Participant Handbook

Integrated Materials and Construction Practices (IMCP) for Concrete Pavilion Workshop

Prepared for
Federal Highway Administration
Office of Pavement Technology
400 7th Street AW
HIPT 20
Washington, D.C. 20590

Prepared by
National Concrete Pavement Technology Center
at Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664

August 2007
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<tr>
<td>Marcia Brink, Dale Harrington, Peter Taylor, Sabrina Shields-Cook</td>
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<td>This document serves as the participant’s handbook for an FHWA workshop based on Integrated Materials and Construction Practices for Concrete Pavements: A State-of-the-Art Manual (IMCP Manual) (Federal Highway Administration publication no. HIF-07-004, December 2006). The manual and workshop materials were developed by a team led by Iowa State University’s National Concrete Pavement Technology Center.</td>
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ACKNOWLEDGMENTS

This participant handbook is part of a package of training deliverables for Federal Highway Administration (FHWA) Cooperative Agreement No. DTFH61-06-H-00011 with Iowa State University. The project team appreciates the significant efforts of Gina Ahlstrom, FHWA’s Agreement Office Technical Representative, whose direction and leadership helped the team improve the presentations and other training materials. Additional valuable input was provided by the Oversight Committee, who reviewed draft training materials and joined Ms. Ahlstrom in evaluating a walk-through workshop and a pilot workshop:

- Gary Crawford, Federal Highway Administration
- Matt Mueller, Illinois Department of Transportation
- Shannon Swietzer, North Carolina Department of Transportation
- Al Johnson, WR Grace
- Wouter Gulden, American Concrete Pavement Association, Georgia
- Rick Bohan, Portland Cement Association
- Tom Van Dam, Michigan Technological University
- Tim Aschenbrenner, Colorado Department of Transportation
- Hassan Barzegar, IHC, Englewood, CO

The training team received additional feedback from approximately 600 people who participated in a 10-workshop training blitz across the country during spring 2007. We thank them for every comment and suggestion and trust that the final training package represents the best of their input.

Finally, we sincerely appreciate the support of FHWA in helping the National Concrete Pavement Technology Center provide low- or no-cost training to accompany the Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual (FHWA HIF-07-004, December 2006). The value of the workshops and manual is being validated by the wave of requests for a second round of training beginning in late 2007. We will begin the second round with a Train-the-Trainer program to enlarge the circle of experts who can take this workshop around the country.

Principal Investigator
Mr. Dale Harrington, Snyder & Associates, Ankeny, IA

Expert Trainers
Dr. Peter C. Taylor, CTLGroup, Chicago, IL
Dr. Michael E. Ayers, American Concrete Pavement Association, Chicago, IL
Mr. Dale Harrington, Snyder & Associates, Ankeny, IA

Managing Editor and Co-Principal Investigator
Ms. Marcia Brink, National Concrete Pavement Technology Center, Iowa State University, Ames, IA

August 15, 2007
## AGENDA

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### IMCP Workshop Evaluation Form

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### Module 9: QA/QC

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### Module 10: Troubleshooting

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B. Complete the following short-answer questions:

1. Which module(s) [or specific topic(s)] would you have liked more information about? ____________________
   ________________________________________________________________________________________
   ________________________________________________________________________________________
   ________________________________________________________________________________________

2. Which module(s) [or specific topic(s)] were most helpful to you? ______________________________
   ________________________________________________________________________________________
   ________________________________________________________________________________________
   ________________________________________________________________________________________

C. Provide any additional comments or suggestions for improving the training:
   ________________________________________________________________________________________
   ________________________________________________________________________________________
   ________________________________________________________________________________________
   ________________________________________________________________________________________
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   ________________________________________________________________________________________

THANK YOU FOR YOUR TIME AND EFFORT!
INTRODUCTION

This workshop is based on Integrated Materials and Construction Practices for Concrete Pavements: A State-of-the-Art Manual (IMCP Manual) (Federal Highway Administration publication no. HIF-07-004, December 2006). The manual and workshop materials were developed by a team led by Iowa State University’s National Concrete Pavement Technology Center.

The emphasis of these materials is on the concrete itself—specifically, on optimizing concrete’s performance in pavement applications.

Overall Workshop Objectives

The IMCP workshop will help participants

- Use the IMCP Manual as a resource and reference. In particular, they will learn how to quickly access and apply how-to and troubleshooting information.
- Understand, at a basic level, the integrated nature of concrete pavement materials and construction practices and apply that understanding on the job.
- Bridge the gap between recent research and common practice so they can exploit the best technologies and practices for preventing or minimizing premature concrete pavement distress.

Intended Audience

In an era of specialization, personnel in various specialties do not necessarily understand how their decisions and activities in one stage of a pavement project affect, and are affected by, other specialists’ decisions and activities, and how all affect the concrete’s performance. Therefore, people with diverse responsibilities in the concrete pavement community, in both public and private organizations, will benefit from the workshop:

- Design and materials engineers.
- Consultants.
- Quality control personnel.
- Contractors.
- Materials and equipment suppliers.
- Technicians.
- Construction supervisors.
- Trades people, etc.

Intended Workshop Format

This workshop is set up as a day-and-a-half event with 10 modules. The agenda may be shortened by eliminating some modules as appropriate for and/or desired by the particular participants.

Chapters 2 and 7 have been combined into one module 2/7. During workshops in winter and spring 2007, the instructors found it useful to combine the related information in these two
chapters into one module. In addition, the order of modules in the workshop varies slightly from the chapter order of the manual. This, too, is a result of lessons learned during the first season of workshops.

The event is designed to be interactive. Participants are encouraged to ask questions and actively participate. They will be provided with many resources to use during the workshop and to take back to work with them.

**Modules**
The day-and-a-half workshop covers 10 topics, or modules, each of which uses information from one or more of the chapters in the IMCP Manual. Each module consists of the following materials:

- A PowerPoint slide presentation (cross-referenced to pages in the IMCP Manual).
- A brief technical summary.

**Module Topics**
The module topics are as follows:

- Module 1—Introduction (chapter 1, plus organizational scheme for all 10 chapters)
- Module 2/7—Design of Pavements and Subgrades/Bases (chapters 2 and 7)
- Module 3—Basics of Materials (chapter 3)
- Module 4—Cement Hydration (chapter 4)
- Module 5—Concrete Properties (chapter 5)
- Module 6—Mix Design Principles (chapter 6)
- Module 8—Construction (chapter 8)
- Module 9—Quality Assurance and Testing (chapter 9)
- Module 10—Troubleshooting and Problem-Solving (chapter 10)

**Slides Presentations**
Each presentation module begins with a set of objectives and ends with questions for participants that reinforce the learning objectives.

**Technical Summaries**
These brief publications highlight main concepts in each module. They will not be used during the workshop, but participants can use them to introduce these concepts to their staffs. A set of technical summaries is included in Appendix A.
WORKSHOP MATERIALS

Participants will receive a copy of the IMCP Manual (with full-size chart and an electronic version of the manual), a participant handbook, and additional electronic files.

IMCP Manual
The IMCP Manual is accompanied by a full-size stages-of-hydration chart and a searchable electronic version of the manual (.pdf).

Participant Handbook
The participant handbook consisting of the following elements:
- Workshop agenda.
- Workshop evaluation form.
- General workshop information.
- For all 10 modules:
  - An introduction.
  - Printout of presentation slides with space for note-taking.
- A set of technical summaries (Appendix A).

Electronic Files
The participant handbook is accompanied by the following electronic files:
- Technical summaries.
- Videotape of the April 2007 workshop held in Iowa.
WORKSHOP ACTIVITIES

Interaction
The workshop will be more successful if participants interact with the instructors. Respond to questions. Ask questions. Ask for examples. Share an example of your own. Don’t monopolize the discussion.

Breaks and Lunch
Frequent breaks will help participants maintain a high level of attention and interest, particularly when the material being presented is highly technical. Twenty-minute breaks are scheduled each morning and afternoon. Feel free to stand up and move around when you need to. A 50-minute lunch is scheduled around the noon hour.

Topics/Questions Identified by Participants
During the first module, you will be asked to list two or three questions you hope will be answered during the workshop. Use the blank index card provided. An instructor or host will pick up your list.

Workshop Evaluations
Evaluation forms are located at the front of this handbook, right behind the workshop agenda. Please use the question/answer time at the end of each half-day session to evaluate the modules presented. Your feedback helps instructors continually improve this workshop.

Write the workshop date(s) and location in the spaces provided. Provide your name if you wish, but you are not required to do so. Use the extra space to provide additional feedback.
POST-WORKSHOP ACTIVITIES

Take what you’ve learned back to other staff in your office or shop. Post the full-size hydration chart in the office, lab, or construction shop. Use the technical summaries provided in Appendix A to give short training sessions. Determine if other personnel would benefit from attending this workshop and encourage them to do so.

Keep the IMCP manual and technical summary 10 (a full copy of the troubleshooting tables) handy for convenient reference. Review the content a chapter at a time. If you have questions, contact one of your instructors.
FOR MORE INFORMATION

For advice or information about the IMCP workshop and materials, contact either of the following:

Peter Taylor, Associate Director
National Concrete Pavement Technology Center
2711 S. Loop Drive, Suite 4700
Ames, IA 50010-8664
515-294-9333
ptaylor@iastate.edu

Gina Ahlstrom
Office of Pavement Technology
Federal Highway Administration
400 7th Street SW, Room 4410
Washington, D.C. 20590
202-366-1324
ahlstrom@fhwa.dot.gov
MODULE 1:
INTRODUCTION TO IMCP MANUAL AND WORKSHOP

Overview
As an introduction to the workshop, module 1 is unique in that it does not provide technical information.

Objectives
The overall objectives for this module are to introduce the IMCP Manual to participants, provide an overview of the IMCP workshop, and make the participants comfortable with the instructor(s) and each other.

Learning Outcomes
At the end of this module, participants will
- Understand in general why, how, and by whom the IMCP Manual was developed and what it’s about.
- Understand the IMCP Manual’s organizational structure so that they can effectively use it as a reference.
- Appreciate the inter-relatedness of the various processes involved in concrete pavement projects.

Presentation Graphics
The following printouts include space for participants to write notes.
**Introductions/Housekeeping**

- Instructors
- Hosts
- Exits, restrooms
- Breaks and lunch
- Shuttle services, etc.

**Today's Participants**

Organizations?
- State DOTs
- FHWA
- Local agencies
- Contractors
- Materials suppliers
- Universities
- Other?

Roles?
- Engineer (design, materials, etc.)
- Technician
- Inspector
- Project manager
- Supervisor
- Other?

And why are YOU here today?

**Today's Resources**

- IMCP manual
- Participant handbook
- Large hydration chart (with manual)
- Technical summaries (appendix in handbook)
- DVD with
  - Electronic (searchable) manual
  - Electronic technical summaries
  - Video of April 2007 workshop in Iowa
IMCP Manual Credits

- 17 authors
- 3 technical editors
- 30 expert reviewers
- 4 editors and designers
- Sponsor: FHWA

IMCP Workshop Credits

- Gina Ahlstrom, FHWA
- Gary Crawford, FHWA
- Matt Mueller, IL DOT
- Shannon Swietzer, NC DOT
- Al Johnson, WR Grace
- Wouter Gulden, ACPA, GA
- Rick Bohan, PCA
- Tim Van Dam, Mich Tech U
- Hassan Barzegar, IHC, Englewood, CO
- Peter Taylor, CTLGroup (project team member)
- Mike Ayers, ACPA (project team member)
- Marcia Brink, CTRE/ISU (project team member)
- Dale Harrington, CTRE/ISU (project team member)

Workshop Agenda

Day 1
- 1. Introduction to the IMCP Manual and Workshop
- 2 & 7. Design of Pavements and Subgrades/Bases
- 3a. Fundamentals of Materials Used for Concrete Pavements
- 3b. Fundamentals of Materials Used for Concrete Pavements
- 5. Fresh Concrete Properties
- Questions/Review and Evaluations
- Lunch
- 4a. Cement Hydration: The Basics
- 4b. Cement Hydration: Incompatibilities
- 5b. Early-Age Cracking

Day 2
- 5c. Hardened Concrete Properties: Durability
- 6. Mix Design Principles
- 8. Construction
- 9. QA/QC
- Questions and Evaluation
- Lunch
- 10. Troubleshooting
- Questions/Review and Evaluations
Why This Manual & Workshop?

A Resource to Fill Knowledge Gaps

- How/why to optimize concrete materials to optimize pavement performance
- How/why decisions in each stage of a pavement project affect other stages
- How/why to test for and make real-time mix and construction adjustments
- How to use the manual as a ready reference and troubleshooting guide

Chapters/Modules

1. Introduction
   Why bother reading this manual?
   How the info is organized so it can be used as a textbook, a reference, and a troubleshooting guide
**Chapters/Modules**

2. Basics of Concrete Pavement Design

*What do we want in a specific pavement? What kind of design will achieve it?*

---

**Chapters/Modules**

3. Fundamentals of Materials for Concrete

*What materials do we have to work with?*

---

**Chapters/Modules**

4. Chemistry of Hydration

*How do those materials from a plastic mix to a solid slab?*
5. Concrete Properties

What concrete properties do we need in a specific project?

6. Mix Proportioning

How do we combine the materials to get the properties we want?

Paste (cement + water)
- 9 - 15% Cement
- 15 - 16% Water

Mortar (paste + fine aggregate)
- 25 - 35% Fine aggregate

Concrete (mortar + coarse aggregate)
- 30 - 45% Coarse aggregate

7. Preparing the Site

What will the concrete slab sit on? Why is it important?
**Chapters/Modules**

8. Construction

*Let’s do it!*

---

**Chapters/Modules**

9. Quality control and testing

*Have we got it right?*

- Purpose – Why Do This Test?
- Principle – What is the Theory?
- Test Procedure – How is the Test Run?
- Test Apparatus
- Test Method
- Output – How Do We Interpret the Results?
- Construction Issues – What Should I Look For?

---

**Chapters/Modules**

10. Troubleshooting

*Avoiding oh *!~&@#!***^#/ dam!*

---
What’s Not in the Manual

- Detailed pavement design information
- Detailed construction information
- Maintenance and rehabilitation information

Finding the Info You Need

- Tables of figures, tables
- Thumb index
- Cross references
- Subject index

Tables of Figures and Tables

- 140 figures
- More than 50 tables
**Specially Formatted Information**

- Key points
- Sidebars
- Hydration charts
- Early-age cracking reference sheets
- Troubleshooting guide (chapter 10)

**Key Points**

**Sidebars**
Hydration Charts

Early-Age Cracking References

Q/C Tests
Finally

Any questions about the materials or workshop?

Has everyone written down 2 or 3 questions?

Thank you. Let's go!
MODULE 2:
DESIGN OF PAVEMENTS AND SUBGRADES/BASES

Overview
Pavement design is the development and selection of slab thickness, joint dimensions, reinforcement and load transfer requirements, and other pavement features. A pavement designer’s objective is to select pavement features that will economically meet the specific needs and conditions of a particular project. This module provides an introduction to pavement design as well as a brief outline of subgrade and base preparation issues that are critical to the life of the concrete pavement.

Objective
The primary objective for module 2 is to help participants understand the relationship between pavement design, construction/materials, and subgrade/base support. This module covers information from both chapter 2 and chapter 7 of the IMCP Manual.

Learning outcomes
Participants will have the ability to
• Identify pavement types and design features.
• Recognize what design variables are controlled by field operations.
• Discuss the two primary types of pavement distress (performance measures).
• Recognize how subgrades and bases affect construction operations and long-term pavement performance.

Presentation Graphics
The following slide printouts include space for notes.
Learning Objectives

The objective of this module is to understand the relationship between pavement design, construction/materials, and subgrade/base support (chapters 2 and 7):

- Identify pavement types and design features
- Recognize what design variables are controlled by field operations
- Discuss the 2 primary types of pavement distresses (performance measures)
- Recognize how subgrades and bases effect construction operations and long-term pavement performance

Goal of Pavement Design

The primary goal of pavement design is to provide a pavement with the following characteristics:

- Safe
- Long lasting
- Cost effective
- Low maintenance
- Constructible

Pavement Types—Jointed Plain Concrete Pavement (JPCP)

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<thead>
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<td>14-20 ft</td>
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</tbody>
</table>
Pavement Types - Continuously Reinforced Concrete Pavement (CRCP)

Plan

2 – 6 ft

Profile

Basic Components of a Concrete Pavement

- Concrete materials
- Transverse joints
- Longitudinal joint
- Surface texture
- Subbase or base
- Subgrade
- Dowel bars
- Thickness design

Pavement Performance

- Pavement performance is characterized in the following ways:
  - Structural performance
  - Functional performance
  - Pavement design is heavily weighted towards structural performance
  - Material durability is typically not considered directly in design
    - It is assumed
Structural or Functional Failure?

(IMCP—page 12)

________________________________________

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Structural or Functional?

Pavement Performance

Pavement Design Methods – AASHTO 1993

- The most common pavement design method is the AASHTO 1993 Pavement Design Guide
- Inputs for the design of new concrete pavements include
  - Design ESALs (traffic)
  - Concrete strength and stiffness
  - Support (subgrade and base)
  - Serviceability
  - Reliability
  - Load transfer
  - Drainage
Pavement Design Methods—Mechanistic-Empirical Pavement Design Guide (M-E PDG)

- The M-E PDG represents a new and different approach to pavement design
- This method combines a scientific approach (mechanistic) with observed pavement performance (empirical)
- The M-E PDG requires many new materials-related variables, some of which are controlled during construction

M-E PDG Construction/Materials Inputs

The following list represents a small portion of the new inputs influenced during construction:

- Coefficient of thermal expansion
- Concrete mix design parameters
- Curing type
- Joint sealant type
- Many others
## Pavement Support Basics

- Firm, uniform, and non-erodible support is essential for concrete pavements
  - Reduces pavement deflections from vehicle loadings
  - Avoids stress concentrations
- Must provide a stable working platform to expedite all construction operations
  - Construction of smooth pavements due to stable trackline for slipform pavers

## Pavement Support Basics

- Results in improved load transfer at pavement joints
  - Not as effective as dowels or edge support
- Must be able to achieve compaction during construction
  - Prevents base consolidation under construction and traffic

## Concrete Pavement Support Requirements

- Concrete pavements distribute loads over a wide area due to slab action
- Support needs to be uniform for proper load distribution
- It is not necessary (or necessarily desirable) to have very high levels of support layer strength and stiffness
Subgrades/PCC Pavements

- PCC pavements are rigid
- Vehicle loads are distributed over large areas (beam strength) (15-20 ft)
  - Minor deflections
- Low subgrade pressures
- Subgrade uniformity is more important than strength

Subgrades/Asphalt Pavements

- Asphalt pavements are flexible
- Distribution of loads depends largely on pavement thickness
  - Load on subgrade is more concentrated
  - Deflections are more extreme
- Subgrade strength/stiffness is very important

Achieving Quality Subgrade

- Achieving uniform subgrade support is one of the most difficult problems facing the paving industry today
- Many factors must be considered, including
  - Inherent variability of soils
  - Influences from water
  - Influences from temperature
  - Influences of construction activities
  - Abrupt changes in soil type, moisture content, and density
Subgrade Soil Must Be Volumetrically Stable

- Non-expansive (shrink and swell)
- Non-frost susceptible
- Non-pumping
- Non-consolidating

Non-Uniform Subgrade Support

- Non-uniform support results in differential deflections, causing stress concentrations in the pavement
- Concentrated stresses can lead to premature failures, including transverse and longitudinal cracking, corner breaks, shattered slabs, faulting, pumping, and other types of pavement distress

Non-Uniform Subgrade Support

Non-uniform subgrades under concrete pavements cause “bridging”: load stresses are concentrated in small areas

Stress Intensities
Properties of Soil Affected by Water

- The following subgrade properties are typically affected by moisture
  - Density
  - Strength/deformation properties
  - Volumetric stability
  - Frost susceptibility
- The level of influence is partially correlated to the following
  - Soil type
  - Permeability
  - Capillary action (effective grain size)
  - Others

Rainfall into Pavement Cracks

Percolating ground water via capillary action

Capillarity, Permeability, and Frost Action

- The finer the grain, the higher the capillarity
  - Very little air content between grains

(IMCP—pages 193–195)

(IMCP—pages 194)
### Capillary Rise

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Height of Capillary Rise (feet)</th>
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<tr>
<td>Coarse Sand</td>
<td>0.5</td>
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<tr>
<td>Fine Sand</td>
<td>1 to 3</td>
</tr>
<tr>
<td>Silt</td>
<td>3 to 30</td>
</tr>
<tr>
<td>Clay</td>
<td>30 - 90</td>
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</tbody>
</table>

### Capillary Potential and Frost Susceptibility

- Clays have highest capillary potential, but highly plastic clays have low permeability, thus reduce susceptibility to frost action.
- Silts are most frost susceptible, as they are very fine (high capillary potential) and can transport more water to ice lenses due to relatively high permeability.
- Fine sands are frost susceptible
  - More permeable than clay
  - Not as much capillary potential as silts

### Frost Action Heave

- Water in large pores freezes at normal freezing temperature
- Water in capillary tubes and small intersects of soil does not freeze and is drawn to ice mass
- Road surface heaved at least as much as combined lens thickness
- Ground water
- Cause
- Ice Lenses
- Effect
- Road Surface

---

Participant Handbook—Module 2  30 of 194
Expansive/Collapsing Soils

- Expansive soils
  - Expand and contract with level of saturation, resulting in non-uniform support
  - Compact wet of optimum
- Collapsing soils
  - Existing structure collapses when wetted or mechanically manipulated
  - Presaturate and collapse (vibration or impact) prior to construction

Subgrade Treatment/Stabilization

- Treatment is not used to cover up unstable locations
- On site soils or borrowed soils (select) are typically the best choice in open rural areas based on economics
- Stabilized or treated subgrade can be accomplished using hydraulic cement, lime, fly ash, CKD, or asphalt
- Could use geosynthetics for mechanical stabilization

Polymer Grid

- A high strength polymer material
- Often used in combination with granular base as an alternative to select or stabilized treatment
- Used when on site materials are not available
- Works well with aggregate base for interlocking
- Has very high tensile strength
**Proof Rolling**

- Proof-rolling can locate isolated soft areas that are not detected in the grade inspection process.
- It involves driving a heavy, pneumatic-tired vehicle over the prepared grade, observing for rutting or unacceptable deformation.
- Steel drum rollers are not recommended.
- Proof-rolling is recommended if an unstabilized base is to be used.

---

**Pumping**

- Pumping is the forceful displacement of a mixture of soil and water (i.e., mud) from underneath a concrete pavement during heavy applied loads.
- Continued, uncontrolled pumping eventually leads to the displacement of soil and void formation.
- Can result in cracking, faulting, and settling of the concrete pavement.
Base

• Under most conditions at least one subbase/base layer is needed on top of the prepared subgrade and immediately below the concrete pavement
• Typical Materials
  ▪ Crushed concrete
  ▪ Crushed limestone
  ▪ Mixture of gravel, sand, soil
  ▪ Stabilized material

Types of Stabilized Base

• Cement-treated
• Cement-treated open-graded
• Lean concrete
• Asphalt-treated
• Asphalt-treated open-graded
• Hot-mix asphalt

Stability versus Permeability for Untreated Base/Subbase
### Material Gradations

**Percent Passing**

<table>
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<tr>
<th>Sieve</th>
<th>Crushed Stone</th>
<th>Special Backfill</th>
<th>Modified Subbase</th>
<th>Granular Subbase</th>
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<td>1 ½&quot;</td>
<td>100</td>
<td>100</td>
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<tr>
<td>3/8&quot;</td>
<td>70-90</td>
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<td>6-16</td>
<td>0-10</td>
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</tr>
</tbody>
</table>

**Permeability:**
- Low
- Moderate
- High
- Highest

**Stability:**
- Highest
- High
- Moderate
- Low

---

### Questions for Discussion

- What are the design features of a typical JPC pavement? CRC pavement?
- What are the 2 general types of pavement distress? Which is the most critical?
- What design parameters are controlled by field operations?
- What is the purpose of a base layer?
- Can soil stabilization be used to “bridge” weak subgrade areas?
- Is design or construction the most important element in pavement performance?

---

Thank you.
MODULE 3A: FUNDAMENTALS OF MATERIALS USED FOR CONCRETE PAVEMENTS: AGGREGATES, REINFORCEMENT, AND CURING COMPOUNDS

Overview
At its simplest, concrete is a mixture of glue (cement, water, and air) binding together fillers (aggregate). But other materials, like supplementary cementitious materials (SCMs) and chemical admixtures, are added to the mixture. During pavement construction, dowel bars, tiebars, and reinforcement may be added to the system, and curing compounds are applied to the concrete surface. All these materials affect the way concrete behaves in both its fresh and hardened states.

Objectives
The primary objective of this module is to give participants an overview of these materials and explain how each one influences concrete performance.

Learning Outcomes
At the end of this module, participants will be able to
- Categorize the three general types of aggregates by origin and outline their effects on concrete properties (fresh and hardened).
- List desirable aggregate properties, including gradation and moisture state.
- Recognize typical aggregate durability problems.
- Describe the types and purpose of reinforcement found in concrete pavements.
- Understand the need for concrete curing.
- Discuss the need for adequate concrete curing and the methods to achieve it.

Presentation Graphics
The following slide printouts include space for participants to take notes.
Fundamentals of Materials Used for Concrete Pavements

Aggregates, Reinforcement, and Curing Compounds

Learning Objectives

The goal of this module is to recognize the importance of the various materials comprising a concrete pavement (chapter 3):

- Aggregate properties, selection criteria, and adverse reactions
- “Reinforcement” including dowels, tiebars, and others
- Curing compounds and evaporation-retarding compounds

Aggregates

- Aggregates comprise the majority of the volume of a concrete mix
- Aggregate properties have a strong influence on the following concrete properties:
  - Durability
  - Workability
  - Strength
  - Dimensional changes in concrete
  - Many others
### Aggregate Types

Aggregates are generally grouped by their mineralogical classification:

- How they were formed
  - Igneous
  - Metamorphic
  - Sedimentary
- Chemical make-up
  - Siliceous
  - Calcareous, etc.

### Aggregate Characteristics

- Aggregates with common features (e.g., limestone) may have very different properties
- Aggregates from the same location may also have different properties based on their location within the deposit or formation
- It is critical to know these differences

### Aggregates in Concrete

- The physical properties of aggregates (natural or manufactured) have a strong effect on the properties of fresh and hardened concrete:
  - Gradation
  - Surface texture
  - Particle shape
  - Absorption
  - Durability
Aggregate Gradation

- Coarse aggregate gradation or particle size distribution is determined by the AASHTO T-27 procedure (sieve analysis).
- The percent retained on each sieve is recorded to determine if a material is well graded or gap graded.
- Coarse aggregates are generally defined as plus #4 (retained on the #4 sieve); sand is minus #4.

The maximum aggregate size used for paving is usually 1 1/2 inches or less.
- Well-graded aggregates are desirable:
  - Maximize aggregate packing
  - Minimize cement content (economical)
  - More workable
  - Less drying shrinkage

Fine aggregate (sand) gradation is specified by AASHTO M 6.
- The sand-to-aggregate ratio is established in the mix design procedure to accommodate local sand sources.
- Sand gradation can have a significant impact on mix water requirements.
**Aggregate Gradation**

- Combined grading is used to obtain the maximum aggregate density with the materials at hand
- Combined grading may use two or more aggregate stockpiles (bins)
- Overall material specifications generally represent the total or combined grading, although individual aggregate specifications may apply

**Particle Shape and Surface Texture**

- Particle shape and surface texture of aggregates have a large effect on workability
- Angular particles are generally used in pavements, as they tend to increase the flexural strength of the concrete
- Virtually any surface texture of aggregates can be used to produce quality concrete
- A rough surface texture can produce higher flexural strength when determined by beam breaks
Absorption

- Absorption is a function of the amount of void space in the aggregate
- Aggregates in concrete tend towards a moisture state known as saturated surface dry (SSD), as shown on the following slide
- The moisture state of the aggregate must be known during batching and adjustments should be made to maintain the desired water/cementitious materials ratio

Aggregate Moisture States

<table>
<thead>
<tr>
<th>State</th>
<th>Oven dry</th>
<th>Air dry</th>
<th>Saturated, surface dry</th>
<th>Damp or wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total moisture</td>
<td>None</td>
<td>Less than potential absorption</td>
<td>Equal to potential absorption</td>
<td>Greater than absorption</td>
</tr>
</tbody>
</table>

Aggregate Durability

- Concrete durability is not directly addressed in design
- Durability issues are handled through appropriate specifications and testing
- Concrete durability is influenced by aggregate durability and the possibility of adverse reactions between the aggregates and cement or environmental conditions
**Aggregate Durability Issues**

Aggregate-related distresses include the following:

- Alkali-aggregate reactivity (ASR)
- D-cracking
- Surface popouts
- Abrasion resistance

**Dowel Bars**

- Dowel bars are smooth bars designed to provide effective load transfer across transverse joints and minimize faulting
- Round dowels are typically 1-1/4 to 1-1/2 inches in diameter and 15 to 18 inches in length, spaced 12 to 15 inches apart
- Steel dowel bars may be red oxide coated, epoxy coated, stainless steel clad, or solid stainless steel
- Elliptical shaped dowels and fiber-reinforced composite bars are currently being evaluated

**Tiebars**

- Tiebars are deformed bars designed to hold lanes together at longitudinal joints and promote aggregate interlock load transfer
- Tiebars are either plain or epoxy coated
- Tiebars are sized depending on the specific pavement design details
Reinforcement

- Reinforcement in concrete pavements is designed to hold random cracks tightly together to facilitate aggregate interlock load transfer
- Continuously reinforced concrete pavement uses a relatively high cross-sectional area of steel to accomplish this (0.7 percent or greater)
- Reinforcement may be plain steel or epoxy coated and can consist of reinforcing bars or welded wire fabric

Curing Compound

- Curing compound is applied to all exposed surfaces of fresh concrete to maintain moisture
- Adequate moisture allows strength development and has a strong influence on durability
- Curing should be applied as soon as practical after finishing to achieve these goals

Curing Compounds

- Liquid membrane curing compounds are used for paving primarily for convenience
  - Wax or resin-based
- Alternatives are water fogging, plastic sheeting, ponding, and other methods impractical for most paving applications
- Evaporation retarders are different from curing compounds in that they are applied immediately after placement and are used to “seal in” the bleed water
Questions for Discussion

• What are the factors to consider in selecting concrete aggregates?
• List several of the durability problems related to non-desirable (poor) aggregates.
• What is the primary function of dowel bars at transverse joints? Tiebars?
• What is the function of curing compound and when is it applied?

Thank you.
MODULE 3B:
FUNDAMENTALS OF MATERIALS USED FOR
CONCRETE PAVEMENTS: REACTIVE MATERIALS

Overview

Hydraulic cements and water react in a process called hydration, resulting in new compounds that glue the aggregates together. This module describes hydration, different kinds of cements and supplementary cementitious materials, and how the differences in these materials affect hydration.

Objectives

The objective of this module is to help participants understand the basic characteristics of “reactive” concrete materials and how they influence concrete performance.

Learning Outcomes

At the end of this module, participants will

• Describe the difference between hydraulic cements and pozzolans.
• List the common supplementary cementitious materials used in concrete mixes for pavements and describe their effect on the mix.
• Determine the suitability of water for use in concrete production.
• List the primary types of chemical admixtures and their intended use.
• Select a combination of materials most likely to achieve a given performance requirement (i.e., strength at a given age or durability in a given environment).

Presentation Graphics and Instructor Notes

The following slide printouts include space for participants to take notes.
Objectives

Understand the basic characteristics of “reactive” concrete materials (Chapter 3)

- Describe the difference between hydraulic cements and pozzolans
- List common SCMs and their effect on concrete
- List primary chemical admixtures and their effect on concrete
- Understand the need for concrete curing

Materials

(What do we have to work with)

- **Paste** (cement + water)
  - 9 - 15% Cement
  - 15 - 16% Water
- **Mortar** (paste + fine aggregate)
  - 25 - 35% Fine aggregate
- **Concrete** (mortar + coarse aggregate)
  - 30 - 45% Coarse aggregate

Reactive Materials

- Cementitious materials
- Water
- Chemical admixtures
Cementitious Materials

- Hydraulic cements
- Supplementary cementitious materials

Cementitious Materials

- Hydraulic cement – reacts under water
- Pozzolan – reacts with cement and water
- Supplementary cementitious materials – cements & pozzolans

Specifying Cements

- Portland cement (ASTM C 150 / AASHTO M 85)
- Blended cements (ASTM C 595 / AASHTO M 240)
- Performance specification for hydraulic cements (ASTM C 1157)
**Cement is Changing?**

“We frankly doubt that concrete of the same 28-day strength made with modern materials will always perform as well (as concrete made 15 years ago).”

Powers, PCA SN 1099, 1934

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**Portland Cements (C 150)**

- Type I – general use
- Type II – moderate sulfate resistance and heat
- Type III – high early strength
- Type V – sulfate resistance

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**Blended Cements C 595**

- IS (x) (slag)
- IP (x) (pozzolan)
- Can require moderate sulfate version of IS
Performance Cements C 1157

- GU General use
- HE High early strength
- MS Moderate sulfate resistance
- HS High sulfate resistance
- MH Moderate heat of hydration

Which Spec to Use?

<table>
<thead>
<tr>
<th>Spec</th>
<th>Prescriptive</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>C150</td>
<td>Chemistry</td>
<td>Strength</td>
</tr>
<tr>
<td></td>
<td>Fineness</td>
<td>Setting…</td>
</tr>
<tr>
<td>C595</td>
<td>Source</td>
<td>Strength</td>
</tr>
<tr>
<td></td>
<td>Less chem.</td>
<td>More phys.</td>
</tr>
<tr>
<td>C1157</td>
<td>-</td>
<td>More phys.</td>
</tr>
</tbody>
</table>

Raw Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Component</th>
<th>Percentage</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime</td>
<td>CaO (C)</td>
<td>~60%</td>
<td>Limestone, calcite</td>
</tr>
<tr>
<td>Silica</td>
<td>SiO₂ (S)</td>
<td>~20%</td>
<td>Clay, shale, fly ash</td>
</tr>
<tr>
<td>Alumina</td>
<td>Al₂O₃ (A)</td>
<td>~10%</td>
<td>Clay, shale, bauxite</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe₂O₃ (F)</td>
<td>~10%</td>
<td>Iron ore, clay, mill scale</td>
</tr>
<tr>
<td>Sulfate</td>
<td>SO₃ (S)</td>
<td>~3%</td>
<td>Gypsum, anhydrite</td>
</tr>
</tbody>
</table>
Manufacturing Portland Cement

What is Cement?

- C₃S – The hare (alite)
- C₂S – The tortoise (belite)
- C₃A – The fox (calcium aluminate)
- C₄AF – … (ferrite)

Microstructure of Hydrated Cement Paste
### Typical Composition

<table>
<thead>
<tr>
<th>Phases</th>
<th>Amount, %</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₃S</td>
<td>50 – 55</td>
<td>Early strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heat</td>
</tr>
<tr>
<td>C₂S</td>
<td>20 – 25</td>
<td>Later strength</td>
</tr>
<tr>
<td>C₆A</td>
<td>5 – 12</td>
<td>Heat</td>
</tr>
<tr>
<td>C₆AF</td>
<td>~ 8</td>
<td>Sulfate resistance</td>
</tr>
<tr>
<td>C₅H₂</td>
<td>~ 5</td>
<td>Setting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shrinkage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Admixture performance</td>
</tr>
</tbody>
</table>

(IMCP—chapter 4)

### Supplementary Cementitious Materials

- Fly ash
- Slag
- Natural pozzolan
- Silica fume

(IMCP—page 31)

### Sources

- Fly ash – utilities
- Slag – iron making (not steel)
- Silica fume – ferro silicon
- Metakaolin – partially calcined clay

(IMCP Manual – Reactive Materials: 20, 21, 22)
### Cementitious Materials

- **Cement + Water** → C-S-H + CH **Hydraulic**
- **Pozzolan + CH + Water** → C-S-H **Pozzolanic**
- **Slag + Water** → C-S-H (no CH) **Hydraulic**
- **Slag + CH + Water** → C-S-H **Pozzolanic**

#### Composition

**CaO**, **SiO₂**, **Al₂O₃**
- **Silica fume**
- **F Fly Ash**
- **C Fly Ash**
- **Metakaolin**
- **Cement**
- **Slag**

#### Sizes

- **Silica fume**
- **Metakaolin**
- **GGBF slag**
- **C fly ash**
- **F fly ash**
- **Cement**

*Average size (D50)*
Specs for Cementitious Materials

- Fly ash and Natural Pozzolans – ASTM C 618
- Slag – ASTM C 989
- Silica Fume – ASTM C 1240

Class F Fly Ash or Class C Fly Ash?

- Definition is based on chemistry:
  - > 70% Fe, Si, and Al = Class F
  - 50% to 70% Fe, Si, and Al = Class C
- Affected by coal source, burning, and collection processes
- Perform differently

Typical Amounts of Pozzolans and Slag

- Class F fly ash: 15% - 25%
- Class C fly ash: 15% - 40%
- Slag: 25% - 50%
- Silica fume: 6% - 10%

Blended at the concrete batch plant, or blended or interground at the cement plant
So What Do They Do?

- F Fly ash – fresh
  - Reduces water requirement
  - Makes air entrainment more difficult
  - Retards setting
  - Slows bleeding
  - Reduces heat
  - Slows initial strength gain

So What Do They Do?

- F Fly ash – hardened
  - Reduces permeability
  - Reduces chloride penetration
  - Reduces ASR expansion
  - Improves sulfate resistance
  - Reported higher risk of scaling
  - Similar mechanical (creep, shrinkage)

So What Do They Do?

- C Fly ash – fresh
  - Reduces water requirement
  - Retards setting (but not as much)
  - Slows bleeding
  - Reduces heat (but not as much)
  - Slows initial strength gain (but not as much)
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So What Do They Do?

- C Fly ash – hardened
  - Reduces permeability
  - Reduces chloride penetration
  - May reduce ASR expansion
  - Reported higher risk of scaling
  - Similar mechanical (creep, shrinkage)

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So What Do They Do?

- Slag – fresh
  - Reduces water requirement (but not as much)
  - May retard setting
  - Reduces heat (but not as much)
  - Slows initial strength gain (but not as much)

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So What Do They Do?

- Slag – hardened
  - Reduces permeability
  - Reduces chloride penetration
  - Reduces ASR expansion
  - Improves sulfate resistance
  - Reported higher risk of scaling
  - Similar mechanical (creep, shrinkage)
So What Do They Do?

- General
  - SCMs change properties
  - Means we have to allow for them
  - Cracking risk changes
  - Finishing and curing needs change

Mixing Water (ASTM C 1602)

- Potable: use
- Non-potable: test and use
  - Strength
  - Time of set
  - Chlorides
  - Sulfates
  - Alkalis
  - Total solids

Mixing Water

- Recycled
### Mixing Water

- **Recycled**

<table>
<thead>
<tr>
<th>Max conc. in combined water</th>
<th>Limits, ppm</th>
<th>Test Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride as Cl&lt;br&gt;prestressed other reinforced concrete</td>
<td>500&lt;br&gt;1000</td>
<td>C 114</td>
</tr>
<tr>
<td>Sulfate as SO₄</td>
<td>3000</td>
<td>C 114</td>
</tr>
<tr>
<td>Alkalis as (Na₂O + 0.658 K₂O)</td>
<td>600</td>
<td>C 114</td>
</tr>
<tr>
<td>Total solids by mass</td>
<td>50,000</td>
<td>C 1603</td>
</tr>
</tbody>
</table>

### Water

- **Sources**
  - Added with batch
  - With aggregates
  - In chemical admixtures
  - Added later

### Effects of Extra Water on Concrete

- Increases workability
- Lowers strength
- Increases drying shrinkage
- Increases permeability and reduces durability
Chemical Admixtures

• Air entraining admixtures (AEA)
• Water reducers
• Set modifying admixtures

Air Entraining Admixtures

• Essential for resistance to freezing and thawing
• Improved workability, reduced water, and reduced segregation
• Reduces strength
• Inexpensive
• ASTM C 260
**AEA Mechanism**

- Air
- Water
- Air-entraining agent

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**Mechanism of Water Reducers**

- Water
- Cement
- Freed Water

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**Water Reducers**

- Reduce water required about 5% (12%)
- ASTM C 494 Type A (or F)
- May affect air entrainment
- May retard setting
**Retarders**

- Slow hydration
  - May reduce slump loss
  - Slows need for sawing in hot weather
  - Reduces heat of hydration peak
  - May improve long-term strength
  - May increase risk of plastic cracking
- Often based on sugars or lignins

**Accelerators**

- Increase rate of hydration
  - Setting time decreased in cold weather
  - Increased early strength
  - May increase risk of shrinkage cracking
- Avoid chloride based products if steel is in the concrete

**Specialty Chemical Admixtures**

- Corrosion inhibitors
- Shrinkage reducing admixtures
- Alkali-silica reactions
- Anti-washout
- Viscosity modifying admixtures
- Color
- Fibers
So

- What type of cement is suitable for paving?
- Which SCM should we use for ASR mitigation?
- Should we use Class F ash in cold weather?
- When should we use an accelerator?
- Some air is good—is more better?

And Now?

Thank you.
MODULE 4A: BASICS OF CEMENT HYDRATION

Overview
At the concrete plant, the cementitious materials, water, aggregates, and chemical admixtures are mixed together. During the next few hours, the mixture changes from a plastic mixture to a solid concrete slab. Central to this transformation is a complex process called hydration—an irreversible series of chemical reactions between water and cement. Hydration is a mystery to many people involved in designing and constructing concrete pavements. The goal of this module is to demystify this process, focusing on the practical implications for designers and construction personnel.

Objectives
The primary objective of this module is to give participants a working understanding of critical physical and chemical occurrences during cement hydration, and the various factors that can adversely affect those occurrences, in order to make real-time mix and construction adjustments (or at least recognize when and by whom such adjustments must be made) to prevent problems and extend concrete service life.

Learning Outcomes
At the end of this module, participants will be able to
- Describe, in general, the four compounds in cement and their role in hydration.
- Describe, in general, the compounds resulting during the stages of cement hydration and the role of these compounds in concrete for pavements.
- Describe heat evolution during hydration and its implications.
- Summarize the effects of various SCMs and chemical admixtures on hydration.

Presentation Graphics
The following slide printouts include space for participants to take notes. Instructor notes are also included in the “Notes” section of the electronic files.
Basics of Cement Hydration

Objective
Understand the cement hydration process
• Building the curve
• Why do you care

Cement Hydration
Hydration is a series of irreversible chemical reactions between hydraulic cement and water.
During hydration, the cement dissolves, and its components react with water to make new components. The cement-water paste sets and hardens, "gluing" the aggregates together into a solid mass.

**Why Should You Care about Hydration?**

- Early reactions influence workability and other concrete characteristics during placing and finishing.
- Later reactions determine the concrete's long-term strength and durability.
- A general understanding of hydration will help you recognize, prevent, and/or correct problems to enhance pavement performance.

**First 72 Hours of Hydration**

- Critical for long-term pavement durability.
- Mixing, transporting, placing, curing, and sawing.
### Five Stages of Hydration

- **Stage 1: Mixing**
- **Stage 2: Dormancy**
- **Stage 3: Hardening**
- **Stage 4: Cooling**
- **Stage 5: Densification**

### Hydration and Strength Curves

- **Strength, %**
- **Time**

### Manufacture of Modern Portland Cements

- **Limestone (Ca)**
- **Clay (Al, Si)**
- **Iron Ore (Fe)**

\[
\text{Clinker} = \text{Limestone} + \text{Clay} + \text{Iron Ore} \]

- **Clinker** ground with **Sulfate (gypsum)**

\[
\text{Portland Cement} = \text{Clinker} + \text{Sulfate (gypsum)}
\]
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**What’s in the Bag?**

- Ground clinker
- Sulfate (Gypsum)

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**Cement Particles**

- **Clinker particle**
- **Sulfate particles**
  - (Gypsum)
  - (Sulfur as in rotten eggs)

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**Aluminates and Sulfates**

- **Silicates**
**IMCP Manual – Basics of Cement Hydration: 13**

**Calcium Aluminates**

(As in pottery clay or the sand in sandpaper)

- Aluminate ($\text{C}_3\text{A}$)
- Ferrite ($\text{C}_3\text{AF}$)

**IMCP Manual – Basics of Cement Hydration: 14**

**Calcium Silicates**

(Silica/glass)

- Alites ($\text{C}_3\text{S}$)
- Belites ($\text{C}_2\text{S}$)
- Clinker

**IMCP Manual – Basics of Cement Hydration: 15**

**Stage 1: Mixing**

This stage happens in about 15 min
Stage 1: Mixing

- Aluminates dissolve and react quickly, with high heat. Danger: flash set.
- Sulfate (Gypsum) dissolves quickly, too. It reacts with aluminate and water, forming a gel.
- The gel limits water’s access to aluminate. Reactions slow. Heat drops. Flash set averted.

Stage 2: Dormancy

This stage takes about 2 to 4 hours to complete.

- The gel controls aluminate reactions. Concrete is cool.
- The mix can be transported, placed, finished, and textured.
- Alites slowly dissolve (and belites even more slowly), releasing calcium ions in solution.
Stage 3: Hardening

This stage takes approximately 2–4 hours to complete.

Stage 3: Hardening

- When solution is supersaturated with calcium ions, new compounds begin forming:
  - Calcium silicate hydrate (C-S-H, fiber-like particles)
  - Calcium hydroxide (CH, crystals)
- “Initial set” occurs when enough C-S-H forms to lock together, and the mix stiffens.

Stage 3: Hardening

- These reactions generate heat. Strength starts to develop.
- “Final set” is when the concrete achieves a defined stiffness, roughly when the concrete is hard enough to walk on.
- During this stage, the gel (C-A-S-H) transforms into a needle-like solid (ettringite). It contributes somewhat to early strength.
Stage 4: Cooling

This process normally occurs within the first 12 hours

- After final set, the buildup of C-S-H limits access of water to the cement.
- Thus the alite reactions slow. The heat peaks and begins to drop.
- Sulfate and aluminate continue to react. After sulfate is consumed, ettringite reacts with remaining aluminate to form monosulfate crystals.
Stage 4: Cooling

- Concrete shrinks as it cools and as water evaporates.
- The shrinkage is restrained, causing tensile stress to develop.
- When stress > strength, the concrete will crack.
- Before this happens, joints must be sawed to control the location of cracks.

Sawing Window

The window for sawing joints varies:
- When it begins
- How long it lasts

Stage 5: Densification
Stage 5: Densification

- Belite reactions occur more slowly. They are noticeable after a couple of days and continue for a long time.
- Belite reactions also produce C-S-H and CH, now forming a solid mass.

Stage 5: Densification

- The concrete must be kept moist (protected with curing compound) as long as possible so hydration continues.
- The longer concrete hydrates
  - The greater its strength
  - The lower its permeability
  - The greater its potential durability

Hydration Duration

- Continues indefinitely as long as water can reach unhydrated cement
- 85%–90% of cement volume typically hydrates in first 28 days
- While hydration continues, concrete strength increases, permeability decreases
Implications of Stages

Aluminates and Sulfates

Why should I care?
Where false set and flash set happens!

False set ➔ Too much sulfate (gypsum)
Flash set ➔ Too little sulfate
**Aluminates and Sulfates**

Why should I care?
Creates the dormancy stage!

**Silicates**

Why should I care?

- Strength happens here!
  - Determines when you can saw
  - Cracking happens here
  - How soon you can drive on it
**Silicates**

- Strength comes from
  - Alites
    - Early reaction
  - Belites
    - Later reaction
- They create: **C-S-H**

**Causes**

**Stuff to Harden**

### From Cement Compounds to Hydration Products

Adapted from Tennis and Jennings 2006

- **C-S-H**: 50%–65% of hydration solids
  - Chemically stable
  - A major contributor to concrete strength
  - Binds other particles together
- **CH**: 20%–25% of hydration solids
  - Gives concrete its high pH
  - Stabilizes C-S-H
Note about Aluminate and Sulfate Reaction

- While the silicates are reacting, aluminate and sulfate continue to react, forming needle-like ettringite (C-A-S-H) crystals
- When the sulfate is gone, ettringite reacts with remaining aluminate to form monosulfate crystals
- This does not significantly affect concrete properties

SCMs

- Today most mixes contain SCMs
- SCMs commonly used in paving
  - Class C fly ash
  - GGBFS (slag)
  - Class F fly ash
- SCMs affect the chemistry of hydration
- SCMs affect concrete properties
- Pozzolans: Require source of CH to hydrate

How SCMs Work

Cement + Water = C-S-H

SCM + Water + CH = more C-S-H
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**Ternary Mix Design - Lab Study**

Permeability AASHTO T277 - Virginia Cure Method

![Graph showing permeability and mixing proportions for ternary concrete mix designs.](image)

- **Concrete Permeability Classifications**
  - Less than 100: Negligible
  - 100-1000: Very low
  - 1000-2000: Low
  - 2000-4000: Moderate
  - Greater than 4000: High

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**SCMs’ Effects**

- Delayed final set
- Reduced heat peak
- Extended heat generation
- Increased long-term strength
- Reduced permeability

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**Water Reducers’ Effects**

- Possibly slower strength gain (slows rate of alite reactions)
- Possibly faster aluminate reactions (and risk of flash set)
- More mix water available for hydration
Retarders' Effects

- Lengthened dormancy
- Slowed hydration
- Reduced heat peak
- Extended heat generation
- Increased long-term strength
- Reduced permeability
- Similar to SCMs

Accelerators' (Calcium Chloride) Effects

- Shortened dormancy (increased rate of ion saturation)
- Earlier initial and final sets (steeper hydration curve)

Basics of Hydration: Key Questions

- Cement hydration releases heat?
- Early aluminate hydration must be controlled by sulfate?
- Hydrating alites, belites result in C-S-H and CH which gives concrete its strength?
- Timing of setting, strength gain affect sawing window?
- SCMs generally convert CH to C-S-H, retard hydration, and reduce permeability?
- Water reducers disperse cement grains which make more mix water available for hydration?
Thank you.
MODULE 4B: CEMENT HYDRATION: INCOMPATIBILITIES

Overview

Some combinations of materials may be prone to problems with setting, stiffening, or other issues. Such problems can occur even if all materials meet their specifications and perform well when used alone or with other materials. This phenomenon is generally known as incompatibility.

Incompatibility is important because small changes in the chemistry of materials, or even in temperature, can make an acceptable mixture in one batch of concrete behave in an unacceptable way in the next batch, causing problems in placing, compacting, and finishing that are often perceived to be unpredictable and uncontrollable.

Objectives

The primary objective of this module is to provide participants with a working understanding of the unexpected problems that can occur as a result of chemical interactions between cements and chemical admixtures.

Learning Outcomes

At the end of this module, participants will have the ability to

• Identify various causes of stiffening and setting problems.
• Describe incompatibilities related to the air-void system.
• Explain how to test for, prevent, and solve incompatibility-related problems.

Presentation Graphics

The following slide printouts include space for participants to take notes.
Objectives

- Understanding types/causes of materials incompatibilities
- Troubleshooting incompatibilities

What is Incompatibility?

- Combinations of acceptable materials interacting in an undesirable or unexpected way, causing …
  - Unusual stiffening and setting
  - Cracking
  - Air void system problems

Stiffening & Setting

- Early stiffening
  - Sets in the mixer / truck
  - Stiffens up on the way through the paver
  - Sets before finishing
  - Cracks before saw cuts can be done
5

**Stiffening & Setting**

![Concrete surface with rough texture]

6

**Stiffening & Setting**

- Retardation
  - Plastic shrinkage cracking
  - Cracks before saw cuts can be done

![Person smoothing concrete surface]

7

**Cracking**

- Concrete always cracks!
- We want our cracks to be
  - In the right place
  - At the right time
8

Cracking

9

Air-Void System

- Wrong amount of air
  - Air content is not predictable
  - Bubbles are unstable
- Wrong sort of air
  - Bubbles too coarse
  - Coalescence

10

Why Do These Happen...Now?

- Changing materials
  - Cements
  - Supplementary cementing materials
  - Chemical admixtures
- Higher demands on the system
11

It’s all in the Chemistry...

- Sulfate and aluminates
- Calcium and silicates
- SCMs
- Admixtures
- Temperature

12

Gypsum and Aluminates

Aluminate & Sulfate & water = Ettringite (Normal)

Aluminate & water = CAH (Flash set or stiffening)

Gypsum precipitate (False set)

13

Sulfate in Solution

- Total sulfate counts – but it is the amount that has dissolved that is critical
  - Gypsum $\text{CS}_2\text{H}$ Dissolves slowly
  - Plaster $\text{CS}\cdot\frac{1}{2}\text{H}$ Dissolves fastest
  - Anhydrite $\text{CS}$ Dissolves slowest
- Plaster solubility decreases with increasing temperature
**Calcium and Silicates**

Calcium dissolves until supersaturated
Alite & water = C-S-H & CH
Belite & water = C-S-H & CH

---

**Calcium and Silicates**

If not enough calcium to reach supersaturation – no hydration

---

**Water Reducers**

(IMCP—page 99)

Accelerate aluminates
Retard silicates
Therefore need more S
17

**Fly ash**

High calcium fly ash may contain extra $C_3A$

Therefore need more $S$

---

18

**High Temperature**

Accelerates reactions

Reduces rate that calcium dissolves

---

19

**Early Stiffening**

- Sulfates (not enough or wrong kind)
- Fly ash with high $C_3A$
- Some admixtures
- Water cementitious materials ratio
- Hot weather
- Batching sequence
- Very fine cement
20

Retardation

• Cold weather
• Excess organic compounds
• Supplementary cementing materials
• System chemistry

21

Cracking

• A function of
  ▪ Shrinkage
  ▪ Restraint
  ▪ Stiffness
  ▪ Strength
  ▪ Creep

22

Air-Void System

• Materials
• Batching sequence
• Retempering
• Time in mixer
Some Test Methods

- Chemistry
- Calorimetry
- Temperature monitoring
- Mini-slump
- Rheology
- Stiffening (C359)
- Slump loss
- Ring shrinkage
- P-Wave
- AVA
- Foam Drainage

Isothermal Calorimetry

Hydration Profile

![Hydration Profile Graph](image)

Time of Hydration (hrs) | J/g
---|---
0.00| 0.00
12.00| 15.00
6.00| 12.00
3.00| 9.00
1.00| 6.00
0.00| 3.00

Sample "CP"
Sample "CP"
Sample "SP"
Sample "SP"
35

**Ring Shrinkage**

![Ring Shrinkage Graph]

- Mix 1
- Mix 2

36

**Foam Drainage**

![Foam Drainage Image]

37

**Foam Drainage**

![Foam Drainage Graph]

---
38

Foam Drainage

39

Foam Index Test

40

Air-Void Analyzer
Discussion

• Several mechanisms in play
• Many are complex
  ▪ Therefore need more than one test
• Often there is no “threshold”
  ▪ Therefore track variability
• Need quick answers
• Need cost-effective tests
  ▪ Therefore take phased approach

So?

• Get familiar with your mixtures and materials (trial mixes)
  ▪ Vary temperature
  ▪ Vary cementitious content
  ▪ Vary SCM dose

So?

• Track, using control charts
  ▪ Cementitious chemistry
  ▪ Foam index
  ▪ Slump loss
  ▪ Setting time
  ▪ Temperature profile
So?

• If you can, track
  ▪ Rheology
  ▪ AVA
  ▪ Ring tests
  ▪ Keep samples

So?

• If something jumps…
  ▪ Change SCM dose
  ▪ Change chemical admixture type
  ▪ Change working temperature
  ▪ Change batching sequence
  ▪ Get help

Why Bother?

• Cost of testing
• Cost of failure
• Safety and health
47

Protocol

• Two stages
  ▪ Pre-construction
  ▪ During construction

48

Protocol

• Pre-construction
  ▪ Test all likely materials
  ▪ All likely environments
  ▪ Calibrate tests
  ▪ Plan for variability

49

Protocol

• During construction
  ▪ Field tests
    ➢ Materials acceptance
    ➢ Materials uniformity
  ▪ Lab tests
    ➢ More rigorous
    ➢ What went wrong
50

Questions

• Which material is to blame?
• Why does temperature matter?
• How do I test new materials at the site?
• Can I buy a cheaper fly ash from another source?

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Thank you.
MODULE 5A: FRESH CONCRETE PROPERTIES

Overview
Making, handling, and protecting fresh concrete is critical to a good pavement. This module discusses critical properties of concrete that are needed to be able to mix, transport, place, finish, and maintain high-quality pavement. Properties that are important to fresh concrete include

- Uniformity.
- Workability.
- Air content.
- Segregation.
- Bleeding.
- Setting.

Objectives
The overall objective for this module is for participants to identify properties of fresh concrete and understand how each property is affected by and can be managed by mix materials and construction techniques.

Learning Outcomes
At the end of this module, participants will

- Describe desired properties of fresh concrete for pavements and how to achieve them.
- Describe how fresh concrete properties can be managed (optimized) in order to maximize concrete pavement performance.
- Discuss the relative importance of different properties to different parties in the design, mix, and construction processes.
- Discuss how selection of one or more property limit may influence activities of other parties involved in the process (e.g., designing a high-strength concrete may increase risk of cracking).

Presentation Graphics
The following slide printouts include space for participants to take notes. Instructor notes are also included in the “Notes” section of the electronic files.
1

Module 5a

Fresh Concrete Properties

2

Learning Objectives

• Define fresh (plastic) properties of concrete for pavements (chapter 5)
• Understand how various concrete properties affect, and are affected by, mix materials and construction techniques
• Describe how to achieve desirable fresh (plastic) concrete properties for pavements

3

Fresh Properties

• Uniformity
• Workability
• Air content
• Segregation
• Bleeding
• Setting
**Uniformity**

Concrete should be the same from batch to batch

- So adjustments are not needed for the paver
- So finished pavement is consistently acceptable

---

- Incoming variables
  - Materials
  - Batching
  - Mixing

- Tests themselves are variable

---

- Tests (From ASTM C 94)
  - Unit weight
  - Air content
  - Slump
  - Coarse aggregate content
  - Strength at 7 days
Workability

- Ease of mixing, placing, consolidating, and finishing
- Measure of uniformity

Workability

- Affected by
  - Water content
  - Aggregates
  - Air
  - Time
  - Temperature
  - SCMs
  - Admixtures

Workability

- Tests
  - Slump
  - Compaction factor
  - Vebe
  - Penetration
  - Rheometers
Air Content

- Why?
  - Frost resistance
- What are we looking for?
  - 9% expansion
  - Therefore depends on paste content and aggregate size
- Air void system is more important than total air content

(IMCP—page 132)

<table>
<thead>
<tr>
<th>Nominal maximum aggregate size, in.</th>
<th>Air content, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Severe exposure</td>
</tr>
<tr>
<td>3/8</td>
<td>7.5</td>
</tr>
<tr>
<td>1/2</td>
<td>7</td>
</tr>
<tr>
<td>3/4</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>1-1/2</td>
<td>b.5</td>
</tr>
<tr>
<td>2&quot;</td>
<td>5</td>
</tr>
<tr>
<td>3&quot;</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Air Content

- Spacing factor: maximum distance of any point in a cement paste from an air void, < 0.008"
- Specific surface: size of voids, > 600 in²
- May need to test (scaling or freeze thaw)
- ACI 318: if strength > 5000 psi, can reduce air by 1%
**Spacing Factor**

**Total Air and Spacing Factor**

\[ A_1 = A_2 \]

**Air Content**

- Entrapped air
  - > 1 mm
  - Irregular shape
  - Not desirable
  - Poor vibration
  - Typically 1%-2%
Air Content

- Entrained air
  - < 1 mm (mostly 0.01 to 0.1 mm)
  - Spherical
  - Desirable
  - Only if air entrainer used

Air Content

- Where?
  - At the batch plant
  - At the pump
  - At point of placement
- When?
  - In the field
  - At the central lab
- How?

Air Content

- Pressure Test, ASTM C 231 / AASHTO T 152
- Volumetric, ASTM C 173 / AASHTO T 196
- Gravimetric, ASTM C 138 / AASHTO T 121
- Air Void Analyzer
- Microscopy ASTM C 457
Pressure Meter

- Valid for normal density aggregate
- Gives only total air content; no details of air void system
- Familiar

Volumetric

- Valid for all aggregates
- Slow and heavy

Gravimetric Unit Weight

- Dependant on knowing materials properties
- Good for uniformity monitoring
Microscopy

- Widely used
- Slow and expensive
- Specialized

AVA

- Measures air void parameters in fresh concrete
- Takes 30 minutes
- Not for total air

Discussion

- Tests are variable
- Not all tests appropriate for acceptance testing
- How much do we really need?
- Overvibration
- Overfinishing
**Segregation**

- When the rock and the mortar separate
  - High paste zone: more shrinkage, cracking
  - Low paste zone: permeable, low strength

(IMCP—page 111)

---

**Segregation**

- Affected by
  - Aggregate grading
  - Fine materials content
- Testing
  - No standard test
  - SCC column test

---

**Segregation**

Max 10% difference in coarse aggregate content between layers
28

**Bleeding**

- Water appearing on surface as solids settle
  - Reduces plastic shrinkage cracking
  - Delays finishing work
  - Reduces durability
  - Reduces abrasion resistance
  - Can cause blisters
  - Results in voids below steel and aggregate

29

**Bleeding**

- Affected by
  - w/cm ratio
  - Fine materials
  - SCMs
  - Aggregate fines and shape
  - Admixtures
- Testing
  - ASTM C 232

30

**Some Bleeding**

![Diagram of bleeding](Image)
No Bleeding—Plastic Cracking

Too Much Bleeding

Setting

- Transformation from liquid to solid
- Affects
  - Finishing work
  - Saw-cutting
- Affected by
  - Temperature
  - System chemistry
  - Admixtures
  - Batching
  - Mixing
### Setting

- Testing
  - ASTM C 232
  - Initial = 500 psi
  - Final = 4000 psi
- Temperature or P-Wave
  - Initial

### Closing

- Making, handling, and protecting fresh concrete is critical to a good pavement

### Questions

- Why do we measure unit weight?
- Is bleeding good or bad?
- What is the perfect slump?
- What is final set?
- So what if it segregates?
Thank you.
MODULE 5B:
EARLY-AGE CRACKING

Overview
While cracking is not strictly a property of concrete, concrete always cracks. A certain amount of early-age, full-depth cracking to relieve tensile stresses is inevitable and normally does not pose a problem. However, the challenge is to control the number and location of these cracks, generally by constructing joints in the concrete, using good curing practices, and/or reinforcing the concrete. This module will discuss a number of factors that affect early age cracking, including
- Volume changes and restraint.
- Curling and warping.
- Strength gain during the stages of hydration.
- Subgrade support.
- Early loading.

Objectives
The primary objective of this module is for participants to understand the combined effects of volume changes, restraint, and strength gain during the stages of hydration that result in early-age cracking.

Learning Outcomes
At the end of this module, participants will
- Describe the various mechanisms that can lead to early-age cracking.
- Explain curling and warping.
- Understand how construction practices can control early-age cracking and prevent random cracking.
- Understand how mix design can affect early-age cracking.
- Identify various early-age random cracks and how to prevent them.

Presentation Graphics
The following slide printouts include space for participants to take notes.
Early-Age Cracking
(temperature, shrinkage, strength)

Learning Objective

Fresh concrete always shrinks. This shrinkage leads to cracking. Cracking is not necessarily bad and can be controlled. A number of factors affect early age cracking:

- Volume changes and restraint
- Curling and warping
- Strength gain during the stages of hydration
- Subgrade support
- Early loading

Learning Outcomes

- Describe various mechanisms that can lead to early-age cracking
- Explain curling and warping
- Understand how construction practices can control early-age cracking and prevent random cracking
- Understand how certain material properties can affect early-age cracking
- Understand the various types of early-age random cracks and how to prevent them
Early-Age Cracking

1. Concrete cracks when tensile stresses exceed tensile strength.

2. The challenge is to control the number and location of cracks:
   - Construct proper and timely joints
   - Use good curing practices
   - Understand that concrete needs to gain strength to resist random cracking

3. Cracking is generally due to a combination of several factors.

Factors Affecting Early-Age Cracking

- Volume change and restraint
- Curling and warping
- Strength and stiffness
- Base condition and support
- Early loading
Primary Factors of Early-Age Cracking

- Concrete expands as temperature rises and contracts as temperature falls.
- Concrete expands as moisture increases and contracts as moisture decreases.

Strength and Stiffness

**Strength**: The greater the concrete strength, the greater stress it can withstand.
- Early-age concrete has not gained all its potential strength.
- Stresses in early-age concrete can surpass the concrete’s strength.

Five Stages of Hydration

- Initial set
- Final set
- Hardening
- Cooling
- Densification
**Strength and Stiffness**

**Stiffness:** The stiffer the concrete (as indicated by modules of elasticity), the greater the stresses resulting from volume change.

- Unfortunately, stiffness increases faster than strength for the first few hours after setting
- First few hours
  - Minimize temperature & moisture change
  - Minimize the build up of stresses when the concrete has not gained sufficient strength

**Volume Shrinkage**

Total shrinkage is the sum of individual shrinkage mechanisms. Minimizing any or all mechanisms will reduce the risk of cracking.

- Autogenous
- Settlement
- Plastic
- Drying
- Thermal

**Restraint**

**External Restraint:** A bonding or friction between a slab and the base or an abrupt change in the slabs cross-section.

**Internal Restraint:** The outer concrete shrinks or expands and the core does not.
**IMCP Manual – Early-Age Cracking: 13**

### Shrinkage/Cracking

**(a)** Cracks generally do not develop in concrete that is free to shrink.

**(b)** Slabs on the ground are restrained by the subbase, creating tensile stresses that result in cracks.

---

**IMCP Manual – Early-Age Cracking: 14**

### Autogenous Shrinkage

The amount of chemical shrinkage that can be measured in a sample.

- Chemical shrinkage is a reduction of volume
- Results from hydration products occupying less space than the original materials
- Only significant for W/C less than 0.42

---

**IMCP Manual – Early-Age Cracking: 15**

### Autogenous Shrinkage

![Diagram showing the process of autogenous shrinkage over time](image)
**Settlement Shrinkage**

- Bleeding is the development of a layer of water at the top or surface of freshly placed concrete.
- It is caused by sedimentation (settlement) of solid particles (cement and aggregate) and the simultaneous upward migration of water.
- Some bleeding is normal. It should not diminish the quality of properly placed concrete.

(IMCP—page 125)

**Plastic Shrinkage**

Rapid loss of water through evaporation causes concrete on the surface to shrink. If shrinkage is restrained, tension develops, which may cause cracking.

(IMCP—pages 125, 158, 159)
Plastic Shrinkage

Plastic Shrinkage Cracks

Some cracks form perpendicular to wind direction.

Drying and Thermal Shrinkage

- Drying and thermal contraction shrinkage
  - Most frequent causes of early-age cracks
  - Thermal-related cracks
    - Normally observed in the first day
  - Drying-related cracks
    - May appear over a longer period
Drying Shrinkage

- Loss of mixing water through hydration and evaporation
  - Overall volume contracts
  - Greater paste content results in greater drying shrinkage and higher tensile stress
  - Low relative humidity of air can affect shrinkage diffusion

Wind on Shrinkage

From Transportation Research Circular E-C107, October, 2006

Drying Shrinkage

More Cement = More Water (W/C)

More Water = More Shrinkage
Drying Shrinkage

- Air temperature can cause significant changes in shrinkage and expansion rates
- Hydration peaks within the first 12+ hours after the concrete is placed
  - Volume starts to contract as hydration slows and concrete temperature drops
  - Movement of slab is constrained by subgrade
  - Contraction produces tension
  - Accelerated contraction (such as cold front) can cause thermal shrinkage cracking

Thermal Shrinkage

- Air temperature can cause significant changes in shrinkage and expansion rates
- Hydration peaks within the first 12+ hours after the concrete is placed
  - Volume starts to contract as hydration slows and concrete temperature drops
  - Movement of slab is constrained by subgrade
  - Contraction produces tension
  - Accelerated contraction (such as cold front) can cause thermal shrinkage cracking
Factors Affecting Thermal Properties

- Aggregate types
  - Account for about 60 to 75 percent of concrete by volume
  - Coefficient of Thermal Expansion (CTE) of aggregates dominates CTE of concrete

Other Factors Affecting Thermal Properties

- Cement fineness
- Amount of Pozzolans
  - Class F fly ash has a heat of hydration that is typically 50 percent of cement
  - Class C fly ash generally has a heat of hydration in the range of 70 to 90 percent of that of cement
- Pozzolans are a secondary reaction
  - Reduce the maximum temperature

SCM Effect
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**Thermal and Drying Shrinkage**

Proper curing helps prevent evaporation loss and temperature changes.

It is imperative to saw stress relief joints in a timely manner.

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**Curling and Warping**

- Differential temperature and moisture levels throughout slab depth typically occur during the first 72 hours.
- As a result, concrete contracts or expands differently throughout the depth.

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**Curling and Warping**

- Variations in contraction and expansion cause differential, non-uniform movements.

*Curling => Change in Temperature*

*Warping => Change in Moisture*

- These movements, especially when restrained, can cause cracking.
**Curling and Warping of Slabs**

<table>
<thead>
<tr>
<th>Temperature curling</th>
<th>Hot days (curling counteracts warping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture warping</td>
<td>Cool nights (curling compounds warping)</td>
</tr>
</tbody>
</table>

**Curling**

If the sum of stresses exceeds established strength, cracks can develop.

**Combined Shrinkage and Curling Stresses**

HIPERPAV curve

If the sum of stresses exceeds established strength, cracks can develop.
Early Loading Stress

Subgrade pressures are widely distributed, except at the edges and corners of the slab.

<table>
<thead>
<tr>
<th>Loading position *</th>
<th>Maximum subgrade pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>psi</td>
</tr>
<tr>
<td>1. Slab interior</td>
<td>3</td>
</tr>
<tr>
<td>2. Transverse joint edge</td>
<td>4</td>
</tr>
<tr>
<td>3. Outside edge</td>
<td>6</td>
</tr>
<tr>
<td>4. Outside corner</td>
<td>7</td>
</tr>
</tbody>
</table>

* 12,000 lb. Load on a 12-in plate (~100 psi)

Key Areas of Pavements

- Unsupported edges and exposed corners
  - Area of high concern for early loading
  - Subgrade is likely to be weakest at edges
    - Rainfall/runoff
  - Shoulders/curbs help
    - Equal to 2' offset

Corner Cracks

Direction of traffic
How to Avoid Random Cracks

Manage Change!

Key Points for Reducing Early-Age Concrete Cracking

1. Optimize the size and amount of coarse aggregate
2. Use low shrinkage aggregate to minimize shrinkage that may cause cracking
3. Consider using a water reducing admixture to reduce paste content
4. Use SCM to help reduce the set temperature and the temperature peak
5. Avoid calcium chloride admixtures, which can significantly increase drying shrinkage

Key Points for Reducing Early-Age Concrete Cracking

6. Time concrete placement so that the temperature peak does not coincide with the hottest time of day
7. Prevent rapid loss of surface moisture while the concrete is still plastic
8. If the ambient temperature is likely to drop significantly, cover the pavement surface with blankets to slow heat loss and prevent extreme differentials in temperature through the slab
Thank you.
MODULE 5C:
HARDENED CONCRETE PROPERTIES

Overview
As concrete hardens and gains strength, it acquires properties that are critical for long-term durability. Many of these properties affect concrete’s permeability; reducing permeability generally enhances concrete durability. Sometimes enhancing one property has an adverse effect on another. The goal is to achieve an optimum balance.

Objectives
The objective of this module is for participants to identify properties of concrete and understand how each property is affected by and can be managed by mix materials and construction techniques. Properties include plastic properties (those manifested from mix to setting) and hardened properties (manifested after hardening).

Learning Outcomes
At the end of this module, participants will have the ability to
• Describe desired hardened properties of concrete for pavements.
• Describe how hardened properties can be managed (optimized) in order to maximize concrete pavement performance.
• Discuss the relative importance of different properties to different parties in the design, mix, and construction processes.
• Discuss how selection of one or more property limit may influence activities of other parties involved in the process (e.g., designing a high-strength concrete may increase risk of cracking).

Presentation Graphics
The following slide printouts include instructor notes as appropriate.
Hardened Concrete Properties

Durability

• Ability of the concrete to survive the environment to which it is exposed
  ▪ Permeability
  ▪ Frost resistance
  ▪ Sulfate resistance
  ▪ Alkali-silica reaction
  ▪ Abrasion resistance

Permeability

• The ease with which fluids can penetrate concrete
• All durability damage is governed by permeability
  ▪ Use low w/cm
  ▪ Use SCMs
  ▪ Cure
  ▪ Minimize cracking
**Porosity and Permeability**

- **Porosity**: Represents the void space within the concrete structure. It is essential for the permeability of the concrete, affecting its ability to withstand water and other fluids.

- **Permeability**: Measures the ability of a material to transmit liquids or gases through it. Higher permeability can lead to water ingress and potential deterioration of the concrete structure.

**Effect of W/C**

- **W/C = 0.40**: Lower water-to-cement ratio results in a denser structure with reduced porosity and permeability. This is beneficial for concrete requiring high durability and resistance to water ingress.

- **W/C = 0.75**: Higher water-to-cement ratio leads to a more porous and permeable concrete. While this might be suitable for某些 applications, it generally results in a less durable and potentially more susceptible to damage from water.

**Dimension, μm**

- **Ca(OH)₂**: Represents calcium hydroxide, a hydration product that forms gel pores within the cement matrix.
- **Capillary pores**: Are the small voids that form due to the capillary action of water in the concrete, affecting its permeability.
- **Entrained air**: Refers to air bubbles or voids intentionally entrained into the concrete to improve workability and reduce the risk of voids or macrocracks.
- **C-S-H**: Calcium-silicate hydrate, a key component of the hardened cement paste, forming gel pores.
- **Entrapped air**: Air that gets trapped during the mixing and consolidation process, contributing to the overall porosity of the concrete.

**Dimension, μm**

- **0.001**
- **0.1**
- **10**
- **1000**
- **100000**
Permeability

- Testing
  - Indicated by rapid chloride (ASTM C1202)
  - Sorption (ASTM C 1585)
  - Boiled water (ASTM C 642)
  - Chloride ponding
  - AASHTO TP 64

Carbonation

- Passivation
- Carbon dioxide + lime $\rightarrow$ carbonate
- pH drops

\[
\begin{align*}
\text{RELATIVE HUMIDITY, %} & \quad \text{RATE OF CARBONATION} \\
0 & \quad 0 \\
50 & \quad 50 \\
100 & \quad 100
\end{align*}
\]
Chlorides

- Electro-chemical reaction
- Catalyst
- Binding
- “Threshold”
*Secondary Anode Cathode*

\[ 4e^- \rightarrow 2Fe(OH)_2 \]

\[ 2H_2O \rightarrow O_2 + 4e^- + 2H_2O \]

\[ 4OH^- \rightarrow 2Fe(OH)_2 + 4e^- \]

\[ Fe_2O_3.H_2O + 2H_2O \]

---

*Cathode*  

\[ 2Fe^+ + 4e^- \rightarrow 2Fe(OH)_2 \]

\[ 2H_2O \rightarrow O_2 + 4e^- + 2H_2O \]

\[ 4OH^- \rightarrow 2Fe(OH)_2 + 4e^- \]

\[ FeCl_2 + 6Cl^- \]

---

**Acid & Soft Water**

- Removes calcium from paste $\rightarrow$ dissolution
Frost Resistance

- Ability to resist damage due to winter weather
  - Freezing and thawing damage
  - Salt scaling
  - D-cracking
  - Popouts

Freeze-thaw / Salt scaling

- Cyclic freezing and expansion of water
- Osmotic pressure
- Salt crystallization

Only occurs if concrete is critically saturated
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**Popouts**

![Image of popouts]

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**Frost Resistance**

- Mitigation
  - Air void system
  - Strength
  - Materials
  - Finishing
  - Curing

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**Frost Resistance**

- Testing: D Cracking
  - Use aggregates in ASTM C 1646 / C 666
  - Pressure release method
  - Iowa Pore Index
  - Magnesium sulfate
**Frost Resistance**

- Testing: Freeze-thaw / scaling
  - ASTM C 666
  - ASTM C 672 / BNQ

**Frost Resistance**

- Testing: Air void system
  - Pressure meter
  - Volumetric
  - Unit weight
  - AVA
  - ASTM C 457

**Sulfate Attack**

- Ability to resist damage from external sulfates
- Need to have
  - Sulfates
  - Water
  - C₃A
- Causes loss of strength / sponginess
### Sulfate Attack

- First reaction forms monosulfate
- Second reaction forms ettringite
- Third reaction forms gypsum
- Increasing expansion…
40

**Sulfate Attack**

- Prevention
  - Low C\textsubscript{3}A cements (Type II and V)
  - Low-calcium fly ash
  - Slag
  - w/cm
  - Cement content
  - Cure
  - Air

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**Sulfate Attack**

- Tests
  - None for concrete (yet)
  - ASTM C 452 and 1152 for cements

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**Alkali-Silica Reaction**

- Water + alkali hydroxide + reactive silicate aggregate \rightarrow alkali silicates
- Alkali silicates + water \rightarrow gel + expansion
- Silicates from aggregates
- Alkalis from cement (Na and K)
Alkali-Silica Reaction

• Factors affecting
  ▪ Aggregate type
  ▪ OH- ions in pore solution
    (i.e., unbalanced Na⁺ and K⁺ ions)
  ▪ Water

Alkali-Silica Reaction

• Prevention
  ▪ Choose aggregates
  ▪ Low-alkali cement
  ▪ Use SCMs (low-calcium fly ash)
  ▪ Consider lithium compounds
  ▪ Combinations of the above

Alkali-Silica Reaction Test Methods

• Need tests to
  ▪ Evaluate aggregates
  ▪ Check mitigation methods
• Protocols available from
  ▪ PCA
  ▪ AASHTO
  ▪ Canada
  ▪ ASTM (in preparation)
Alkali-Silica Reaction Test Methods

- History
- ASTM C 289 (chemical) and C 295 (petro)
  - Insufficient to pass/fail on this test alone

Alkali-Silica Reaction Test Methods

- ASTM C 227
  - To test aggregates
  - Can pass poor material
  - Takes months
- ASTM C 441 (Pyrex glass)
  - To test SCMs
  - No fixed criterion

Alkali-Silica Reaction Test Methods

- ASTM C 1260 (mortar bar)
  - To test aggregates
  - Can fail good material
  - Quick (16 days)
- ASTM C 1293 (concrete prism)
  - To test aggregates
  - Considered the most reliable
  - Takes up to 2 years
Alkali-Silica Reaction Test Methods

- ASTM C 1567
  - To test SCMs with aggregates
- ASTM C 1293 modified
  - To test systems
  - Not standardized

Abrasion and Polishing

- Ability to resist surface wear
  - Abrasion is primarily a result of studded tires causing ruts in concrete pavement
  - Polishing is a type of abrasion in which traffic eliminates the texture necessary for skid resistance
- Affected by
  - Aggregate type
  - Strength
  - Finishing
  - Curing

Abrasion

- Testing
  - Los Angeles abrasion for aggregate
  - Micro Deval
  - Acid soluble content for aggregate
  - ASTM C 779 for concrete
  - ASTM C 944 for concrete
Questions

- What is the primary parameter critical for good durability?
- List the mitigation techniques for ASR
- How do we test for abrasion resistance?
- Should I use high-calcium fly ash for sulfate resistance?
- Why bother curing?

Thank you.
MODULE 6:
MIX DESIGN PRINCIPLES

Overview
Mix design is the process of determining required and specifiable properties of a concrete mixture, i.e., concrete properties required for the intended use, geometry, and exposure conditions. The parameters for almost all concrete properties for a specific concrete mixture are determined or specified during mix design by taking into consideration the following factors:
- Workability.
- Placement conditions.
- Strength.
- Durability.
- Economy.

Objectives
The objective of this module is to help participants understand the basic process for designing and proportioning concrete mixtures that will optimize the properties for a required pavement performance.

Learning Outcomes
At the end of this module, participants will be able to
- Select the parameters critical for success of a given pavement.
- Select available materials to achieve the required performance.
- Evaluate a mix design for acceptability for their needs.
- Modify mix proportions for optimum performance, based on trial mix data.

Presentation Graphics
The following slide printouts include space for participants to take notes. Instructor notes are also included in the “Notes” section of the electronic files.
Mix Design Principles

Learning Objectives

The goal of this module is understand the basic elements of concrete mix design (chapter 6), including
- Selection of appropriate materials
- Optimizing mix proportions
- Trial batch preparation
- Trial mix evaluation

Goal of Mix Design

The overall goal of the mix design process is to determine an “optimal” mix that considers the following factors:
- Durability
- Strength
- Constructability
- Economy
- Uniformity
Mixture Design

- Process of determining required and specifiable characteristics of a concrete mixture:
  - Prescriptive approach (limits on materials)
  - Performance approach (desirable characteristics)
- Mixture design requirements are based on intended use, environment, etc.

Mixture Proportioning

- Process of determining the quantities of concrete ingredients
- The primary considerations include the following:
  - Economy
  - Readily available supply of raw materials
  - Ability to continually meet or exceed specifications

Basic Mix Proportioning

| 9 - 15% Cement | Paste (cement + water) |
| 15 - 16% Water | Mortar (paste + fine aggregate) |
| 25 - 35% Fine aggregate | Concrete (mortar + coarse aggregate) |
| 30 - 45% Coarse aggregate | |
| |
| |
| |
Theoretical vs. Laboratory vs. Field

- Mix designs can be generated “on paper” as a starting point
- Laboratory trial batches are required to verify and optimize mix proportions
- There is no substitute for trial batches and testing to determine incompatibility of materials and numerous other potential problems
- Field trials using regular batching and mixing techniques are the final verification of the mix

Laboratory Testing Plan

- A suggested laboratory testing plan is shown in Table 6-1 for the following characteristics:
  - Workability
  - Strength
  - Air content
  - Density
  - Permeability
- The relative size and importance of a project determine which of these parameters are evaluated

Field Testing Plan

- A suggested field trial batch testing plan is shown in Table 6-2 and is divided into the following categories:
  - Prior to production
  - Mix design evaluation
  - Mixer uniformity test
- These procedures are suggested regardless of project size when a new mix is being evaluated
Paste Content

Consolidated Bulk Density

Aggregate Grading Optimization

- Aggregates are the most dimensionally stable and least expensive constituents in concrete
- It is desirable to minimize the amount of paste required by optimizing aggregate gradation
- Optimized gradation simply means combining available aggregates in the proper proportions to minimize void space
**Shilstone Method of Optimized Gradation**

- The Shilstone method uses 3 separate evaluation tools to determine optimal gradation:
  - Coarseness factor chart
  - 0.45 power chart
  - Percent aggregate retained chart
- Use of these three charts greatly simplifies combined aggregate grading and checks for potential problems

---

**Combined Grading**

---

**Shilstone Coarseness Chart**
Calculating Mix Proportions

Mix design includes the following selections:
- Binder types (cement, SCM)
- Binder percentages
- Aggregate sources
- Aggregate gradation
- Maximum aggregate size
- Water/cementitious materials ratio
- Target air-void system
- Appropriate admixtures and dosage

Absolute Volume Method

The absolute volume method specified by ACI 211.1 consists of 12 steps:

1. Strength
2. w/cm
3. Coarse aggregate
4. Air content
5. Workability and slump
6. Water
7. Cementitious content
8. Cement type
9. Admixture types and dosages
10. Fine aggregate, fill the space
11. Aggregate moisture
12. Trial batches

(IMCP—pages 179–184)
Trial Batches

- Adjust for aggregate moisture
- Make batches: check workability, freedom from segregation, finishing
- Make appropriate adjustments
- If satisfactory fresh properties, make samples for hardened properties

Adjusting Properties

- Subject to results of the trial batches, adjustments to the mix are likely necessary
- The IMCP manual presents a brief overview of common mix adjustments:
  - Workability
  - Stiffening/setting
  - Bleeding
  - Air-void system
  - Unit weight
  - Others

Additional Effects of Added Water

Adding 1 gal. of water to 1 yd³ of concrete:
- Increases slump 1 in.
- Decreases compressive strength by 200 psi
- Wastes the effect of 1/4 sack (23.5 lb) of cement
- Increases shrinkage by 10%
- Increases permeability by up to 50%
Questions for Discussion

- If some cement is good, is more cement better?
- If low w/cm ratio is good, is lower better?
- Is a well-graded system essential?
- Why do we need trial batches?

Thank you.
MODULE 8: CONSTRUCTION

Overview
The starting point for constructing good-quality concrete pavement is to design and use good-quality concrete during construction. The plastic properties of concrete affect many construction operations, including mixing, transporting, placing, paving, curing, and jointing. Concrete’s hardened properties affect long-term pavement performance.

The other significant requirement is to use appropriate, high-quality equipment and good practices. Failures in construction are often due to a combination of marginal materials used in marginal equipment operated by insufficiently trained operators.

This module discusses various concrete pavement construction operations and addresses how decisions made about the concrete or its constituent materials may affect constructability or pavement performance.

Objectives
The primary objective of this module is for participants to understand general construction methods and how those methods should be adjusted to accommodate specific mixes, weather, and other variables.

Learning Outcomes
At the end of this module, participants will be able to
- Summarize the typical quality control tests performed during concrete paving projects.
- Outline the key points in producing quality and uniform concrete.
- Discuss typical field adjustments.
- Discuss the critical elements of both fixed form and slipform paving operations.
- Explain the key points in curing concrete pavements.
- Summarize issue related to hot and cold weather concrete placement.
- Recognize the importance of timely joint sawing and proper sawing techniques.

Presentation Graphics
The following slide printouts include space for participants to take notes.
Module 8

**Construction**

**Learning Objectives**

- The goal of this module is to overview principles of good quality construction

**Keys to Quality Concrete Pavement**

- Adequate pavement design
- Appropriate mix design
- Quality materials
- **Good construction practices**

**Field Verification**

- Test mixture properties (before and during construction)
- Use production equipment
- Organize preconstruction meeting
- Prepare quality control plan
- Minimize variability
  - Production process
4

**Setting up the Plant**

- Optimize the traffic flow
- Testing personnel
- Environmental impact
  - Drainage

---

5

**Plant Checklist**

(IMCP—page 206)

<table>
<thead>
<tr>
<th>No.</th>
<th>Operation</th>
<th>Test/Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Check foundations of stockpiles for proper support and adequate drainage.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Check fines in aggregate portion to prevent segregation of aggregates.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Check soil in dirt stack weights throughout range of its use.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Check suitable for use by proper agencies.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Ensure water meter is accurate.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Check for damage of pipe.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Check capacity of loaders and shovels if their use in not required.</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Check water for fresh and concrete around storage.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Inspect concrete handling unit for cleanliness.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Check to ensure that all concrete making materials are furnished in certified and approved forms.</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Ensure proper grading so that no segregation and contamination will occur.</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Ensure bearing the label, verify that.</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Download appropriate or use of.</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Review aggregate moisture tests.</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Review batching operations at start and periodically during production.</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Check suitability for covering.</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Check to ensure proper batch weights are set on the scales.</td>
<td></td>
</tr>
</tbody>
</table>

---

6

**Handling Materials**

(IMCP—pages 206–207)

- Cementitious storage
- Multiply material feeds
- Stockpile management is a key element
Stockpile Management

- Delivery, storage, loading
- Place a pad or aggregate separation layer
  - Prevent contamination
- Maintain uniform
  - Gradation
  - Moisture
- Basic stockpile principles
  - Page 206

Batching

- Key items to control uniformity
  - Consistent materials
  - Accurate weights and measures
  - Batching sequence
- Considerations for controlling batch-to-batch consistency are critical

Concrete Mixing and Delivery

- The concrete must be thoroughly mixed:
  - In the stationary mixer
  - In the transit mixer
- If allowed by specifications, adjustments to the mix are possible if a transit mixer is used.
- Ideally, the paver controls the production and delivery rate.
Field Adjustments
- Ambient temperatures
  - Daily temperature rises
  - Add water
  - Cool aggregate
- Material variability
  - Moisture content—daily
  - Aggregate gradation—daily
  - Cementitious
- Material supply changes

Paving Operations
- Placement (fixed form)
- Consolidation (fixed form)
- Placement (slip form)
- Consolidation (slip form)
- Stringlines
- Alternatives to stringlines
- Edge slump

Slipform Paver Components

---
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Equipment Setup

Equipment Setup

- The following vital elements should be in place before production paving starts (IMCP 213):
  - Check all the equipment in the paving train to make sure it is in operational condition.
  - Verify that an acceptable length of grade is available for concrete paving.
  - Check that appropriate tools are available for all necessary concrete jobs on the plant site.
  - Verify that backup testing equipment is available.

- Make sure that all necessary concrete placements are available, such as: hand tools, straight edges, level tools, and level publications.

- Make sure that adequate communication with the plant is operational.

- Make sure that equipment is available to move the grade,лись, and

- Make sure there is no interference and/or obstruction on the grade.

- Check the boxes for proper training (red box only).

- Notify the daily work leader in place or (at least one of the necessary).

- Keep an emergency rescue personnel on hand.

- Check the weather forecast for each day of paving.

- Make sure a sufficient length of pipe is available in case of weather and unexpected rain.

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Slipform Placement

• Extrusion process
  - Workable concrete
  - Consistency
• Use lower slump concrete
• Weight of the machine
  - Not mount up over a concrete pile
  - Key to smoothness

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Consolidation

• The internal vibrators on the paver fluidize the concrete for extrusion
• Adequate consolidation
  - Required around dowels and tie bars
  - Throughout the slab
**Consolidation**

- Over vibration can cause settlement
- Iowa specification
  - 4000 vpm - 8000 vpm
- Note the effect of vibration in relation to paver speed
- Vibrator trails are not the problem—they are the symptom of a problem

**Stringlines**

- Stringlines control the “steering” of the paver
- Stringlines control the elevation and slab thickness
- Keep stringlines taunt
  - Pavement smoothness and uniformity
- Stringless paving:
  - Uses lasers and GPS in place of the stringlines and sensors

**Edge Slump**

- Edge slump can arise from a number of factors
  - Materials
  - Equipment
- Early detection and corrective action are required
- Most important with stage construction
**Dowel Bars and Tiebars**

- Pre-placed bars
  - Staked adequately
  - Cut/don’t cut the tie wires
  - Careful marking of location
- Inserted bars

**Finishing**

- Hand finishing is generally not required
- Check surface with straight edge
- Headers are generally a source of localized roughness (several options are available)

**Texturing and Smoothness**

- Provide friction and skid resistance
- Texturing options:
  - Drag textures
  - Longitudinal tining
  - Transverse tining
  - Diamond grinding
  - Innovative techniques

Table 8-4
Integrated Materials and Construction Practices for Concrete Pavements Workshop

22

Noise Zones

23

Noise vs. Friction

24

Texturing and Smoothness

- Table 8-4
  - Description of Various Concrete Pavement Texturing Options
- Table 8-5
  - Specification Factors that Influence Pavement Smoothness
- Table 8-6
  - Construction Factors that Influence Pavement Smoothness

(IMCP—pages 221–223)
**Curing**

- Curing compound
  - Reduce the rate of moisture loss
  - Complete coverage
  - Recommendations for curing compound application
- Other methods
  - Plastic sheeting
  - Curing blankets

---

**Weather Considerations**

- Hot weather concreting
  - Reduce the rate of evaporation
    - Rate of evaporation chart—page 227
  - General precautions
    - Moisten the aggregate
    - Cool the aggregate and water
  - General recommendations
    - Do not exceed the maximum W/C ratio
    - Use SCMs
    - Increase air entrainment dosage

---
Weather Considerations

- Cold weather placement
  - Increase cement content
  - Reduce SCM usage
  - Heat mix water
  - Use blankets
  - Avoid thermal shock

Weather Considerations

- Protection from rain
  - Do not finish rain water into the surface
    - Raises the W/C ratio
  - Can provide a moist curing
  - Cover with plastic

Crack Prediction with HIPERPAV

- FHWA website to download
- Factors considered in the program
- Input parameters

www.hiperpav.com
1. **Joint Sawing**
   - Why saw?
   - Saw timing
     - Sawing window
     - Maturity testing
     - HIPERPAV
     - Early-entry saws
     - Joint width
   - Mixture effects

2. **Joint Sawing**
   - Sawing window
     - Too early: cracking
     - Too late: sawing in the window
     - Minimum strength to avoid excessive saw cut ravelling
   - Time

3. **Joint Sealing**
   - Minimize infiltration of water and incompressibles
   - Types
     - Hot pour
     - Silicone
     - Compressive seals
   - Reservoir preparation
     - Clean
     - Shape
   - Recommended procedures

---

*IMCP—pages 233–236*

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*IMCP Manual – Construction: 31*
Questions and Discussion

- What measures are used to prevent contamination?
- **Consistency** is the key to smooth, long-lasting pavements
- The loader operator needs to insure uniform **gradation** and **moisture**
- Excessive vibration **frequency** can lead to vibrator trails
- Curing compound **reduces** the rate of moisture loss

Thank you.
MODULE 9: QUALITY ASSURANCE AND QUALITY CONTROL TESTING

Overview
This module discusses quality assurance and quality control systems as they influence concrete pavement, with special emphasis on materials. The module also describes actions that are needed to monitor and adjust for critical parameters, such as the water-cementitious materials (w/cm) ratio, the air-void system, and the risk of cracking. Finally, tests commonly used to monitor materials and concrete quality are described.

Objectives
The primary objective of this module is for participants to understand and be able to test for common QC/QA parameters.

Learning Outcomes
At the end of this module, participants will be able to

- Explain the necessity of keeping adequate and accurate records for specified QC/QA parameters.
- Summarize the key QC/QA parameters used in concrete production and paving operations.

Presentation Graphics
The following slide printouts include space for participants to take notes.
Learning Objectives

The goal of this module is to familiarize you with the following info in chapter 9:
- Basic QA/QC terminology and record keeping requirements
- Statistical quality control chart use
- Common QA/QC tests performed for concrete paving projects

Quality Assurance (QA)

- QA typically involves testing by the agency or its representative to determine compliance with specifications
- The most frequently used QA criteria for paving jobs include
  - Slab thickness
  - Concrete strength
  - Entrained air content
  - Ride quality

Quality Control (QC)

- QC generally refers to testing by the contractor for the purpose of process control and to ensure meeting or exceeding specifications
- A comprehensive QC program is much more involved than QA because all aspects of the project must be proactively monitored (materials, batching, placement, etc.)
### Qualifications

- QC/QA personnel must be adequately trained (and certified in a number of states)
- The testing facilities must be certified by AASHTO, ASTM, or other qualifying organizations
- Repeatability and reproducibility of results are critical for both QC and QA functions

### Basis for Testing

- Random testing assumes that the results are normally distributed
- The mean and standard deviation of test results are used to determine if the samples are within specified limits
- Variability is due to the operator (and equipment), the test procedure, and the material being tested

### Precision and Bias

- Established test procedures (ASTM, AASHTO) have accounted for test variability through precision and bias statements
- All physical tests have built in variability that must be accounted for in some manner
- The following slide illustrates the problem in determining a “right answer”
**Precision and Bias**

<table>
<thead>
<tr>
<th>Test</th>
<th>Sample result</th>
<th>90% lower limit</th>
<th>90% upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading (5% passing %)</td>
<td>25%</td>
<td>15%</td>
<td>35%</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>75%</td>
<td>2 in.</td>
<td>3 in.</td>
</tr>
<tr>
<td>Air content</td>
<td>5.0%</td>
<td>1.0%</td>
<td>8.1%</td>
</tr>
<tr>
<td>Residual air weight for aggregate</td>
<td>120 lb/ft³</td>
<td>114.1 lb/ft³</td>
<td>123.6 lb/ft³</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>3,000 psi/m²</td>
<td>2,750 psi/m²</td>
<td>3,000 psi/m²</td>
</tr>
<tr>
<td>Expansion</td>
<td>0.002 in/ft²</td>
<td>0.00060 in/ft²</td>
<td>0.002 in/ft²</td>
</tr>
</tbody>
</table>

**Record Keeping**

- Keeping accurate records is mandatory under QC/QA specifications and is highly desirable for any project.
- Information must be clearly recorded in a logical and systematic manner.
- All pertinent information should be entered as it is received to avoid confusion later.

**Quality Control Charts**

- Quality control charts (QCC) are statistically based and used primarily for process control.
- The graphical format of QCC provides a simple and effective means to determine when a specific process is trending out of limits.
- An example of standard tabular records and the corresponding QCC is shown in the following slide.
**Statistical Process Control**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Unit weight (lb/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>190.3</td>
</tr>
<tr>
<td>1-2</td>
<td>150.0</td>
</tr>
<tr>
<td>1-3</td>
<td>180.0</td>
</tr>
<tr>
<td>1-4</td>
<td>150.1</td>
</tr>
<tr>
<td>1-5</td>
<td>150.1</td>
</tr>
<tr>
<td>1-6</td>
<td>180.0</td>
</tr>
<tr>
<td>2-1</td>
<td>187.0</td>
</tr>
<tr>
<td>2-2</td>
<td>182.7</td>
</tr>
<tr>
<td>2-3</td>
<td>187.1</td>
</tr>
<tr>
<td>2-4</td>
<td>180.0</td>
</tr>
<tr>
<td>2-5</td>
<td>187.2</td>
</tr>
<tr>
<td>2-6</td>
<td>187.2</td>
</tr>
<tr>
<td>3-1</td>
<td>187.0</td>
</tr>
<tr>
<td>3-2</td>
<td>180.0</td>
</tr>
<tr>
<td>3-3</td>
<td>160.0</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>180.0</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>1.6</td>
</tr>
</tbody>
</table>

**Concrete Batching QC**

- Uniformity between concrete batches is critical in producing a smooth and long-lasting pavement.
- The following parameters are routinely checked during batching:
  - Aggregate moisture
  - Water content
  - Water/cementitious materials ratio
- Plant calibration and continuous monitoring are required.

**ASTM Batching Tolerances**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Individual**</th>
<th>Cumulative***%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cementitious materials</td>
<td>x1</td>
<td>x1</td>
</tr>
<tr>
<td>Water</td>
<td>x1</td>
<td>x3</td>
</tr>
<tr>
<td>Aggregates</td>
<td>x2</td>
<td>x1</td>
</tr>
<tr>
<td>Admixtures</td>
<td>x3</td>
<td>NR****</td>
</tr>
</tbody>
</table>

* Batch weights should be greater than 30 percent of scale capacity.
** Individual refers to separate weighing of each constituent.
*** Cumulative refers to cumulative weighing of cement and (or) water of fine and coarse aggregate, or water from all sources (including wash water).
**** Not recommended.
Construction Operations QC

Construction operations require many varied types of QC measures, including the following:

- Concrete temperature at time of placement
- Entrained air content
- Consolidation (internal vibration)
- Dowel bar placement
- Potential for many others depending on specification requirements

Test Methods for QC/QA

- Established testing procedures are generally balloted and approved by ASTM, AASHTO, or both
- Recently developed test procedures may not yet be approved but can still provide much needed information (e.g., AVA)
- Tests applicable to paving projects
  - Materials and mix design
  - Preconstruction verification
  - Construction QC

Test Categories

- The tests contained in the IMCP Manual are grouped as follows:
  - Workability
  - Strength development
  - Air content
  - Permeability
  - Thermal movement
- Refer to Table 9-4 for a listing of included test methods
Test Methods

- The test methods included in the IMCP manual do not represent all available tests.
- This information is provided for guidance only; the actual AASHTO or ASTM specification should be consulted when performing a test.
- The ultimate goal is to assess materials or process variability.

Test Method Information

The IMCP manual includes the following information for each of the listed tests:

- Purpose of the test
- Principle or theory
- Test procedure basics
- Test apparatus
- Test methodology
- Interpretation of test results
- What to look for

Flexural, Compressive Strength

- Flexural or compressive strength of concrete is one of the most common tests performed.
- It is usually a combination of field preparation and laboratory (or mobile laboratory) testing.
- Although the test is relatively simple, variability in results can often be attributed to slight variations in procedure.
- Please refer to page 264.
Questions for Discussion

- What is the basic definition of QA? QC?
- How is a statistical quality control chart developed? How is it used?
- What are the most common QC measures used for concrete paving projects?
- Where do you find specific information regarding how to perform one of the tests listed in the IMCP manual?

Thank you.
MODULE 10: TROUBLESHOOTING AND PROBLEM SOLVING

Overview
Most materials-related problems that occur during paving operations are due to actions taken or conditions met during materials selection or concrete mixing and placing. To prevent and fix problems, all members of the construction team need to understand the materials they are working with and be prepared to address potential scenarios.

This module recommends actions to be taken when problems are observed—before the concrete has set, during the first few days after placement, or some time after the concrete has hardened.

Objectives
The primary objective of this module is for participants to have the ability to use the data available in the manual to identify and diagnose problems related to concrete pavement construction and to develop a plan to address problems.

Learning Outcomes
At the end of this module, participants will be able to
- Use the tables to rapidly characterize the problem, and to gather “next action” recommendations.
- Use the cross references in the table to refresh understanding of why the problem is likely to have occurred – and so prevent recurrence.

Presentation Graphics
The following slide printouts include space for participants to take notes.
Troubleshooting...

• Nothing ever goes wrong…
• Right?

Just in case, see chapter 10

Learning Objectives

The goal of this module is to understand the basic process of troubleshooting paving-related problems:
• Problem identification
• Use of the IMCP Manual to diagnose problems
• Development of a plan to address the problem

When Do We See the Problem?

• Before the concrete has set 10.1
• First days after placing 10.2
• Some time after construction 10.3
• Assessing the damage 10.4
Case History 1

The problem:
- It’s August and hot
- Concrete coming out of the paver is honeycombed
- It looks OK when unloaded from the truck
- 10-minute haul

Actions taken:
- Phoned the batch plant (They say the slump is in spec at loading)
- Added WRA (It got worse)
- Turned up the vibrators (The inspector complained about losing air and signs of vibrator trails)

New observation: The color has changed
Case History 1

Now what?
• Panic (Doesn’t help)
• Visit the batch plant
  ▪ Concrete looks great in the truck
  ▪ Calibrations are OK
  ▪ Aggregates are the same
  ▪ Fly ash is different!!!

Actions:
• Leave out fly ash (Inspector refuses; it has to be there for ASR mitigation)
• Revert to original fly ash supply (No longer available)
• Delay WRA addition by 30 seconds (It works)

Why?
• Classic incompatibility
• Fly ash with high C₃A content
• WRA at high temperature
Case History 1

A lane of workability dropping less nearly affecting
External elements: Weather; material
Temperature changes: Change in temperature from day to night
Zonal temperature in & out: Change in temperature from day to night
Temperature at placement: Change in temperature from day to night
Temperature at curing: Change in temperature from day to night

Case History 2

A problem arose on the following project:
- Located in a Midwestern state
- Rural paving
- 2 lanes each direction
- Slipform operation
- Concrete produced by portable batch plant
- Paved during summer
- Problem evident within 1 year of paving

What questions are relevant and what do you think caused the problem??
Possible Solutions

• Refer to page 163 for discussion of random longitudinal cracks

Case History 3

The problem:
• It’s October and warm
• Everything is going well, until…
• One 200-yard section is cracked laterally every 20 feet

Case History 3

Review:
• No change in materials
• No change in saw timing
• No change in base and subgrade
• Concrete placed between 9 and 11 am
• It rained at 4 pm
Case History 3

Cause:
• Sharp drop in temperature when concrete is at its hottest

Solution:
• Keep it warm
• Early entry sawing

Case History 4

A problem arose on the following project:
• Located in South America
• Rural paving
• 2 lanes each direction
• Slipform operation
• Concrete produced at a remote batch plant
• Problems evident during paving

What happened??
Case History 4

Possible Solutions

- Refer to page 281 for discussion of edge slump
Case History 5

The problem:
• Pavement is 20 years old
• No faulting or abrasion
• But it's cracked!

Case History 5

Fundamentals:
• It's expanding
• Soil is not sulfate rich
• Send for petrography:
  • ASR
  • Frost damage
Case History 5

What now?
• Assess the life remaining
• Plan to replace
• Suitable for overlay?

Questions for Discussion

• What are the steps in identifying paving-related problems?
• How is the IMCP Manual best used to assist in identification of the problem and its solution?
• Is there a unique solution to most problems?
Thank you.
APPENDIX A Technical Summaries
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August 2007
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