National Cooperative Highway Research Program

RESEARCH RESULTS DIGEST

October 2002—Number 270

Subject Area: IIIB Materials and Construction

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Relationship of Portland Cement Characteristics to Concrete Durability

An NCHRP digest of the findings from the final report on NCHRP Project 18-05, "Relationship of Portland Cement Characteristics to Concrete Durability," conducted by Pennsylvania State University. Dr. Della M. Roy served as Principal Investigator.

INTRODUCTION

This digest describes the findings of the research conducted under NCHRP Project 18-05 on the relationship of portland cement characteristics to concrete durability and presents tentative recommendations for modifying cement specifications and test methods.

The chemical requirements and physical properties of portland cement are set forth in AASHTO M 85, "Standard Specification for Portland Cement." However, many concrete bridge decks, pavements, and other highway structures, built with concrete mixtures incorporating portland cement meeting these requirements, have exhibited varying degrees of premature deterioration caused by factors such as freezing and thawing, internal and external sulfate attack, alkali-aggregate reaction, and reinforcing steel corrosion. There has been considerable debate recently about the contribution of cement to this deterioration, particularly in view of the adoption of cost-effective, energy-efficient, and environmentally beneficial cement production methods that seem to influence cement characteristics. Although a great deal of research has been performed to address the various aspects of concrete durability, this research has not provided clear conclusions concerning the combinations of portland cement characteristics that will enhance concrete durability. Therefore, there is a need to assess the effects of cement characteristics on concrete durability; identify combinations of chemical, physical, and mineralogical requirements to ensure durability; and develop recommendations to help improve cement specifications. NCHRP Project 18-5 was conducted to address this need.

The research was conducted under NCHRP Project 18-5, "Relationship of Portland Cement Characteristics to Concrete Durability," by Pennsylvania State University. Completed in April 2001, the research included a laboratory investigation of portland cement characteristics and their relationship to durability of concrete used in highway applications. This digest provides a summary of the work performed in this research. The materials in this digest are extracted from the project's final report.

FINDINGS

As part of this project, changes in portland cement composition that occurred in recent years were identified, a laboratory investigation was conducted to determine the effects of cement characteristics on certain aspects of concrete durability, and recommendations for changes to cement specifications were made.

Changes in Portland Cement Composition

Review of related literature revealed that several studies were conducted to determine the changes over the years in characteristics of portland cement produced in the United States and other countries. These studies revealed the following observations:

- C_3S content has risen steadily, corresponding C_2S has fallen, and proportions of C_3A and C_4AF have not changed;
- Modern cements are finer than earlier cements;

change in particle size distribution over time is not well documented;
- Alkali level has increased, because of the increased use of more energy-efficient dry manufacturing processes;
- Heat of hydration has increased, particularly at earlier ages of curing; and
- Increases in C_3S/C_2S ratio have resulted in increases in compressive strength at earlier ages.

Durability Properties

Long-term performance of concrete used in highway applications depends on its ability to resist chemical and physical reactions resulting from the interaction of concrete ingredients and effects of climate, environment, and applied loads. To ensure long-term durability, concrete is expected to provide adequate resistance to external sulfate attack, secondary ettringite formation, alkali-aggregate reaction, shrinkage cracking, corrosion potential, and freezing and thawing.

Laboratory Investigation

To evaluate the effects of cement characteristics on concrete durability, a laboratory investigation involving different cements and mortar and concrete mixtures was conducted. In this investigation, 21 portland cements with a wide range of compositions were used. For example:

- SO_3 content ranged from 1.8 to 4.2%,
- C_3A content ranged from 3.0 to 15.0%,
- Equivalent alkalis ranged from 0.1 to 1.1%, and
- Blaine Fineness ranged from 300 to 460.

All cements were categorized as Type I or Type II according to AASHTO M 85 and were subjected to a series of chemical and physical characterization tests. Mortar mixtures were prepared for alkali-silica reaction, sulfate attack, and delayed ettringite tests. Concrete mixtures were prepared for compressive strength, chloride ion permeability, and cracking tendency tests. All tests were conducted in accordance with applicable AASHTO or ASTM test methods.

Highlights of Test Results

Statistical analyses of the relationships between 71 cement characteristics and durability properties were performed using multi-variant and response surface modeling approaches. Excerpts of the findings made based on these analyses are presented.

Chemical and Physical Characterization

Test results showed the presence of nested belite crystals in more than 50% of the clinker samples. Results of the tests conducted on cement samples and concrete specimens indicated that the presence of nested belite crystals has contributed to higher equivalent alkali concentrations, and below average 180-day compressive strength. Also, the results indicated an apparent influence of the size of alite crystals on cement and mortar properties. For example, low equivalent alkali concentrations with large size alite crystals were associated with lower than average mortar compressive strength.

Alkali-Silica Reaction

Based on tests performed according to ASTM C 441, "Standard Test Method for Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction," the total equivalent alkali content reflected the strongest contribution to expansion due to alkali-silica reaction. Tests showed the presence of potassium and sodium oxides in the cement; the potassium oxide content was the dominant component in controlling ASR reaction with the sodium oxide provided somewhat lesser effect. The analysis of test results revealed a positive correlation with total equivalent alkali content and negative correlation with silica content. One-year tests performed according to ASTM C 227, "Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations," using highly reactive aggregates, did not discriminate between the different cements.

Compressive Strength

Results of the 28- and 90-day compressive strength tests showed a strong negative single-variable correlation with total equivalent alkali. An analysis using response surface modeling showed a strong negative correlation of the 28- and 180-day compressive strength with total equivalent alkali and Fe_2O_3.

Delayed Ettringite Formation

Test results for air-entrained specimens cured at 80°C produced a weak single-variable correlation with sulfate content; slightly better correlation was noted for the ratio of sulfate to calcium oxide. A weak correlation with sulfate and a negative correlation with calcium oxide were observed for non-entrained specimens cured at 60°C.

Chloride Ion Permeability

A very strong correlation was found between current passed at 30 minutes and current passed after 6 hours. In general, chloride ion permeability decreased with the increase in compressive strength. A weak correlation was observed between heats of hydration at 1, 7, and 14 days and chloride permeability at 28 and 90 days. Strong statistical correlation between fineness or total equivalent alkali con-

tent and rapid chloride permeability test results could be established.

Sulfate Attack

The analysis showed a very high negative correlation of sulfate attack with C_4AF and Fe_2O_3. Also, a strong correlation was noted between C_3A/C_4AF ratio and 6-month expansion. A much weaker correlation was observed for both total equivalent alkali and alumina contents.

Cracking Tendency

A correlation between the chemical and physical characteristics of the cement and the time to cracking could not established based on the results of cracking tendency tests.

TENTATIVE RECOMMENDATIONS

Based on the test data obtained in this research, the following recommendations are proposed for modifying current cement specifications and related tests:

1. Provisional acceptance of cements with SO_3 content greater than 3.5 percent if supported by test data,
2. Limiting K_2O content to no more than 0.8 percent,
3. Use of C_3A/C_4AF ratio instead of C_3A for cement type classification,
4. Extension of test duration for delayed ettringite formation testing, and
5. Reduction of duration of the rapid chloride ion permeability test.

Recognizing that these recommendations were made on the basis of a limited investigation, they should be regarded as preliminary and further assessment should be encouraged.

CONCLUSIONS

The need to assess the effects of cement characteristics on concrete durability; identify combinations of chemical, physical, and mineralogical requirements to ensure durability; and develop recommendations to help improve cement specifications has been recognized by state highway agencies and other organizations. This research presented the results of a laboratory investigation designed to address this need. However, because of the limited scope of the investigation, tentative recommendations for modifying the current cement specifications and test methods could be made. Further evaluation of these recommendations are encouraged for ensuring their validity prior to incorporation in specifications and test methods.

FINAL REPORT

The agency's final report, titled "Relationship of Portland Cement Characteristics to Concrete Durability," gives a detailed account of the project, findings, and conclusions and includes a CD-ROM that contains test data. The report, which was distributed to NCHRP sponsors (i.e., the state departments of transportation), is available for loan on request to the National Cooperative Highway Research Program, Transportation Research Board, 500 Fifth Street, N.W., Washington, DC 20001.

ACKNOWLEDGMENTS

The research summarized herein was performed under NCHRP Project 18-05 by Pennsylvania State University. Dr. Della M. Roy served as principal investigator. Other key researchers were Drs. Paul Tikalsky, Barry E. Scheetz, and James L. Rosenberger.

These digests are issued in order to increase awareness of research results emanating from projects in the Cooperative Research Programs (CRP). Persons wanting to pursue the project subject matter in greater depth should contact the CRP Staff, Transportation Research Board of the National Academies, 500 Fifth Street, NW, Washington, DC 20001.

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