NCHRP

REPORT 540

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Guidelines for Early-Opening-to-Traffic Portland Cement Concrete for Pavement Rehabilitation

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 540

Guidelines for Early-Opening-to-Traffic Portland Cement Concrete for Pavement Rehabilitation

T. J. Van Dam
K. R. Peterson
L. L. Sutter
A. Panguluri
J. Sytsma
Michigan Technological University
Houghton, MI

N. Buch
R. Kowli
P. Desaraju
Michigan State University
East Lansing, MI

Subject Areas
Pavement Design, Management, and Performance • Materials and Construction

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2005
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

Note: The Transportation Research Board of the National Academies, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

NCHRP REPORT 540

Project 18-04B

ISSN 0077-5614

ISBN 0-309-08835-6

Library of Congress Control Number 2005932287

Price $20.00

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. William A. Wulf are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is a division of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation through research. In an objective and interdisciplinary setting, the Board facilitates the sharing of information on transportation practice and policy by researchers and practitioners; stimulates research and offers research management services that promote technical excellence; provides expert advice on transportation policy and programs; and disseminates research results broadly and encourages their implementation. The Board's varied activities annually engage more than 5,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS STAFF FOR NCHRP REPORT 540

ROBERT J. REILLY, *Director, Cooperative Research Programs*
CRAWFORD F. JENCKS, *Manager, NCHRP*
AMIR N. HANNA, *Senior Program Officer*
EILEEN P. DELANEY, *Director of Publications*
BETH HATCH, *Editor*

NCHRP PROJECT 18-04B
Field of Materials and Construction—Area of Concrete Materials

KIRSTEN STAHL, *California DOT* (Chair)
LAWRENCE W. COLE, *Carmeuse North America, Pittsburgh, PA*
CHARLES J. KORHONEN, *US Army Corps of Engineers*
CHARLES F. SCHOLER, *Purdue University*
DONALD A. STREETER, *New York State DOT*
WILLIAM L. TRIMM, *Jefferson City, MO*
SUNEEL VANIKAR, *FHWA*
ANDREW J. WIMSATT, *Texas DOT*
STEPHEN W. FORSTER, *FHWA Liaison*
FREDERICK HEJL, *TRB Liaison*
INAM JAWED, *TRB Liaison*

AUTHOR ACKNOWLEDGMENTS

The guidelines presented herein were prepared under NCHRP Project 18-04B, "Durability of 'Early-Opening-to-Traffic' Portland Cement Concrete for Pavement Rehabilitation," by researchers at Michigan Technological University (MTU), Michigan State University (MSU), and the Michigan Department of Transportation (DOT). MTU was the prime contractor for this study; MSU and the Michigan DOT were subcontractors. Thomas J. Van Dam, Associate Professor of Civil and Environmental Engineering, MTU, was the principal investigator.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents guidelines to facilitate highway agencies' use of "early-opening-to-traffic" (EOT) concrete for pavement rehabilitation, thereby reducing pavement closure and accruing economic and environmental benefits. These guidelines address the proportioning, testing, construction, and other aspects of EOT concrete. This report will be of particular interest to engineers, researchers, and others concerned with the construction and rehabilitation of concrete pavements.

With increasing traffic in urban areas, motorists are becoming less tolerant of delays during pavement rehabilitation. To minimize delays, state highway agencies use EOT rehabilitation strategies that allow work to be completed at night or during periods of low traffic. Generally, portland cement concrete used in these applications is expected to become strong enough to carry traffic within 6 to 24 hours after placement. Rigorous requirements for mix design and strength development have usually been stipulated for EOT concrete applications, often with limited consideration given to materials and construction aspects that influence long-term performance and durability. Much of the recent research on EOT concrete focused on its mechanical properties; limited research dealt with durability aspects of this type of concrete. Thus, research was needed to evaluate the durability of the concrete used in these applications and to recommend guidelines that address relevant aspects of EOT concrete to help achieve long-term performance, durability, and cost-effectiveness.

Under NCHRP Project 18-4B, "Durability of 'Early-Opening-to-Traffic' Portland Cement Concrete for Pavement Rehabilitation," Michigan Technological University of Houghton was assigned the objective of developing guidelines for materials, mixtures, and construction techniques of portland cement concrete used in EOT pavement rehabilitation. The research focused on durability aspects of EOT concrete used for full-depth rehabilitation (e.g., full-depth repair and slab replacement) and dealt with concrete mixtures that are suited for opening to traffic within 6 to 8 hours or 20 to 24 hours after placement. To accomplish this objective, the researchers performed the following tasks:

1. Reviewed and synthesized information relevant to the materials and practices used for EOT concrete construction.
2. Evaluated six in-service EOT concrete rehabilitation projects located in four states.
3. Conducted laboratory tests on a large number of concrete specimens involving a wide range of mixtures appropriate for use in EOT pavement rehabilitation.
4. Conducted statistical analysis of the data obtained from the field and laboratory evaluations.
5. Developed guidelines for the proportioning, testing, and construction of EOT concrete.

The guidelines recommended in this project address the different issues associated with the use of EOT concrete for pavement rehabilitation. In these guidelines, the researchers summarized the state of practice for EOT concrete repairs, identified material properties that impact EOT concrete performance, discussed materials and mixture design considerations that pertain to the durability of EOT concrete, and identified performance-related tests of fresh and hardened concrete. The researchers concluded that, while designing and constructing durable 6- to 8-hour and 20- to 24-hour EOT concrete is feasible, proportioning and constructing durable 6- to 8-hour EOT concrete is particularly challenging. The researchers also highlighted the importance of ensuring an adequate entrained air-void system and further recommended that certain tests be conducted on actual job mixtures to account for potential adverse interactions between concrete constituents. These guidelines will assist in selecting materials and mixtures that are suited for EOT concrete and, therefore, will help pavement engineers consider rehabilitation methods that will reduce pavement closure and yield economic and environmental benefits.

The guidelines recommended in this project are presented herein. The agency report on the research performed in this project is accessible on the web as *NCHRP Web-Only Document 76* at www.trb.org/news/blurb_detail.asp?id=5203.

CONTENTS

GUIDELINES FOR EARLY-OPENING-TO-TRAFFIC PORTLAND CEMENT CONCRETE FOR PAVEMENT REHABILITATION

SUMMARY

Because of its unique properties, early-opening-to-traffic (EOT) concrete is more susceptible to durability-related distress than conventional concrete. For example, the use of high cement contents and multiple admixtures can lead to increased shrinkage, altered microstructure, and unexpected interactions. Further, the ability of standard testing to detect durability-related problems is limited, and thus deficiencies may go undetected through the mixture design and construction process.

NCHRP Project 18-04B was conducted to evaluate the durability characteristics of EOT concrete to develop guidelines for materials, mixtures, and construction techniques that enhance long-term durability of EOT concrete for pavement rehabilitation. The research dealt with concrete mixtures that are suited for opening to traffic within (a) 6 to 8 hours and (b) 20 to 24 hours after placement and was limited to full-depth rehabilitation, such as a full-depth repair and slab replacement. In the course of the project, a review of literature was used to design an experiment that evaluated both field- and laboratory-prepared EOT concrete mixtures. In the experiment, 6- to 8-hour and 20- to 24-hour EOT concrete mixtures obtained from four states (Ohio, Georgia, Texas, and New York) were evaluated to determine typical mixture properties and performance characteristics. Also, a laboratory study was undertaken to produce and test 28 different EOT concrete mixtures (two replicates or batches were made for each mixture for a total of 56 batches). The testing included assessment of the properties of the fresh concrete, volume change, freeze-thaw durability, microstructural characterization, and the absorption/porosity of the concrete. The results were analyzed to draw conclusions regarding the durability of the mixtures and to form the basis for the guidelines. It is expected that the application of these guidelines will enable SHAs to better understand mixture design, proportioning, and construction practices that affect EOT concrete durability and to achieve longer-lasting EOT concrete repairs.

The following general observations were made based on the results of this study:

- In general, the concrete obtained in the field and the concrete produced in the laboratory were of good quality. Difficulty was encountered in obtaining non-durable concrete for use in the analyses. This finding indicates that, although some durability problems have been observed in EOT concrete repairs, durable, long-lasting EOT concrete can be produced both in the laboratory and in the field.

- One problem observed in both the field and the laboratory concrete was poorly formed air-void systems that were adequate to protect the concrete against freeze-thaw damage. In the laboratory, the creation of inadequate air-void systems appeared to be linked to interactions between mixture constituents (e.g., the type of cement and high-range water reducer [HRWR] used in this study). Three of the four 6- to 8-hour EOT concrete and two of the 20- to 24-hour EOT concrete mixtures that were made with Type III cement and Type F HRWR had insufficient air contents as measured in the hardened concrete. It was difficult to control the air content in mixtures made with high cement contents, low water/cement (*w/c*) ratio, and multiple admixtures, especially if Type III cement was used. No specific conclusions can be drawn regarding the general use of Type III cement and/or Type F HRWR as only a single source of each was used in this study. Thus, testing must be conducted to determine if damaging interactions occur. It is noted that all mixtures made with the Type III cement in this study required the use of the Type F HRWR to obtain sufficient workability.
- In general, less homogeneous paste and more microcracking were observed in the field concrete as well as in the laboratory-prepared, 6- to 8-hour EOT concrete specimens. Paste homogeneity of laboratory-prepared specimens, as assessed using the relatively low magnification of the petrographic optical microscope, was better in the 20- to 24-hour mixtures. It appeared that the mixtures made with the Type III cement were slightly less homogenous than those made with Type I cement. Better cement grain dispersion was even observed when the Type F HRWR was used with Type I cement. Severe microcracking of the paste was observed in all of the laboratory-prepared, 6- to 8-hour concrete mixtures. Less severe microcracking was observed in the 20- to 24-hour EOT concrete mixtures, indicating a more consistent and less stressed paste.
- In the field study, although attempts were made to avoid EOT concrete with known alkali-aggregate reactivity problems, alkali-silica reactivity (ASR) was observed in both types of materials obtained from Ohio. However, it was far less prevalent in the 20- to 24-hour EOT concrete repairs, which contained microsilica as a supplementary cementitious material.
- In the laboratory study, all of the 20- to 24-hour EOT concrete mixtures performed well in the cyclic freeze-thaw testing (AASHTO T 161), whereas some of the 6- to 8-hour mixtures performed poorly, exhibiting relatively high dilation values. Some of these 6- to 8-hour EOT concrete mixtures were made with Type III cement and Type F HRWR and had low air contents. In cases where significant dilation occurred, the dilation correlated mildly with the spacing factor as determined by ASTM C 457. There was some correlation between the air content measured in the hardened concrete and that measured in the fresh concrete, although the air content measured in the fresh concrete was higher than that measured in the hardened concrete when the air content was less than 6 percent. Also, there was little correlation between the air content of fresh concrete and the spacing factor as measured by ASTM C 457. These findings indicate that the air content measured in fresh concrete is not always a good predictor of the suitability of the air-void system to protect the concrete against freeze-thaw damage. The spacing factor was generally found to be a fairly reliable predictor of potential freeze-thaw performance, although in one instance a mixture with a spacing factor below the recommended maximum of 0.200 mm had relatively high dilations.
- In the laboratory study, the scaling results were variable, although the degree of scaling was significantly higher for the 6- to 8-hour EOT concrete mixtures than

for the 20- to 24-hour EOT concrete mixtures. The mixtures with Type III cement and Type F HRWR suffered high degrees of deicer scaling, but there was little correlation between the two batches. These results illustrate the importance of using multiple batches and replicates when conducting durability testing. Further, analysis using the x-ray microscope revealed significantly less overall penetration of chloride ions into the 6- to 8-hour EOT concrete mixtures than into the 20- to 24-hour EOT concrete mixtures, probably due to the reduced *w/c* ratio.
- The majority of the 6- to 8-hour EOT concrete mixtures did not meet the compressive and flexural strength criteria at 6 hours, although most gained sufficient strength by 8 hours. Almost all of the 20- to 24-hour concrete mixtures met the strength criteria by 20 hours. The 6- to 8-hour EOT concrete mixtures had higher 24-hour strengths than the 20- to 24-hour concrete mixtures. Test results did not show a consistent relationship between compressive strength and flexural strength, indicating that if such a correlation is required for construction monitoring, it should be determined on a mix-by-mix basis.

The following findings should be considered in selecting EOT concrete mixtures:

- Durable 6- to 8-hour and 20- to 24-hour EOT concrete repairs can be constructed, but the 6- to 8-hour EOT concrete materials are more prone to durability-related problems, and thus the risk of premature failure is heightened when the fastest-setting materials are used. Since these materials are also more costly, 6- to 8-hour EOT concrete should be used only in applications where the decrease in user costs incurred from shortened lane closures can justify the added expense and risk.
- Difficulty in achieving an adequate entrained air-void system is an important durability problem associated with EOT concrete, resulting in paste freeze-thaw deterioration and deicer scaling. It is therefore recommended that additional efforts be expended to verify the adequacy of the air-void system for the concrete mixtures, especially those for 6- to 8-hour EOT.
- Increasing cement content does not necessarily increase concrete strength and may adversely influence the durability of EOT concrete mixtures. The early strength criterion and enhanced durability may be effectively achieved by reducing the *w/c* ratio while increasing the aggregate volume as long as workability is maintained.
- Because possible problems may result from interactions between the various mixture constituents, it is essential that testing be conducted on the actual job mixture during mixture design and construction monitoring. More rigorous testing may be employed during research studies and investigations.
- State-of-the-practice construction practices must be followed to ensure durability of the repair. Because EOT concrete repairs are generally done rapidly, the quality of construction is critical. When good mixture design and construction practices are followed, premature failure will be minimized.

These guidelines are expected to help SHA personnel to better understand mixture design, proportioning, and construction practices that affect EOT concrete durability.

CHAPTER 1

INTRODUCTION

With increasing traffic in urban areas, motorists are becoming less tolerant of delays during pavement rehabilitation. To minimize delays, state highway agencies (SHAs) use early-opening-to-traffic (EOT) rehabilitation strategies that minimize the time of lane closure. Generally, portland cement concrete (PCC) used in these applications is expected to gain sufficient strength to carry traffic within 6 to 24 hours after placement. Rigorous requirements for strength development have usually been stipulated for EOT concrete applications, often with limited consideration given to materials and construction aspects that influence long-term durability. Much of the research conducted on EOT concrete investigated the mechanical properties of the mixtures, but not the durability aspect. Information on the durability of the concrete used in these applications is needed to assess the long-term performance of the rehabilitated pavement.

The unique properties of EOT concrete make it more susceptible to durability-related distress than conventional concrete. For example, the use of high cement contents and multiple admixtures can lead to increased shrinkage, altered microstructure, and unexpected interactions. Further, the ability of standard testing to detect durability problems is limited, and thus deficiencies may go undetected through the mixture design and construction process.

Research to address these needs was conducted under NCHRP Project 18-04B, "Durability of 'Early-Opening-to-Traffic' Portland Cement Concrete for Pavement Rehabilitation." The research focused on concrete mixtures suited for opening to traffic within (a) 6 to 8 hours and (b) 20 to 24 hours after placement and was limited to full-depth rehabilitation, such as a full-depth repair and slab replacement. In this project, both field- and laboratory-prepared EOT concrete mixtures were evaluated. Core specimens from eight mixtures from four states were obtained, and 28 different EOT concrete mixtures were prepared in the laboratory. These mixtures were tested and the results analyzed to assess the properties of the fresh and hardened concrete. The work performed under this study provided the basis for the guidelines presented herein. The agency report is available on the web as *NCHRP Web-Only Document 76* at www.trb.org/news/blurb_detail.asp?id=5203.

These guidelines include a summary of state-of-the-practice construction techniques and specifications used by state DOTs for EOT concrete materials. Performance considerations related specifically to EOT concrete materials—including strength, shrinkage, durability, microstructure, and absorption/permeability—are discussed. Materials and mixture design considerations are then reviewed along with various test methods used to assess the fresh concrete properties, measures of compressive strength and/or flexural strength, volume change, durability in freeze-thaw environments, absorption/permeability, and microstructural characterization techniques. A recommended program for material testing during mixture design and in the course of related investigations and research is also described. The guidelines are expected to assist engineers in selecting appropriate materials, mixtures, and construction techniques for use in EOT concrete repairs. The next two chapters summarize the state of the practice with regards to EOT concrete materials, placement, and performance considerations. Recommendations for selecting materials and testing EOT concrete mixtures are presented in Chapters 4 and 5.

CHAPTER 2

STATE OF THE PRACTICE FOR EOT CONCRETE REPAIRS

Full-depth repair is a commonly used concrete pavement restoration technique for restoring both structural integrity and ride quality to concrete pavements suffering distresses listed in Table 1 (FHWA 2003). By definition, full-depth repairs are made through the entire depth of the pavement slab, are almost always full width across the lane, and have minimum specified lengths dependent upon the design of the existing pavement. After the repair boundaries are demarcated with full-depth saw cuts and the deteriorated concrete is removed, the base is repaired, the load-transfer devices are installed, and new PCC is placed. EOT concrete is commonly used in situations where lane closure must be kept to a minimum.

There are a number of sources of information regarding full-depth repair of concrete pavement, including publications by the Federal Highway Administration (FHWA 2003), the American Concrete Pavement Association (ACPA 1995), and the National Highway Institute (NHI 2001). Although these publications do not specifically address EOT concrete, they discuss the selection of candidate projects, the sizing of repairs, the installation of load transfer, material selection, construction procedures, and to some degree performance and cost considerations. Only limited discussions of material selection are contained in these documents, and little if any guidance is provided for assessing the durability characteristics of the EOT concrete mixtures. This chapter details the state of the practice for mixture constituents and proportioning, construction practices, durability concerns, and test methods commonly used to assess durability.

2.1 MIXTURE CONSTITUENTS AND PROPORTIONS

The main difference between EOT concrete and normal paving concrete is that strength gain occurs much more rapidly in EOT concrete, thus more cement, less water, admixtures, and aids to retain heat are commonly used. This section discusses the various constituents and mixture proportioning of EOT concrete.

2.1.1 Constituent Materials

For the most part, EOT concrete is composed of the same constituents as normal paving concrete. Coarse and fine aggregates are blended with portland cement, water, and admixtures to produce a stiff but moldable mass that hardens through a chemical process referred to as hydration. In the resulting stone-like mass, the aggregates have been bound together by the hydration products formed through chemical reactions between the water and cement. Air is also entrapped and/or entrained, typically making up 5 to 7 percent of the total mixture volume.

Aggregates

Aggregates make up 70 to 80 percent of the total volume of hardened concrete (Folliard and Smith 2003). As such, they have a large impact on the behavior of the composite. Many characteristics and test methods are used to assess aggregates. Folliard and Smith (2003) recommended essential (Level I) and optional/additional (Level II) tests (shown in Table 2) for evaluating aggregates to be used in concrete pavements. The concrete durability can be compromised through aggregate reactivity (alkali-silica or alkali-carbonate reactivity) or aggregate susceptibility to freeze-thaw damage. These topics are not covered in these guidelines, but relevant information is available elsewhere (Farney and Kosmatka 1997, ACI 2003a, Folliard and Smith 2003, Schwartz 1987, and Stark 1976).

Another aggregate property that may impact EOT concrete durability is the coefficient of thermal expansion (CTE) of the aggregate, which strongly influences the CTE of the concrete. The CTE of a material is defined as the change in unit length per degree of temperature change. Differences in the CTE between aggregate and cement paste can lead to the development of thermal stresses within the concrete (Mindess et al. 2003) and in extreme cases may result in separation between the aggregate and the paste (Neville 1996). These differential thermal movements—either between the aggregate and cement paste or between different aggregates in the same concrete—could lead to deterioration (Lea 1971). In addition, because the CTE influences the thermal stresses developed in concrete, its consideration is particularly important in EOT concrete pavement materials selection.

As previously stated, the CTE of concrete is strongly related to the proportion and type of coarse aggregate used. The CTE for the aggregate is generally lower than the coefficient for cement paste. For example, the CTE is approximately $11–13 \times 10^{-6}$/°C ($6.1–7.2 \times 10^{-6}$/°F) for a quartzite

TABLE 1 General distress criterion for full-depth repair (FHWA 2003)

Pavement Type	Distress Type	Minimum Severity Level Required for Full-Depth Repair
Jointed Plain and Jointed Reinforced Concrete (JPC and JRC) Pavement	Blowup	Low
	Corner Break	Low
	D-Cracking	Medium
	Deterioration Adjacent to Existing Repair	Medium
	Joint Deterioration	Medium (with faulting 6 mm [0.25 in.])
	Spalling	Medium
	Reactive Aggregate	Medium
	Transverse Cracking	Medium (with faulting 6 mm [0.25 in.])
	Longitudinal Cracking	High (with faulting 12 mm [0.5 in.])
Continuously Reinforced Concrete Pavement (CRCP)	Blowup	Low
	Punchout	Medium (with faulting 6 mm [0.25 in.])
	Transverse Cracking (Steel Rupture)	Medium (with faulting 6 mm [0.25 in.])
	Localized Distress	Medium
	Construction Joint Distress	Medium
	D-Cracking	High
	Longitudinal Cracking	High (with faulting 12 mm [0.5 in.])
	Repair Deterioration	High

aggregate and 6×10^{-6}/°C (3.3×10^{-6}/°F) for a limestone aggregate, and in the range of 18–20×10^{-6}/°C (10–11×10^{-6}/°F) for cement paste (Mindess et al. 2003).

Research has led to some correlation between CTE for concrete and durability of mixtures. Lab tests have shown that concrete having higher CTEs are less resistant to temperature changes than concrete with lower CTEs (Neville 1996).

Portland Cement

In many applications, the use of a standard AASHTO M 85 Type I cement can provide satisfactory results for EOT concrete repairs. However, Type III cement is commonly used in EOT concrete materials because of its high–early-strength gain. The required chemical properties of Type III cements are similar to those of Type I, but Type III cements are ground more finely to promote the development of higher early strength. In some cases, Type II cements have been used in EOT concrete materials. Regardless of the cement type used, the engineer must carefully evaluate the properties of the cement in the context of the long-term physical and chemical stability and their effect on durability.

Standard specifications for blended hydraulic cements are provided in AASHTO M 240. These cements are formed by intimately blending portland cement with fine materials such as ground granulated blast-furnace slag, fly ash or other pozzolans, hydrated lime, and pre-blended cement combinations of these materials (Kosmatka et al. 2002). These cements have not been commonly used in EOT concrete projects in the United States because of their generally slower rate of hydration.

Chemical Admixtures

Chemical admixtures—such as air entrainers (AASHTO M 154), accelerators, and water reducers (AASHTO M 194)—are commonly added to EOT concrete mixtures during proportioning or mixing to enhance the properties of freshly mixed and/or hardened concrete. Descriptions of these and other chemical admixtures can be found in a number of sources (Kosmatka et al. 2002, Mehta and Monteiro 1993, Mindess et al. 2003). It is reported that cement/admixture interactions are not well understood and that compatibility problems can result in non-durable concrete (Kosmatka et al. 2002, Mindess et al. 2003).

Air Entrainers. Air-entraining admixtures are specified and tested under AASHTO M 154 and T 157, respectively. Air-entraining admixtures are added just prior to or during concrete mixing. When a high-range water reducer (HRWR) is used, the air entrainer should be added first to form a stable air-void system that protects the hardened concrete against freeze-thaw damage and deicer scaling (Mindess et al. 2003). The entrained air also improves the workability of the fresh concrete, thus helping reduce segregation and bleeding.

The amount of entrained air required to protect normal concrete depends on the exposure level and the nominal maximum aggregate size. The ACI recommended air contents for frost-resistant concrete (ACI 2003b) are reproduced in Table 3.

One concern for EOT concrete mixtures, especially those made with an HRWR, is the ability to achieve a desirable air-void system in high–cement-content mixtures (Whiting and Nagi 1998). Thus, not only should such mixtures be tested for total air, but the spacing factor should also be measured during the mix design process (Mindess et al. 2003).

The air content of fresh concrete can be determined using AASHTO T 152 or T 196. Air content alone does not ensure the adequacy of the air-void system, but relatively good correlations exist between air content and frost resistance for air-entrained concrete. In recent years, the Air Void Analyzer (AVA) has been used for air-void system characterization in fresh concrete, with some SHAs using it during concrete pavement construction (FHWA 1996). The complete air-void system in hardened concrete can be assessed microscopically using procedures described in ASTM C 457. It has been observed in some mixtures, particularly those of high strength, that adequate freeze-thaw durability exists even though the air-void system parameters are judged to be inadequate.

Accelerating Admixtures. Accelerating admixtures meeting the requirements of Type C or E in AASHTO M 194 are

TABLE 2 Recommended (Level I) and optional/additional (Level II) testing of aggregates for concrete pavements (Folliard and Smith 2003)

Level	Property	Test Method
I	Absorption	AASHTO T 84: *Specific Gravity and Absorption of Fine Aggregate* AASHTO T 85: *Specific Gravity and Absorption of Coarse Aggregate*
	Aggregate gradation	AASHTO T 21: *Sieve Analysis of Fine and Coarse Aggregate*
	Properties of microfines	AASHTO T 11: *Materials Finer than No. 200 Sieve and Mineral Aggregates by Washing* AASHTO T 176: *Plastic Fines in Graded Aggregates and Soils by the Use of the Sand Equivalent Test*
	Aggregate shape, angularity, and texture	AASHTO T 304: *Uncompacted Void Content of Fine Aggregate* AASHTO TP 56: *Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading)* ASTM D 4791: *Test Method for Flat and Elongated Particles in Coarse Aggregate*
	Aggregate thermal expansion	AASHTO TP-60: *Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete*
	Aggregate abrasion	CSA A23.2-23A: *Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* AASHTO TP 58: *Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* AASHTO T 96: *Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angles Machine*
	Elastic modulus	ASTM C 469: *Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*
	Polishing	ASTM D 3042: *Test for Acid Insoluble Residue in Carbonate Aggregates*
	Aggregate strength	British Standard 812 (Part 3): *Aggregate Crushing Value*
	Aggregate mineralogy	ASTM C 295: *Guide for Petrographic Examination of Aggregates for Concrete*
	Alkali-aggregate reactivity	ASTM C 295: *Guide for Petrographic Examination of Aggregates for Concrete* AASHTO T 303: *Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction* CSA A23.2-26A: *Determination of Potential Alkali-Carbonate Reactivity of Quarried Carbonate Rocks by Chemical Composition*
	Freezing and thawing resistance (D-cracking)	CSA A23.2-24A: *Unconfined Freezing and Thawing of Aggregates in NaCl Solution* AASHTO T 104: *Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate* (only magnesium sulfate is recommended) *Iowa Pore Index Test* *Modified Washington Hydraulic Fracture Test* (based on modifications detailed by Embacher and Snyder [2001])
II	Properties of microfines	AASHTO TP 57: *Standard Test Method for Methylene Blue Value of Clay, Mineral Fillers, and Fines*
	Aggregate mineralogy	X-ray diffraction (XRD) analysis Thermogravimetric analysis (TGA) X-ray fluorescence (XRF) analysis
	Alkali-aggregate reactivity	ASTM C 1293: *Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*
	Freezing and thawing resistance (D-cracking)	AASHTO T 161 (modified Procedure C): *Resistance of Concrete to Rapid Freezing and Thawing*

commonly used in EOT concrete repair materials. The American Concrete Institute, in "Chemical Admixtures for Concrete," defines an accelerating admixture as "a material added to concrete for the purpose of reducing the time of setting and accelerating early strength development" (ACI 2003c).

One group of accelerating admixtures contains a variety of soluble inorganic salts, such as calcium chloride, which is the best known and most commonly used accelerating admixture because it is relatively inexpensive and readily available. However, calcium chloride promotes corrosion of embedded steel and may have other negative effects on concrete durability, including increasing the amount of drying shrinkage (Lackey 1992) and adversely affecting the pore structure (Suryavanshi et al. 1995, Wang and Gillott 1990). These characteristics are believed to be at least partly responsible for the reduced freeze-thaw resistance exhibited in some mixtures containing calcium chloride accelerators (Neville 1996).

Calcium chloride is commercially available in an anhydrous and a dihydrate form. Commercial anhydrous calcium chloride is typically 94 to 97 percent calcium chloride by weight, whereas commercial flake products, which are close to dehydrate, typically are composed of 77 to 80 percent calcium chloride by weight (ACI 2003c). Although opinions vary slightly, the optimum dosage recommended is typically 2 percent for Type I calcium chloride (88 percent pure), and 1.5 percent for anhydrous calcium chloride (ACI 2003c, Mindess et al. 2003).

Several commercial non-chloride accelerators conforming to AASHTO M 194 Type C requirements for accelerating

TABLE 3 Recommended air contents for freeze-thaw distress resistant concrete (ACI 2003b)

Nominal Maximum Aggregate Size, mm (in.)	Average Air Content, Percent[1]	
	Moderate Exposure[2]	Severe Exposure[3]
9.5 (3/8)	6	7.5
12.5 (½)	5.5	7
19 (3/4)	5	6
25 (1)	5	6
37.5 (1½)	4.5[4]	5.5[4]
75 (3)	3.5[4]	4.5[4]
150 (6)	3	4

[1]A reasonable tolerance for air content in field construction is ± 1.5 percent.
[2]Exposure is outdoor in a cold climate where the concrete will be only occasionally exposed to moisture prior to freezing and where no deicing salts will be used. Examples are certain exterior walls, beams, girders, and slabs not in direct contact with soil.
[3]Exposure is outdoor in a cold climate where the concrete may be in almost continuous contact with moisture prior to freezing or where deicing salts are used. Examples are pavements, bridge decks, sidewalks, and water tanks.
[4]These air contents apply to the whole as for the preceding aggregate sizes. When testing these concretes, however, aggregate larger than 37.5 mm (1½ in.) is removed by handpicking or sieving and the air content is determined on the minus 37.5 mm (1½ in.) fraction of the mixture. (The field tolerance applies to this value.) From this, the air content of the whole mixture is computed.

admixtures contain calcium nitrate and ammonium calcium nitrate as active ingredients. Others conforming to AASHTO M 194 Type E requirements for water-reducing and accelerating admixtures and also conforming to Type C requirements contain calcium nitrate as a principal active ingredient. Research has shown that calcium nitrite is useful as a corrosion inhibitor in addition to its accelerating capabilities (Neville 1996). Other non-chloride, non-corrosive accelerators are available that contain compounds such as triethanolamine, sodium thiocyanate, and calcium formate.

It has been generally observed that concrete microstructure produced in rapidly setting concrete is coarser and composed of more soluble hydration products, which in turn is more prone to physical and chemical attack. It is therefore recommended that accelerators be used only when necessary and that the designer/engineer recognize that the use of accelerators may have a negative impact on the long-term durability of the concrete.

Water-Reducing Admixtures. Water-reducing admixtures are added to reduce the quantity of mixing water required to produce concrete of a given consistency. This reduction allows for a reduction in the water-to-cement (*w/c*) ratio while maintaining a desired slump, thus increasing strength while reducing permeability. A reduction in water content by 5 to 10 percent is obtainable through the use of conventional water reducers that are specified under AASHTO M 194 Type A. This class of water reducer will typically retard set, so accelerators are often added to offset this effect. Water reducers that act as accelerators are specified under AASHTO M 194 Type E.

The effect of water reducers on the fresh concrete properties varies with the chemical composition of the admixture, the concrete temperature, cement composition and fineness, cement content, and presence of other admixtures (Kosmatka et al. 2002). For Type A and Type E water reducers, the effect on the air-void structure is unclear, with some sources reporting either no effect or an improvement (Kosmatka et al. 2002) while others reporting possible adverse effects (Pigeon and Plateau 1995). HRWRs, also called superplasticizers, are specified under AASHTO M 194 Type F and Type G and can reduce water content by 12 to 30 percent. In some instances, they have application in EOT concrete mixtures where high cement contents and low *w/c* ratios are desired. This is particularly true if the cement is finely ground, as are many Type III cements. One drawback is that air voids produced in concrete made with HRWRs are often large, which increases the spacing factor and, on occasion, creates instability in the air-void system (Kosmatka et al. 2002, Pigeon and Plateau 1995). Thus, the fresh and hardened concrete properties of mixtures containing water reducers should be thoroughly evaluated during design to determine the extent of detrimental interactions that may occur.

2.1.2 State-of-the-Practice Mixture Proportioning

This section presents a brief summary of common practice regarding EOT concrete mixture proportioning as presented in publications by the FHWA (2003), ACPA (1995), and the NHI (2001). In these publications, it is noted that EOT concrete repair materials use similar constituents and proportioning as normal paving concrete, except that higher cement contents and lower *w/c* ratios are common. In addition, materials that lead to accelerated strength gain—such as Type III cement, chemical accelerators, and water-reducing admixtures—are also used. Specifically, the following items are reported in these publications:

- Type I or III cements are commonly used in EOT concrete. Additional water may be required to enhance workability with Type III cements. The use of a water reducer can reduce this need for additional water (ACPA 1995).
- Common cement contents for mixtures that are to be opened to traffic within 24 hours range from 385 to 530 kg/m^3 (650 to 890 lb/yd^3), with more cement being added for earlier opening times. For 24-hour accelerated strength concrete, a draft specification stipulates a minimum cement content of 446 kg/m^3 (750 lb/yd^3) (FHWA 2003).
- The *w/c* ratio in EOT concrete is typically between 0.40 and 0.48. A draft specification for 24-hour accelerated strength concrete stipulates a maximum *w/c* ratio of 0.45 (FHWA 2003).
- An accelerator is commonly employed and is almost a necessity for mixtures that are to be opened in 6 to 8 hours. The most common accelerator is calcium chloride, which is commonly added at 1 percent by weight of cement when the air temperature exceeds 27°C (80°F) and up to 2 percent by weight of cement when the air temperature is lower.

Tables 4 and 5 summarize SHA specifications for EOT concrete repair materials for 6- to 8-hour opening time and 20- to 24-hour opening time, respectively.

Six- to 8-hour EOT Concrete

Table 4 summarizes the mixture characteristics of the 6- to 8-hour EOT concrete specified by 16 SHAs. Although time to opening was frequently stipulated in the specifications, strength requirements were also used. For example, the time-to-opening criterion presented in Table 4 vary from as early as 4 hours (Kansas and Ohio) to as late as 12 hours (Maryland and Minnesota). In some cases, only a time to opening or a strength criterion was established, and some SHAs used a strength criterion in addition to time to opening. Florida, for example, specified that the compressive strength must exceed 21 MPa (3,000 psi) in 24 hours while allowing a 6-hour time to opening. In New York, the repair was opened to traffic once the surface temperature of the repair reached 65°C (150°F). Although it is difficult to glean from these specifications and special provisions the exact strength requirements during the initial 6- to 8-hour period, the required compressive strength at opening varied from 8.3 to 24.0 MPa (1,200 to 3,500 psi), whereas the required minimum flexural strength (as measured by third-point loading) ranged from 1.8 to 2.8 MPa (260 to 400 psi).

In NHI's *PCC Pavement Evaluation and Rehabilitation*, both minimum strength requirements and time to opening requirements are recognized as being acceptable (NHI 2001). According to this publication, the flexural strength criterion for opening to traffic is 1.7 MPa (250 psi) for third-point loading and 2.1 MPa (300 psi) for center-point loading, and the compressive strength criterion is 13.8 MPa (2,000 psi) (FHWA 2003). The NHI document also states that having a strength requirement is preferable and that maturity meters or pulse-velocity devices may be useful for monitoring the strength development of very high–early-strength materials (e.g., 4 hours or less of curing time).

All of the 16 states except California that specify use of calcium sulfoaluminate (CSA) cement used either Type I or Type III portland cement in the 6- to 8-hour EOT concrete materials. When specified, the minimum cement contents varied, ranging from 440 to 534 kg/m^3 (740 to 900 lb/yd^3) for Type I and 390 to 490 kg/m^3 (660 to 825 lb/yd^3) for Type III. The use of accelerators was specified for mixtures containing Type I cement, with the most common accelerator being calcium chloride. Notable exceptions to this standard were New Jersey and Pennsylvania, which prohibited the use of a chloride-based accelerator. Some of the mixtures proportioned with Type III cement did not specify the use of an accelerator, relying on the early strength gain of the cement. The *w/c* ratios for the 6- to 8-hour EOT concrete mixtures vary widely, with maximum values ranging from 0.33 to 0.49. In general, higher *w/c* ratios were allowed for mixtures containing Type III cement. In no instance was a supplementary cementitious material (e.g., fly ash, ground granulated blast furnace slag [GGBFS], and silica fume) specified for use in 6- to 8-hour EOT concrete mixtures.

Admixtures commonly specified for use in 6- to 8-hour EOT concrete mixtures included air entrainers, accelerators, and water reducers. In no case was the type of air-entraining agent specified, but instead air content was specified either directly or through reference to the SHA's standards for normal paving concrete. The most commonly specified accelerator was calcium chloride, either in solution or in flakes. Addition rates ranged from 1 to 2 percent, and in many cases the recommended rate was based on ambient conditions, with cooler temperatures requiring an increase in the calcium chloride added. Other accelerators allowed included non–chloride-based admixtures meeting AASHTO M 194 Type C or Type E. The Type E admixture also acts as a water reducer, having the added benefit of being able to reduce the *w/c* ratio while maintaining the same workability. Water reducers were not often specified in SHA specifications for 6- to 8-hour EOT concrete materials. When specified, water reducers conforming to AASHTO M 194 Type A, Type D, Type E, or Type F were permitted. In Ohio, which is the one state specifying a Type D admixture, the retardation effect of the admixture would likely be offset by the specified high cement content (534 kg/m^3 [900 lb/yd^3]) and relatively low *w/c* ratio (<0.40) of the mixtures. As noted previously, there are concerns that the use of Type F admixtures (high-range water reducers) may result in instability of the entrained air-void system.

TABLE 4 Summary of SHA specifications for 6- to 8-hour EOT repair materials in 2000

State	Mixture Designation	Opening Criterion	Cement Type	Cement Factor	*w/c* Ratio	Coarse Aggregate	Fine Aggregate	Accelerator	Air Content	Mineral Admixture	Water Reducer
AR	Accelerated Strength	>14 MPa (2,000 psi) completed @ 6 hours	Type III	NS	NS	No. 57	NS	CC or other	NS	NS	NS
CA	Type FSHCC	>2.8 MPa (400 psi) flexural @ 8 hours	CSA	NS	NS	37.5 or 25 mm (1.5 or 1.0 in.) maximum	NS	Retarder and Type C used	NS	NS	NS
FL	Patching	>21 MPa (3,000 psi) completed @ 24 hours 6-hour opening	NS	>446 kg/m^3 (750 lb/yd^3)	< 0.45	57 Stone	NS	1% CC or Type C	2 to 6%	NS	Type F allowed
IL	Class PP(2)	8-hour opening	Type I	440 kg/m^3 (740 lb/yd^3)	< 0.38	1,020 kg/m^3 (1,720 lb/yd^3)	665 kg/m^3 (1,120 lb/yd^3)	Type E or Type C	4 to 6%	NS	Type F
IA	Class M	5-hour opening	Type I or Type II	~470 kg/m^3 (790 lb/yd^3)	~0.33	Volume specified	Volume specified	CC	5% w/ CC 6.5% w/o	No	NS
	Class FF	5-hour opening	Type III	~490 kg/m^3 (825 lb/yd^3)	~0.43			Not Allowed	6.0%		Yes
KS	Accelerated Cure	4- to 6-hour opening	Type III	>390 kg/m^3 (658 lb/yd^3)	NS	NS	NS	1 to 2% CC	NS	NS	NS
MD	6 hours or 7 hours	> 17 MPa (2,500 psi) completed @ 12 hours	Type I	>445 kg/m^3 (750 lb/yd^3)	< 0.42	No. 57	NS	CC or NC Type C	5.5%	NS	Type F, Melamine
MN	3A32HE	12-hour opening time	Type I	30% extra	NS	NS	NS	Type E	6.5%	NS	Type E
MI	Type SLP	> 2.0 MPa (290 psi) flexural @ 8 hours	Type I	502 kg/m^3 (846 lb/yd^3)	NS	MDOT 6A	NS	CC	5.5%	NS	NS
MO	4 hours	> 24 MPa (3,500 psi) completed	Type I or III	475 kg/m^3 (800 lb/yd^3) for Type I	NS	NS	NS	CC or other	NS	NS	NS
NJ	VHES	> 2.4 MPa (350 psi) flexural @ 6.5 hours	Type I w/ accelerator or Type III	>390 kg/m^3 (658 lb/yd^3)	0.37	No. 57	NS	NC required	6.5%	NS	Type F
NY	Patch	Surface temperature of 65^{o}C (150^{o}F)	Type III	490 kg/m^3 (825 lb/yd^3)	0.39	NYDOT CA2	NS	2% CC	6.0%	NS	NS
OH	Class FS	2.8 MPa (400 psi) flexural @ 4 hours	Type I	534 kg/m^3 (900 lb/yd^3)	< 0.40	No. 57, No. 6, No. 67, or No. 8	NS	1.5% CC or other	6.0%	NS	Type D
PA	Accelerated	8.3 MPa (1,200 psi) completed @ opening 10 MPa (1,450 psi) completed @ 7 hours	NS	NS	NS	No. 57	Type A	NC allowed	6.0%	NS	NS
TX	Class K	2.9 MPa (420 psi) flexural @ 24 hours, Open @ 1.8 MPa (260 psi) flexural	Type III	390 kg/m^3 (658 lb/yd^3)	< 0.49	Grade 2 or 3	Grade 1 FM 2.6 to 2.8	Type C	NS	NS	Type A
WI	Special HES	21 MPa (3,000 psi) completed @ 8 hours	NS	>502 kg/m^3	NS	NS	NS	CC or other	NS	NS	NS

CC: calcium chloride.
CSA: Calcium sulfoaluminate cement.
NC: non-chloride.
NS: not specified.
VHES: very high early strength.

TABLE 5 Summary of SHA specifications for 20- to 24-hour EOT repair materials in 2000

State	Mixture Designation	Opening Criterion	Cement Type	Cement Factor	*w/c* Ratio	Coarse Aggregate	Fine Aggregate	Accelerator	Air Content	Mineral Admixture	Water Reducer
AR	HES	>21 MPa (3,000 psi) completed @ 24 hours	Type I Type III	25% extra NS	NS	NS	NS	NS	NS	NS	NS
GA	24-Hour Accelerated	>17 MPa (2,500 psi) completed @ 24 hours	Type I or Type III	420 kg/m^3 (700 lb/yd^3)	< 0.45	NS	NS	CC Or Type E	3 to 6%	NS	NS
IL	Class PP(1)	> 22 MPa (3,100 psi) completed > 4.2 MPa (600 psi) flexural @ 48 hours	Type III or Type I	NS	NS	NS	NS	Accelerator required	NS	NS	NS
IN	High Early	3.8 MPa (550 psi) flexural @ 48 hours	Type I or Type III	>335 kg/m^3 (564 lb/yd^3)	<0.42 <0.45	NS	NS	NS	6.5%	10% flyash 15% GGBFS	Type A
KS	Normal Cure	24-hour opening	Type I or II	>445 kg/m^3 (750 lb/yd^3)	NS	NS	NS	No	NS	NS	NS
MD	24 hours	> 17 MPa (2,500 psi) completed @ 12 hours	Type I	>475 kg/m^3 (800 lb/yd^3)	NS	NS	NS	NS	NS	NS	Type F
MN	3A32HE	24-hour opening time	Type I	30% increase	NS	NS	NS	NS	6.5%	NS	Type A
MI	Type P-MS	> 3.5 MPa (500 psi) flexural @ 24 hours	Type I	502 kg/m^3 (846 lb/yd^3)	NS	NS	NS	CC below 18°C (65°F)	5.5%	NS	NS
MO	24 hours	>24 MPa (3,500 psi) completed	Type I	475 kg/m^3 (800 lb/yd^3) for Type I	NS	NS	NS	NS	NS	NS	NS
OH	Class MS	2.8 MPa (400 psi) flexural @ 24 hours	Type I	475 kg/m^3 (800 lb/yd^3)	< 0.43	No. 57, No. 6, No. 67, or No. 8	NS	NS	6.0%	NS	Type D
TX	Class K "Modified"	2.1 MPa (300 psi) flexural @ 24 hours	Type I or Type III	390 kg/m^3 (658 lb/yd^3) 335 kg/m^3 (564 lb/yd^3)	< 0.53	Grade 2 or 3	Grade 1 FM 2.3 to 3.1	Type C allowed	NS	NS	Type A or D

CC: calcium chloride.
GGBFS: ground granulated blast furnace slag.
HES: high early strength.
NC: non-chloride.
NS: not specified.

Twenty- to 24-hour EOT Materials

Table 5 summarizes the 20- to 24-hour EOT concrete mixture characteristics as specified by 11 SHAs. As was true with the 6- to 8-hour EOT concrete mixtures, time to opening with the 20- to 24-hour EOT concrete mixtures is frequently stipulated in the specifications, most often being linked to strength requirements. The opening criterion presented in Table 5 lists time to opening that varied from as early as 12 hours to as late as 48 hours. In two cases, only a time to opening criterion is provided, but in all other cases, a strength criterion exists in addition to time to opening, or strength is used as the sole criterion for opening. The range in required compressive strength at opening varied from 17 to 24 MPa (2,500 to 3,500 psi), whereas the range in required minimum flexural strength (as measured by third-point loading) was 2.1 to 4.2 MPa (300 to 600 psi). Although some states (Maryland, Missouri, and Ohio) specified the same strength criterion for both the 6- to 8-hour EOT concrete and the 20- to 24-hour EOT concrete, others (Michigan and Arkansas) reported higher strength requirements for the 20- to 24-hour EOT concrete.

All of the 11 states required use of Type I, II, or III portland cement for the 20- to 24-hour EOT concrete. The specified minimum cement content ranged from 335 to 502 kg/m^3 (564 to 846 lb/yd^3), with only one state, Texas, specifying different minimum cement contents for Type I versus Type III (390 versus 335 kg/m^3 [658 versus 564 lb/yd^3], respectively). The use of accelerators was either not specified or optional for many of these mixtures. Exceptions were Michigan, which specified that calcium chloride be used if ambient temperatures fell below 18°C (65°F), and Georgia and Illinois, which specified that an accelerator be used. The *w/c* ratio for the 20- to 24-hour EOT concrete mixtures were typically higher than those specified for 6- to 8-hour mixtures, ranging from 0.42 to 0.53. None of the states except Indiana approved the use of a supplementary cementitious material (fly ash, GGBFS, and silica fume) for use in 20- to 24-hour EOT concrete. Indiana allowed the use of a 10-percent fly ash or 15-percent GGBFS addition.

2.2 CONSTRUCTION CONSIDERATIONS

In addition to the selection and proportioning of constituent materials, specialized construction aspects need to be considered when repairs are constructed with EOT concrete. Construction of EOT concrete repairs consists of five basic operations: repair boundary identification and material removal, load transfer installation, batching, finishing, and curing. Although many ways exist to accomplish each task, generally accepted guidelines and practices are presented in a number of publications (ACPA 1994, NHI 2001, FHWA 2003). The following is a brief summary of the sequence used to construct full-depth pavement repairs with a particular emphasis on EOT concrete installations.

2.2.1 Boundary Identification and Material Removal

The first step in the repair process is to identify the extent of deterioration and establish the repair boundaries. Guidance is provided in several publications (ACPA 1995, NHI 2001, FHWA 2003), but the critical factor is to ensure that the entire area of deterioration is removed and that minimum repair lengths (1.8 m [6 ft]) are obtained when the repair is dowelled. The width of the patch should always be a full lane width for jointed concrete pavements.

Saw cutting and subsequent removal of existing materials depend primarily on the type of pavement being rehabilitated. In the case of jointed concrete pavement (JCP), a full-depth saw cut with a diamond saw blade is recommended. The result of this process is a smooth surface with reduced potential for spalling during removal. When saw cutting a continuously reinforced concrete pavement (CRCP), two cuts are made at each end of the repair. The first is a partial-depth cut made at the outside edge of the repair area. This cut is followed by a full-depth cut in the interior of the repair at a distance dependent on the lap length requirement (610 mm [24 in.] for tied laps and 200 mm [8 in.] for mechanical or welded laps) (FHWA 2003).

Upon completion of the saw cutting, the concrete can be removed by one of two methods. One method involves breaking up the concrete into small pieces and removing them using hand tools or construction equipment. The other method, called the lift-out method, involves removing the existing slab section in one or more large pieces, thus causing less damage to the subbase than the first method does.

After removal of the concrete, the subbase must be carefully prepared to ensure uniformity of support. If the existing subbase was damaged during removal, it may require the addition and compaction of new subbase material. Often it is difficult to adequately compact a disturbed subbase within the confines of a repair area. If the subbase disturbance is isolated to the very surface, the disturbed material can be removed and replaced with EOT concrete.

2.2.2 Load Transfer Restoration

The restoration of load transfer ensures that spalling of the concrete and damage to the subbase does not occur because of rotation or movement of the patch. This restoration can be accomplished by splicing together existing rebar, installing new rebar (in the case of CRCP), or installing dowel bars in JCP (FHWA 2003). Current practice is to drill multiple holes for dowel bars simultaneously using gang-mounted drill bits. Grout is inserted into the hole, the dowel bar is inserted with a twist, and a grout retention disk is used to prevent outflow. Proper dowel bar alignment is critical and must be ensured.

TABLE 6 Blanket use recommendations (FHWA 1994)

Minimum Ambient Temperature in Period	Opening Time, Hr				
	8	16	24	36	48
<10°C (50°F)	Yes	Yes	Yes	Yes	No
10–18°C (50–65°F)	Yes	Yes	Yes	No	No
18–27°C (65–80°F)	Yes	No	No	No	No
>27°C (80°F)	No	No	No	No	No

2.2.3 Batching

Regardless of whether the EOT concrete materials are batched at the job site or at a batching facility, it is important that the concrete produced be uniform in consistency and that the constituent materials be intimately blended through adherence to a proper mixing sequence and time. Also, admixtures must be added to fresh concrete in appropriate dosages and order to avoid potential harmful effects. Concrete-containing, air-entraining admixtures must be sufficiently mixed to ensure the development of an adequate air-void system. Delays in placing the concrete, especially after the accelerator has been added, must be avoided because early setting may negatively impact consolidation of the repair.

2.2.4 Finishing

Finishing operations should be performed in a timely fashion. It is imperative with EOT concrete, as with other types of concrete, that the surface not be overworked. However, because the high–early-strength materials set rapidly, timing of this step is even more critical. Surfaces that are overworked often become brittle, more susceptible to abrasion and/or freeze-thaw damage, and may exhibit a lowered resistance to chemical attack. Trapping of bleed water must also be avoided.

2.2.5 Curing

Internal concrete temperature and moisture directly influence early and ultimate concrete properties, and thus curing takes on special importance in EOT concrete installations. Proper curing provisions are necessary to maintain a satisfactory moisture and temperature condition for a sufficient time to ensure proper hydration (FHWA 1994). Compared with normal paving concrete, curing is even more essential to retain moisture and heat necessary for hydration during the early strength gain of EOT concrete materials. Protection against moisture loss becomes critical for EOT concrete repairs if high temperature, low humidity, high winds, or a combination of these environmental conditions exists.

Many SHAs use AASHTO M 148 Class A liquid curing compounds for accelerated concrete paving under normal placement conditions. Among these curing compounds, white-pigmented compound (Type II Class A) is the most commonly used. This material has the potential to create a seal that minimizes evaporation of mixing water when it is applied to the surface and exposed edges of concrete. The white color also assists in reflecting solar radiation during bright days to prevent excessive heat development on the concrete surface. This might not be a desirable outcome for EOT concrete repairs where heat generated by solar radiation accelerates hydration and thus early strength gain. Concrete repairs located in mountainous and arid climates may require heavier dosage rates of resin-based curing compound meeting AASHTO M 148, Type 2, Class B requirements. This is largely because concrete in harsher climatic conditions is more susceptible to plastic-shrinkage cracking. An application rate of 5.0 m^2/L (22 yd^2/gal) is recommended for these materials (FHWA 2003).

In addition to curing compounds, insulating blankets are often used in conjunction with EOT concrete materials to assist in holding in heat produced by the rapidly hydrating cement paste, thereby aiding in early strength development of the concrete. These blankets are often essential when cool ambient temperatures are present. Insulating blankets do not reduce the need for a curing compound, as blankets typically do not decrease the likelihood that plastic-shrinkage cracking will occur. Table 6 indicates when insulation is recommended based on ambient temperatures and desired opening time (FHWA 1994). It is not recommended to place blankets too soon after applying a curing compound. In warm conditions, waiting several hours and placing the blankets as the work progresses is acceptable. Concrete exposed to temperature below 4°C (40°F) may need additional blankets.

CHAPTER 3

PERFORMANCE CONSIDERATIONS RELATED TO THE DURABILITY OF EOT CONCRETE

A number of material characteristics impact the behavior of EOT concrete. Various test methods can be used to determine these characteristics, including methods to assess the strength, shrinkage, durability, microstructure, and absorbtion/permeability characteristics of the mixture.

3.1 STRENGTH

The mechanical behavior of EOT concrete is commonly assessed through measurement of its compressive or flexural strength. Although concrete strength is not directly related to durability, strength criterion are an important consideration in deciding when a pavement can be opened to traffic. This is especially true where concrete strength is not assessed in days or weeks, but in hours. By definition, early strength is readily attainable in EOT concrete mixtures; however, if any concrete is loaded prematurely, its long-term performance will be compromised. Therefore, EOT concrete repair materials must meet or exceed criterion set for opening strength.

Concrete strength is essentially a function of the constitutive materials used, their proportions, temperature, and time of hydration. Strength development is typically accelerated in mixtures by using high cement content, low *w/c* ratios, and accelerating admixtures. High curing temperatures also promote rapid strength gain.

The compressive strength test on cylindrical specimens, described in AASHTO T 22, is the most common strength test made on concrete. For pavement applications, the flexural strength test (AASHTO T 97 [third-point loading test] or AASHTO T 177 [center-point loading test]) is often used. The major limitation to the use of flexural strength is that the specimens are more difficult to properly prepare, and thus the variability within the test is higher.

As discussed in Chapter 2, the compressive and flexural strengths are both commonly used as strength criterion in SHA specifications for EOT concrete.

3.2 SHRINKAGE

The total shrinkage that occurs in a concrete mixture is composed of several types of shrinkage that occur at different ages in the life of the material. Although shrinkage of concrete cannot be totally eliminated (excluding the use of expansive cements), it can be reduced or controlled by the use of an appropriate mix design and proper construction techniques. Controlling shrinkage contributes to crack prevention, which helps prevent the physical and chemical attack of concrete. This section discusses three types of shrinkage that can affect EOT concrete mixtures: plastic, drying, and autogenous.

3.2.1 Plastic Shrinkage

Plastic shrinkage is the result of free, or "bleed," water evaporating from the surface of concrete faster than it appears during finishing operations (Kosmatka et al. 2002). Generally, an evaporation rate of 0.5 kg/m^2/hour (0.1 lb/ft^2/hour) or more is considered critical (Mindess et al. 2003). If the amount of evaporation is significant, small irregular cracks can form over the entire surface of the concrete. These cracks, although at first isolated to the slab surface, can progress into full-depth cracks under the influence of additional shrinkage and/or traffic loading. They also provide pathways for chemical attack by destroying the water tightness of the concrete.

Generally, the potential for plastic shrinkage is increased by elevated temperatures (both concrete and air), low relative humidity, high wind velocity, a low *w/c* ratio, and high cement content (Mindess et al. 2003). Many of these factors are accentuated with EOT concrete installations. This concern is thus particularly important. Any factor that either increases the rate of evaporation or decreases the rate of bleed water rising to the surface makes the concrete more susceptible to plastic shrinkage cracking. Plastic shrinkage can be virtually eliminated by maintaining a wet surface during finishing operations and initial curing (Neville 1996, Mindess et al. 2003), but this is almost impossible to do under EOT concrete construction limitations. Instead, curing compounds are used to minimize evaporation. Curing compounds must be applied early and uniformly, thoroughly coating the exposed concrete surface.

3.2.2 Drying Shrinkage

Drying shrinkage occurs after the paste has hardened and results from the strain produced by the loss of water from the hardened material (Mindess et al. 2003). The factors that influence drying shrinkage that are most relevant to EOT concrete materials are the aggregate volume/cement content, the *w/c* ratio, admixtures, aggregate characteristics, and curing. According to Neville (1996), the most important influence on shrinkage is the restraint provided by the aggregate. The amount of restraint provided directly relates to the aggregate volume; as the aggregate volume decreases (with a commensurate increase in cement paste volume), the amount of shrinkage increases.

The *w/c* ratio also directly and significantly affects drying shrinkage, with lower *w/c* ratio mixtures having reduced shrinkage (Neville 1996, Mindess et al. 2003). Thus, EOT concrete mixtures will benefit from the low *w/c* ratio that they commonly employ. For a given aggregate source and volume, the *w/c* ratio of concrete is one of the most important parameters for limiting drying shrinkage. Holding all other factors equal, a lower *w/c* ratio reduces the amount of evaporable water available to cause drying shrinkage of concrete mixtures (Neville 1996). Kosmatka et al. (2002) approach this issue a little differently, stating that the most important factor affecting drying shrinkage is the amount of water added per unit volume of concrete and that shrinkage can be minimized by keeping the amount of added water low. Obviously, the aggregate volume, the *w/c* ratio, and the water added all relate to each other, but the main objective is to minimize the amount of evaporable water in the mixture.

There is an AASHTO provisional test method for assessing the potential for cracking due to drying shrinkage. The test is specified in AASHTO PP 34-99, "Standard Practice for Estimating the Crack Tendency of Concrete." In this test, ring specimens are molded and the top and bottom faces of the rings are covered to prevent moisture loss other than through the outside circumferential area. A steel ring inside the concrete specimen restrains the concrete specimen as it shrinks. This restraint results in internal tangential tensile stresses, which will cause the concrete to crack if its tensile strength is exceeded (Kraai 1985). The time to cracking and the width and length of these cracks represent the damaging effect.

3.2.3 Autogenous Shrinkage

Concrete with a low *w/c* ratio can undergo a process of self-desiccation that can lead to autogenous shrinkage (Mindess et al. 2003). This process is characterized by the removal of water from the capillary pores through the internal use of water in the formation of hydration products. Autogenous shrinkage is relevant to EOT concrete materials because it seems to increase at higher temperatures, in mixtures with higher cement contents, and in mixtures made with finer cements (Neville 1996).

In the past, this type of shrinkage was considered to be quite rare and of little consequence because its contribution to total shrinkage was small. But because low *w/c* ratios are often used in modern concrete, including EOT concrete, there has been speculation that autogenous shrinkage might be partly contributing to microcracking. Unlike drying shrinkage, autogenous shrinkage increases as the *w/c* ratio decreases. This increase may be particularly relevant for EOT concrete mixtures, which in some cases have *w/c* ratios as low as 0.32.

Similar to drying shrinkage, autogenous shrinkage only occurs in the paste fraction of the concrete. Thus, the relative volume of aggregate to paste can directly impact the magnitude of the measured autogenous shrinkage. Because concrete made with higher volumes of aggregate have less measured autogenous shrinkage due to increased restraint, increased cement contents generally result in increased autogenous shrinkage.

3.3 DURABILITY

The performance of EOT concrete repairs can be adversely affected by the concrete's lack of durability (i.e., ability to maintain its integrity in the environment in which it was placed). In general, durability problems can be attributed to either physical or chemical mechanisms, although the two mechanisms often act together to bring about the development of distress. Furthermore, problems with completely different causes may develop simultaneously, thereby complicating the determination of the exact cause(s) of material failure. The information presented in this section is based on research conducted for the FHWA (Van Dam et al. 2002a, Van Dam et al. 2002b). Only material-related distress that can be directly attributed to the unique properties of EOT concrete are discussed, including freeze-thaw deterioration, deicer scaling/deterioration, and sulfate attack. Certain types of material-related distress, such as alkali-aggregate reactivity and corrosion of embedded steel, can be significantly affected by some characteristics of EOT concrete mixtures (e.g., high–cement-content and chloride-based accelerators). These topics are not addressed in these guidelines.

3.3.1 Freeze-Thaw Deterioration

Freeze-thaw deterioration is caused by the deterioration of saturated cement paste under repeated freeze-thaw cycles. The mechanisms responsible for internal damage resulting from freeze-thaw actions are not fully understood, but the most widely accepted theories stipulate the development of internal stress in the concrete as a result of hydraulic or osmotic pressures caused by freezing. A review of the literature related to these phenomena is provided by Marchand et al. (1994).

Deterioration of the cement paste due to freeze-thaw damage manifests itself in the form of scaling, map cracking, or severe cracking and deterioration, most commonly occurring at joints where moisture is more readily available. The addition of an air-entraining agent (an admixture that introduces a system of dispersed, microscopic spherical bubbles in the concrete) could effectively prevent this deterioration if a sufficient air-void system forms.

Measurements of the total air content of fresh concrete are made during construction. Three AASHTO test methods are available for measuring the air content of fresh concrete during construction: AASHTO T 152, AASHTO T 196, and AASHTO T 121. These methods, however, do not determine whether the air is truly entrained or entrapped or whether an adequate air-void system has been developed to protect the concrete against freeze-thaw damage. A test method that has been under investigation for a number of years provides a means for measuring the air-void system parameters for fresh concrete. The test equipment, known as the Air-Void Analyzer (AVA), has received mixed reviews (Price 1996, Magura 1996).

The only currently accepted method to characterize the air-void system in the hardened concrete is through microscopic analysis in accordance with ASTM C 457, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." The freeze-thaw resistance of hardened concrete is often tested using AASHTO T 161, "Resistance of Concrete to Rapid Freezing and Thawing," which is used to assess the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing. Only Procedure A in the standard, in which the specimens are frozen and thawed in water, should be used (TRB 1999). Many SHA's have modified this procedure to address their specific needs and experiences.

3.3.2 Deicer Scaling/Deterioration

Deicer scaling/deterioration is typically characterized by scaling or crazing of the slab surface due to the repeated application of deicing chemicals in a freeze-thaw environment. Although the exact causes of deicer scaling are not known, this scaling is believed to be primarily a form of physical attack similar to paste freeze-thaw deterioration. Both thermal stress and osmotic pressures are accentuated, magnifying the conventional freeze-thaw phenomena (Mindess et al. 2003, Pigeon and Plateau 1995). It has also been speculated that pressure exerted by salt crystallization in voids is a contributing factor (Hansen 1963). Recent studies suggest that chemical degradation of the cement paste may also be occurring, resulting in dissolution of calcium hydroxide, coarsening of the concrete pore system, and potentially the formation of deleterious compounds.

Deicer scaling/deterioration is more likely to occur if the concrete was over-consolidated or improperly finished—actions that create a weak layer of paste or mortar just below the finished surface (Mindess et al. 2003). Even adequately air-entrained concrete can be susceptible to the development of deicer scaling. Recommendations for the prevention of deicer scaling include providing a minimum cement content of 335 kg/m^3 (564 lb/yd^3) and using a maximum *w/c* ratio of 0.45, both of which are common in EOT concrete mixtures. Providing adequate curing and a minimum of 30 days of concrete "drying" before applying deicing chemicals is also recommended (ACPA 1992). ASTM C 672, "Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals," is the most commonly used test to investigate the scaling potential of concrete.

3.3.3 External Sulfate Attack

External sulfate attack results when external sulfate ions (present in groundwater, soil, deicing chemicals, etc.) penetrate into the concrete and react with the hydrated cement paste. Although the mechanism of sulfate attack is complex, sulfate attack is likely caused by two chemical reactions: (1) the formation of gypsum through the combination of sulfate and calcium ions and (2) the formation of expansive ettringite through the combination of sulfate ions and hydrated calcium aluminate (ACI 2003b). In either case, the reaction leads to an increase in solid volume that can be very destructive to the hardened paste.

In EOT concrete repairs, deterioration due to external sulfate attack would likely first appear as cracking near joints and slab edges, generally within a few years of construction. Fine longitudinal cracking may also occur parallel to longitudinal joints. Actions taken to prevent the development of distress due to external sulfate attack include reducing the tricalcium aluminate (C_3A) content in the cement or using pozzolanic materials to reduce the quantity of calcium hydroxide (CH) in the hydrated cement paste. Both these actions are not easily accomplished in EOT concrete mixtures, and if calcium chloride accelerator is used, even greater amounts of CH are formed. A *w/c* ratio should be less than 0.45 to help mitigate external sulfate attack (ACI 2003b).

Performance testing using ASTM C 452 and C 1012 should be considered to examine the sulfate resistance of portland cements and combinations of cements and pozzolans/slag, respectively. These tests only evaluate the cementitious materials. There is currently no standard test to evaluate the sulfate resistance of the mixture.

3.3.4 Internal Sulfate Attack

Internal sulfate attack is similar in many ways to external sulfate attack, except that the source of the sulfate ions is internal. Potential internal sources of sulfate are (1) the slowly soluble sulfate contained in the cement, aggregate, or other concrete constituents (such as fly ash) and (2) the decomposition of primary ettringite due to high curing temperatures.

Secondary ettringite formation (SEF) and delayed ettringite formation (DEF) might both be considered types of internal sulfate attack that result for different reasons. SEF is commonly a product of concrete degradation, characterized by the dissolution and subsequent precipitation of ettringite into available void space and into preexisting microcracks. SEF is possible if the concrete is sufficiently permeable and saturated, allowing for the dissolution and precipitation process to occur. Although most experts agree that secondary ettringite formation will not generate sufficient expansive pressures to cause concrete fracture, its presence in the air-void structure may limit the ability of the paste to resist freeze-thaw deterioration (Ouyang and Lane 1999).

DEF, on the other hand, can lead to destructive expansion within the paste, resulting in microcracking and separation of the paste from aggregate particles. DEF is most often associated with steam curing the concrete because primary ettringite will not properly form at elevated temperatures (Thaulow et al. 1996, Klemm and Miller 1997). After the concrete has cured and temperatures are reduced to ambient conditions, sulfates and aluminate phases in the paste may react to form expansive ettringite, disrupting the concrete matrix. It is still speculative, however, whether cast-in-place concrete can experience DEF. But there is little doubt that under certain conditions (e.g., thick slab, high cement content, and high ambient temperature), EOT concrete may experience temperatures in excess of that required for DEF during curing, especially if curing blankets are used during summer placements.

The manifestation of internal sulfate attack is characterized by a series of closely spaced, tight map cracks, with wide cracks appearing at regular intervals. DEF can only be identified through petrographic microscopic analysis in accordance with ASTM C 856, "Standard Practice for Petrographic Examination of Hardened Concrete."

3.4 MICROSTRUCTURE

For the most part, concrete mechanical properties and durability are controlled by the paste microstructure. Detailed discussions of concrete microstructure can be found in Mindess et al. (2003) and Mehta and Monteiro (1993). The hydrated cement paste microstructure that binds the aggregates together consists of solid phases and a pore system. The solid phases, which consist of both unhydrated cement grains and the related hydration products, can be characterized by type, size, and relative percentages. The number of unhydrated cement grains increases markedly in high–cement-content, low–*w/c*-ratio EOT concrete mixtures. While a variety of hydration products exist in cement paste, the primary phases of interest in determining the behavior of concrete are calcium-silicate-hydrate (C-S-H), calcium hydroxide (CH), and calcium sulfoaluminates (ettringite [AF_t] and monosulfate [AF_m]). The nature of the solid phases in a cement paste changes with time. At time zero, when the anhydrous cement grains first come into contact with the mix water, the microstructure consists of the unhydrated cement particles surrounded by water. As hydration proceeds, space that was initially water-filled is progressively occupied by hydration products.

The cement paste pore structure can generally be classified into three distinct groups: cement gel pores, capillary pores, and air voids (Neville 1996). The paste/aggregate interfacial transition zone and microcracking represent additional elements of the concrete pore structure. The pores within the C-S-H, referred to as gel pores or interlayer hydration space, make up the smallest individual elements of the total cement paste porosity. Their characteristics cannot be altered by changing mix design parameters.

In contrast, capillary porosity can be significantly modified by altering mixture properties, especially the *w/c* ratio. The capillary pore system is the space between anhydrous cement grains that is filled with water and not hydration products. This system is typically irregular in both shape and spatial distribution, with the pore sizes and connectivity dependent on the size of the initial water-filled space (a direct function of the *w/c* ratio) and on the degree of hydration. In well-hydrated, low–*w/c*-ratio systems common in EOT concrete mixtures, capillary pores will be much smaller than in high–*w/c*-ratio systems or systems at early stages of hydration (Mehta and Monteiro 1993). The use of admixtures that disperse cement grains, such as water reducers, typically result in smaller, more uniformly distributed capillary pores.

The largest elements of the pore structure are the air voids. The air voids are generally classified into two groups, those that are intentionally entrained and those that are unintentionally entrapped. Entrained air voids are essentially spherical and tend to be randomly distributed throughout the cement paste. They are created through the addition of admixtures specifically designed to produce large quantities of microscopic air bubbles when mixed into fresh concrete. While it is virtually impossible to clearly distinguish between entrained and entrapped air voids, quite often voids larger than 1 mm (0.04 in.) in diameter and/or irregular in shape are labeled as entrapped (ASTM C 125). These larger air voids contribute significantly to the total air content of concrete, but not to the frost resistance of concrete.

The interfacial transition zone (ITZ) between hydrated cement paste and the coarse aggregate particles is also an important element of the paste microstructure. The ITZ usually has a different microstructure than the rest of the paste system, with a higher proportion of CH and a greater porosity than the bulk paste. With time, the highly porous transition zone may become filled with additional hydration products resulting from chemical reactions between the cement paste phases and the aggregates (Mehta and Monteiro 1993). Because these reactions reduce the porosity of the interfacial zone and consume calcium hydroxide, they tend to increase the paste strength in this zone.

Microcracking of hydrated cement paste may occur relatively early in the hydration process (before the paste had gained significant strength) when internal stress exceeds the strength of the paste. Shrinkage and/or thermal strain could produce such stress when restrained by the aggregates. Both autogenous shrinkage and rapid changes in temperature of EOT concrete mixtures could lead to excessive microcracking of the paste.

A number of techniques are commonly used to characterize the microstructure of concrete, including staining and various microscopy techniques (Van Dam et al. 2002b). Of all the available methods, the stereo optical microscope is the first major analytical instrument to use when analyzing concrete. It is used to examine key microstructural features in concrete, including those present in the aggregates, paste, air-void structure, reaction products, and cracks. Often, a petrographer can diagnose durability problems with this approach alone. The stereo optical microscope is also commonly used for determining the air-void system parameters in hardened concrete in accordance with ASTM C 457, "Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete."

The petrographic optical microscope can also be used for evaluating microstructure and identifying the composition or mineralogical characteristics of phases within concrete. However, the petrographic optical microscope requires detailed sample preparation and a highly trained analyst. ASTM C 856, "Practice for Petrographic Examination of Hardened Concrete," outlines many of the procedures required for the petrographic examination of concrete. Included in ASTM C 856 are sections on qualifications of petrographers, purposes of examination, required apparatus, sampling, sample preparation procedures, microscopical examination, and suggested diagnostic features to examine in concrete. Although ASTM C 856 is very useful and comprehensive, it does not relate observed diagnostic features to specific mechanisms of distress. The analyst must interpret the results obtained (Van Dam et al. 2002b).

Like the petrographic optical microscope, the scanning electron microscope (SEM) can be used to identify microstructural features and cracks in concrete and the composition or mineralogical characteristics of the various phases. Given the high magnification level of a conventional SEM, it would seem ideally suited for studying concrete. However, the instrument operates at a very low pressure (10^{-6} mm [4×10^{-8} in.] Hg), which dehydrates the concrete when it is placed in the instrument, altering the microstructure. This dehydration can lead to significant cracking and decomposition of certain phases of interest. Specialized SEMs (i.e., the low-vacuum SEM and the environmental SEM) operate at higher relative pressures, reducing this effect to a minimum. However, some cracking and desiccation still occur when these instruments are used, and care should be exercised in interpreting features seen in SEM images.

3.5 ABSORPTION/PERMEABILITY

The absorption characteristics and permeability of concrete directly influence concrete durability. Concrete that is more permeable to air, water, or other substances is far more likely to suffer some kind of durability distress. The ingress of gases and liquids leads to solubility of some components in the hardened paste, can result in expansive reactions, and in general provides a medium through which ions can be transported. For this reason, changes in mixture design that decrease permeability often lead to an increase in durability.

Currently, there is no readily available method to measure concrete permeability. Hooton et al. (2001) summarized the effectiveness of various methods that can be used to assess chloride penetration (only one method measures permeability) into concrete. In general, tests that accurately modeled chloride ingress were long-term tests that were not suitable for design or construction quality control. The rapid tests exhibited a number of limitations, the most relevant to EOT concrete being that the results were affected by the presence of ions in the concrete such as occurs when common accelerators are used. For this reason, simple tests based on absorption offer a potential alternative to permeability testing.

Absorption is a measure of the volume of pore space in concrete irrespective of the interconnectivity of the pores (Neville 1996). Although absorption and permeability are related, they are not necessarily correlated. A variety of techniques are used for determining the absorption rate of concrete. One common test is ASTM C 642, "Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete," which is commonly used as a quality control test for precast members (Neville 1996).

A related measure of concrete permeability is sorptivity, which measures the rate of absorption of water into the concrete (Neville 1996). Generally, it is too difficult to mathematically model this flow in all but a single direction, and thus sorptivity tests are configured to establish one-directional flow into the specimen (Hooton et al. 2001). Sorptivity tests typically require that the sample be at a standard moisture content before testing is begun. The benefits of sorptivity testing are reduced testing time, low equipment cost, and simplicity of procedure. The proposed ASTM standard test for sorptivity requires only a scale, a stopwatch, and a shallow pan of water (Stanish et al. 1977).

A variety of test methods exist for estimating concrete permeability using the saturated flow of water. The majority of these tests determine permeability by measuring the steady-state flow of water through concrete due to a pressure differential (Neville 1996), but these tests are difficult to conduct, lack good correlations to each other, and are long term or require specialized equipment.

The most common rapid chloride penetration test used in North America is AASHTO T 277, "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." Although this test has been accepted by many transportation agencies, it has serious limitations that make it impractical for evaluating EOT concrete. The three main limitations are that (1) the current passed relates to all ions in the pore solution and not just chloride ions, (2) the measurements are made before a steady-state migration is achieved, and (3) the temperature of the specimen increases because of the applied voltage (Stanish et al. 1977). The first limitation is most relevant for the study of EOT concrete, since EOT concrete commonly contains various admixtures that will affect the ion concentration of the pore solution.

CHAPTER 4

MATERIALS AND MIXTURE DESIGN CONSIDERATIONS

This chapter discusses materials and mixture design considerations relevant to the durability of EOT concrete. As with all concrete, EOT concrete is a blend of cement (and potentially other cementitious materials), water, aggregates, and admixtures. Assuming that good concreting practices are followed, the primary considerations for proportioning and mixture design of EOT concrete are selection of cement type, cement content, *w/c* ratio, accelerator (if used), and water-reducing admixture (if used). In general, altering one or more of these mixture constituents to accelerate early strength gain can negatively impact the durability of the mixture. Other factors that contribute to performance of the material in a less direct manner are the type of coarse aggregate and the curing temperature. Because of the complexity inherent in EOT concrete, the actual job mixture (i.e., constituent materials and proportions) should be tested in accordance with recommendations presented in Chapter 5.

Table 7 summarizes common ranges for constituent materials used in EOT concrete. In comparison with 20- to 24-hour EOT concrete, 6- to 8-hour EOT concrete will have higher cement contents and lower *w/c* ratios. Type III cement, accelerators, and water reducers are more ofen used in 6- to 8-hour EOT concrete than in 20- to 24-hour EOT concrete. It was clearly observed from the laboratory test results that the 6- to 8-hour mixtures had less desirable durability characteristics than the 20- to 24-hour mixtures. This observation was reflected in the overall poorer performance in freeze-thaw and scaling tests, increased shrinkage, increased difficulties in achieving desirable air-void system characteristics, increased amounts of paste microcracking, decreased paste homogeneity, and increased absorption. This is not to suggest that durable 6- to 8-hour EOT concrete mixtures cannot be made; it simply points out the difficulty in achieving the desired characteristics of a durable mixture in these higher early strength mixtures. Thus, there is a higher level of risk associated with using a 6- to 8-hour EOT concrete than a 20- to 24-hour EOT concrete that must be considered when selecting a specific mixture to reduce lane closure time.

Six concrete mixture designs (three for 6- to 8-hour EOT concrete and three for 20- to 24-hour EOT concrete) found to meet both strength and durability requirements are presented in Appendix A. The performance of these mixtures depends on the unique combination of constituents used, and thus the designs are presented only to provide guidance in the development of new mixtures.

4.1 CEMENT TYPE

Either AASHTO M 85 Type I or Type III cement is almost universally used in the construction of EOT concrete and Type III is generally more finely ground to achieve higher early strength gain. The increased fineness may result in reduced workability, especially in low–*w/c*-ratio mixtures, necessitating the use of a Type F HRWR. The use of Type III cement produces higher compressive and flexural strengths during the first 24 hours and increases heat of hydration, which can further accelerate strength gain. At a microstructural level, smaller Type III cement grains hydrate more completely, creating a paste that appears more uniform than that in the Type I mixtures. In some instances, the air-void system parameters are negatively affected by the use of Type III cement rather than Type I cement (Whiting and Nagi 1998). The problem appears even more acute when calcium chloride accelerator is used.

The chemical and physical properties of cement vary greatly within the types specified under AASHTO M 85. Although no generalized conclusions can be drawn regarding the durability of mixtures made with Type I versus Type III cement, it is clear that the properties of the cement can profoundly impact the durability of EOT concrete mixtures. It is therefore recommended that the actual job mixture be thoroughly tested in the laboratory to evaluate the durability of the EOT concrete.

4.2 CEMENT FACTOR

The cement factor (or cement content) of EOT concrete is typically much higher than that used in conventional paving concrete. For 6- to 8-hour EOT concrete with Type I cements, some SHA specifications stipulate cement factors as high as 525 kg/m^3 (885 lb/yd^3) (lower values are normal if Type III cement is used). Although the cement factors of 20- to 24-hour EOT concrete are lower, they can still be as high as 475 kg/m^3 (800 lb/yd^3). These high cement factors contribute

TABLE 7 Common ranges of constituent materials for EOT

Time to Opening	6- to 8-hour EOT concrete		20- to 24-hour EOT concrete	
Range of Strength	Low	High	Low	High
Cement Type	I	III	I	III
Cement Content	425 kg/m^3 (715 lb/yd^3)	525 kg/m^3 (885 lb/yd^3)	400 kg/m^3 (675 lb/yd^3)	475 kg/m^3 (800 lb/yd^3)
w/c ratio	0.36	0.40	0.40	0.43
Accelerator	No	Yes	No	Yes
Water Reducer	No	Yes	No	Yes

to increased paste porosity, as reflected in an increase in percent of permeable voids, absorption, and sorptivity. Further, the increase in paste volume increases the amount of shrinkage, potentially producing more cracking. However, increased cement contents often resulted in decreased scaling for the 6- to 8-hour mixtures.

Interestingly, increasing cement content beyond a certain point does not necessarily increase early strength and actually may reduce it. This suggests that increasing the cement content will not necessarily improve the early (or long-term) strength of the EOT concrete. Instead, other methods of increasing early strength (such as lowering the *w/c* ratio) are likely to be more effective. It is therefore recommended that mixtures with lower cement contents (with corresponding higher aggregate volumes) be investigated for use in EOT concrete.

4.3 w/c RATIO

Decreasing the *w/c* ratio of the mixture (over the range of 0.43 to 0.36) will increase the various measures of strength at all ages of testing, decrease absorption, and improve paste homogeneity with no observed disadvantages as long as workability is maintained. It is therefore advantageous both from the perspective of strength gain and durability to use a *w/c* ratio at or below 0.40 for 6- to 8-hour EOT concrete mixtures, although a slightly higher *w/c* ratio appears to be acceptable for 20- to 24-hour EOT concrete mixtures. Although it is feasible, the use of *w/c* ratios below 0.36 provides a potential for increased autogenous shrinkage.

4.4 ACCELERATING ADMIXTURES

Accelerating admixtures (also called accelerators [Type C or E in AASHTO M 194]) are a common admixture in EOT concrete, profoundly affecting strength gain and potentially durability. Calcium chloride is the most common accelerator used in concrete, yet it promotes corrosion of embedded steel and may have other adverse impacts on concrete durability. Calcium nitrite is the most common non-chloride accelerator used in concrete.

To achieve high early strength, an accelerator is used in most 6- to 8-hour EOT concrete mixtures. In some cases, mixtures made with calcium chloride accelerator had lower early strengths but higher long-term strengths than those made with a non-chloride accelerator. Type E water-reducing and -accelerating admixtures were not effective in achieving early strength even when using a high cement content and a low *w/c* ratio.

Scaling test results varied with respect to accelerator use, where in some cases calcium chloride improved the scaling resistance and in others made it worse. Similar conflicting results were observed for the air-void system parameters and paste homogeneity. The literature suggests that the use of accelerators in general and calcium chloride specifically creates a coarser microstructure that is more susceptible to durability-related distress such as scaling. This observation was not evident in the mixtures used in this study, although under the high magnification of the SEM (1000×), the hydrated cement paste appeared more uniform in mixtures made with the non-chloride accelerator than in mixtures made with calcium chloride or no accelerator at all.

In general, an accelerator will likely be required for the 6- to 8-hour EOT concrete mixtures, but no definitive advantages or disadvantages were observed for either the calcium chloride or non–chloride-based accelerators. For the slower-hydrating 20- to 24-hour EOT concrete mixtures, accelerators are not required. It is therefore recommended that judicious use of accelerators be made in accordance with manufactures' recommendations to achieve required early strength.

4.5 WATER REDUCER

Water reducers (AASHTO M 194 Type A, Type E, and Type F) are often used in 6- to 8-hour EOT concrete mixtures and sometimes in 20- to 24-hour EOT concrete mixtures to assist in producing workable concrete at low *w/c* ratios. The use of the Type F HRWR may negatively impact the air-void system parameters, creating a network of rather large bubbles with insufficient spacing factors, thus compromising the freeze-thaw performance of the concrete (Whiting and Nagi 1998).

Early strength characteristics of the concrete can be negatively impacted by the use of some of the water reducers. For example, Type E water-reducing and -accelerating admixtures being particularly problematic, and Type F HRWR may also retard strength development. Improved paste homogeneity was observed with the use of a Type F HRWR but not with a Type E water-reducing and -accelerating admixture. These latter mixtures had the highest level of paste inhomogeneity, the highest volume of permeable voids, and a high degree of microcracking.

Various water-reducing admixtures are available for use in EOT concrete, and it is impossible to categorize their interaction with other concrete constituents. However, the final selection of the water-reducing admixture must be done only after testing of the job mixture, including evaluation of the impact on both strength and durability characteristics. This testing is of particular importance when HRWRs are being considered, as difficulties have been reported in obtaining satisfactory air-void systems in mixtures containing Type F HRWR.

4.6 COARSE AGGREGATE

The type of coarse aggregate used markedly affects the concrete's density and CTE. The coarse aggregate can also impact some strength properties of the mixtures and scaling resistance. Thus, care must be exercised in selecting coarse aggregate that will provide both the desired strength and the durability properties.

CHAPTER 5

TESTING OF FRESH AND HARDENED CONCRETE

Testing of fresh and hardened EOT concrete is required to monitor the construction process as well as ensure that desirable concrete properties are achieved. Routine standard tests for fresh concrete include workability, air content, and maturity. The most common, and often the only, testing of hardened concrete is measuring compressive strength and/or flexural strength. Other tests of hardened concrete that could be considered include methods to assess volume change, durability in freeze-thaw environments, absorption/permeability, and microstructural characterization. A number of tests are recommended for evaluation of EOT concrete mixtures.

5.1 TEST METHODS

5.1.1 Testing Fresh Concrete

Testing of fresh EOT concrete entails measuring workability, air content, and maturity. Workability is most often assessed through the slump test (AASHTO T 119), with a desired range in slump for EOT concrete often specified between 50 and 150 mm (2 to 6 in.). The time of setting (AASHTO T 131) can also be used to establish the time in which the mixture is workable. This time should be sufficient to provide time for mixing, placing, and finishing the EOT concrete.

Air content of the fresh concrete is measured as an indirect indication of the air-void system in the paste. In a freeze-thaw environment subjected to deicer use, the air content for concrete mixtures containing coarse aggregates with a nominal maxium size of 1 in. (25 mm) or less should range from 6 to 7.5 ± 1.5 percent depending on coarse aggregate size, as recommended in Table 3. Air contents are commonly measured using the pressure method (AASHTO T 152), although the volumetric method (AASHTO T 196) is also used.

The AVA is currently being used for the analysis of paving concrete (Price 1996). The AVA measures changes in buoyancy using a special buoyancy recorder that captures bubbles as they rise from the concrete through a viscous medium. Since larger bubbles rise more quickly, monitoring the change in buoyancy as a function of time provides a measure of the air-void size distribution, total air content, and specific surface from which a spacing factor can be calculated. Although the use of this device for large paving projects might be justified, it seems unlikely that the device will be used extensively to monitor field installations of EOT concrete. The device, however, might be useful in the laboratory during mix design to verify the sufficiency of the air-void system.

Another fresh concrete test that will see increasing use in EOT concrete applications is maturity (ASTM C 1074). The maturity concept relates the time-temperature relationship directly to strength gain for a given mixture. It is an excellent way to determine the time to opening. The relatively new use of wireless technology has eliminated the need for wires and continual recording of data common in older maturity meters. As wireless technology continues to develop, it is foreseeable that each repair will have a wireless maturity gauge installed that reports to a hand-held unit, which in turn computes the time to opening based on stored mix design information.

5.1.2 Testing Hardened Concrete

Strength Testing

Strength testing is an integral part of the mixture design process and construction monitoring for EOT concrete. Compressive strength (AASHTO T 22), measured on cylindrical specimens, is often specified to be at least 13.8 MPa (2,000 psi) at time of opening (FHWA 2003). Some agencies prefer the use of a flexural strength (AASHTO T 97) opening criterion. Testing is conducted on beam specimens with common criterion of 1.7 MPa (250 psi) for third-point loading and 2.1 MPa (300 psi) for center-point loading. The minimum required compressive or flexural strength is commonly raised for the slower-setting 20- to 24-hour concrete mixtures.

For construction monitoring, early strength testing is often not conducted because of the short time available. If logistics preclude strength testing prior to opening, the use of the maturity concept is recommended. Strength-maturity relationships established for a given mixture can be used during construction to ensure that adequate strength has been achieved prior to loading.

Testing of Volume Change

Two tests that can be used to assess volume change in hardened concrete are the determination of the CTE (AASHTO TP 60-00) and the restrained drying shrinkage test ring (AASHTO PP 34-99). Neither test is adaptable to field applications, and thus they are of little value for monitoring construction. However, they may be useful for material selection and establishing mixture design parameters. For example, measuring the CTE of the EOT concrete mixture will help assess the mixture's thermal compatibility with the existing pavement concrete.

In the laboratory phase of this recent study, it was observed that the CTE results were in general highly repeatable, but the results from the restrained shrinkage ring test were highly variable. Also, the relevance of the results of the restrained shrinkage concrete to the performance of EOT concrete has yet to be established.

Freeze-Thaw Testing

The durability of EOT concrete in a freeze-thaw environment can be assessed by testing the resistance of concrete to freezing and thawing (AASHTO T 161) and the exposure to deicers (ASTM C 672). These tests are long term and can be used only on hardened concrete and therefore are not applicable for construction monitoring. Further, because of the relatively long period of testing and the complexity of the test procedure, these tests likely will be used only when evaluating EOT concrete mixtures to establish mixture design parameters (e.g., to investigate failures and qualify new materials). Most agencies in freeze-thaw climatic zones conduct some version of AASHTO T 161 and possibly ASTM C 672 as part of the material approval process for paving concrete. It is recommended that these agencies use their test procedures for evaluating the proposed EOT concrete mixture designs.

Absorption/Permeability Testing

Absorption/permeability can be assessed by testing the specific gravity, absorption, and voids (ASTM C 642) or sorptivity (proposed ASTM test). Both tests are conducted on hardened concrete and are thus not suitable for use in construction monitoring. Another commonly accepted method to measure permeability is the rapid chloride permeability test (AASHTO T 277), although this test can be difficult to apply to EOT concrete containing certain admixtures. Other rapid chloride permeability tests may be appropriate, but standards need to be established before these techniques can be employed for EOT concrete.

Microstructural Characterization

The final type of testing is microstructural characterization of the concrete, such as air-void analysis (ASTM C 457) and petrographic examination of hardened concrete (ASTM C 856). These techniques would not be routinely applied to EOT concrete because of the rigor and expense of the testing, but they should be considered when a better understanding of EOT concrete performance is desired, especially when unexpected deterioration has occurred. It has been found that an adequate air-void system can be difficult to achieve in EOT concrete, even when the air content of the fresh concrete was satisfactory. Thus, if durability problems have been observed in EOT concrete repairs, an agency should consider measuring the air-void system parameters of the concrete. The only accepted method to determine the characteristics of the air-void system is ASTM C 457, which requires manual observation with a stereo optical microscope. Automated methods based on digital image analysis currently under development are expected to significantly shorten the time needed to conduct this test, thus making it more suitable for routine use.

In some instances, full petrographic analysis in accordance with ASTM C 856 might be warranted. The unique characteristics of EOT concrete make it more susceptible to various kinds of material-related distress (e.g., alkali-aggregate reactivity and sulfate attack). When durability-related distress in EOT concrete repairs is observed, it would be prudent to conduct a thorough investigation of the cause of deterioration using ASTM C 856 to avoid similar distress in future applications.

5.2 TESTING RECOMMENDATIONS

There are three reasons for testing EOT concrete: to design a mixture for a specific application, to monitor the mixture during construction, and to conduct generalized investigations to improve specifications. The type and extent of testing depends on the purpose for which the testing is being done. For each purpose, the suggested testing is divided into recommended and optional.

5.2.1 Mixture Testing Recommendations

Table 8 shows the recommended and optional testing for the mixture design process.

5.2.2 Construction Monitoring

Table 9 shows the recommended and optional testing for construction monitoring.

5.2.3 Investigations and Research

Table 10 shows the recommended and optional testing for investigations and research.

TABLE 8 Recommended and optional testing for the mixture design process

Test Method	Property Assessed	Performance Characteristic
Recommended Testing		
AASHTO T 119	Slump	Workability
AASHTO T 152 or 196	Air Content of Fresh Concrete	Freeze-Thaw Durability
ASTM C 1074	Maturity	Strength Gain
AASHTO T 22 or AASHTO T 97	Compressive or Flexural Strength	Strength Criterion
AASHTO TP 60-00	Coefficient of Thermal Expansion	Thermal Stress
ASTM C 642	Specific Gravity, Absorption, and Voids	Absorption
Optional Testing		
ASTM C 457	Air-Void System Characteristics	Freeze-Thaw Durability
AVA (non-standard)	Air-Void System Characteristics	Freeze-Thaw Durability

TABLE 9 Recommended and optional testing for construction monitoring

Test Method	Property Assessed	Performance Characteristic
Recommended Testing		
AASHTO T 119	Slump	Workability
AASHTO T 152 or 196	Air Content of Fresh Concrete	Freeze-Thaw Durability
ASTM C 1074	Maturity	Strength Gain
AASHTO T 22 or AASHTO T 97	Compressive or Flexural Strength	Strength Criterion
Optional Testing		
AASHTO T 131	Time of Setting	Early Set

TABLE 10 Recommended and optional testing for investigations and research

Test Method	Property Assessed	Performance Characteristic
Recommended Testing		
AASHTO T 119	Slump	Workability
AASHTO T 152 or 196	Air Content of Fresh Concrete	Freeze-Thaw Durability
ASTM C 1074	Maturity	Strength Gain
AASHTO T 22 or AASHTO T 97	Compressive or Flexural Strength	Strength Criterion
AASHTO TP 60-00	Coefficient of Thermal Expansion	Thermal Stress
ASTM C 642	Specific Gravity, Absorption, and Voids	Absorption
ASTM C 457	Air-Void System Characteristics	Freeze-Thaw Durability
AVA (non-standard)	Air-Void System Characteristics	Freeze-Thaw Durability
AASHTO T 161	Resistance to Freezing and Thawing	Damage Due to Cyclic Freezing and Thawing
ASTM C 672	Resistance to Deicer Scaling	Scaling Resistance
Optional Testing		
AASHTO PP 34-99	Restrained Shrinkage	Resistance to Drying Shrinkage Cracking
ASTM C 856	Concrete Microstructure	General Appearance at Microscopic Level

REFERENCES

American Concrete Institute (ACI), "State-of-the-Art Report on Alkali-Aggregate Reactivity." *ACI Manual of Practice—Part 1,* ACI 221.1R-98, Farmington Hills, Michigan, ISSN 0065-7875 (2003a).

American Concrete Institute (ACI), "Guide to Durable Concrete." *ACI Manual of Practice—Part 1,* ACI 201.2R-92, Farmington Hills, Michigan, ISSN 0065-7875 (2003b).

American Concrete Institute (ACI), "Chemical Admixtures for Concrete." *ACI Manual of Practice—Part 1*, ACI 212.3R-91. Farmington Hills, Michigan, ISSN 0065-7875 (2003c).

American Concrete Pavement Association (ACPA), *Scale-Resistant Concrete Pavements.* Information Series IS117.02P, Skokie, Illinois (1992).

American Concrete Pavement Association (ACPA), *Concrete Paving Technology—Fast Track Concrete Paving*. TB004.02, Skokie, Illinois (1994).

American Concrete Pavement Association (ACPA), *Concrete Paving Technology—Guidelines for Full-Depth Repair*. TB002-02P, Skokie, Illinois (1995).

Embacher, R. A., and M. B. Snyder. *Refinement and Validation of the Hydraulic Fracture Test.* Final Report, Minnesota Department of Transportation (2001).

Farney, J. A., and S. H. Kosmatka, *Diagnosis and Control of Alkali-Aggregate Reactions in Concrete.* Concrete Information Series No. IS413.01T. Portland Cement Association, Skokie, Illinois, ISBN 0 89312 146 0 (1997).

Federal Highway Administration (FHWA), *Air Void Analyzer Evaluation*, Report No. FHWA-SA-96-062, U.S. Department of Transportation, Washington, D.C. (1998).

Federal Highway Administration (FHWA), *Full-Depth Repairs*. U.S. Department of Transportation, Washington, D.C. www.fhwa.dot.gov/pavement/full.htm (Accessed 2/19/03).

Federal Highway Administration (FHWA), *Temperature Management of Slabs.* Final Report, Special Project 201, U.S. Department of Transportation, Washington D.C., June (1994).

Folliard, K. J., and K. D. Smith, *NCHRP Research Results Digest 281: Aggregate Tests for Portland Cement Concrete Pavements: Review and Recommendations.* National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., September (2003).

Hansen, W. C., "Crystal Growth as a Source of Expansion in Portland-Cement Concrete." *Proceedings,* American Society for Testing and Materials (ASTM), Vol. 63, Philadelphia, Pennsylvania (1963).

Hooton, R. D., M. D. A. Thomas, and K. Stannish, *Prediction of Chloride Penetration in Concrete.* FHWA-RD-00-142, Federal Highway Administration, McLean, Virginia, October (2001).

Klemm, Waldemar A., and F. MacGregor Miller, *Internal Sulfate Attack: A Distress Mechanism at Ambient and Elevated Temperatures? PCA R&D Serial No. 2125,* Portland Cement Association, Skokie, Illinois (1997).

Kosmatka, S. H., B. Kerkhoff, and W. C. Panarese, *Design and Control of Concrete Mixtures*. Fourteenth Edition. Engineering Bulletin 001. Portland Cement Association. Skokie, Illinois, ISBN 0-89312-217-3 (2002).

Kraai, P. P., "A Proposed Test to Determine the Cracking Potential Due to Drying Shrinkage of Concrete," *Concrete Construction*, Sept. (1985).

Lackey, H. B. "Factors Affecting Use of Calcium Chloride in Concrete." *Cement, Concrete, and Aggregates*, Vol. 14, No. 2 (Winter 1992).

Lea, F. M., *The Chemistry of Cement and Concrete*. Chemical Publishing Company (1971).

Magura, D., "Evaluation of the Air Void Analyzer." *Concrete International*, August (1996).

Marchand, J., E. J. Sellevold, and M. Pigeon, "The Deicer Salt Scaling Deterioration of Concrete—An Overview." *Durability of Concrete.* Third International Conference, Nice, France, V.M, Malhotra, ACI SP-145 (1994).

Mehta, P. K., and P. J. M. Monteiro, *Concrete: Structure, Properties, and Materials*. Second Edition. Prentice Hall. Englewoods Cliffs, New Jersey (1993).

Mindess, S., J. F. Young, and D. Darwin, *Concrete,* Second Edition, Prentice-Hall Pearson Education, Inc., Upper Saddle River, New Jersey, ISBN 0-13-064632-6 (2003).

National Highway Institute (NHI), *PCC Pavement Evaluation and Rehabilitation*. Reference Manual, NHI Course Number 131062, Federal Highway Administration, U.S. Department of Transportation, October (2001).

Neville, A. M., *Properties of Concrete.* John Wiley and Sons, Inc., New York, New York, ISBN 0-470-23527-6 (1996).

Ouyang, C., and O. J. Lane, "Effect of Infilling of Air Voids by Ettringite on Resistance of Concretes to Freezing and Thawing." *Ettringite—The Sometimes Host of Destruction.* SP-177. American Concrete Institute. Farmington Hills, Michigan (1999).

Pigeon, M., and R. Plateau. *Durability of Concrete in Cold Climates.* E & FN Spon, ISBN 0-419-19260-3 (1995).

Price, B., "Measuring Air Voids in Fresh Concrete." *Concrete*, Vol. 30, No. 4 (1996).

Schwartz, D. R. *NCHRP Synthesis of Highway Practice 134: D-Cracking of Concrete Pavements.* Transportation Research Board, Washington, D.C. (1987).

Stanish, K. D., R. D. Hooton, and M. D. A Thomas, *Testing the Chloride Penetration Resistance of Concrete: A Literature Review.* FHWA Contract DTFH61-97-R-00022, University of Toronto, Toronto, Ontario, Canada, June (1977).

Stark, D. *Characterization and Utilization of Coarse Aggregate Associated with D-Cracking.* RD047.01p, Portland Cement Association, Skokie, Illinois (1976).

Suryavanshi, A. K., J. D. Scantlebury, and S. B. Lyon, "Pore Size Distribution of OPC and SRPC Mortars in Presence of Chlorides." *Cement and Concrete Research*, Vol. 25, No. 5 (1995).

Thaulow, N., V. Johansen, and U. H. Jakobsen. *What Causes Delayed Ettringite Formation?* Bulletin No. 60, presented to the Fall 1995 Meeting of the Material Research Society, Boston, Massachusetts (1996).

Van Dam, T. J., L. L. Sutter, K. D. Smith, M. J. Wade, and K. R. Peterson, *Guidelines for Detection, Analysis, and Treatment of Materials-Related Distress in Concrete Pavements, Volume 1: Final Report.* FHWA-RD-01-163, Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, Virginia, March (2002a).

Van Dam, T. J., L. L. Sutter, K. D. Smith, M. J. Wade, and K. R. Peterson, *Guidelines for Detection, Analysis, and Treatment of Materials-Related Distress in Concrete Pavements, Volume 2: Guidelines Description and Use.* FHWA-RD-01-164, Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, Virginia, March (2002b).

Wang, H., and J. E. Gillott, "The Effect of $CaCl_2$–Based Accelerator on Alkali Silica Reaction." *Cement and Concrete Research*, Vol. 20 (1990).

Whiting, D. A., and M. A. Nagi, *Manual on Control of Air Content in Concrete*. EB116, Portland Cement Association, Skokie, Illinois (1998).

APPENDIX

EXAMPLES OF MIXTURE DESIGNS

There are many ways to achieve high early strength while maintaining durability of EOT concrete. The goal is to select the most cost-effective combination of materials that will produce a mixture meeting strength criterion while achieving the desired level of durability. To some degree, this will depend on the environment in which the repair is to be made. For example, in some states, issues of freeze-thaw durability and scaling resistance are not big concerns, and the need for air entrainment is reduced. For the vast majority of states, however, air entrainment must be considered because of the freeze-thaw environment and use of chemical deicers. In this study, several mixture designs were found to provide appropriate fresh and hardened concrete properties.

Mixtures 1, 2, and 3, all of which were made using a vinsol resin air-entraining agent, provided good performance for 6- to 8-hour EOT concrete:

- Mixture 1
  - Cement Type: Type I
  - Cement Content: 525 kg/m^3 (885 lb/yd^3)
  - *w/c* ratio: 0.40
  - Accelerator Type: non-chloride
  - Water Reducer: none
  - Coarse Aggregate: 1,030 kg/m^3 (1,736 lb/yd^3) crushed limestone
  - Fine Aggregate: 427 kg/m^3 (720 lb/yd^3) natural sand
  - Average Slump: 140 mm (5.5 in.)
  - Average Air Content: 5.0 percent
  - 8-hour Compressive Strength: 16.4 MPa (2,375 psi)
  - 28-day Compressive Strength: 44.0 MPa (6,400 psi)
  - 8-hour Flexural Strength: 2.4 MPa (350 psi)
- Mixture 2
  - Cement Type: Type I
  - Cement Content: 525 kg/m^3 (885 lb/yd^3)
  - *w/c* ratio: 0.36
  - Accelerator Type: non-chloride
  - Water Reducer: none
  - Coarse Aggregate: 1,030 kg/m^3 (1,736 lb/yd^3) crushed limestone
  - Fine Aggregate: 482 kg/m^3 (812 lb/yd^3) natural sand
  - Average Slump: 70 mm (2.75 in.)
  - Average Air Content: 5.0 percent
  - 8-hour Compressive Strength: 20.4 MPa (3,000 psi)
  - 28-day Compressive Strength: 56.3 MPa (8,150 psi)
  - 8-hour Flexural Strength: 3.0 MPa (435 psi)
- Mixture 3
  - Cement Type: Type I
  - Cement Content: 425 kg/m^3
  - *w/c* ratio: 0.40
  - Accelerator Type: calcium chloride
  - Water Reducer: none
  - Coarse Aggregate: 1,030 kg/m^3 (1,736 lb/yd^3) crushed limestone
  - Fine Aggregate: 425 kg/m^3 (716 lb/yd^3) natural sand
  - Average Slump: 65 mm (2.5 in.)
  - Average Air Content: 5.6 percent
  - 8-hour Compressive Strength: 17.0 MPa (2,465 psi)
  - 28-day Compressive Strength: 53.8 MPa (7,800 psi)
  - 8-hour Flexural Strength: 2.4 MPa (350 psi)

Mixtures 4, 5, and 6, all of which were made using a vinsol resin air-entraining agent, provided good performance for 20- to 24-hour EOT concrete:

- Mixture 4
  - Cement Type: Type I
  - Cement Content: 400 kg/m^3
  - *w/c* ratio: 0.43
  - Accelerator Type: calcium chloride
  - Water Reducer: none
  - Coarse Aggregate: 1,030 kg/m^3 (1,736 lb/yd^3) crushed limestone
  - Fine Aggregate: 628 kg/m^3 (1,060 lb/yd^3) natural sand
  - Average Slump: 85 mm (3.35 in.)
  - Average Air Content: 6.6 percent
  - 20-hour Compressive Strength: 24.5 MPa (3,550 psi)
  - 28-day Compressive Strength: 46.0 MPa (6,670 psi)
  - 20-hour Flexural Strength: 3.4 MPa (490 psi)
- Mixture 5
  - Cement Type: Type I
  - Cement Content: 400 kg/m^3
  - *w/c* ratio: 0.40
  - Accelerator Type: non-chloride
  - Water Reducer: none
  - Coarse Aggregate: 1,030 kg/m^3 (1,736 lb/yd^3) crushed limestone
  - Fine Aggregate: 659 kg/m^3 (1,110 lb/yd^3) natural sand
  - Average Slump: 50 mm (2 in.)
  - Average Air Content: 5.7 percent
  - 20-hour Compressive Strength: 19.9 MPa (2,890 psi)
  - 28-day Compressive Strength: 40.6 MPa (5,890 psi)
  - 20-hour Flexural Strength: 3.8 MPa (550 psi)
- Mixture 6
  - Cement Type: Type I
  - Cement Content: 475 kg/m^3
  - *w/c* ratio: 0.43
  - Accelerator Type: none

– Water Reducer: none
– Coarse Aggregate: 1,030 kg/m^3 (1,736 lb/yd^3) crushed limestone
– Fine Aggregate: 659 kg/m^3 (1,110 lb/yd^3) natural sand
– Average Slump: 150 mm (6 in.)
– Average Air Content: 5.9 percent
– 20-hour Compressive Strength: 17.8 MPa (2,580 psi)
– 28-day Compressive Strength: 39.3 MPa (5,700 psi)
– 20-hour Flexural Strength: 3.6 MPa (520 psi)

These examples of cement mixtures were identified from the investigations conducted in NCHRP 18-04B. Other suitable mixtures could be proportioned with the same or different cements, aggregates, and admixtures.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation