Development of Concrete Durability Specification and Ratings in Florida

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A major research program is underway in Florida to develop a durability specification and rating system for concrete mixtures and structures. As part of the program, field and laboratory water-permeability tests have been developed and are being used with the AASHTO T277 rapid chloride permeability test to predict concrete durability. Presented are the scope and accomplishments to date, including descriptions and applications of the laboratory and field permeability tests, and the development of a permeability classification system on the basis of water permeability results. The durability specification and rating system should result in significant long-term improvement of concrete structures in aggressive environments. Other benefits include effective concrete quality control, efficient use of bridge maintenance funds, and substantial reduction in the cost of bridge rehabilitation.

Durability plays an important role in determining the long-term performance of concrete bridges in aggressive environments. Poor concrete durability can result in premature deterioration of bridges and other structures, resulting in substantial repair costs. Sea water can cause corrosion of the reinforcing steel and damage to the bridge substructure, and, in cold climates, deicing salts contribute to steel corrosion and deterioration of the bridge superstructure. Millions of dollars are spent annually to repair bridges. In the Florida Keys, for example, the cost of repairing corrosion-related damage on a 10-year-old bridge was approximately 25 percent of the original construction cost.

Despite its significant impact, concrete durability has not been emphasized in most specifications. Compressive strength traditionally has been considered as the only criterion on which concrete quality is assessed. Most material engineers design concrete mixtures on the basis of target strength, and they tacitly assume that this strength will ensure high durability. Results from a study in Florida (*1*) indicated that concrete mixtures of equal strength yielded variable levels of permeability (a property closely related to concrete durability). Tests also revealed that high strength did not automatically produce high durability, (i.e., compressive strengths of 45 to 50 MPa may not produce consistently low permeability values). Only at compressive strengths of at least 55 MPa (8,000 psi) would the concrete develop low permeability and corresponding high durability.

Designing mixtures for 55 MPa (or greater) may require a high cement content, an option that may not be favored in certain situations. In warm environments with mass concrete elements, for example, high cement content produces excessive heat and can cause high thermal volume change. That problem often results in macro or micro cracking, which obviously offsets any improvement in durability.

Another option is to engineer concrete mixtures with moderate strengths and low permeability. In such mixtures, the cement is partially replaced by pozzolans, such as fly ash, blast furnace slag, and microsilica. The mixtures require low water-to-cement (W/C) ratios and the use of ordinary and high-range water reducers to achieve desired workability. The key to developing durable mixtures and ensuring their in-service quality is to establish ratings and specifications for durability in terms of strength and permeability. To achieve this objective, development of standardized permeability tests is necessary.

In 1989, the Florida Department of Transportation (FDOT) embarked on a long-term, multiphase research program to develop a durability specification and rating system for concrete mixtures and structures. This paper presents an overview of the FDOT research program and describes the laboratory and field tests developed to measure permeability. It also includes a tentative permeability classification system that has been derived from water permeability test results. Anticipated benefits from ongoing research are also cited.

FDOT RESEARCH PROGRAM

The study has two primary goals: (a) develop a durability specification for concrete mixtures in terms of strength and permeability, and (b) devise standard durability ratings for concrete structures. A number of tasks were formulated to accomplish these goals.

The first task involved developing equipment and procedures for testing concrete permeability, in the laboratory and the field. Water permeability tests were designed to provide predictive estimation of concrete durability. The task was completed, and the resulting new field and laboratory equipment were used to complete subsequent tasks.

Figure 1 shows a flow chart of the major components of the program. A wide range of concrete mixtures and structures were tested and the results compiled in a large data base. From the data base, permeability classifications were developed and durability classes established for concrete mixtures and structures. Finally, tentative durability specifications and rating standards for concrete were developed and are being implemented.

PERMEABILITY TESTS

Research was directed toward developing equipment and procedures for measuring water permeability, in the laboratory and field. This portion of the research was a cooperative effort between FDOT and the University of Florida. The rapid chloride permeability test (RCPT) was used in the testing program.

As the laboratory water permeability test (LPT) and the apparatus for the RCPT were set up in the FDOT research laboratory, a

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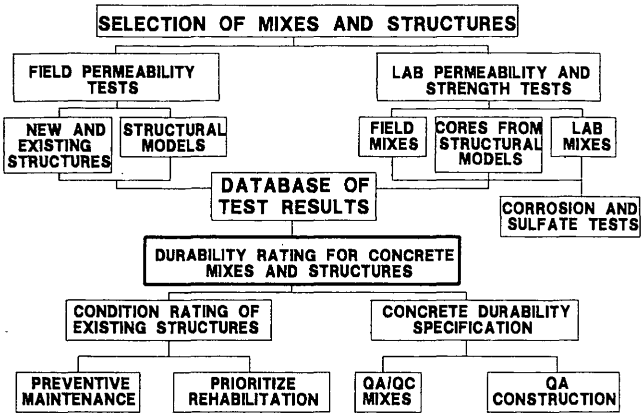

FIGURE 1 Flow chart of main tasks of the research program.

field permeability test (FPT) was used to measure the permeability of various in-place structural elements of bridges around the state.

LPT

The LPT used for this study is a water permeability test developed at the University of Florida (*2*). Figure 2 shows the test apparatus. The test specimen is a 50-mm (2-in.) thick slice of concrete cut from a 100-mm (4-in.) diameter cylinder or core. The specimen's perimeter is coated with a 25-mm (1-in.) thick epoxy layer, then sealed in a permeameter cell and connected to a manometer tube, as shown in Figure 2. The test begins by injecting water into the manometer tube and reservoir of the permeameter cell. Then 0.69 MPa (100 psi) of pressure is applied to the top of the manometer tube to force water into the specimen. The 0.69 MPa pressure was chosen sufficiently high to simulate a constant head flow test and at the same reduce potential injury to operators.

The amount of water flowing into the specimen is monitored via the manometer tube until a steady-state flow is reached. Experience has demonstrated that steady-state flow is reached after 14 to 21 days. The test is continued for an additional 7 days, during which time the flow of water is recorded at 24 hr intervals.

To obtain the coefficient of permeability, the amount of water, Q, is plotted versus time, after steady-state flow is achieved. Then, by regression, the best fit linear curve and its slope is established for the data points. Finally, Darcy's law is used to determine the water permeability.

Because the permeability of concrete decreases as it is curing, it has been common practice to test the permeability at 28 and 91 days. At each time, two replicate samples are tested and the average of the two is calculated. The test is normally completed between 28 and 31 days. Efforts are underway to reduce testing time by using nitrogen as the fluid.

RCPT

RCPT is the AASHTO T277 and ASTM C 1202-91 test procedure for rapid determination of concrete resistance to the penetration of chloride ions. Various components of the test apparatus are shown in Figure 3. A 50-mm (2-in.) thick specimen is cut from a 100-mm (4-in.) diameter cylinder or core. The specimen is coated on its perimeter with a thin layer of epoxy, then placed and sealed between two acrylic cells. The amount of electric charge that passes through the sample indicates the sample's chloride permeability. Permeability classification is determined by comparing the sample's coulomb value to those of the classification chart in AASHTO/ ASTM standards.

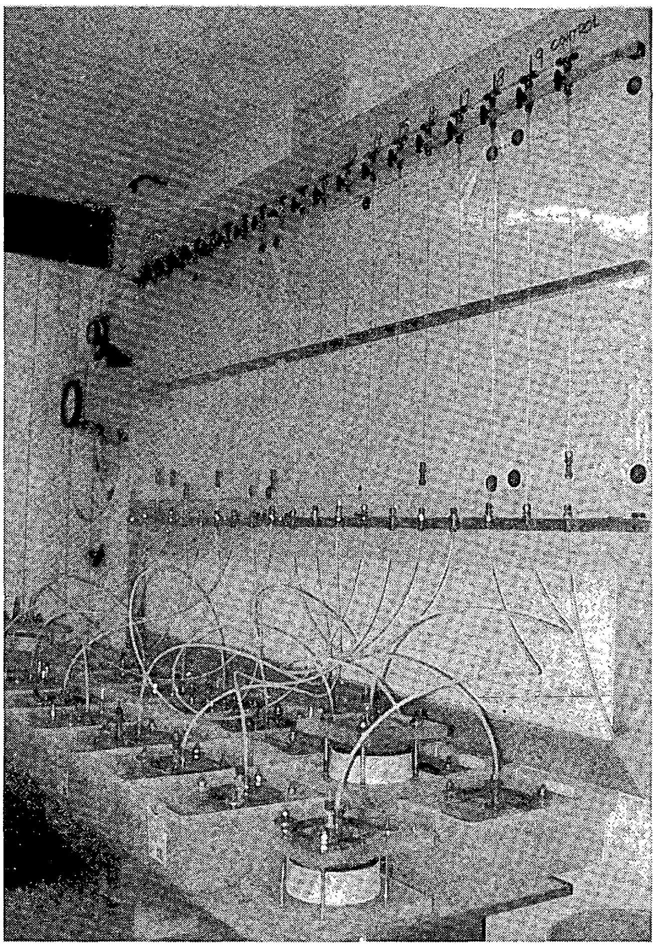

FIGURE 2 Laboratory water-permeability test system.

FPT

The FPT, also developed at the University of Florida (*3*), was designed to measure the permeability of in-place structural elements. Several modifications to the equipment were made by FDOT to simplify the test procedure and to reduce the test's duration. Figure 4 shows various components of the apparatus. The control panel and manometer loop for monitoring water flow are housed inside an aluminum case. A pressure-regulated nitrogen supply, air compressor, and hand-held pump provide pressure and vacuum at various stages of the test. The system also uses a drill and coring machine with a 22-mm (⅞-in.) diameter core bit to drill test holes in the member. An array of testing probes is used to force water into the member. Figure 5 shows several of the probes with different test-regions lengths. The area to be tested is sealed off by means of neoprene "packers," cylindrical shaped pieces that, when compressed, expand to seal and isolate the test region. The packers expand as the knurled knobs at the top end of the probe are tightened.

To run a test, a 150-mm (6-in.)-deep hole is drilled in the concrete. The probe is inserted and sealed by the rubber packers' ex-

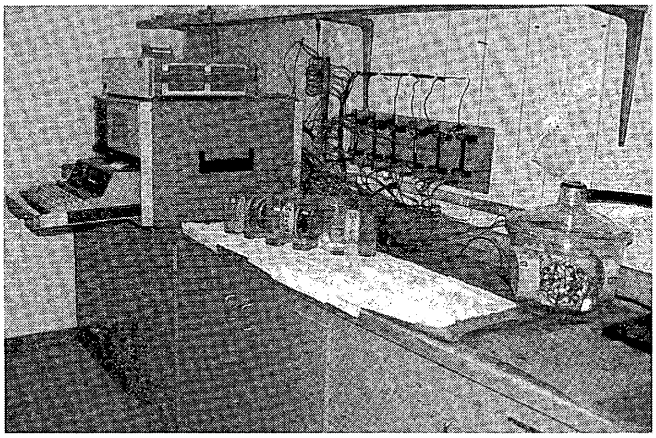

FIGURE 3 Chloride permeability test apparatus.

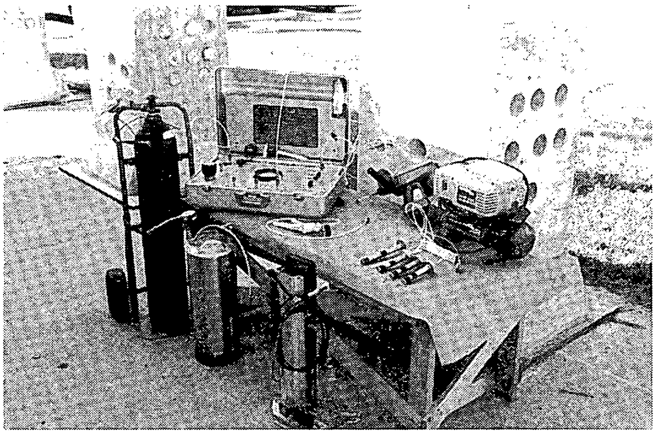

FIGURE 4 Components of field permeability test (FPT) apparatus.

pansion against the hole wall. Depth of the test region inside the concrete is adjustable, ranging from 32 to 89 mm (1.25 to 3.5 in.)

The concrete area around the probe is saturated for at least 1 hr before starting. The test begins by removing air from the system, then water under pressure is injected through holes in the probe and forced into the concrete. The pressure applied to the water may range from 0.69 to 2.1 MPa (100 to 300 psi), depending on the concrete's strength and permeability. Water flow is monitored on the manometer loop at equal time intervals ranging from 5 to 30 min. The test normally is completed in 2 to 3 hrs., depending on how rapidly a steady-state flow condition is reached. The flow rate is measured and applied to a permeability formula (commonly referred to as the Packer/Lugeon equation) to compute the permeability coefficient, *k*, of the concrete. The equation is given as

$$k = \frac{q}{2\pi L\,h} \sinh^{-1} \frac{L}{2\,r}$$

where

q = constant rate of flow into the concrete,
L = length of the test section,
h = differential head, and
r = radius of the hole.

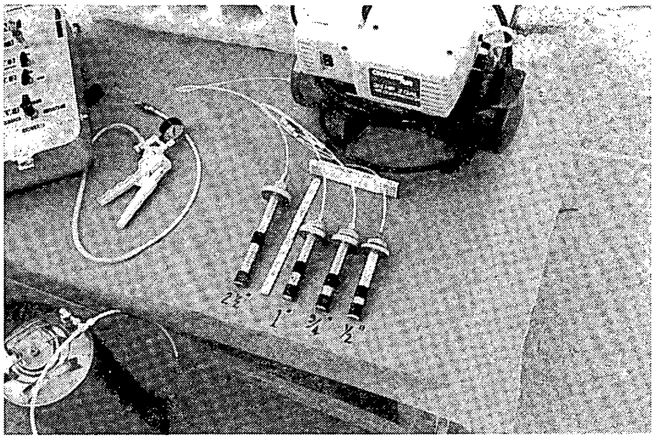

FIGURE 5 Field permeability test probes.

Note that the actual flow pattern into the surrounding concrete is not known but is modeled as a sphere emanating from the probe center, with ellipsoid-shaped equipotential surfaces.

DETAILS OF TESTING PROGRAM

Laboratory Sampling and Testing

A wide range of concrete mixtures produced in laboratory and field environments is being tested. More than 100 laboratory-produced mixtures have been batched and tested since 1989. These concrete mixtures have W/C ratios ranging from 0.25 to 0.45 and cementitious contents ranging from 335 to 580 kg/m^3 (564 to 977 lb/yd^3). Fly ash, microsilica, and slag were included as part of the cementitious material added to concrete mixtures. The fly ash contents ranged between 10 and 50 percent, whereas microsilica contents ranged between 5 and 15 percent. Slag was incorporated at a rate of 50 percent cement replacement. Various types of aggregates were used in the concrete mixtures, including crushed limestone, granite, and river gravel. ASTM Type II cement was used in all but a few mixtures. In every mixture, 222 cc/45 kg of cement (7.5 fl. oz/100 lb cement) of Type D (ASTM C 494) water reducer admixture was used to achieve a target slump of 50 to 100 mm (2 to 4 in.). In addition, Type F (ASTM C 494) high range water reducer was used in several mixtures to supplement the ordinary water reducer to achieve the target slump.

Concrete samples from each mixture were tested for various properties including, compressive, tensile, and flexural strengths; elastic properties; water and chloride permeability; and corrosion and sulfate resistance. The material properties, mixture designs, and results of strength, permeability, and corrosion resistance of 22 of the mixtures evaluated to date are detailed elsewhere (*1*). Design variables for these mixtures included W/C ratio, cement content, and the incorporation of variable rates of fly ash and silica fume as cement replacement.

Results of compressive strength and chloride permeability tests for the 22 mixtures are correlated and presented in Figure 6 (*1*). Concrete mixtures that fall within the same compressive strength range are grouped together. Chloride permeability test results for individual mixtures and the different permeability classes are shown on the vertical axis of Figure 6. The correlation between both test

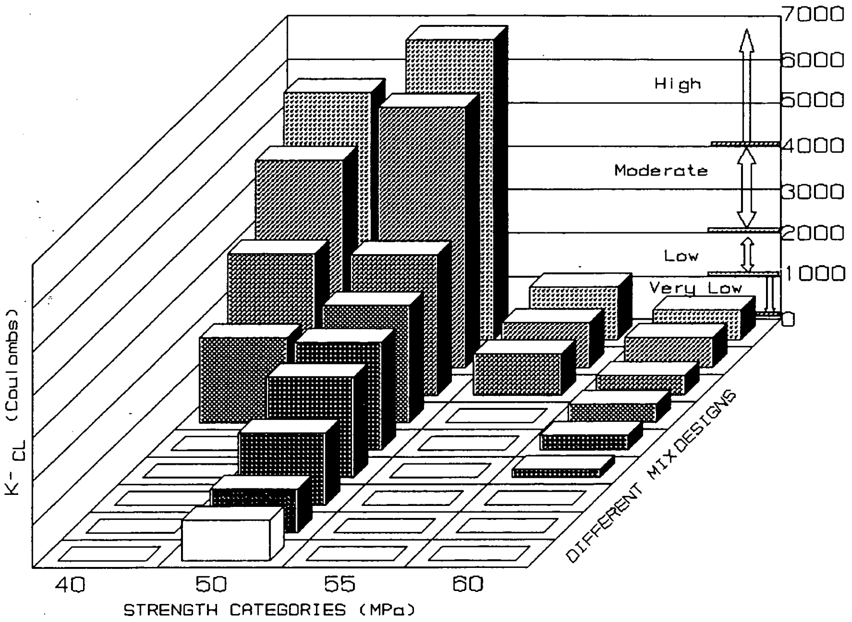

FIGURE 6 Correlation between compressive strength and chloride permeability (K-CL).

results suggests that concrete mixtures in the same strength category do not necessarily fall in the same permeability classification. That finding further demonstrates the need to perform both compressive strength and permeability tests to arrive at a better assessment of concrete durability.

Field Sampling and Testing

The field testing program involves obtaining core samples and testing elements of bridges representing different age groups, including those under construction. It also involves obtaining core samples and testing large, 0.75-m × 0.75-m × 1.50-m (2.5 × 2.5 ft 5 ft) models of columns. The models were cast and cured in two locations outside the laboratory and at bridge construction sites.

Models outside the laboratory were cast with laboratory concrete mixtures that have a proven record of high durability. Figure 7 shows six column models, each representing two concrete mixtures cast outside the laboratory. Each model was cored at several locations; the cores then were tested for laboratory water permeability, chloride permeability, and compressive strength. Field permeability tests were also performed on the column models. Figure 8 shows a previously cored model being presaturated at several points in preparation for field permeability testing. Test results from the models were used to establish correlation between the three permeability tests, and between the permeability and strength of concrete.

Models in the field were cast with the same concrete that was delivered to the construction site and were subjected to the same environmental conditions as the actual structure. Test results obtained from these models should represent properties of concrete within the structure. Figure 9 shows a field model being tested with the FPT apparatus.

Figure 10 shows FPT apparatus testing of a newly placed bridge pile. The tests were performed to evaluate the quality of the bridge pile after construction. Each structural element or model is tested at 2 or 3 locations. Cores also are obtained from the structure for subsequent laboratory testing of permeability and compressive strength. Test results from the actual elements are compared with those obtained from the field models to determine how they compare. Additional specimens are extracted from bridges of various age groups to determine the chloride content and to detect carbonation. Finally, a thorough condition evaluation (and corrosion detection) is conducted.

FIGURE 7 Column models cast outside the laboratory.

Whereas this aspect of the research program was time-consuming, labor intensive, and required close coordination with field engineers and contractors, conducting such field tests on actual structural elements and models is essential to developing a durability specification and rating system that is practical to implement.

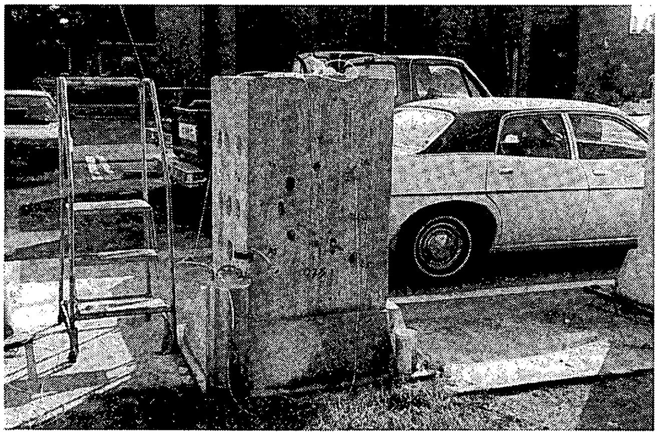

FIGURE 8 Field permeability testing of a column model.

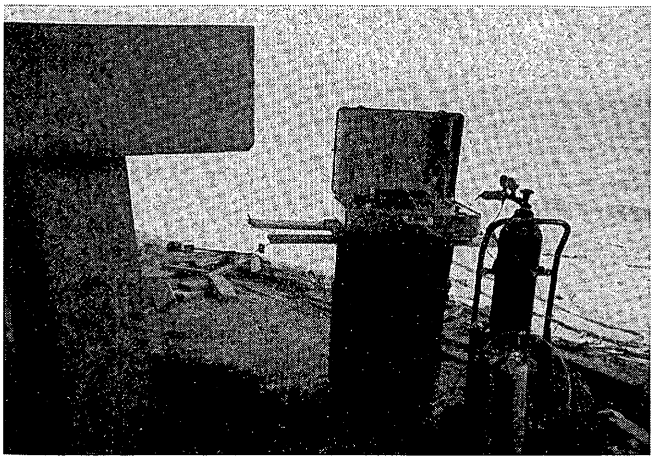

FIGURE 10 Field permeability testing of a bridge pile.

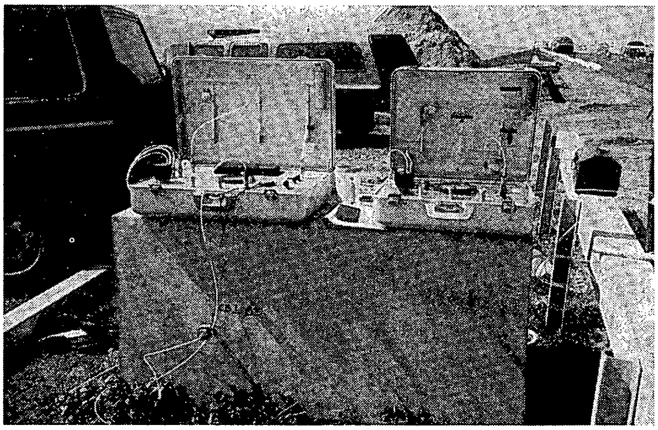

FIGURE 9 Field permeability testing of a field model.

DURABILITY RATINGS AND SPECIFICATIONS

Data Base of Test Results

As part of the testing program, a data base computer program, FLAGCONS (*4*), was developed to manage the laboratory test data. The program was upgraded to handle the field permeability data as well. It provides averages and standard deviations for groups of test results, maintains testing and batching schedules, and flags days on which conflicts exist between sample testing and concrete batching. It has simplified storage, processing, and analysis of the massive amount of data generated by ongoing research.

Correlation of Test Results

From the data base, various correlations between test results are performed. The main correlation established to date is the one among laboratory, field and chloride permeability test data (*1,5*). Table 1 shows the tentative permeability classifications for concrete, the different classifications are basically the same as those listed in AASHTO T277, with the exception of one class termed "very high." The range of chloride permeability values follows AASHTO/ASTM criteria. Ranges for laboratory water permeability (K-water) and field water permeability (K-field) were derived from the data base of more than 100 test results. The data base represents all field and laboratory tests obtained thus far, including test results from research and field models, as well as from old and new structures.

The range of water permeability (laboratory and field) for each classification was established by using a series of steps. First, each concrete mixture prepared in the laboratory or field was sampled for three different permeability tests. Also, where possible, cores were obtained from models and actual elements for laboratory testing of chloride and water permeability. In addition, field permeability tests were performed on the same models and elements. Second, the results for the three tests were tabulated and grouped according to chloride permeability classifications. Finally, ranges for laboratory and field water-permeability values for each permeability class were determined from the data groups corresponding to each chloride permeability classification.

The difference between laboratory and field values is likely because of the test setup (i.e., size of test area) and assumptions made in the field permeability equation derivation. Another difference, that the permeability in the horizontal direction (field) is not the same as the vertical (lab) direction, is possibly due to placement effects. Efforts are underway to develop correlations between permeability and other tests, such as corrosion resistance, sulfate resistance, and chloride content. In addition, results of the condition surveys and corrosion evaluation of existing bridges will be compared with results of concrete permeability and strengths tests on the same bridges.

Durability Rating System for Existing Structures

From the correlation between the condition of the bridges versus concrete permeability and strength, a durability rating system will be developed for in-service structures. The rating values will form a standard by which the condition of bridges can be inferred. The classification could range from very poor to excellent, depending on the rating value assigned. On the basis of this classification, a priority list of deteriorated bridges can be created, resulting in a more accurate assessment of necessary rehabilitation funds. Durability

TABLE 1 Permeability Classification

Concrete Permeability Classification	Permeability Range		
	K-Chloride [a] Coulomb	K-Water (Lab) [b] cm/s (10^{-12})	K-Field [b] cm/s (10^{-12})
Negligible	< 100	< 0.25	< 25
Very Low	100 - 1000	0.25 - 2.5	25 - 150
Low	1000 - 2000	2.5 - 25	150 - 750
Moderate	2000 - 4000	25 - 250	750 - 1500
High	> 4000	250 - 2500	1500 - 5000
Very High	N/A	> 2500	> 5000

1 cm = 0.39 in

[a] According to AASHTO T277 & ASTM C1202

[b] Derived From FDOT Data Base

ratings would also allow identification of those bridges that are in the early stages of deterioration. In these cases, less costly preventive maintenance might be initiated to halt further deterioration. Early prevention tends to reduce the potential for more costly rehabilitation in the future and ensures longer service life. Implementation of a durability rating system would allow better management and substantial cost savings of bridge maintenance programs.

Durability Specification for Concrete Mixtures

After analyzing various correlations between test results, different classes of durability can be established for concrete mixtures as well. The classes would have requirements for both strength and permeability and range from high to very low. Specification requirements would then be developed for concrete in different environments. For example, requirements for high durable concrete would be adopted in the design of mixtures for severely aggressive environments, such as sea water. Specifications provide guidance for material selection and mixture proportioning. Laboratory permeability and strength tests would be performed on concrete mixtures to ensure compliance with the specification requirements. During construction, quality, in terms of strength and durability, would be verified and samples of concrete prepared and tested for strength and permeability. The quality of the as-built structure is evaluated by performing field permeability tests on the structural elements and models. Results of strength and durability tests are compared with the standard ratings for high-durable structures, providing the project engineer with an excellent tool for quality assurance of the final product. The permeability tests are particularly valuable in settling disputes between owners and contractors over different interpretations of quality construction. In cases where the FPT was used, FDOT engineers were able to make a more accurate assessment of quality and thereby arrive at rational decisions regarding concrete acceptance.

SUMMARY

This paper presents the findings to date of an extensive research program to develop a durability specification and rating system for concrete. A major product of this research is the development of tentative permeability classifications on the basis of laboratory and field water-permeability.

Significant benefits are expected from this research, including accurate evaluation and classification of durability for concrete mixtures and structures, effective management of bridge rehabilitation and maintenance programs, and efficient use of bridge maintenance funds through savings in bridge rehabilitation costs.

The rating system described allows a material engineer to design mixtures that produce concrete with optimum strength and high durability. A project engineer can use FPT and standard durability ratings for quality assurance of newly constructed structures. A maintenance engineer and consultant can test the permeability of a structure and use the test results to evaluate present conditions and predict a structure's future performance.

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REFERENCES

1. Armaghani, J., T. Larsen, and D. Romano. Aspects of Concrete Strength and Durability. In *Transportation Research Record No. 1335,* TRB, National Research Council, Washington, D.C., 1992, pp. 63–69.
2. Soongswang, P., M. Tia, D. Bloomquist, C. Meletiou, and L. Sessions. An Efficient Test Setup for Determining the Water-Permeability of Concrete. In *Transportation Research Record No. 1204,* TRB, National Research Council, Washington D.C., 1988, pp. 77–82.
3. Meletiou, C., M. Tia, and D. Bloomquist. Development of a Field Permeability Apparatus and Method for Concrete. *ACI Materials Journal,* Jan/Feb. 1992, pp. 83–89.
4. Adegodegoke, O., and J. Armaghani. Software for Managing Concrete Test Data. *Proc., 9th ASCE National Conference on Microcomputers in Civil Engineering,* Orlando, Fla., Oct. 30–31 1991, pp. 237–241.
5. Armaghani, J., D. Romano, M. Bergin, and J. Moxley. High Performance Concrete in Florida Bridges. *Proc., ACI Symposium on High Performance Concrete in Severe Environments.* ACI Convention, Nov. 1993.

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