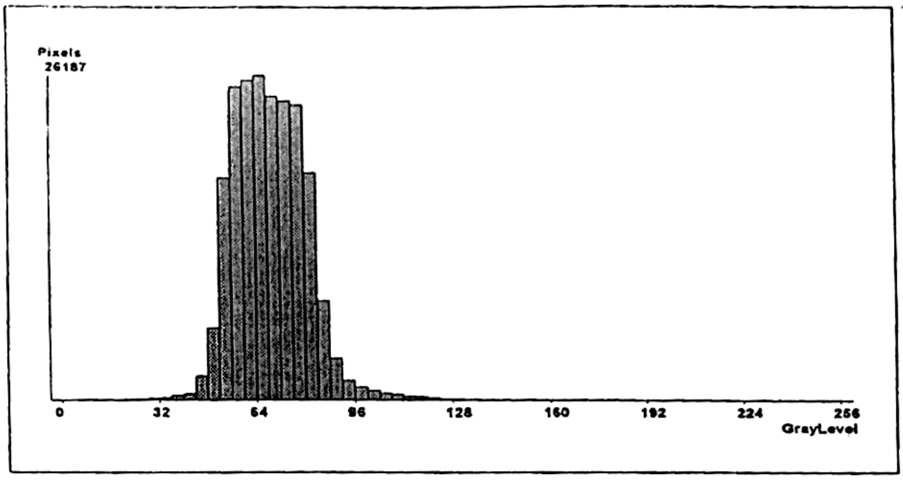


(b)

Figure 3. RLIA histograms for red silicone rubber replicas of limestone blasted with alumina powder measured at slightly different tilts



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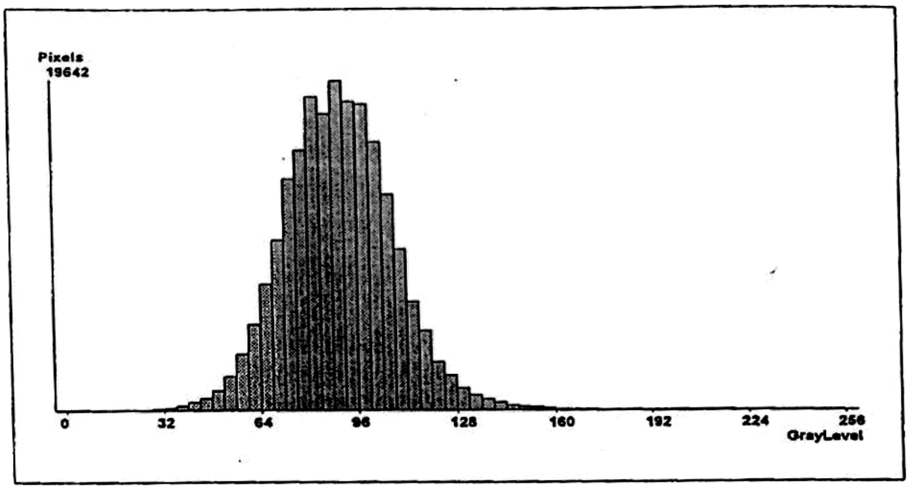

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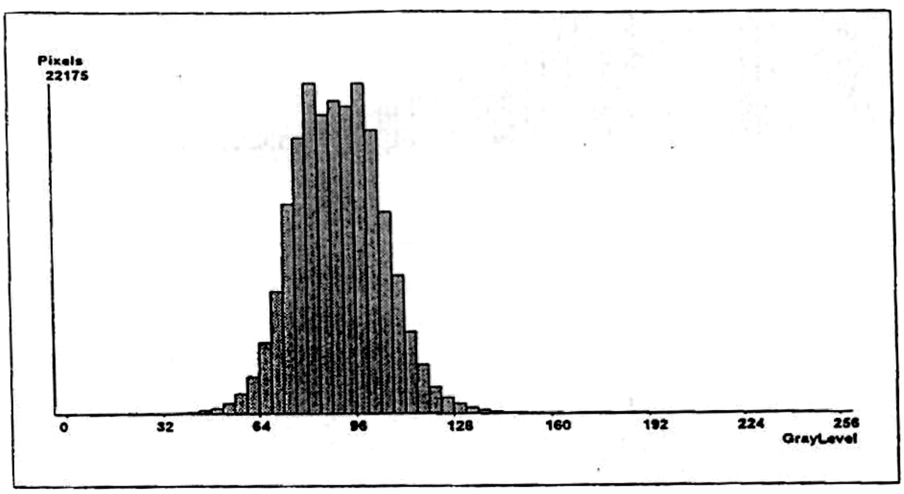


(c)

Figure 4. RLIA histograms for red silicone rubber replicas of polished marble: (a) control, (b) glass bead-blasted area, and (c) alumina powder-blasted area

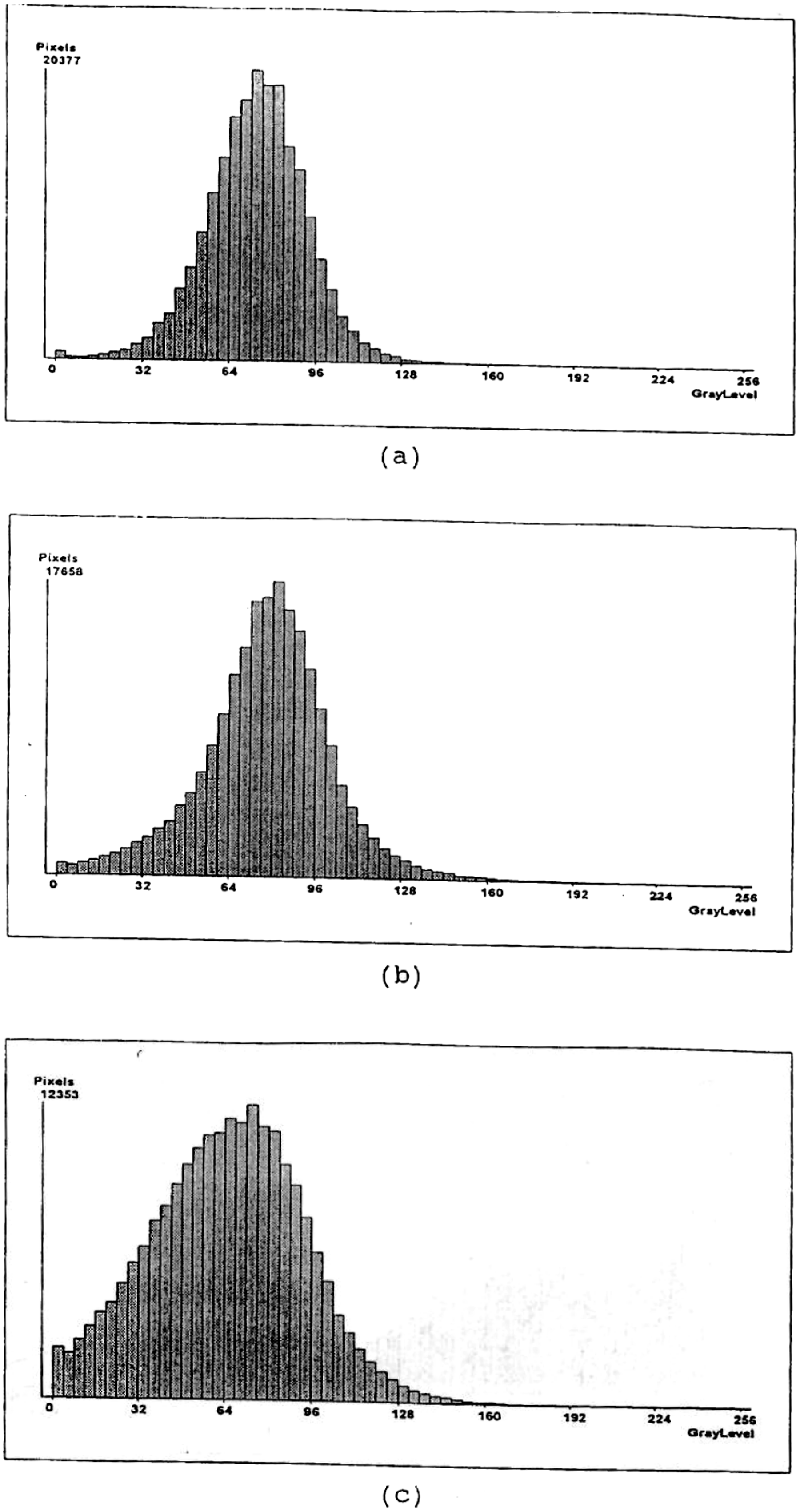
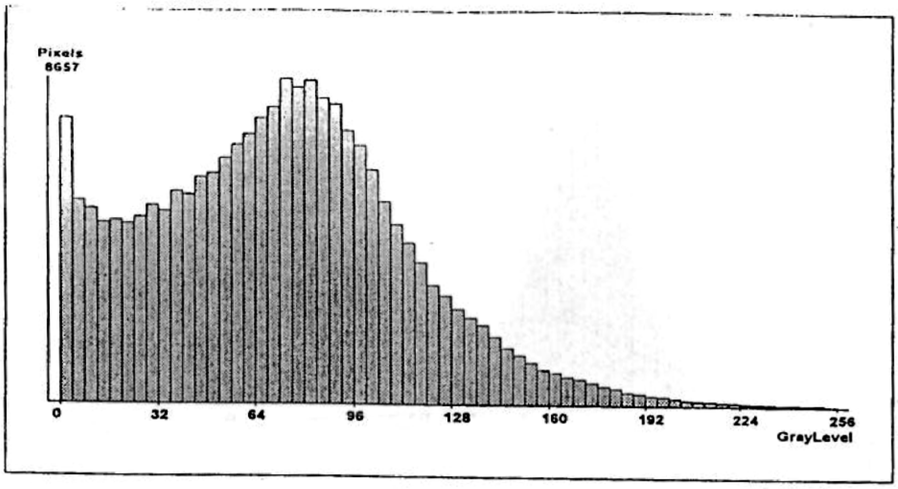


Figure 5. RLIA histograms for red silicone rubber replicas of a brick paver: (a) control, (b) glass bead-blasted area, and (c) alumina powder-blasted area



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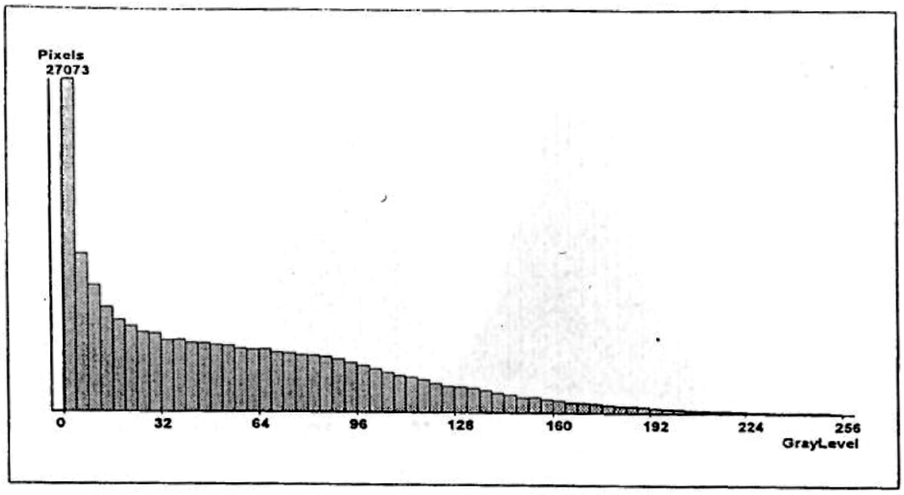

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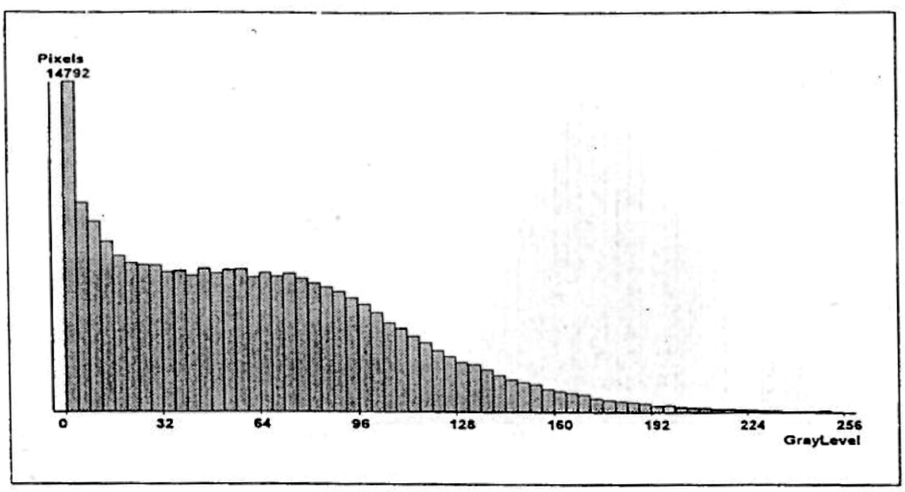

(c)

Figure 6. RLIA histograms for red silicone rubber replicas of sawn limestone: (a) control, (b) glass bead-blasted area, and (c) alumina powder-blasted area

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