Influence of sand angularity on standard test for strand bond

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- This project explored the influence of sand angularity on ASTM A1081, *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Steel Strand.*

- Four sands were tested, each of which was subjected to a full ASTM A1081–style test and angularity tests using two different methods.

- It was determined that the angularity of the sand does influence the strand bond, but not enough to cause a strand to fail the ASTM A1081 test.

The ability to effectively transfer force from a pretensioned steel strand to a concrete element is fundamental to achieving structural performance in a prestressed concrete member.[1] The distance over which this transfer occurs (referred to as transfer length) is typically computed according to code guidance found in either the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*[2] or in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[3,4] Because tests have shown that the quality of strand bond may have a significant impact on transfer length,[1] various forms of strand bond pull-out tests were developed and tested in the 1970s, 1980s, and 1990s to evaluate the bond quality of a strand embedded in concrete. Through four rounds of testing, Russell and research teams developed a strand bond pull-out test[5] that is now known as ASTM A1081, *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Strand*.[6] It incorporated elements from several other existing tests, namely the Post-Tensioning Institute (PTI) bond test.[7]

The applicability and reliability of the ASTM A1081 test method continues to be investigated in ongoing research. According to Russell,[5] results from the protocol have been shown to be reproducible across test sites, and it reliably indicates beam flexural behavior and transfer length. Recent research sponsored by PCI confirmed these results with some indication of variability in ASTM A1081 results across testing sites.[8,9] Reliability across test sites could be improved, however, if the effects of certain test procedure variables were known. For example, results reported by Polydorou[8] suggested that a standard water-cement ratio *w/c*, a reduced allowable flow, and a common sand source would reduce variability between testing sites and that the cement source had a significant effect on the results. Sand type is not specified in the most current ASTM A1081 procedure outline. The only requirement is that the sand meet the gradation guidelines found in ASTM C33.[10] Because of this minimal requirement, many sand gradations can be used. Fine, medium, or coarse sand of differing angularities could all meet the requirements.

It is not known if all test sites in the original testing used the same sand. In fact, it is likely that each testing site used local materials for the test. Therefore, the results could have been influenced by this variable. The recent work sponsored by PCI included interlaboratory testing using sand from the same source.[8] If sand angularity has an impact on the bond strength, the sand angularity as well as gradation may require consideration in future specifications of the ASTM A1081 protocol.

The flow of the mortar used in an ASTM A1081 test is checked prior to its use in the strand-bond cans and cubes. Mortar flow has been shown to be a statistically significant variable affecting ASTM A1081 results.[8] According to Hawkins and Ramirez,[11] the homogeneity, cohesiveness, and workability of fresh mortar can all be influenced by the angularity of the sand used. They have also indicated that the variability in mortar strength and flowability are such that establishing allowable degrees of sand angularity bears consideration and maintain that the fineness modulus is not a reliable indicator of angularity.[11] Because packing density and consolidation also depend on the nature of the particle surfaces, sand angularity could play a role in determining the consolidation and density of the mortar.[11] Consequently, the potential influence of varying sand gradation and angularity should be investigated.

An extensive review of the literature strongly supports the conjecture that sand angularity may affect the results of the ASTM A1081 test (that is, strand bond pull-out strength). Consequently, the objective of the tests discussed here was to accurately quantify the relationship, if any, between sand angularity and strand bond strength. The broader goal of this project is to more fully understand the mechanical bonding effects present in the ASTM A1081 test. Because the ASTM A1081 test, by design, mimics prestressed concrete behavior, a better understanding of the bond mechanics in the test is inherently desirable.

Improved knowledge of the bonding effects present in the ASTM A1081 test will facilitate the determination of the test's reliability. If no consistent variation based on angularity type, grain size, or sand origin can be identified, the test protocol's reliability could be further established. Eliminating or accounting for the variations in the ASTM A1081 test will improve its reproducibility and increase its acceptance in industry.

Testing program

The testing program in this study was organized into two distinct phases of sand angularity testing and strand bond testing in general accordance with ASTM A1081. The work performed in this research project predates the initial adoption of ASTM A1081, but the procedure is fundamentally similar because both are driven by the earlier protocol developed by Russell.[5] To compare behavior across a spectrum of angularities, the project included four different sands, ranging from angular to rounded. The naming protocol is based on the city in which the sand is mined. The angular sand is from Anaheim, Calif., while the subangular is a blasting sand from Sand Springs, Okla. The subrounded is from Dover, Okla., and the rounded is from Ottawa, Ill. All of the type III portland cement was from the same production run in Chanute, Kans. A single source of seven-wire, low-relaxation, 0.6 in. (15 mm) diameter, 270 ksi (1860 MPa) strand manufactured on May 2, 2012, was used for all tests. The testing program consisted of material characterization using ASTM C33 sieve analysis, the ASTM C1252 angularity test, and the three-dimensional digital and scanning electron microscope visual analysis using ASTM D2488 angularity. When these tests were completed, the ASTM A1081 standard test method for evaluating the bond of seven-wire steel prestressing including the ASTM C109 mortar cube test was performed.

Material characterization

All of the sands used were subjected to rigorous material characterization tests. Standard sieve analysis was conducted to determine the material's compliance with ASTM C33.[10] To draw conclusions concerning the influence of angularity on strand bond, it was also necessary to fully categorize the angularity of the various sands in the testing program. The most recent accepted ASTM standard test for fine aggregate angularity is ASTM C1252,[13] though researchers in the Superior Performing Asphalt Pavement (Superpave) industry have questioned the accuracy of this method.[14] Chowdhury and other researchers[15] performed extensive testing in 2001 to determine whether a better method could be found to measure fine aggregate angularity. After experimenting with a variety of computer-based visual test methods, Chowdhury et al.[15] concluded that the visual (image-based) methods showed promise and good correlation with each other. They also concluded that the ASTM C1252 test was not a reliable indicator of angularity. Based on these findings by Chowdhury and others, the decision was made to both incorporate ASTM C1252

Table 1. Three-dimensional digital and scanning electron microscope visual analysis using ASTM D2488 angularity

Camera position	Sieve size	Sand angularity using ASTM D2488				
		Sieve opening, mm	Anaheim	Sand Springs	Dover	Ottawa
1	<325	0.0	Angular	Subangular	Subangular	n.d.
2	325	0.0450	Angular	Subangular	Subrounded	n.d.
3	170	0.090	Angular	Subangular	Subrounded	Subrounded
4	140	0.106	Angular	Subangular	Subangular	Rounded
5	80	0.178	Angular	Subangular	Subrounded	Rounded
6	60	0.250	Angular	Subangular	Subrounded	Rounded
7	40	0.419	Angular	Subrounded	Subrounded	Rounded
8	25	0.706	Subangular	Subangular	Subangular	Rounded
9	20	0.841	Subangular	Subrounded	Subrounded	Rounded
10	18	1.001	Subangular	Subrounded	Subrounded	Subrounded
11	14	1.410	Angular	Subrounded	Subrounded	Subrounded
12	12	1.679	Subangular	Subrounded	Subrounded	Subrounded

Note: n.d. = no data. 1 mm = 0.0394 in.

testing and perform additional visual analysis beyond the standard ASTM protocol. In 2015, following completion of this research, ASTM C1252 was withdrawn by ASTM without replacement, but the methods are still appropriate for classifying the angularity of sand used for the ASTM A1081 strand bond test.

Of the three different procedural guidelines set forth in ASTM C1252, the document states that test method A is the most useful as an indication of angularity.[13] Test method A was therefore used to test all four sands. Test method A requires combinations of material from the mass retained on specific sieves selected from the standard ASTM C33 sieve test. The ASTM C1252 test setup allows the sand sample to free-fall into a container of known volume. The aggregate specific gravity is then used to calculate the percentage of void space in the sample collected in the container. ASTM C1252 approximates angularity by equating it to the uncompacted void content in the fine aggregate sample.

As an independent verification of the ASTM C1252 angularity test, a visual analysis of angularity was performed. Sand samples were separated into specific gradations using a set of fine sieves (**Table 1**). These sieve sizes do not correlate to those required in ASTM C33; imaging with the scanning electron microscope requires a different sieving scheme for optimal analysis. The sieves in Table 1 were used to allow the examination of similarly sized particles at discrete magnification levels.

The equipment used was a scanning electron microscope and an optical digital microscope system. These systems were used to capture high-resolution pictures of the sand at various image types and sieve sizes to facilitate a qualitative determination of angularity. The scanning electron microscope images were captured using three image and detector types. These are designated on the images as variable pressure secondary electron, standard secondary, or standard backscatter. The appearance of the particles at specific gradation sizes and image types was compared with the other sand samples and the ASTM C1252 results.

ASTM A1081 strand bond testing

A standard ASTM A1081 test was performed with each of the four sand types. According to the ASTM A1081 testing protocol, a single test consists of 15 mortar cube compression tests and 6 can strand bond tests. The ASTM A1081 test consists of an untensioned strand embedded in an 18 in. (460 mm) tall steel can with a 2 in. (50 mm) bond breaker at the bottom of the can; the remaining height of the can filled with mortar. The live end (lower end) of the strand is engaged with a chuck where the tension is applied to the assembly below the can. At the dead end (upper end) of the can, the displacement (slip) of the strand is measured using a gauge mounted on the can.

Per ASTM A1081 protocol, the displacement rate of the gripping device was 0.1 ± 0.005 in./min (2.5 ± 0.13 mm/min) and the loading rate did not exceed

Figure 1. Testing frame in place on testing machine.

8500 lb/min (38 kN/min). The test was terminated when the strand slipped a total of 0.1 in. (2.5 mm) as measured at the dead end. The mortar strength is tightly controlled by the ASTM A1081 procedure outline, as is the testing time period. These aspects of the test are regulated to mitigate the effects of certain variables, such as mortar strength and modulus of elasticity. These restrictions are discussed in greater detail with the testing results. **Figure 1** shows the ASTM A1081 testing apparatus used for this investigation.

There were two variations from the ASTM A1081 standard test method for evaluating the bond of seven-wire steel prestressing strand. The first was the use of a thrust bearing assembly at the chuck plus an assembly free to rotate above the tensioning crosshead to eliminate any torsional restraint instead of using a polychloroprene pad, as mentioned in section 9.1.4 of ASTM A1081 (Fig. 1). The other variation was that for three of the mixtures, water-reducing admixtures were used to achieve the correct flow and strength requirements at the time required for the bond evaluation test per section 8.3.4 of ASTM A1081. All other requirements of the ASTM A1081 standard test method were met.

Results and discussion

Material characterization

ASTM C33 dictates the minimum and maximum percentage passing for each sieve used (**Table 2**). This table also tabulates the fineness moduli. **Figure 2** plots the percentage passing of each sand, along with the ASTM limits for comparison.

Figure 2 indicates that the tested sands showed variations in gradation within the requirements of ASTM C33. All were found to be in compliance with ASTM C33 limits. Table 2 indicates that the fineness modulus values of the four sands tested were all within ASTM limits as well and show variation within the ASTM limits.

Table 2. Comparison of U_s values for all sands

Sand	Fineness modulus	U_s, %	Specific gravity	ASTM D2488 description	Minimum strand bond at 1 in. slip, lb	Maximum strand bond at 1 in. slip, lb	Average strand bond at 1 in. slip, lb	Mortar flow, %	Average compressive strength, psi
ASTM C33 high	3.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Anaheim	2.75	41.4	2.65	Angular	22,710	26,320	24,460	103	4860
Sand Springs	3.05	38.2	2.65	Subangular	21,050	27,480	24,940	108	4660
Dover	2.43	37.6	2.63	Subrounded	19,640	26,340	23,860	103	4720
Ottawa	2.68	37.5	2.65	Rounded	17,630	25,890	23,030	111	4930
ASTM C33 low	2.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Note: n/a = not applicable; U_s = ASTM C1252 uncompacted voids using test method A. 1 lb = 4.448 N; 1 psi = 6.895 kPa.

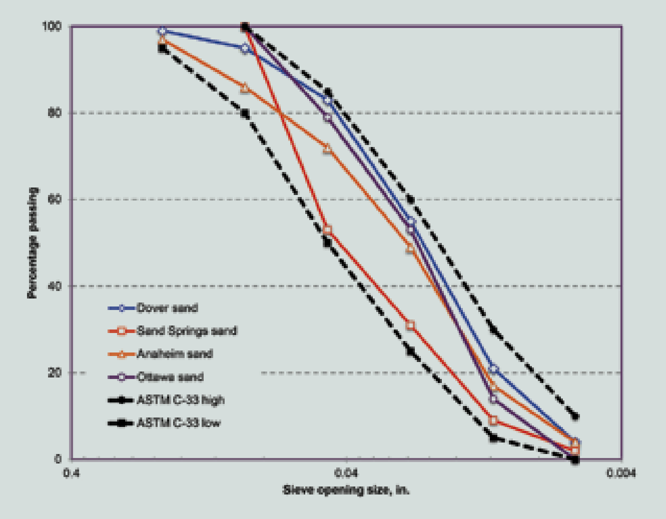

Figure 2. Comparison of sand gradation and ASTM C33 limits. Note: 1 in. = 25.4 mm.

ASTM C1252 testing

Table 2 also compares the ASTM C1252 test results. The table is arranged from highest to lowest uncompacted voids using test method A, also known as U_s, with a higher U_s value indicating greater angularity (per ASTM C1252[13]). The rankings in Table 2 indicate that Anaheim sand was the most angular, followed by the Sand Springs sand. Because both the Dover and Anaheim sands were river sands, they were initially expected to have comparable U_s values. This anticipated similarity was reinforced by the similar behavior of the two sands during batching and testing. However, the high U_s value of the Anaheim sand suggests the presence of highly angular or possibly elongated particles. The ASTM C1252 test results do not exhibit correlation with the fineness modulus values for the four sands (Table 2).

Visual angularity analysis

The optical digital microscope and scanning electron microscope pictures of each sand type were analyzed to determine a qualitative measure of angularity. The images were ranked using the guidelines of ASTM D2488,[16] which is intended to be used as a visual, qualitative procedure for describing and identifying soils. Section 10.1 of ASTM D2488 is dedicated to the visual determination of sand angularity. The document ranks aggregate particles as angular, subangular, subrounded, or rounded.[16]

The images captured for visual analysis were high-resolution photographs with the appropriate scale indicated on each photo.

Preliminary analysis of these images indicated that a single sieve size was not sufficient to adequately determine the angularity of a given sand type. In fact, certain sieve sizes contained similarly shaped particles regardless of sand type. As a result, all sieve sizes were examined and each sieve size was assigned an individual ASTM D2488 angularity rating for the particles on that sieve. The result was 12 angularity ratings for each sand. The overall angularity for a given sand was based on the majority rating for all 12 sieve sizes. For example, a sand that is classified as subrounded on 7 out of the 12 sieve sizes would be classified as subrounded overall. Table 1 presents this system. No data were available for the Ottawa sand in the sieves sizes that were less than or equal to no. 325 (0.0450 mm).

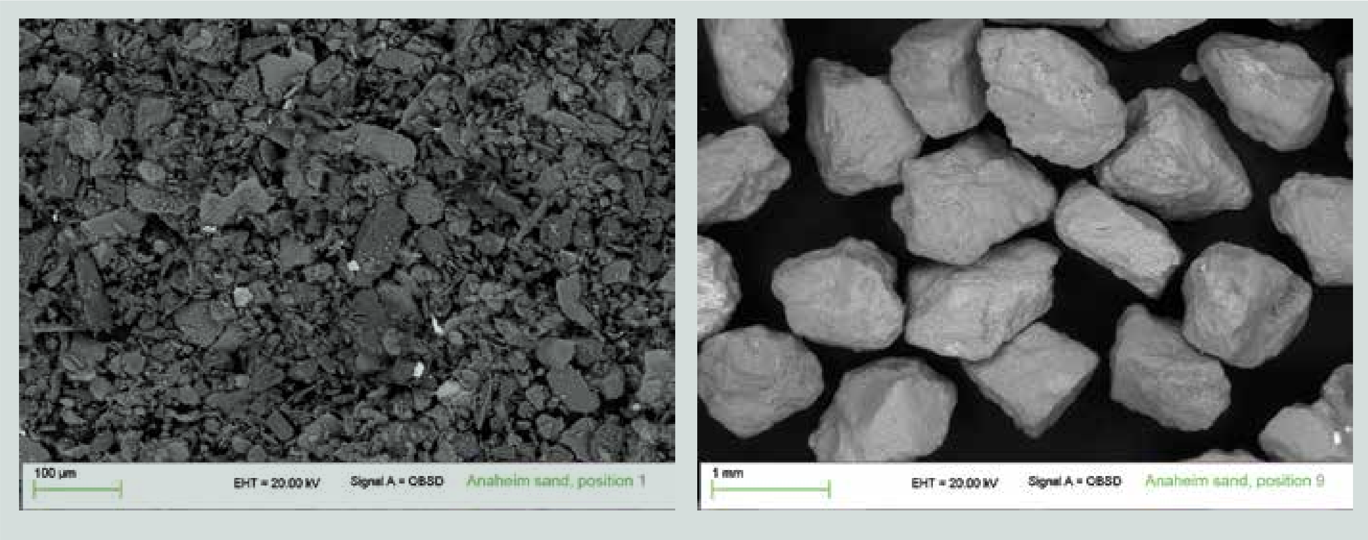

Figure 3. Comparison of sieve size angularity for Anaheim sand using scanning electron microscope standard backscatter with sieve size 325 (0.0450 mm) on the left and sieve size 20 (0.841 mm) on the right. Note: EHT = electron high tension; QBSD = quadrant back scattered detector. 1 µm = 3.937 × 10^{-5} in.; 1 mm = 0.0394 in.

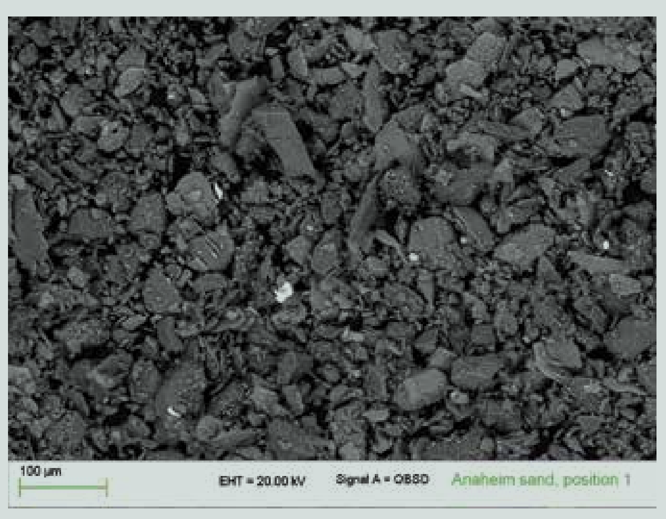

Figure 4. Scanning electron microscope standard backscatter image of Anaheim sand on < no. 325 (0.0450 mm) sieve. Note: EHT = electron high tension; QBSD = quadrant back scattered detector. 1 µm = 3.937 × 10^{-5} in.

During this analysis, it was common for different sieve sizes of the same sand to have different angularity characteristics. For example, **Fig. 3** shows scanning electron microscope images of two sieve sizes for the Anaheim sand. The finer sieve size (no. 325 [0.0450 mm]) contains angular, elongated particles, whereas the larger sieve size (no. 20 [0.841 mm]) contains particles that are subangular. The differences in particle surface texture from one sieve size to the next necessitated individual sieve angularity ratings. This makes it clear that a single sieve was not necessarily representative of a given sand's overall angularity characteristics. Once the images for all sands had been thoroughly examined and compared with each other, an ASTM D2488 angularity designation was assigned to each one. Anaheim sand was determined to be predominantly angular, Sand Springs sand was determined to be subangular, Dover was subrounded, and Ottawa was rounded.

The fine-sieve results were useful as a quantitative measure of the most prevalent particle size in each sand sample.

In general, the fine-sieve results indicated that the Anaheim sand had more fine material than any of the other sands from the no. 140 (0.106 mm) sieve to the less than no. 325 (0.045 mm) sieve. In addition, most sands were primarily retained on the no. 40 and 60 (0.419 and 0.250 mm) sieves. In fact, the Ottawa sand had a combined 59.5% of the total sample retained on the no. 40 and 60 sieves. The Sand Springs sand did not conform to this trend, however. Its particles were concentrated on the no. 12, 14, and 18 (1.679, 1.410, and 1.001 mm) sieves.

The profusion of fine particles indicated by sieve analysis in the Anaheim sand was verified by both the optical digital microscope images and the scanning electron microscope images. **Figure 4** shows the scanning electron microscope standard backscatter image for the Anaheim sand retained on the less than no. 325 (0.045 mm) sieve.

The Anaheim sand comprised many elongated, highly angular particles. This corroborates with the fine-sieve results and the ASTM C1252 test. It was expected that the Ottawa sand would comprise mostly spherical particles, which was confirmed. Also, the concentration of particles on the no. 40 and 60 (0.419 and 0.250 mm) sieves was not surprising given the ASTM C33 gradation results. The Ottawa sand was primarily retained on the no. 16, 30, and 50 (1.190, 0.595, and 0.297 mm) sieves, which have opening sizes close to those of the no. 40 and 60 sieves. However, the optical digital microscope and scanning electron microscope images indicated that although uniformly graded, the Ottawa sand was not uniformly shaped. The microscope photos captured clumped concretions of small particles that appeared to be fused together. **Figures 5** and **6** show several examples of these particles.

These objects were not limited to a specific sieve size: similar concretions were observed along with particles at nearly every sieve size. These objects were more common in the larger sieve sizes of no. 10 and 12 (2.0 and 1.690 mm). This is, in part, the reason for the subrounded angularity rating for larger sieve sizes. In the scanning electron microscope images, the concretions were observed to be the same size as the spherical particles. Figure 6 visually suggests that the concretions may have been quartz.

The Sand Springs and Dover sands exhibited no unique features in the scanning electron microscope and optical digital microscope images. Thorough analysis of the pho-

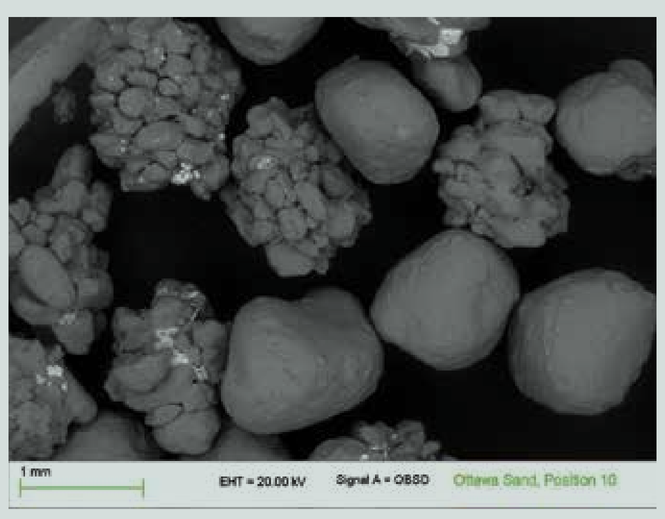

Figure 5. Scanning electron microscope standard backscatter image of clumped concretions in Ottawa sand on no. 18 (1.001 mm) sieve. Note: EHT = electron high tension; QBSD = quadrant back scattered detector. 1 mm = 0.0394 in.

Figure 6. Optical digital microscope image of clumped concretion in Ottawa sand. Note: 1 in. = 25.4 mm.

tos from both data sets led to the conclusion that the Dover sand was slightly less angular than the Sand Springs sand.

Comparison of ASTM C1252 test results with visual angularity analysis

The angularity designations using a qualitative approach per ASTM D2488 were correlative to the results of the ASTM C1252 test. Table 2 compares the results. This table is ordered according to ASTM D2488 angularity.

Scanning electron microscope analysis of each sand confirmed the ASTM C1252 results, indicating that the U_s values obtained for each sand reliably predicted angularity in this study. Both methods determined that the most angular sand was the Anaheim sand. The particles of this sand were found to be elongated and angular, as had been suggested by the results of the ASTM C1252 test. Similarly, the visual analysis confirmed that the Sand Springs sand was slightly more angular than the Dover sand and that the Ottawa sand was the most rounded sand used in this project.

ASTM A1081 test results

Mortar fresh properties The ASTM A1081 requires mortar flow per ASTM C1437 to be greater than or equal to 100% but not to exceed 125%. All four fresh mortar batches fell within the ASTM A1081 protocol limits for mortar flow (Table 1). The only mortar that did not require an admixture to meet the minimum flow was the Sand Springs sand mortar. It was observed during batching that the high-range water-reducing admixture meeting the criteria for ASTM C494 Type A and Type F was a slower-acting water-reducing admixture than was the ASTM C494 Type A water-reducing admixture. It was also observed in test batches that large amounts of Type A water-reducing admixture appeared to decrease the early-age compressive strength of the specimens, whereas large additions of the Type A and F water-reducing admixture did not appear to adversely affect the early age strength of the mortar cubes. Therefore, the water-reducing admixture meeting Type A and F was used in the last two batches, and the Type A water-reducing admixture was only used in the first batch with Dover sand. Table 1 compares the flow and angularity designations. This table is ordered according to ASTM D2488 angularity (highest to lowest).

Hawkins and Ramirez[11] mention that sand angularity can influence workability and flow. In mortar that has not been dosed with a water-reducing admixture, this is likely true. However, because each batch (except for the Sand Springs sand) was cast using a water-reducing admixture, the flow values did not exhibit any observable correlation to sand angularity. Even if no water-reducing admixture had been used in the batches, the flows still would not necessarily be indicative of sand angularity because each sand required a different *w/c* in the mixture proportions. While angularity of the sand could potentially play a role in workability and flowability, no quantifiable effect was observed.

Compressive strength Numerous test batches were cast to determine the optimal mixture proportions to meet the ASTM A1081 mortar performance requirements of flow and strength for each sand. However, scale effects and the inherent variability of ASTM C109 mortar cubes made it difficult to make strong correlations between cube strength in full batches and cube strength in test batches. In general, it was expected that the full-batch cube strengths would increase gradually from the beginning of the testing period to the end. However, few batches showed this trend across the testing period. All batches finished the testing period at strengths higher than the starting strength, but the trend was not linear. Moreover, some cube sets' compressive strengths varied to such an extent that no discernible trend could be determined from the hourly compressive tests.

The performance of the mortar cubes was easily influenced by ambient temperature and mold temperature. The small volume of mortar placed in the molds could be easily chilled by a mold that was cooler than the fresh mortar. Test batches done in cold weather required indoor batching, heated mixture water, and heated cube molds to achieve performance comparable to the batches made with the same cement and sand in warmer weather. The variability of the cube strengths can be illustrated by superimposing the compressive strength testing window dictated by the ASTM A1081 protocol on the strength data (**Fig. 7**). The time cutoff is the time at which all strand bond tests were completed. According to the protocol, tests are allowed to go to 26 hours after casting, but in this project all of the tests were completed by 24 hours after casting.

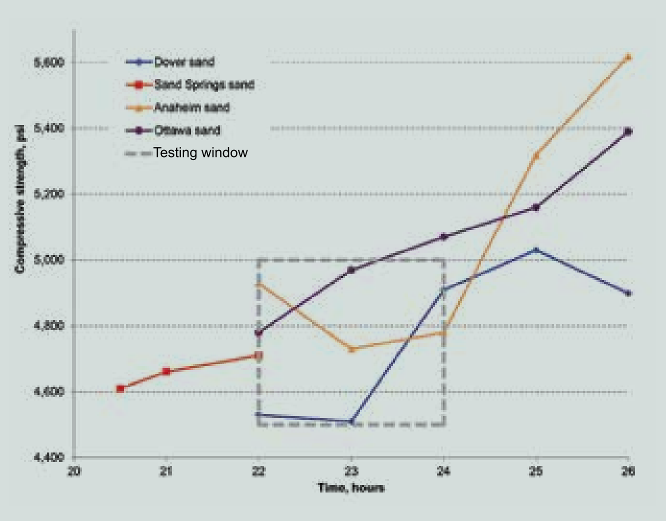

Figure 7. Time versus compressive strength with testing window. Note: 1 psi = 6.895 kPa.

The ASTM A1081 protocol requires that the strand bond tests be terminated when the cube compressive strength exceeds 5000 psi (34 MPa); however, strand bond tests were continued in this project despite minor overstrength. This was allowed because of the large effort required to achieve four independent mixture proportions that met the strict ASTM A1081 testing requirements (Fig. 7). Mortar that did not exceed the maximum allowable strength by more than 100 psi (0.7 MPa) was considered satisfactory and was not retested. Only the Dover and Anaheim sand specimens finished within the strength limitations of the ASTM A1081 protocol. The Sand Springs sand was tested outside the typical time window because the Sand Springs samples were observed to gain strength more quickly than compressive strength specimens of the other three sands. To prevent violation of the maximum allowable strength, ASTM A1081 tests with the Sand Springs specimens were commenced when the Sand Springs cubes reached the minimum allowable compressive strength at 20.5 hours after casting. Although the ASTM A1081 specimens and the compression specimens were cast from the same batches, the cubes were apparently more sensitive to certain variables than were the cans. Consolidation practices, early-age drying shrinkage, different curing conditions, and temperature differences due to the influence of the sample size or of surface area–to–volume ratio differences between the cans and the cubes on the heat of hydration are all potential variables.

Strand bond testing results Figure 8 summarizes the ranking of the ASTM A1081 strand bond testing results by minimum, maximum, and average values. The strand bond testing values of the Ottawa samples were consistently the weakest, exhibiting the lowest maximum, minimum, and average strand bond testing values. The Sand Springs sand samples resulted in the highest maximum and average strand bond testing values. Finally, the Anaheim sand samples consistently showed moderate to high strand bond testing performance for maximum, minimum, and average strand bond testing rankings.

Comparison of strand bond testing values with ASTM C1252 angularity Table 2 lists the minimum, maximum, and average strand bond force observed among the six specimens tested relative to the results of ASTM C1252. Figure 8 illustrates these trends. The minimum values in Fig. 8 show the expected trend of increasing strand bond with increasing angularity. The maximum and average strand bond testing values show the same trend for three sand types, but there is a slight decrease at the highest angularity. The Sand Springs sand had higher maximum and average strand bond testing values than the Anaheim sand, though the Anaheim sand was found to be more angular than the Sand Springs sand. The difference in measured angularity was 3.2%, and the strand bond testing values differed by only 480 lb (2100 N) (2.0%) for the average values. The maximum strand bond testing values of the Anaheim and Sand Springs sand samples differed by 1160 lb (5160 N) (4.4%). Given the similar angularity measurements for the two sands, the strand bond testing results are satisfactory.

Comparison of strand bond testing values with visual angularity Table 2 lists the minimum, maximum, and average strand bond testing values in terms of decreasing ASTM D2488 angularity designation.

The minimum strand bond testing values have a range of 5080 lb (22,600 N) and show the exact trend that would be expected if angularity does influence strand bond. The minimum stand bond testing value decreases as the angularity decreases. Unlike the maximum and average strand bond

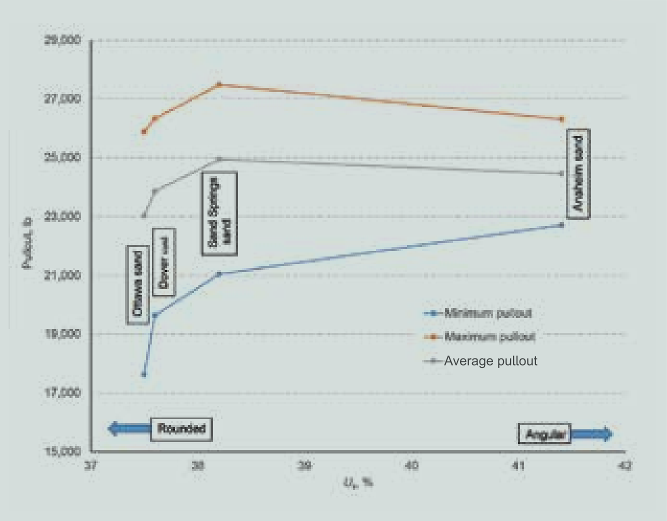

Figure 8. Comparison of strand bond test and ASTM C1252 angularity. Note: U_s = uncompacted voids using test method A of ASTM C1252. 1 lb = 4.448 N.

testing values, the minimum strand bond testing values follow this trend consistently. However, the minimum strand bond testing values for the four sands are widely scattered, with a range equal to about 25% of the average minimum strand bond testing value. Conversely, the overall average values of the four sands have a range of only 1910 lb (8500 N). This is only 7.9% of the range of the overall average strand bond testing value.

Angularity of the sand particles appears to have some influence on bond strength because the most spherical sand type (Ottawa sand) consistently had the lowest strand bond testing values. The mortar compressive strength for the ASTM A1081 test of the Ottawa sand was within the allowable strength range set forth by the ASTM A1081 protocol. Also, the strand surface condition was not different from the other strands tested. Therefore, the Ottawa sand's low angularity is a satisfactory explanation for its performance compared with the other sand types.

Strand bond testing results and compressive strength Compressive strength influence on bond capacity has long been a subject of debate among researchers in the field of prestressed concrete research. Research has often been inconclusive with respect to the relationship of compressive strength and strand bond. To evaluate the relationship (if any) in this study, the strand bond testing values were plotted as a function of compressive strength over the testing time period to evaluate whether any discernible relationship existed between them within the requirements of the ASTM A1081 protocol.

Figure 9 shows the values at the beginning, middle, and end of testing each specimen set. The figure does not show a strong trend of strand bond testing dependence on compressive strength from beginning to end. The Anaheim sand with a coefficient of determination R^2 equal to 0.93 is the only comparison in this case that strongly indicates a relationship between strand bond and compressive strength. To further investigate the relationship of strand bond and compressive strength, the average values were examined. The average strand bond test value and average compressive strength over the testing time period were expected to exhibit less variability than the individual compressive strength and strand bond testing values. Table 2 tabulates the average compressive strength and average strand bond testing values for each sand. **Figure 10** shows a weak relationship between average compressive strength and average strand bond testing value. The maximum average strand bond value in Table 2 corresponds to the lowest average compressive strength. This occurred in the Sand Springs sand test. Therefore, within the allowable range, compressive strength of the mortar does not seem to have a significant influence on the strand bond testing values.

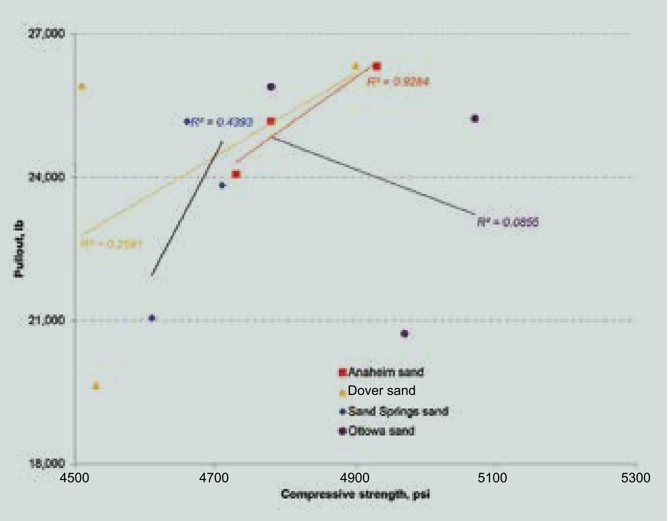

Figure 9. Compressive strength versus strand bond test. Note: R^2 = coefficient of determination. 1 lb = 4.448 N; 1 psi = 6.895 kPa.

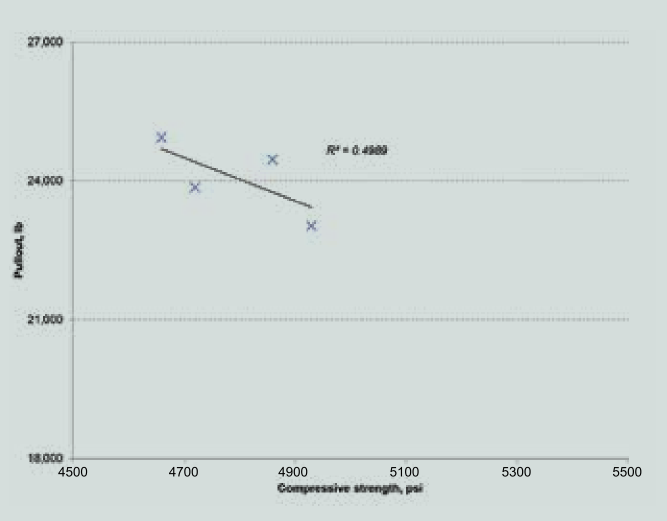

Figure 10. Average compressive strength versus average strand bond test for all sands. Note: R^2 = coefficient of determination. 1 lb = 4.448 N; 1 psi = 6.895 kPa.

Conclusion

ASTM A1081 test and sand angularity

Although the tested sands covered 77.5% of the ASTM C33 fineness modulus range and 100% of the ASTM D2488 angularity range, the average strand bond testing values for all sand types varied only 7.9% with respect to the overall average strand bond testing value. Therefore, it may be concluded that substantial variation in particle surface texture does not significantly influence the ASTM A1081 strand bond testing values. The primary goal of this project was to determine the relationship, if any, between sand angularity and strand bond testing value. The conclusion appears to depend largely on the method used to determine sand angularity.

In this project, sand angularity as measured according to ASTM C1252 indicated a relationship between angularity and strand bond testing values verified by ASTM D2488 methods. However, this influence can only account for about an 8% variation in the overall average strand bond testing values. ASTM C1252 has since been withdrawn by ASTM without replacement, but the methods are still appropriate for classifying angularity of sand used for the ASTM A1081 strand bond test. The methods of ASTM D2488 may also be an appropriate alternative.

The most rounded, spherical sand (the Ottawa sand) had the lowest minimum, maximum, and average strand bond testing values. The most angular sand (Anaheim sand) had the highest minimum strand bond testing values. Therefore, it may be concluded that angularity does influence strand bond testing values, though this influence will likely be small.

The 2006 version of the ASTM A1081 testing protocol specified a minimum individual strand bond test value of 10,800 lb (48.0 kN) and a minimum average strand bond test value of 12,600 lb (56.0 kN).[5] The most recent research sponsored by PCI indicated that a value of 14,600 lb (64.9 kN) would ensure that 95% of the time the available moment capacity would exceed the ACI 318-14 moment capacity for prestressed beams released at 3500 psi (24 MPa).[9] The single strand used for these tests passed these requirements with all sands.

The lowest strand bond testing value recorded was in the Ottawa sample, which still passed the minimum strand bond testing requirements by more than 5000 lb (22,000 N). Bond capacity did not approach the minimum allowable strand bond testing value despite sand that was almost entirely spherical. Therefore, although sand angularity can influence the strand bond test value, it is unlikely to reduce capacity enough to cause a strand to fail the ASTM A1081 test. In summary, although sand angularity does appear to influence the strand bond testing value, the strand will likely still pass the ASTM A1081 requirements if the strand is of acceptable quality.

Angularity of the sand may account for 7.9% of the strand bond testing values, but angularity was not the only variable in this research project. Because various sand sources were used in these tests, the fineness modulus and Mohs hardness of the sands are not constant. Also, due to the ASTM A1081 mortar performance requirements for flow and strength, each mixture design has a different *w/c*, which results in differences in the modulus of elasticity of the mortar, the shrinkage percentage, and the paste quantity. These variations are acceptable within the framework of ASTM A1081 and its predecessors, such as the North American Strand Producers test.

A considerable body of work[5,17] now exists in which Mohs hardness, *w/c*, modulus of elasticity, shrinkage percentage, and paste quantity are not controlled while the fineness modulus is allowed an acceptance range. Ramirez and Russell[17] say that the ability of a prestressing strand to bond with concrete is affected by concrete strength and that increasing concrete strength improves the bondability of a given prestressing strand. ASTM A1081 has strict mortar performance requirements that minimize the influence of uncharacteristic mortar strength. While this test program suggests a variation of 7.9% due to the angularity of the sand, this only holds true within the working boundaries of the ASTM A1081 test format.

Concerning the dependence of fresh mortar flow on sand angularity, no real conclusion could be formed. The use of water-reducing admixtures to meet flow requirements and variations in *w/c* to meet the ASTM A1081 requirements obviated any comparison of flow based on angularity. For the flow values to be comparable, the mixtures would need to be repeated without water-reducing admixtures, and the mixtures would need to employ identical or similar *w/c*. Consequently, assertions by Hawkins and Ramirez[11] that flowability and workability would be influenced by angularity could not be substantiated.

ASTM A1081 test protocol

Although sand angularity is unlikely to cause a strand to fail the ASTM A1081 test, each sand required unique mixture proportions to meet the ASTM A1081 performance criteria. This makes it difficult to adjust the mixture proportions for local materials. The mortar will vary in reactivity, workability, and performance due to the local sand and cement. Moreover, the lack of large aggregate requires a higher cement content to achieve the required 24 hour strength. The higher cement content typically results in stiff mixtures that often require significant additions of water reducer to properly mix and meet flow requirements.

Because this work predates the first adoption of ASTM A1081, water-reducing admixtures were used to address mortar performance requirements for workability and strength. Because ASTM A1081 prohibits the use of admixtures, batches will often require additional water to achieve flow, which will make it more difficult to meet the strict mortar performance requirements. The use of water-reducing admixtures raises a question of whether their use influences the strand bond and, if so, by how much. It also raises question of whether the influence is due solely to the admixture or the increased concrete strength generally associated with the use of a water-reducing admixture because Ramirez and Russell[17] have shown that this relationship exists.

In conducting this research program, the understanding was that mortar strength has a strong influence on bond strength and that this was the most important aspect of ASTM A1081 that had to be controlled. It is recommended that more research be conducted to understand the influence of water-reducing admixtures on strand bond, especially given the use of these admixtures by the precast/prestressed concrete industry.

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Notation

R^2 = coefficient of determination

U_s = uncompacted voids using test method A of ASTM C1252

w/c = water-cement ratio

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Abstract

This project explored the influence of sand angularity on ASTM A1081, *Standard Test Method for Evaluating Bond of Seven-Wire Steel Prestressing Steel Strand*. The procedure specified by ASTM A1081 uses only fine aggregate in the mixture proportions. Sand angularity is a variable of interest because it could affect strand acceptance and the reliability of the ASTM A1081 strand bond test. Four sands were tested, each of which was subjected to a full ASTM A1081–style test. In addition, the angularity of each sand sample was tested via two different methods: the ASTM C1252 procedure and a visual process guided by ASTM D2488 that included the use of a scanning electron microscope and an optical digital microscope system. Ultimately, it was determined that the angularity of the sand does influence the strand bond. This influence is generally not pronounced enough to cause a strand to fail the ASTM A1081 test.

Keywords

Angularity, ASTM A1081, bond, gradation, mixture, pullout, sand angularity, sand origin, strand.

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