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Evaluation of Test Methods for Measuring the Bond Strength of Portland-Cement Based Repair Materials to Concrete

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National Bureau of Standards
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U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Three bond strength test methods were evaluated for screening and selecting repair materials used in overlaying and patching portland cement concrete. Bond strengths of three repair materials to base concrete were investigated using two uniaxial tensile bond strength test methods and a slant shear bond strength test method. The differing strengths of the repair materials caused different failure patterns, which had to be considered in the analyses of the failure stresses.

Substantial differences in the failure stresses of the uniaxial tension and slant shear test methods were attributed to their different geometries and loading conditions. These differences emphasized the need to select test method(s) with geometry and loading conditions which are anticipated for the in-service repair material.

For the two higher strength repair materials investigated, the relative precision (repeatablilty) of the slant shear and one of the uniaxial tensile test methods (pipe nipple grips) were comparable and relatively good (coefficient of variation values were about 5 percent). It was concluded that both the slant shear test method and the pipe nipple grips uniaxial tensile test method are promising methods for screening and selecting repair materials of the type investigated (portland cement concrete or latex-modified concrete) for overlaying or patching portland cement concrete.

Keywords: overlaying, patching, portland-cement concrete, repair materials, slant shear bond strength, test method, uniaxial tensile bond strength

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1. BACKGROUND

There is a need for performance tests and performance criteria for screening and selecting materials for overlaying and patching portland cement concrete[1a]. For example, there are existing ASTM test methods and specifications for using epoxy-resin bonding systems (C 881[2], C 882[3], C 883[4], C 884[5]) and latex bonding agents and systems (C 1042[6], and C 1059[7]) with hardened portland cement concrete. However, test methods and specifications are needed for other types of repair materials, such as freshly mixed plain portland cement concrete or latex modified concrete bonded to hardened portland cement concrete.

The Tri-Service (U.S. Army, Navy, and Air Force) Building Materials Investigational Program has sponsored research at the National Bureau of Standards (NBS) to develop performance tests for concrete repair materials. A previous study[8] developed a test method to determine the uniaxial tensile bond strength. That study concentrated primarily on the bond strength of new portland cement paste to old portland cement paste.

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[a] Raised numerals refer to references in Section 8.

2. PURPOSE AND SCOPE

The purpose of the current study was to evaluate three bond[b] strength test methods for use in screening and selecting repair materials used in overlaying and patching portland cement concrete. The current study extended the previous study (reference 8) by investigating the uniaxial tensile bond strength of concrete (instead of cement paste) with 76 mm (3 in.) (instead of 38 mm (1.5 in.)) diameter specimens. In the current study, two methods of gripping uniaxial tensile specimens were investigated. Also, a modified ASTM C 882[3] slant shear bond strength test method was conducted concurrently with the uniaxial tensile bond test methods. Three repair materials were investigated: (1) 13 to 14 day-old portland cement concrete (PCC) on 80 day-old base PCC, referred to as "14 Day-Old PCC"; (2) a 7 day-old latex modified concrete (LMC) with an excessive air content on 94 day-old base PCC, referred to as "Excessive Air LMC"; and (3) a 10 day-old LMC with a normal air content on 129 day-old base PCC, referred to as "Normal Air LMC"[c]. The test methods were evaluated by analyzing the failure patterns, the magnitude and relative precision of the failure stresses, and the differences in the geometry and loading conditions between the test methods.

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[b] When testing for bond strength, failure could occur in the repair material, in the base concrete, or on the bond plane.

[c] Additional information on the use of styrene/butadiene latex in concrete overlays can be found in reference 11.

3. SPECIMENS AND TEST METHODS

3.1 Uniaxial Tensile Bond Strength Specimens and Test Methods

The following two methods of applying uniaxial tensile stress to bond strength specimens were used. A bond strength specimen consisted of a 76 mm (3 in.) diameter by approximately 76 mm (3 in.)-long cylinder of repair material bonded to a 76 mm (3 in.) diameter by approximately 76 mm (3 in.)-long cylinder of base PCC. A screw-driven testing machine was used to conduct both uniaxial tensile test methods.

3.1.1. Friction Grips.

The required friction around the lateral surface area of the bond strength specimen was developed by closing together the sides of a 76 mm (3 in.) inside diameter[d] by 76 mm (3 in.)-long steel pipe which had been split along its longitudinal axis (the pipe was one piece with a 76 mm (3 in.)-long seam). Two identical split pipe pieces (friction grips) were used: one to grip the repair material and the other to grip the base concrete. Figure 1 shows the test setup, including the split pipe friction grips and their

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[d] The inside diameter of the steel pipe was near 76 mm (3 in.) and allowed sufficient friction to develop around the repair material or base concrete to prevent slippage during testing.

universal ball and socket connections. A rubber "O"-ring provided a 4.8 mm (3/16 in.) spacing between the split pipe pieces at the bond plane.

3.1.2. Pipe Nipple Grips[e]

The lateral circumference of a 76 mm (3 in.) diameter by approximately 76 mm (3 in.)-long base PCC cylinder with a sawn surface was bonded with epoxy inside of a nominal 76 mm (3 in.) inside diameter, black steel pipe nipple (see Appendix A, Part I and figure A1, for details). After the epoxy had cured, the specimen was inverted and an empty, nominal 76 mm (3 in.) inside diameter by 76 mm (3 in.)-long, black steel pipe nipple was mounted on top of the base concrete-pipe nipple "O"-ring assembly, and the repair material was poured into the empty steel pipe nipple (Appendix A, Part II). The rubber "O"-ring provided about 4.8 mm (3/16 in.) spacing between the pipe nipples at the bond plane. Base concrete filled this 4.8 mm (3/16 in.) spacing. The bond plane coincided with the plane formed by the end of the pipe nipple that contained the repair material. After curing, the repair material had bonded to the sawn surface of the base concrete and to the inside of the pipe nipple into which it had been poured. In order to attach the specimen to the testing machine, pipe caps with special attachments, including universal ball and socket

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[e] This method was developed at Dow Chemical Co. (see footnote g) by L. Kuhlmann.

connections, were screwed on the pipe nipples at both ends (figure 2).

3.2 Modified ASTM Slant Shear Bond Strength Test Method

A modification of the ASTM C 882[3] slant shear bond strength test consisted of replacing one-half of the slant shear specimen with repair material. That is, one-half of the specimen was repair material bonded to the other half, which was base concrete. The angle of the shear plane was approximately 30° with respect to the longitudinal axis of the cylinder. Figure 3 shows a slant shear specimen being compressed.

4. MATERIALS, MIXING, AND CURING PROCEDURES

The mix proportions of base concrete and repair materials tested are given in table 1. A nominal 12.5 mm (1/2 in.) maximum size, crushed dolomitic limestone[f] aggregate (100 percent passing a 12.5 mm (1/2 in.) sieve and approximately 9 percent retained on a 9.5 mm (3/8 in.) sieve) was used in both the base PCC and the repair material. A concrete sand with a fineness modulus of about 2.6 and ASTM Type I portland cement were used in both the base PCC and repair materials. In the LMC repair material, a styrene-butadiene polymer emulsion (latex) manufactured by Dow

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[f] As reported by the supplier.

Chemical[g] was used in which the polymer comprised about 48 percent by weight of the total emulsion. The high air content (about 15 percent, table 1) of the Excessive Air LMC repair material was caused by the omission of the antifoam agent in the latex.

4.1 Base Concrete

After casting, the specimens of base concrete were covered with plastic sheeting, stripped at 2 days of age, immersed in saturated lime water for 26 days, and then air dried until tested. The base concrete was sawn to the required geometry (either at 90° or 30° to the cylinder's longitudinal axis) using a water-lubricated, diamond saw blade. The sawn section was placed in either a 76 mm (3 in.) diameter by 152 mm (6 in.)-long plastic cylinder mold (type used for molding concrete) or epoxied in a steel pipe nipple (see Appendix A, Part I). All sawn surfaces were sanded using sandpaper and then wiped with a damp towel to remove any debris.

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[g] Certain manufacturers' names, and names of commercial equipment, instruments, and materials are identified in this report to adequately specify the experimental procedure. Such an identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the equipment, instruments, or materials identified are necessarily the best available for the purpose.

4.2 Repair Material Specimens

Immediately prior to casting the 14 Day-Old PCC and the Excessive Air LMC repair materials onto the sawn surface of the base concrete, a thin layer of repair material was applied to the base concrete surface with a brush. Immediately prior to placing the Normal Air LMC repair material, the base concrete surface was first dampened with water and then brushed with a thin layer of repair material. All repair materials were placed in three layers, with each layer rodded and then tapped as necessary on the outside of the mold for further consolidation (except that the Normal Air LMC was vibrated instead of being tapped). After casting, the repair materials were covered with plastic sheeting and then stripped at the desired age. Stripping consisted of removal of the plastic sheeting and the plastic molds. Plastic molds were used in fabricating the friction grips, slant shear, and control compression specimens. Stripping the pipe nipple grips specimens consisted of removal of the plastic sheeting, but the lateral surfaces of the cylinders remained adhered to and sealed by the steel pipe nipples. Specimens consisting of the 14 Day-Old PCC repair material were stripped at 12 days of age and air dried 1 to 2 days prior to testing. Specimens consisting of the Excessive Air LMC repair material were stripped at 1 day of age and air dried for 6 days prior to testing. Specimens consisting of the Normal Air LMC repair material had their plastic sheeting removed at 1 day of age and their plastic molds removed for air drying 1 day prior to testing. (The latex manufacturer had recommended that the LMC be stripped at 1 day of age for air drying. The Normal Air LMC repair material was cast at the latex manufacturer's laboratory and shipped by air to NBS for testing.) All base concrete and repair materials were cast and cured at room temperature. Specimens were dried at approximately 40 percent relative humidity. The ages of the base concrete and repair materials when they were tested are given in tables 2 to 4.

5. TEST RESULTS AND DISCUSSION

Tables 2, 3, and 4 list the failure stress and the location and approximate amount of the failure surface from the bond testing of the 14 Day-Old PCC, Excessive Air LMC, and Normal Air LMC repair materials, respectively, for the three bond test methods studied. The information given in tables 2 to 4 regarding the location and amount of the failure surface is explained in Section 5.1.

With the slant shear test method, the tables give the failure stress based on the cross-sectional area (4.561×10^{-3} m^2 (7.07 $in.^2$)) and on the elliptical bond plane area, 9.123×10^{-3} m^2 (14.14 $in.^2$)[h], as specified by ASTM C882[3] (see below). The failure "bond" stress based on the elliptical bond plane area was used when

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[h] ASTM C 882 actually specifies 9116 mm^2 (= 9.116×10^{-3} m^2 and 14.13 $in.^2$).

"comparing" the failure stress from the slant shear test method with that from the tensile test methods. The failure stress (not a "bond" stress) based on the cross-sectional area was used when comparing the strength of a slant-shear specimen with the compressive strength of a comparable 76 mm (3 in.) diameter by 152 mm (6 in.)-long control cylinder (see Section 5.2.2).

The failure "bond" stress as used in this paper was calculated per ASTM C 882[3] by dividing the failure load (P), which was collinear with the cylindrical axis of the slant shear specimen, by the elliptical bond plane area (9.123×10^{-3} m^2 (14.14 $in.^2$)). The nominal shear bond stress (($\cos 30^{o} \times P$)/14.14 $in.^2$) which acts parallel to the bond plane, however, is lower than the ASTM stress.

Based on plots of crosshead movement versus applied load in some of the friction grips tests, the grips appeared to "seat" themselves by slipping slightly relative to the concrete surface as the load was being increased to its maximum value. It is believed that this apparent "seating" did not appreciably affect the test results. In contrast, and as expected, no apparent slippage of the pipe nipple grips specimens was observed.

5.1 Failure Patterns

The approximate percentages of the failure surface area which failed in the repair material, in the base concrete, or on the bond plane, are given in columns 3, 4, and 5 in tables 2, 3, and 4 (the sum of columns 3, 4, and 5 is 100 percent). The percentage of the failure surface area which occurred on the bond plane was further distinguished as: (i) a thin layer of repair material which adhered on the base concrete, (ii) a thin layer of base concrete which adhered on the repair material, or (iii) a "clean" break, where neither the repair material nor the base concrete adhered to the other. Also, in some of the slant shear cases (see column 6, tables 2 and 4), the failure process produced a separate piece which contained both the repair material and the base concrete bonded together. Because the determinations of the percentages of the failure surface area were estimated visually, they are approximate values. Additional approximation occurred when determining whether a layer of repair material or base concrete which was adhered on the bond plane should be treated as a "thin" layer on the bond plane (column 5) or be treated as a separate material. For example, a "thin" layer of repair material on the bond plane could have been entered either in column 5 with an "r" (designating repair material) or in column 3 as a failure in the repair material. (The repair material, however, could always be distinguished from its base concrete). Despite these approximations, it was considered that the percentages and locations of the failure surfaces provided a good basis for analyzing the failure trends. As shown in tables 2 to 4, depending on the repair material and the test method used, failure occurred in the repair material, in the base concrete, on the bond plane, or a combination of these. The failure patterns for each of the three repair materials are discussed below.

5.1.1 14 Day-Old PCC Repair Material

With the 14 Day-Old PCC repair material (table 2), preferential failure patterns for the friction grips tensile and the slant shear test methods were not evident. This lack of failure patterns was not unexpected with the friction grips test method, since the tensile strength of the control repair material specimens (1.98 MPa (287 psi) at 13 days of age, table 1) was about the same as that estimated for the base concrete (about 2.07 MPa (300 psi)[i]). A lack of failure patterns also was not unexpected with the slant shear test, since the average compressive strength of the control repair material cylinders (26 MPa (3.8 ksi), table 1) was somewhat close to that of the control base concrete cylinders (34 MPa (4.9 ksi), table 1).

There appeared to be a pattern of preferential failure in the 14 Day-Old PCC repair material for the pipe nipple grips test method. (Because no pipe nipple grips tensile control tests were conducted with specimens consisting entirely of 14 Day-Old PCC,

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[i] The 2.07 MPa (300 psi) stress corresponds to the failure of primarily base concrete, based on the average of the three friction grip failure stresses in table 4 with 75 percent or more of the failure surface having failed in the base concrete (column 4).

it was not possible to comment on the apparent failure pattern by comparing the strength of the 14 Day-Old PCC repair material to that of the base concrete.)

5.1.2 Excessive Air LMC Repair Material

With all three test methods, there was a clear pattern of preferential failure in the Excessive Air LMC repair material. That is, with each specimen, the total percentage of the failure surface which failed in the repair material in all cases exceeded the sum of the percentage which failed in the base concrete and the percentage which failed as "clean" breaks. (The total percentage which failed in the repair material can be found in table 3 by adding the percentage of repair material on the bond plane which adhered to the base concrete, denoted by "r" in column 5, to the percentage of failure in the repair material, given in column 3.)

This failure pattern was as expected for the slant shear test, since the average compressive strength of the Excessive Air LMC control repair material cylinders (16 MPa (2.3 ksi), table 1) was substantially below that of the control base concrete cylinders (about 34 MPa (4.9 ksi), table 1).

This failure pattern was also expected for both tensile test methods. With the friction grips tensile test method, the estimated average tensile strength of the repair material (0.903 MPa (131 psi), which represents the failure primarily of repair material, table 3) was less than that estimated for the base concrete (about 2.07 MPa (300 psi[j])). Similarly, with the pipe nipple grips tensile test method, the estimated average tensile strength of the repair material, 1.50 MPa (217 psi), which represents the failure primarily of repair material (table 3), was less than that estimated for the base concrete, 2.71 MPa (393 psi), which represents primarily the failure of base concrete (table 4, see Section 5.1.3).

5.1.3 Normal Air LMC Repair Material

There was a clear pattern of preferential failure in the base concrete with the Normal Air LMC repair material and with the two tensile test methods (table 4), especially for the pipe nipple grips method. That is, with each test specimen, the total percentage of the failure surface which failed in the base concrete (entries in column 4 plus "b" entries in column 5) in almost all cases exceeded the sum of the percentage which failed in the repair material and the percentage which failed as a "clean" break. (Because no tensile control tests were conducted with specimens consisting entirely of Normal Air LMC, it was not possible to comment on the failure pattern by comparing the strength of the Normal Air LMC repair material to that of the

[j] See footnote "i" in Section 5.1.1.

base concrete.)

With the Normal Air LMC repair material, all the slant shear specimens had "clean" break values of 75 percent or greater (column 5, table 4). This pattern of failure along the bond plane appeared reasonable, since the average compressive strength of the control repair material cylinders (36 Mpa (5.2 ksi), table 1) was fairly close to that of the control base concrete cylinders (about 34 MPa (4.9 ksi), table 1). This failure trend, which differed from that of the tensile tests with the Normal Air LMC, may have been caused by (i) the nature of the bond of the repair material to its base concrete, i.e., when subjected to slant shear, the bond plane was weaker as compared to the repair material and the base concrete, (ii) the possible preferential failure on the bond plane in the slant shear test or, (iii) a combination of (i) and (ii).

5.2 Precision and Magnitude of the Failure Stresses

Because the repair material, the base concrete, and the bond of the repair material to the base concrete each has its characteristic strength and variability, the amount and location of the failure surface had to be considered when analyzing the failure stresses. For example, and as discussed in Section 5.1.2, with the Excessive Air LMC, there was a preferential failure in the repair material as compared to the "remainder of the specimen" (base concrete or "clean" breaks on the bond plane). Therefore, the properties of this repair material had a greater influence on the failure stress statistics than the properties of the "remainder of the specimen" for the three test methods. Similar statements can be made regarding the other failure patterns discussed in Section 5.1.

The average and coefficient of variation values of the failure stress for the three test methods and the three repair materials are given in table 5.

With each of the three test methods, the average and coefficient of variation values of the failure stress for the 14 Day-Old PCC repair material were approximately the same as those corresponding to the Normal Air LMC repair material (table 5). It is worth noting that, although the average failure stresses were approximately the same for the 14 Day-Old PCC and the Normal Air LMC repair materials, their failure patterns were different (see Section 5.1).

5.2.1. Precision of the Test Methods

It was considered inappropriate to use the standard deviation to measure the precision (repeatability about a given base line) because of the large differences in the averages and standard deviations of the slant shear as compared to the two tensile tests for a given repair material (tables 2, 3, and 4). Rather, the coefficient of variation (=(standard deviation/average)x100), which is a measure of precision adjusted for the magnitude of the average, was used as a measure of the relative precision.

The coefficient of variation values of the slant shear test ranged from about 5 to 11 percent and were less than or equal to those for both tensile tests when comparing with each of the three repair materials (table 5). This trend, though not statistically significant[k], suggests that the relative precision of the slant shear test was as good, and in some cases better, as compared to the relative precision of the two uniaxial tensile test methods.

With the two higher strength repair materials, the relative precision of the slant shear test and the pipe nipple grips test were comparable and relatively good (coefficient of variation values of about 5 percent, table 5).

With each of the three repair materials, the coefficient of variation value of the pipe nipple grips test was always less than that of the friction grips test (table 5). This trend, though not statistically significant (see footnote k in Section

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[k] In this study, the difference in the coefficient of variation values from two samples (1 and 2) were considered to be statistically significant if the test statistic, z, given by Sachs[9] ($z = |V_1-V_2| \,/((V_1^2/2n_1)+(V_2^2/2n_2))^{1/2}$; V = coefficient of variation and n = sample size) was 3 or greater. Use of Sach's test statistic was an approximation because it is for "sample sizes not too small ($n_1, n_2 \gtrsim 30$)" (compared to the sample sizes of 7 or 8 of this study) and it was assumed that the test statistic is normally distributed.

5.2.1.), suggests that the relative precision of the pipe nipple grips test method was better than that of the friction grips test method.

With the 14 Day-Old PCC and the Normal Air LMC repair materials, the coefficient of variation values were relatively low for all three test methods and ranged from 5 to 10 percent (table 5). The Excessive Air LMC repair material, however, had considerably higher coefficient of variation values (but not statistically significant - see footnote k in Section 5.2.1.) as compared to the other two repair materials (table 5) for all three test methods. Because there was a clear pattern of preferential failure in the Excessive Air LMC repair material, it was suspected that the higher coefficient of variation values were caused, at least in part, by a physical property of the repair material, such as its high air content or possibly, a lack of homogeneity. Such a physical property could cause a greater variety of failure locations within the repair material. The value of the coefficient of variation is increased by an increase in the standard deviation of the strength and by a decrease in the average strength. For a given test method, the Excessive Air LMC had substantially decreased average strength values (attributed to the high air content) and increased standard deviation values as compared to the other two repair materials (tables 2,3, and 4).

5.2.2 Magnitude of the Failure Stress

For each of the three repair materials, the failure stress in the slant shear test (failure stress computed as failure load divided by the 9.123×10^{-3} m^2 (14.14 in.^{2}) elliptical bond plane area - ASTM C 882[3]) was substantially greater[1] than that for the two tensile tests (table 5). This substantial difference in failure stress was attributed primarily to the different test geometry, loading, and stresses in the slant shear test as compared to the two tensile tests.

Values of the ratio of the slant shear average failure stress (computed by dividing the failure load by 4.56×10^{-3} m^2 (7.07 in.^{2}), tables 2 to 4) to that of the compressive strength of the base concrete control cylinders (about 34 MPa (4900 psi), table 1) were 0.81 for the 14 Day-Old PCC, 0.40 for the Excessive Air LMC, and 0.86 for the Normal Air LMC. This ratio represents the fraction of the strength of the slant shear composite specimen (repair material and base concrete) relative to the compressive strength of the base concrete control cylinders. As the strength of the slant shear composite specimen approaches that of the base concrete control specimen, the value of the ratio approaches unity. A selected ratio value, then, could serve as a useful performance

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[1] Values of the "t" statistic (reference 10, Natrella, page 3-23) were 17 or more. These "t" values indicated that the difference between the mean failure stress for the slant shear test method as compared to each of the two tensile test methods was statistically significant for each of the three repair materials.

criterion, provided the base concrete strength is desired to be the basis for comparison.

The average failure stress for the pipe nipple grips test method exceeded[m] that of the friction grips test method for each of the three repair materials (table 5). It was believed that the higher average failure stress was caused, at least in part, by less eccentricity in the pipe nipple grips test method as compared to the friction grips test method.

With each of the three test methods, the Excessive Air LMC repair material had substantially lower average failure stresses as compared to the other two repair materials (table 5). The lower strength was attributed to the excessive air content (about 15 percent).

6. CONCLUSIONS

1. Selection of Test Methods. The two types of test methods investigated (slant shear and uniaxial tension) had different geometry and loading conditions which resulted in substantially different failure stresses. These differences in failure stresses emphasized the

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[m] Values of the "t" statistic (reference 10, Natrella, page 3-23) were 4 or more. These "t" values indicated that the difference between the mean failure stress for the two test methods was statistically significant for each of the three repair materials.

need to select test method(s) with geometry and loading conditions which are anticipated for the in-service repair material.

It was concluded that both the slant shear test method and the pipe nipple grips uniaxial tensile test method are promising methods for screening and selecting repair materials of the type investigated (portland cement concrete or latex-modified concrete) for overlaying or patching portland cement concrete. As indicated above, the test method(s) chosen should have geometry and loading conditions which are anticipated for the in-service repair material.

2. <u>Importance of Failure Patterns.</u> Because the repair material, the base concrete, and the bond of the repair material to the base concrete each has its own characteristic failure stress and variability, failure pattern (amount and location of the failure surface) needs to be considered when analyzing the failure stresses. The different characteristics of the repair materials studied resulted in different failure patterns. The failure pattern is important because it indicates where the composite bond specimen (repair material and base concrete) failed. Failure in the

base concrete, for example, can be desireable and indicates that the base concrete is controlling the strength rather than the repair material or its bond to the base concrete.

3. Relative Precision of the Three Test Methods. With the three repair materials studied, the relative precision, as measured by the coefficient of variation, of the slant shear test method was as good, and in some cases possibly better[n] as compared to the two uniaxial tensile test methods (table 5). For the two higher-strength repair materials investigated, however, the relative precision of both the slant shear and the pipe nipple grips tensile test methods were comparable and relatively good (coefficient of variation values of about 5 percent).

4. Selection of Uniaxial Tensile Test Method. The pipe nipple grips tensile test method was considered to be the more promising of the two uniaxial tensile test methods investigated because of its higher average failure stress and possibly better[n] relative precision as compared to the friction grips test method. It was believed that the higher average failure stress was

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[n] The relative precision was "possibly better" because of the trend of lower, though not statistically significant, coefficient of variation values.

caused, at least in part, by less eccentricity introduced in the pipe nipple grips test method as compared to the friction grips test method.

5. <u>Slant Shear Test Method Criterion.</u> A potentially useful criterion in establishing the minimum strength for the slant shear test method is the fraction of the strength of the slant shear composite specimen (repair material and base concrete) relative to the base concrete control specimen. Both slant shear and control specimens need to be loaded in compression at the same load rate and also the same cross-sectional area needs to be used to calculate the stresses. As the strength of the slant shear composite specimen approaches that of the base concrete control specimen, the value of the ratio approaches unity. A selected ratio value, then, could serve as a useful performance criterion, provided the base concrete strength is desired to be the basis for comparison.

7. RECOMMENDATIONS FOR FURTHER RESEARCH ON SLANT SHEAR AND PIPE NIPPLE GRIPS TENSILE TEST METHODS

1. Minimum strength levels related to field performance (performance criteria) should be developed.

2. The effects of the environment (e.g., temperature or moisture cycling or both) on the bond strength of the repair material to its base concrete should be investigated.

3. The feasibility of using the test methods to determine the bond strength of different types of repair materials, such as polymer concrete or rapid set concretes, should be investigated.

4. The feasibility of using the test methods to accurately determine the bond strength of repair materials at early ages (e.g., 1 to 24 hours of curing) should be evaluated.

5. The effects of surface preparation and surface conditions of the base concrete (e.g., texture and moisture content) on the bond strength of the repair material should be investigated.

6. Analytical analyses, such as finite element analyses (e.g., see reference 12), of the test methods should be considered. These analyses, which take into account the differences in strength and stiffness of the components (e.g.,repair material, base concrete, pipe nipples), should provide additional insight into

the failure patterns and information on the stress distributions.

7. In addition to the bond test methods investigated in this report, other bond test methods which simulate different types of loading conditions (e.g., flexure, direct shear, and thermal compatibility) should be investigated.

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Table 1. Mix Proportions, Strength, and Density of Base Concrete and Repair Material Mixes

	Mix Proportions[a] (by weight)				Approximate Air Content (%)	Approximate Density[f] (pcf)[g]	Compressive[h] Strength (control)				Uniaxial[j] Tensile Strength (control)			
	Water/Cement	Sand/Cement	Coarse Aggregate/Cement	Latex Solids/Cement			n	Age (d)	Avg. (ksi)[i]	Cov. (%)	n	Age (d)	Avg. (psi)[i]	Cov. (%)
Base Portland Cement Concrete (PCC)	0.520[b]	2.62	1.75	-	8[d]	133	2 3 1	58 80 129	4.9 4.9 4.2	14 13 -	-	-	-	-
Repair Material 14 Day-Old PCC	0.520[b]	2.62	1.75	-	9[d]	132	8	14	3.8	1.7	8	13	287	7.8
Repair Material Excessive Air Latex Modified Concrete (LMC) (without antifoam agent)	0.371[c]	2.58	1.72	0.149	15[e]	121	3	7	2.3	1.5	-	-	-	-
Repair Material Normal Air LMC (with anti-foam agent)	0.373[c]	2.60	1.70	0.152	5	146	8	10	5.2	2.3	-	-	-	-

a In the ratios listed, the "water" weight includes that absorbed by the sand and coarse aggregates, and "sand" and "coarse aggregate" weights are based on their air dried weights.

b Water reducing agent (WRDA, W.R. Grace and Co.) added at dosage of 456 ml/100 kg cement (7 fluid oz./100 lb. cement).

c According to the manufacturer, the latex emulsion consisted of 0.52 water to 0.48 parts latex solids. Proportions of water in LMC were 0.21 parts plain water to 1 part cement and 0.16 parts water in latex solution to 1 part cement for a total of 0.37 parts water to 1 part cement by weight. (There were 0.15 parts latex solids per 1.0 part cement by weight)

d Air entraining agent (DARAVAIR-M, W.R. Grace and Co.) added at dosage of 65 ml/100 kg cement (1 fluid oz./100 lb. cement).

e Estimated at about 15 percent. Based on linear interpolation of air content of fresh LMC versus density of hardened LMC (air content of 5 percent with density of 2340 kg/m^3 (146 pcf) and air content of 20 percent with density of approximately 1700 kg/m^3 (106 pcf)).

f Density calculated by dividing the weight in air of hardened 76 mm (3 in.) diameter x 152 mm (6 in.)-long cylinders by their calculated volume of 6.95×10^{-4} m^3 (42.4 in^3). The number of days the cylinders were air dried prior to being weighed to determine their density varied (Base PCC, 63 days; 14 Day-Old PCC, 13 days; Excessive Air LMC weighed when stripped, 0 days ; Normal Air LMC, only cylinder tops air dried, 9 days).

g 1 lb/ft^3 = 16.02 kg/m^3.

h n = number of 76 mm (3 in.) diameter x 152 mm (6 in.)-long cylinders tested; Age = age in days when tested; Avg. = average stress; Cov. = coefficient of variation = (standard deviation/average) x 100; rate of loading was approximately 89,000 N/min. (20 kips/min.) except those cylinders tested at 58 days where approximately 178,000 N/min. (40 kips/min.) was used.

i 1 Ksi = 6.895 MPa; 1 psi = 6895 Pa.

j Friction grips test method (figure 1) used with a rate of straining (cross-head speed) of 1 mm/min. See Footnote "h" for definitions of "n", "Age.", "Avg.", and "Cov." Also, in Section 5.1, the uniaxial tensile strength was estimated based on data in tables 3 and 4.

Table 2. Failure Stress and Location and Amount of Failure Surface for 14 Day-Old Portland Cement Concrete Repair Material Bonded to 80-Day Old Base Portland Cement Concrete

Bond Test Method	Failure Stress (psi)ǂ based on 7.07 in.^{2} cross-sectional area. (1)	Failure Stress (psi)ǂ based on 14.14 in.^{2} elliptical bond plane area. (2)	Approximate Percentage of Failure Surface Area which Failed: in Repair Material (3)	in Base Concrete (4)	on Bond Plane+ (5)	in Repair Material and Base Concrete++ (6)
Tension,	287	-	70	30	0	0
Friction	321	-	0	95	5r	0
Grips*	281	-	75	25	0	0
	256	-	25	15	30c,30r	0
	299	-	80	20	0	0
	287	-	60	40	0	0
	278	-	20	30	25c,25r	0
	250	-	25	15	60c	0
Avg.┼	282					
Std. dev.┼	22.6					
COV (%) ┼	8.0					
Tension,	418	-	75	5	20r	0
Pipe Nipple	412	-	90	10	0	0
Grips*	440	-	0	100	0	0
	396	-	90	10	0	0
	440	-	65	20	15r	0
	415	-	95	5	0	0
	465	-	60	40	0	0
	421	-	90	10	0	0
Avg.	426					
Std. dev.	21.4					
COV (%)	5.0					
Slant	3860	1930	45	0	20c,30r	5
Shear**	4120	2060	10	0	25c,25r	40
	3990	2000	35	0	25c,25r	15
	4020	2010	25	0	30c,30r	15
	3580	1790	10	0	75c	15
	3840	1920	80	0	20c	0
	4190	2090	0	0	30c	70
	4000	2000	5	0	60c	35
Avg.	3950	1980				
Std. dev.	191	96				
COV (%)	4.8	4.8				

* Tested at crosshead speed of 1 mm/min.

** Loaded at approximately 89,000 N/min. (20,000 lbf./min.).

+ c = clean break, neither in repair material nor base concrete; r = thin layer of repair material adhered on base concrete.

++ Failure process produced a separate piece which contained both the repair material and the base concrete bonded together.

┼ Avg. = average, Std. dev. = standard deviation, COV = coefficient of variation = ((standard deviation)/average) x 100.

ǂ 1 psi = 6895 Pa; 7.07 in.^{2} = 4.56 x 10^{-3} m^2; 14.14 in.^{2} = 9.123 x 10^{-3} m^2.

Table 3. Failure Stress and Location and Amount of Failure Surface for 7 Day-Old Latex Modified Concrete ("Excessive Air") Repair Material Bonded to 94 Day-Old Base Portland Cement Concrete

Bond Test Method	Failure Stress (psi)ǂ based on 7.07 in.^{2} cross-sectional area. (1)	Failure Stress (psi)ǂ based on 14.14 in.^{2} elliptical bond plane area. (2)	Approximate Percentage of Failure Surface area which Failed: in Repair Material (3)	in Base Concrete (4)	on Bond Plane+ (5)	in Repair Material and Base Concrete++ (6)
Tension,	119	-	30	0	70r	0
Friction	128	-	30	0	70r	0
Grips*	140	-	35	0	5c,60r	0
	200	-	70	0	10c,20r	0
	128	-	50	0	5c,45r	0
	75	-	60	0	10c,30r	0
	128	-	30	0	70r	0
	131	-	20	0	80r	0
Avg. †	131					
Std. dev. †	34.1					
COV (%) †	26.0					
Tension,	196	-	85	0	15r	0
Pipe Nipple	206	-	50	0	50r	0
Grips*	212	-	70	0	30r	0
	203	-	10	0	90r	0
	153	-	60	0	40r	0
	312	-	90	0	10r	0
	234	-	70	0	30r	0
Avg.	217					
Std. dev.	48.6					
COV (%)	22.4					
Slant	1900	950	0	0	100r	0
Shear**	1810	905	0	0	100r	0
	1870	935	0	0	100r	0
	2310	1155	0	0	5c,95r	0
	2340	1170	0	0	100r	0
	1750	875	0	0	100r	0
	1930	965	0	0	5c,95r	0
	1960	980	0	0	100r	0
Avg.	1980	990				
Std. dev.	222	111.				
COV (%)	11.2	11.2				

* Tested at crosshead speed of 1 mm/min.

** Loaded at approximately 89,000 N/min. (20,000 lbf./min.).

\+ c = clean break, neither in repair material nor base concrete; r = thin layer of repair material adhered on base concrete.

++ Failure process produced a separate piece which contained both the repair material and the base concrete bonded together.

† Avg. = average, Std. dev. = standard deviation, COV = coefficient of variation = ((standard deviation)/average) x 100.

ǂ 1 psi = 6895 Pa; 7.07 in.^{2} = 4.56 x 10^{-3} m^2; 14.14 in.^{2} = 9.123 x 10^{-3} m^2.

Table 4. Failure Stress and Location and Amount of Failure Surface for 10 Day-Old Latex Modified Concrete ("Normal Air") Repair Material Bonded to 129 Day-Old Base Portland Cement Concrete

Bond Test Method	Failure Stress (psi)ǂ based on 7.07 in.^{2} cross sectional area. (1)	Failure Stress (psi)ǂ based on 14.14 in.^{2} elliptical bond plane area. (2)	Approximate Percentage of Failure Surface area which Failed: in Repair Material (3)	in Base Concrete (4)	on Bond Plane+ (5)	in Repair Material and Base Concrete++ (6)
Tension,	315	-	0	50	30c,20b	0
Friction	318	-	0	5	50c,45b	0
Grips*	306	-	0	95	5c	0
	299	-	5	40	30c,25b	0
	271	-	0	75	15c,10b	0
	274	-	0	30	35c,35b	0
	237	-	0	40	40c,20b	0
	321	-	0	100	0	0
Avg. ǂ	293					
Std. dev. ǂ	29.5					
COV (%) ǂ	10.1					
Tension,	362	-	0	80	10c,10b	0
Pipe Nipple	421	-	0	95	5b	0
Grips*	390	-	0	100	0	0
	393	-	0	100	0	0
	402	-	0	40	20c,40b	0
	371	-	0	100	0	0
	390	-	0	85	15c	0
	412	-	5	60	35c	0
Avg.	393					
Std. dev.	19.6					
COV (%)	5.0					
Slant	4370	2185	0	0	90c	10
Shear**	4200	2100	0	0	100c	0
	4510	2255	0	5	95c	0
	4100	2050	0	20	80c	0
	4020	2010	0	15	85c	0
	4280	2140	0	10	85c	5
	4230	2115	0	25	75c	0
	3880	1940	0	25	75c	0
Avg.	4200	2100				
Std. dev.	199.	100				
COV (%)	4.7	4.7				

* Tested at crosshead speed of 1 mm/min.

** Loaded at approximately 89,000 N/min. (20,000 lbf./min.).

+ c = clean break, neither in repair material nor base concrete; b = thin layer of base concrete adhered on repair material.

++ Failure process produced a separate piece which contained both the repair material and the base concrete bonded together.

ǂ Avg. = average, Std. dev. = standard deviation, COV = coefficient of variation = ((standard deviation)/average) x 100.

ǂ 1 psi 6895 Pa; 7.07 in.^{2} = 4.56 x 10^{-3} m^2; 14.14 in.^{2} = 9.123 x 10^{-3} m^2.

Table 5. Average and Coefficient of Variation Values for the Three Test Methods and Three Repair Materials

Repair Material	Bond Test Method					
	Friction Grips (Tensile)		Pipe Nipple (Tensile)		Slant Shear	
	Avg.[a] (psi)[b]	COV[a] (%)	Avg. (psi)[b]	COV (%)	Avg. (psi)[b,c]	COV (%)
14 Day-Old PCC	282	8.0	426	5.0	1975	4.8
Excessive air LMC	131	26.0	217	22.4	990	11.2
Normal air LMC	293	10.1	393	5.0	2100	4.7

a Avg. = Average and COV (%) = Coefficient of variation = ((standard deviation)/average) x 100

b 1 psi = 6895 Pa

c Failure stress based on 9.123×10^{-3} m^2 (14.14 $in.^2$) elliptical bond plane area

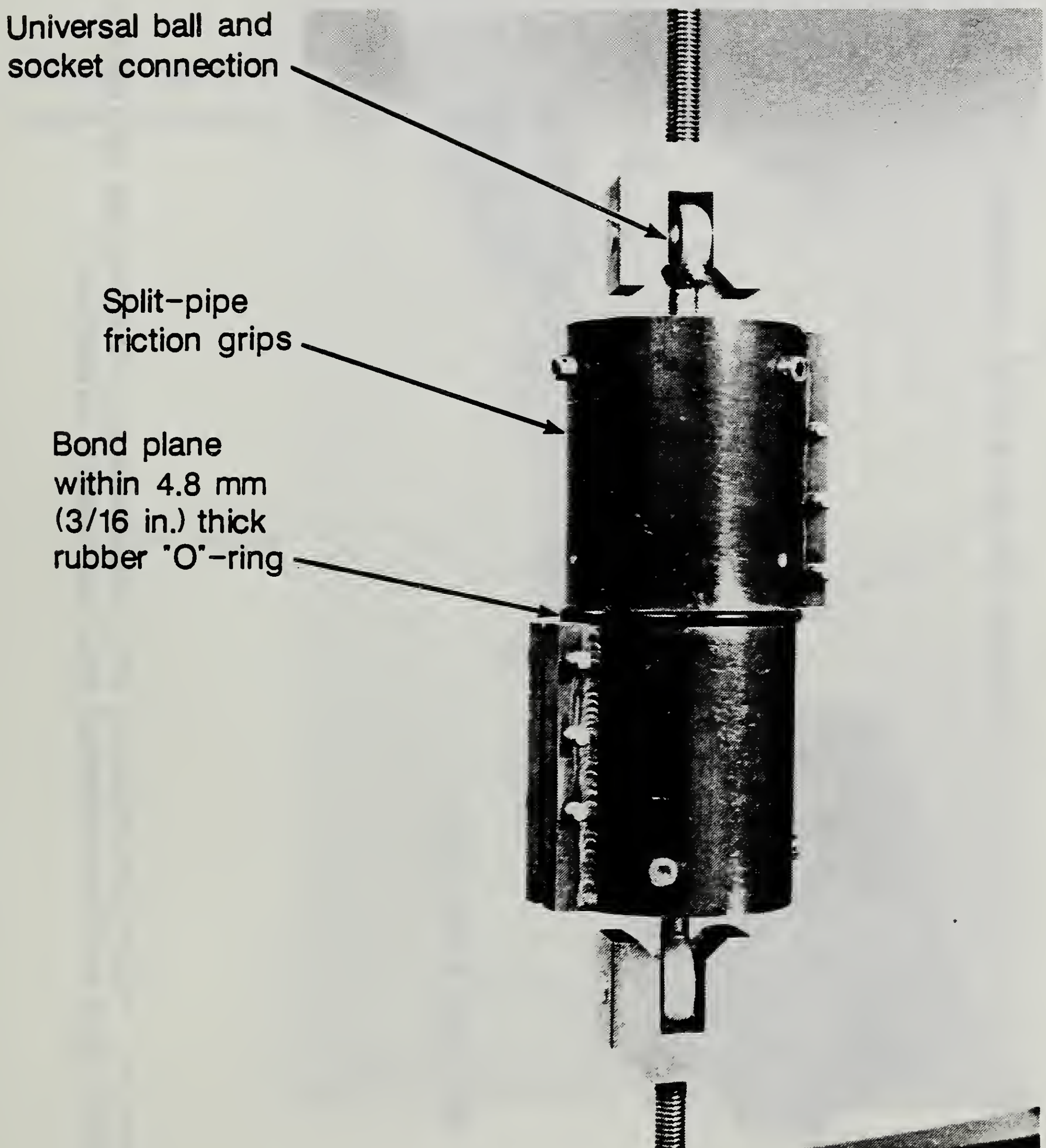

Figure 1a. Friction-grip test setup. Friction grips attached on a specimen, then installed in screw-driven testing machine, and pulled in tension. Two split-pipe friction grips were used: one gripped the repair material and the other gripped the base concrete. A rubber "O"-ring provided a 4.8 mm (3/16 in.) spacing between the split pipe grips at the bond plane. A universal ball and socket connection was used at each end of the specimen - see figure 1b for details.

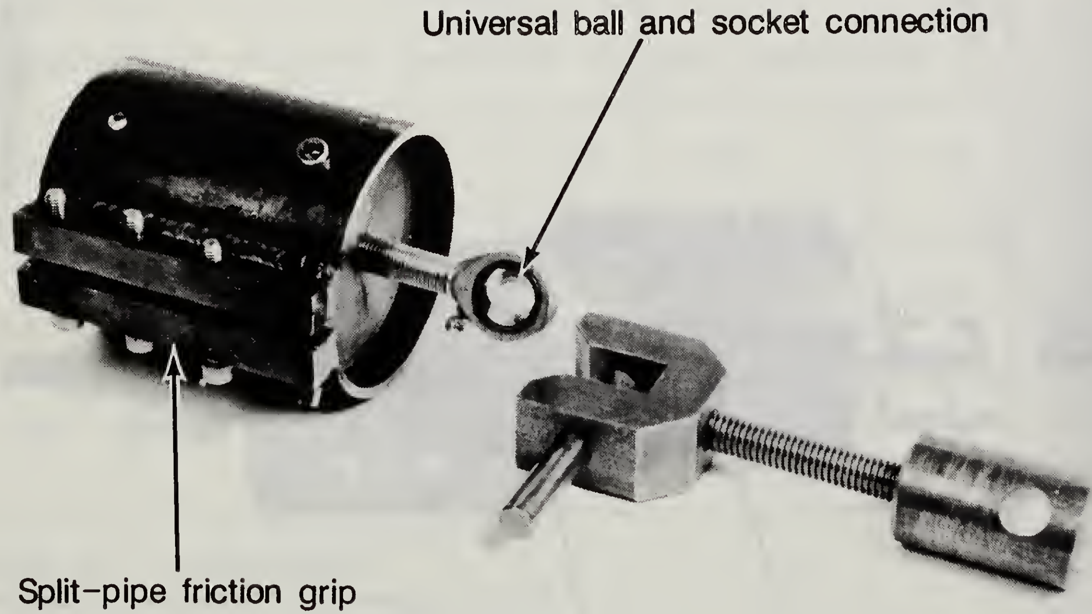

Figure 1b. Split-pipe friction grip attachments, including one split-pipe friction grip and its universal ball and socket connection.

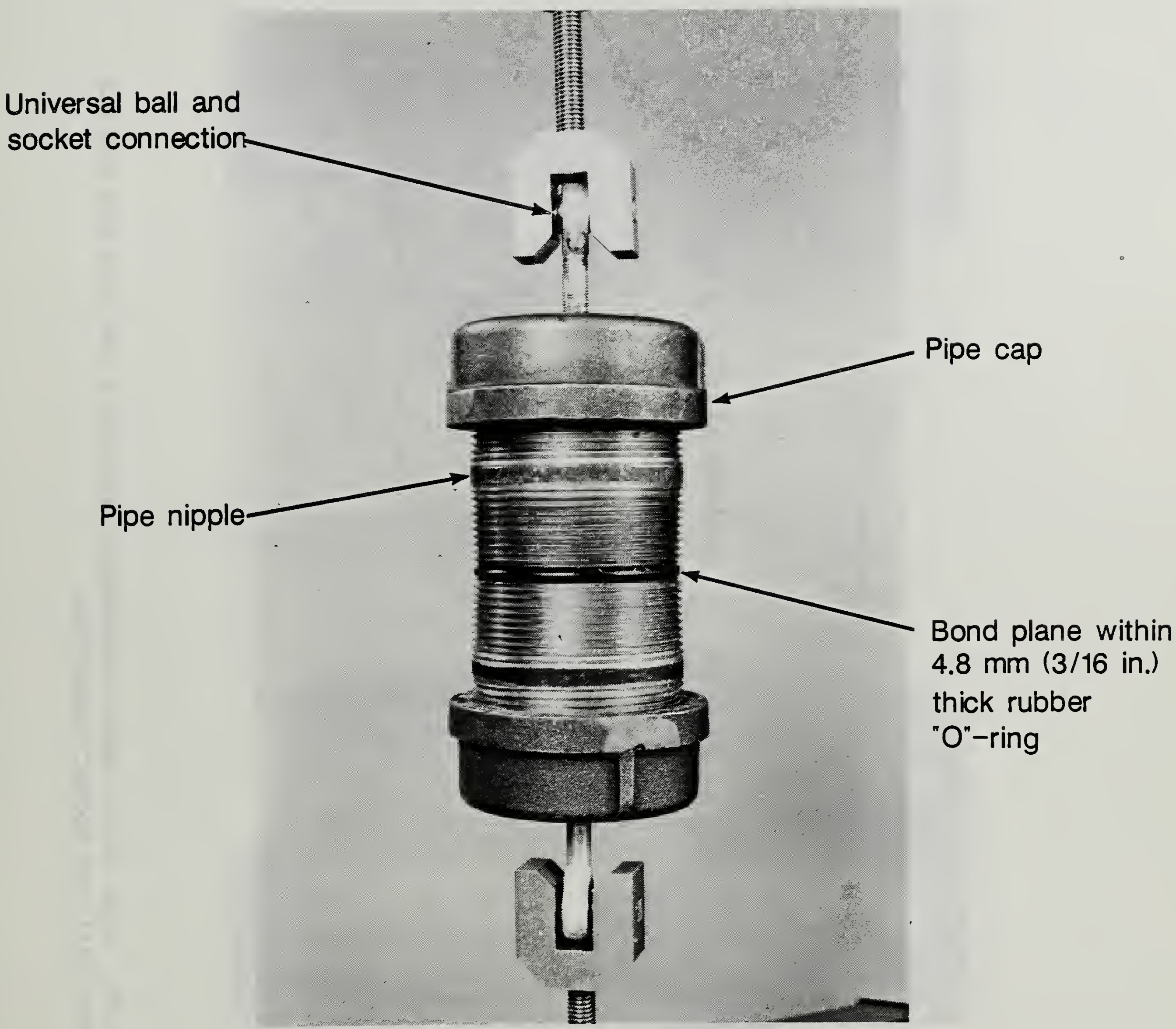

Figure 2a. Pipe-nipple grip test setup. Pipe caps screwed on pipe nipples, then installed in screw-driven testing machine, and pulled in tension. Two pipe nipples were used: one bonded to the base concrete and the other bonded to the repair material (Appendix A). A rubber "O"-ring provided about 4.8 mm (3/16 in.) spacing between the pipe nipples at the bond plane. A universal ball and socket connection was used at each end of the specimen - see figure 2b for details.

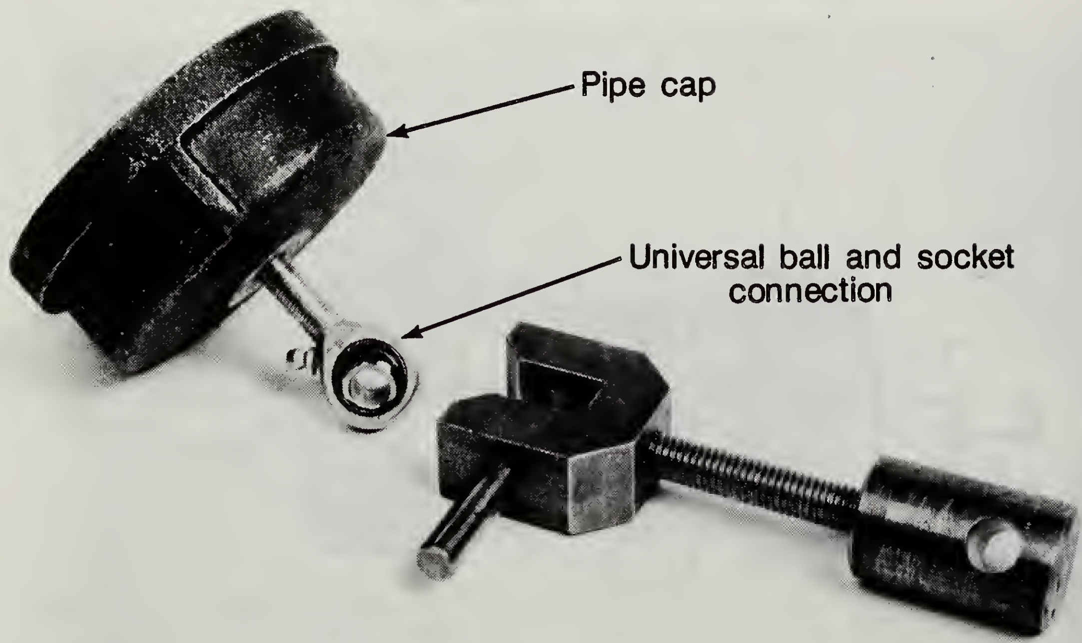

Figure 2b. Pipe nipple grip attachments, including one pipe cap and its universal ball and socket connection.

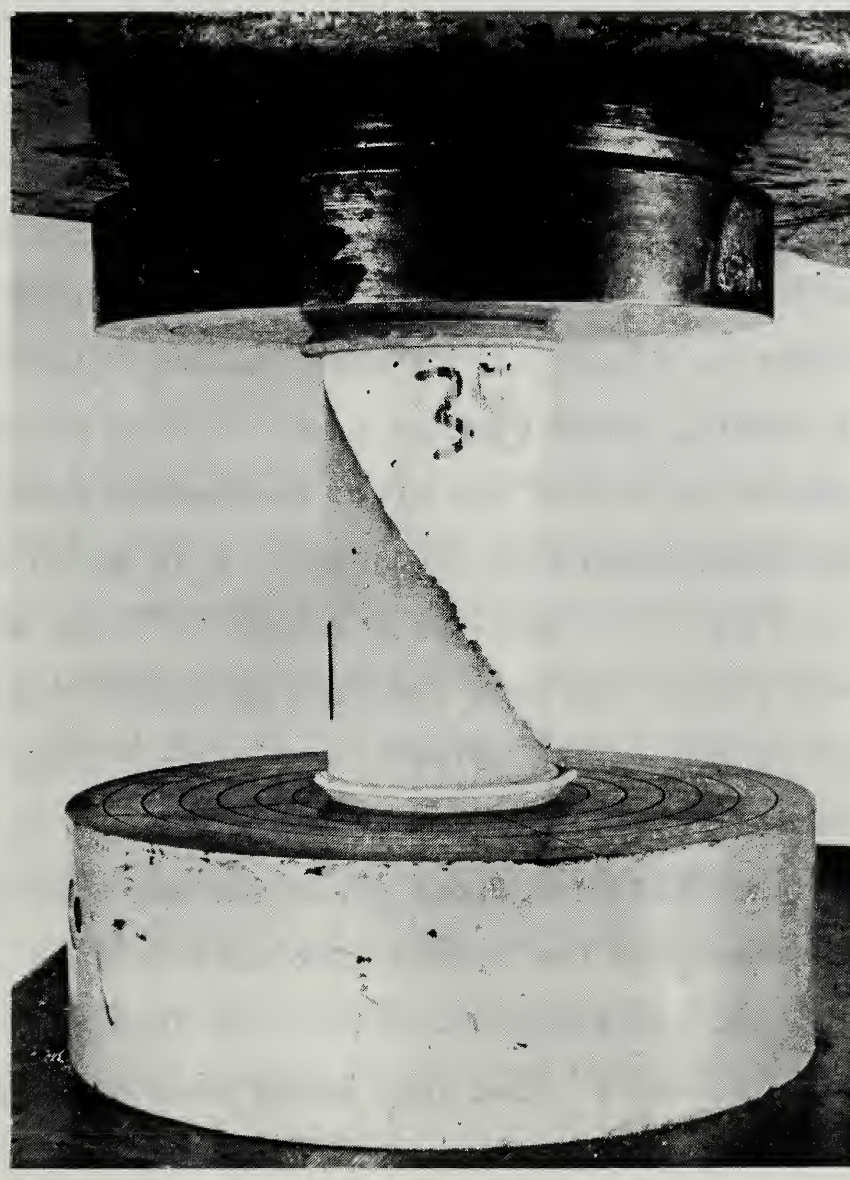

Figure 3. Slant shear specimen being compressed. One half of the specimen is base portland cement concrete and the other half is repair material.

APPENDIX A . PROCEDURE[o] FOR PREPARATION OF PIPE NIPPLE GRIPS SPECIMENS USED IN UNIAXIAL TENSILE BOND STRENGTH TEST METHOD

I. Method Used to Bond Base Concrete to a Nominal 76 mm (3 in.) Inside Diameter, Black Steel, Pipe Nipple

The arrangement used to bond the base concrete to a nominal 76 mm (3 in.) inside diameter by 76 mm (3 in.)-long, black steel, pipe nipple is shown in figure A1. A flat, smooth, glass plate was placed on a smooth, level working area. A thin polyethylene sheet was placed on top of the glass surface to prevent any excess epoxy from bonding to the glass. A 76 mm (3 in.) inside diameter x 4.8 mm (3/16 in.)-thick rubber "O"-ring was placed over the sawn end of the base concrete cylinder (figure A1) and that end was placed on the polyethylene sheet. (The lateral surface of the 76 mm (3 in.) diameter by 76 mm (3 in.) long base concrete cylinder had been wiped clean and had been air dried to insure good bonding to the epoxy. The sawn surface of the concrete cylinder was perpendicular to the longitudinal axis of the concrete cylinder.) Then four steps were performed in the following order:

1. A wax seal was applied completely around the "O"-

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[o] Appropriate safety measures need to be followed, including protection from acetone and the epoxy resin and its curing agent.

ring-polyethylene interface to prevent any excess epoxy from contacting the sawn concrete surface (which was to be bonded to the repair material). The wax was applied in its molten state and allowed to solidify by cooling to room temperature.

2. A silicone rubber adhesive (G.E. RTV 108) seal was applied completely around the "O"-ring-concrete interface to insure that excess epoxy would not contact the sawn surface of the base concrete.

3. The inside surface of a nominal 76 mm (3 in.) inside diameter[p], black steel, pipe nipple was cleaned with acetone to provide good bonding to the epoxy. Its entire inside surface was then coated liberally with epoxy (Shell Oil Co.: 3 parts by mass EPON 828 epoxy resin to 1 part by mass Shell V-25/V-125 curing agent for epoxy resins). Sufficient epoxy was applied so that excess epoxy would pond between the top (non-sawn end) of the base concrete cylinder and the pipe nipple after the pipe nipple was placed over the base concrete cylinder (see next step).

4. To insure that the epoxy made complete contact with

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[p] The inside diameter of the pipe nipple was slightly greater than the 76 mm (3 in.) diameter of the base concrete cylinder.

the base concrete cylinder's lateral surface, the pipe nipple was slowly and gently pushed down over the base concrete cylinder while turning the pipe nipple until it contacted the "O"-ring (figure A1). The inside diameter of the pipe nipple was large enough to fit over the base concrete cylinder and yet close enough in size to insure that the longitudinal axis of the concrete cylinder was aligned with the longitudinal axis of the pipe nipple. In some cases, after having placed the pipe nipple (with epoxy) over the base concrete, it was seen that the pipe nipple diameter was a little too large to provide good alignment. In these cases, several thin pieces of wire, fitted between the pipe nipple and the lateral surface of the base concrete and running parallel to the longitudinal axis of the pipe nipple, were used to insure that the longitudinal axes of the base concrete cylinder and the pipe nipple were aligned. The wires were inserted immediately after the pipe nipple was placed over the base concrete cylinder and were spaced equally around the circumference of the base concrete cylinder.

II. Mounting a Nominal 76 mm (3 in.) Inside Diameter Pipe Nipple to Cast and Hold the Repair Material

After the epoxy in the base concrete-pipe nipple assembly (Part I. above) had cured for at least four days at room temperature and had attained the necessary strength to prevent slippage during testing, the following steps were performed:

1. The base concrete-pipe nipple "O"-ring assembly (Part I. above) was removed from the polyethylene sheeting and was inverted so that the sawn surface of the base concrete was facing upward.

2. An empty, nominal 76 mm (3 in.) inside diameter, black steel pipe nipple (inside surface of pipe nipple had been cleaned with acetone to assure good bonding of the repair material to the pipe nipple) was seated on the "O"-ring and on the sawn surface end of the base concrete. The empty seated pipe nipple was aligned with the pipe nipple containing the base concrete and maintained in alignment by taping with duct tape; splints can be used, if necessary, to align and hold both pipe nipples. After the repair material had been cast into the empty pipe nipple and had cured, the duct tape (and splints, if used) was removed prior to testing.

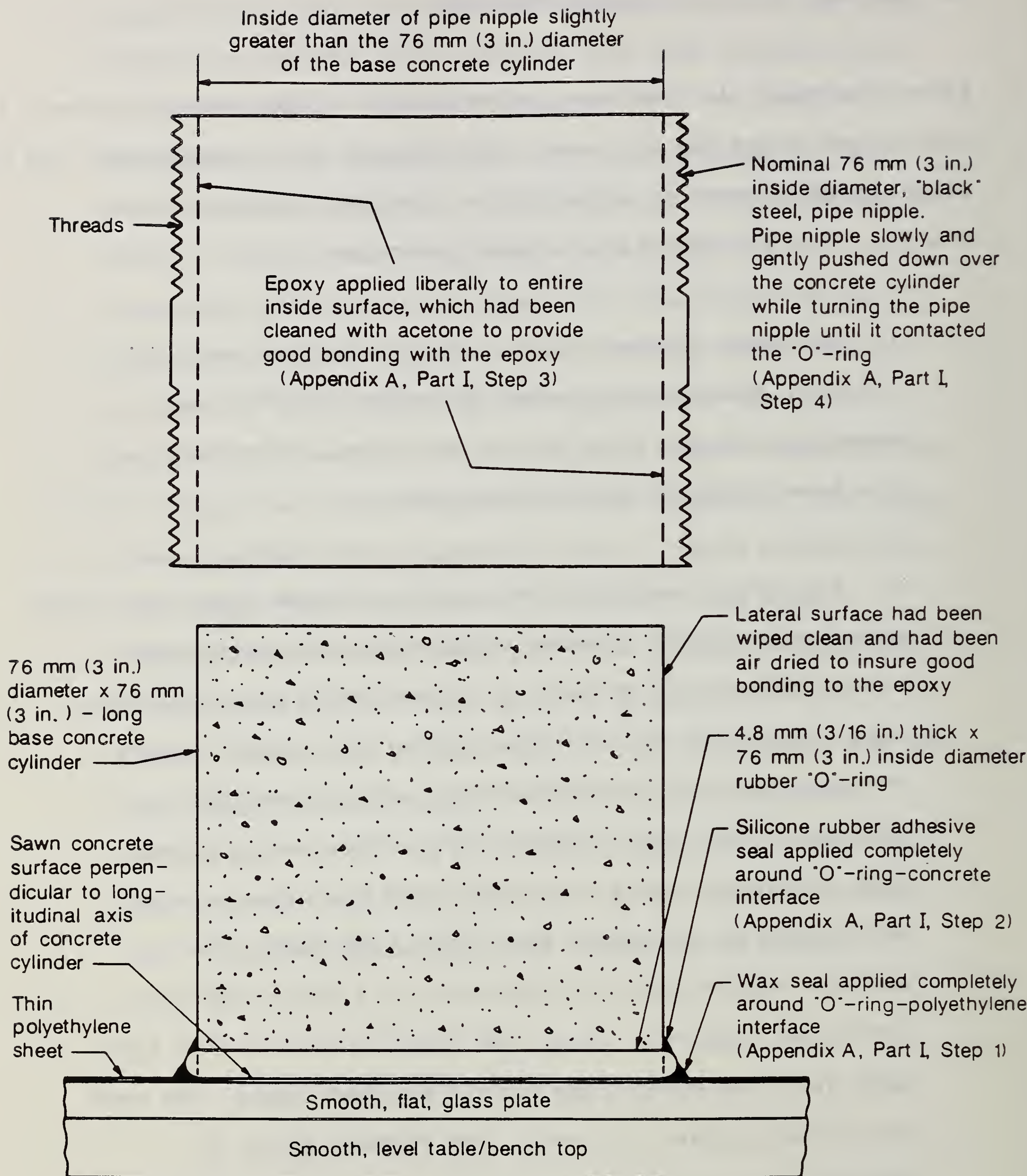

Figure A1. Sketch of setup for method to bond a nominal 76 mm (3 in.) inside diameter, black steel pipe nipple to a 76 mm (3 in.) diameter by 76 mm (3 in.)-long base concrete cylinder using an epoxy-resin adhesive. See Appendix A, Part I for further details.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Three bond strength test methods were evaluated for screening and selecting repair materials used in overlaying and patching portland cement concrete. Bond strengths of three repair materials to base concrete were investigated using two uniaxial tensile bond strength test methods and a slant shear bond strength test method. The differing strengths of the repair materials caused different failure patterns, which had to be considered in the analyses of the failure stresses.

Substantial differences in the failure stresses of the uniaxial tension and slant shear test methods were attributed to their different geometries and loading conditions. These differences emphasized the need to select test method(s) with geometry and loading conditions which are anticipated for the in-service repair material.

For the two higher strength repair materials investigated, the relative precision (repeatability) of the slant shear and one of the uniaxial tensile test methods (pipe nipple grips) were comparable and relatively good (coeffiecient of variation values were about 5%). It was concluded that both the slant shear test method and the pipe nipple grips uniaxial tensile test method are promising methods for screening and selecting repair materials of the type investigated (portland cement concrete or latex-modified concrete) for overlaying or patching portland cement concrete.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

overlaying, patching, portland-cement concrete, repair materials, slant shear bond strength, test method, uniaxial tensile bond strength

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