TABLE 6 — HUMIDITY IN SITU AND CALCULATED POROSITIES

Material	Humidity in situ		Suction porosity	Total porosity
	(% of tot vol)	(% of suc vol)	(% of tot vol)	(% of tot vol)
Substrate concrete	9 9 10 10	68 68 73 77	13 13 13 12	15 15 15 15
Mortar No. 2, 1980	17	72	24	27
Mortar, 1986	13	47	24	32

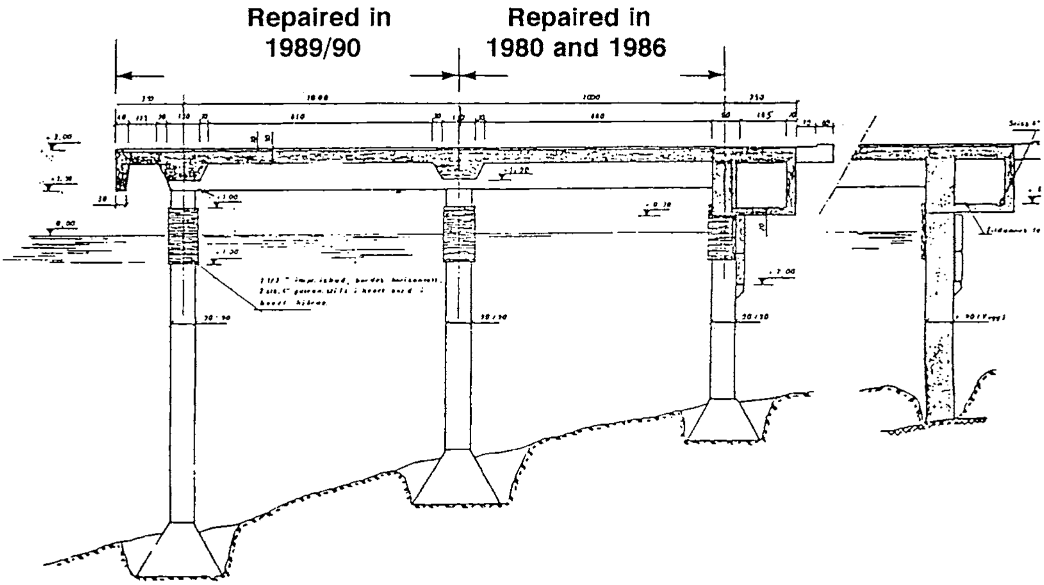

Fig. 1—Cross section of wharf at Norsk Hydro, Karmøy Fabrikker, Norway

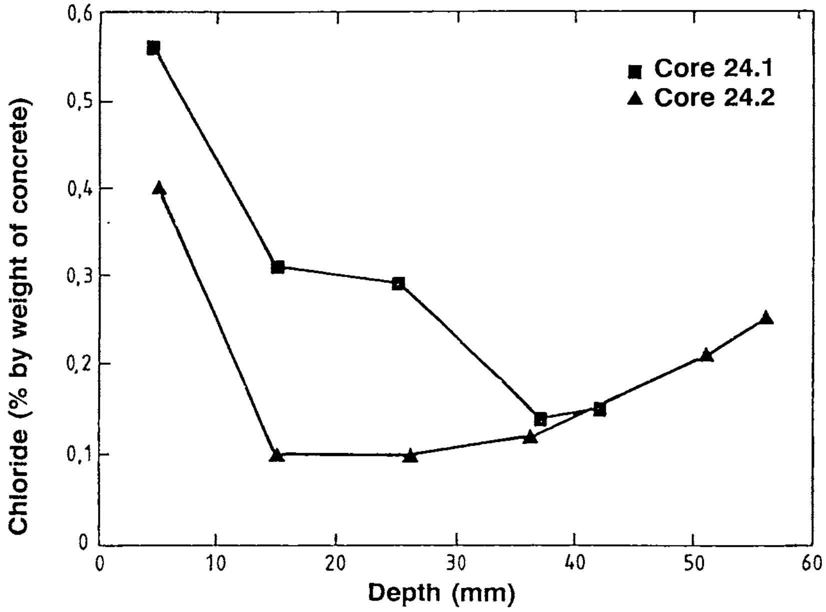

Fig. 2—Chloride profiles in 1986 repair mortar. Core 24.1 closest to the back wall

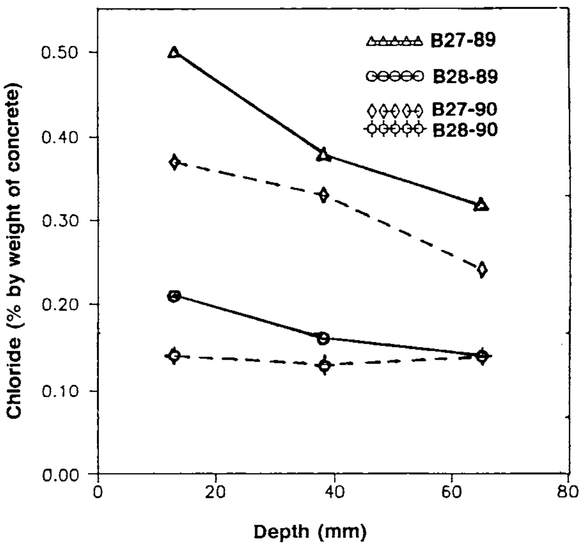

Fig. 3—Chloride profiles in substrate concrete before mortar was applied (B27-89 and B28-89) and five months later (B27-90 and B28-90)

Durability of Concrete for Early Opening of Repaired Highways—Field Evaluation

by M. Nagi, D. Janssen, and D. Whiting

Synopsis: Under the Strategic Highway Research Program (SHRP) contract C-206, "Optimization of Highway Concrete Technology," constructibility and performance of concrete for early opening of highway repairs were evaluated. A variety of concrete mixes using different types of rapid strength cements and admixtures were used for full-depth repair (slab replacement) of concrete pavements and for bridge deck overlays in the states of Ohio, Kentucky, and Georgia.

For pavement applications, eight mixtures having different strength-gain capacity allowing for a variety of traffic opening times ranging from 2 to 24 hours were evaluated. Latex modified concrete with Type III cement and silica fume mixes were used for bridge deck overlays.

Durability evaluation of these mixtures included freeze-thaw resistance, characterization of the air void system and deicer scaling tests, and measurement of chloride permeability. Specimens for these tests were prepared in the field and were subject to standard field curing. Tests were also conducted on cores taken from pavements and overlays at opening time. Freeze-thaw tests on beams were conducted following a modified procedure of method ASTM C 666B using specimens wrapped in towels during the air freeze so as to reduce drying from the surface during the freeze cycle. Follow-up surveys were conducted to examine the performance of these concretes under the effects of environmental exposure and traffic loading.

Test results showed that overlay mixes have excellent freeze-thaw resistance. Latex modified concrete mixes showed moderate scaling using the deicer scaling test. Chloride permeability of cores taken from silica fume overlays were lower than those of latex modified concrete overlays.

Poor freeze-thaw performance of many of the pavement repair mixes indicates that many questions still remain regarding durability of concretes designed for early opening applications. Proper air content and adequate air void systems are necessary, but not sufficient, conditions for obtaining the desired freeze-thaw durability. Microcracking in the concretes may account for some of the poor performance in freeze-thaw testing. The use of calcium chloride should be avoided, as it contributes to reduced freeze-thaw resistance.

Keywords: Air entrainment; bridge decks; cements; concretes; curing; deicers; durability; exposure; freeze thaw durability; highways; latex; pavements; permeability; repairs; resurfacing; scaling; silica fume

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BACKGROUND

Bridge Deck Overlays

The continued deterioration of reinforced concrete bridge decks brought about by chloride-induced corrosion of the reinforcing steel has led to increased use of rigid concrete bridge deck overlays. Other than periodic painting of steel support beams, deck overlays are now perhaps the most common maintenance procedure applied to concrete bridges. By placement of a concrete overlay the riding surface is restored and further penetration of chloride salts into the deck is reduced. In order to meet these objectives the overlays must be strong, must be well-bonded to the underlying concrete, and must have low permeability and good freeze-thaw resistance.

Latex-modified concrete (LMC) overlays are one of the most widely used systems, and have exhibited generally good performance in terms of their ability to reduce chloride penetration. In a study of 132 bridge decks, Bishara (1) reported much lower chloride contents in decks overlaid with LMC than in unprotected decks. Studies by Indiana, Kentucky, and Michigan (2), show equally good performance for LMC. Distress in LMC overlays in Ohio, however, was reported by Abdulshafi, et. al. (3) who attributed problems to ongoing corrosion in the original deck, as well as deficiencies in construction practices. LMC mixtures have been modified to obtain overlays which can be opened to traffic within 24 hours. This has been accomplished through the use of Type III cement and a lower w/c ratio and higher cement content than normally employed in LMC mixes to produce early-opening latex-modified concretes (LMC-III). Published data on the effects of these changes to conventional LMC mixes, however, are limited (4, 5). Further study of such early opening overlays was needed as this would allow traffic resumption on bridges in a much shorter time period after repairs had been completed.

Silica fume concrete (SFC) overlays started to gain interest in the U.S. in the early 1980's. The first SFC bridge deck overlays were placed in Ohio in 1984, and within the next three years eight states had placed SFC in bridges (6). Low permeability and higher bond strength make this material attractive for use in bridge deck overlays. Additions of silica fume have ranged from 5 to 15%, based on cement weight. Laboratory data (7) indicate that reduction in permeability to chloride ions is a function of silica fume addition, the greatest reductions occurring at additions above 10 percent by weight of cement. SFC is very resistant to penetration of chlorides, with laboratory ponding tests carried out over 2-1/2 years (8) indicating that chloride contents at 44 mm depth remained significantly below threshold corrosion levels of 0.8 kg/m^3 over the period of test. Short-term field data (9) are promising, but long-term field performance data are lacking.

Full-Depth Pavement Repairs

The purpose of full-depth repair of concrete pavements is to restore structural integrity and improve rideability of concrete pavements having certain types of distress that cannot be corrected by using partial-depth repairs. Working cracks and badly deteriorated joints are the most common problems that require full-depth repairs or slab replacements (10, 11).

Full-depth repair and slab replacement are used to address several types of distress that occur at or near transverse cracks and joints. These include spalling, D-cracking, failure of joint load transfer devices, slab breakup (corner breaks or diagonal cracks near the joint), and breakup of the slab into several pieces (10, 11). A detailed description of these types of distress is given by Darter, Barenberg, and Yrjanson (10) and the Transportation Research Board (12). The severity of the distress is the main criterion by which the decision to repair is made and repair size is determined. In general, low-severity distress do not require full-depth repair within the first 2 years of their onset.

The materials used in full-depth repairs to-date have predominantly been conventional concrete mixes with high cement content . Typical patch mixes contain between 390 and 558 kg/m^3 of cement. Depending on the required opening time and availability, Types I, II, or III portland cement are used. Opening times can range from 6 to 48 hours after placement, unless an accelerating admixture is used (10). Calcium chloride or other accelerating admixtures are used if early opening of the repair to traffic is desired.

Many States now allow early opening when early opening or "Fast Track" mixtures are used (13). The high-early strength is typically obtained by using a high cement content, low w/c, and accelerating admixtures. A rich, low-water-content mix containing 1 to 2 percent calcium chloride will produce adequate strength and abrasion resistance for opening to traffic in 4-5 hours at temperatures above 10°C (14).

It is now possible to perform full-depth repair of concrete pavements and open the pavement to traffic in 4 hours or less (15, 16). This involves not only the use of Fast-Track mixes, but also rapid techniques for concrete removal and dowel placement. A combination of innovative techniques has been used in New York to make full-depth repairs of concrete pavements overnight on the Long Island Expressway (16). Slab removal by liftout, the use of gang drills, and a Fast Track mix were the key elements that made this possible. Utah used regulated-set portland cement for opening 5 hours after concrete placement (15). Other proprietary products, such as blended cement using alkali-activated alumino-silicates (17), and sulfo-aluminate based cement, have the potential for allowing opening of repairs in less than 4 hours time. High performance concrete mixes developed under SHRP C 205 (18) also have the potential for use when early opening of repairs is required. Evaluation of early opening of repairs made with conventional and proprietary materials including their durability performance was a major focus of this part of this research program.

RESEARCH PROGRAM

Bridge Deck Overlays

For the study of bridge deck overlay applications, two important developments were evaluated. These are the use of Type III cement combined with latex modifiers (LMC-III) in order to achieve early (24 hour) opening of a latex-modified concrete overlay, and the use of silica fume concrete (SFC) overlays to achieve extremely low chloride permeability and hence increase the life of the overlay. Two states were chosen for evaluation of these new overlay systems. Within each state two test sites were selected. Each site consisted of twin bridges, so that LMC-III could be placed on one bridge and SFC on the opposing bridge. This would allow for long-term monitoring on an equivalent exposure basis. Thus, four bridge sites were included in the experiment, with a total of eight test sections. Mixtures used at the four sites are given in Table 1.

Site No.1- US 52 over Twelve Mile Creek, New Richmond, Ohio

Materials selected for the LMC-III mix consisted of: 1) a Type III cement; 2) an angular to rounded natural sand consisting of a mixture of siliceous and calcareous minerals having specific gravity of 2.68, absorption of 1.16 %, and FM of 2.67; and 3) a partially crushed limestone coarse aggregate having a maximum topsize of 12mm with specific gravity of 2.63 and absorption of 2.09% . Latex used was styrene-butadiene latex emulsion .

A Type I cement was used in the SFC mixture. Aggregates were from the same sources used for the LMC-III mix at this site. Admixtures included: 1) Densified Microsilica (compacted powder form); 2) a benzyl-sulfonate based air-entraining agent ; 3) a Type D water-reducer/retarder; and 4) a Type F high-range water reducer. Fresh concrete properties of LMC-III and SFC mixtures are shown in Table 2. Static modulus of elasticity and compressive strength were measured at 7 and 28 days on duplicate 100 X 200 mm cylinders in accordance with ASTM C 459 and C 39 respectively, (see Table 3).

Site No. 2 - Interstate 270 over Raymond Run, Columbus, Ohio

At this site, LMC-III mix materials consisted of: 1) a Type III cement; 2) a subrounded to rounded natural sand, consisting of a mixture of siliceous and calcareous minerals having specific gravity of 2.62, absorption of 1.54 %, and FM of 3.36; and 3) a crushed limestone coarse aggregate having a maximum topsize of 12mm with specific gravity of 2.62 and absorption of 1.96% . Latex used was styrene-butadiene latex emulsion.

A Type I cement was used in the SFC mix. Aggregates were from the same sources used for the LMC-III mix at this site. Admixtures included: 1) silica fume (slurry form); 2) neutralized Vinsol resin air-entraining agent ; 3) Type D water-reducer/retarder; and 4) Type F high-range water reducer. Fresh concrete properties of LMC-III and SFC mixtures are shown in Table 2. Static modulus of elasticity and compressive strength were measured at 7 and 28 days on duplicate 100 X 200 mm cylinders in accordance with ASTM C 459 and C 39 respectively, (see Table 3).

Site No. 3 - Interstate I 265 over KY 22, Jefferson County, Kentucky

Materials selected for the LMC-III mix consisted of: 1)Type III cement ; 2) a subangular to rounded natural sand consisting of a mixture of siliceous and calcareous minerals having specific gravity of 2.60, absorption of 1.40 %, and FM of 2.56; and 3) a crushed limestone coarse aggregate having a maximum topsize of 12mm with specific gravity of 2.71 and absorption of 0.6% . Latex used was a styrene-butadiene latex emulsion.

A Type I cement was used in the SFC mix. Aggregates were from the same sources used for the LMC-III mix at this site. Admixtures included: 1) silica fume (slurry form); 2)an organic-acid salt based air-entraining agent; and 3) a Type F high-range water reducer. Fresh concrete properties of LMC-III and SFC mixtures are shown in Table 2. Static modulus of elasticity and compressive strength were measured at 7 and 28 days on duplicate 100 X 200 mm cylinders in accordance with ASTM C 459 and C 39 respectively, (see Table 3).

Site No. 4 - US 41 over Ky 351, Henderson, Kentucky

The materials for the LMC-III mix at this site consisted of: 1) a Type III cement; 2) an angular to rounded siliceous natural sand having specific gravity of 2.61 and absorption of 1.00 %; and 3) a crushed limestone coarse aggregate having a maximum topsize of 12mm with specific gravity of 2.71 and absorption of 0.7% . Latex used was a styrene-butadiene latex emulsion.

A Type I cement was used in the SFC mix. Aggregates were from the same sources used for the LMC-III mix at this site. Admixtures included: 1)silica fume (compacted powder form); 2) a synthetic air-entraining agent; and 3)a Type F high-range water reducer. Fresh concrete properties of LMC-III and SFC mixtures are shown in Table 2. Static modulus of elasticity and compressive strength were measured at 7 and 28 days on duplicate 100 X 200 mm cylinders in accordance with ASTM C 459 and C 39 respectively, (see Table 3).

Full-depth Pavement Repairs

The materials selected for evaluation covered a range of opening times which could be associated with various types of "early-opening" scenarios. Early opening times for full-depth repair applications now can be considered to lie in the intervals of 12 to 24 hours (certainly an accelerated schedule but not requiring advanced materials) and 4 to 6 hours (a very rapid schedule requiring modified-conventional or advanced materials). In the future, demands for even earlier openings will become pronounced, leading to demands for openings times of 2 to 4 hours even for full depth repairs, something now seen mainly for patching applications. The latter will require highly modified conventional materials or the use of very fast-setting proprietary products.

Materials and concrete mixes were chosen so as to fall within the projected opening times of 12 to 24 hours, 4 to 6 hours, and 2 to 4 hours. Two sites were selected for field evaluations, one a section of I-20 near Augusta, Georgia and the other a section of State Route 2 near Vermilion, Ohio. At the first site three concrete mixes were evaluated. At the second site more sections were made available to the research team, and a total of eight mixes were evaluated.

I 20 Site - Augusta, Georgia

Materials selected for the pavement repair mixes at this site consisted of: 1) Type I and III cements; 2) an angular quartz natural sand having specific gravity of 2.68, absorption of 0.56 %, and FM of 2.62; and 3) crushed siliceous natural gravel having a maximum topsize of 19mm with specific gravity of 2.66 and absorption of 0.5% . Admixtures included: 1) chloride free Type C accelerator; 2) an organic-acid salt based air-entraining agent; 3) Type A water reducer; 4) a Type F (melamine-based) high-range water reducer; and 5) a 40% solution of calcium chloride.

Mixes used for the repairs are presented in Table 4. These were: "Very Early Strength" (VES) concrete developed by the SHRP C 205 investigators (18) with the objective of opening approximately 4 to 6 hours after placement; "Fast Track I" developed originally by Iowa DOT (13) for opening times of 12 to 24 hours, and the mix being used by the contractor on the I-20 repair project, which was designed for opening 4 hours after placement of the last patch. This latter mix was designated "GADOT" mix by the authors. Fresh concrete properties are shown in Table 5. Static modulus of elasticity and compressive strength were measured at 7 and 28 days on duplicate 100 X 200 mm cylinders in accordance with ASTM C 459 and C 39 respectively, (see Table 6).

SR 2 Site - Vermilion, Ohio

Materials selected for the pavement repair mixes at this site consisted of: 1) Type III cement ; 2) proprietary rapid strength gain cementitious materials including blended cement using alkali-activated alumino-silicates (BC) and meeting ASTM C 595 (modified) and sulfo-aluminate based cement (SA) not covered by any ASTM specifications; 3) a sub-angular to rounded natural sand consisting of a mix of siliceous and calcareous minerals having specific gravity of 2.58, absorption of 1.54 %, and FM of 2.62; and 4) an angular, somewhat elongated and bladed crushed limestone having a maximum topsize of 12 mm with specific gravity of 2.60 and absorption of 2.63% . Admixtures included: 1) calcium-nitrite based inhibitor meeting ASTM Type C requirements for set accelerator; 2) synthetic surfactant based air-entraining agent ; 3) Type A water reducer; 4) Type B and D set retarding admixture; 5) Type F high-range water reducer; 6) Type F (melamine-based) high-range water reducer; 7) anhydrous fine granular citric acid (a set control agent for SA cement); and 8) flake calcium chloride (77 to 80 % assay).

Mixtures used for the repairs are shown in Table 7. For the 2 to 4 hour openings the two proprietary products were employed. For 4 to 6 hour openings the proprietary products were compared with a modification of the VES formulation and a mix being used by ODOT for fast setting repair requirements. This mix was similar in some respects to the "GADOT" mix used at the I-20 site, although it had a higher content of Type III cement and used a set retarder to extend working time. For the 12 to 24 hour openings the "Fast Track" mix and a High Early Strength (HES) mix developed by the C 205 investigators were used. Fresh concrete properties are shown in Table 8. Static modulus of elasticity and compressive strength were measured at 7 and 28 days on duplicate 100 X 200 mm cylinders in accordance with ASTM C 459 and C 39 respectively, (see Table 9).

TEST RESULTS AND DISCUSSION

Bridge Deck Overlays

Resistance to Freezing and Thawing

Test specimens were prepared for evaluation of freeze-thaw resistance testing using modified procedures developed under SHRP C 203. The modified procedures consist essentially of an ASTM C 666 B method (freeze in air / thaw in water) with the specimens wrapped in towels during the air freeze so as to reduce drying from the surface during the freeze cycle. This compares to Procedure A, where specimens are continuously immersed in water throughout the period of test. Janssen (19), has found the modified Procedure B to be somewhat more severe than Procedure A. He has attributed this to the more rapid rate of decrease in temperature in the cloth-wrapped Procedure B specimens, as a reservoir of water is not available to release heat during the phase change from water to ice. Prismatic test specimens 75x100x1025 mm long were cast, given the standard field cure as specified in ASTM C 31 "Making and Curing Concrete Test Specimens in the Field," and transported back to the laboratory the following day. During transport to the laboratory, specimens were left in their molds, wrapped with moist burlap, and sealed in plastic bags to minimize moisture loss. The LMC-III specimens were air cured until time of test at age 14 days, as moist cure is inappropriate for this material. The SFC specimens were cured in saturated limewater until time of test. Results after 300 cycles of testing are presented in Table 10. Shown are durability factor (DF), expansion of the prisms, and mass changes. All reported results represent the average of three test prisms. All mixes show acceptable behavior through 300 cycles, commonly taken as the limit of the test. The only mixture which exhibited less than ideal behavior was the I-270 SFC mix, where DF was 88 at 300 cycles and expansion was slightly higher than desirable at 0.05%.

Characteristics of Air Void Systems

Companion 100x200 mm cylinders were cast from overlay mixes and transported back to the laboratory. They were then cut longitudinally and one cut surface of each cylinder lapped so as to allow microscopic determination of air content and air void system parameters using the linear traverse technique (ASTM C 457). Only specimens cast from SFC overlays were subjected to the linear traverse analysis, as LMC-III mixes do not require the use of entrained air in order to obtain freeze-thaw resistance. Air void system parameters are presented in Table 11. All air void systems can be considered adequate.

Permeability

An indication of relative permeability of the overlay concretes was obtained using the rapid determination of the chloride permeability of concrete procedure (AASHTO T 277). Specimens were prepared as 100x200 mm cylinders and cured identically to the compressive strength specimens. Tests were carried out at an age of 28 days. Cylinders were cut to obtain a 50 mm thick test slice from the top of each cylinder and prepared for testing. Test results are summarized in Table 12. As this test normally exhibits considerable data dispersion, individual test results are shown. Results are in the ranges of what normally is to be expected with LMC and SFC mixes. Typically, LMC exhibits charge passed in the range of 500 to 1500 coulombs. SFC permeabilities are significantly less, normally less than 1000 coulombs. For all sites, charge passed by SFC mixes was much less than for LMC. While SFC permeabilities were roughly equivalent for all sites (falling into what would be classified as the "very low" range), only LMC-III permeability for Site 3 fell well into the "very low" range. This may be attributed to the lower w/c ratios at this site, as permeability is known to be a strong function of w/c (20).

Bridge Deck Overlay Core Testing

The actions of concrete placement, consolidation, finishing, and curing, may either separately or in combination, result in as-placed concrete having significantly different properties from specimens prepared in a standard manner from as-received samples of fresh concrete. Testing of concrete cores taken from in-place overlays was done as verification of results obtained from molded specimens. The following durability tests were conducted on 100 mm diameter cores, obtained by State forces approximately 1 week after the placement of each overlay section.

Resistance to Deicer Scaling

After receipt at the laboratory, SFC cores were placed in a moist room until 14 days of age so as to obtain the 14 days of moist curing suggested by the ASTM C 672 test procedure. LMC-III specimens were allowed to stand in laboratory air to obtain the recommended air cure for LMC. SFC specimens were also transferred to lab air at 14 days of age until both sets had reached an age of 28 days. They were then tested following ASTM C 672 procedures, modified for the use of cores. This was done by sealing a 100 mm diameter rigid plastic cylinder mold around the periphery of each specimen so that the top surface could be ponded with a 4 percent solution of calcium chloride. The specimens were rated visually, based on a scale of 0 (no scaling) through 5 (severe scaling with coarse aggregate visible over the