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INVESTIGATION OF CONCRETE REPAIR MATERIALS

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BACKGROUND

The purpose of this report is to present a laboratory testing regimen, appropriate specification recommendations and a proposed specification for the use of repair materials for the Department of Transportation (FDOT). Currently the Standard Specification for Road and Bridge Construction Section 930-3 provides the specification for materials for limited types of concrete repair. Currently, the FDOT standard specification outlines requirements of compressive strength and maximum length change for the qualification of concrete repair materials per hardened physical properties [1].

The purpose of this research is to provide a more rigorous laboratory testing program for the quantification of repair materials per their physical, and durability properties. The testing regimen was performed on the 15 of most readily available repair materials and two FDOT pile repair jacket mixes, incorporating physical properties, and durability properties of each. The testing of each repair material was performed at the FDOT State Materials Office (SMO) laboratories to determine capacity for use in the repair of structural concrete materials and components. The objective of this analysis was to determine the performance of each material type and to properly assign its repair application for use in FDOT owned structures. Furthermore, the testing regimen was created to evaluate the tests themselves to determine their applicability to evaluate specific material properties, and the possible usage of each test for production acceptance. The final objective of this research is to revise the FDOT Section 930 to incorporate necessary tests, create specific repair material categories, and qualify the materials tested in this regimen accordingly.

EVALUATION PROGRAM

The intent of this experiment was to compare the physical, strength and durability properties for each of the repair materials via the use of applicable tests. The physical property testing program consisted of the following:

- Density
- Standard Test Method for Length Change of Hardened Hydraulic-Cement, Mortar, and Concrete (ASTM C157-03)
- Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes (ASTM C531-00)

The Strength Testing Regimen consisted of the following:

- Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Cylindrical Concrete Specimens (Using 2" or 50mm cube specimens) (ASTM C-109M-05)
- Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C-39-05e1)
- Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM C496-02)
- Standard Test Method for Flexural Strength and Modulus of Elasticity for Chemical Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes (ASTM C-580M-02)
- Standard Test Method for Bond Strength of Epoxy-Resin Systems Used With Concrete By Slant Shear (per ASTM C882-99)
- Standard Test Method of Test for Determining the Shearing Strength at the Interface of Bonded Layers of Portland Cement Concrete (AASHTO T 323-03)
- Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method) (ASTM C1583-04)

The Durability Testing Regimen consisted of the following:

- Standard Test Method for Absorption of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacings, and Polymer Concretes (ASTM C413-03)
- Modified Version of Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (ASTM C1202-05)
- Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability (FM 5-578)

Each of the following repair materials were incorporated into the testing regimen. The name denoted by parenthesis, is the product name used in the Figures and Tables per our experiment:

- Repair Material #1
- Repair Material #2
- Repair Material #3
- Repair Material #4
- Repair Material #5
- Repair Material #6
- Repair Material #7
- Repair Material #8
- Repair Material #9
- Repair Material #10
- Repair Material #11
- Repair Material #12
- Repair Material #13
- Repair Material #14
- Repair Material #15
- FDOT – Type I Jacket Mix
- FDOT – Type II Jacket Mix

MIXTURE DESIGN

Each of the 15 repair materials was mixed in accordance with manufacturer's recommendations specifications. Some of the repair materials allow for a range of water to be added for material consistency. It was decided to use the maximum allowable water content per manufacturer's specifications as most repair materials have some Portland cement characteristics that result in lower relative strength upon the addition of excess water. Thus, the most conservative approach to repair material mixture design was used for the purposes of this research.

The research incorporated two fill mixes which are typically used for cathodic protection of bridge pile jackets. Each mix was designed to simulate typical pile jacket mixes as used in the field. Tables 1 & 2 describe the mixture proportions used for the jacket mixes. Coarse aggregate was not used for the jacket mixes.

Table 1. Mixture Proportions for Jacket Mix I (w/c = 0.49)

MATERIAL	SOURCE	WT. PER YD^3 (LB)	VOL. PER YD^3 (FT^3)
CEMENT	Rinker, Columbia	940	4.8
WATER	Local	458	7.3
FINE AGG.	76-137	2451	14.9
COARSE AGG.	N/A	0	0.0
ADMIXTURE	WR Grace WRDA 60	54.8 oz	
TOTAL			27.0

Table 2. Mixture Proportions for Jacket Mix II (w/c = 0.45)

MATERIAL	SOURCE	WT. PER YD^3 (LB)	VOL. PER YD^3 (FT^3)
CEMENT	Rinker, Columbia	940	4.8
WATER	Local	425	7.3
FINE AGG.	76-137	2538	14.9
COARSE AGG.	N/A	0	0.0
ADMIXTURE	WR Grace WRDA 60	54.8 oz	
TOTAL			27.0

RESULTS

Physical Properties

Density

The density of the samples was obtained via the physical measurements of 2-inch mortar cubes cast at the time of the experiment. Figure 1 contains a summary of the test data and results.

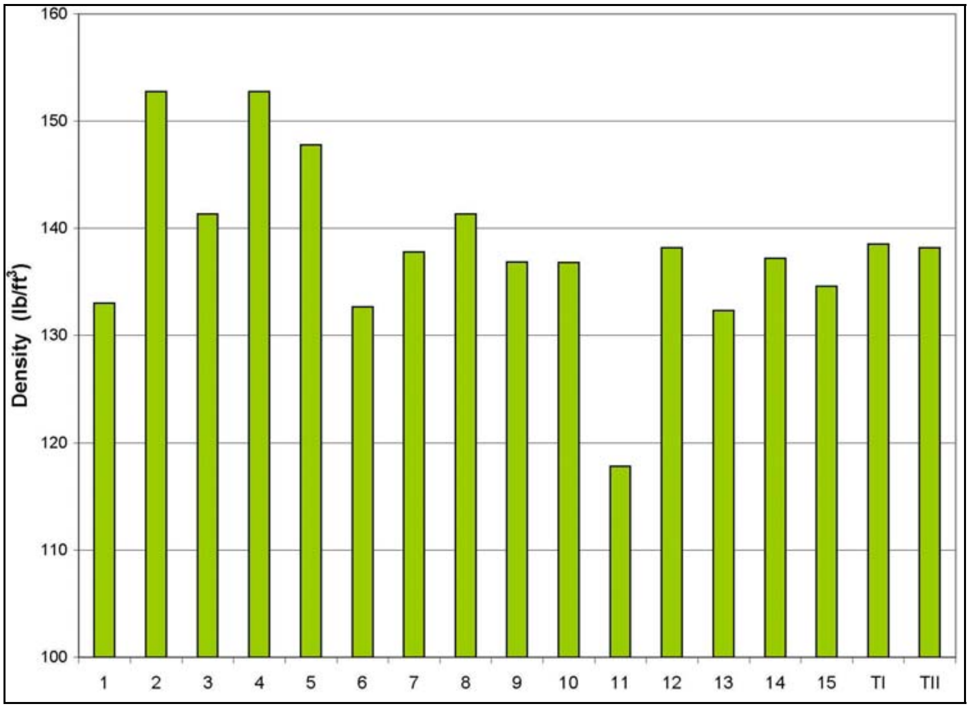

Figure 1: Density Testing Results

The density testing results indicate that the range of densities or unit weight of the repair materials (numbered 1-15) and the jacket mixes (T1 and TII) in figure 1, range from approximately 117lb/ft^3 to approximately 152lb/ft^3. Typically, the unit weight of concrete is approximately148lb/ft^3 [2]. However, the coarse aggregates available in Florida are less dense than typical coarse aggregates throughout the United States resulting in a slightly lower unit weight. The density of cementitious materials is sometimes correlated to the overall quality of the material, as it is often the case that strength and durability characteristics are typically correlated to the density of concrete materials.

Length Change

Expansion and shrinkage characteristics of repair materials are of importance to the repair systems as the relative movement of the repair material can result in the loss of bond and integrity of the repair material. Thus, expansion and shrinkage testing of the repair materials was necessary to evaluate the characteristics of the repair materials. The standard test method for length change of hardened hydraulic-cement mortar and concrete as per ASTM C157-03 was used to obtain the length change or shrinkage measurements of the repair materials. Currently, Table 1 of the 930 Specification allows for a maximum length change at one day to be +0.15% for moist cured samples, -0.15% for air cured samples and a maximum absolute difference between moist cure and dry cure of 0.20% [1]. Recently, ASTM has created a standard specification for rapid hardening cement. The length change requirement within that specification for rapid hardening cement, is a maximum drying shrinkage in dry cure of 0.06-0.12% dependent upon the age and application of the cement [3].

For the purposes of this evaluation, length change measurements were taken at 1 day, 7 day and 28 day in both wet cure and dry cure environments to evaluate the differences within material properties with respect to length change and decide if the current requirements per Table 1. in the 930 specification are applicable for repair materials currently available to FDOT. Figures 2 - 4 are the length change data summaries which include the 7 day and 28day minus 1 day measurements. Please note the “Maximum Allowable per 930” in each of the figures refer to the current maximum allowable length change as per the current specification at an age of 28 days minus 1 day data.

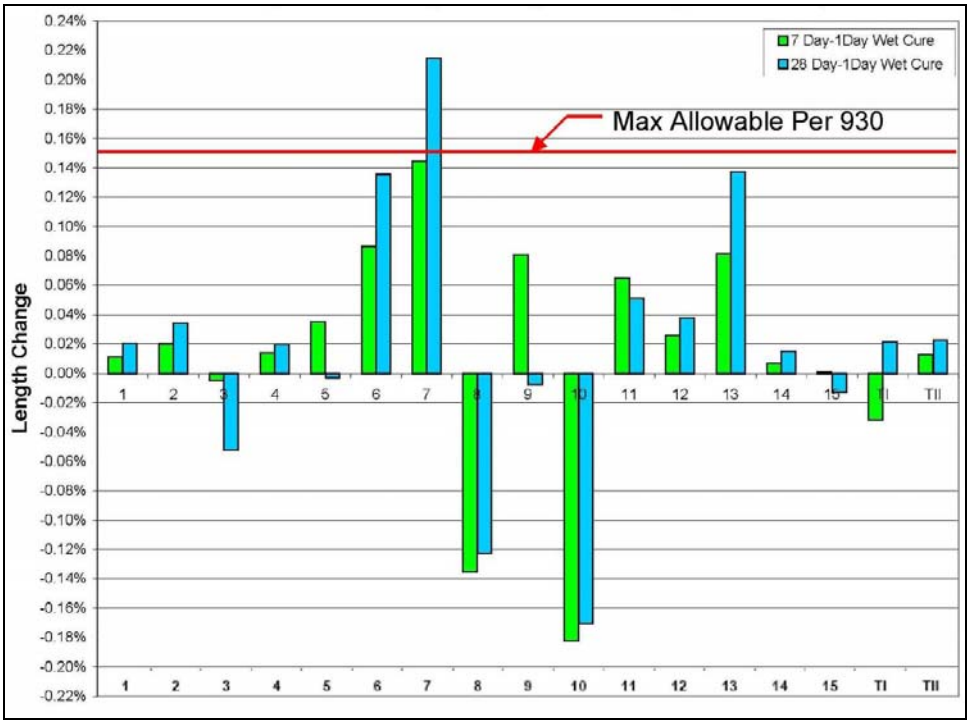

Figure 2: Length Change Data Summary – Moist Cure

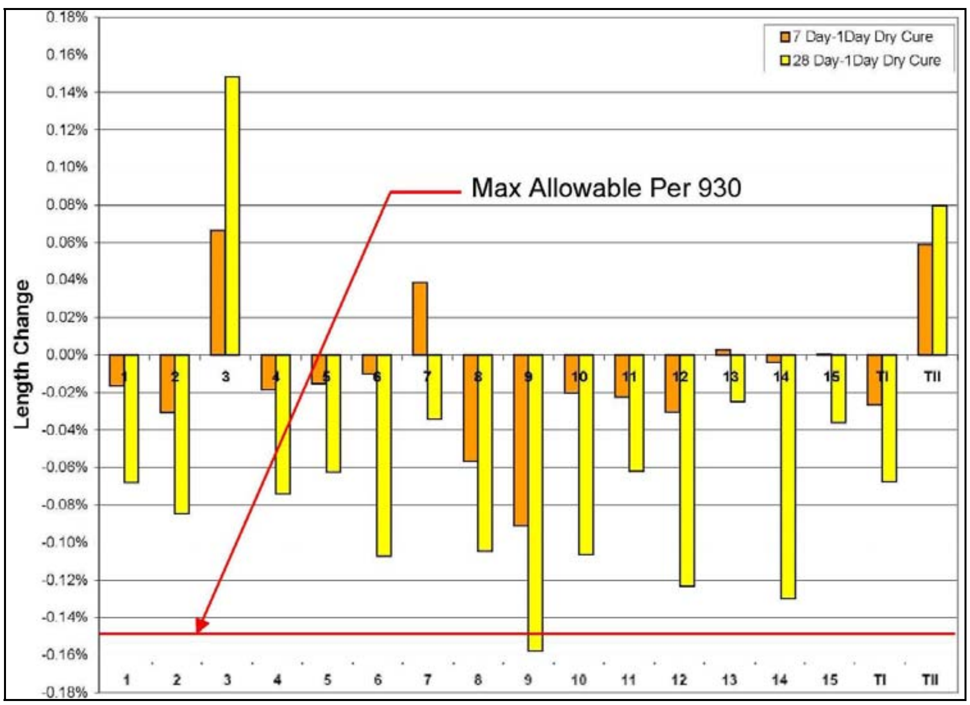

Figure 3: Length Change Data Summary – Dry Cure

Figure 4: Length Change Difference, (Moist Cure minus Dry Cure) Per table 1. 930.3.3

The data in Figures 2, 3 and 4, indicate that majority of the repair materials meet specification 930 in its current form. The new specification created by ASTM does not address moist curing of samples [3]. However, it does indicate that lower values of expansion and shrinkage may more applicable for the use of rapid hardening cements. Upon revision of the 930 specification, it may be beneficial to revisit and perhaps lower limits of shrinkage and expansion of certain repair materials depending upon their application service use and application.

Thermal Expansion

The standard test method for linear shrinkage and coefficient of thermal expansion of chemical resistant mortars, grouts, monolithic surfacings, and polymer concretes as per ASTM C531-00 was used to obtain the coefficient of thermal expansion of each repair material and the two jacket mixes. Figure 5 provides the resultant values of each. A portion of the graph indicates a "typical range for concrete" approximately 4.1-7.3 in/in/ °F as provided by research [4]. The results indicate the jacket mixes used for this evaluation have a slightly higher coefficient of thermal expansion than normal concrete. This is to be expected as the jacket mixes do not contain coarse aggregate. One of the many benefits to adding coarse aggregate to concrete is the lower the coefficient of thermal expansion the resultant product. Since the jacket mixes the mix have a large portion of cement paste, the resultant thermal expansion valued should be slightly higher than typical concrete [4].

Figure 5. Coefficient of Thermal Expansion

The importance of the coefficient of thermal expansion test is to ensure the compatibility of the repair materials with the concrete substrate materials. In the event the two materials have a substantial difference, there is a possibility the repair material will lose its bond with the substrate material due to temperature fluctuations between each.

Strength Properties

Compressive Strength

The compressive strength of concrete is the primary physical property and one that is frequently used for the design calculation of structures. Compressive strength is often used as an index other strength properties of concrete such as, flexural strength, tensile strength, torsional strength, and shear strength. Traditionally, the compressive strength testing has been the most widely used method of test for quality assurance in concrete materials. The standard test method for the compressive strength of hydraulic mortars as per ASTM C109-02 using 2" mortar cubes was used to obtain the compressive strength of each of the repair materials at ages of 1 hour, 3 hour, 1 day, 7 day, 28 day. For comparison purposes, compression testing was performed on 4"x 8" cylinder as per ASTM C39-05 at the age of 28 days. Figure 6 presents the results from the compressive strength testing. Figures 7 and 8 are representations of the compressive strength data vs. early age and late age respectively, which present the exact same data as figure 6. The reason for presenting the strength data in a manner that illustrates early age and later age compressive strength vs. age of each repair material.

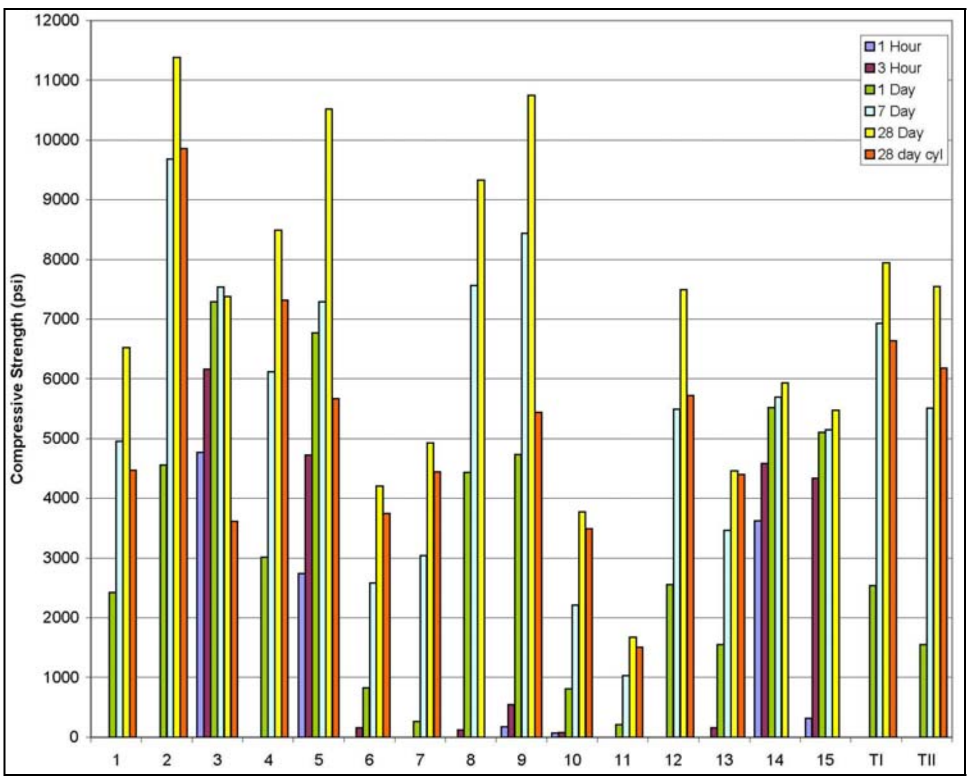

Figure 6: Compressive strength Summary

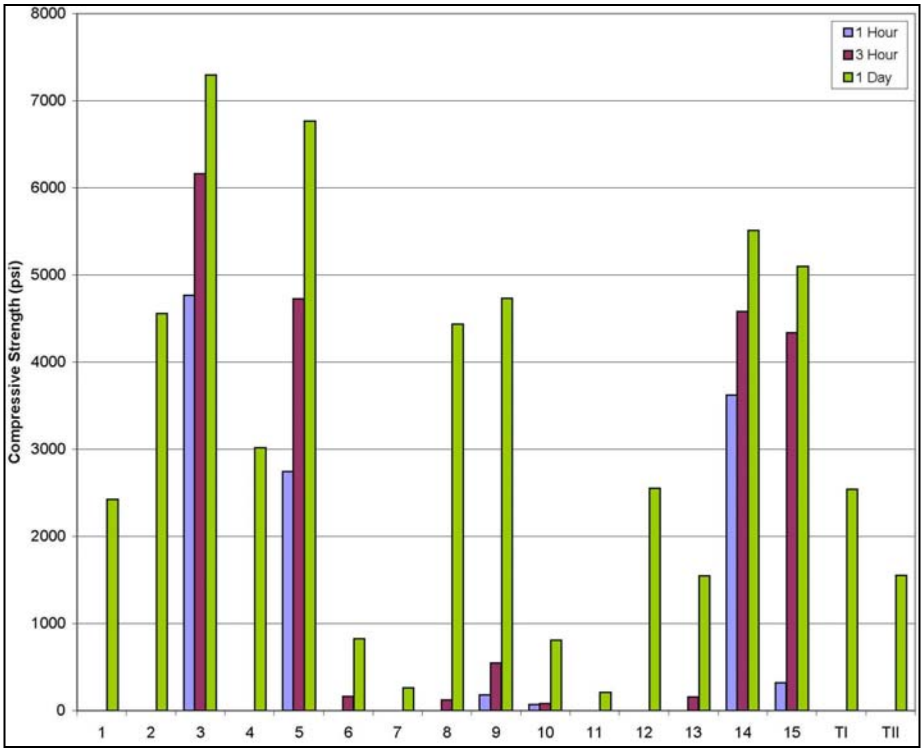

Figure 7: Early age compressive strength summary

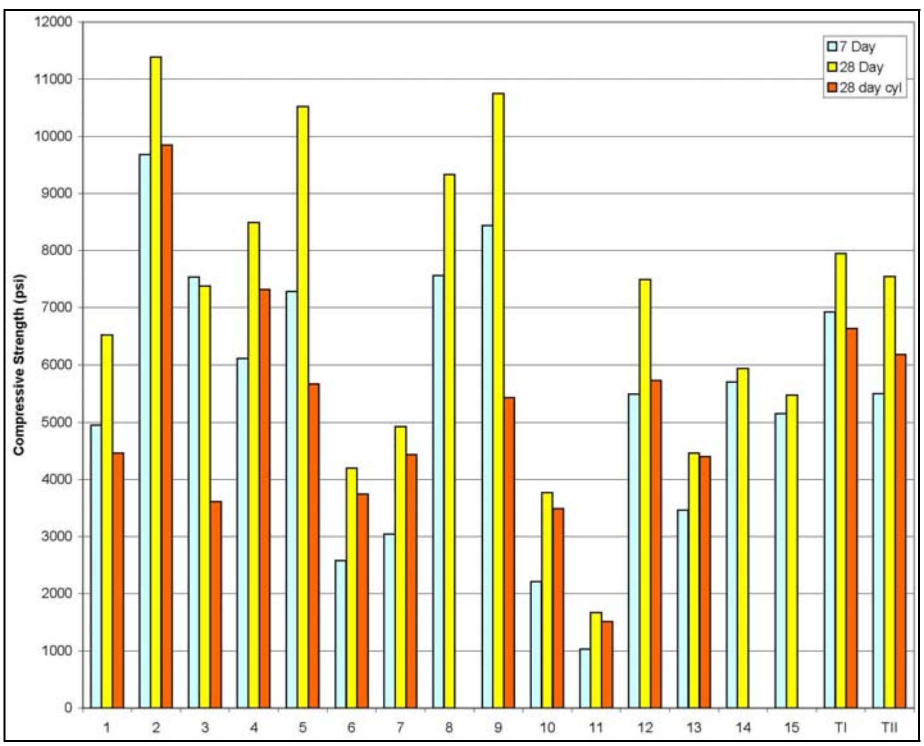

Figure 8: Late age compressive strength summary

Currently, the 930 specification provides requirements for rapid and very rapid hardening materials as illustrated in Table 3. below, which specifies the requirements for each. Of the repair materials tested, repair material #5 passes the specifications for very rapid hardening repair materials, while 11 pass the specification for rapid hardening material.

Table 3. Compressive strength requirements per current specification

Table 1 Physical Properties			
Requirement	Rapid Hardening	Very Rapid Hardening	Test Method
Minimum Compressive Strength			
3 hours, psi	500	2,000	ASTM C 39 or ASTM C 109
24 hours, psi	2,000	4,000	
7 day, psi	4,000	6,000	
28 day, psi	The strength at 28 days shall not be less than the strength at seven days		

Although four of the materials tested obtained the 2,000 psi strength at three hours, two of them failed to meet 6,000 psi strength at 7 days. Materials #3,, had a lower compressive strength at 28 days than at 7 days. This phenomenon is most likely due to micro cracking and cracking issues that can become prevalent with concrete materials that have high early strength development. Typically, those materials that hydrate at accelerated rates, strength at a rapidly and experience elevated temperatures as a result of the early-age hydration. As a result, cracking, resultant strength loss and integrity loss can occur [5, 6, 7]

As illustrated in figures 6 and 8, the testing involved compressive testing of 4”x8” cylinders at 28 days for comparison purposes. The research shows that, for each repair material, the 4”x8” cylinders obtained a lower compressive strength at 28 days than the 2” cubes obtained. The reasons for this phenomenon are several. First, the geometry ratio of the cylinders are 2:1, length to diameter, where as the cubes are a ratio of 1:1, length to width. When comparing a 2:1 Length to diameter ratio to a 1:1 length to diameter ratio, it is typical to expect the longer sample to have an ultimate strength of 80-87% of the shorter sample due to geometric effect of the length to diameter ratio of cylinders [8,9]. However, the data in figures 6 and 8 depict some of the 4”x8” cylinders obtained approximately 50% the ultimate strength as 2” cubes cast from the same mix. A possible reason for this phenomenon is most likely due to the differences within heats of hydration. The larger 4”x8” cylinder has approximately 12 times more volume than the smaller cube. As a result, the potential for heat development and strength loss previously discussed is greater for the 4"x8" cylinders. The results show that the materials which have very rapid hardening characteristics tend to have the biggest compressive strength difference when comparing cubes to cylinders. Therefore, another possibility for the large compressive strength disparities between the cylinders and cubes are most likely a result of the temperature differences experienced between the two specimen types.

Tensile Strength

The tensile strength of concrete of is a particularly important strength parameter due to the fact the localized tensile loading of concrete structures is the most common cause of cracking in structural concrete due to loading. The standard test method for the splitting tensile strength of cylindrical concrete specimens as per ASTM C496-04 was used to obtain the tensile strength various repair materials at ages of 1 day, 7 days and 28 days. Figure 9 presents a summary of the tensile strength testing results.

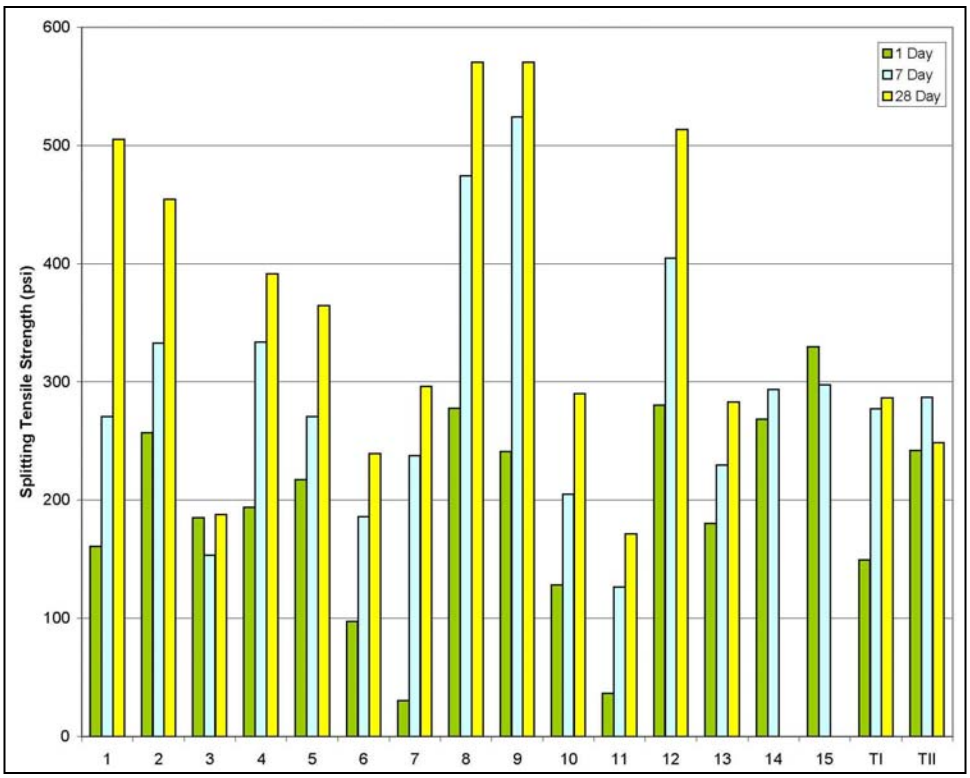

Figure 9: Splitting tensile strength summary

Typically the ratio of tensile to compressive strength is (tensile / compressive) is 10-11% for low strength concrete, 8-9% for medium strength concrete and 7% for high strength concrete [2]. Figure 10 provides a summary of the tensile strength to compressive strength percentages.

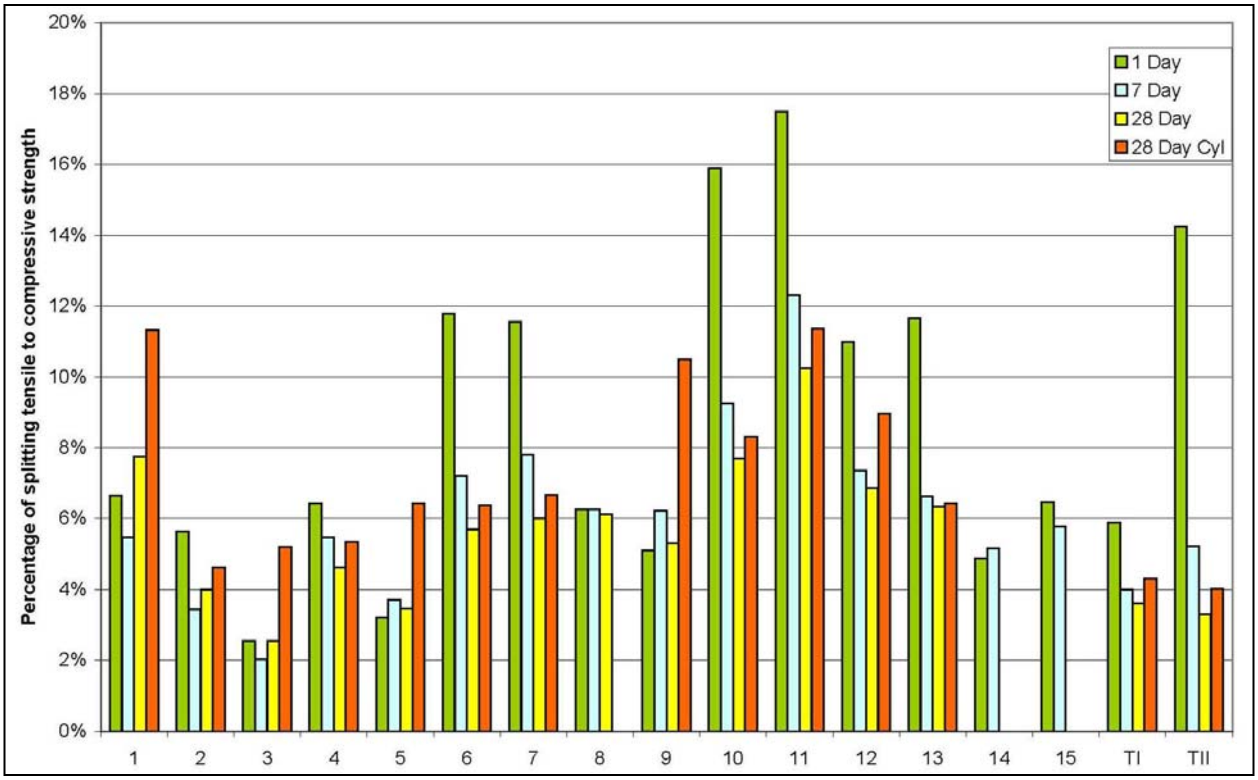

Figure 10: Percentage of splitting tensile to compressive strength

Several trends in the data are revealed by the incorporating the data summaries in figure 6, (compressive strength summary) and figure 10. The most notable trend is that the majority of the repair materials have tensile-compressive strength ratios (f'_{st}/f'_c) below 10%. Upon review of figure 6, there are three repair materials (Euco Crete, Euco Versaspeed, and Lambco Spe-D-Patch) that have 28 day compressive cube strength that exceeds 10,000psi. The f'_{st}/f'_c for each of these materials is below 6% for each of the materials when comparing cube strength. However, for each of the materials, f'_{st}/f'_c is slightly higher for the comparison of the tensile samples to compressive cylinder samples. This phenomenon is due to the lower compressive strengths of the cylinders. However, despite difference in the ratios, f'_{st}/f'_c is still significantly lower than 7% for the majority of the repair material. It is most likely that the size of the splitting tensile cylinders experienced the issues associated with rapid hydration and strength gain. The elevated temperatures as a result of the early-age hydration most likely resulted in relatively low tensile strength obtained for the cementitious materials.

Shear Strength

As part of this research, the shear strength was obtained for each of the repair materials. Although, the shear strength is not a relevant parameter regarding the use of repair materials, it is necessary to acquire the shear strength of the materials in order to assess the shear bond strength of the materials. Typically, the shear strength of concrete materials is higher than the shear bond strength of materials due to the interconnectivity of the crystalline structure of hardened cement paste vs. a bond between the repair material and a smooth hardened concrete surface. The Method of Test for Determining the Shearing Strength of Bonded Concrete (Iowa DOT Test Method No. 406-C) was used for the determination of the shear strength of the repair materials. Figure 11, provides a summary of shear strength data for the repair materials.

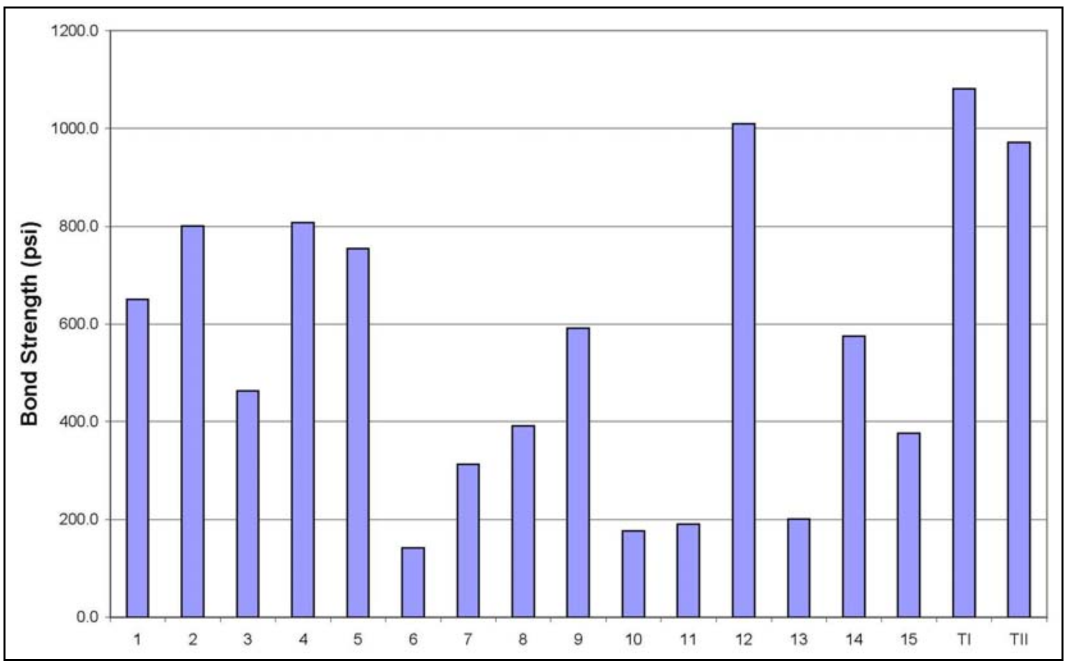

Figure 11: Summary of Iowa shear strength data

Flexural Strength and Flexural Modulus of Elasticity

Flexural strength and modulus of elasticity of concrete repair material are important properties for repair materials due to the fact that many repair materials are applied to the substrate in an orientation which experiences areas of high flexural stresses and strains within the repair material. Therefore, it was decided to incorporate flexural strength and flexural modulus of elasticity testing into this testing regimen. The standard test method for mortars grouts, monolithic surfacings, and polymer concretes (ASTM C580-02) was used to obtain flexural strength and modulus of elasticity for the repair materials at ages of 1 day, 7 days, and 28 days. Figures 12 and 13 provide data summaries of flexural strength and flexural modulus testing.

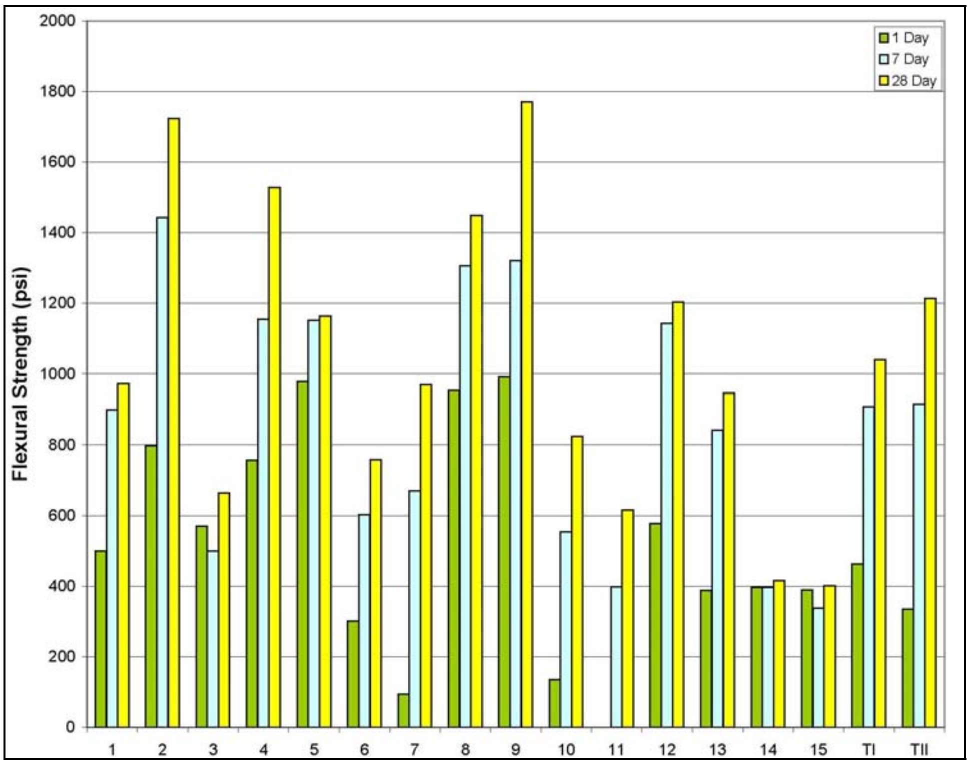

Figure 12: Flexural strength summary

The results from figure 12 illustrate that the flexural strength for each material is approximately 15%-20% of the compressive strength. Some of the repair materials of lower quality do not have a representative correlation between flexural and compressive strength. However, with the removal of several outlying repair materials, the results correspond quite well with results obtained for concrete materials reported by Mindess and Arkoyd [4,7].

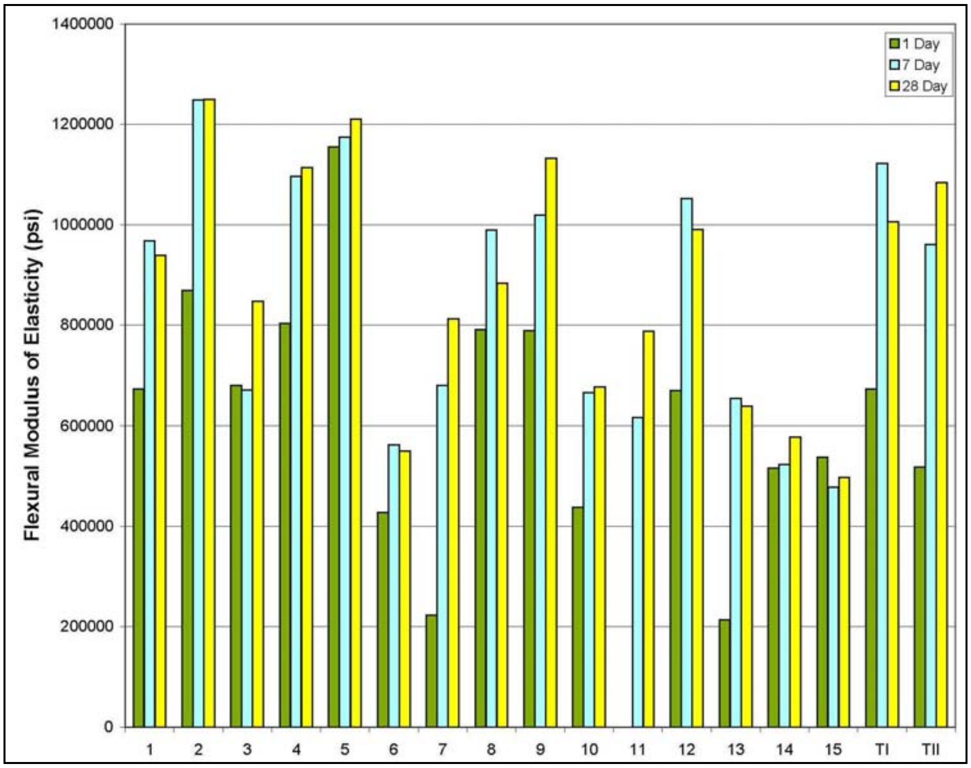

Figure 13: Flexural modulus of elasticity summary

The results obtained from the flexural modulus of elasticity testing correlate very well with the flexural strength testing. This result is to be expected as the Standard Test Method for Flexural Strength and Modulus of Elasticity per ASTM C-580M-02, requires the modulus of both values be taken from the same sample. Therefore. the similar trends should be expected from each. The Flexural Modulus of Elasticity is not often performed on concrete materials and there is not a standardized test similar to ASTM C580 for the laboratory testing of flexural modulus of elasticity for concrete materials. However, Barde et.al published some results for typical concrete specimens in a manner similar to ASTM C580. The research reports that the typical value for flexural modulus of concrete is approximately 1,400,000 - 3,000,000 psi [11] The results in Figure 12 indicate that the maximum flexural modulus obtained via the testing in this regimen is 1,200,000 psi. The jacket mixes obtained a flexural modulus of elasticity of 1,100,000 (slightly lower than concrete) which is most likely attributed to the absence of coarse aggregate. As a result it can be expected that the each of repair materials will behave in a manner that will distribute flexural stresses between the concrete substrate and the repair material in a manner that will not be detrimental to the repair system.

Bond Strength

The bond interaction between the concrete repair material and the substrate is perhaps the most important parameter of repair materials due to the fact that the lack of bond quality can render the repair useless. For the purposes of this research, it was decided to utilize three different bond tests to evaluate the repair materials. The test regimen was designed to not only, test the bond characteristics of the repair materials, but also to evaluate the bond tests themselves to see which were most reliable, efficient, and applicable for bond strength testing. The three bond tests chosen for this testing regimen are as follows:

- Bond Strength by Slant Shear
- Bond strength by Iowa Shear
- Bond strength by Direct Pull-Off Method

In an effort to determine the in-situ bond strength of the repair materials, concrete was used to serve as the substrate material. The concrete mixture design for the substrate material qualifies as a Class V per section 346 of the FDOT Standard Specifications for Road and Bridge Construction (1). Table 4 is a summary of mixture design and of the substrate material used for the bond testing regimen. The compressive strength of the substrate was obtained via testing (3) 6”x12” cylinders at 28 days, per ASTM C39-05 (10), and was determined to be 7711psi.

Table 4. Mixture Proportions for Substrate Mix

Cement Content:	846 lbs		C. A. Gradation:	# 89
W/CM (lbs/lbs):	**0.350**		Air Content (%):	0.0-5.0
Material	Source	Wt./Yd^3 (lb)	Vol./Yd^3 (ft^3)	Wt. Per Batch (lb)
CEMENT	Cemex	609	3.10	90.2
FLY ASH	Boral	152	1.19	22.5
METAKAOLIN	Burgess	85	0.54	12.6
WATER	Local	296	4.74	43.9
FINE AGG.	76-137	1278	7.76	189.3
COARSE AGG.	87-089	1367	9.13	202.5
AIR ENTRAINER	WR Grace Daravair 1000	3.0 oz	0.54	13.1 ml
ADMIXTURE	WR Grace WRDA 60	22.6 oz		99.0 ml
ADMIXTURE	WR Grace ADVA 140	67.7 oz		296.6 ml

Bond Strength by Slant Shear

ASTM has standardized several test methods using the slant shear method to test the bond strength of repair material and hardened grout. However, these methods employ the use of Portland cement mortar for the use of the substrate. It was decided that, for the purposes of this testing regimen, the most representative test required concrete instead of mortar for the substrate material. The standard test method for the bond strength of epoxy resin systems used with concrete by slant shear as per ASTM C882-99 with the following exceptions was used for testing:

7.1 – Concrete was used for the substrate material instead of mortar
– Type III cement was replaced with Type I cement.

10.2 – Conditioning of the sample followed the procedure specified in ASTM C192-02 section 7.3.2 – 7.5

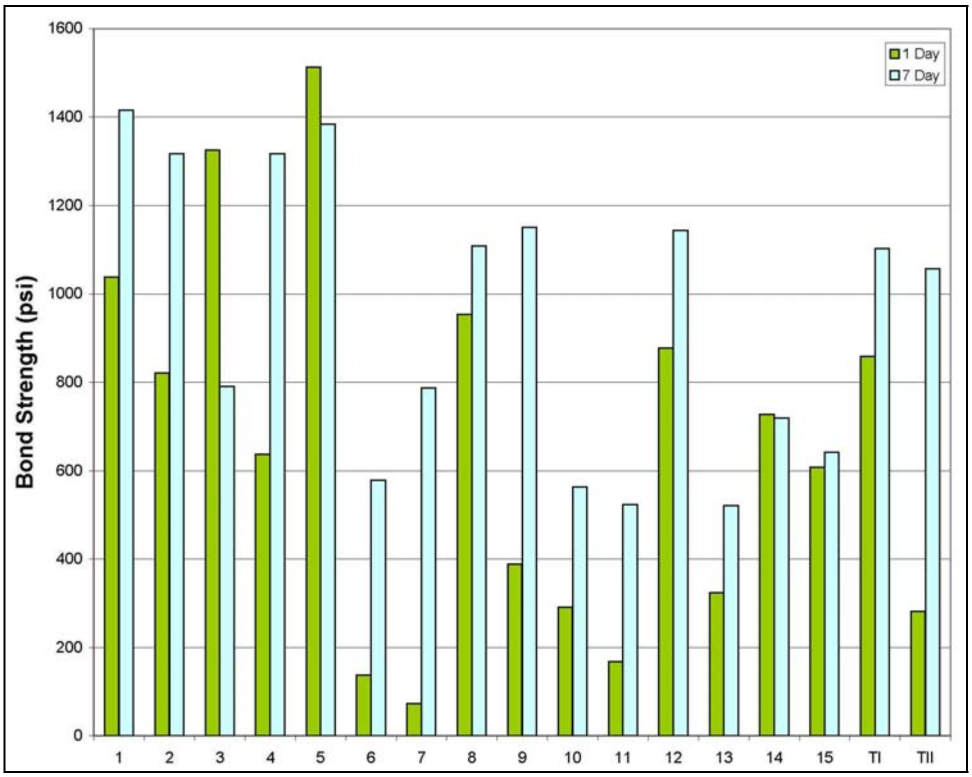

Figure 14: Slant shear bond strength summary

Figure 14 provides a data summary of the slant shear bond strength. Testing for slant shear was performed at ages of one day and 7 days. Some of the results indicate significant strength reduction of the bond strength between the one day strength and the 7 day strength for three of the materials tested. Possible reasons for the strength loss are most likely due to the issues with early age hydration and cracking as previously discussed. Each of the three repair materials that experienced significant bond strength loss are the repair materials which obtained compressive strength of above 2500 psi within 1 hour of casting. Therefore it is thought that the repair materials that have high early strength properties lose bond strength as a result of hydration and cracking issues.

Bond Strength by Iowa Shear

The Iowa shear test is used to determine the bond strength of composite specimens of concrete bonded with a repair material. The Iowa shear test is commonly used to determine the bond strength between asphalt and concrete interfaces. Four by eight inch solid composite specimens were used to determine the bond strength of concrete substrate bonded and the repair material at an age of 7 days. Figure 15 is a summary of results from the shear bond strength testing of composite specimens.

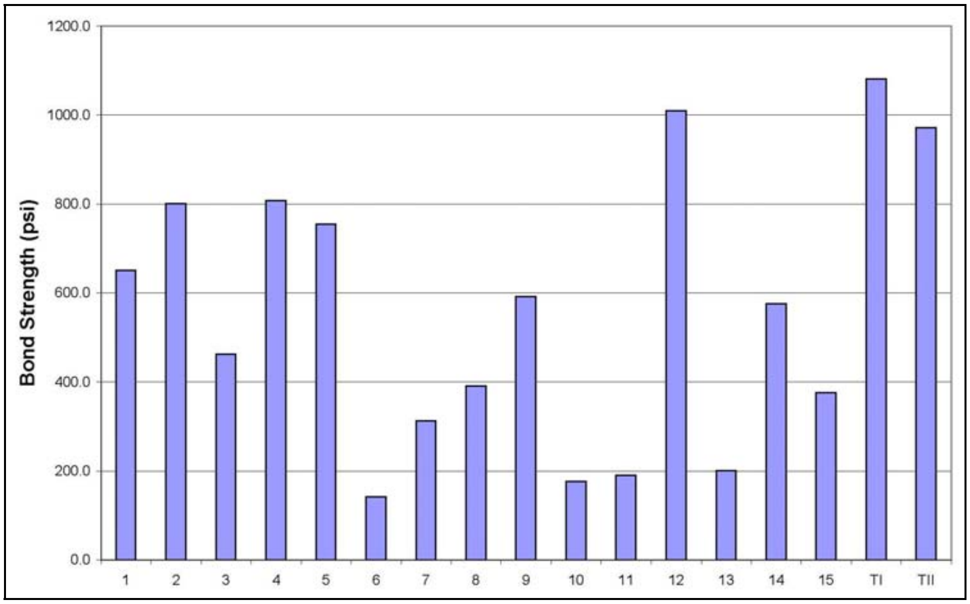

Figure 15: Iowa shear bond strength summary

Since the slant shear strength testing revealed that the some of the repair materials showed a reduction in bond strength between 1 day and 7 days, it was decided to use 7 day testing for evaluation purposes for the remaining bond strength testing regimen. The Iowa shear testing resulted in bond strengths lower than those obtained by slant shear testing, which is most likely due to the physical nature of the test. Figure 16 provides a side-by-side photograph both slant shear and Iowa shear specimens subsequent to testing. The geometry of the slant shear test incorporates the provision of a normal force which will result in slightly higher bond strength between materials as a portion of the force provided by the testing device does not contribute to the loading of the bond. However, the for the Iowa shear test, the entire force is carried by the bond for testing. Therefore, it is to be expected that Iowa shear strength would be of a lower value than slant shear strength. A literature review did not find any research directly correlating Iowa shear bond strength testing to slant shear bond strength testing. Although, research incorporating slant shear testing to other bond tests (slant shear vs. pull-off testing and slant shear vs. modulus of rupture) [12,13].

Figure 16: Slant shear testing (left) and Iowa shear testing (right)

Bond Strength by Direct Tension

The direct tension test is used to determine the bond strength of composite specimens of concrete bonded with a repair material. The direct tension test was incorporated into this research to acquire the bond strength of these materials directly, and to evaluate potential differences between the direct tension test to the shear bond tests. The use of 6”x 6”cylindrical specimens with a ½” overlay of repair material were used to determine the bond Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method) (ASTM C1583-04). Figure 17 is a photograph of a sample subsequent to testing. The direct tension test was first standardized in 2004 therefore; the use of the direct tension test in comparison with other tests for bonding is a relatively new concept for materials acceptance. Figure 18 is a data summary of direct tensile testing results.

Figure 17: Direct tensile specimen

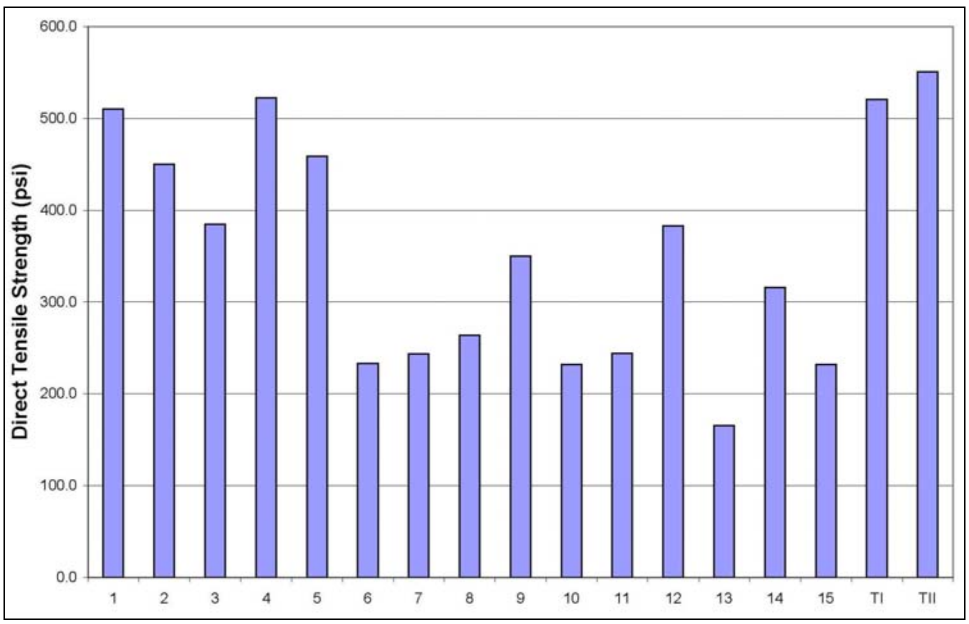

Figure 18: Direct tensile bond strength summary

Comparison of Bond Strengths

One of the purposes of this research was to determine the variability and differences between the bond strength tests themselves. Figure 19 presents a summary of the bond strength testing results with a side-by-side analysis.

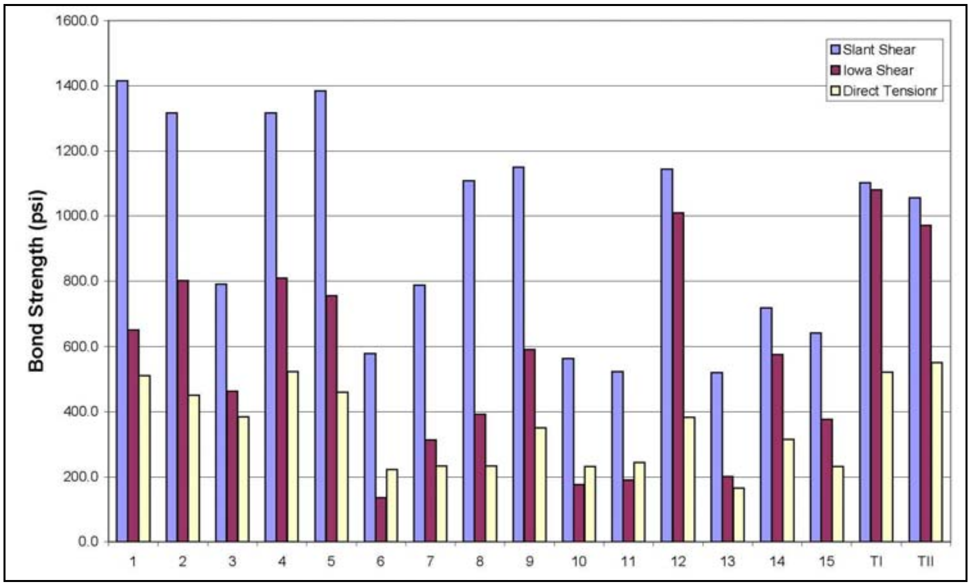

Figure 19: Side-by-side bond strength summary

As previously discussed, the slant shear testing results indicate higher bond strengths primarily due to the geometrical configuration of the test. Per the testing results, the shear bond tests resulted in larger bond strengths than the direct tensile bond results. This phenomenon is to be expected as the data from figures 9 and 11 indicate that the shear strength of the repair materials is significantly greater than the tensile strength of the repair materials. However, the material strengths are not the only basis for the differences in strength.

The testing revealed that the 13 of the 17 direct tensile bond strengths are higher than the splitting tensile strength of the obtained for the repair material. If the splitting tensile strength was a true representation of the tensile strength of these repair materials then, the specimens would not be able to obtain tensile bond strengths higher than the tensile strength of the repair material itself. Although it may be considered that tension testing of the repair materials was performed using the splitting tension test thus differences in tensile strength obtained by spitting tension and direct tension would be expected. Yet, research has shown that tensile strength obtained by the splitting tension test and the direct tension test are equivalent or that splitting tension can result in slightly higher strength than direct tensile strength [4,8,14]. Therefore, it can be assumed that the tensile strength results of the repair material indicate and abnormal trend in the tension testing data. Figure 20 is a percentage comparison of tensile bond strength to splitting tensile strength. For example, Cook Grout obtained a direct pull off strength of approximately 135% of its splitting tensile strength.

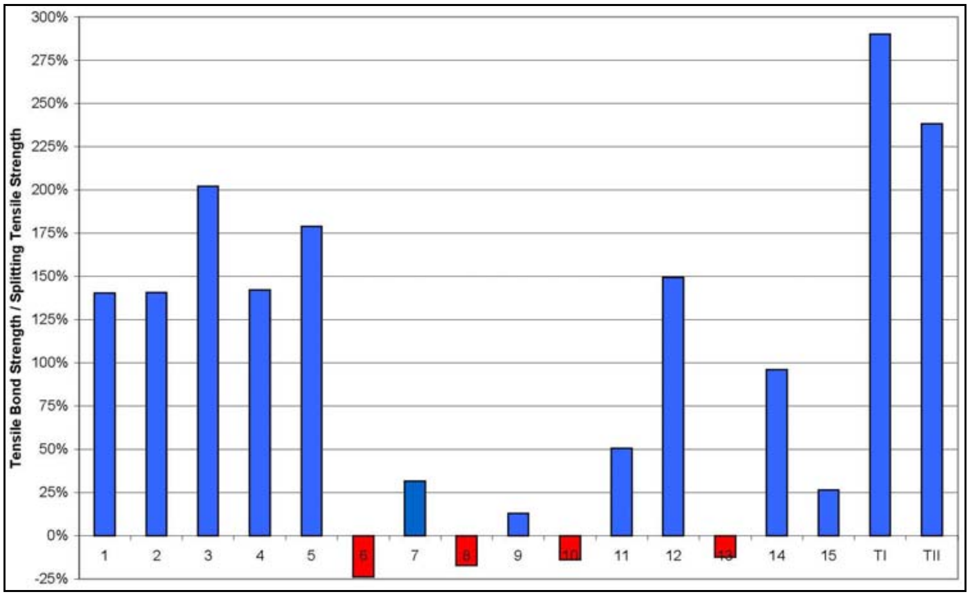

Figure 20: Percentage of tensile bond strength to splitting tension strength repair material

Figure 20 reveals that the majority of the repair materials have uncharacteristically high tensile bond strength in comparison to the splitting tensile strength. This phenomenon is most likely due to the relatively large size of the splitting tensile cylinders and the issues associated with rapid hydration and strength gain. The elevated temperatures as a result of the early-age hydration most likely resulted in relatively low tensile strength obtained for the cementitious materials.

Since the splitting tensile samples are significantly larger than the bond strength samples, the heat evolution within the splitting tensile samples was most likely higher than the heat evolution in the bond strength samples. Furthermore, the preparation of the bond samples involved casting significantly smaller sample to a mature (colder) concrete sample. Thus, it is most likely that the substrate impeded the heat evolution experienced by the splitting tensile sample. It is most likely that the splitting tensile samples experienced possible micro cracking near the center of the sample itself. Upon loading, the micro cracks which were initiated by the intense heat of the samples, only had to coalesce and were most likely not initiated by the loading of the splitting tensile sample itself, resulting in a lower splitting tensile strength than those tensile samples cast with geometries which did not facilitate the evolution of heat within.

The bond testing results were plotted and compared with each other in an effort to relate each. Figure 21 is a plot of direct tensile bond strength vs. Iowa bond and slant shear bond strengths.

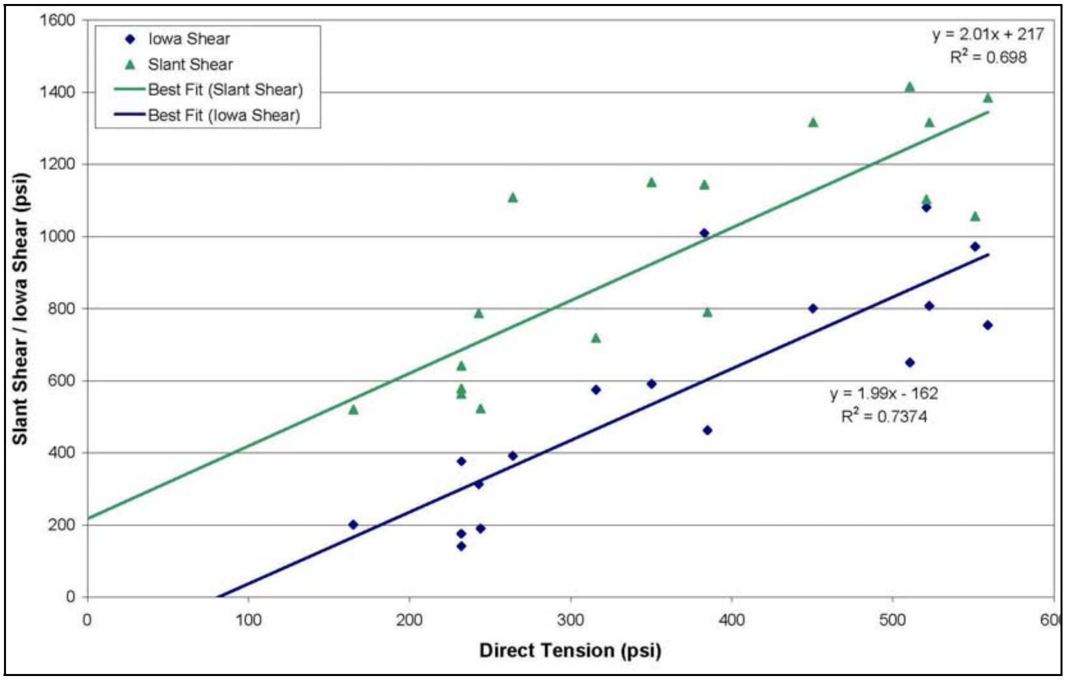

Figure 21: Direct tensile bond strength vs. slant/Iowa shear bond strength

The results indicate that both Iowa shear bond and slant shear bond strengths correlate relatively well to the direct tensile bond tests for the repair materials. Additionally, it can be stated that the rate of strength change between the two is very similar. For the use of qualification of future repair materials, it is feasible to use either Iowa shear bond strength or slant shear bond strength to make predictions about direct tensile bond strength between repair materials and concrete substrates.

Durability Properties

Absorption

The standard test method for absorption of chemical resistant mortars, grouts, monolithic surfacings, and polymer concretes as per ASTM C413-01 was used to obtain the absorption characteristics of the repair material at the age of 7 days. Figure 22 is a data summary of the results obtained from the absorption testing.

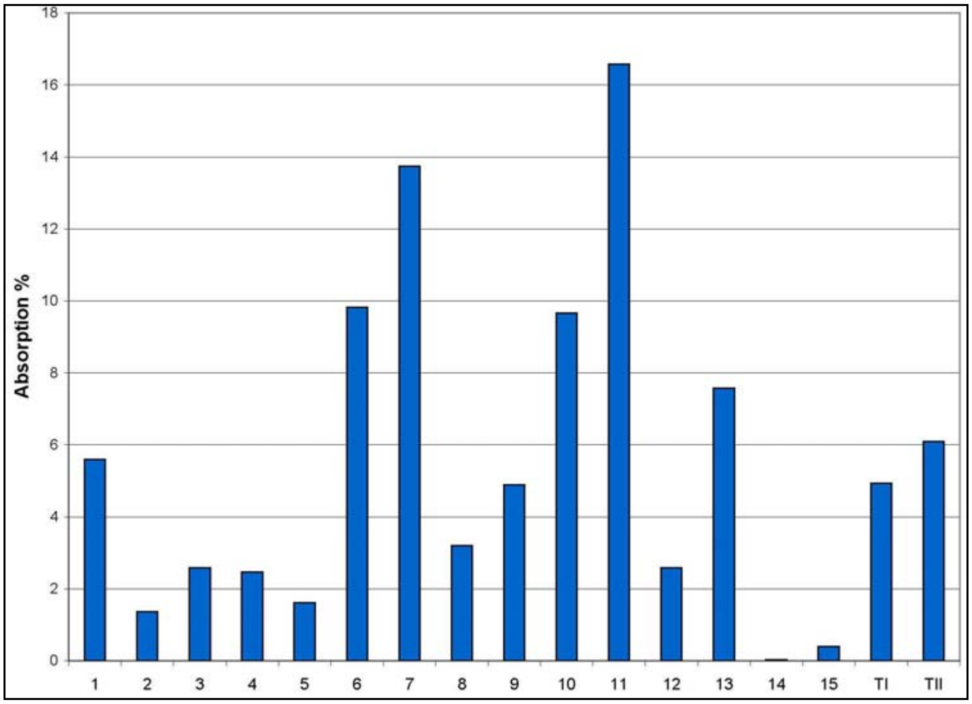

Figure 22. Absorption results

Absorption testing is used to obtain an indication of the size and connectivity of the pore structure of the repair material. Per reference 6, the higher the percentage of absorption, the more likely the material is to have durability issues when placed in service in locations with moderate to severe exposure conditions.

Chloride Ion Penetration

The standard test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration is prescribed by ASTM C1202-05. However, for the purposes of this research, the test was modified in the following manner;

3.1 – A potential difference of 30V (instead of 60V) was maintained across the ends of the specimen. The reason for the reduction in potential difference was due to the fact that the testing, using 60V, resulted in a charge passing through the sample which exceeded the capacity of the data readout apparatus.

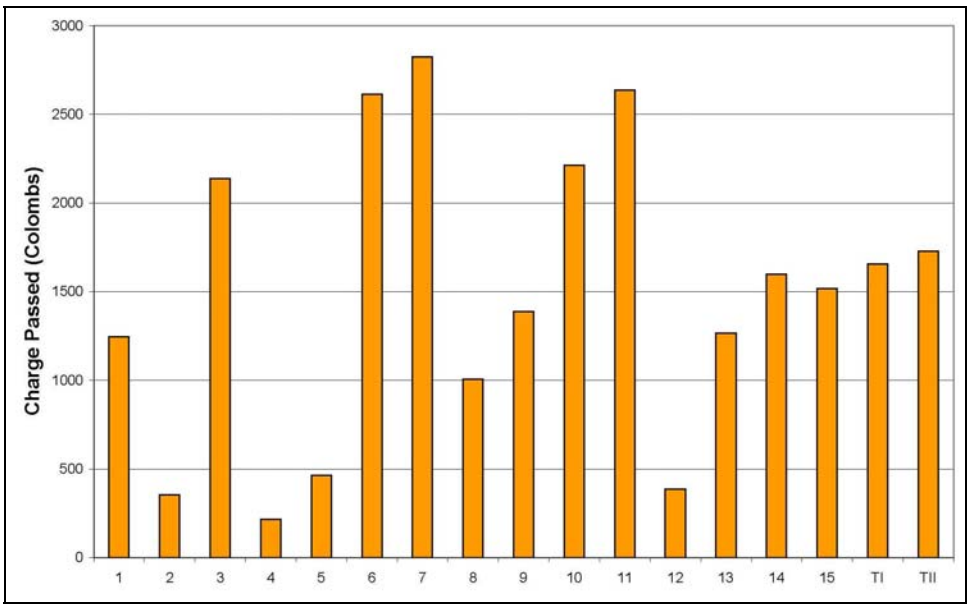

Figure 23. Chloride ion penetration results

Figure 23 is a summary of the chloride penetration results. Many of the charge passed (coulomb) values are lower than 2000, which according to Table 1. of ASTM C 1202-05 which indicate a low chloride ion penetrability [15]. However, since it was necessary to lower the voltage to 30V from 60V to obtain reasonable results, the use of this test for the classification of repair materials is not feasible. Especially since this test has received criticism by many researchers [15-18].

Surface Resistivity

The standard test Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability is FM 5-578 in which an surface resistivity meter with a Wenner array prove is used acquire the electrical resistance of concrete materials [19]. The surface resistivity has been used successfully to correlate chloride ion penetration results in concrete materials in for the assessment of the performance characteristics of concrete materials [20]. Therefore, it was decided to use the surface resistivity test method to assess the repair materials. Figure 24, is a summary of the surface resistivity testing results.

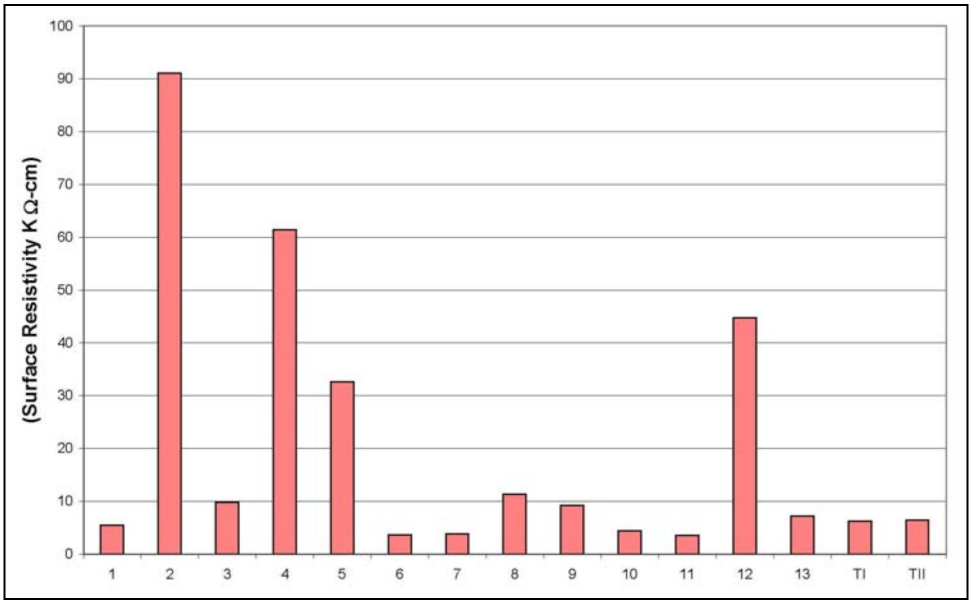

Figure 24. Surface resistivity results

Research has shown that materials with surface resisitivity over 22 KΩ-cm have adequate durability characteristics for most concrete applications, where those materials with a value of 12 or less tend to have poor durability characteristics. However, for the purposes of cathodic protection of pile jackets, a more permeable material is desired for the transfer of electrical currents and potentials [20].

RECOMMENDATIONS

The purpose of the research performed herein was to evaluate the testing methods applicable to the evaluation of repair materials, evaluating the repair materials themselves, and making appropriate revisions to testing methods to the FDOT Standard Specification for Road and Bridge Construction section 930.3 Based on the testing results it is recommended the following tests be incorporated into the revised specification for the acceptance of repair materials:

- The physical testing program
    - Standard Test Method for Length Change of Hardened Hydraulic-Cement, Mortar, and Concrete (ASTM C157-03)
    - Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes (ASTM C531-00)
- The Strength Testing Regimen
    - Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Cylindrical Concrete Specimens (Using 2” or 50mm cube specimens) (ASTM C-109M-05)
    - Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C-39-05e1)
    - Standard Test Method for Flexural Strength for Chemical Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes (ASTM C-580M-02)
    - Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM C496-02)
    - Standard Test Method for Bond Strength of Epoxy-Resin Systems Used With Concrete By Slant Shear (per ASTM C882-99)
- The Durability Testing Regimen:
    - Standard Test Method for Absorption of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacings, and Polymer Concretes (ASTM C413-03)
    - Florida Method of Test for Concrete Resistivity as an Electrical Indicator of its Permeability (FM 5-578)

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