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Concrete Roughness Characterization Using Laser Profilometry for Fiber-Reinforced Polymer Sheet Application

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The failure of a reinforced concrete member strengthened with fiber-reinforced polymer (FRP) laminates may be caused by crushing of concrete, rupture of FRP laminates, or delamination of the FRP sheet. Therefore, the effectiveness and failure mode of FRP sheets applied to beams and columns is related to the degree of adhesion of the epoxy to the concrete surface. When a peeling or delamination failure can be avoided, a more effective engagement of the FRP sheet occurs, which results in more efficient use of the material. One of the principal factors affecting the bond behavior between the concrete and epoxy is the roughness of the concrete substrate. To prepare the bond surface, sand blasting or grinding is typically used to roughen the concrete. To that end, a portable device has been developed to measure the roughness of concrete surfaces. This device can be used as a quality-control tool to characterize surface roughness and identify when an adequate surface preparation has been attained. The method uses laser striping and image analysis. The method was tested on six slabs of sandblasted concrete, which were sandblasted to varying degrees of surface roughness, and a series of nine plastic model concrete surface profiles.

The use of fiber-reinforced polymers (FRP) for reinforcement of concrete members has emerged as one of the most promising technologies in materials and structural engineering to repair and strengthen the U.S. national infrastructure (*1–7*). Current FHWA statistics indicate that approximately one-fifth of U.S. bridges constructed between 1950 and 1960 are structurally deficient (FAWA National Bridge Inventory Database). Of these, the vast majority are composed of reinforced or prestressed concrete. Much of the deterioration is attributed to aggressive environments and durability-related issues. In particular, for highway structures where deicing salts are predominantly used, corrosion problems associated with mild steel reinforcing or prestressing strands have stood out as a major contributor to the deterioration.

Fiber-reinforced polymers are ideally suited for repair and strengthening of concrete structures in aggressive environments due to their noncorrosive, nonmagnetic characteristics. They have high tensile strength-to-weight ratio and high elastic limit. Externally applied FRP sheets or laminates (Figure 1) are bonded directly to a concrete surface with an epoxy providing additional flexural or shear strength capacity depending on the application and fiber alignment. This significantly increases the load-carrying ability of a structural component or structural system.

Although durability-related concerns for new structures can be addressed using modern techniques that include cathodic protection, epoxy-coated reinforcing, and noncorrosive materials, existing deficient structures must be rehabilitated and upgraded in a cost-effective way with minimal disruption to service. Research has shown that repair of concrete structures with FRP products, including externally applied FRP materials, has proved to be a viable and cost-effective alternative to traditional repair and strengthening techniques to upgrade deficient structures to meet today's design standards (*3–6, 7, 8*).

SUBSTRATE ROUGHNESS, BOND STRENGTH, AND FRP PERFORMANCE

The load-carrying ability of FRP-reinforced members and their long-term durability performance are very much related to the bonding characteristics of the epoxy to the concrete substrate. Experience has shown that when delamination of the FRP sheets occurs (Figure 2), the load-bearing capability of the strengthened member is greatly reduced because the FRP sheet is no longer fully engaged to the concrete. Research conducted has indicated that the bond strength between the FRP-epoxy matrix and the concrete depends on a number of factors including the material properties of the epoxy as well as the properties of the concrete substrate (*9–11*). The epoxy-concrete bond strength is affected by the strength, roughness, and cleanness of the prepared concrete surface.

The effectiveness of any externally bonded FRP reinforcement is affected by the quality of the bond between the reinforcement and the concrete surface to which it is applied and also by the strength of the concrete substrate. Improper bonding may cause failure resulting from the FRP reinforcement detaching or peeling from the concrete substrate.

Observations of delamination of the FRP sheets have led to the speculation that the roughness of the concrete surface is an important factor for obtaining the best bond strength of the concrete and FRP (*9–11*). If surface roughness were measured accurately and controlled during the installation process, more reliable bond strength and bond failure mode could be predicted.

Surface characterization of concrete surfaces requires that a surface or surface profile can be measured and characterized in terms of its roughness. The focus of this paper is on the development of a laser-based device designed to measure the roughness of prepared concrete surfaces before the application of FRP sheets.

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FIGURE 1 Application of FRP sheet on one-way joist.

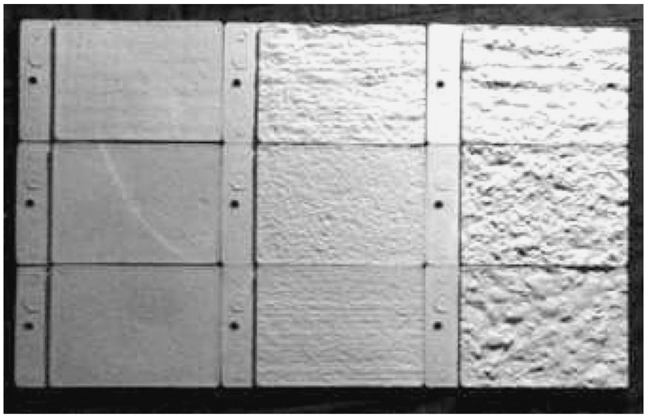

FIGURE 3 Plastic model CSPs. Profiles are ordered 1 to 9 by increasing roughness and correspond to acid etching, grinding, light shotblast, light scarification, medium shotblast, medium scarification, heavy abrasive blast, scabbing, and heavy scarification.

CONCRETE SURFACE ROUGHNESS

State of the Art

There is currently no means to effectively measure roughness of concrete. The state of the art is to subjectively compare the concrete surface with concrete surface profiles (CSPs) in the form of nine plastic model surfaces produced by the International Concrete Repair Institute (ICRI) (*12*) (Figure 3).

Measurements in Other Fields

According to American Society of Mechanical Engineers (*13*), the methods for measuring roughness and surface texture can be classified into three types: contacting methods, taper sectioning, and optical methods.

Among the contacting methods (*13*), stylus-type profilometers give precise measurements along a linear traverse. Usually the vertical deflection of the stylus is recorded as a function of position. Other contacting methods include tactile tests, measurement of kinetic friction, measurement of static friction, use of rolling ball measurements, and measurement of the compliance of a metal sphere with a rough surface (*14*). Taper sectioning is used in metallurgy and consists of cutting across a surface at a low angle α to physically amplify the height of asperities by cot α (*14*).

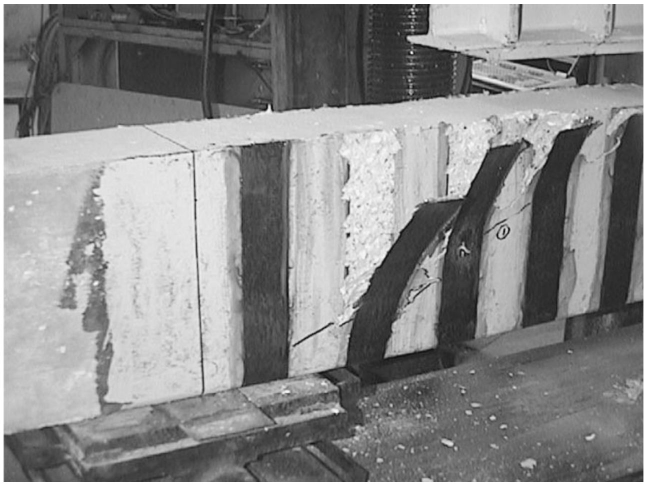

FIGURE 2 Delamination of externally bonded FRP sheets.

Noncontacting (*13*) or optical methods include optical reflecting instruments, light microscopy, electron microscopy, speckle metrology, interferometry, and laser profilometry. Light section microscopy (*15*) illuminates a rough surface with a thin slit of light at an angle of 45°. The surface is observed at an angle of 90° from the direction of illumination. The projected slit appears as a straight line if the surface is flat and as a progressively more undulating line as the roughness of the surface increases.

Interferometry and speckle interferometry (*15*) make use of interference fringes produced when monochromatic or laser light is reflected off a rough surface and a flat reference surface. The fringes are contours of roughness of about one-half the wavelength of the light used. This method is thus applicable only to surfaces with roughness of small amplitudes.

In civil engineering, the traditional method for measuring surface quality has been to place a 3-m straightedge on the surface and to measure the maximum deviation between the straightedge and the surface (*16*, Appendix E). This measurement can then be compared with a specification of finishing tolerances. The difficulty with this method is that this measures not roughness but rather the maximum amplitude of the surface, typically at a large wavelength.

In rock mechanics, where roughness of discontinuity surfaces plays a vital role in the stability of rock slopes, a pragmatic approach has typically been applied. As with measuring roughness of concrete on bridges and other structures, the techniques are oriented to fieldwork rather than laboratory investigations.

Barton and Choubey (*17*) developed a joint roughness coefficient scale to quantify roughness of a 100-mm surface profile. The values for the smoothest to the roughest discontinuities range from 1 to 20, and type profiles can be subjectively compared with actual surfaces.

Franklin et al. (*18*) developed a photographic technique, using the principles of the Schmaltz microscope (*19*), for obtaining a shadow profile by casting a shadow with a straightedge, keeping the light source at 45 degrees to the joint surface to avoid distortion. Maerz (*15*) used shadow profilometry to measure the roughness of rock discontinuity surfaces, for the purpose of predicting rock stability, deformity, and hydraulic conductivity.

PRINCIPLES OF LASER PROFILING

Introduction

A new portable concrete roughness testing device, an optical laser–based imaging system, has been developed along the principles of the Schmaltz microscope (*19*) and the method of shadow profilometry (*15*). It uses a laser profiling line rather than a shadow edge. This procedure is called laser striping. The laser used has a multiple line generator that produces a nongaussian (i.e., uniform) distribution of light intensity along the line. This new device is a portable imaging device that can be used to measure roughness in both research and production environments.

Imaging

Using laser striping, a rough concrete surface is illuminated with thin slits of red laser light at an angle of 45°, and the surface is observed at 90° (Figures 4–8). The projected slit of light appears as a straight line if the surface is flat, and as a progressively more undulating line as the roughness of the surface increases. A 20-mW, 678-nm striping laser with 11 stripes is mounted at 45° with a standoff distance of about 170 mm to the surface. Lasers with 1, 5, or 11 stripes were used.

A high-resolution (tiny) board charge coupled device (CCD) camera with a 7.5-mm lens is mounted vertically in the housing with a standoff distance of about 150 mm. A 678-nm bandpass filter is placed over the camera lens that rejects both high-frequency and low-frequency light and allows only the laser light to pass through to the camera. The video image of the laser stripes is digitized with a personal computer memory card international association framegrabber on a laptop computer, at a resolution of 640 by 480 picture elements (pixels) color image.

Image Processing

Classical image-processing techniques are used to transform the image of the laser stripes into a series of profiles in *x-y* space, using a C++ development environment. The following are the image-processing steps.

1. The image is transformed from a 24-bit color image to an 8-bit gray-tone image by isolating the red color information in the picture.
2. A 5- × 1-pixel despeckling (median) filter is applied in a horizontal direction to remove noise. Applying it parallel to the laser stripes makes it most efficient in terms of increasing the signal-to-noise ratio.

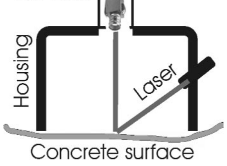

FIGURE 4 Schematic representation of laser profiling equipment.

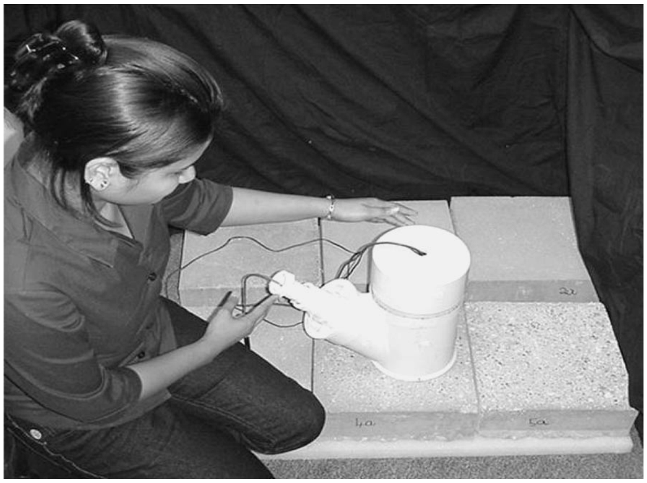

FIGURE 5 Prototype of laser profiling device.

3. A low-pass (gaussian) filter is applied to further remove unwanted noise from the image.
4. A thresholding filter is used to isolate the leading edge of each of the stripes.
5. A "line walking" technique is used to walk the edge of each stripe and record the *x-y* coordinates of each stripe.

Analysis

The profiles in *x-y* space are analyzed to provide various statistics. The most useful of the statistic are the Z_2, R_p, and i_A parameters. The root mean square of the first derivative of the profile (*20*) is a single parameter measure that characterizes a profile based on its average slope:

$$Z_2 = \sqrt{\frac{1}{n(dx)^2}\sum_{i=1}^{n}(dy)^2} \qquad (1)$$

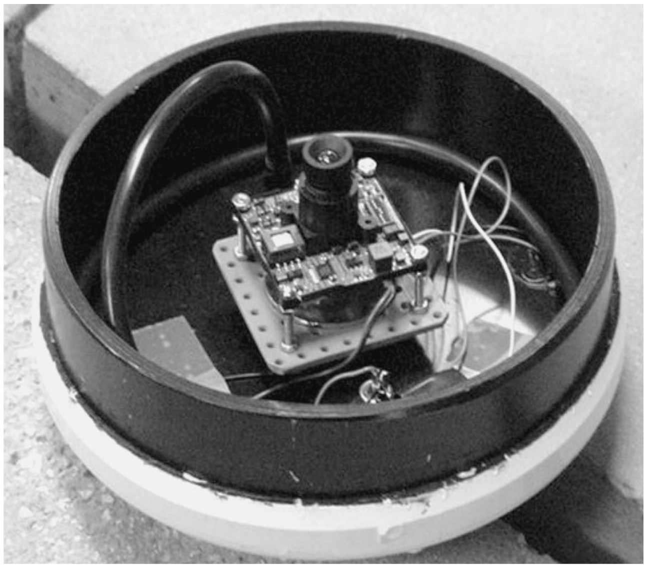

FIGURE 6 CCD camera.

FIGURE 7 Line laser.

where

n = number of evenly spaced sampling points;
x = points along sampling line; and
y = points normal to sampling line.

The roughness profile index (R_p) is defined as the ratio of the true length of a fracture surface trace to its projected length in the fracture plane (*21*).

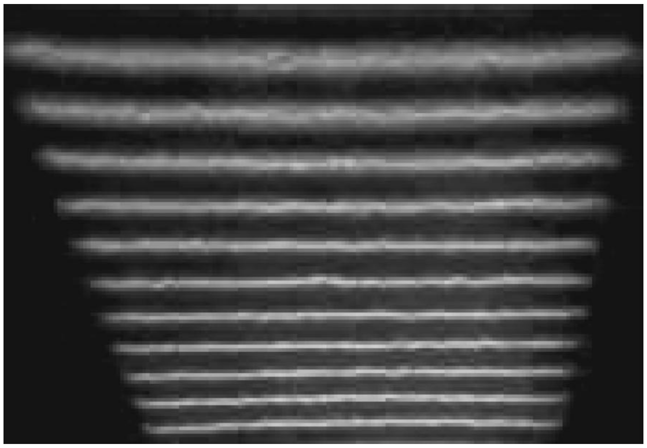

FIGURE 8 Image of concrete surface illuminated by 11-line generator.

The microaverage inclination angle (i_A) (*16*) is the average of the pixel-to-pixel angles of the stripe profile

$$i_A = \frac{1}{n}\sum_{i=1}^{n}|I_j| \qquad (2)$$

where I is the inclination angle between points along the sampling line.

MEASUREMENT RESULTS

Manufactured Concrete Surfaces

For the purpose of evaluating the measurement technique, two sets of concrete surfaces were studied for analysis. The first series (Set A) consists of six concrete blocks that are 300 mm × 300 mm × 100 mm (Figure 9). The second series (Set B) is a replication of the first set. Five of the concrete surfaces were prepared by sandblasting. Surfaces 1–5 were progressively made rougher by increasing the duration of sandblasting. (Although there was nominally a linear increase in the duration of sandblasting, the difference in roughness between samples was found to be decidedly nonlinear.) Surface 0 was made smooth by grinding. (The two sets were originally manufactured as 600- × 300-mm slabs and then cut in half.)

For the purpose of characterizing the surfaces, for each of the surfaces, measurements were taken (Figure 9) at three different orientations, two different positions, with two replicates for each measurement. In total, 144 measurements were taken. All measurements were taken with an 11-line laser at a 100-mm base length.

The result of the analysis (Figure 10) reveals that the surfaces can be characterized in terms of the average inclination angle of the profiles. Whereas Surfaces 0 and 1, and Surfaces 5 and 6 are very distinctive, Surfaces 2 and 3 are very similar to each other. This reflects the fact that the actual roughness of the two surfaces is very similar.

Statistical Results

The experimental design was set up so that the following factors, which may influence the measurement, were considered:

- Surface roughness (the desired parameter),
- Set (two sets of surfaces were analyzed),
- Profile orientation (to determine anisotropy),
- Profile position (to determine homogeneity), and
- Control (replicates to test the variability in the method).

Analysis of variance was performed on the experiments using split-split-plot design, producing the following results.

- The different blocks within each series were of significantly different roughness (Figure 11). (The results for both series indicated that the roughness of the blocks did not increase linearly.)
- There was a two-way interaction effect of the set within the blocks for Set A and Set B.
- The orientation of the profile lines was not very significant.
- The position of the profile lines was significant.

Conclusions

From these results the following conclusions can be drawn.

1. Laser profilometry is capable of measuring differences in roughness.

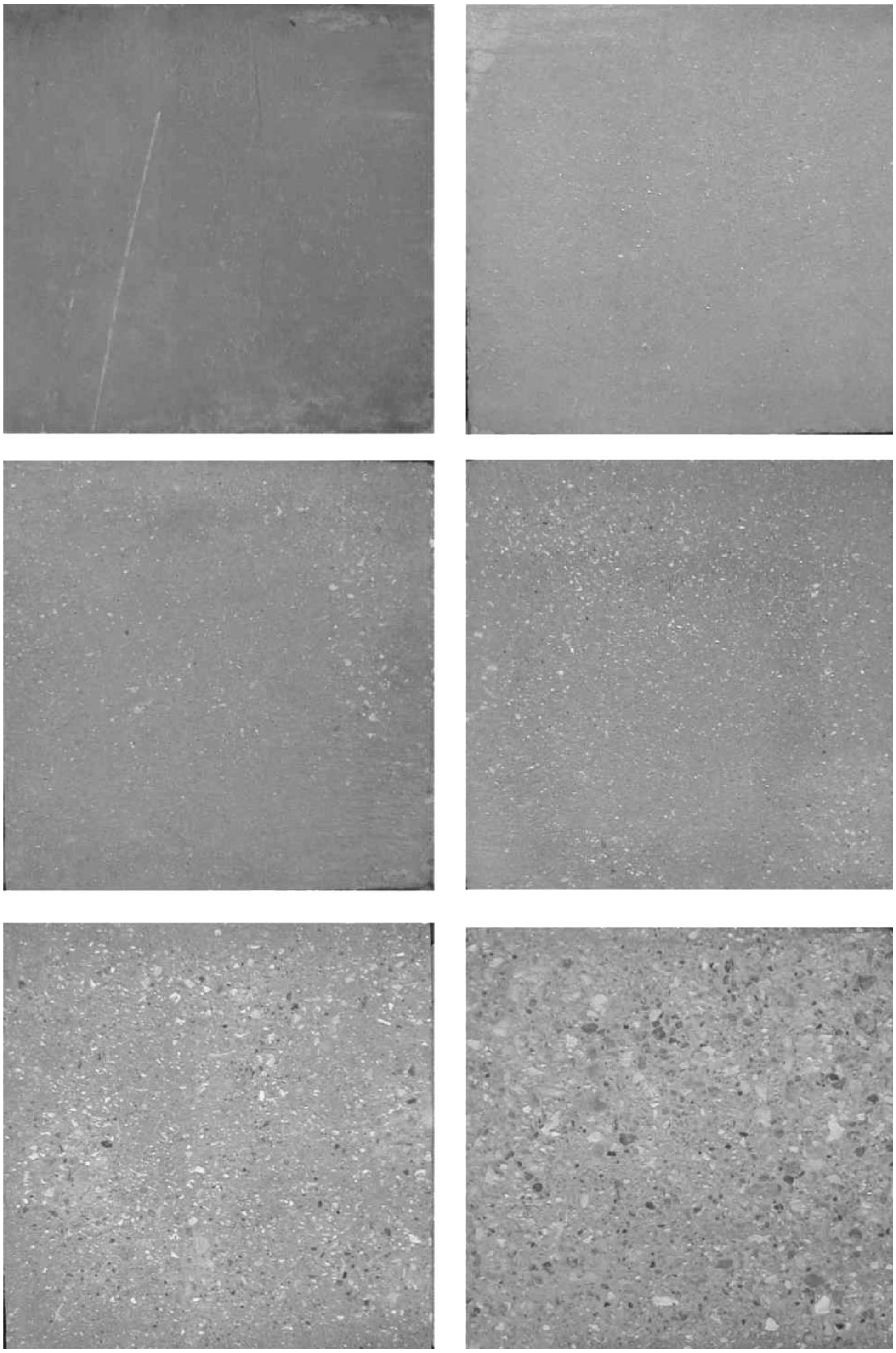

FIGURE 9 Manufactured CSPs.

2. The sample surfaces, prepared by sandblasting with manual control, were inhomogeneous, indicating that for characterizing this type of process multiple measurements at different locations may be needed.

3. The sample surfaces were isotropic, indicating that multiple measurements at different orientations may not be needed.

Standard Concrete Type Surfaces

The third series consists of plastic models of nine CSPs prepared by ICRI (*13*) (Figure 3). These profiles replicate the degrees of roughness, which were considered for the purpose of application of coatings and sealers up to a thickness of 6.35 mm. Each profile carries a

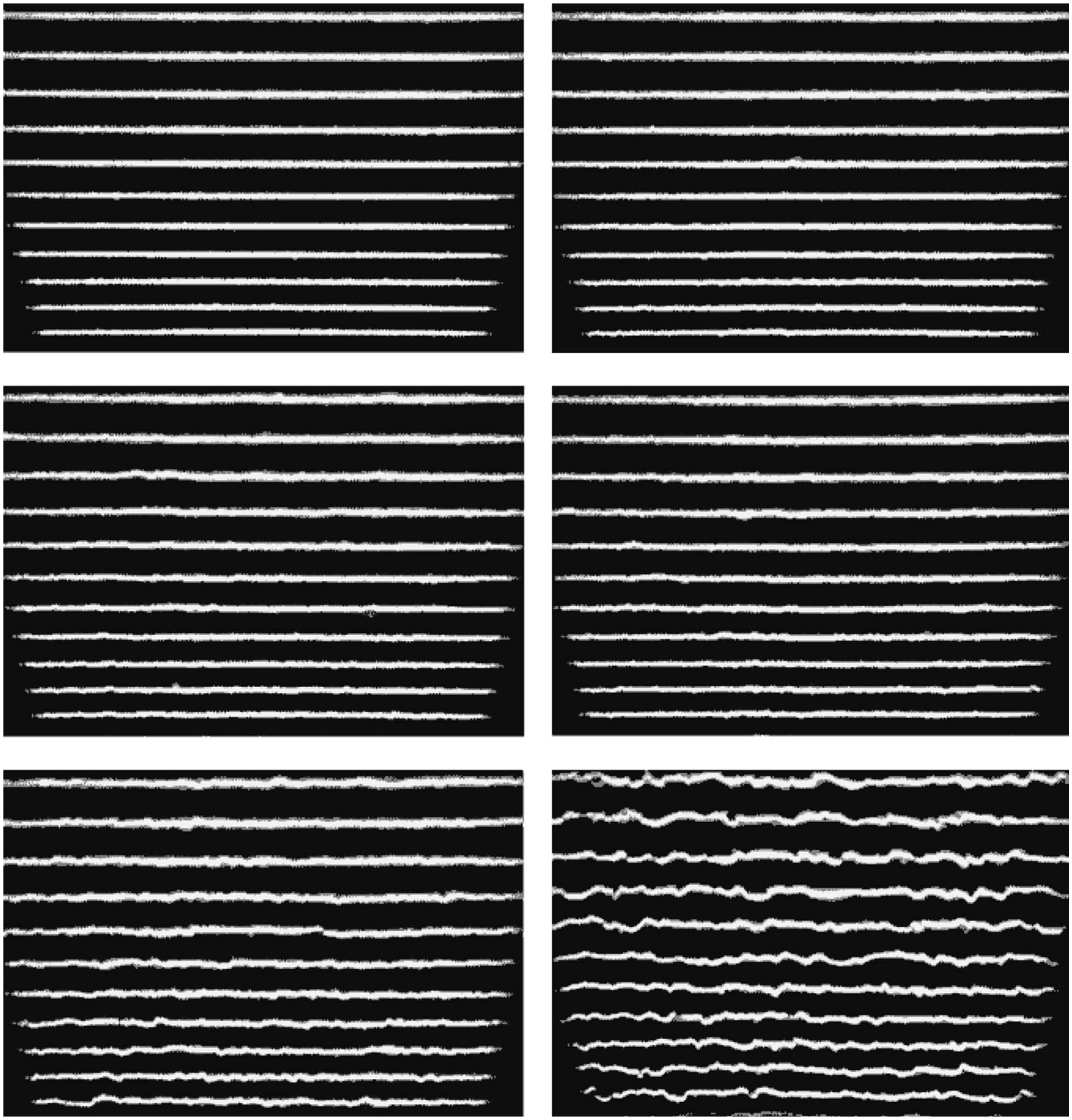

FIGURE 10 **Laser profiles for roughened concrete surfaces of Figure 9.**

CSP number ranging from a baseline of 1 (nearly smooth) through 9 (very rough).

For the purpose of evaluating the measurement technique, the laser striping technique was applied directly to the plastic models (Figure 12). For each plastic model, three different threshold values for the thresholding filter were selected, and three replicate measurements were taken. In total, 81 measurements were analyzed at a 100-mm base length.

The results of the analysis (Figure 13) reveal that the surfaces can be characterized in terms of the Z_2 parameter. With the exception of Surface 8, the plastic model surfaces are in order of ascending roughness, and although not completely linear, are nevertheless fairly evenly spaced. Surface 8 is clearly much rougher than the other surfaces.

Statistical Results

The experimental design was set up such that the following factors, which may influence the measurement, were considered:

- Surface roughness (the desired parameter),
- Threshold value (the user selectable parameter used in the threshold filter), and
- Control (replicates to test the variability in the method).

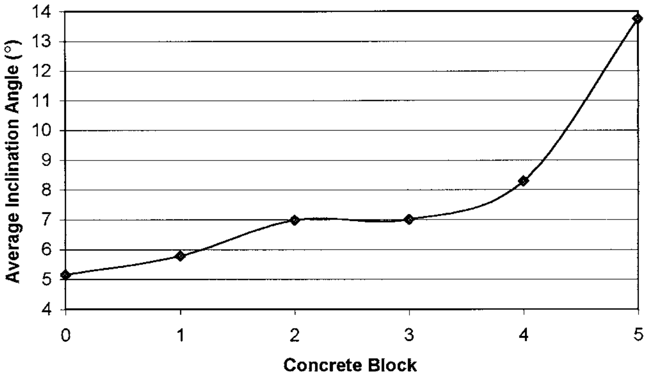

FIGURE 11 Roughness measurement results for concrete surfaces in terms of average inclination angle of profiles.

Analysis of variance tests produced the following results:

- The different CSP plastic models were of significantly different roughness.
- Threshold values of 125 and 150 produced results that were not significantly different.
- A threshold value of 175 produced results that were significantly different.

Conclusions

From these results, the following conclusions can be drawn:

1. Laser profilometry is capable of measuring differences in roughness.
2. The choice of the threshold parameter can be significant. This indicates that the selection of that parameter may need to be standardized or automated so that measurement results are not skewed by subjective selection of parameters on the part of the user.
3. The CPS plastic samples were in general in ascending order of roughness, and the increase is close to linear, with the exception of one model (no. 8), which is much rougher than the others.

SUMMARY

The manufactured roughness is probably an important requisite in the proper adhesion and performance of fiber-reinforced polymers on concrete substrates. Characterization of that roughness is then also of

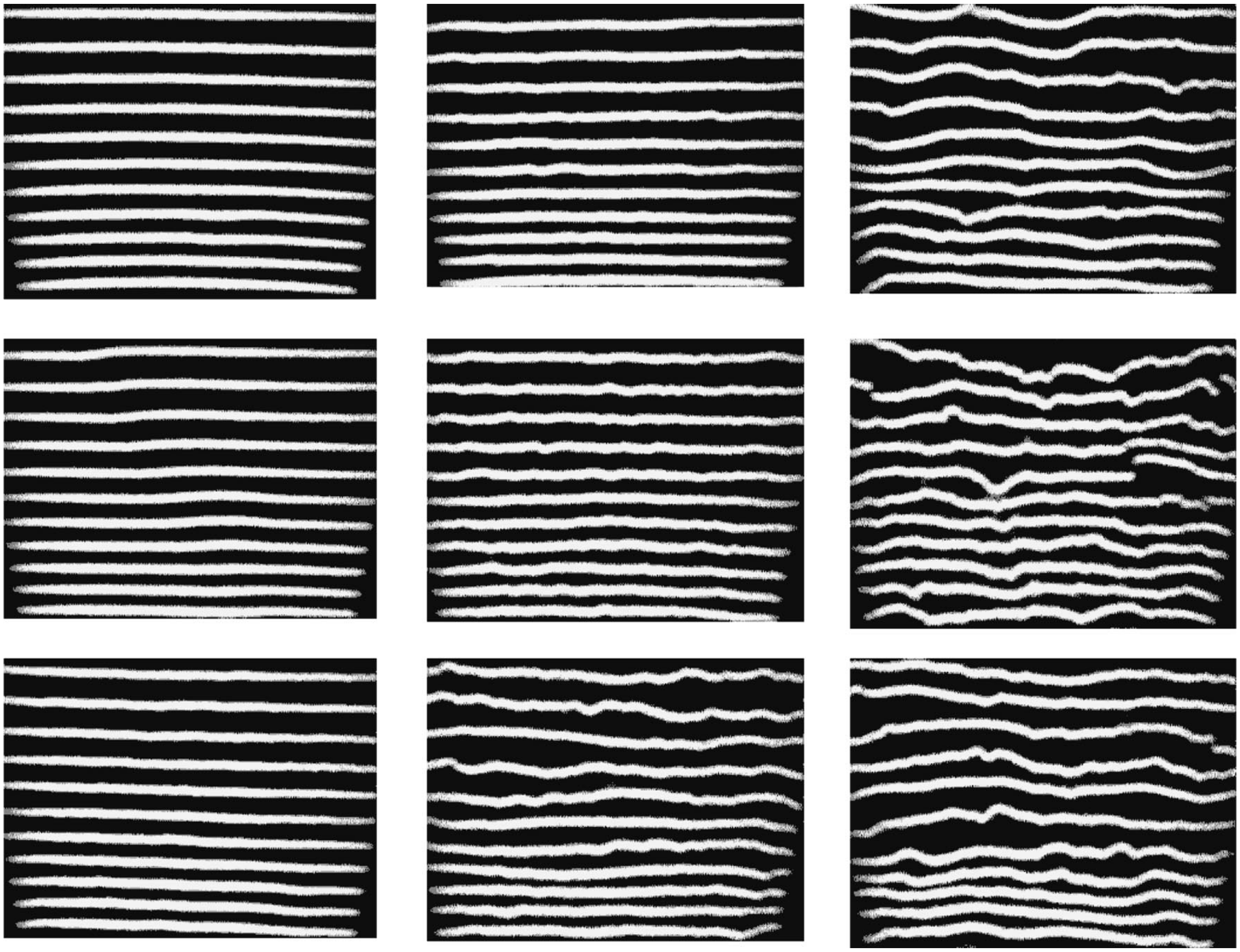

FIGURE 12 Laser profiles for plastic type profiles of Figure 3.

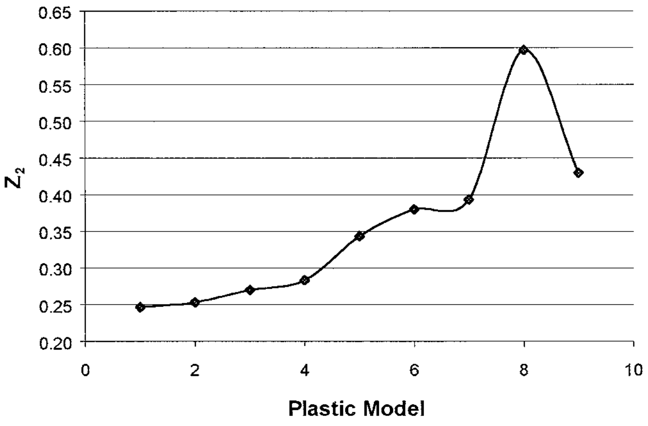

FIGURE 13 Roughness measurement results for plastic type profiles in terms of average inclination angle of profiles.

significant importance, although the current state of the art allows only subjective evaluation of roughness, not measurement. A prototype of a new device for measuring roughness in the laboratory and in the field has been developed. Preliminary studies have shown the device to be effective in measuring and characterizing roughness.

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