METHODS OF CORRELATING PRECAST CONCRETE SURFACE ROUGHNESS TO TENSILE BOND STRENGTH IN CONNECTIONS

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ABSTRACT

This research project investigated three methods of measuring precast concrete surface roughness and the correlation of these measurements with the tensile bond strength developed in connections. Connections were represented with composite split cylinder samples composed of concrete and grout. The interfaces of each concrete surface were prepared to different degrees of roughness and measured using three techniques: the ASTM E965 Sand Patch Test, the International Concrete Repair Institute classification method, and a manual profilograph. Two types of standard concrete, a lightweight mix and a Virginia A4 mix, were used to represent precast concrete and a standard high strength, low shrinkage grout was bonded to the concretes to represent the cast-in-place connection material.

The composite cylinders were tested in tension along the concrete-grout interface using the ASTM C496 Split Cylinder Test. The strength of the interface bond for each cylinder was recorded and correlations were made to each of the roughness measurement techniques. The results showed the profilograph and sand patch techniques provided effective quantifiable roughness measurements while the ICRI technique provided a threshold roughness for better performance. A properly roughened interface could be identified with each technique and the tensile bond strength could be increased up to a factor of 3.5 when compared to a smooth interface.

Keywords: Precast Concrete Connections, Surface Roughness, Grout, Tensile Strength

INTRODUCTION

The engineering and construction industries continue to make advances in the use of precast concrete as a building material. Because of this, precast concrete components have become a popular and effective solution for engineering projects, particularly for bridges. In many applications, precast concrete components are used in combination with cast-in-place materials, such as grout. Grout is primarily used to help form connections between precast concrete pieces or to fill pockets used on composite bridges with full-depth precast deck panels. A typical example of this is the connection of two precast bridge deck panels shown in Figure 1.

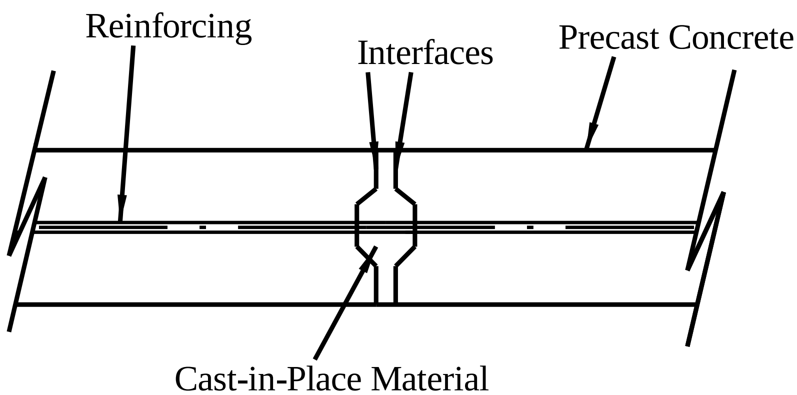

Fig. 1 – Typical precast concrete connection on a bridge deck.

Connections may be the most significant aspect of precast construction. An interface exists between the precast concrete and cast-in-place embedment materials making this a prime location for deterioration. A weak bond between the materials at the interfaces may lead to cracking and a shortened service life for the precast structure.

Current designs reference the "Guidelines For Accelerated Bridge Construction Using Precast/Prestressed Concrete Components", developed by the Precast/Prestressed Concrete Institute (PCI), and the American Association of State Highway and Transportation Officials (AASHTO) Bridge Manual.[1,2] Section 4 of the PCI guidelines gives general commentary for the design of joints. The PCI guidelines categorize joints as structural and non-structural connections and the commentary calls for the use of an "approved non-shrink grout". However, the guidelines do not mention the surface condition of the precast pieces. Similarly, the AASHTO guidelines do not specify the surface conditions at precast concrete joints. Because of this, most designers simply call for an as-cast surface (normally smooth) or a sand blasted surface.

The goal of this research was to quantify surface roughness with a simple procedure that can be easily replicated and used to predict a strong interface bond in precast concrete connections. The first step was to find a practical method of quantifying surface roughness. Three unique methods varying in complexity and cost were compared. The second step was to apply the surface roughness techniques to an array of trial precast concrete surfaces and then bond a grout material to the surfaces. The interfaces were then tested for tensile strength. The results were studied to determine if the surface roughness techniques predict the tensile strength of the surfaces.

BACKGROUND

SURFACE ROUGHNESS TECHNIQUES

Quantifying the surface roughness of concrete or aggregates is a question that has arisen in a number of similar applications. There are cases in transportation engineering and geological engineering that might be applicable to precast concrete connections. Research on concrete surface profiling is also applicable; however, many techniques are generally cumbersome and expensive.

Previous research by Santos and Julio investigated the correlation between surface roughness and bond strength of two concrete materials through the use of the Slant Shear Test and a Splitting Test. This research is significant in that it attempts to correlate shear and tensile strength of the interface bond between new and old concrete with a roughened surface. This research developed surfaces that were roughened to different degrees that ranged from left-as-cast, smooth specimens, to hand-scrubbed, rough specimens. The researchers used a two dimensional roughness analyzer (2D LRA) to obtain a profile of the surface. The results demonstrated that statistical roughness parameters did indicate an increase in bond strength. However, the method is very complex and difficult to use from a practical standpoint.[3]

In a similar study entitled "Correlation Between Concrete-to-Concrete Bond Strength and the Roughness of the Substrate Surface", the same researchers took a more in-depth analysis of surface roughness by using statistical data to determine which parameters provided the best correlation to strength. Digital imaging was used to enhance profiles of the surface. Once the profile was obtained, it was analyzed using roughness parameters including maximum peak height (R_p), maximum valley depth (R_V) and average total height (R_c). Concrete was then bonded to the rough surfaces and tested using the Slant Shear Test and Pull-off Test. Through their research, Santos, Julio and Silva concluded "It is advisable to use roughness parameters like maximum peak-to-valley, total roughness height or maximum valley depth, since these correspond to the highest coefficient of correlation [to bond strength]."[4]

Another set of researchers set out to obtain surface profiles for rock mechanics samples. Roughness plays an important role in rock mechanics because of its effects on shear between two surfaces. The Joint Roughness Coefficient (JRC) is a method to rate rough surfaces in rock mechanics and requires a profile of the surface. In his research, Du Shigui, described that accurate methods to obtain a surface profile are needed. His team proposed a simple profilograph method that manually maps the change in profile of the surface. This was then used to quantify the surface using different statistical approaches.[5] The key variables used in profilograph techniques include the mean change in height, the maximum change in height, and the arithmetic mean across the profile. Each of these statistical parameters can be computed, but only if a profile of the surface is available.

A separate technique for measuring surface roughness is ASTM E965 “Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique”, more commonly referred to as the Sand Patch Test.[6] This test is not labor intensive, is easy to replicate, and is already commonly used among pavement engineers. The downside is it only provides mean texture depths and doesn’t result in the detailed statistics available with profilograph techniques. The question remains whether this method provides enough information for estimating roughness in precast concrete applications.

Another common method of estimating surface roughness is defined by the International Concrete Repair Institute (ICRI), Concrete Surface Profile (CSP) chips. CSP chips are used by concrete sealing and coating technicians to characterize a surface profile. As defined by the ICRI, “a prepared [roughened] surface is the process by which a sound, clean and suitably roughened surface is produced on a concrete substrate” (ICRI ii). The chips were developed from different techniques including acid-etching, grinding, abrasive blasting and mechanical milling. Nine chips, or surface profile samples, are used to estimate the roughness of concrete based on visual comparisons. This technique is used in combining old and new concrete in slab on grade construction as well as in composite member applications to increase shear strength.[7]

BOND STRENGTH TESTING

Once the surface roughness is quantified the next step is to test the bond strengths between the precast concrete and a grout. A number of studies have used a modified split cylinder test to estimate tensile bond strength.[8,9] Creating standard cylinders out of two materials with a bond longitudinally placed down the center of the samples provides a reasonable comparison among bond strengths. Past studies have looked at different grout materials, but typically used a standard surface condition.

It has been shown that using a smooth surface or sand blasted surface with grouted joint connections will result in weak interfaces. One study showed that a smooth surface will result in a tensile strength of approximately $1.5\sqrt{f'c}$, with f’c as the weaker compressive strength of the two materials being bonded.[10] Similar results were shown with a wider sample of high early strength grouts and deck concretes joined at sand blasted surfaces.[11]

PROCEDURES

The procedures of this study involved a twofold process: creating half cylinders for bond tests and measuring the precast concrete half cylinder bond strength. The first section of the procedures explains how the split cylinder samples were made and tested. The second section of the procedures explains the three roughness measuring techniques used to quantify surface roughness used in the split cylinder test. The surface roughness measurements were made while the concrete half cylinders were curing prior to placing the grout half of the samples.

HALF CYLINDER SAMPLES

An experimental program was devised to test tensile bond strength between grout and concrete surfaces. ASTM C496, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,” was chosen because of its standardization, prior use in bond tests, simplicity and the consistent tensile stress induced in the testing specimen. To use this testing method, the standard ASTM was modified to determine tensile strength between concrete-grout connections by creating a specimen composed of two materials. This is shown in Figure 2.[12]

Fig. 2- Modified Split Cylinder Composed of Concrete and Grout

The next step was to select the materials for testing. Two typical reinforced concrete mixes with 28 day compressive strengths of 4,000 psi and one standard high early strength, low shrinkage grout mix were chosen. The first standard concrete mix was based on the Virginia A4 standard bridge mix with 1 in. nominal aggregate size and the second was based on a locally available lightweight concrete mix with 3/8 in. nominal aggregate size. The grout mix was selected to meet the requirements of a standard grout mix based on recent data published by The Federal Highway Administration for precast concrete connections.[11] Forty-five specimens were created; fifteen with the lightweight concrete mix and thirty with the normal weight concrete mix. All samples were bonded with the same grout mix.

The two sides of the samples were cast at different points in time. The first half of the cylinders composed of concrete were cast in standard 4 in. x 8 in. molds cut in half along the longitudinal dimension creating an eight inch long, semicircular mold (Figure 3). The concrete was placed in the cylinders, rodded 25 times, and then trowel finished. A retardant was then placed on the concrete surface and the samples were cured for 18 hours at a constant temperature of 70 degrees Fahrenheit under burlap and plastic.

Fig. 3- Modified 4 in. x 8 in. Cylinder Molds for Concrete Curing

Water jetting and hand scrubbing were used to create a wide variety of surfaces. This was done by spraying a water jet from a standard hose onto the surfaces and gently scrubbing the surface with a glove. Once the surfaces were roughened, the specimens were then allowed to fully cure under wet burlap and plastic at 70 degrees Fahrenheit.

The concrete cylinders were allowed to cure until shrinkage began to taper. The shrinkage data was based on ASTM C157 "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete."[13] For the lightweight concrete this was 84 days, while the second phase with the normal weight concrete is currently not complete. The goal was to bond dimensionally stable concrete mixes to the grout. During the curing phase the surfaces roughness was measured for each cylinder as described in the next section of the procedures.

To create a full 4 in. by 8 in. cylinder, the cured concrete halves were placed in full cylinder molds and the grout was placed in the other half. The grout was mixed to a fluid consistency as recommended by the manufacturer and designed for a 6000 psi 28 day strength. The grout was placed in two layers and rodded 25 times per increment. In addition, three full grout test cylinders were created to be tested in the Split Cylinder test. Figure 4 shows the cylinders after the grout was placed.

Fig. 4 – Casting the Full Cylinders

Once all the grout was poured, the samples were placed in a curing room and covered in wet burlap. The conditions were kept within a constant temperature range of 70-72 degrees Fahrenheit with humidity at 100 percent. After twelve hours, the cylinders were removed from the molds. Specimens continued to cure after the molds were removed for twenty-eight days.

After the curing process, the tensile strength of the bond between the concrete and grout was tested using the Split Cylinder Test (Figure 5). ASTM procedures required 1 in. wide by 9 in. long pieces of wood to act as bearing strips to create a uniform surface for the compressive force.[12] The specimens were aligned in the testing apparatus so the bond interface was perpendicular to the compression plate, thus creating the tensile stress at the joint between the concrete and grout. The load rate was kept within a range of 5,000-10,000 lbs/min until failure.

Fig. 5- Setup for ASTM C496 Split Cylinder Test

The maximum load that caused failure was recorded from the testing apparatus. This test was performed for all fifteen concrete-grout cylinders as well as for the all grout cylinders and all concrete cylinders. The full grout and full concrete cylinders acted as control samples and would provide data for comparing the strength of the composite cylinders. Using the failure load (P) from the testing apparatus, the diameter (d) and length (l) of the specimen, the tensile stress was calculated by the ASTM equation shown in Equation 1.[12]

$$T = \frac{2P}{\pi l d} \qquad (1)$$

SURFACE ROUGHNESS MEASUREMENTS

To characterize the surface roughness of each concrete sample, three measuring techniques were employed. These techniques included ASTM E965 “Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique”, more commonly referred to as the Sand Patch Test; the International Concrete Repair Institute (ICRI) Concrete Surface Profile (CSP) chip; and a manual profilograph.

The Sand Patch Test is commonly used to measure pavement roughness in transportation engineering. It uses a known volume of sand that is placed on the surface and smoothed to the shape of a circle using a rubber puck. Once the sand circle is constant and cannot be spread out larger, the diameters are measured as shown in Figure 6.

Fig. 6 - Measuring Mean Texture Depth Using ASTM E965 Sand Patch Test

Using the diameters of the circles and the known sand volume, the mean texture depth (MTD) of the surface can be calculated. By using the volume of sand applied, V, and diameter of the circle, D, the average depth of the surface can be determined by Equation 2.[6]

$$MTD = \frac{4V}{\pi D^2} \tag{2}$$

For this research, the sand patch test was performed three times per surface, and three diameters were measured for each circle. This provided an average diameter and MTD that characterized the whole surface and accounted for oblong circles.

The second technique used to characterize the roughness was Concrete Surface Profile (CSP) chips from the International Concrete Repair Institute (ICRI). The ICRI CSP chips are rubber rectangles (Figure 7.) Each CSP chip is assigned a number where an ICRI value of 1 is a smooth surface and a value of 9 is rough. This technique is a visual subjective characterization of roughness based on the CSP chips. Because of this, each profile was assigned an ICRI value by two different researchers to compare relative consistency. The CSP chips were also measured using the sand patch test and manual profilograph to perform a quantifiable comparison between methods.

Fig. 7- ICRI Concrete Surface Profiles: 1-Upper Left, 9-Lower Right

The final technique used to measure the surface profile of the concrete half cylinders was a manual profilograph. This method was developed by placing a tip on the end of a two inch dial gage. The dial gage was fixed to a base that suspended the tip over the concrete surface. The tip was raised and lowered onto the surface to measure the height at a particular location. The profilograph is show in Figure 8.

Fig. 8 - Manual Profilograph Developed to Measure Surface Profiles

Height measurements were taken at half inch intervals, parallel to the eight inch side of the specimen and were repeated at half inch intervals from the edge of the four inch side of the specimen. A total of seven lines were made per specimen and each line consisted of seventeen height data points. In total, a single specimen had 119 data points that characterized the roughness of the sample as shown in Figure 9.

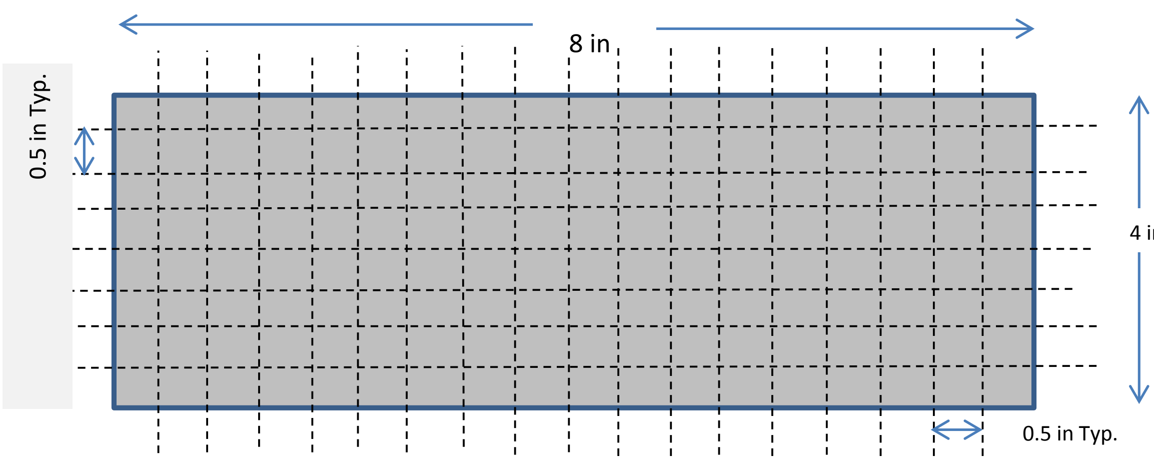

Fig. 9- Measurement Grid used with the Manual Profilograph

RESULTS

The first phase of the research focused on the set of 15 samples consisting of lightweight concrete. This phase of the research is complete. The second phase of the research focusing on the normal weight concrete is ongoing and not currently reported.

SURFACE ROUGHNESS MEASUREMENTS

When using the Sand Patch Test, the mean texture depth (MTD) was measured at three different locations on the surface and the measurements were averaged. Results of the Sand Patch Test are shown in Table 1.

Table 1- Mean Texture Depth of Cylinder Surface Roughness – Lightweight Concrete

Cylinder Sample	Sand Patch Test Average MTD (in)
1	0.061
2	0.096
3	0.112
4	0.057
5	0.050
6	0.128
7	0.058
8	0.067
9	0.030
10	0.061
11	0.073
12	0.062
13	0.033
14	0.036
15	0.061

The second method used was the International Concrete Repair Institute Concrete Surface Profile chips. The maximum difference between the researchers on evaluating any surface was two but this only occurred on one sample. For every other surface, the two evaluations were either off by one CSP value or were evaluated with the same CSP value. The results of the ICRI matching by the two researchers are shown in Table 2.

Table 2- Assigned ICRI CSP Values

Cylinder	IRCI Matching		
Sample	Researcher 1	Researcher 2	Difference
1	7	6	1
2	9	8	1
3	8	9	1
4	7	6	1
5	5	6	1
6	9	8	1
7	6	6	0
8	8	9	1
9	3	3	0
10	6	7	1
11	7	7	0
12	7	5	2
13	6	6	0
14	5	6	1

In the final technique, the manual profilograph, height measurements of the surfaces were taken at half inch intervals in the grid pattern previously described. This data was used to develop the statistical parameters. The data was standardized so that the mean surface height was zero and measurements of peaks and valleys were described as a positive or negative change from the average. This was done by finding the average height for each line and in turn taking the average of the seven lines. This overall average height was then subtracted from the height at each location to give the change from the average at each point. This data was plotted to create a surface profile of each cylinder surface (Figure 10).

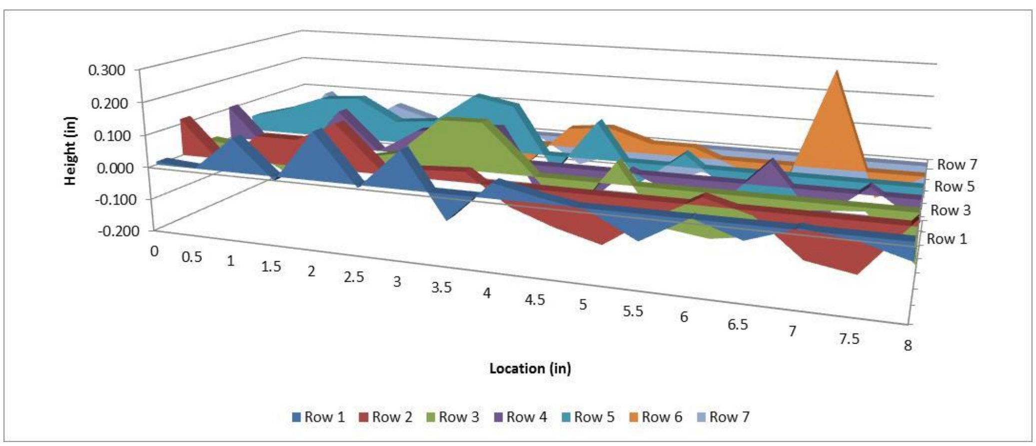

Fig. 10 - Cylinder 2 Surface Profile Obtained from the Manual Profilograph

From the height data provided by the profilograph, different statistical values to characterize the surface roughness were analyzed. It was determined that the average total height value, or R_c, of the surface was useful in comparisons. It represents the average depth from a peak to a valley. This is comparable to the mean texture depth from the Sand Patch Test in that both show a total depth measurement incorporating both the peak and valleys into a single measurement. These statistical values are shown in Table 3.

Table 3- Statistical Value, R_c, from the Profilograph Data

Sample	**Ave Total Height, R_c (in.)**
1	0.178
2	0.270
3	0.292
4	0.153
5	0.155
6	0.245
7	0.157
8	0.265
9	0.108
10	0.164
11	0.194
12	0.202
13	0.180
14	0.152
15	0.158

In addition to the data calculated above, the profilograph data was used to show the change from one measurement point to the next. This back-to-back change was determined by taking the absolute value of the difference of each consecutive point on the surfaces. The change from one data point to the next was plotted for each surface. The back-to-back change for the surface of Cylinder 2 is shown in Figure 11.

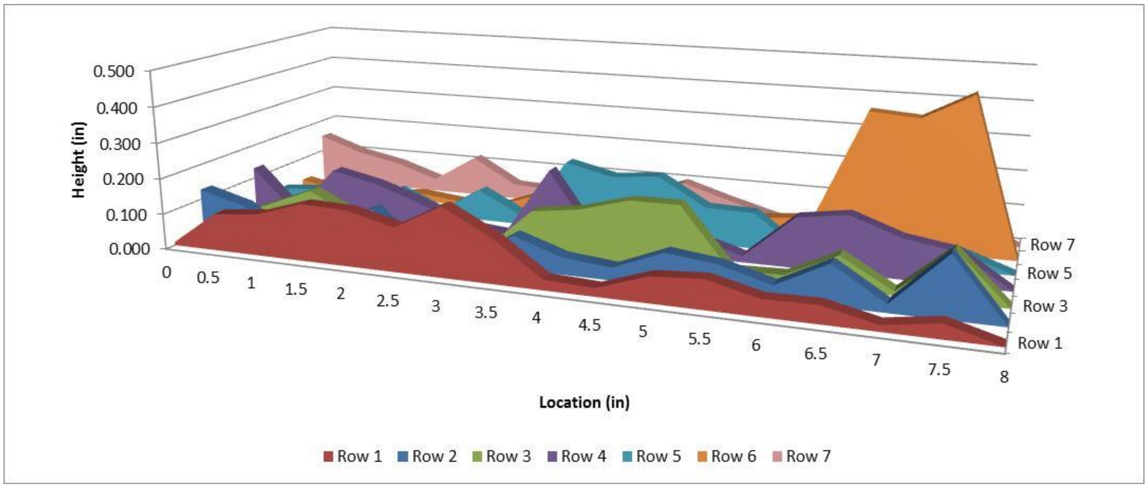

Fig. 11 – Cylinder 2: Back-to-Back Change in Height

Table 4 tabulates the back-to-back data of each cylinder. This table shows the average change, which is the mean value for the difference of one point to the next; the max change, which is the largest change of the surface; and the minimum change, which is the smallest change of the surface. This can be used to compare the jaggedness of the surface. If there is large change from one point to the next, the surface would have high back-to-back values, representing steep elevation changes. Conversely, if there is small change from one point to the next, the surface would have low back-to-back values, representing small elevation changes.

Table 4- Back-to-Back Change for Fifteen Concrete Surfaces

Sample	Ave Change (in)	Max Change (in)	Min Change (in)
1	0.036	0.110	0.002
2	0.080	0.220	0.003
3	0.068	0.211	0.003
4	0.030	0.078	0.001
5	0.029	0.090	0.002
6	0.086	0.204	0.007
7	0.037	0.102	0.003
8	0.053	0.139	0.008
9	0.019	0.055	0.002
10	0.040	0.110	0.002
11	0.056	0.131	0.004
12	0.045	0.126	0.002
13	0.025	0.076	0.001
14	0.029	0.084	0.002
15	0.036	0.108	0.004

BOND TESTING

Different breaks were observed in the split cylinder tests, but all cylinders fractured vertically near the joint as intended. The type of fracture ranged from a smooth fracture along the grout to an aggregate fracture within the concrete. The different breaks are shown in Figure 12.

Aggregate Pullout/Fracture Grout Failure

Fig. 12 - Half Cylinder Breaks

The types of fracture are significant because they demonstrate that in some cases the bond was strong enough to pull aggregate out of the concrete or even fracture the aggregate. When the highly roughened surfaces were used, aggregate was exposed and the grout cured around the aggregate. This allowed the aggregate to contribute to the strength by being embedded in both the concrete and grout, resulting in aggregate fracture. However, in the most severe roughened surfaces, the aggregate was pulled out of the concrete because of the higher grout strength. This is important to note because the full strength capacity of the aggregate may not be utilized. When smoother surfaces were used, aggregate contributed little to the strength and the concrete paste interface fractured instead of the aggregate.

Using the Split Cylinder testing apparatus, the maximum compressive load that caused the tensile failure was recorded (Table 5). As provided by the ASTM, the tensile stress of the bond can be quantified. Using Eq. 2, the tensile stress was calculated based on the variables of the equation. The diameter and length of each cylinder was measured to accurately calculate the stress. The compressive strength, tensile strength, and calculated tensile strength results for the grout and lightweight concrete are in Table 6. The strengths were all significantly higher than the design strengths. The lightweight concrete used was designed for a compressive strength (f'c) of 4000 psi at 28 days but reached an average 112 day (the day of testing) compressive strength of 6180 psi. Likewise, the grout was designed for a 28 day strength of 6000 psi, but reached 8890 psi at 28 days (the day of testing).

Table 5- Bond Strength Data for Lightweight Concrete Samples

Cylinder Sample	Max Compressive Load (lbs)	Tensile Strength (psi)	% of Lightweight Concrete Tensile Strength
1	18360	361	64.4
2	22010	441	78.7
3	19930	401	71.7
4	19460	385	68.8
5	19220	382	68.3
6	17140	346	61.9
7	22050	431	76.9
8	21760	428	76.4
9	21100	418	74.7
10	22080	448	80.0
11	20380	406	72.4
12	14350	287	51.3
13	26100	509	90.9
14	20830	423	75.6
15	25310	494	88.1
Average	20672.0	410.7	73.3

Table 6 – Material Properties at 28 Days

Material	Compressive Strength (psi)	Measured Tensile Strength (psi)	Calculated Tensile Strength (psi)
Lightweight Concrete	6190	560	590
Grout	8890	640	710

As shown in the Table 6, the strength of the full grout cylinders exhibited the highest tensile strength, followed by the full concrete cylinders. This was expected because there was no discontinuity, or joint, within these specimens. The calculated value was computed using an estimate of $7.5\sqrt{f'c}$. The calculated values were within 10% of the measured values although both calculated values were higher.

The group of 15 samples was first viewed as a group and the values were averaged. The composite concrete-grout cylinders exhibited very high tensile strength, reaching an average of 73.3% of the strength when compared to the full concrete cylinders. The average tensile strength of the fifteen cylinders was 411 psi. This is approximately $5.2\sqrt{f'c}$ on average, a significant increase in strength over the predicted value of $1.5\sqrt{f'c}$ presented in the background section of this paper.. Using this predicted equation, the estimated tensile strength would be 118 psi based on the lightweight concrete strength. The concrete-grout bond is greater than the estimator by a factor of 3.5 on average. This shows great strength potential when using roughened surfaces. Even the smallest tensile stress observed, Cylinder 12, had a tensile bond strength of 287 psi, over 2.4 times higher than the predictor equation.

After the initial analysis, the roughness of each sample was compared to the strength of the bond. Figure 13 shows the roughness of the surface measured by the profilograph method, using the R_c parameter, and the tensile strength of the bond. The vertical line represents half the nominal aggregate size of 0.1875 in.

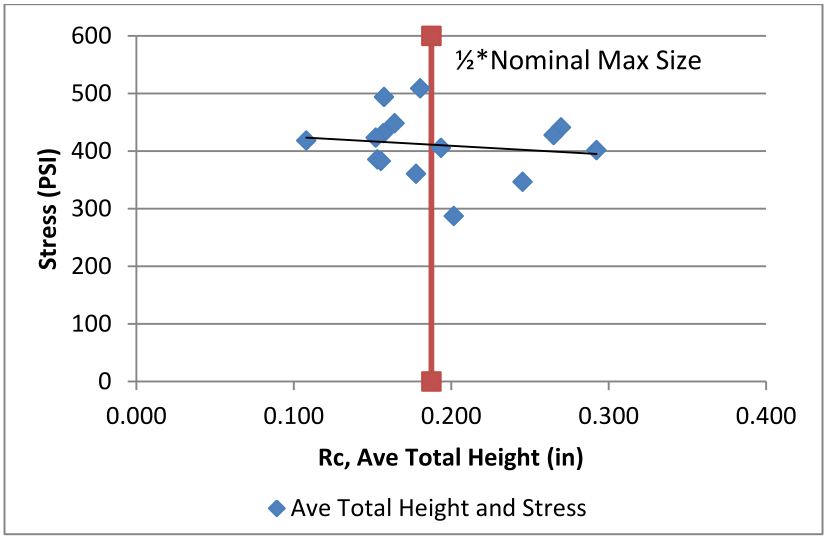

Fig. 13-Tensile Strength Compared to R_c, Average Total Height from Profilograph

Most of the surfaces exhibited average total heights around the 0.1875 inch line or half the aggregate size. Ten of the fifteen values were between 0.152 in. and 0.202 in. There was not a wide range of roughness measurements as anticipated. However, because of the many samples within this tight range of roughness, it shows that the strength of the bond at this roughness tends to provide a much higher average tensile stress. This is significant because all the roughened surfaces except one had a tensile stress greater than 3.0 times the value if smooth surfaces were used.

In Figure 14 the tensile strength is compared to the mean texture depth as measured by the Sand Patch Test. This shows a very similar distribution of stress to the manual profilograph, however the mean texture depth is not as close to the nominal aggregate size. This may be due to intrinsic error in the mean texture depth measurement using sand particles. However, the cluster of data points suggest that at a mean texture depth of approximately 0.03 to 0.07 inches correlates to the profilograph reading of half the nominal aggregate size. This is approximately one-eighth the nominal max size of the lightweight aggregate.

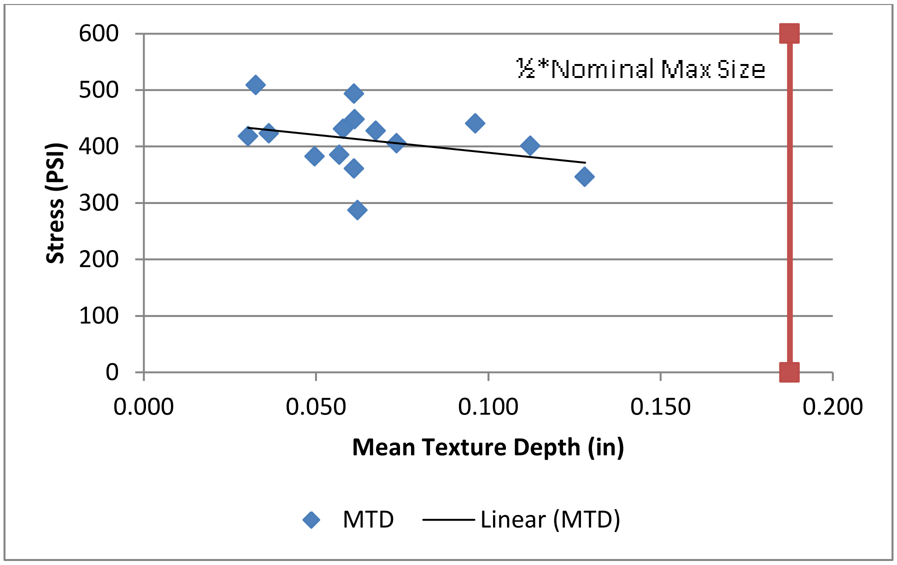

Fig. 14 - Tensile Stress Compared to Mean Texture Depth

The final comparison in Figure 15 shows the strength of the bond compared to the ICRI ratings by the two researchers. When comparing the ratings numerically to the strength, the ICRI CSP chip ratings did not provide a significant range. However, the ICRI ratings did demonstrate that roughness values of 6 or higher exhibited average tensile strengths at least 3.0 times what can be produced by a smooth surface.

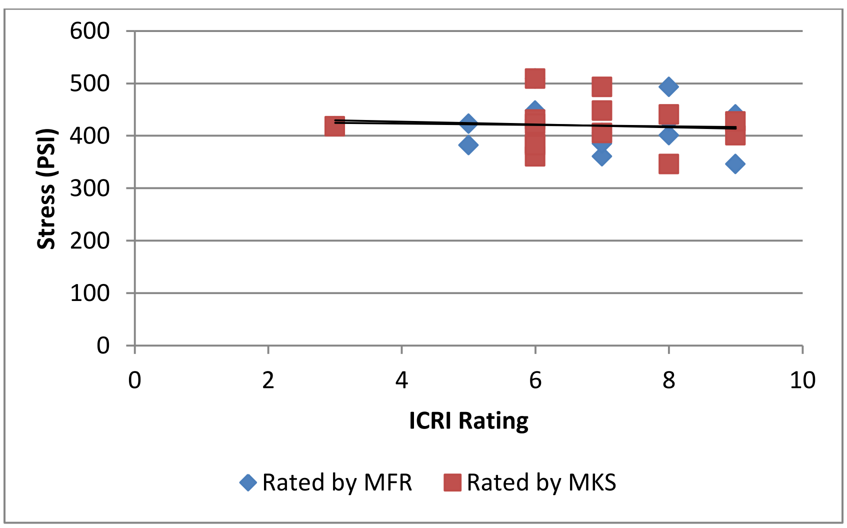

Fig. 15 - Bond Strength Compared to ICRI Ratings

CONCLUSIONS

Preliminary conclusions have been drawn concerning the tensile bond strength, the roughening methods, and the roughness measurements with respect to the lightweight aggregate concrete. The analysis concerning the samples with the normal weight concrete is ongoing.

1) The manual profilograph creates the most accurate characterization of the surface; however, it takes a significant amount of time. The Sand Patch Test creates data that is comparable to the profilograph in significantly less time and is easy to analyze. The easiest and quickest method was the ICRI CPS chips, but the chips are qualitative and more subjective.
2) This research concludes that the use of roughened surfaces has great potential for increasing the tensile bond strength in precast concrete connections. Through the analysis of the data on lightweight concrete samples, roughened surfaces were shown to reach an average of 70 percent of the tensile strength of a concrete split cylinder per ASTM C496. This is approximately 3.5 times greater than the estimated tensile strength of a smooth connection. The tension strength data was shown to remain consistent for surfaces roughened to an average total height, Rc, equal to ½ the nominal maximum aggregate size.
3) Little variation was seen in the tension bond strength among all the samples roughened to various average total heights, Rc. This may suggest that many roughness measurements will create similar results as long as the aggregate is exposed to the grout layer. Further study is warranted.
4) The mean texture depth from ASTM E965 showed similar patterns to the results from the profilograph. However, the values were a factor of 4 lower than the average total height, Rc, from the profilograph. This does not imply the method is ineffective, but shows that the two methods produce similar, scaled results.
5) The method of ICRI CSP chips provided an easy method to compare surface roughness. They were ineffective in providing a significant range of roughness values but the roughest chips (values of #6 or higher) could be used as a threshold roughness measurement. As long as the concrete was roughened to these levels, the tensile bond strength was at least 3 times stronger than what was formed with a smooth surface.
6) It was demonstrated that the use of a retarding agent along with the water-jetting and hand-scrubbing processes can roughen concrete surfaces effectively.

FUTURE PLANS

In this project, the nominal aggregate size was 3/8 in. for the lightweight concrete and therefore, most of the roughened surfaces with exposed aggregate had depths around half this value as measured by the profilograph. Additional research is ongoing on a normal weight concrete with a 1 in. nominal aggregate size. This will provide a wider range of roughness measurements and could lead to a better understanding of the effects of various roughness levels. In addition to using full concrete and full grout cylinders as control samples, smooth, as-cast surfaces are also being developed as control specimens to confirm the strength of smooth connections. These additional samples are needed in order to make significant correlations between the degrees of surface roughness and the tensile bond strength.

REFERENCES

1. PCI, "Guidelines For Accelerated Bridge Construction Using Precast/Prestressed Concrete Components". *Precast/Prestressed Concrete Institute*, 2006.
2. American Association of State Highway and Transportation Officials, "AASHTO LRFD Bridge Design Specifications". *AASHTO*, 2010 Interim Revisions, 2010.
3. Santos, Pedro and Eduardo Julio, "Factors Affecting Bond between New and Old Concrete". *ACI Material Journal*. 108 (4) 449-456, 2011.
4. Santos, Pedro, Eduardo Julio and Vitor Silva, "Correlation between Concrete-to-Concrete Bond strength and the Roughness of the Substrate Surface". *Construction and Building Materials*. 21 (8) 1688-1695, 2006.
5. Shigui, Du, Hu Yunjin and Hu Xiaofei, "Measurement of Joint Roughness Coefficient by Using Profilograph and Roughness Ruler." *Journal of Earth Science*. 20 (5) 890-896, 2009.
6. ASTM, "E965 Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique". *American Society of Testing and Materials (ASTM) International.* West Conshohocken, PA., 2011.
7. ICRI, "Technical Guidelines No. 310.2R-2013: Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings Polymer Overlays, and Concrete Repair". *International Concrete Repair Institute*. Rosemont, IL., 2013.
8. Scholz, D. P., Wallenfelsz, J. A., Lijeron, and Roberts-Wollmann, C. L., "Recommendations for the connection between full-depth precast bridge deck panel systems and precast I-beams," Virginia Transportation Research Council, Charlottesville, Va., 2007.
9. De Murphy, M.L., Kim, J., Sang.Z., Xiao, C., "Determining More Effective Approaches & Materials for Grouting Shear Keys," Pennsylvania Transportation Institute, Pennsylvania Department of Transportation, 2010.
10. Swenty, Matthew, "The Investigation of Transverse Joints and Grouts on Full Depth Concrete Bridge Deck Panels," Virginia Polytechnic Institute and State University, 2009.
11. Swenty, Matthew and Benjamin Graybeal, "Material Characterization of Field-Cast Connection Grouts", Federal Highway Administration, FHWA Publication No. FHWA-HRT-13-042, 2013.
12. ASTM, "C496 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens". *American Society of Testing and Materials (ASTM) International*. West Conshohocken, PA., 2011.
13. ASTM, "ASTM C157 Standard Test for Length Change of Hardened Hydraulic-Cement Mortar and Concrete". *American Society of Testing and Materials (ASTM) International.* West Conshohocken, PA., 2011.