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Application of Pulloff Test to Assess the Durability of Bond between New and Old Concrete Subjected to Deicer Salts

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Synopsis: A test method, which uses pull-off test and partial coring techniques, was developed in this study. This test method is particularly suitable for assessing the durability of bonding new to old concrete subjected to freeze-thaw cycling and exposed to deicing salt. This test method also combines bond evaluation and ASTM C-672 test (Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals) into one test method. Laboratory experimental research investigated important factors which influence the test results and their scatter. Test results show that this test method is very promising.

Keywords: bond (concrete to concrete); deicers; durability; freeze thaw durability; patching; pavements; pullout tests; scaling

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INTRODUCTION

As the interstate highway system in the United States nears the end of its design life, maintenance and rehabilitation has become more critical. The deterioration of highway pavements and bridge decks poses many serious durability problems. Repairs may be confined to small areas in the upper portion of the pavement or may be a full thickness repair in a small area or may be an overlay of the existing concrete. In many instances, it is most economical to use a thin concrete overlay repair. Recent research indicates the durability of thin concrete overlays is generally related to the durability of the bond between the old and the new repair concrete, not to the durability of the repair concrete [1]. The deterioration of bond with time may be caused by freeze-thaw cycling, and may be accelerated by the application of deicer salts. Laboratory studies of such bond loss is seriously lacking, perhaps due to the lack of available test methods. The pull-off test, along with partial depth coring, is frequently used for testing the bond strength between new and old concrete in the field, but little research has applied it to laboratory studies. This paper presents a pull-off test method that is particularly suitable for assessing the bond of new to old concrete subjected to freeze-thaw cycling and exposure to deicing salts. This test method can also combine bond evaluation and deicer scaling resistance into one test method.

With the developed test method, laboratory experiments were conducted to investigate a number of important factors which influence the test results and including the surface preparation of old concrete base prior to

overlay, testing either from the top surface (new concrete) or bottom surface (old concrete), depth of coring holes, deicing salt application and freeze-thaw cycling. Test results show that this test method effectively assesses the durability of bond between new and old concrete.

RESEARCH SIGNIFICANCE

Application of deicer salt on highway pavements and bridge decks is common in many states in the United States. Damage due to deicer salt is one of the most important durability problems. There is no available ASTM standard test method for assessing the durability of bonding of new to old concrete subjected to freeze-thaw cycling and exposed to deicing salt. Development of such a test method is needed. The test method presented here, provides a measure of the durability of bond between two different concretes exposed to freeze-thaw and deicer salt.

LITERATURE REVIEW

There are many kinds of test methods used to evaluate the bond strength between two different concrete materials, including direct tension, indirect tension, direct shear, shear-compression and pull-off methods. A representative test from each of these methods is shown in (Fig. 1).

The pull-off method is a relatively new bond test compared with the other four methods. The first modern development of the pull-off concept for strength testing was undertaken at Queens University, U.K. in the 1970's [2]. With the use of partial coring technique, a pull-off test is particularly suitable for the bonding evaluation between old and new concretes. It can more accurately represent real site conditions and more precisely assess in-situ bond strength than any of the other four test methods. Due to these two factors, the pull-off test has been increasingly used in field conditions during the last two decades [3, 4, 5, 6, 7]. On the contrary, very few test results of pull-off tests in laboratory conditions [8] have been published.

Reference [9] gives the key details of eleven types of proprietary pull-off test equipment, which are illustrated and whose features are compared. The compared features include manufacturer, model, dolly, adhesive, reaction frame, load application, load measuring and cutting/coring.

General procedure of performing a pull-off test can be described as follows:

(1) Surface preparation of "old concrete" base (to be covered by "new concrete"), using various techniques;
(2) Application of "new concrete" overlay to "old concrete" base;
(3) Curing of "composite" sample, using defined curing methods;
(4) Marking and preparing area where the loading disc is to be epoxied;
(5) Epoxing disc onto the sample;
(6) Partial coring around the disc, perpendicular to the planed surface;
(7) Attaching load frame to disc and pulling the disc against a centered counter pressure bearing on the sample until the maximum pull force is reached;
(8) Recording the failure load and the mode of failure.

MATERIALS

A concrete satisfying Connecticut Department of Transportation Requirements [10] for Class "F" was used as "old concrete". Normal Type I-II Portland cement was used in all "old concrete" mixes. "New concrete" consisted of a common patching material used in Connecticut. It was a water activated repair cement, a blend of Portland cement and gypsum (calcium sulphate). Although this gypsum based material typically is only used for "temporary" repairs, sometimes "temporary" becomes "long term," and the ConnDOT had interest in studying this material under exposure to deicing salts. As part of the overall research program (not reported here), three different types of repair concretes were studied.

Due to the specimen sizes tested, the coarse aggregate was a 3/8 in. (9.5 mm) maximum trap rock, a basaltic rock from a local quarry. The fine aggregate was obtained from local gravel plant. Both coarse and fine aggregates met the Connecticut Department of Transportation (ConnDOT) requirements for gradation. All aggregates were used oven dry. Their properties are listed in Table 1 and Table 2.

The "old concrete" mix was designed as Class "F" concrete used in bridge decks and pavements. The ConnDOT requirements are:
(1) Minimum 28-day compressive strength, f'c=4,000 psi (27.6 MPa);
(2) Maximum water/cement ratio=0.44;
(3) Minimum cement content=658 lb. per cubic yard (390 kg/m^3).

The Portland Cement Association recommended an air content 7.5%±1% for all pavement concrete with 3/8 in. (9.5 mm) maximum size aggregate and exposed to freezing and thawing, regardless of climatic conditions [11]. The 7.5% air content was accomplished by using an air-entraining admixture. The admixture, a mixture of organic salts in an aqueous solution, complied with ASTM C 260 requirement. After several trial batches, the final mix proportions were developed (Table 3). This final mix produced concrete with a slump of approximately 3$^1/_2$ in. (90 mm). When "old concrete" was cast, at least 6 cylinders were also made to monitor the consistency from batch to batch. Three cylinders were tested at the age of 14 days and 3 cylinders were tested at the age of 28 days.

The patching cement manufacturer's recommended mix, which yields 1.07 cu. ft. (0.03 m^3) concrete, is 50 lbs. (22.7 kg) cement, 50 lbs. (22.7 kg) fine aggregate, 50 lbs. (22.7 kg) coarse aggregate and 14.6 lbs.(6.62 kg) water. Using this mix with oven dry aggregates resulted in a too dry mix. To attain adequate workability, additional water was added to the subsequent mixes to account for the absorption of the aggregates. These mixes were very workable. The adopted mix proportions for "new concrete" are listed in Table 4. Six cylinders were cast with each batch of new concrete and were air-cured.

EXPERIMENTAL PROCEDURES

Test Equipment

A commercially available bond-test equipment [12] was used in this study. It had the following characteristics:
(1) Design for maximum drill depth of 7 in. (180 mm);
(2) Steel pull-off disc: 3 in. (76 mm) in diameter and 1.2 in. (30.5 mm) thick, epoxied to concrete;
(3) Pull-off machine: hydraulic with capacity of 0 - 5.6 kip (0-25 kN);
(4) Loading rate: 22 - 110 lb/sec (0.1 - 0.5 kN/sec).

Fig. 2 shows the test apparatus.

Test Specimens

As mentioned before, this test method is characterized by combining bonding evaluation between two different concretes and scaling resistance of concrete surface exposed to deicer chemical into one test method. Selection of the size and shape of composite deicer specimens are based on the following guidelines:
(1) ASTM C-672-94 -- Specimens shall have a surface area of at least 72 in^2 (0.0465 m^2) and be at least 3 in. (76 mm) in depth [13].
(2) Core Location -- British Standard BS 1881, Part 207, which describes a near-to-surface pull-off test, states that centers of core test positions should be at least two block or core hole diameters apart and one diameter from an edge [14].
(3) Convenience for fabrication and moving test specimens -- Composite deicer

specimens and the dike along the perimeter of the top surface of the specimens should be easily fabricated. During the deicer test, our test specimens were removed daily from the freezer, thawed in laboratory environment, and then put back in the freezer. As all handling was done manually, it was desirable to make specimens as small as possible.

(4) Area-efficiency of the specimens -- The area-efficiency, defined as the total cross-sectional area of core holes divided by the specimen top surface areas, is a good index to evaluate the effectiveness of specimen size.

(5) Core depth -- ½ in. (12.7 mm) below bond line, based on manufacturer's recommendation of 0.4 to 0.8 in. (10 to 20 mm).

Rectangular specimens were chosen for convenience of fabrication. Four coring holes on a single specimen yield a good area-efficiency ratio. The composite deicer specimens were 14 in. x 14 in. x 4½ in.(356 mm x 356 mm x 114 mm), 2½ in. (63.5 mm) depth of "old concrete" base and 2 in. (50.8 mm) depth of "new concrete" overlay (Fig. 3). Two people were generally needed to move a specimen into or out of the freezer.

Three batches of "old concrete" bases were made. Each batch of bases was used for one of the test series C, D, and E, respectively, in order to make composite specimens. Four separate batches of "new concrete" were made, 1 batch formed each test series B, C, D and E.

After casting, the "old concrete" bases and cylinders were covered with plastic sheeting, demolded at 1 day of age, immersed in saturated lime water for 6 days, then air cured in a storage room until the "new concrete" overlays were applied. The ambient temperature in the storage room was 73 ± 5 °F and the humidity ranged from 50% to 60% (no effort was made to control humidity).

The "old concrete" surface was prepared by sandblasting or grinding prior to casting the overlay. The "new concrete" overlays were applied when the age of the "old concrete" bases was a minimum of 2 months. The base concrete surface was dry prior to placing the "new concrete". Our preliminary testing with this material and this test method showed that higher bond strengths were achieved using dry rather than wet or damp surfaces. Similar results have been reported by others [15,16]. After casting the "new concrete" overlays, the composite specimens and "new concrete" cylinders were left in the molds uncovered until the next day. The manufacturer's instruction recommends this material be air-cured. At 1 day of age, the specimens were demolded and air-cured in the laboratory until testing. The ambient laboratory temperature was 73 ± 5 °F and the humidity ranged from 30% to 60%. Table 5 summarizes the types and the number of specimens for all test series.

Test Series

Series A - Material Strength--This test series was designed to develop the compressive strength vs age relationship for both "old concrete" and "new concrete." Eighteen cylinders of old concrete and 18 cylinders of new concrete were cast. Old concrete specimens were wet-cured for the first 7 days and then air-cured until tested. New concrete specimens were air-cured until tested.

Series B - Coring Depth--This test series was designed to study the effect of the different depths of coring holes on the results of pull-off strength. Three solid specimens of "new concrete" and 6 cylinders were made. All specimens were air-cured until tested at the age of 28 days. Pull-off testing was performed from the bottom casting surface of the solid specimen. Each specimen had four coring holes with depth of holes of ½, 1, 2 and 3 in. (13, 25, 51 and 76 mm) respectively. Three cylinders were tested at the age of 7 days and the other 3 were tested at the age of 28 days for compressive strength. The "new concrete" cylinders of test series C, D, and E were cured and tested in the same way as those in this test series.

Series C - Pull Location--This test series was designed to study how the measured pull-off strength of composite deicer specimens is affected when the pull-off test is done from the bottom of the "old concrete" base or from the top surface of "new concrete" overlay. Although "in-situ" testing would be done only from the top surface, laboratory testing can be done from either the top or bottom of the specimen. Testing from the bottom surface of old concrete is easier because testing from the top surface of new concrete is difficult, or even impossible if the top surface is deteriorated due to salts. All specimens used the same batch of "old concrete", same batch of "new concrete", same surface preparation and same curing methods. Sand-blasting was used for the surface preparation due to its simplicity. Twelve composite specimens and 6 cylinders were cast. The composite specimens were air-cured until tested at the age of 28 days. Six specimens were tested from the bottom of the "old concrete" base. The other 6 specimens were tested from the top surface of "new concrete" overlay.

Series D - Surface Preparation--This test series was used to study how the pull-off strength between new and old concrete is affected by different surface preparations of "old concrete" bases. Three surface preparation techniques were investigated; sand-blasting, grinding, and grinding/sand-blasting. Nine composite specimens and 6 cylinders were cast for this series. Each group of 3 composite specimens were treated by one of the surface preparation techniques. All specimens were air-cured in laboratory conditions until tested at the age of 28 days. Testing was from the bottom of the "old concrete".

Series E - Deicer Salt and Freeze Thaw--This test series was used to assess how the deicer salt affects the scaling resistance of the "new concrete" surface and the durability of new to old concrete bonding. Twelve composite deicer specimens were cast with the same batch of "old concrete", same batch of "new concrete", same surface preparation (sand-blasting) and same curing methods. Six specimens were air-cured in laboratory until testing (3 were tested at the age of 14 days which was the beginning of deicer test, and 3 were tested at the age of 84 days which corresponded to the end of 50 freeze-thaw cycles of ASTM C 672-92). Six specimens were air-cured in laboratory for 14 days prior to being subjected to the deicer test. This deicer test conformed to ASTM 672-92 except that the laboratory relative humidity was 30% to 60% instead of 45% to 55%. The specimens subjected to freeze-thaw cycles with the deicer salt solution on top of the "new concrete" surface were kept frozen during the weekends. Therefore, only 5 cycles could be achieved each week. Three of the 6 specimens were tested at 25 cycles (49 days) and the other 3 specimens were tested at 50 cycles (84 days).The surface scaling due to deicer salt was rated for every 5 cycles.

ANALYSIS OF TEST RESULTS

Analytical Method

Statistical analysis by ANOVA [17], the analysis of variance, was used to interpret the effects of the above mentioned factors on the test results. The ANOVA can determine whether observed differences among compared sample test results really exist or if the differences can reasonably be attributed to chance. All ANOVA tests were performed by personal computer spreadsheet software using the confidence limits of 95% ($\alpha=0.05$).

Compressive Strength

The compressive strength vs age curves for both "new" and "old" concrete are shown in Fig. 4 from the test series A. Compressive strengths also were determined at age of 28-day from the other test series. The compressive strength of old concrete at 28-day varied from 5930 psi (40.9 MPa) to 6370 psi (43.9 MPa) for the 4 test series, the average strength was 6090 psi (42.0 MPa) and the coefficient of variation was 3.2%. The compressive strength of new concrete at 28-day varied from 7710 psi (53.2 MPa) to 8480 psi (58.5 MPa) for the 5 test series, the average strength was 8090 psi (55.8 MPa) and the coefficient of variation was 3.7%. The old and new concrete were very consistent.

For composite specimen tests the old concrete was typically about 3 months of age with a compressive strength of about 6,800 psi (47 MPa), and the new concrete was typically 14 - 28 days old with a compressive strength of about 7,000 - 7,700 psi (48 - 53 MPa), about 10% higher than the old concrete.

Failure Modes of Cores

There were five possible kinds of failure modes; (1) failure on epoxy coating, (2) failure in "old concrete", (3) failure in "new concrete", (4) bond failure at interface or (5) combination of modes. Only Type (2) (3) (4) were seen in this study (Fig. 5). The pull-off test of composite specimens really gives an estimate of the minimum bond between the two layers. If the failure occurs at the interface, the pull-off strength is the bond strength. If the failure occurs in either the new or old concrete, it can be concluded that the bond strength is at least as high as this pull-off strength.

Depth of Coring Hole

The pull-off strengths of the solid specimens of test series B are presented in Table 6. For this test series, the only variable was the depth of hole. Each specimen was used to provide one pull-off test at each depth level. The average values of the pull-off strength performed on 4 different depths of holes were very close. ANOVA tests yield no significant difference between the pull-off strength performed on the 4 different depths of holes (Table 11). However, less failures were observed in the top thin layer with ⅛ to ½ in. (3 to 12.7 mm) of concrete and coarse aggregate remaining bonded to the disc than on the bottom of hole; 3 of 12 failures in the top thin layer and 9 of 12 failures on the bottom of holes. Because of the limited test specimens, it is not clear whether or not the depth of hole has a significant effect on the failure mode. Three inch depth of hole was used for the subsequent test series.

Test Performed on Top or Bottom Surface

The pull-off strengths of test series C are presented in Table 7. This test series only had one variable; test performed from the old concrete (bottom surface of specimen) or from the new concrete (top surface of specimen). All specimens used same batch of old concrete and new concrete, same surface preparation, and same curing methods. ANOVA tests yield no significant difference between the pull-off strength performed on the bottom surface of old concrete (429 psi, or 2.96 MPa) or the top surface of new concrete (416 psi, or 2.87 MPa) (Table 11). Pull-off tests performed on the bottom of the old concrete gave more consistent results than on the top of new concrete. Although pull-off tests are only performed from the top surface of new concrete in field conditions, test results confirm that testing from the bottom surface of old concrete produces similar results to testing from the top surface of new concrete in laboratory conditions.

Required Test Specimens and Accuracy of Estimating the Mean Pull-off Strength

The following assumptions were made in order to determine the required sample size for estimating the mean:

(1) Using 90 percent confidence, Z=1.65;
(2) Using ±10 percent required range of error, E=10%;
(3) Test results of pull-off strengths from population are normally distributed;
(4) A population coefficient of variation COV=20.7%, based on 24 testing samples from bottom of "old concrete" bases of test series C. Note that this assumed population coefficient of variation is probably a high assumed value. As shown by the later test series data, the coefficient of variation was generally much less than 20.7%.

Therefore, the required number (n) of test specimens for estimating the mean [18] is as follows.

$$n \geq \left[\frac{Z \cdot (COV\ \%)}{E\ \%}\right]^2 = \left[\frac{1.65 \cdot (20.7\ \%)}{10\ \%}\right]^2 = 11.7 \approx 12$$

For the various series tested, the average coefficient of variance was 9.8%. If the population COV is taken as 15%, which is probably a more realistic estimate than the 20.7% used above, then using n=12 testing samples would produce an estimate of pull-off strength that is with ±7.1% of the true value with a confidence of 90%.

$$E\% = \frac{Z \cdot (COV)}{\sqrt{n}} = \pm\frac{1.65 \cdot (15\%)}{\sqrt{12}} = \pm 7.1\%$$

Surface Preparation of Old Concrete

The pull-off strengths of test series D are presented in Table 8. All pull-off tests were performed from the bottom of old concrete bases. This test series only had one variable: surface preparation of old concrete bases prior to new concrete overlays. ANOVA tests indicate no significant difference of the pull-off strength between the surface preparations of grinding or sand-blasting, but significant difference of the pull-off strengths among the three surface preparations (Table 11). Grinding/sand-blasting seemed to increase the pull-off strength. Sand-blasting method is easiest to perform and one person can do it, but grinding needs at least two persons. Grinding produced less bond failures than sand-blasting did. This is Talbot's test results [19]

Deicer Salt

The pull-off strengths of test series E are listed in Table 9. Comparing the pull-off strengths of specimens subjected to deicer salts at 25 cycles with the pull-off strengths of specimens tested prior to beginning of deicer test indicates that deicer salts greatly weakened the new concrete. At 25 cycles, there was no observed surface deterioration of the new concrete, however, all failure occurred in the new concrete. ANOVA tests also show significant difference of the pull-off strength between specimens with (345 psi, or 2.38 MPa) or without (439 psi, or 3.03 MPa) exposure to deicer salts (Table 11). Comparison of the failure modes between the above-mentioned specimens reveals that deicer salts severely deteriorated the new concrete since failure always occurred in the new concrete at 25 cycles.

ANOVA tests also show little significant difference of the pull-off strength between specimens exposed to deicer salts for 50 cycles and 25 cycles (Table 11). However, comparison of the failure modes reveals that further deicer cycles beyond the first 25 cycles may also deteriorate the bond strength at the interface since ⅓ of the failures occurred in bond and ⅔ in the new concrete at 50 cycles vs all of the failures in the new concrete at 25 cycles.

Effect of New Concrete Age

Test results from series E also show the change in pull-off strengths with time. The pull-off strength of specimens without exposure to deicer salts at age of 84 days, decreased by about 10% compared with the strength at age of 14 days. Since most of failure modes at 84 days were in old concrete, it is not clear if the age of new concrete had significant influence on the bond strength at interface or in new concrete.

Comparison of Pull-off Strengths of Different Failure Modes

Compared with other kinds of test methods, one unique feature of the pull-off test is that it can measure the in-situ tensile strength and identify the location and nature of failure. Especially for assessing the bond of old and new concrete, the pull-off test can detect the weakest location of "old concrete", "new concrete" or interface.

Table 10 lists the pull-off strengths of the different failure modes from test series B, C, D, and E. For each test series, the average pull-off strengths of failures

at interface, in "old concrete" or in "new concrete" are given. The pull-off strength
vs. failure mode is also presented in Fig. 6. Test results indicate:
(1) Specimens without exposure to freeze-thaw cycling and deicing salt
(a) The overall mean material tensile strengths of "new concrete" and
"old concrete" are very consistent across all test series.
(b) As expected, the bond interface strength has more scatter since
bond also depends on fabrication techniques as well as material properties.
(c) The overall mean pull-off strengths of all three failure modes are
close, although the compressive strength of "new concrete" was slightly higher
than that of "old concrete" at the time of the composite specimen testing.
(2) The pull-off strengths of "new concrete" and the bond strengths at interface
for specimens with exposure to freeze-thaw cycling and deicing salt are
significantly lower than for specimens without such exposure.

Scaling Resistance of New Concrete to Deicer Salts

ASTM C 672 test results on the scaling resistance of the new patching
concrete from test series E, are listed in Table 12.The composite deicer specimens
were air-cured in the laboratory for 14 days before beginning the deicer test instead
of using ASTM C 672 curing method of 28 days and 50±5% relative humidity.
Visual rating of the surface was recorded at the end of each 5 cycles. After 50
cycles, the scaling rating of new concrete surfaces exposed to deicer salt averaged
3.7 (moderate to severe scaling, coarse aggregate visible over 65~75% of whole
surface) for the three companion specimens.

CONCLUSIONS

The results of this laboratory study indicate that the pull-off test can assess
the durability of bond between new and old concrete subjected to deicer salts. It
can combine bond evaluation and deicer scaling resistance into one test method.
It can detect if the weakest strength is in the old concrete, in the new concrete, or
at the interface. Test results that relate to specific pull-off strengths are obviously
dependent on the materials tested. Materials other then the ones studied here may
show different behavior when subjected to deicer salt exposure. Based on these
test results, the following conclusions can be drawn.

(1) The size of test specimen is very efficient and it satisfies the requirements of both ASTM C-672 and BS 1881, Part 207.

(2) The depth of core, extending ½ in. (12.7 mm) beyond the interface, appears to be adequate

(3) Using the average value of pull-off strength from three specimens (12 cores tested) produced coefficient of variations that varied from 5.1% to 22.9%, but was usually less than 15%.

(4) All three surface preparations used in this study, including sand-blasting, grinding, and grinding plus sand-blasting, are good surface preparation methods.

(5) Testing from the bottom surface of old concrete produced similar results to testing from the top surface of new concrete in laboratory conditions for specimens without surface deterioration due to deicing salts.

(6) Deicing salts reduced the pull-off strength of the patching concrete by 20% after 25 cycles, with all failures occurring in the new concrete, even though at that time there was no observed deterioration on the surface of new concrete exposed to deicer salts. Additional cycling seemed to reduce the bond strength at the interface, with 33% of failures occurring at the interface.

RECOMMENDATIONS

(1) The size of test specimens was selected based on the manual operation of the ASTM C-672 deicer test and the size of the available freezer in our concrete lab. One large specimen, that can contain all tests, may be better, and further study is needed to determine the number of test specimens (drilled cores) to be tested at each time.

(2) Information is needed to correlate the durability of bonding between patching materials and regular pavement concrete tested in laboratory conditions and field conditions.

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REFERENCES

1. Pigeon, M., and Saucier, F., "Durability of Repaired Concrete Structures", *Proceedings of the International Symposium on Advances in Concrete Technology*, Athens, May 11-12, 1992

2. Bungey, J.H., and Madandoust, R., "Factors Influencing Pull-off tests on Concrete", *Magazine of Concrete Research*, 1992, 44, No. 158, pp 21-30.

3. Langlois, M., Pigeon, M., Bissonnette, B., and Allard, D., "Durability of Pavement Repairs: A Field Experiment", *Concrete International*, Vol. 16, No.8, August 1994, pp.39-42.

4. Virginia Department of Transportation (1993b), "Virginia Test Method for Testing Epoxy Concrete Overlays for Surface Preparation and Adhesion". Designation, VTM-92. Richmond, 12pp.

5. Petersen, C.G., Dahlblom, O., and Worters, P., "Bond-Test of Concrete and Overlays", Presented at the International Conference "Non-Destructive Testing in Civil Engineering", The British Institute of Non-Destructive Testing, Liverpool, England, April 14-16th, 1993.

6. Petersen, C.G., "New Bond Testing Method Developed", *Concrete Repair Bulletin*, September 1990, pp 6-8.

7. Hindo, K.R., "In-place Bond Test of Concrete", Presented at the 1987 ACI Annual Convention, San Antonio, Texas, March 22-27, 1987, 12pp.

8. Mathey, R.G., and L.I. Knab, "Unixaial Tensile Tests to Measure the Bond of In Situ Concrete Overlays", National Inst. of Standards and Technology (BFRL), NISTIR 4648, Oct. 1991.

9. McLeish, A., "Standard Tests for Repair Materials and Coatings for Concrete -- Part 1: Pull-off Tests", CIRIA Technical Note 139, 1993.

10. State of Connecticut, Department of Transportation, *Standard Specifications for Roads, Bridges and Incidental Construction, FORM 814*, 1988.

11. Kosmatka, S.H., and Panarese, W.C., *Design and Control of Concrete Mixtures*, 13th edition, Portland Cement Association, 1988, pp. 205.

12. Germann Instruments, INC., *Bond-Test Manual*, 4th edition, November 1992.

13. "Test for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals", C-672 - 92, *Annual Book of ASTM Standards*, Vol. 04.02, 1994, pp.336-338.

14. British Standards Institution, "Recommendations for the Assessment of Concrete Strength by Near-to-Surface Tests," *BS1881*: Part 207: 1992.

15. Beer, G.P., Fowler, D.W., Meyer, A.H., and Paul, D.R., "Laboratory Tests on Selected Rapid-Setting Repair Materials", *FHWA Report TX-84/11+311-2, Research Report 311-2*, Center for Transportation Research, The University of Texas at Austin, February 1984.

16. Macadam, D.S., Fowler, D.W., and Meyer, A.H., "Evaluation of Accelerated Concrete as Rapid-setting Highway Repair Material", *FHWA Report TX-85/4+311-3, Research Report 311-3*, Center for Transportation Research, The University of Texas at Austin, April 1984

17. Devore, J.L., *Probability and Statistics for Engineering and the Sciences*, Brooks/Cole Publishing Company, A division of Wadsworth, Inc., 1982.

18. Tashman, L.J., and Lamborn, K.R., *The Ways and Means of Statistics*, Harcourt Brace Jovanovich, INC., 1979.

19. Talbot, C., Pigeon, M., Beaupré, D., and Morgan, D.R., "Influence of Surface Preparation on Long-Term Bonding of Shotcrete", *ACI Material Journal*, Vol. 91, No.6, December 1994, pp 560-566.

TABLE 1 — PROPERTIES OF AGGREGATES

Property	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity (Oven Dry)	2.88	2.73
Bulk Specific Gravity (Saturated Surface Dry)	2.92	2.75
Absorption	1.29%	0.85%
Fineness Modulus	***	2.73

TABLE 2 — GRADING OF AGGREGATES

Sieve Size	Percent by weight passing individual sieve			
	Coarse Aggregate	ConnDOT Requirement	Fine Aggregate	ConnDOT Requirement
1/2"	100%	100%	***	***
3/8"	99%	85% - 100%	***	***
#4	20.3%	5% - 30%	99.5%	95% - 100%
#8	4.2%	0 - 10%	88.2%	80% - 100%
#16	***	***	69.0%	50% - 80%
#30	***	***	43.5%	25% - 60%
#50	***	***	20.0%	10% - 30%
#100	1.5%	0 - 1.5%	6.9%	2% - 10%

TABLE 3 — MIX PROPORTIONS OF "OLD CONCRETE"

Water/Cement Ratio	0.44
Batch Water	360 lb./cu. yd.
Type I-II Portland Cement	752 lb./cu. yd.
Coarse Aggregate (dry)	1312 lb./cu. yd.
Fine Aggregate (dry)	1465 lb./cu. yd.
Air-entraining Admixture	525 ml./cu. yd.

Note: 1 lb/yd^3 = 0.5933 kg/m^3.

TABLE 4 — MIX PROPORTIONS OF "NEW CONCRETE"

Patching Cement	50 lb./bag
Coarse Aggregate (dry)	50 lb./bag cement
Fine Aggregate (dry)	50 lb./bag cement
Batch Water	15.68 lb./bag cement

Note: 1 lb = 0.4536 kg.

TABLE 5 — LIST OF ALL SPECIMENS

Series	Test Variable	Pull-off Test			Compression Test	
		Composite		Solid	Cylinder	
		Size: 14"x14"x4 ½"			3"x6"	
		w/o Salt	w/ Salt	w/o Salt	"Old"	"New"
A	Compression Strength	***	***	***	18	18
B	Core Depth	***	***	3	***	6
C	Pull Location	12	***	***	6	6
D	Surface Preparation	9	***	***	6	6
E	Salt & Freeze-thaw	6	6	***	6	6

Note: 1 in. = 25.4 mm.

TABLE 6 — COMPARISON OF PULLOFF STRENGTH USING DIFFERENT DEPTHS OF CORING HOLES, TEST SERIES B

Depth of Coring Hole	Spec. #1		Spec. #2		Spec. #3		Average Pull-off Strength (psi)	COV† (%)
	Strength (psi)	Failure	Strength (psi)	Failure	Strength (psi)	Failure		
½"	534	at bottom*	534	at bottom*	345	at bottom*	471	18.9
1"	502	at bottom*	406	at bottom*	486	at top**	464	9.1
2"	502	at bottom*	502	at bottom*	470	at bottom*	491	3.1
3"	470	at top**	502	at top**	502	at bottom*	491	3.1
Ave.	502		486		450		479	

Note: 1 in. = 25.4 mm; 1000 psi = 6.895 MPa.

*Bottom of coring hole.

**Thin layer of 1/8 to 1/2-in.-thick with coarse aggregate on top of coring hole.

†Coefficient of variation of pulloff strengths.

TABLE 7 — COMPARISON OF PULLOFF STRENGTH PERFORMED ON TOP OR BOTTOM SURFACE, TEST SERIES C

(a) Test performed from top surface of new concrete overlay

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number*				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#1	438	470	502	438	462	6.6	(O)	(N)	(O)	(I)
#3	518	502	486	470	494	4.2	(I)	(O)	(O)	(O)
#5	422	281	345	249	324	23.6	(N)	(I)	(I)	(I)
#7	438	265	406	313	356	22.6	(N)	(O)	(N)	(I)
#9	361	422	217	377	344	25.8	(N)	(N)	(I)	(I)
#11	249	345	377	406	344	19.8	(O)	(N)	(N)	(N)
For All 6 Cast Specimens **					387	18.5	Failure at (I) Interface (O) Old concrete (N) New concrete			
For all 24 Coring Holes					387	22.9				
For the 20 Coring Holes***					416	15.9				

Note: 1000 psi = 6.895 MPa.

*Every cast specimen has four test coring holes.

**Strength of cast specimen defined as average strength of its four coring holes.

***Disregard #4 of Cast #5, #2 of Cast #7, #3 of Cast #9, and #1 of Cast #11 because measured strength was so much different from other values.

(b) Test performed on bottom surface of old concrete base

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#2	422	297	377	406	376	6.6	(I)	(I)	(I)	(I)
#4	486	438	486	518	482	6.8	(O)	(I)	(I)	(I)
#6	422	438	393	470	431	7.5	(I)	(O)	(O)	(O)
#8	406	406	438	454	426	5.6	(O)	(O)	(I)	(O)
#10	186*	470	406	454	443*	7.5*	(I)	(O)	(I)	(I)
#12	186*	329	438	486	418*	19*	(I)	(I)	(I)	(O)
For All 6 Cast Specimens					429	8.0	Failure at (I) Interface (O) Old concrete (N) New concrete			
For All 24 Coring Holes					408	20.7				
For the 22 Coring Holes*					429	12.1				

Note: 1000 psi = 6.895 MPa.

*Disregard #1 of Cast Specimen #10 and #1 of Cast #12; big voids seen at interface due to poor casting.

TABLE 8 — COMPARISON OF PULLOFF STRENGTH USING DIFFERENT METHODS OF SURFACE PREPARATION, TEST SERIES D

(a) Sand-blasting only

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#1	470	470	438	438	454	4.1	(O)	(O)	(O)	(N)
#2	438	438	N/A	454	443	2.1	(I)	(O)	N/A	(I)
#3	470	454	438	454	454	2.9	(O)	(N)	(N)	(I)
For All 3 Cast Specimens					450	1.4	Failure at (I) Interface (O) Old concrete (N) New concrete			
For the 11 Coring Holes					451	3.0				

Note: 1000 psi = 6.895 MPa.

(b) Grinding only

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#4	438	406	422	438	426	6.6	(O)	(N)	(N)	(O)
#5	470	502	470	438	470	5.6	(O)	(I)	(O)	(N)
#6	406	438	454	454	438	5.2	(O)	(O)	(N)	(O)
For All 3 Cast Specimens					445	5.1	Failure at (I) Interface (O) Old concrete (N) New concrete			
For the 12 Coring Holes					445	6.2				

Note: 1000 psi = 6.895 MPa.

(c) Grinding and sand-blasting

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#7	470	470	454	438	458	3.4	(O)	(N)	(I)	(O)
#8	502	470	454	470	474	4.2	(O)	(I)	(N)	(N)
#9	486	502	438	502	482	6.3	(N)	(N)	(N)	(N)
For All 3 Cast Specimens					471	2.6	Failure at (I) Interface (O) Old concrete (N) New concrete			
For the 12 Coring Holes					471	4.9				

Note: 1000 psi = 6.895 MPa

TABLE 9 — COMPARISON OF PULLOFF STRENGTH OF SPECIMENS WITH AND WITHOUT EXPOSURE TO DEICER SALT, TEST SERIES E

(a) Specimens without exposure to deicer salt and tested prior to beginning deicer test (age 14 days)

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#1	406	454	438	438	434	4.6	(O)	(O)	(N)	(N)
#3	313	454	422	502	423	18.9	(I)	(O)	(I)	(I)
#5	470	438	N/A	470	459	4.0	(O)	(O)	N/A	(O)
For All 3 Cast Specimens					437	11.1	Failure at (I) Interface (O) Old concrete (N) New concrete			
For the 11 Coring Holes					439	18.5				

Note: 1000 psi = 6.895 MPa.

(b) Specimens without exposure to deicer salt and tested at end of deicer test (age 84 days)

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#7	422	454	438	422	434	3.5	(O)	(O)	(O)	(O)
#9	377	313	345	377	353	8.8	(O)	(O)	(I)	(O)
#11	406	422	377	345	388	8.8	(O)	(O)	(O)	(I)
For All 3 Cast Specimens					392	10.9	Failure at (I) Interface (O) Old concrete (N) New concrete			
For the 12 Coring Holes					392	10.4				

Note: 1000 psi = 6.895 MPa.

TABLE 9 (CONTINUED)

(c) Specimens subjected to deicer salt and tested at 25 cycles (age 49 days)

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#2	345	345	345	377	353	4.5	(N)	(N)	(N)	(N)
#4	361	281	345	329	329	10.5	(N)	(N)	(N)	(N)
#6	361	345	345	361	353	2.6	(N)	(N)	(N)	(N)
For All 3 Cast Specimens					345	6.9	Failure at (I) Interface (O) Old concrete (N) New Concrete			
For the 12 Coring Holes					345	4.0				

Note: 1000 psi - 6.895 MPa.

(d) Specimens subjected to deicer salt and tested at 50 cycles (84 days)

Cast Spec. No.	Pull-off Strength (psi)						Failure Mode			
	Coring Hole Number				Average	COV	Coring Hole Number			
	#1	#2	#3	#4		(%)	#1	#2	#3	#4
#8	313	281	345	377	329	12.6	(N)	(N)	(N)	(N)
#10	361	281	345	313	325	10.9	(I)	(I)	(I)	(I)
#12	313	345	377	377	353	8.7	(N)	(N)	(N)	(N)
For All 3 Cast Specimens					335	10.5	Failure at (I) Interface (O) Old concrete (N) New concrete			
For the 12 Coring Holes					335	4.5				

Note: 1000 psi - 6.895 MPa

TABLE 10 — COMPARISON OF PULLOFF STRENGTHS OF DIFFERENT FAILURE MODES

(a) Without freeze-thaw cycling and deicing salts

Test Series	Test Variables	Failure at Interface		Failure in Old Concrete		Failure in New Concrete	
		No.	Average Strength (psi)	No.	Average Strength (psi)	No.	Average Strength (psi)
B	Depth of Coring	---	---	---	---	12	479
C	Test from Top	8	342	7	416	9	405
	Test from Bottom	13	417	9	445	---	---
D	Sand-blast	3	448	5	457	3	443
	Planning	1	502	7	445	4	430
	Planning/Sand-blast	2	462	3	470	7	474
E	Tested at 14-day	3	412	6	448	2	438
	Tested at 84-day	2	345	10	401	---	---
Overall mean pull-off			418		440		445
Coefficient of Variation			14.2%		5.4%		6.2%

Note: 1000 psi - 6.895 MPa

(b) With freeze-thaw cycling and deicing salts

Test Series	Testing Variables	Failure at Interface		Failure in Old Concrete		Failure in New Concrete	
		No.	Average Strength (psi)	No.	Average Strength (psi)	No.	Average Strength (psi)
E	at 25 cycles	---	---	---	---	12	345
	at 50 cycles	4	325	---	---	8	341

Note: 1000 psi - 6.895 MPa

TABLE 11 — ANOVA TEST RESULTS

Series	Variable		P_{value}	α	F	F_{crit}	Difference[1]
B	Core Depth		0.927	0.05	0.15	4.066	Not Significant
C	Pull Location		0.397	0.05	0.732	4.052	Not Significant
D	Surface Preparation	(2)	0.496	0.05	0.479	4.325	Not Significant
		(3)	0.018	0.05	4.556	3.295	Significant
E	Deicer salt & Freeze-thaw	(4)	8.31e-06	0.05	34.223	4.325	Very Significant
		(5)	0.453	0.05	0.584	4.301	Not Significant

[1] If both $P_{value} < \alpha$ and $F > F_{crit}$ significant difference existed.
[2] Comparison of pulloff strengths between planning and sand-blasting surface preparations.
[3] Comparison of pulloff strengths among all three surface preparations.
[4] Comparison of pulloff strengths of specimens with and without exposure to deicer salts.
[5] Comparison of pulloff strengths of specimens exposed to deicer salts at 25 and 50 cycles.

TABLE 12 — SCALING RESISTANCE TO DEICER SALT (ASTM C 672)

No. of Cycle	ASTM C672 Scaling Rating*	Description of Surface Condition
0	0	No Scaling
25	0	No Scaling
30	0.5	Very Slight Scaling
35	1	Very Slight Scaling
40	2	Slight to Moderate Scaling
45	2.67	Slight to Moderate Scaling
50	3.7	Moderate to Severe Scaling

*Average of three companion specimens.

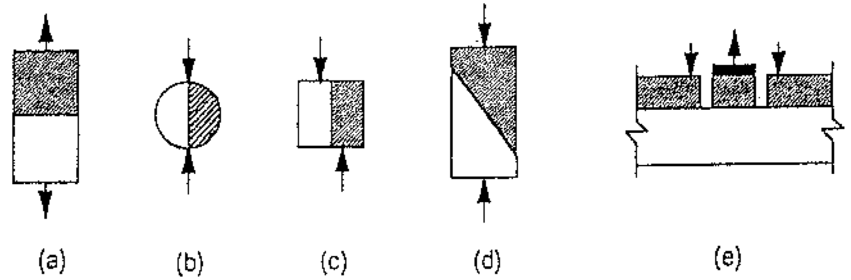


Fig. 1

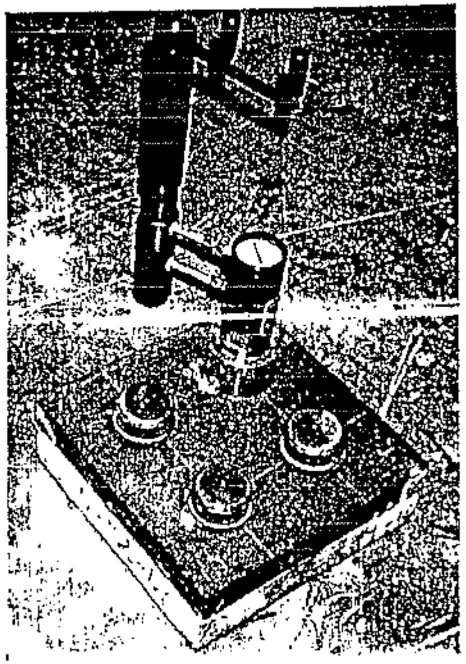


Fig. 2

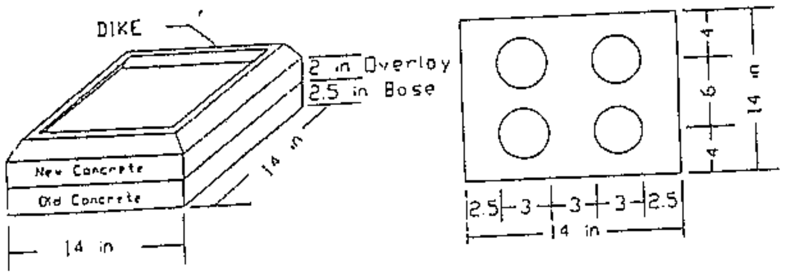


Fig. 3

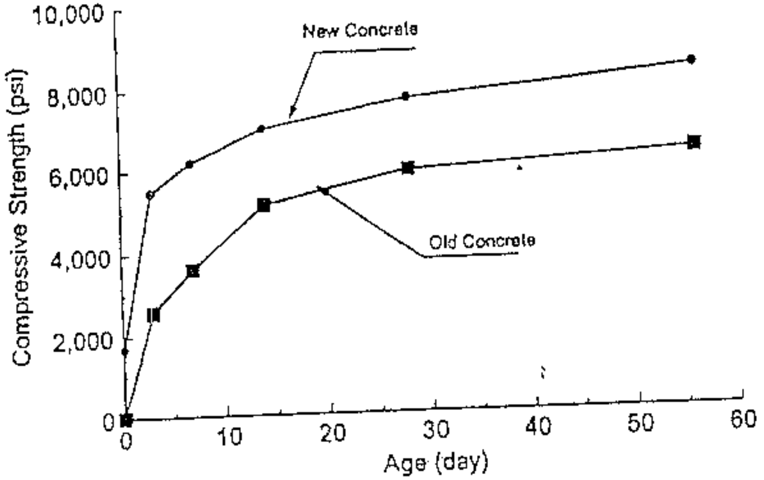
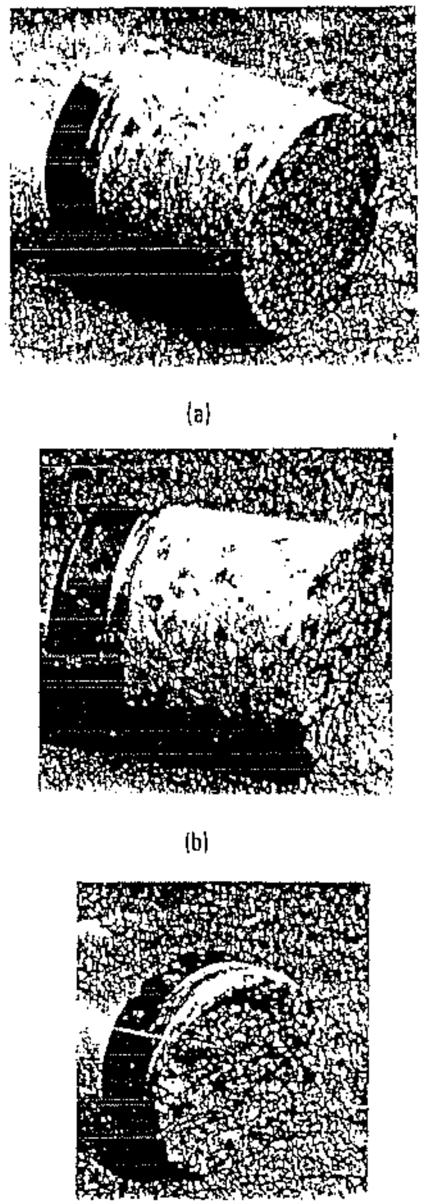


Fig. 4


(a)

(b)

(c)

Fig. 5

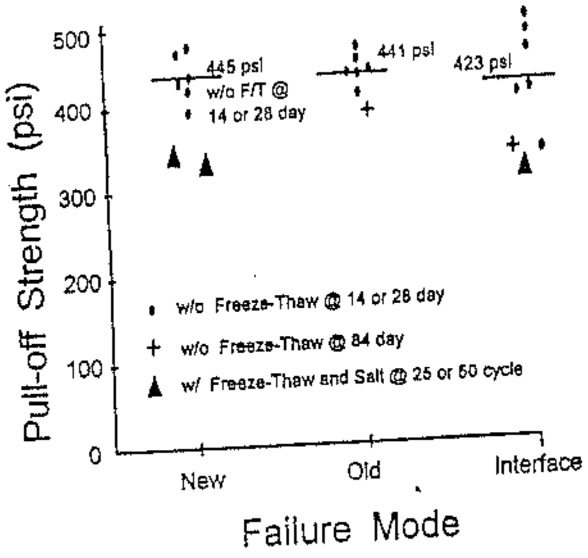

500
400
300
200
100
0
Pull-off Strength (psi)
445 psi
w/o F/T @
14 or 28 day
441 psi
423 psi
● w/o Freeze-Thaw @ 14 or 28 day
+ w/o Freeze-Thaw @ 84 day
▲ w/ Freeze-Thaw and Salt @ 25 or 50 cycle
New
Old
Interface
Failure Mode

Fig. 6