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Subject Area: IIB Pavement Design, Management and Performance; IIC Bridges, Other Structures, and Hydraulics and Hydrology; and IIIB Materials and Construction

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Durability Testing of High-Strength Concrete Containing High-Range, Water-Reducing Admixtures

This NCHRP digest has been derived by excerpting the agency report for NCHRP Project 10-32A, "Durability Testing of High-Strength Concrete Containing High-Range, Water-Reducing Admixtures." Project 10-32A was conducted under the supervision of J. Derle Thorpe, Engineering Experiment Station, Utah State University, Logan, Utah.

ABSTRACT

Laboratory freezing and thawing tests were used to evaluate the durability of concretes containing high-range, water-reducing admixtures. Two types of concretes were studied—the first had the desired range of slump and air-void system with the admixtures, the second had the desired range of slump and air-void system without the admixtures. To this second concrete, the admixtures were added in order to increase the slump significantly. Among the overall findings of this research was that the characteristics of a well-developed air-void system normally associated with durable concretes also are required for durable concretes containing high-range water-reducing admixtures.

INTRODUCTION

For more than 40 years, the value of using entrained air to produce concrete that resists the deterioration caused by saturated freezing and thawing has been well understood. The levels of entrained air required have increased steadily as the use of deicing salts on roads, highways, and bridges has made exposure conditions more severe. In the past 15 years, however, high-range, water-reducing (HRWR) admixtures (i.e., superplasticizers) have seen wider acceptance and use in the construction industry; this has led to uncertainty about the importance of air entrainment when used with HRWR admixtures.

These admixtures were first introduced in Japan in the late 1960s, used in Europe in the early 1970s, and finally introduced into North America in the mid to late 1970s. Originally, HRWR admixtures were used to increase either workability or strength in concretes with normal water-cement ratios (0.45 to 0.55). Next, HRWR admixtures were used to produce workable concrete with ever lower water-cement ratios; strength increases were proportional to the reductions in the water-cement ratio. Finally, projects required that these high-strength concretes also be durable. The use of HRWR admixtures has permitted the production of concrete with extremely low water-cement ratios, producing densities that approach the densities of included aggregate particles. Do these high-density concretes require air entrainment for freezing and thawing durability? Use of HRWR admixtures alters the characteristics of the air-void system—admixtures often produce

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air-void parameters that are unacceptable in conventional concretes. Therefore, can the parameters of the air-void system be altered without reducing freezing and thawing durability?

OBJECTIVES AND SCOPE

As the use of concretes containing HRWR admixtures grows, knowledge grows in proportion; however, questions remain. This study was designed to answer some of these questions. The general objectives of this study were as follows:

- To evaluate the durability characteristics of various concretes containing HRWR admixtures in a laboratory setting,
- To evaluate various freezing and thawing tests and compare the relative severity of the tests, and
- To evaluate the various test methods used to determine the deterioration of concrete.

Specifically, the study focused on the following detailed objectives:

1. Establish correlations between the measured properties of plastic and hardened high-strength concrete containing HRWR admixtures and the durability characteristics by subjecting the test specimens to the four different freezing and thawing tests listed below:

    a. Resistance of Concrete to Rapid Freezing and Thawing, ASTM C 666, Procedure A, 5 hours per cycle;
    b. Resistance of Concrete to Rapid Freezing and Thawing, ASTM C 666, Procedure A, 2 hours per cycle;
    c. Resistance of Concrete to Rapid Freezing and Thawing, ASTM C 666, Procedure A, 5 hours per cycle, after 14 days of drying;
    d. Resistance of Concrete to Rapid Freezing and Thawing, ASTM C 666, Procedure B, 5 hours per cycle;

2. Establish correlations between the various characteristics of the air-void system in hardened, high-strength concrete containing HRWR admixtures and the durability characteristics by subjecting the test specimens to the four different freezing and thawing tests (listed above); the characteristics of the air-void system in the hardened concrete include total air voids, spacing factor, specific surface, and average chord length;
3. Determine if ASTM C 666 can be modified to reduce its severity and improve the correlation between durability in the laboratory and durability observed in the field;
4. Determine if there is any significant difference between the results of ASTM C 666 conducted at the lower end of the allowable time range (2 hours per cycle) and the results conducted at the upper end of the allowable time range (5 hours per cycle);
5. Determine if there is a water-cement ratio below which a well-established air-void system is not required for durability;
6. Determine if the allowable time range per cycle, as specified by ASTM C 666, needs to be narrowed to ensure uniformity of results between tests;
7. Correlate simple change in length measurements with durability characteristics as determined by fundamental frequency measurement;
8. Correlate simple change of weight measurements with durability characteristics as determined by fundamental frequency measurement;
9. Study a comparison of the relative harshness of various freezing and thawing testing procedures to determine if one method has advantages over another;
10. Identify alterations that may be allowed in the characteristics of the air-void system of hardened, durable, high- strength concrete using HRWR admixtures; and
11. Identify changes to specifications, for concrete containing HRWR admixtures, that could be permitted without sacrificing durability.

RESEARCH APPROACH

Although evaluating the durability characteristics of high-strength concrete containing HRWR admixtures was the primary goal of the study, the research was organized to answer other questions as well. The relative severity of various freezing and thawing tests was examined. This includes the effect of cycle length on the deterioration of concrete.

ASTM C 666 allows a freezing and thawing cycle as short as 2 hours or as long as 5 hours. The research plan required that companion specimens be tested at each end of the cycle range of the ASTM procedure. The study was also designed to determine if ASTM C 666 could be modified to make the tests less severe. Some specimens were air dried for 14 days after the standard submerged cure before being subjected to saturated freezing and thawing in the accordance with ASTM C 666, Procedure A.

The study was limited to laboratory investigations with all concrete prepared and evaluated only for the purposes of the study. More than 60 mixes were prepared to answer the questions outlined in the Objectives and Scope. These included mixes without HRWR admixtures, mixes with naphthalene-based HRWR admixtures, mixes with melamine-based HRWR admixtures, and mixes with HRWR admixtures modified with a lignosulfonate admixture. The ranges of entrained air in the plastic concrete included 0 to 2 percent (i.e., control, no air entraining admixture), 3 to 4 percent, 6 to 7 percent, and 8 to 10 percent.

Two types of concrete were studied—the first had the desired range of slump and air-void system with HRWR admixtures, the second had the desired range of slump and air-void system without HRWR admixtures. HRWR admixtures were then added to this second concrete to increase the slump significantly. This type of concrete was called flowing concrete. The target slump for the normal concrete and the flowing concrete before the addition of HRWR admixtures was in the normal workable range of 3 to 4 in. to allow the development of an adequate air-void system. Specimens made from concrete from each mix were tested with four freezing and thawing tests. Two sets of two specimens were tested in accordance with ASTM C 666, Procedure A. These specimens were never allowed to dry; they remained saturated throughout the curing and testing phases. The duration of the freezing and thawing cycle was 2 hours for one set and 5 hours for the second set. Two additional specimens from each mix were air dried 14 days after the curing period before being tested in accordance with ASTM C 666, Procedure A. One specimen from each mix was tested in accordance with ASTM C 666, Procedure B.

INTERPRETATION

Standard Tests

The study verified that different freezing and thawing tests had different levels of severity and, consequently, produced different deterioration rates. Field exposures show similar differences because of wide variations in exposure conditions. Some of the variables affecting field concrete are the number of freezing and thawing cycles, the rate of freezing, the degree of saturation, the rate of drying, the number of drying cycles, and the duration of drying cycles. The location of the concrete, with respect to shade and the sun at its low winter angle, affects the freezing and thawing rate and number of cycles. Additional variables are introduced by the deicing practices of the agency responsible for maintaining the concrete and other agencies that may be responsible for adjacent highways and roads (because vehicles carry deicing salts from one highway jurisdiction to another). Although state departments of transportation (DOTs) seek to establish a correlation between standard freezing and thawing tests and the performance of field concrete, they recognize that differences exist between the relative deterioration of various tests just as major differences exist in the exposure conditions of concrete in service. Thus, comparing a standard laboratory test to the non-uniformity of field conditions is uniformative.

It may be desirable to establish a severity index for each standard freezing and thawing test. A severity index would permit a DOT to match the laboratory evaluation to anticipated exposure conditions in the field. It also would allow DOT personnel to know the relative severity of the test or tests they use and would permit correlation between laboratories. For a DOT to have the capability of several different freezing and thawing tests would require additional laboratory equipment. Establishing cooperative agreements among states or creating a testing consortium within regions would give each DOT access to various test methods while limiting how much laboratory equipment any one agency would have to purchase and fostering cooperation among agencies.

Entrained Air Requirements

The study showed that low water-cement ratio concretes without entrained air were slightly more durable than high water-cement ratio concretes without entrained air. This also was true in similar concretes with marginal air-void systems. When the concrete had properly developed air-void systems, there were no significant differences in the durabilities of high and low water-cement ratio concretes. Therefore, it is more cost-effective to produce durable concrete using a well-developed air-void system than by lowering the water-cement ratio.

Effect of Drying

This study demonstrated the benefits of drying concrete before resaturation and freezing. The test methods that included a drying segment in the freezing and thawing cycle were the test methods that produced the least deterioration. This was true of the modified ASTM C 666, Procedure A (5h ADA) (which allowed 14 days of air drying in the laboratory before the beginning of the freezing and thawing testing) and ASTM C 666, Procedure B (which allowed some drying at the beginning of each freezing cycle). Once concrete is allowed to dry, it will not resaturate to its original level under normal conditions; therefore, as long as concrete dries naturally in the field and is not allowed to dry in the laboratory freezing and thawing tests, correlating laboratory test results with field performance will be difficult.

Specifications

The study indicates that specifications must provide careful control over air-entrained concrete containing HRWR admixtures. The inherent loss of slump automatically limits the time any HRWR concrete, including air-entrained concrete, should remain in the mixer. One purpose of HRWR admixtures is to produce high slump without sacrificing quality. Specifications must be written to control the time that air-entrained HRWR concrete remains in the mixing truck because the deterioration of the air-void system is proportional to the change in slump.

Specifications also must prohibit significant changes in slump. The findings of this study verify the wisdom of avoiding major slump changes in air-entrained HRWR concrete—whether it be gradual loss occurring naturally during mixing and delivery or rapid increase because of the delayed addition of HRWR admixtures. This does not mean that HRWR admixtures cannot be used in air-entrained concrete—it is possible to produce high-slump concrete that has a well-developed air-void system while using HRWR admixtures.

Changes in Acceptable Air-void Parameters

One of the goals of this study was to determine if the use of HRWR admixtures in air-entrained concrete would permit changes in the acceptable parameters of the air-void system. The generally accepted limits on the parameters of the air-void system in durable concrete include the following:

- A specific surface (α) greater than 600 in.^{2} per in.^{3} (in.$^{-1}$). This is a measure of the size of the average air void. The larger the specific surface, the smaller the average air void.
- A spacing factor (L) of less than 0.008 in. This is a measure of average spacing between air voids; it is actually the average distance a water molecule must travel to reach the nearest air void.

Other parameters measured during the linear traverse of a hardened concrete specimen include the chord length of each void intercepted along the traverse line and the number of voids per inch. The only parameter that can be accurately measured in the plastic concrete is the percentage of the total air in the concrete.

Those familiar with the production of air-entrained concrete are also familiar with the variability in the percentage of total air voids in that concrete. In carefully controlled, air-entrained concrete, the percentage of total air voids in the plastic concrete will have a standard deviation of ± 1 percent. Approximately one-sixth of the air-void tests will be more than 1 percent above the average. A like number will be more than 1 percent below the average. When the production of air-entrained concrete is not carefully controlled, or when weather conditions are adverse, the variability associated with the production of air-entrained concrete can be even greater.

Proper levels of entrained air in concrete result from using materials that meet acceptable standards to produce air-void systems with desirable characteristics. The measurements of the air voids in the hardened concrete indicate that the use of HRWR admixtures slightly increases the size of the average air void, but this limited increase has no measurable effect on the durability of the concrete.

The data indicate that the durability of concrete improves with the addition of even a small amount of an air-entraining admixture. Figure 1 shows the spacing factor plotted against the percentage of air voids in the hardened concrete. The curve shows a definite change in the slope of the curve near 3 percent air voids. As the air voids in the hardened concrete increase to 3 percent, because of an increase in entrained air, the spacing factor drops rapidly. Above 3 percent, the best-fit line is nearly horizontal. This figure verifies the transition zone identified by Cordon and Merrill, which shows a significant increase in durability as the air voids in the hardened concrete increase above 3 percent.

The relationship between the size of the average air void, as determined by the length of the average chord intercept, and the percent of air voids in the hardened concrete can be seen in Figure 2. The average air-void size drops as the air increases, until the percentage of air reaches approximately 3 percent. Above 3 percent, the average air-void size is relatively constant. Figure 2 further verifies the transition zone and the fact that entrained air voids of 3 percent or more in hardened concrete provide good resistance to deterioration caused by saturated freezing and thawing in the laboratory.

Modifications to accepted limits for the parameters of air-void systems are not being recommended for the following reasons: producing air-entrained concrete, including that with HRWR admixtures, is variable; the acceptable changes, as suggested from the data, are small; and most water saturating field concrete contains deicing salts that create exposure conditions requiring better air-void systems. Altering the air-void requirements will reduce the probability that a concrete will be durable. Leaving the recommended air-void parameters as they are provides a factor of safety in concrete requiring freezing and thawing durability.

CONCLUSIONS AND SUGGESTED RESEARCH

Principles Suggested in Findings

1. The characteristics of a well-developed air-void system normally associated with durable concrete (i.e., percentage of air voids, spacing factor, and specific surface) are required for durable concretes containing HRWR admixtures.

2. The addition of HRWR admixtures to concrete with a well-developed air-void system destroys the air-void system. However, the air-void system is slowly restored with continued mixing as the normal slump loss occurs.

3. When HRWR admixtures are already part of concrete with a well-developed air-void system, the alteration of the air-void system is proportional to the loss of slump when mixing is continuous.

4. Air entrainment is more important than a low water-cement ratio in producing durable HRWR concrete. Concretes with low-water cement ratios and marginal air-void systems are slightly more durable than concretes with higher water-cement ratios and similar air-void systems.

5. Different freezing and thawing tests and modifications of those tests produce different deterioration rates in concrete. Faster freezing and thawing cycles produce more rapid deterioration. Tests or modifications of tests that allow drying slow the deterioration rate. The differences between tests narrowed slightly as the percentage of air voids increased. Concrete with a well-developed air-void system will perform better than concrete with a poor air-void system in the same test.

6. The durability factor, calculated from measurements of the fundamental transverse frequency, is a more reliable and discriminating measure of deterioration than either the length change or weight change.

7. The characteristics of flowing concrete change rapidly and occur while sampling, testing, and fabrication of the test specimens are being completed. Wide variations in the test results can occur—even though ASTM testing procedures are being followed strictly.

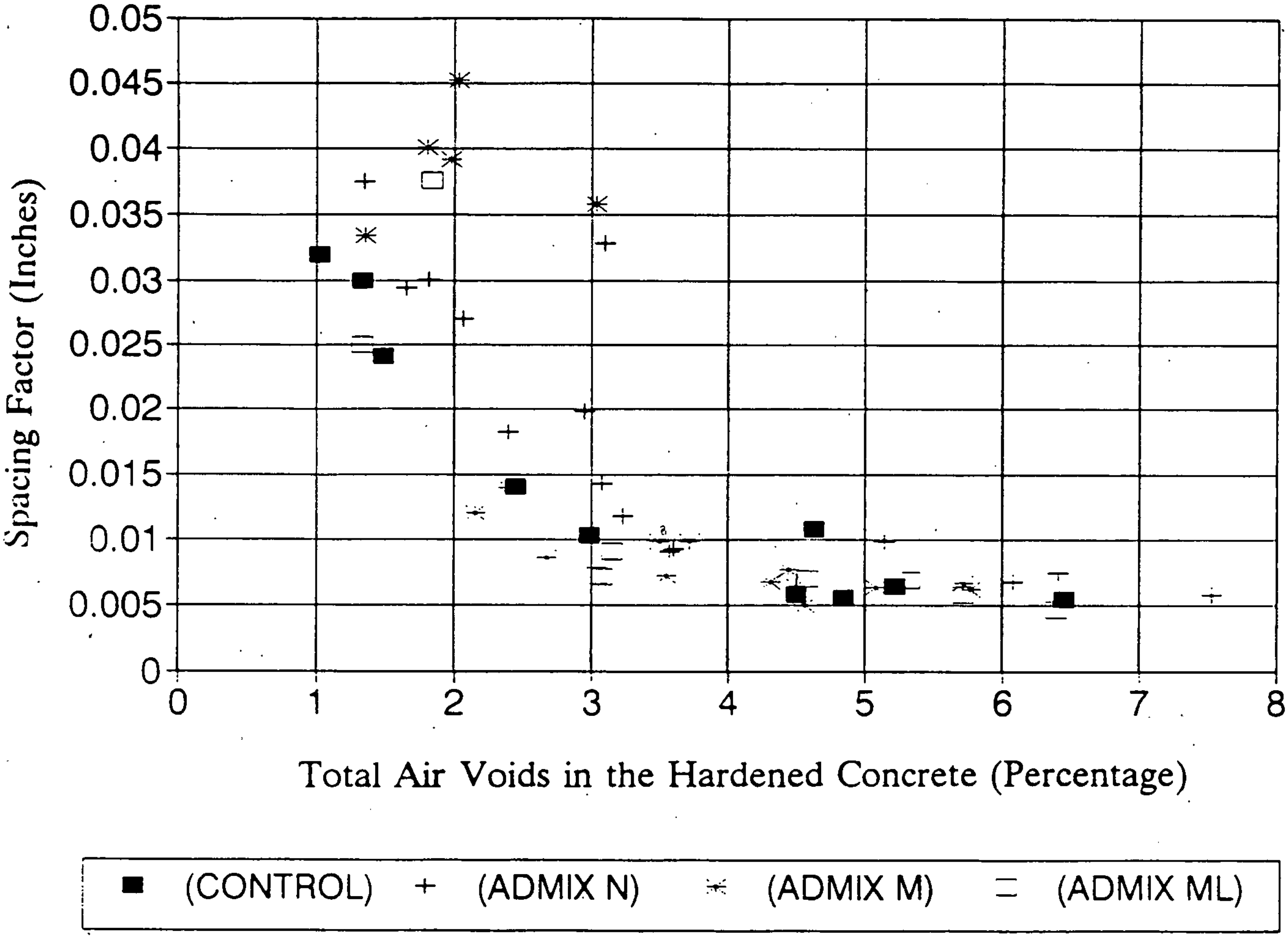

Figure 1. Spacing factor in inches plotted against the air voids in the hardened concrete in percent. (Source: Thorpe)

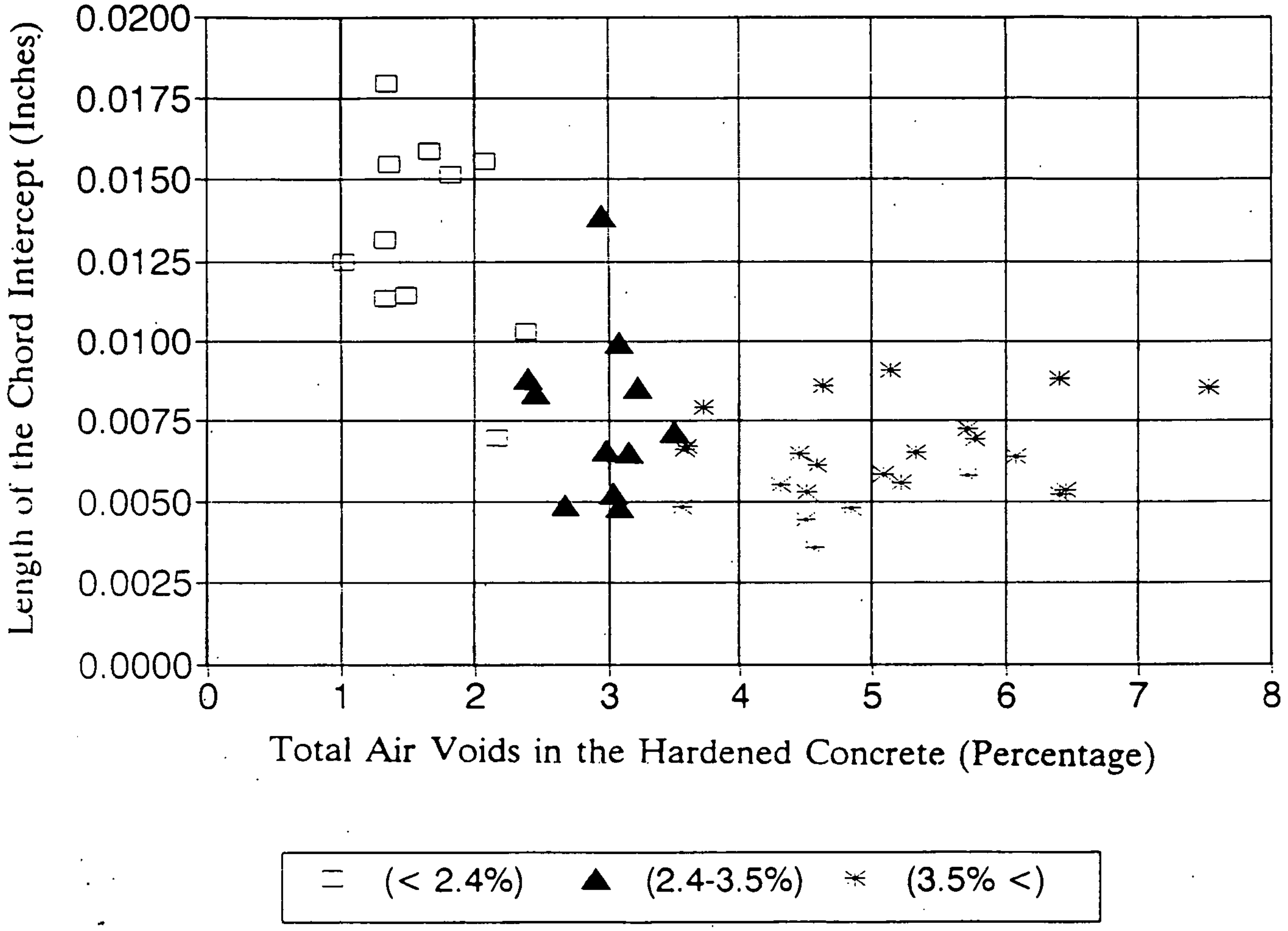

Figure 2. The length of the average chord intercept in inches plotted against the air voids in the hardened concrete in percent. (Source: Thorpe)

Suggested Research

1. The significant changes in the characteristics of the air-void system in concrete when the HRWR admixtures are added later, rather than being part of the original mix, warrants an extension of this study to include lower dosages of HRWR admixtures. It may be possible to identify a dosage below which the alterations in the air-void system are held within acceptable limits.
2. The changes in the air-void system caused by the addition of HRWR admixtures requires a thorough investigation into the stability of these systems when used with HRWR admixtures. Air-entrained concrete containing HRWR admixtures changes constantly. The material must be understood thoroughly before confidence in the durability of the material is achieved.
3. Much of the water of saturation in field concrete in the nation's transportation systems contains dissolved salts. These salts cause greater deterioration in concrete. The findings of this study need to be extended using dissolved salts in the water of saturation.
4. The rapidly increasing use of silica fume in concrete used in severe exposures requires that similar studies be conducted using concrete with HRWR admixtures and silica fume.
5. The limits of the allowable changes in slump of HRWR concrete must be investigated in order to determine how much HRWR admixture can be added without damaging the air-void system and to determine the slump loss that can be permitted before the air-void system becomes ineffective.
6. The changes in air-void characteristics must be investigated for each basic type of air-entraining admixture. Rising costs of some basic raw materials and shortages of others are forcing admixture manufacturers to investigate new chemicals from which to produce air-entraining admixtures.

IMPLEMENTATION OF RESULTS

Tests Methods

The study identified different rates of deterioration with different ASTM tests or modifications of those tests. The "perfect" freezing and thawing laboratory test is one that duplicates nature. As long as field concrete dries between freezing and thawing cycles and the laboratory test does not, correlating field performance and laboratory testing will be difficult. Test methods that require shorter cycle lengths or continuous saturation or both cause more rapid deterioration; test methods that require longer cycle lengths or permit drying or both (either before the initiation of freezing and thawing tests or between the freezing and thawing cycles) will cause slower deterioration (i.e., extend the testing period).

Test results are relative. Marginal concrete will fail rapidly—regardless of the test method used—but number of cycles to failure may vary. Durable concrete will endure many more cycles under any test method. Thus, it is important to know the relative severity of the method used by the DOT and to accept the results as an indication that the concrete will perform well (or poorly) under nature's most severe exposure conditions. There are too many variations in nature to permit comparison with any one test.

The study also has identified modifications in test methods that can make them more or less severe. If a DOT wishes to modify tests now in use, it would be wise to change to a more severe test to produce results faster and at lower cost.

Results from this study would indicate that when ASTM C 666 was changed from a 4-hour to a 5-hour maximum cycle length, the variability of test results increased. Narrowing the cycle limits will produce more uniform results.

Specifications

This study demonstrated that significant increases or decreases in slump in concrete containing HRWR admixtures affects air entrainment and the durability of concrete. Large increases in slump must be avoided when HRWR admixtures are added to concrete that already has a well-developed air-void system. This does not mean, however, that it is impossible to produce durable concrete with HRWR admixtures—durable concrete can be produced if the HRWR admixture is part of the original system. Specifications must restrict or prohibit the addition of HRWR admixtures to concrete that already has a well-developed air-void system. Decreases in the slump during mixing of concrete containing a well-developed air-void system and HRWR admixtures must also be avoided—changes in the parameters of the air-void system will be proportional to the changes in slump. A decrease in slump is less likely to occur if the HRWR admixture was part of the original mix and the concrete is placed before significant slump loss occurs; therefore, specifications must restrict the mixing and delivery time of HRWR concrete.

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AVAILABILITY OF REPORT

The agency's full report documenting NCHRP Project 10-32A, "Durability Testing of High-Strength Concrete Containing High-Range Water-Reducing Admixtures," is available for loan on request to: Cooperative Research Programs, 2101 Constitution Avenue, N.W., Washington, DC 20418.

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