CONCRETE SUBSTRATE PREPARATION AND CHARACTERIZATION PRIOR TO ADHESION OF EXTERNALLY BONDED REINFORCEMENT

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ABSTRACT

The bond between externally bonded FRP reinforcement and concrete substrate is highly dependent on the quality of the surface preparation. Accordingly, accurate measurement of surface roughness could lead to the more reliable and predictable bond behavior. This paper presents the results of an experimental study aimed at investigating the effect of surface preparation on bond performance of externally applied reinforcement other than FRP. Water jetting was used as the abrading method. The quantitative assessment of surface roughness was conducted using a newly-developed laser profilometer. Samples of externally applied steel reinforced polymer (SRP) and steel reinforced grout (SRG) reinforcement were pull-off tested. Comparison to the state-of-the-art surface characterization method using plastic concrete surface profiles was undertaken, yielding a relationship between the roughness of the concrete surfaces and the roughness of the plastic models. Experimental results of this project showed that the effect of the surface roughness on the pull-off strength of the externally applied SRP and SRG reinforcement was not a key factor. This was because in the first instance failure always occurred in the concrete substrate, while in the latter it occurred in the gout layer.

KEYWORDS

Bond strength, concrete surface profiles (CSP), laser profilometer, pull-off test, steel reinforced grout (SRG), steel reinforced polymer (SRP), surface roughness.

INTRODUCTION

The effectiveness and the overall performance of an externally applied composite system are highly dependent on the quality of bond between composite and the concrete substrate (De Lorenzis et al. 2001). Improper bond characteristics may cause the premature failure of the system resulting from the composite peeling from the concrete substrate. Various research projects have indicated that the bond strength between composite and concrete substrate depends on factors such as concrete substrate and reinforcement material properties. Material properties of the concrete substrate affecting the bond strength include the tensile strength of the concrete layer underneath the externally applied composite, surface roughness and cleanness of the prepared concrete surface (Galecki et al. 2003). Surface roughness when accurately measured could lead to a more predictable bond behavior of the externally applied composite (Maerz et al. 2001). Presently, there are no effective means to measure roughness. The North American state-of-the-art method is to visually compare the concrete surface to the concrete surface profiles in the form of nine plastic coupons developed by the International Concrete Repair Institute (ICRI, 1997). This highly subjective means of capturing the concrete surface roughness, in addition to operator sensitivity, does not allow keeping the record of the inspection data. Trying to overcome these drawbacks, a concrete roughness testing device, using laser profilometry, has been developed to effectively characterize the surface prior to application of the composite and thus lead to more predictable and controlled behavior of the bond performance of the composite system. This paper aims to present the analytical relationship between the roughness measured using both the ICRI's plastic coupons and the laser profilometry, as well as to present the effect of the surface roughness on the bond performance of the externally applied reinforcement using the pull-off test.

LASER PROFILOMETRY

A portable concrete roughness testing device (an optical laser-based system) has been developed for field and laboratory measurements (Maerz et al. 2001). Housing for the laser is made of a lightweight aluminum case provided with handles to hold the device against a wall or upwards against the ceiling. The device has a single retractable leg so that it can stand freely on horizontal surfaces. A concrete surface is illuminated with five thin slits of red laser at an angle of 45º and the surface is observed at 90º (Figure 1-a). The projected slit of light appears as a straight line if the surface is flat and as a progressively more undulated line as the roughness of the surface increases. Classical image processing techniques are used to transform the image of the laser stripes into a series of profiles in x-y coordinates, using a C++ development environment (Figure 1-b). The profiles in x-y coordinates are analyzed to provide various statistics. Ten measurements of roughness are reported as the results of image processing. It has been shown that the most useful parameters for surface characterization are the two reported below (Maerz et al, 2001). First is the microaverage inclination angle (i_A) defined as the average of pixel-to pixel angles of the stripe profile:

$$i_A = \frac{1}{n}\sum_{i=1}^{n}\left|Ii\right| , \qquad (1)$$

where:
I_i = the inclination angle between points along the sampling line.

The second useful parameter is the root mean square of the first derivative of the profile (Z_2), a single parameter measure that characterizes a profile based on its average slope:

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

where:
n = number of evenly spaced sampling points;
x = distance between points along the sampling line; and
y = distance between points normal to sampling line.

From the various laser profilometry feasibility studies undertaken, the following conclusions were drawn (Maerz et al. 2001):

- Laser profilometry is capable of measuring differences in roughness.
- In the analysis of smooth surfaces, some random noise is introduced in the stripe and this is interpreted as texture and thus smooth surfaces measure rougher than they really are.

(a) Laser stripping (b) Video image of the laser stripes

Figure 1. Laser profilometry

CONCRETE SURFACE PROFILES (CSP)

Prepared by the International Concrete Repair Institute (ICRI, 1997), nine plastic Concrete Surface Profile (CSP) models are replicates of concrete surfaces that represent the degrees of roughness ranging from CSP 1 (nearly smooth) to CSP 9 (very rough). These surfaces are considered for the purpose of application of coatings and sealers up to a thickness of 0.25-in (6.35-mm). Ordered in ascending roughness, surface profiles are meant to correspond to acid etching, grinding, light shotblasting, light scarification, medium shotblast, medium scarification, heavy abrasive blast, scabbing and heavy scarification (Figure 2). Although representative replicas of concrete surfaces, CSP models were found to be devoid of high frequency roughness that is an inevitable part of concrete surface roughness. Therefore, laser profilometry performed directly on the CSP models yielded lower surface roughness in terms of microaverage inclination angle i_A than the corresponding concrete surfaces (Maerz et al. 2001).

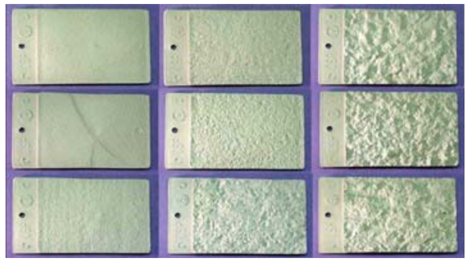


Figure 2. Concrete Surface Profiles (CSP) ordered from 1 to 9 (ICRI, 1997)

EXPERIMENTAL PROGRAM AND RESULTS

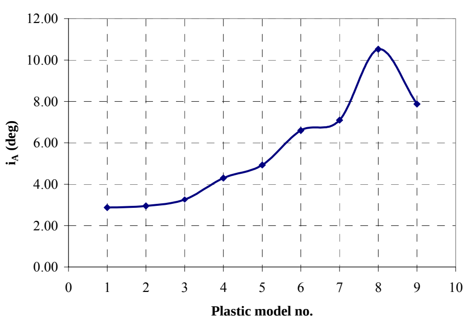
Laser Profilometry of Concrete Surface Profiles (CSP)

In order to establish a relationship between roughness measurement taken by laser profilometer on concrete and ICRI profiles, a small study was undertaken. In this study, for each of the nine plastic models, six measurements were taken during two perpendicular directions (i.e., symmetry axis of the rectangles).

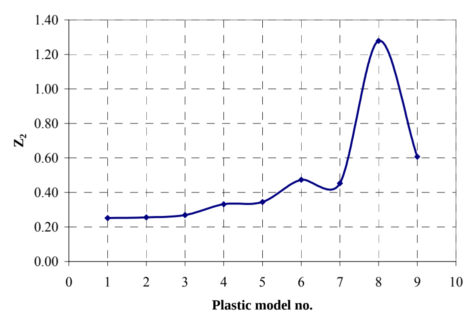
Roughness of the CSP models

The effect of the reading direction was proven to be significant when surface preparation is performed using a technique leaving the surfaces anisotropic. As for the profiles, the largest scatter was observed in the results of CSP 9. The visual comparison of each model surface reveals that the CSP 9 surface has been prepared in a way that there is a visible stroke in the vertical direction which would, obviously, yield higher results for i_A and Z_2 in the horizontal direction as compared to those taken in the vertical direction.

Plotted results of the analysis clearly show that the CSP models can be characterized both in terms of the i_A (Figure 3-a) as well as in terms of the Z_2 parameter (Figure 3-b).



(a)



(b)

Figure 3. Laser profilometry results in terms of i_A and Z_2

The results of the measurements show that the roughness differences among models are statistically significant and in ascending order near to linear, with the exception of CSP 8. Both parameters i_A and Z_2 show that this profile has a surface that is much rougher than the others and, in particular, of that of CSP 9.

Although in the ascending order of roughness, since these plastic profiles are just the replicas of real concrete surfaces, they are devoid of high frequency roughness that is highly present in concrete surfaces. Since measurements reported by the laser profilometer are average values taking in account both low and high frequency roughness, it is expected that laser profilometry will always show CSP's "smoother" than the corresponding real surface.

Analytical correlation between CSP models and concrete

The attempt to propose the analytical relationship that ties CSP models to concrete surfaces was undertaken. The assumptions necessary for the derivation of the equation include:

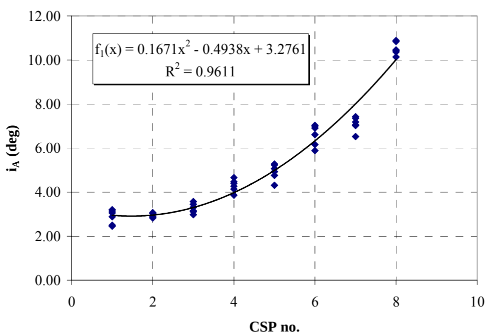
- The CSP model #9 was disregarded.

- Obtained concrete surface roughness values in terms of i_A from zero to 25 were made to correspond to the 8 equivalent CSP's no. 1 through 8. Consequently, every reading of concrete surface roughness was fit into a corresponding range and assigned the corresponding CSP no.

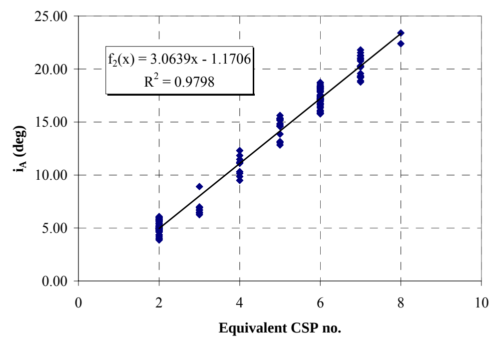
Concrete specimens used for this study consisted of cast unreinforced concrete blocks with dimensions 8-in × 8-in × 10-in (203-mm × 203-mm × 254-mm) and blocks with dimensions 6-in × 6-in × 12-in (152-mm × 152-mm × 305-mm). After the blocks had cured for approximately 14 days, the concrete surfaces were prepared using waterjetting technique. Waterjetting in this project was performed in a controlled fashion. Nozzle diameter, waterjet pattern, pressure and stand-off distance were the parameters simultaneously varied in order to obtain the desirable surface roughness. Conclusions obtained from trial waterjetting state that the surface roughness, represented with the i_A, increases as the water pressure increases. In addition, denser pattern of waterjet results with the increase in roughness as well. Increase in stand-off distance leads to the less rough surface. Water pressure was varied between 10 and 15-ksi (69-MPa and 103-MPa), stand-off distance between 0 and 2-in (0 and 51-mm), while jet pattern was varied between 0.090-in and 0.210-in (2.3-mm and 5.3-mm). Nozzle diameter was kept constant with D = 0.012-in.

The steps for the establishment of the analytical relationship include the following:

- Plot the statistically significant readings taken for each of the CSP models in terms of CSP number versus the microaverage inclination angle i_A (Figure 4-a). The best fit was a second order polynomial equation, $f_1(x)$, with R^2 value equal to 0.9611.
- Plot all readings taken for concrete surfaces in terms of equivalent CSP number versus the microaverage inclination angle i_A (Figure 4-b). The best fit was linear equation, $f_2(x)$, with R^2 value equal to 0.9798.



(a) Concrete Surface Profiles



(b) Concrete surfaces

Figure 4. Relationship between CSP no. and i_A

- Plot of functions $f_1(x)$ and $f_2(x)$ for the same values of x ranging from 1 to 8 (Figure 5). The best fit was logarithmic equation shown below with R^2 value equal to 0.9621 (Eq. 3):

$$y = 10.393Ln(x) - 8.4364, \quad (3)$$

where x corresponds to the value of i_A of a CSP model and y to the value of i_A of the concrete surface.

From Figure 5, it can be concluded that a relationship between the laser profilometer readings of CSP models and concrete surfaces can be established. The importance of this correlation is the possibility to quantitatively determine the roughness of the concrete surface using laser profilometer and "translate" it into a corresponding CSP number. Namely, presently state-of-the-art method specifies that the concrete surface prior to application of external reinforcement has to have acceptable roughness visually determined to match one of CSP models. The proposed correlation is used in reporting the pull-off strength of tested specimens in this project.

The points on Figure 5 represent the values of CSP models from 1 to 8, x-axis showing the i_A value of the CSP model and y-axis showing the corresponding i_A value of the concrete surface. Consequently, measuring the roughness of the real concrete surface can be therefore directly "translated" to the CSP models. It can be noted that the x-axis has the maximum of i_A = 12, while the y-axis has the maximum of i_A = 18. This difference between the maximums shows the presence of the high frequency roughness in concrete specimens as opposite to the CSP models.

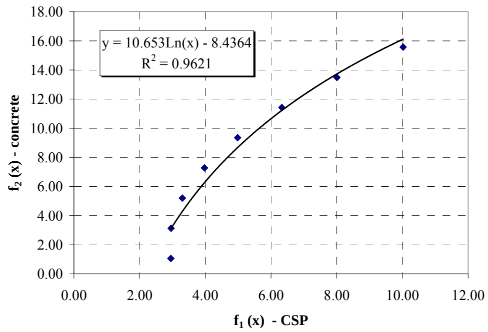


Figure 5. Relationship between CSP and concrete in terms of i_A

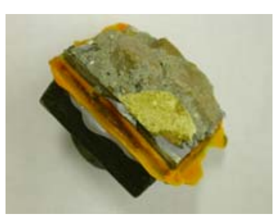
Pull-off Testing

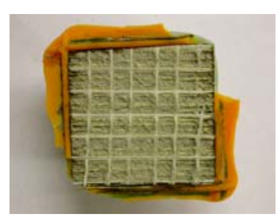
Quality assessment of bond using the pull-off test method was conducted using 34 plain concrete blocks. Two groups of blocks, representing different concrete compressive strengths, were cast; both groups included similar values of surface roughness. Unreinforced concrete blocks with dimensions 8 in × 8 in × 10 in (203 mm × 203 mm × 254 mm) were cast for the first batch and blocks with dimensions 6 in × 6 in ×12 in (152 mm × 152 mm × 305 mm) were cast for the second batch. In addition to concrete strength, surface roughness and embedment material, research variables related to the reinforcement included density of cords and number of plies. After the blocks had cured for approximately 14 days, the concrete surfaces were prepared using waterjetting technique as described in the previous section.

Surface characterization of the waterjetted surfaces was performed using laser profilometer. Out of the possible results reported by the laser profilometer, microaverage inclination angle i_A was chosen as the most relevant parameter to characterize the surface roughness. The pull-off test involves applying a direct tensile normal-to-surface load to the test fixture according to the ASTM D 4541 – 02. The force was applied manually to the pull-off fixture using a HILTI Tester 4 and the failure load was recorded.

The testing matrix included 210 pull-off tests, varying type of reinforcement (SRP or SRG), number of plies (one or two), type of plies (medium density with 12 cords/inch (4.7 cords/cm) and high density with 23 cords/in (9.1 cords/cm)), nominal concrete compressive strength (8000-psi and 4000-psi (55-MPa and 28-MPa)) and the surface roughness. Level of surface roughness is taken as low, medium and high, represented with range of average inclination angle i_A from 0 – 7, 8 – 15 and 16 – 23 degrees, respectively. Representative surfaces were tested without any surface treatment as well as with high level sandblasting producing high roughness.

All SRP specimens tested, regardless of any other research variables, failed with the same failure mode, i.e. they failed in the substrate (Figure.6-a). SRG specimens, regardless of any other research variables as well, failed with a different mode (Figure.6-b), namely, all the specimens consisting of one ply failed in the overlay i.e. in the layer of grout just above the concrete substrate, while all the specimens consisting of two plies failed in the layer of grout as well, but in between of the two steel cord plies.

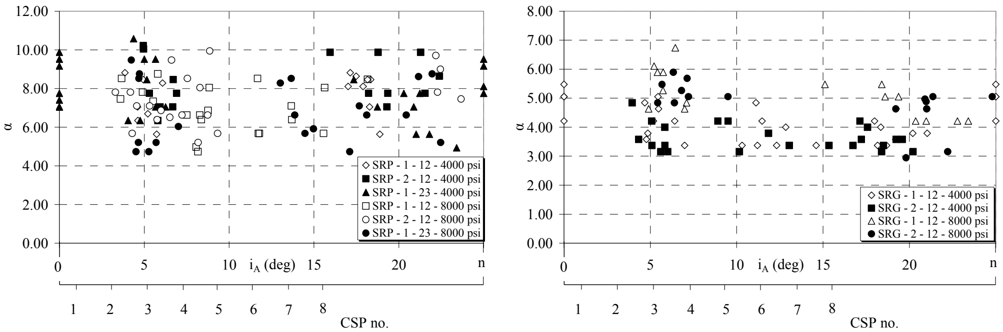




(a) SRP specimen (b) SRG specimen

Figure.6. Pull-off tested specimens - failure mode

Due to the failure modes in the concrete substrate and the layer of grout for SRP and SRG specimens respectively, the pull-off strength can be related to the tensile strength of the concrete and grout, respectively. The pull-off strength, taken as the tensile strength of the concrete, is proportional to the square root of f'_c. For all the specimens with the failure in the concrete substrate Figure 7-a shows the factor α representing the proportion between the pull-off strength and f'_c of concrete. For all the specimens with the failure in the layer of grout Figure 7-b shows the factor α representing the proportion between the pull-off strength and f'_c of grout. In calculation of factor α, concrete strength was taken as 3975-psi (27 MPa) and 8814-psi (61 MPa) for batch 1 and batch 2, respectively. Compressive strength of grout was taken as 2786-psi (19 MPa) as determined from the compressive strength testing according to the ASTM C 109/C 109 M-02.



(a) i_A vs. α - concrete failure (b) i_A vs. α - grout failure

Figure 7. Factor α for all the specimens with failure in concrete

While concrete failure specimens confirm that indeed the pull-off strength can be taken as the tensile strength of the concrete, grout failed specimens show pull-off strength being quite lower than measured splitting tensile strength of the grout that was obtained to be 770-psi (5.3 MPa). As seen on Figure , it can be concluded that there is no significant effect of the surface roughness on the pull-off strength. In addition, sandblasted and no-treatment surfaces as extreme cases of surface preparation did not change the failure mode. This can be explained with the type of failure mode, i.e. only the failure in the interface could be the one where surface roughness could influence the value of pull-off strength. Since SRP specimens failed in the layer of concrete substrate and SRG specimens failed in the layer of grout this does not occur.

CONCLUSIONS

This paper presents a study to investigate first the measurement and then the effect of the surface roughness on the bond performance of the externally applied reinforcement in the form of SRP and SRG. Conclusions regarding these two major objectives are:

- Roughness can be effectively measured with laser profilometry in the laboratory and in the field. A relationship between CSP models, the state-of-the-art method to visually measure roughness, and the roughness of concrete surfaces measured with the laser profilometer was established.

- The effect of the surface roughness on the pull-off strength of SRP and SRG showed to be insignificant due to the failure modes obtained. Extreme cases of surface preparation did not change the failure mode.

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