



HMEC

Highway Materials Engineering Course

PARTICIPANT WORKBOOK



Portland Cement Concrete



U.S. Department of Transportation
Federal Highway Administration

MODULE

G

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About This Workbook

This workbook has been developed as a resource for participants. This workbook can be used during the training session to follow along with the instructor and take notes, as well as for reference after the module has ended.

Course Overview

The Federal Highway Administration (FHWA) Highway Materials Engineering Course (HMEC) is a comprehensive multi-week training event that consists of eight content “modules” that provide students with the knowledge to develop materials specifications and guidance, make effective acceptance decisions, and design, construct, and maintain assets with a long service life.

Modules range in duration for the number of days they take to complete. The modules are:

- Module A: Quality Assurance
- Module B: Soils and Foundations
- Module C: Steel, Welding, and Coatings
- Module D: Aggregates for Transportation Construction Projects
- Module E: Mechanistic Empirical Pavement Design Guide
- Module F: Asphalt Materials and Paving Mixtures
- Module G: Portland Cement Concrete
- Module H: Evaluating Recycled Materials for Beneficial Uses in Transportation

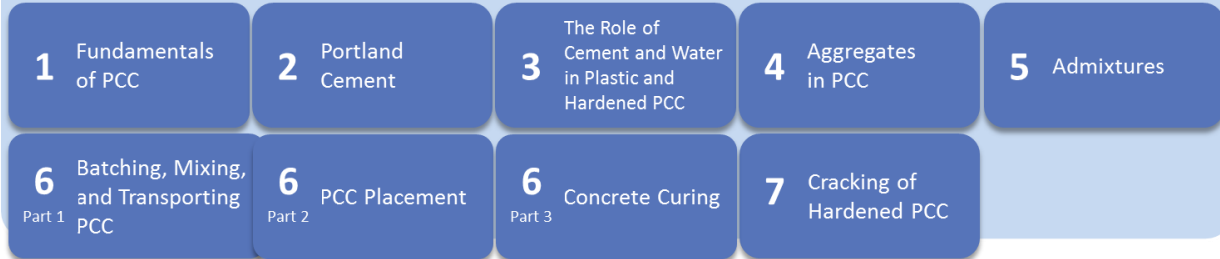
Introduction

Module G: Portland Cement Concrete (PCC) is the seventh module in the FHWA HMEC. Module G provides participants with the latest information and guidance available for PCC, as well as technical content related to Portland cement concrete. The original course materials are somewhat limited in content, which is something that has been updated in the new version of this course. The newly designed modules provide numerous opportunities to apply the content; experiences such as laboratory testing, analysis, mixture design, and other identified opportunities are included in the updated module. Many of the processes associated with PCC are particularly appropriate for visual representations. Besides hands-on experiences, this module will include a variety of graphics, animated process flows, photographs, and videos.

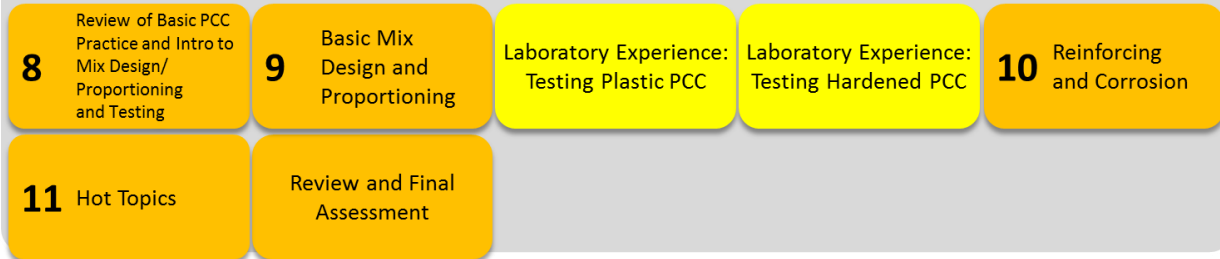
Module G Overview

Below is a visual overview of all of the lessons covered in this module:

Web-based Training (WBT)



Instructor-led Training (ILT)



Module Goals

The goals for this module are as follows:

- Describe the characteristics and engineering properties of Portland cement concrete components and their effects on PCC when utilized in highway applications
- Describe the characteristics and engineering properties of Portland cement concrete
- Identify common durability issues and appropriate mitigation measures
- Calculate mixture proportions for PCC used in highway applications
- Explain how construction operations affect the engineering properties of PCC
- Explain the significance of common field and laboratory testing of PCC
- Determine appropriate parameters for quality control and quality assurance to support the development of an effective acceptance program
- Interpret test results to make an acceptance determination
- Discuss current best practices, potential issues, technology, and trends that may affect PCC

Learning Outcomes

Lesson 1: Fundamentals of PCC

- LO 1.1: Identify the types of PCC used for highway applications
- LO 1.2: Describe fundamental properties of PCC used in highway applications
- LO 1.3: Describe the key factors influencing the mechanical properties of PCC
- LO 1.4: Describe typical durability issues in PCC

Lesson 2: Portland Cements

- LO 2.1: Explain the effect of different types of cement on plastic and hardened PCC properties
- LO 2.2: Describe the production process for Portland cement
- LO 2.3: Relate the chemical and physical properties of Portland cement to the concrete
- LO 2.4: Evaluate chemical and physical properties of Portland cement

Lesson 3: The Role of Cement and Water in Plastic and Hardened PCC

- LO 3.1: Explain the basics of Portland cement hydration
- LO 3.2: Explain the potential effects of impurities in the mix water on PCC properties
- LO 3.3: Explain the effects of temperature on PCC properties

Lesson 4: Aggregates in PCC

- LO 4.1: Describe the key aggregate properties for use in PCC
- LO 4.2: List the primary influences of aggregates in PCC

Lesson 5: Admixtures

- LO 5.1: Describe types of admixtures and their effects on PCC
- LO 5.2: Identify the three basic chemical admixture groups and their benefits and limitations
- LO 5.3: Describe the basic function of air-entraining admixtures and how they are controlled
- LO 5.4: Describe the basic function of water-reducing admixtures and how they are controlled
- LO 5.5: Describe the basic function of set-controlling admixtures and their use
- LO 5.6: Explain the importance of using corrosion-inhibiting admixtures for prestress applications
- LO 5.7: Identify additional types of chemical admixtures and their application in highway construction
- LO 5.8: Identify the most common types of supplemental cementitious materials (SCMs)

Lesson 6: Construction Practices

- LO 6.1: List the most common types of batching and mixing equipment for producing quality PCC
- LO 6.2: Describe best practices for batching and mixing PCC
- LO 6.3: Explain the effects of temperature on PCC as related to mixing
- LO 6.4: Explain how hauling practices can affect plastic properties of the PCC
- LO 6.5: Describe the most common placement methods for highway and structural applications
- LO 6.6: Describe the primary methods for consolidating PCC
- LO 6.7: Describe the most common methods for finishing and texturing PCC pavements and bridge decks
- LO 6.8: Explain the effects of ambient temperature, concrete temperature, and component temperature on PCC as related to placing, finishing, and curing
- LO 6.9: Describe the other factors that need to be considered prior to or during PCC placement
- LO 6.10: Explain the need for timely and proper PCC curing
- LO 6.11: Explain how curing impacts hardened PCC in terms of durability, rate of hydration, and early age cracking potential
- LO 6.12: Describe the benefits of maturity monitoring

Lesson 7: Cracking of Hardened PCC

- LO 7.1: Explain the rationale for jointing Portland cement concrete (PCC)
- LO 7.2: Discuss the types of cracking that may occur as a result of improper curing of PCC
- LO 7.3: Identify common types of PCC cracking and their potential causes
- LO 7.4: List some common crack repair methods and/or materials
- LO 7.5: Describe the capabilities of HIPERPAV software

Lesson 8: Review of Basic PCC Practice and Introduction to Mix Design/Proportioning and Testing

- LO 8.1: Describe the cement acceptance standards for your State and emphasize the overall key elements of an effective cement acceptance plan
- LO 8.2: Explain the role of water in cement hydration and why the water-cement (w/c) ratio must be carefully controlled
- LO 8.3: Describe how aggregate properties affect the workability of plastic PCC
- LO 8.4: Explain some of the more common effects of aggregate properties on the strength and durability of hardened PCC
- LO 8.5: Describe the necessary elements of an acceptance plan for admixtures in your State
- LO 8.6: Explain how your agency's evaluation process leads to approval of a plant for production
- LO 8.7: Explain the relationship between PCC specifications and best construction practices
- LO 8.8: Describe the necessary elements of a comprehensive acceptance plan for PCC

Lesson 9: Basic Mix Design and Proportioning

- LO 9.1: Describe the steps involved in mix design and mix proportioning using American Concrete Institute (ACI) 211.1
- LO 9.2: Evaluate an existing mix design to ensure it meets a given set of criteria
- LO 9.3: Describe how proportioning affects the engineering properties of Portland cement concrete (PCC)
- LO 9.4: Relate mix proportions to distress and durability issues
- LO 9.5: Explain the consequences of substituting materials in terms of mix performance and behavior
- LO 9.6: Describe the most common tests used for determining the properties of plastic and hardened PCC
- LO 9.7: Describe the tests used for determining the properties of plastic PCC and their use in controlling the quality of PCC
- LO 9.8: Describe the tests used for determining the properties of hardened PCC and their use in controlling the quality of PCC

Lesson 10: Reinforcing and Corrosion









- LO 10.1: Compare reinforcing types and the appropriate uses of each
- LO 10.2: Describe the primary reasons for corrosion of steel in PCC
- LO 10.3: Relate mix design properties to corrosion potential
- LO 10.4: Describe the selection of reinforcement types based on environmental conditions and corrosion potential
- LO 10.5: List the most commonly used methods to detect corrosion
- LO 10.6: Recommend an appropriate corrosion mitigation technique for a given scenario
- LO 10.7: Describe the necessary elements for an acceptance plan for reinforcing materials



Lesson 11: Hot Topics

- LO 11.1: Describe current and emerging initiatives, trends, technologies, and potential issues affecting PCC

ILT Instruction Icons

The following icons are used on the slides as a cue to the instructor and participants:

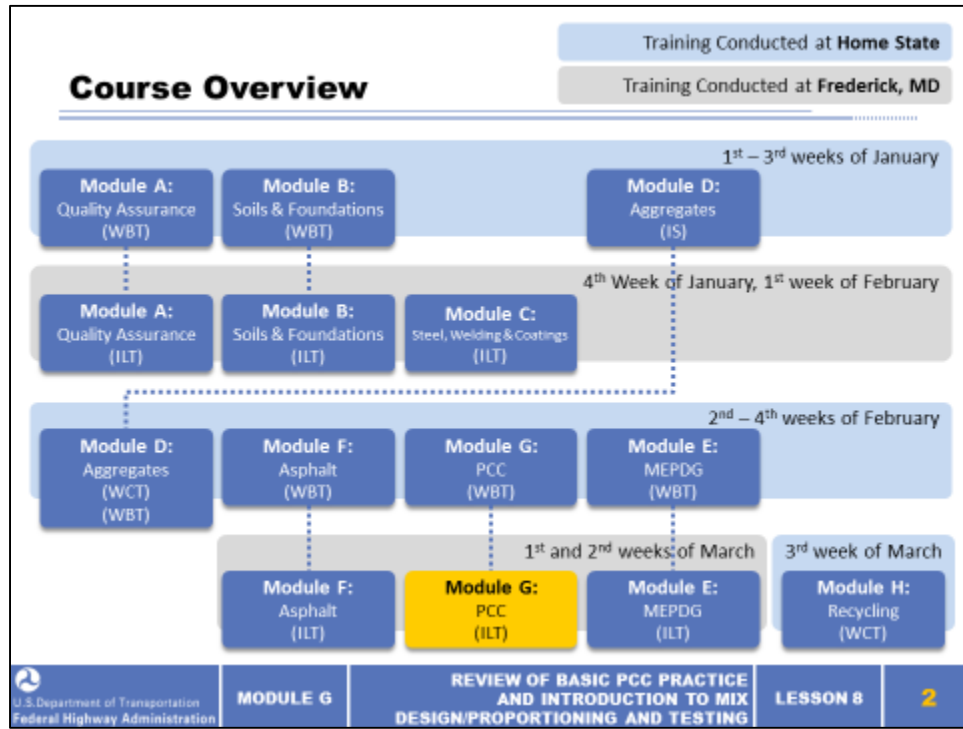
Icon	Icon Name	Typical Use
	Timer	<ul style="list-style-type: none"> Call out the estimated time for the lesson
	Important Information	<ul style="list-style-type: none"> Call out important information.
	Q & A	<ul style="list-style-type: none"> Check for understanding or agreement. Survey participants. Solicit feedback.
	Breakout/Small Group Exercise	<ul style="list-style-type: none"> Break participants into groups. Provide directions for exercise.
	Video/Sound	<ul style="list-style-type: none"> Show a video.
	Reference	<ul style="list-style-type: none"> Reference another document or resource.
	Links	<ul style="list-style-type: none"> Share a Web link for additional resources.
	Whiteboard	<ul style="list-style-type: none"> Draw or document something on a whiteboard or easel pad.

Icon	Icon Name	Typical Use
	Safety	<ul style="list-style-type: none">▪ Call out important safety information.
	Common Error	<ul style="list-style-type: none">▪ Call out a system or process that is often misused.

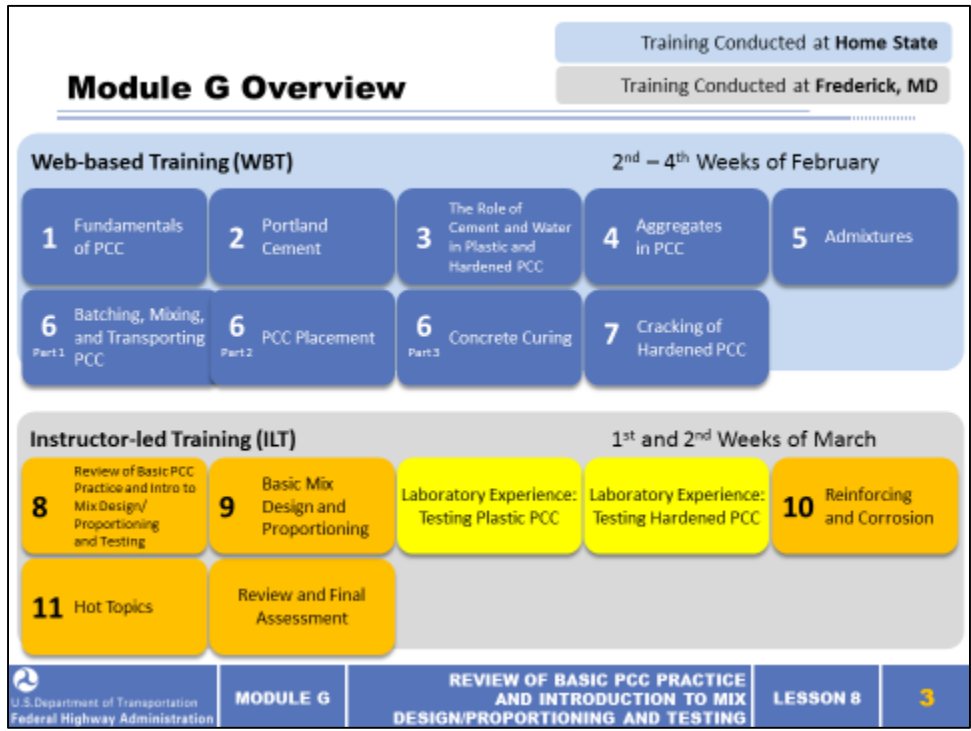
Slide 1




Slide 2



Slide 3




Slide 4




Learning Outcomes

By the end of this lesson, you will be able to:

- Describe the cement acceptance standards for your State and emphasize the overall key elements of an effective cement acceptance plan
- Explain the role of water in cement hydration and why the water-cement (w/c) ratio must be carefully controlled
- Describe how aggregate properties affect the workability of plastic PCC
- Explain some of the more common effects of aggregate properties on the strength and durability of hardened PCC
- Describe the necessary elements of an acceptance plan for admixtures in your State
- Explain how your agency's evaluation process leads to approval of a plant for production
- Explain the relationship between PCC specifications and best construction practices
- Describe the necessary elements of a comprehensive acceptance plan for PCC

 This lesson will take approximately 6 hours to complete.

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Slide 5

Lesson Overview

- In this lesson, we will review the material that has been previously discussed in the Web-based training (WBT) portion of the course (Lessons 1–7)
- This is your opportunity to ask questions and supplement the information presented with your own experiences
- In addition, we will be reviewing the assignments that were given in a number of the WBT lessons

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Portland Cements 

AASHTO M 85, Standard Specification for Portland Cement, (ASTM C150) lists the following Portland cements:

Type I	Type V
Type II	Types IA, IIA, IIIA
Type III	Type II (MH)
Type IV	Type II (MH)A

 Which cements are used in your State?

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The cement types listed and discuss their availability and use.


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Blended Hydraulic Cements



- Blended hydraulic cements
 - Two (binary) or three (ternary) interground materials combining:
 - Portland cement
 - Slag cement
 - Fly ash
 - Silica fume
 - Calcined clay
 - Hydrated lime
- Three primary classes:
 - Type IS, Portland blast furnace slag cement
 - Type IP, Portland-pozzolan cement
 - Type IT, ternary blended cement

 The most widely used blended cements are those specified by AASHTO M 240, Standard Specifications for Blended Hydraulic Cements, (ASTM C595).

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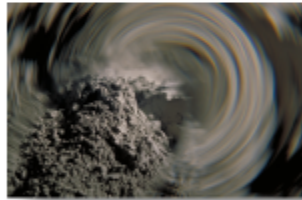
The blended hydraulic cements are becoming increasingly popular because they offer the benefit of complete and uniform blending of the materials.

Slide 8


Selection of Appropriate Cement Type



- Specific characteristics that may make it the best choice for a specific project
- Properties that are most often considered include:
 - Set time
 - Rate of compressive or flexural strength gain
 - Heat of hydration
 - Sulfate resistance
 - Low alkali content
 - Sustainability initiatives



Q&A What are your experiences with cement selection?



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The availability and economy may figure strongly into the final decision as to the selected cement type.

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Exercise 1: Select a Cement Type

- The task at hand is to select the most appropriate cement type for the following 4 scenarios:
 - Group 1: Rapid repair of a high volume roadway, harsh environment, limited closure time.
 - Group 2: New construction, large diameter drilled shaft, high sulfate environment.
 - Group 3: New construction, interstate highway, not subject to early opening criteria, moderate environment.
 - Group 4: Bridge deck replacement, moderate to harsh environment, limited closure time available.





Let's break into groups for an exercise. Take 7 minutes to determine the most appropriate cement type and document your assumptions.



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Slide 10

Key Components in Portland Cement



Oxide form of the primary elements comprising Portland cement

C = Calcium Oxide = "Lime" = CaO


S = Silicon Dioxide = "Silica" = SiO_2

A = Aluminum Dioxide = "Alumina" = Al_2O_3

F = Iron Oxide = Fe_2O_3

H = Hydrated Form

- Using this terminology, one of the four primary cement compounds, $3\text{CaO} \cdot \text{SiO}_2$ (tricalcium silicate) becomes C_3S


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It is desirable to know the basic chemistry involved in Portland cement hydration in order to identify issues that may occur with incompatibility of materials, set problems, and so on. This slide shows the basic building blocks of Portland cement written in cement chemist's nomenclature for simplicity.


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Typical Kiln Output

- Typical kiln output in terms of percentages of the four major compounds



Compound	Approximate %
C_3S	49%
C_2S	25%
C_3A	12%
C_4AF	8%



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Note that the relative percentage of each will change as a function of cement type. These compounds form in the kiln at various temperatures and then solidify in the form of cement clinker as the molten mass cools.

The clinker is then processed to produce Portland cement. Cements can be tailored to specific needs and requirements.

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Hydration Reactions




- Compounds responsible for the formation of the primary structure of hydrated cement include:
 - C₂S (dicalcium silicate)
 - C₃S (tricalcium silicate)
- When these compounds react with water, they form calcium silicate hydrates (C-S-H). Note that the C-S-H is not stoichiometrically fixed


Calcium hydroxide is also found in the hydrated cement as shown here:

$$C_3S + (1.3+x)H \rightarrow C_{1.7}SH_x + 1.3CH$$

$$C_2S + (0.3+x)H \rightarrow C_{1.7}SH_x + 0.3CH$$

Where $C_{1.7}SH_x = C-S-H$ and $H = \text{Calcium Hydroxide}$


Let's review the hydration reaction. What occurs during the reaction?


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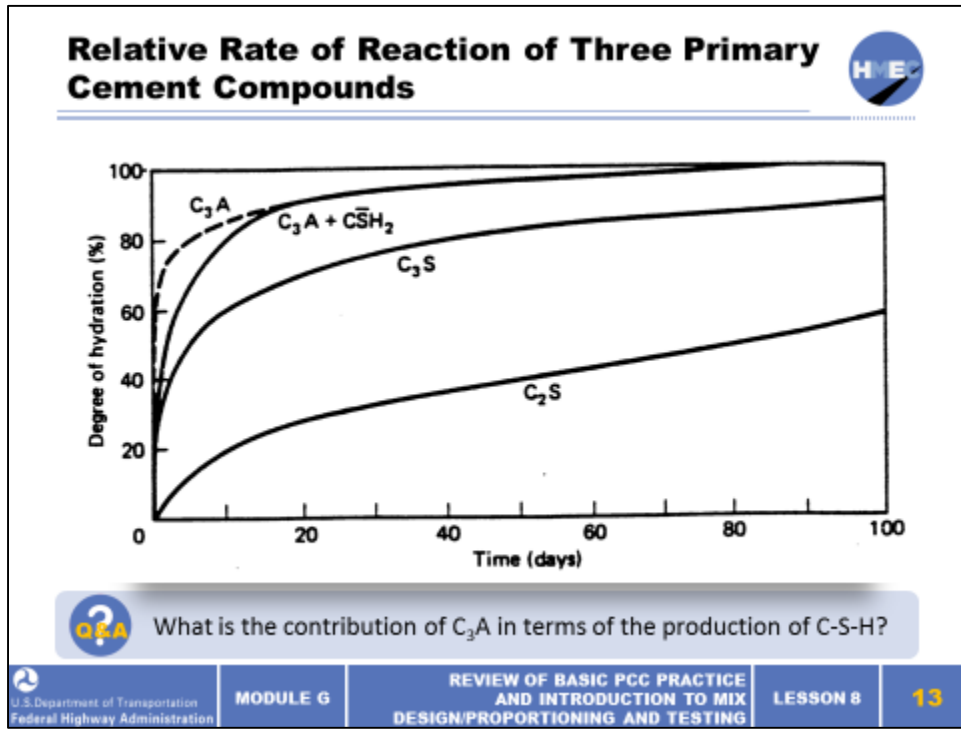
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The hydration reactions shown emphasizing that the formation of calcium silicate hydrates (C-S-H) is desirable, while the formation of calcium hydroxide is not. C-S-H is responsible for the majority of the physical attributes of the hydrated cement paste. Calcium hydroxide is also found in the hydrated cement as shown in the table. The structure of the C-S-H is the most important factor in determining the strength and durability of the hydrated cement paste. We will not discuss the reactions of the secondary compounds as they are quite complex and, in some instances, reversible.

The formation of ettringite is due to the reaction of aluminates (primarily C₃A). This is a reversible reaction with monosulfoaluminate.

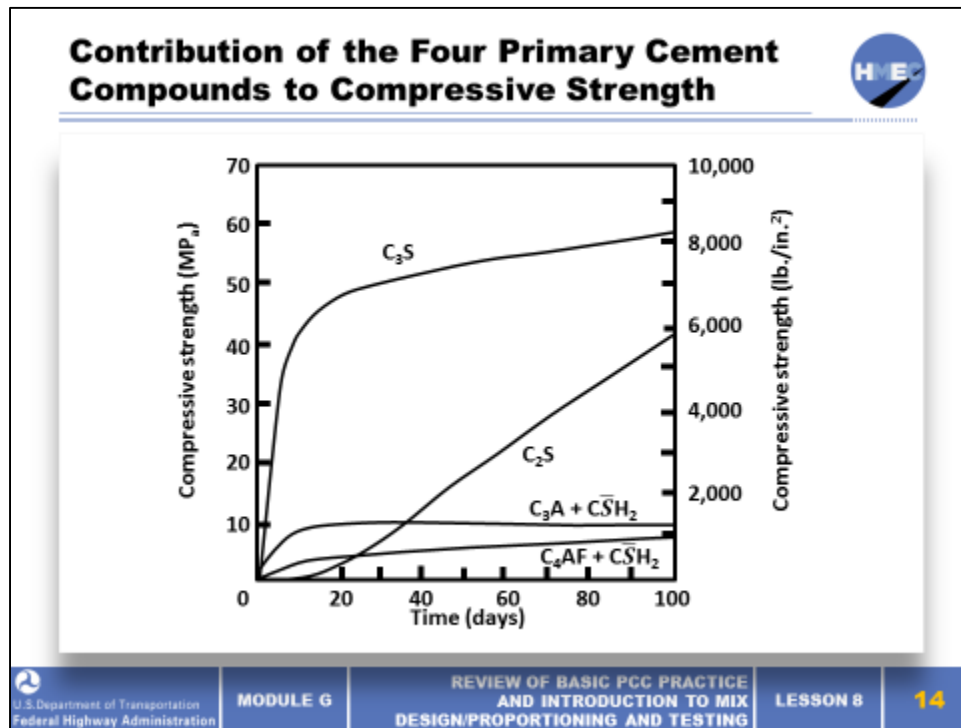
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The reaction rates shown on the graph, emphasizes that the C_2S and C_3S react at substantially different rates. The initial formation of C-S-H is due primarily to the hydration of C_3S .

Note that C_4AF is not shown.


Slide 14




That after about 14 days, the increase in strength due to the hydration of C_3S tends to somewhat level out. On the other hand, the rate of strength gain for the C_2S is significantly increased after the first 28 days. In practice, the interrelationship between the compounds makes this much more complex in an actual PCC mix. However, in general, long-term strength gain is much more a function of the C_2S reaction. When discussing the increase in strength of PCC over the span of many years, C_2S is the primary contributor.

Slide 15

Portland Cement Fineness



- Most common physical property of Portland cement is the fineness of the material after grinding
 - Fineness of cement is specified in terms of Blaine fineness
 - Both the AASHTO and ASTM specifications provide limits on fineness for each cement type
 - The finer the clinker is ground, the faster the rate of reaction will be due to increased surface area
 - Type I cement ground at the upper end of the specification limit will have different set characteristics (faster setting) than if it is ground at the coarse limit; however, ultimate strength of both will be approximately the same

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The most common physical property of Portland cement is the fineness of the material after grinding. The fineness of cement is specified in terms of the Blaine fineness. Both the AASHTO and ASTM specifications provide limits on fineness for each cement type. The reason that fineness is important is that for a given cement, the finer the clinker is ground, the faster the rate of reaction will be due to the increased surface area.

Slide 16


Developing an Acceptance Plan for Portland Cement 

- Acceptance plans for Portland cement are well established in most agencies
- Cement manufacturing plants typically have extensive laboratory facilities that conduct routine (sometimes daily) tests on raw feed materials and the finished product
- Cement manufacturers then produce a mill test report indicating all of the key chemical and physical parameters
- Laboratories routinely perform tests such as:
 - Penetration (initial set time)
 - Heat evolution
 - Rate of strength gain
 - Numerous other qualitative tests

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Acceptance plans for Portland cement are well established in most agencies. The testing protocols used in these evaluations are established by AASHTO and ASTM.


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Mill Test Report

- A mill test report represents the average of a series of tests and characterizations performed on Portland cement at the point of manufacture
- The highly detailed reports indicate the chemical and physical properties of the cement and are often used for source acceptance
- Extensive testing is required for developing the mill test report results.
- The example mill test report represents an actual production run

 Refer to the Example Mill Test Report, which can be found in the Resources folder.

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Many agency acceptance plans for cement make use of the mill test reports obtained from the manufacturers to determine compliance with both physical and chemical specification requirements. Note that mill test reports generally represent average values and are not representative of a single day's production.


The tests required include strength, set time, x-ray diffraction, x-ray fluorescence and numerous others.

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Exercise 2: Portland Cement Acceptance Plan by State



- What constitutes a thorough acceptance plan for Portland cement?
- Be sure to address proportions of the four primary compounds (C_4AF , C_3A , C_2S , and C_3S), Blaine fineness, and alkali content
- Note that the alkali content is of particular importance if aggregate reactivity is suspected



What is your State's acceptance plan for Portland cement?



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Water



- Water is a key component in PCC and greatly affects both strength and durability
- We typically speak of water in a PCC mix in terms of the w/c ratio and have specifications governing this parameter
- Water quality is not generally an issue but should be verified prior to use if it is a new source
- In this section, we will review the most important aspects of water in PCC




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Water plays an important role in both fresh and hardened PCC.


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Mixing Water Considerations



- Water should be of suitable quality as not to impact the performance of the PCC
- Almost all water that is suitable for drinking is acceptable for use as mix water in PCC
 - Exception would be if the dissolved mineral content is high
 - Taste
 - Odor
- Standard includes provisions
 - Potable water, non-potable water, water from production operations, and combined water

 The acceptance standards for mixing water are covered in ASTM C1602, Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete.

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The ASTM standard includes provisions for potable water, non-potable water, water from production operations, and combined water. Under the specification guidelines, all potable water is automatically qualified for used in PCC production. If the water from the other sources is questionable, it should be tested to ensure that it does not impact performance. The most common impacts of poor quality mixing water is a reduction in strength and a deviation from normal set time.


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Sources of Mixing Water

- Mixing water may be from a number of different sources depending on the PCC plant location
- Common sources include the following:
 - Municipal water supply
 - Municipal reclaimed water (from wastewater treatment plants)
 - Site-sourced water
 - Recycled water (from PCC production)





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These water sources may be used with the limitations.


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Mixing Water Quality



- ASTM specification suggests chemical limits for certain types of applications:
 - Sulfates (SO_4) should be limited to 3,000 parts per million (ppm)
 - Alkalis ($\text{Na}_2 + 0.658 \text{K}_2$) should be less than 600 ppm
 - Total solids (by mass) should be less than 50,000 ppm
 - Chlorides (Cl) should be less than 500 ppm for prestressed and 1,000 ppm for all other PCC



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The ASTM C1602 specification establishes guidelines for mixing water. However, the limitations for dissolved chemicals are considered optional and are frequently waived if it can be demonstrated that the water will not adversely affect performance. If CaCl_2 accelerating admixtures are used, the calcium limitation is always waived.

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Potential Effects of Mixing Water Deficiencies

- Potential problems associated with poor quality mix water include the following:
 - Increased (or decreased) set time
 - Lower compressive strength
 - Higher permeability
 - Lower freeze-thaw resistance



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The effects of poor quality mixing water may be readily apparent (for example, changes in initial set time), or it may be a delayed effect such as a reduction in strength. The testing procedures for water are straightforward and do not require extensive sample preparation and time. Therefore, if there is a question about the impact of a particular water source, test it or refer to its historical use to see if problems were encountered.

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Water Requirements for Hydration



- For the hydration reactions to initiate and progress steadily, water must be continually available:
 - Water is consumed chemically and physically in the hydration process
 - The chemical and physical binding of water must proceed simultaneously
 - Mix water occupies pore space prior to facilitating hydration
 - The cement particles (grains) must be surrounded by liquid water for hydration to occur
 - Wet curing sustains hydration without increasing pore space

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Water is required for the hydration reactions in Portland cement to initiate and progress. However, too much water results in excessive space between the hydrating cement grains, thereby resulting in a less dense matrix of hydration products.

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Water/Cement (W/C) Ratio



- **W/C Ratio**
 - Used to specify the amount of water relative to the amount of cement in a PCC mix
 - Practical limit
 - Close to 0.50 (due to stiffness of mix and placement issues)
 - Use of normal and high range water reducers have allowed much lower w/c ratios to be used without concern for placement difficulties
 - Benefits of lowering the w/c ratio
 - Higher strengths
 - Lower permeability
 - Enhanced durability



What is the typical w/c ratio specified for highway construction and bridge decks in your State?



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The term w/c ratio is used to specify the amount of water relative to the amount of cement in a PCC mix. We have equated higher strengths, lower permeability, enhanced durability, and other benefits with low w/c ratios.

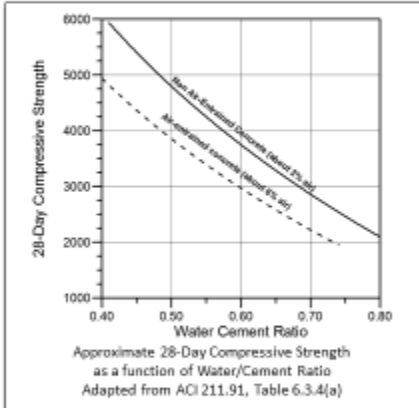
Prior to the advent of water reducing admixtures, the practical limit for water-to-cement was close to 0.50 because of the stiffness of the mix and placement issues. Note that a w/c ratio of greater than 0.27 is required for complete hydration of the cement, although 100% hydration is rarely achieved even after many years.

G8-25

Effect of W/C Ratio on the Strength of PCC



- Effect on Air-Entrained Concrete:



Approximate 28-Day Compressive Strength as a function of Water/Cement Ratio
Adapted from ACI 211.91, Table 6.3.4(a)

Why is the compressive strength lower for air-entrained PCC versus non-air-entrained mixes for the same w/c ratio?

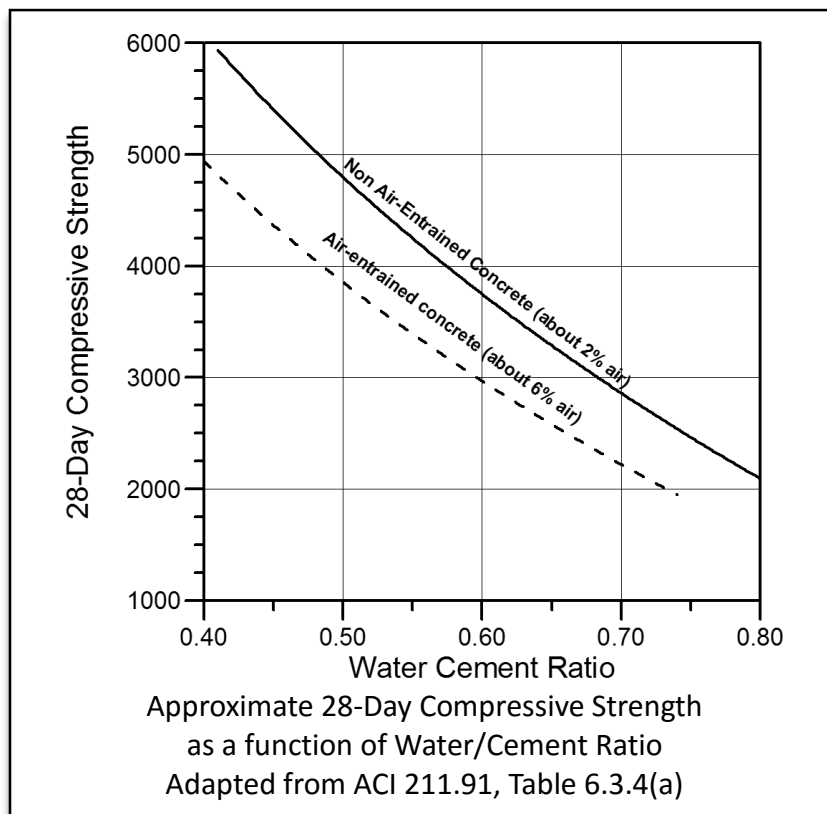
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The w/c ratio has a significant effect on almost all PCC properties, but perhaps none more important than strength. This graph shows the effect of w/c ratio on compressive strength when all other variables are held constant. Let's look at the effect on air-entrained concrete:

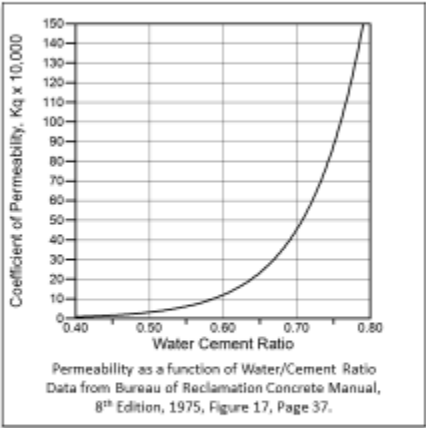
- If the w/c is specified as 0.40, the resulting compressive strength is approximately 5,000 pounds per square inch (psi);
- If the w/c ratio is increased to 0.50, the compressive strength falls to approximately 3,800 psi; and
- This figures out to be about a 24% drop in strength for an increase of 0.10 in w/c.

Or looking at it another way, if we assume a PCC mix has 564 pounds of cement per cubic yard, the difference between a w/c of 0.4 and 0.5 is approximately 6.8 gallons of water per cubic yard of concrete.

Slide 27

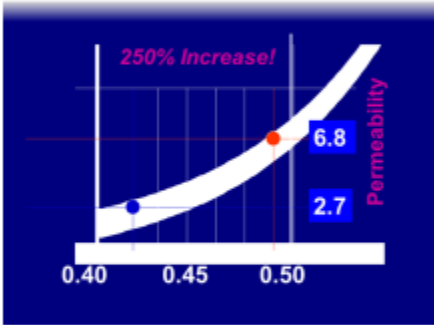
Effect of W/C Ratio on the Permeability of PCC






Permeability as a function of Water/Cement Ratio
Data from Bureau of Reclamation Concrete Manual,
8th Edition, 1975, Figure 17, Page 37.

250% Increase!



? **Q&A** Are there permeability requirements for highway pavements and bridge decks in your State?

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Another critical aspect of the w/c ratio is the effect on permeability. Permeability relates to freeze-thaw durability, sulfate attack, and potentially the ingress of deleterious chemicals.


The graph on the left shows that for w/c ratios greater than approximately 0.6, small changes result in dramatically higher levels of permeability. However, for the w/c ratios typically encountered in transportation-related applications, the graph on the right shows a 250% increase in permeability, which corresponds to a dramatic reduction in performance and service life.

Slide 28

Drying Shrinkage and Cracking



- Drying shrinkage, as the name implies, is the removal (evaporation) of the water in PCC that is not required for hydration
- As the water is removed from the PCC, there is a resulting volume change, shrinkage
- Only a portion of the water added to PCC during the mixing process is necessary for hydration (corresponding to a w/c ratio of 0.27); the remainder is to provide workability
- Drying shrinkage is a long-term process, although the majority of the volume changes occur roughly within 90 days; however, this is subject to many variables, including total water added during mixing and ambient conditions

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Drying shrinkage, as the name implies, is the removal (evaporation) of the water in PCC that is not required for hydration. As the water is removed from the PCC, there is a resulting volume change, shrinkage. Drying shrinkage refers to a volume change in PCC due to moisture loss.

Only a portion of the water added to PCC during the mixing process is necessary for hydration; the remainder is to provide workability. Drying shrinkage is a long-term process although the majority of the volume changes occur roughly within 90 days. This, however, is subject to many variables, including total water added during mixing and ambient conditions.

For typical mixes, approximately half of the water is used for hydration; the remaining water is responsible for the early stages of drying shrinkage.

Slide 29


Effect of Water Content on Drying Shrinkage



- Drying shrinkage is difficult to eliminate, but is relatively easy to control by lowering the amount of total water in the mix

Cement Content and Drying Shrinkage*			
Cement Content, bags/cy (pounds/cy)	Water Content, cy	Water-Cement Ratio	Shrinkage, %
5 (470)	0.20	0.72	0.03
6 (564)	0.21	0.62	0.03
7 (658)	0.21	0.54	0.03
8 (752)	0.21	0.46	0.03

* 3 x 3 x 10-in. prisms cured wet 7 days, dried 14 days


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This slide illustrates the effect of w/c ratio. It is interesting to note that the w/c ratio seems to have no appreciable effect on the drying shrinkage.


Taking this to the next level, you have to lower the cement content if you need to reduce the overall water content at an already low w/c ratio. We will discuss this in greater detail in the mix proportioning lesson.

The important point to remember is that total water, not w/c ratio, is important in controlling drying shrinkage.



Note that 1 bag of cement weighs 94 lbs.



Slide 31


Mix Water and Fresh and Hardened PCC Discussion




- The photos shown below illustrate two different w/c ratios at time of placement



How does mix water affect the properties of fresh and hardened Portland cement concrete?



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We are going to begin by looking at photos of field placement showing a range of slumps. We will then look at samples similar to those shown in the photos and compare the physical properties. We will conclude the exercise by looking at scanning electron microscope (SEM) photos illustrating the difference in structure as a result of water content.

The SEM photos were provided by Dr. Peter Taylor and show the structure of the paste at a w/c ratio of 0.43 on the left and 0.66 on the right. These correspond approximately to the construction photos immediately above the SEM photos.

Slide 32

Aggregates and Their Effect on the Properties of Plastic PCC



- Aggregates occupy a large volume (70% or more) in a typical PCC mix and therefore have a substantial effect on the properties of both fresh and hardened PCC
- In this section, we are going to review the most significant effects and relate them to specific aggregate properties

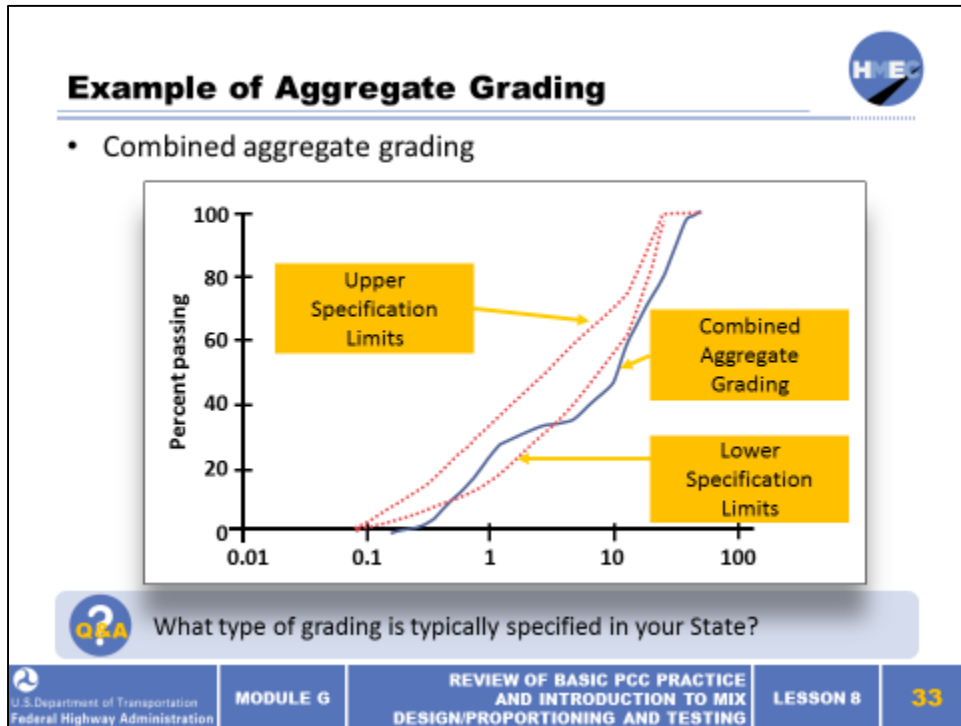
The properties of fresh PCC most affected by aggregates include:

- Workability
- Finishability
- Water Demand

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Aggregate properties along with w/c ratio, cement content, and admixtures are the primary factors controlling the properties of fresh PCC.

Slide 33



This example shows a combined aggregate grading, which is represented by the blue line. The upper and lower specification limits for this aggregate are shown by the two red dashed lines. Note that the gradation shown falls outside of the specifications on the lower bound.

Slide 34

Aggregate Moisture States

The diagram illustrates four aggregate moisture states in blue vertical panels:

- Oven Dry:** Represented by a white circle on a blue background.
- Air Dry:** Represented by a white circle with a blue, irregular shape inside, indicating some moisture.
- Saturated Surface Dry:** Represented by a solid light blue circle.
- Damp or Wet:** Represented by a light blue circle with a white, irregular shape around its perimeter, indicating surface moisture.


Footer information:

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Aggregates in fresh PCC tend toward saturated surface dry (SSD) moisture. If the aggregates are drier than SSD, they absorb a portion of the mix water, thereby affecting workability. If they are wetter than SSD, they provide excess water and again affect workability.


Slide 35

Lightweight Aggregates



- Uses of lightweight aggregates
 - Bridge decks and members (coarse)
 - Pavement slabs (fine)
- Primary reason for use
 - Reduces the unit weight of the PCC
- Unit weights
 - Normal PCC is approximately 145–150 lbs. per cubic foot (pcf)
 - Lightweight PCC is approximately 90–115 pcf



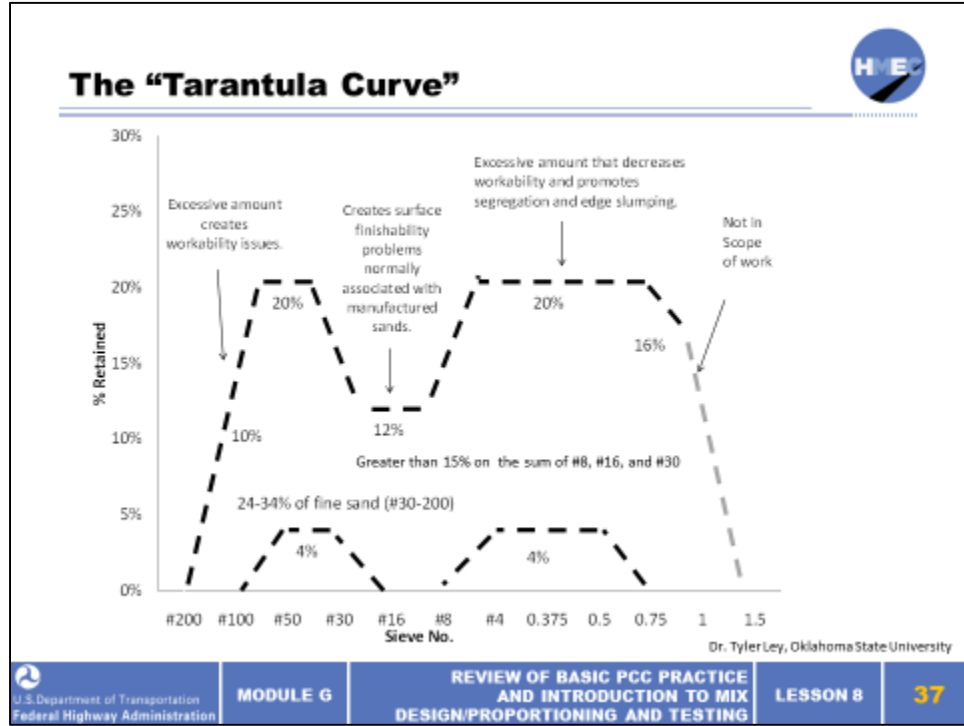
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The primary reason for using lightweight coarse aggregate is to reduce the unit weight of the PCC, thereby reducing the size of the structural elements due to dead loads. Normal weight PCC is approximately 145–150 pounds per cubic foot (pcf) compared to lightweight PCC at 90–115 lbs. pcf.

Lightweight aggregates are naturally occurring (volcanic) or manufactured products with a high degree of internal void space. Lightweight coarse aggregates are used primarily in structures to reduce the amount of dead load. Lightweight fine aggregates are sometimes used to provide internal curing by providing moisture within a low w/c ratio PCC during hydration.


Saturated lightweight fine aggregate is added to low w/c ratio PCC mixes to provide an internal supply of water for curing. The result is less drying shrinkage and more complete hydration, particularly under difficult placement conditions, such as high temperature, low humidity, and wind, which results in a high rate of surface evaporation.

Slide 37




Slide 38


Aggregates and Their Effect on the Properties of Hardened PCC



Aggregates affect the hardened PCC properties in three primary ways:



1. Strength
2. Durability
3. Dimensional stability

 Many of the effects of aggregates on PCC behavior and performance are not readily apparent and may take years to develop

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The long-term performance of PCC is strongly influenced by aggregate type and characteristics. We are going to review how aggregates influence each of the listed properties.


Slide 39

Factors Affecting Alkali-Silica Reactivity (ASR)			
<ul style="list-style-type: none">• In order for ASR to progress, it is necessary to have a high alkali content in the cement, aggregates with significant amounts reactive silica and water• ASR potential can be limited by thorough testing of the aggregates and/or PCC mix and remedial measures employed prior to construction• If reactive aggregates must be used due to aggregate availability issues, other actions can be taken, such as adding pozzolans to the mix, using a low alkali cement, adding lithium during batching, and lowering the permeability of the PCC			
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Aggregate selection, cement type, mix design, pozzolan additions, etc., all play a role in the potential for and the severity of ASR. Specifications should be written in such a way that one or more of these factors is controlled so as to eliminate ASR.

Slide 40

Admixtures



- Admixtures are used to alter or enhance the PCC in terms of workability, set-time, durability, and other factors we will review in this section
- Admixtures can be classified as either chemical or mineral
- It is safe to say that all of the PCC mixes used in highway and other transportation-related uses contain one or more admixtures

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Admixtures are used to modify the characteristics of fresh or hardened PCC. There are generally two types of admixtures: chemical and mineral. There are many different types of admixtures within these larger designations.

Slide 41

Air-Entraining Admixtures



- Air-entraining admixtures (AEA) are the oldest type of chemical admixture and the most widely used
- AEA are used primarily to improve the freeze/thaw resistance of PCC
- Other effects include:
 - Improves durability
 - Improves workability
 - Potentially lower permeability (where bleed water is present)
 - Reduced segregation potential
- Primary drawback of air entrainment is a reduction in strength

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The first category we will discuss is air entraining. Air-entraining admixtures (AEA) are probably the oldest type of chemical admixtures and the most widely used. AEA are used primarily to improve the freeze/thaw resistance of PCC.

These benefits typically outweigh the loss in strength. The improved workability is due to the lubricating properties of entrained air. Consider the entrained air bubbles as acting similar to microscopic ball bearings, thereby allowing the aggregate particles to reorient more readily. If the workability is improved, the water demand for a fixed level of workability is reduced.

Slide 42

Water-Reducing Admixtures (WRAs)

- Water-reducing admixtures (WRAs) are identified by their ability to reduce water at a set workability
- Designations:
 - Normal
 - Mid-range
 - High-range (commonly known as superplasticizers)



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Water-reducing admixtures (WRAs) are identified by their ability to reduce water at a set workability. The three designations listed perform the same basic function of allowing the use of a reduced amount of water while maintaining workability.

Slide 43

Set Accelerating Admixtures: Benefits and Limitations

<ul style="list-style-type: none"> • Benefits: <ul style="list-style-type: none"> – Increased rate of hydration – Reduced initial set time – Increased rate of strength gain – Higher early strength 	<ul style="list-style-type: none"> • Limitations: <ul style="list-style-type: none"> – Potential for increased shrinkage cracking – Corrosion of embedded steel (chloride-based accelerators)* – The ultimate strength of the PCC is typically less for an accelerated mix – The rapid strength gain is significantly diminished after the first 24 hours
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All DOTs prohibit the use of chloride-based accelerators where rebar or prestressing is used.


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In addition to cold weather placement, accelerators are sometimes used to promote more rapid strength gain under normal temperate placement conditions. As a rule, the higher the placement temperature, the less effective accelerators are in promoting higher early strengths. Note that in many cases, accelerators alone are not sufficient for cold weather placement and the use of heated aggregates, hot water, and potential changes to the mix proportions may also be required. Calcium chloride is a widely used accelerator but can cause corrosion of reinforcing steel. If reinforcement is present, it is highly desirable to use a non-chloride accelerator.

Slide 44

Set Retarding Admixtures: Benefits and Limitations



<ul style="list-style-type: none"> • Benefits: <ul style="list-style-type: none"> – Slower rate of hydration – Reduced rate of slump loss – Reduced peak heat of hydration – Potential for improved long-term strength – Additional time for placement and consolidation – Minimize cold joints during large or complex placements (for instance, bridge decks) – Allows for exposed aggregate finishes 	<ul style="list-style-type: none"> • Limitations: <ul style="list-style-type: none"> – Potential for increased plastic shrinkage cracking – Delayed construction operations <div style="text-align: center; margin-top: 20px;">  </div>
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Set retarding admixtures are widely used for hot weather conditions but also in challenging placements where extra time is required. Retarders are frequently used if long haul times are possible due to haul distance or traffic conditions. Note that for high temperature placement, the addition of a retarder may not be sufficient and the mix may require chilled water or ice (extreme cases may require liquid nitrogen) and aggregates cooled by misting the stockpiles with water (evaporative cooling).


The photo shows an exposed aggregate finish that can be used for pavements to potentially reduce noise and increase skid resistance.

Slide 45

Compatibility Issues with Admixtures



- Incompatibility issues may arise between admixtures due to a number of factors:
 - Combining admixtures from different manufacturers
 - Incorrect admixture dosage
 - Chemical incompatibility between admixture types
- Incompatibility can also be caused by a chemical imbalance between the cement, SCMs, and admixtures
- Incompatibility issues result in problems both during and after construction
 - Most result in unusual stiffening and setting, cracking, and air void problems

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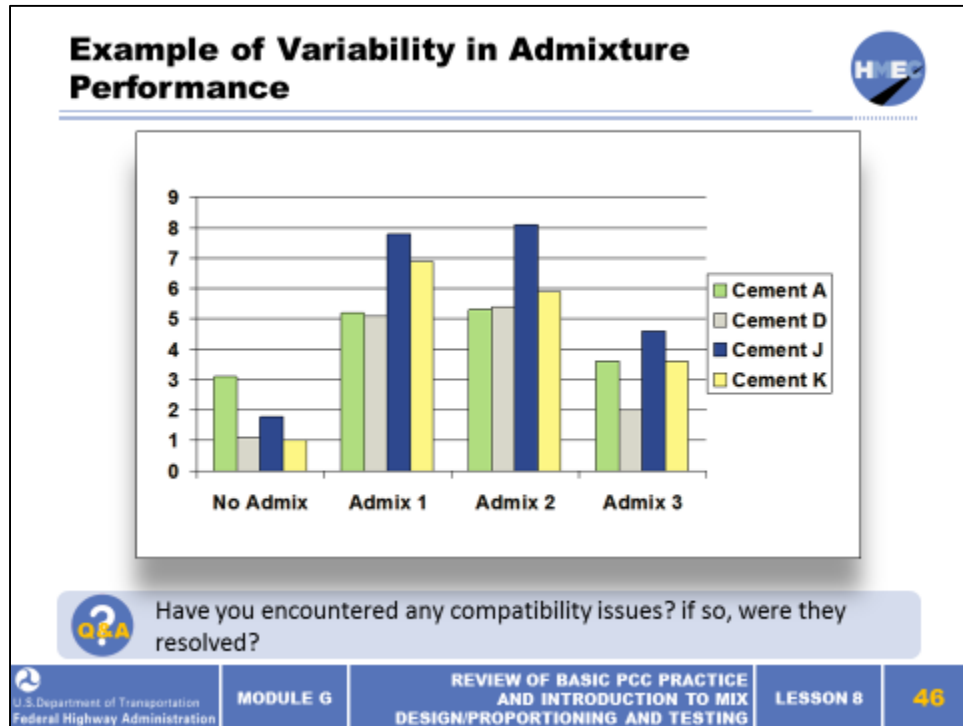
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Compatibility issues are essentially combinations of acceptable materials interacting in an undesirable or unexpected way. These issues may arise between admixture types in a mix, combining products from different manufacturers, cement types, and brands.

Incompatibility issues related to admixtures can be very significant and result in problems both during and after construction. Incompatibilities are chemical in nature and require a detailed look at all of the active compounds in the cement, admixtures, and on occasion, the aggregates and mix water. When ready mix is used, the truck driver can also have a considerable impact on admixture performance primarily through mixing operations and adding water at the job site (and not emptying drum prior to charging). Most incompatibility issues result in unusual stiffening and setting, cracking, and air void problems.

Slide 46



The graph above shows the air content of a PCC mix using the same mix proportions. Note the differences in air content with no admixtures present and the relative differences due to the addition of three admixtures. The differences are due to the physical and chemical properties of the cements and the chemical properties of the admixtures.


Slide 47

The slide features a title 'Supplementary Cementitious Materials' at the top left and an HVE logo at the top right. Below the title, four green rounded rectangular boxes are stacked vertically, each containing a material name: 'Fly Ash', 'Ground Granulated Blast Furnace Slag', 'Silica Fume', and 'Natural Pozzolans'. At the bottom of the slide is a blue footer bar with white text. From left to right, it contains: the U.S. Department of Transportation Federal Highway Administration logo, 'MODULE G', 'REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING', 'LESSON 8', and the number '47' in yellow.


These supplementary cementitious materials (SCMs) are used for a variety of reasons to improve the characteristics of PCC mixes. Fly ash and ground granulated blast furnace slag are in widespread use while silica fume and natural pozzolans are not as widely used. They are composed primarily of a reactive form of silicon dioxide, although they may also contain appreciable amounts of other compounds.

Slide 48

Supplementary Cementitious Materials



- Due to slower rate of strength gain of some SCMs, standard specifications governing traditional mixes may not be appropriate
 - Ultimate strength of fly ash mix will be a higher than normal mix but 28-day strengths may be lower
 - Testing protocol and specifications should be adjusted accordingly
- Similarities
 - Due to presence of amorphous silica, materials participate in pozzolanic reaction in the presence of Portland cement
 - Reaction product (C-S-H) is the same basic hydration product as Portland cement and serves to strengthen the matrix
 - All of these supplementary cementitious materials enhance strength, lower permeability, help mitigate ASR, and slow the rate of strength gain

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It is important to note that due to the slower rate of strength gain for most SCMs, when using these materials, the standard specifications governing traditional mixes may not be appropriate. In other words, the ultimate strength of a fly ash mix will be higher than a normal mix, but the 28-day strengths may be lower. Note that the type of SCM and the relative amount can have varied effects on the set time and rate of strength gain. For instance, Type F fly ash typically slows the initial set while silica fume may accelerate initial set. The testing protocol and specifications should be adjusted accordingly. Supplementary cementitious materials including fly ash, silica fume, and ground granulated blast furnace slag have a number of similarities in the reaction mechanism and hydration products.


Note that some agencies are now considering 56-day strengths rather than 28-day strengths to account for the typically lower rate of strength gain of SCM mixes.


Slide 49

Incompatibility Example


- In order to understand incompatibility issues, consider the chemical makeup and interaction of the compounds within the “chemical system”
- Fly ash in a mix containing Type I cement is often a desirable addition
 - If the C_3A content of the fly ash is too high, there will be insufficient sulfates in the cement to compensate for the increased demand resulting in premature stiffening of mix







Have you encountered any compatibility issues? If so, what were they and were they resolved?


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The use of fly ash in a mix containing Type I cement is often a desirable addition. However, if the C_3A content of the fly ash is too high, there will be insufficient sulfates in the cement to compensate for the increased demand. The result will likely be premature stiffening of the mix. For instance, the initial set characteristics of Type I Portland cement is due to a balance between tricalcium aluminate (C_3A) and gypsum (sulfates)—a balance maintained during the cement manufacturing.

Slide 50

Admixture Quality



- Quality assurance testing on supplementary cementitious materials is very important
- SCMs are industrial byproducts and not manufactured specifically for use in PCC
- However, secondary processing of SCMs is common leading to more consistent properties
- Chemical admixtures are the result of considerable research and development prior to release by the manufacturers
- Chemical admixture industry is highly competitive and quality is typically assured by extensive internal quality control during manufacturing

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Quality assurance testing on supplementary cementitious materials is very important but is very rarely an issue for chemical admixtures. Some states require certified samples from the silo on a specified basis for testing and approval before use. Others maintain lists of approved sources and accept project suppliers' certifications of fly ash quality. The degree of quality control requirements depends on the intended use, the particular fly ash, and its variability. Testing requirements are typically established by the individual specifying agencies.

This testing is typically done by the supplier but may also be validated by the owner/agency. However, things can happen during transport and storage that may affect admixture efficiency. Supplementary cementitious materials for the most part are industrial byproducts and not manufactured specifically for use in PCC. Chemical admixtures are the result of considerable research and development prior to release by the manufacturers.

The chemical admixture industry is highly competitive and quality is typically assured by the extensive internal quality control during manufacturing. That is not to say that incompatibility issues cannot arise in use. On the other hand, supplementary cementitious materials are not manufactured for the PCC industry and their properties may vary significantly, even on a daily basis.


Note that the AASHTO NTPEP (National Transportation Product Evaluation Program) has a Concrete Admixture (CADD) technical committee to evaluate new and existing products.


Slide 51



Assignment from Lesson 5

- We are now going to discuss the following questions:
 - What supplementary cementitious materials are currently used in your State?
 - Under what circumstances are they used (specialty applications or routinely)?
 - If they are used as a partial replacement for Portland cement, what are the limits?
 - Have you experienced difficulty in obtaining any of these materials?


 This “homework” was assigned in Lesson 5.



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Develop an Acceptance Plan for Admixtures Discussion

- We discussed admixtures at length in Lesson 5 and just reviewed a number of key points concerning both chemical admixtures and supplementary cementitious materials
- Next, we will compare this generalized plan with your State requirements





What should be included in a generalized acceptance plan? Are these consistent with State-specific requirements?

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The objective is to discuss the necessary elements of a general acceptance plan for admixtures.

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Production


- PCC production is based on the mix design that is established based on end use requirements and mix proportioning
- There are two primary methods of producing PCC—central batch and transit mix—that will be reviewed in this section
- Keep in mind that quality PCC can be produced with either method, although project demands may favor one method over the other

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In this section, we are going to discuss PCC production and plant certification. Production must be based on proper mix proportioning in order to produce a PCC mix that meets specific project goals. We will be discussing mix design and proportioning in Lesson 9.

Slide 54

PCC Batching, Mixing Equipment, and Methods



- There are two basic production methods for PCC:
 - Central mix plant
 - Portable batch plant
 - Transit mix plant (also referred to as ready mix plant)
- There are many variations in the types of equipment falling into each of these categories
- The main distinction between the two methods is:
 - A central mix operation batches and thoroughly mixes the PCC prior to discharge into a haul vehicle
 - A ready mix operation batches the PCC materials into a transit mix truck for mixing and hauling



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The manufacture of PCC begins with the selection and processing of raw materials, a well-proportioned mix based on intended use, and the selection of a production technique that matches the job requirements.

Slide 55



The photo shows a large “portable” central mix plant. This plant is capable of producing up to approximately 550 cubic yards (cy) of PCC per hour.

Point out the various components of the plant, including the aggregate bins, cement and SCM silos, and the 12 cy mixing drum.

In this type of plant, all of the PCC constituents are charged into the central mixing drum, thoroughly mixed, and then discharged into a haul vehicle for transport to the job site. These plants are capable of producing very consistent and uniform PCC. These plants are computer-controlled and can produce sufficient volume for virtually any transportation-related use.

Slide 56



The production rate of this plant is approximately 130 cy per hour but is much more easily transported and erected at the job site than the central mix plant shown on the previous slide.

Point out the various components of the plant, including the aggregate bins, cement surge hopper, and the mixing drum.

Slide 57



The photo shows a typical transit mix plant. Unlike the central mix plants, the production rate is not controlled as much by the plant as by the number of trucks and charging rate per truck.

In this type of plant, all of the PCC constituents are charged into the transit trucks for mixing. Point out the key components of the plant, including the aggregate bin, conveyor, and silos. Also note the end loader that feeds aggregates to the plant where they are batched into the transit mix trucks according to the mix proportioning. The silo stores both cement and supplementary cementitious materials (SCMs) and discharges into the trucks by gravity.

These plants are capable of producing consistent and uniform PCC but additional variables must be accounted for, including the efficiency of mixing.

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Transit Mix Truck





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The photo shows a rear discharge transit mix truck. The mixing drum is visible as is the plant in the background. There are numerous variations in the configurations of these trucks, including front and rear discharge and a range of drum sizes.

Slide 59

Best Practices for Batching and Mixing



- Batching is essentially measuring the correct proportions of the components required to make a specific amount of PCC
- The batch or mix proportions are the result of certain mix design assumptions and calculations (note that this will be covered in a later lesson)
- Correct batching includes:
 - Adjustments to the amount of water added (mix water) based on aggregate moisture state
 - Admixture dosage (particularly to control entrained air content)
 - Charging the mixer in the correct sequence (adding the materials to the mixing drum in the proper order to assure uniform mixing)

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Batching PCC has been made much easier with the development of computer-controlled batching operations. The correct mix proportions (based on a specific mix design) are input into the computer along with the desired volume of PCC required (i.e. typically an 8 or 10 cy batch). The materials are weighed (cement, SCMs, and aggregates) or metered (water and admixtures) subject to the adjustments listed on the slide. The changes to the batch weights may be adjusted by the computer or by the operator depending on the level of instrumentation present (i.e. moisture probes on the aggregate feeds).

Slide 60

NRMCA Plant and Truck Certification



- The National Ready Mixed Concrete Association (NRMCA) certification program is generally regarded as the standard for ready mix operations
- Note that some agencies have developed their own certification and acceptance protocols
- We will review key components of this document in regards to both plant and truck inspection and certification
- After review of the elements of NRMCA program are presented, we will discuss your State standards and how they compare to these guidelines

 Refer to the NRMCA Guidelines, which can be found in the Resources folder.


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LESSON 8

60

The NRMCA certification program covers all aspects of the production of PCC using ready mix facilities. Note that some agencies have developed their own certification and acceptance protocols.

Slide 61


Developing an Acceptance Plan for Production Facilities Discussion





?

How does your agency's evaluation process lead to approval of a plant for production?



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Slide 62



Construction, Sampling, and Testing


- Specifications are designed to ensure minimum acceptable standards for workability, strength, and durability
- The most frequently specified parameters for fresh PCC include:
 - Slump
 - Temperature
 - Entrained air content
 - Unit weight and yield
- The most frequently specified parameters for hardened PCC include:
 - Compressive strength
 - Flexural strength
 - Permeability

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Specifications are a key element in assuring quality. We will briefly review the tests listed on the slide.

Slide 63

Sampling and Testing



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Refer to AASHTO M 157, Ready Mix Concrete, for details and limits on many of these tests for ready mix concrete.

Note that only basic information is presented for the following test methods. Please consult the appropriate test standards for details on performing the tests, recommended testing frequencies and reporting.

Specifications govern the number and timing of the tests performed on a specific project. The frequency of testing listed are intended as general guidance only.

Slide 64

Sampling Fresh Concrete



AASHTO T 141 (ASTM C172)
Sampling Freshly Mixed Concrete



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64

Take the sample at two or more regular intervals at about the middle portion of the batch. The sample should be representative of the concrete used in the project. The timing of sampling is important. Be alert for water addition.

Requirements:

- Sample size $\geq 1 \text{ ft}^3$;
- Less than 15 minutes between first and last portion of sample; and
- Sample should not be taken from first or last portion of batch discharge.

Slide 65

Slump Test

AASHTO T 119 (ASTM C143)
Slump of Hydraulic Cement Concrete



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The slump test is most useful as a measure of consistency or uniformity. High slump indicates a risk of segregation. The relationship of slump to strength and durability is unclear.

Batch-to-batch changes in slump (for constant time from batching) signal changes in materials, proportions, aggregate moisture content, temperature, or admixtures—not just a change in water content.

Timing is important—all concrete eventually has zero slump. The rate of slump loss increases with temperature and some admixtures.

Frequency of testing:

- First batch of concrete each day;
- Every 150 cy or as directed by the engineer;
- Whenever the consistency of concrete appears to vary; or
- Whenever strength-test cylinders are made at job site.

Note that for structural concrete, a test every 100 cy is typical.

In all cases, random sampling is required.


Slide 66

Temperature Measurement



AASHTO T 309 (ASTM C1064)

Temperature of Freshly Mixed Portland Cement Concrete




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66

A thermometer is used to take the temperature of fresh concrete.


- Thermometer accuracy ± 0.5 °C (± 1 °F);
- Remain in sample minimum of 2 minutes;
- 75 mm (3 in.) minimum of concrete surrounding the sensing portion; and
- Complete test within 5 minutes after obtaining the sample.

Frequency of testing:

- First batch of concrete each day;
 - Every 150 cy or as directed by the Engineer
 - Whenever a slump test is performed; or
 - Whenever strength-test cylinders are made at job site.
-
-
-


Slide 67


Density (Unit Weight) and Yield



AASHTO T 121 (ASTM C138)

Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete



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Fresh concrete is measured in a container of known volume to determine density (unit weight).

- Scale must be sensitive to 0.3% of anticipated mass of sample and container;
- Size of container varies according to the size of the aggregate, the 7-L (0.25-ft³) air meter container for up to 25 mm (1 in.) nominal max. size aggregate; 14-L (0.5 ft³) container for aggregates up to 50 mm (2 in.); and
- Container should be calibrated at least annually (ASTM C1077).

Frequency of testing:

- First batch of concrete each day;
 - Every 150 cy or as directed by the engineer;
 - Whenever a slump test is performed; or
 - Whenever strength-test cylinders are made at job site.
-
-


Slide 68

Air Content

AASHTO T 152 (ASTM C231)
Air Content of Freshly Mixed Concrete by the
Pressure Method

AASHTO T 196 (ASTM C173)
Air Content of Freshly Mixed Concrete by the
Volumetric Method

AASHTO T 121 (ASTM C138)
Density (Unit Weight), Yield, and Air Content
(Gravimetric) of Concrete



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The entrained air content can be determined in a number of ways but is most frequently tested with one of the devices pictured on this slide.

The photo on the upper right shows a pressure meter air test. This is the most commonly used device, but is not appropriate for lightweight or porous aggregates.

The photo on the bottom right shows a volumetric air test that can be used for all types of aggregates.


Frequency of testing:

- First batch of concrete each day;
- Every 150 cy or as directed by the engineer;
- Whenever a slump test is performed; or
- Whenever strength-test cylinders are made at job site.

Slide 69

Preparation of Strength Specimens

AASHTO T 23 (ASTM C31)
Making and Curing Concrete Test Specimens in the Field



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Time limit: start molding \leq 15 minutes after sampling.


Frequency of testing:

- First batch of concrete each day; or
- Every 150 cy or as directed by the engineer.

Slide 70

Curing Test Specimens

AASHTO M 201 (ASTM C511)
Mixing Rooms, Moist Cabinets,
and Water Storage Tanks Used for the Curing of
Hydraulic Cements and Concrete



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The temperature and moisture conditions are very important in terms of test results. The most representative curing approximates the conditions in the field. The photo in the upper left shows a field curing box with thermostat and heating pad for initial curing of PCC test cylinders. The photo on the lower left shows a controlled curing “moist room” in the laboratory for standard test specimens at a relative humidity of 95% to 100% and temperature of 23 ± 2 °C (73 ± 3 °F). The lab curing represents the idealized curing conditions and may not mirror actual field conditions.

Maturity monitoring of the in-place PCC is an effective way to minimize the differences between lab and field curing conditions. Use of a maturity meter and development of maturity curves relies on the relationship between time, temperature and strength.

Slide 71

Testing Compressive Strength

AASHTO T 22 (ASTM C39)
Compressive Strength of
Cylindrical Concrete Specimens



Do you think a faster loading rate results in increased or decreased strength? Why?

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The compressive strength of PCC is specified for virtually all structural applications and is commonly used for other uses as well due to the ease of sample preparation, handling and testing. The photo shows a PCC being loaded to failure to assess the unconfined compressive strength. Note that the load rate has a significant effect on the strength and is included in the test protocol.

Slide 72

Testing Flexural Strength

AASHTO T 97 (ASTM C78)
Flexural Strength of Concrete
(Using Simple Beam with Third-Point Loading)



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The flexural strength of PCC is a design input for pavement design. The third-point loading beam break, as pictured here, is used to assess that value. However, since beams are difficult to prepare and handle and even slight imperfections in the beam can result in significant strength variation, compressive strength of cylinders is often used and then correlated to flexural strength. Note that maturity testing can also be used to estimate flexural strengths.

Slide 73

Core Testing



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Cores are frequently taken from in-place pavements as a quality assurance measure for new pavements or to perform forensic analyses on deteriorated pavements. The photo on the right illustrates a split tensile test used to determine the tensile strength of PCC, as placed.

Slide 74

Core Testing



- Cores can be used to determine the following:
 - Slab thickness
 - Tensile strength
 - Compressive strength
 - Presence of adverse aggregate-related reactions
 - Hardened air content
 - Others
- Cores must be carefully drilled and extracted so as not to damage the PCC

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The information obtained for cores is highly dependent on the care used during drilling and extraction. For instance, an eccentric core bit or using too high of a down pressure during drilling can result in the formation of microcracks (thereby reducing strength).

Slide 75

Development of a Comprehensive PCC Acceptance Plan 


A comprehensive PCC acceptance plan has four major components:

- Cement
- Aggregates
- Admixtures
- Construction

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A comprehensive acceptance plan for PCC must include all of the major constituents: cement, aggregates, admixtures, and construction. In this section, we are going to develop a plan for each of these components as a group activity.


Slide 76



Example Acceptance Plan

- An acceptance plan for Portland cement would include a mill test report or certificate generated by the cement manufacturer
- An example of a mill test report is shown in your participant workbook
 - What are the key points to look for?
 - Will there be subsequent testing for verification?
 - What if there is some aspect out of compliance ?

 Who is familiar with this type of document and in what capacity is it used in your State?

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Note that there are numerous items that are tested that do not have to be covered in the plan.

Slide 77

Exercise 3: Develop a Comprehensive Acceptance Plan


- We will now develop the comprehensive acceptance plans for the four subject areas (cement, aggregates, admixtures, construction)
- Please elect a spokesperson to present your findings to the group
- Some of the key points to address in your discussion include:
 - What are the important criteria for acceptance?
 - What testing is required?
 - Who performs the tests and reviews the results?
 - What is the protocol for acceptance/rejection?
 - What is the appeal process or resubmission criteria?
 - What other factors do you consider important?

 Let's break into groups to generate a list of key points to be addressed in an acceptance plan. Take 15 minutes to formulate your plan.

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Slide 78

Learning Outcomes Review




You are now able to:

- Describe the cement acceptance standards for your State and emphasize the overall key elements of an effective cement acceptance plan
- Explain the role of water in cement hydration and why the water-cement (w/c) ratio must be carefully controlled
- Describe how aggregate properties affect the workability of plastic PCC
- Explain some of the more common effects of aggregate properties on the strength and durability of hardened PCC
- Describe the necessary elements of an acceptance plan for admixtures in your State
- Explain how your agency's evaluation process leads to approval of a plant for production
- Explain the relationship between PCC specifications and best construction practices
- Describe the necessary elements of a comprehensive acceptance plan for PCC


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Slide 2

Learning Outcomes 

By the end of this lesson, you will be able to:

- Describe the steps involved in mix design and mix proportioning using American Concrete Institute (ACI) 211.1
- Evaluate an existing mix design to ensure it meets a given set of criteria
- Describe how proportioning affects the engineering properties of Portland cement concrete (PCC)
- Relate mix proportions to distress and durability issues
- Explain the consequences of substituting materials in terms of mix performance and behavior
- Describe the most common tests used for determining the properties of plastic and hardened PCC
- Describe the tests used for determining the properties of plastic PCC and their use in controlling the quality of PCC
- Describe the tests used for determining the properties of hardened PCC and their use in controlling the quality of PCC

 This lesson will take approximately 3 hours and 30 minutes to complete.

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Slide 6

The slide is titled "ACI 211.1 Mix Proportioning" and features the HMEC logo in the top right corner. It is structured as follows:


- Three boxes at the top: "Mix Design Requirements", "Materials Characteristics", and "Production Technology".
- A dark blue bar below them labeled "Controlling Relationships".
- A central grey box titled "General trends suggested by ACI 211.1" containing four graphs showing various trends (e.g., decreasing, increasing, and leveling off).
- Below the graphs, the text "Specifics from user data and experience" is displayed.

At the bottom of the slide, there is a blue navigation bar with the following text from left to right: "U.S. Department of Transportation Federal Highway Administration", "MODULE G", "BASIC MIX DESIGN AND PROPORTIONING", "LESSON 9", and "6".

The ACI 211.1 procedure makes use of a large amount of generalized historical data in developing the relationships between the variables. Sound judgment in applying these principles is still required.


Slide 8


Calculations and Worksheets



Batch Weight/Cubic Yard	
Aggregate	nearest 10 lbs.
Cement	nearest 5 lbs.
Water	nearest 5 lbs.
Volumes/Cubic Yard	2 decimal places

- Round-off guidelines:
 - No need to be more accurate than the scales


Clear accounting/record keeping is critical.


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8

These tolerances are based on the ability of most production plants to measure or meter the individual materials.


It is important to note that depending on the specific plant configuration and the weighing and metering system, the batching tolerances may be different than those stated. For instance, some plants may require a 20 lb. tolerance for aggregates, others may be able to batch to 1 lb. increments for the cement.

Slide 9

Definitions



Terms	Definitions
Maximum aggregate size	The smallest sieve through which 100% of the sample must pass
Nominal maximum aggregate size	The smallest sieve size through which the majority of the sample passes (up to 15% can be retained)
Bulk volume of coarse aggregate	Based on the dry rodded aggregate volume and empirical data related to workability and the FM of the sand
The fineness modulus (FM) of the fine aggregate	The cumulative percent retained on the, #4, #8, #16, #30, #50, and #100 sieves/100



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Clearly state the importance of using the correct terminology as it influences the calculations going forward.


Slide 10

Example Using the Absolute Volume Method (ACI 211.1)



The absolute volume method specified by ACI 211.1 consists of eight steps, plus adjustments

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8



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MODULE G BASIC MIX DESIGN AND PROPORTIONING LESSON 9 **10**

Although it is not the only way to do a quality mix design, the ACI procedure is widely used. The goal of the following example is to show the eight basic steps and establish a baseline example to illustrate how important minor changes in proportions can be on workability, durability, and strength, for example.

These calculations will be used to generate a baseline mix that will be used throughout this lesson.

Slide 11

Step 1 of 8: Specify Required Strength



1 • The strength requirements are based on specifications and design assumptions

2

3 • Strength may be specified as compressive strength ($f'c$) or flexural strength (MR), or both

4

5

6

7

8

• **4,500 psi at 28 days**

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Keep in mind that variability exists in both materials and testing procedures. On the right side of the slide, we see an example, which will be carried out as we go through the steps.

Slide 12

Step 2 of 8: Determine Required W/C Ratio

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8


- Establish w/c based on strength and durability requirements
- The most limiting criteria is selected (lowest w/c ratio, highest strength)
- Ensure w/c ratio satisfies both the strength and durability requirements

- 4,500 psi at 28 days
- 4,500 psi required due to exposure**
- W/c ratio = 0.45**

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The next four slides show the sequence of steps to follow in determining the required strength (may be higher than specified in the mix design) and the corresponding maximum w/c ratio.

Slide 13



Requirements for Exposure Conditions

1	Exposure Condition	Maximum W/C Ratio, by Mass	Minimum Strength, f _c , psi
2	No freeze-thaw, deicers, aggressive substances	Select for strength, workability, and finishing needs	Select for structural requirements
3			
4	Concrete with low permeability, exposed to water	0.50	4,000
5			
6	Concrete exposed to freezing and thawing in a moist condition or deicers	0.45	4,500
7			
8	For corrosion protection for reinforced concrete exposed to chlorides	0.40	5,000

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The information highlighted in yellow pertains to the example we are currently working on.

Slide 14

Requirement for Concrete Exposed to Sulfates

	Sulfate Exposure	Sulfate (SO ₄) in Soil, % by Mass	Sulfate (SO ₄) in Water, ppm	Cement Type	Maximum W/C Ratio, by Mass	Minimum Strength, f'c, psi
1	Negligible	Less than 0.10	Less than 150	No special type required	—	—
2						
3	Moderate	0.10 to 0.20	150 to 1,500	II, MS, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	4,000
4						
5						
6	Severe	0.20 to 2.00	1,500 to 10,000	V, HS	0.45	4,500
7						
8	Very severe	Over 2.00	Over 10,000	V, HS	0.40	5,000


Q&A What are the exposure conditions typically encountered in your State?

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The information highlighted in yellow pertains to the example we are currently working on.

Slide 15

Relationship Between W/C Ratio and Strength

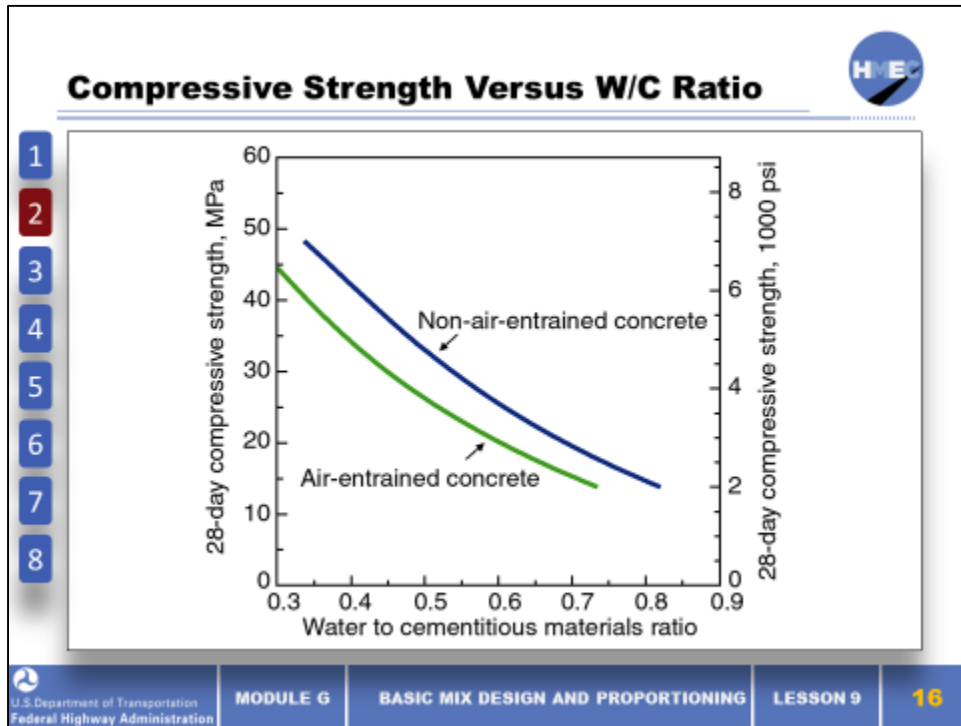


Compressive Strength at 28 Days, psi	Water-Cementitious Materials Ratio by Mass	
	Non-air-entrained Concrete	Air-entrained Concrete
7,000	0.33	—
6,000	0.41	0.32
5,000	0.48	0.40
4,000	0.57	0.48
3,000	0.68	0.59
2,000	0.82	0.74

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Strength is based on cylinders moist-cured 28 days in accordance with ASTM C31 (AASHTO T 23). Relationship assumes nominal maximum size aggregate of about 3/4 in. to 1 in.


Slide 16



Approximate relationship between compressive strength and water to cementing materials ratio for concrete using 19 mm to 25 mm (¾ in. to 1 in.) nominal maximum size coarse aggregate.

Slide 17

Step 3 of 8: Determine Aggregate Grading Requirements and Coarse Aggregate



- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

- The maximum aggregate size (MAS) depends on a number of factors:
 - Availability of materials
 - Economy
 - Placement method
 - Required workability

- 4,500 psi at 28 days
- W/c ratio = 0.45
- **MAS = 1.5 in.**
- **Nominal MAS = 1.0 in.**
- **Coarse aggregate content = 1,822 lbs./cy**


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Note that many factors are influenced by the determination of this step.

The aggregate grading (size distribution) is not specifically addressed in the ACI 211.1 procedure. However, the maximum aggregate size (MAS) and nominal MAS are the basis for a number of calculations.

Slide 18

Bulk Volume of Coarse Aggregate

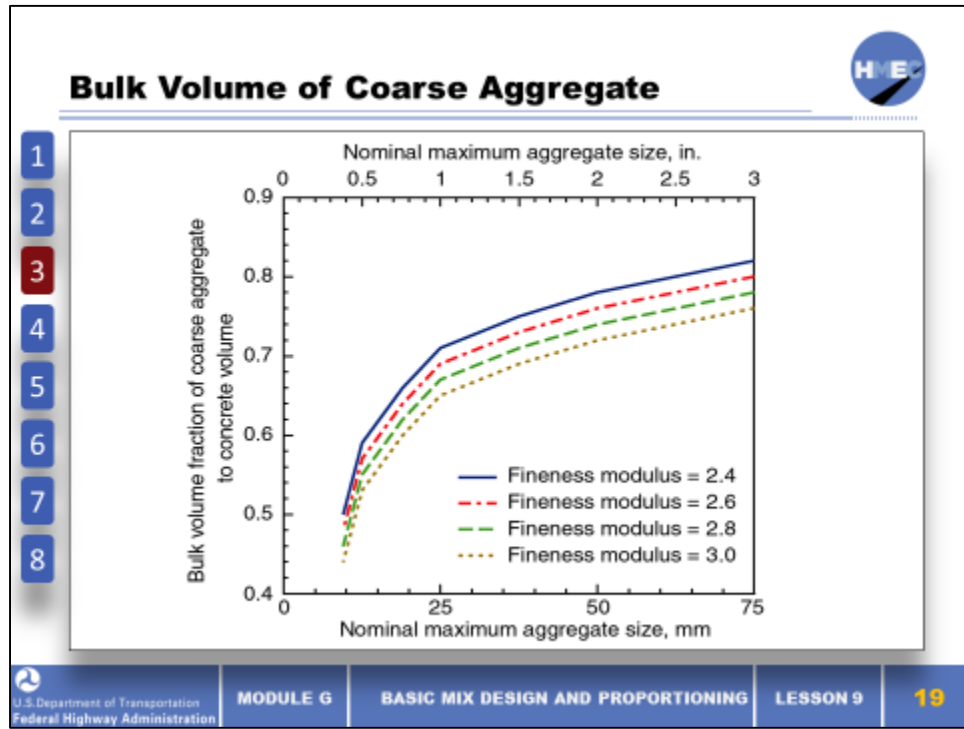


Nominal Maximum Aggregate Size (in.)	Fineness Modulus of Sand			
	2.40	2.60	2.80	3.00
$\frac{1}{8}$	0.50	0.48	0.46	0.44
$\frac{1}{4}$	0.59	0.57	0.55	0.53
$\frac{3}{8}$	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1½	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

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This value is representative of the void space in the coarse aggregates in the dry rodded state.

Slide 19



This graph shows the bulk volume of coarse aggregate per unit volume of concrete. For more workable concrete, such as may be required when placement is by pump, they may be reduced up to 10%.

Calculate the Absolute Volume of Coarse Aggregate per yd³ of Concrete

1 The bulk volume of coarse aggregate = 0.69 → $0.69 \times 27 = 18.6 \text{ ft}^3$

2

3

4 Bulk density = 98 lbs./ft³ (dry rodded) → $18.6 \times 98 = 1,822 \text{ lbs.}$

5

6

7 Relative density = 2.65 → Absolute Volume = $1,822 / (2.65 \times 62.4) = 11.02$


8 Water = 62.4 lbs./ft³ → $11.02 / 27 = 0.41$

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The bulk density and dry rodded weight were assumed in this example calculation.

Slide 21

Step 4 of 8: Establish Target Air Content



- 1
- 2
- 3
- 4**
- 5
- 6
- 7
- 8

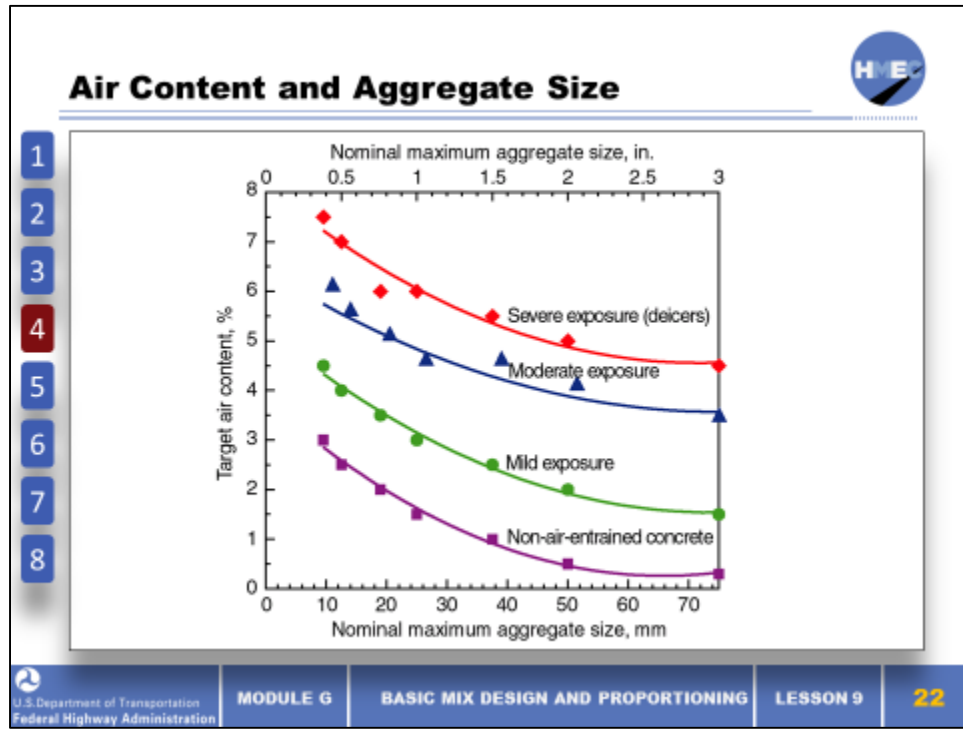
- Establish target air content based on exposure conditions and nominal maximum aggregate size

- 4,500 psi at 28 days
- W/c ratio = 0.45
- MAS = 1.5 in.
- Nominal MAS = 1.0 in.
- Coarse aggregate content = 1,822 lbs./cy
- 6.0% air**

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The target air content is based on exposure conditions and the nominal MAS.

Slide 22




The air content in job specifications should be specified to be delivered within -1 to +2 percentage points of the target value for moderate and severe exposures.


Slide 23

Step 5 of 8: Establish Target Workability 

-
-
-
-
- Target workability (in terms of slump) is based on method of placement
-
-
-

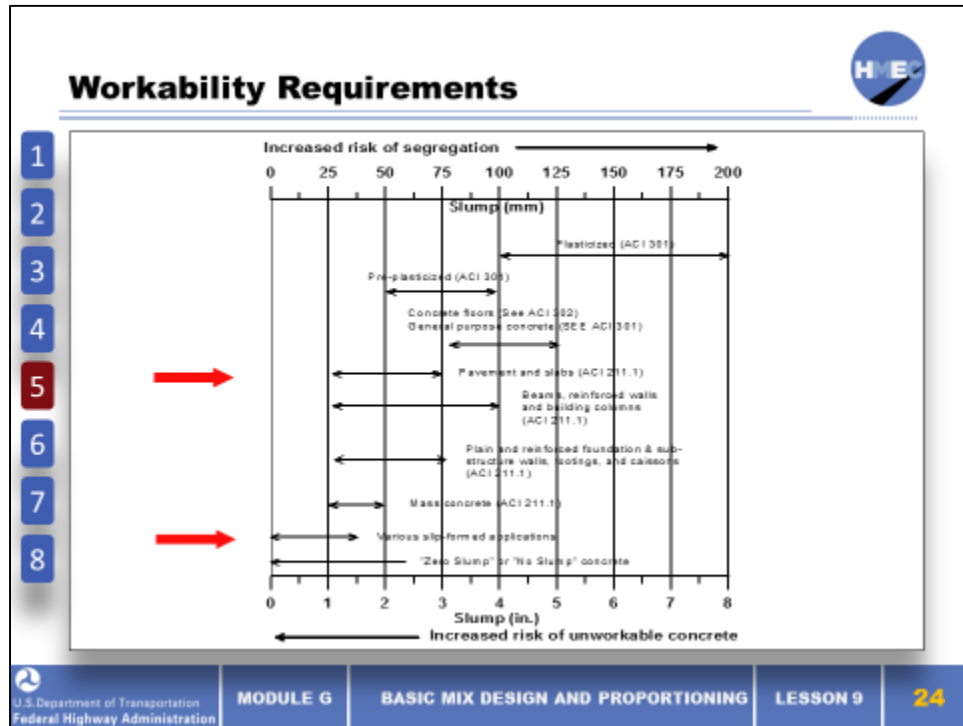
- 4,500 psi at 28 days
- W/c ratio = 0.45
- MAS = 1.5 in.
- Nominal MAS = 1.0 in.
- Coarse aggregate content = 1,822 lbs./cy
- 6.0% air
- Slump = 1.5 in.**

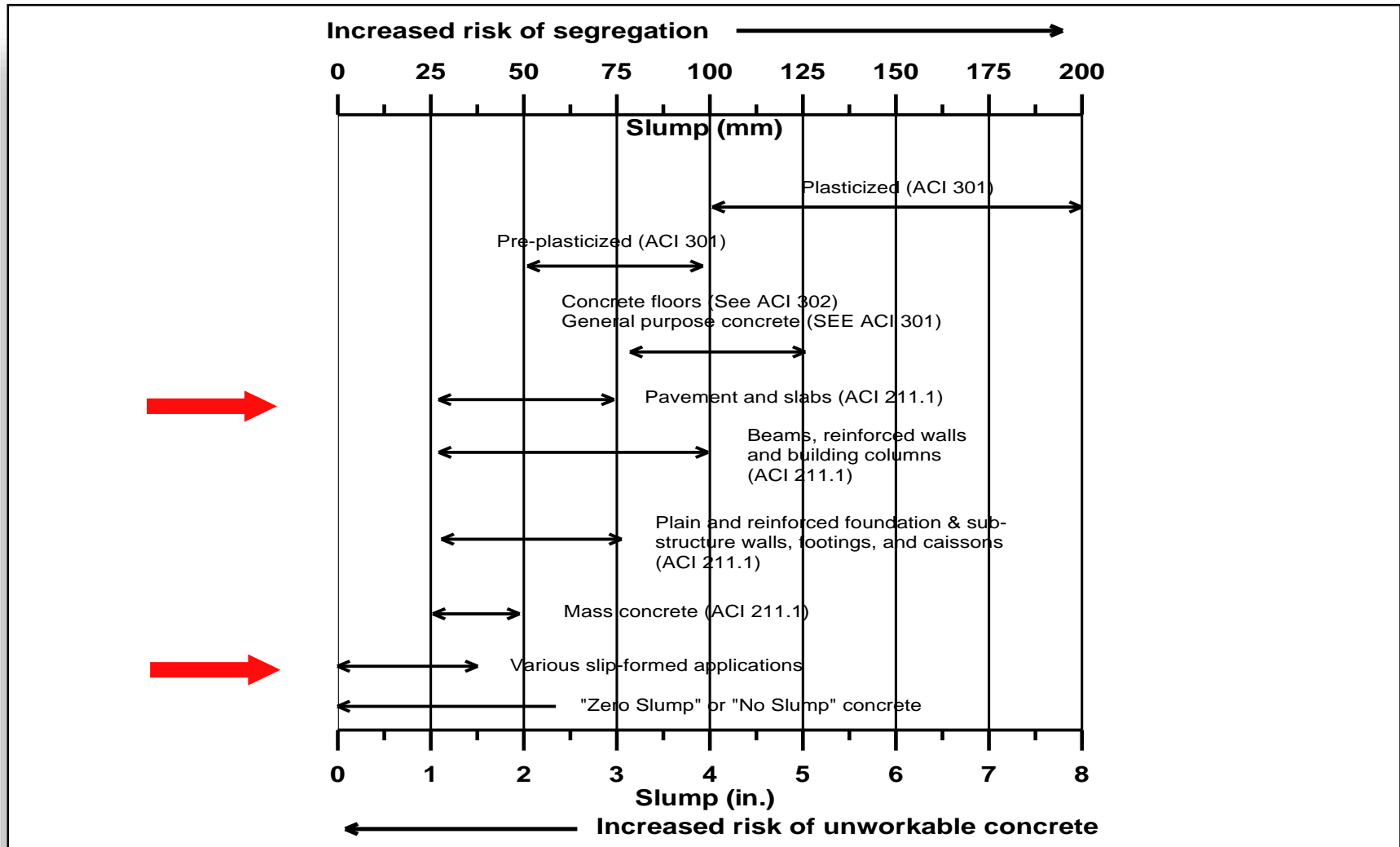
 What slump ranges do you think are appropriate for flatwork, form placement, slipform paving, and wall forms?

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MODULE G BASIC MIX DESIGN AND PROPORTIONING LESSON 9 **23**

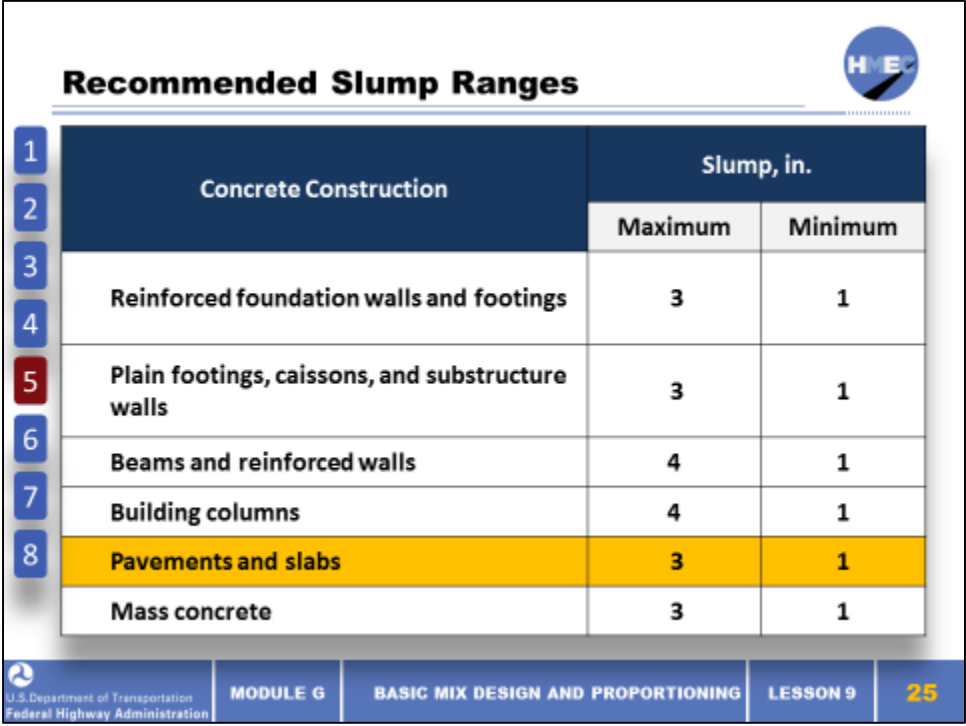
Workability is important for placement and consolidation and is a function of the method of placement and the type of placement.





The red arrows show the suggested slump ranges for the mix we are proportioning in the example.

Slide 25




Recommended Slump Ranges

Concrete Construction	Slump, in.	
	Maximum	Minimum
Reinforced foundation walls and footings	3	1
Plain footings, caissons, and substructure walls	3	1
Beams and reinforced walls	4	1
Building columns	4	1
Pavements and slabs	3	1
Mass concrete	3	1

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The example we are working on is highlighted in yellow. Maximum slump may be increased by 25 mm (1 in.) for consolidation by hand methods, such as rodding and spading. Plasticizers can safely provide higher slumps.


Slide 26

Step 6 of 8: Determine Water Requirement 

- 1
- 2
- 3
- 4
- 5
- 6**
- 7
- 8

- The amount of water to be added to the mix is a function of the nominal maximum aggregate size and required slump

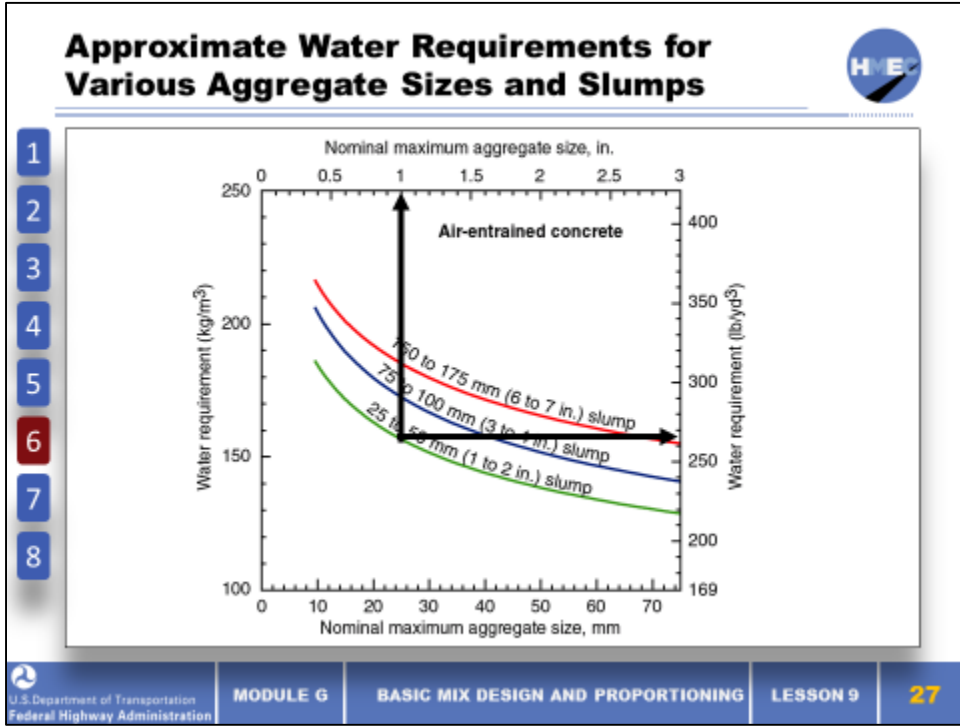
- 4,500 psi at 28 days
- W/c ratio = 0.45
- MAS = 1.5 in.
- Nominal MAS = 1.0 in.
- Coarse aggregate content = 1,822 lb./cy
- 6.0% air
- Slump = 1.5 in.
- Water content = 265 (lbs./cy)**

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The water requirement is based on the nominal MAS and the desired slump.

Slide 27




Slide 28

Step 7 of 8: Determine Cement Content



1	Cement Content =	<ul style="list-style-type: none"> • 4,500 psi at 28 days • W/c ratio = 0.45 • MAS = 1.5 in. • Nominal MAS = 1.0 in. • Coarse aggregate content = 1,822 lbs./cy • 6.0% air • Slump = 1.5 in. • Water content = 265 lbs./cy • Cement content = 589 lbs./cy
2		
3	= $\frac{\text{Required Water Content}}{\text{Water-Cement Ratio}}$	
4		
5	= $\frac{265 \text{ lb./yd}^3 \text{ water}}{0.45 \text{ w/c ratio}}$	
6		
7		
8	= 589 lb. cement per yd³ of concrete	

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This slide shows the determination of the cement content and is based on the previously determined w/c ratio and the total water content.

Slide 29

Minimum Cementing Materials Content for Flatwork


	Nominal Maximum Size of Aggregate, in.	Cementing Materials, lbs./yd ³
1		
2		
3		
4	1½	470
5	1	520
6	¾	540
7	½	590
8	¾	610

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Cementing materials quantities may need to be greater for severe exposure. For example, for deicer exposures, concrete should contain at least 335 kg/m³ (564 lbs./yd³) of cementing materials.

Slide 30

Step 8 of 8: Determine Fine Aggregate Content



- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8**

- Determining the fine aggregate content is based on the previous calculations for volume of water, coarse aggregate, entrained air, and cement


- 4,500 psi at 28 days
- W/c ratio = 0.45
- MAS = 1.5 in.
- Nominal MAS = 1.0 in.
- Coarse aggregate content = 1,822 lbs./cy
- 6.0% air
- Slump = 1.5 in.
- Water content = 265 lbs./cy
- Cement content = 589 lbs./cy
- **Fine aggregate content = 1,176 lbs./cy**

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The final component in the PCC is the fine aggregate. The following slide illustrates the determination of the fine aggregate content and is based on previously determined values of all of the other components.

Slide 31

Absolute Volume Computation for Fine Aggregate Content




1			Water	=	$\frac{265}{1 \cdot 62.4}$	=	4.25 ft ³
2							
3			Coarse Aggregate	=	$\frac{1822}{2.65 \cdot 62.4}$	=	11.02 ft ³
4							
5			Air	=	$\frac{6.0 \cdot 27}{100}$	=	1.62 ft ³
6							
7							Subtotal = 19.89 ft³
8							Fine Aggregate Volume = 27.00 – 19.89 = 7.11 ft³
							Fine Aggregate Mass = 7.11 • 2.65 • 62.4 = 1,176 lbs.

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Admixture dosages are too small to account for in the volumetric method, but play a vital role in the mix performance.

Slide 32

Mix Proportioning Example Summary 

- The following weights (mass) of materials form the basis for a trial batch

Coarse Aggregate	=	1,822 lbs./cy
Fine Aggregate	=	1,176 lbs./cy
Cement	=	589 lbs./cy
Water	=	265 lbs./cy
Air Content	=	6%

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MODULE G BASIC MIX DESIGN AND PROPORTIONING LESSON 9 **32**

The long-standing relationship of three parts coarse aggregate, two parts fine aggregate and one part cement (by volume) can be used to get a rough idea as to the validity of your calculations.

Slide 33

Trial Batch Preparation



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




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We now have the initial proportions of a trial batch. Remember that the job is not done until the batch is tested and adjusted.


We don't have the technology to account for surface shape, texture, grading, dust, fines, and to predict workability of a mix just based on calculations. We also have to watch for incompatibility.

Slide 34


Adjusting Properties



- The most typical mix proportion adjustments are made to control or affect:
 - Workability
 - Stiffening/setting
 - Bleeding
 - Air void system
 - Unit weight
 - Others



What adjustments would likely be the most effective in modifying these properties?



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Slide 35

Exercise 1: Recalculating Mix Proportions 

- Using the baseline example, each group will vary one parameter and recalculate the mix proportions
- We will then record the differences on the flip chart and discuss the results
 - Group 1: Change MAS to 1 in., NMAS to 1/2 in.
 - Group 2: Change FM of sand to 3.00
 - Group 3: Change required strength to 6,000 psi
 - Group 4: Change to non-air entrained

 Let's break up into groups for an activity. Vary one parameter and recalculate the mix proportions.

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Slide 36


Historical Mix Design and Proportioning Data




- Historical data are often used in determining the mix proportions for “routine” projects
- If the cement type, aggregates, admixtures, and the other PCC mix components and design criteria are the same, historical mix data should be valid but may require adjustment
- Cataloged mix designs are often used by ready mix plants and central mix plants, but on a much more limited basis
- The benefit of using historical mix designs and proportioning is that the performance is known to some extent (unless significant changes to proportions or use are made)

Slide 37


Validation to Meet Current Standards



- The performance of cataloged mixes is assumed to be similar to past use, assuming no substantial changes to materials or production have been made
- However, changes typically do occur and it is generally required that mix designs and proportions be re-evaluated to check compliance with new criteria



Do you rely on historical or cataloged mix designs versus developing new mixes?

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Validating or Repurposing an Existing Mix





- Assume that a cataloged 4,500 psi PCC mix has been used for a number of years in above-ground structures (retaining walls)
- The historical performance of this mix has been generally good
- We are now intending on using this mix for a pavement that will be subjected to both high sulfates in the groundwater and exposure to deicing salts
- You are tasked with determining suitability
- In order to simplify the process, it is necessary to know the original assumptions for exposure and the procedure used to determine proportions

Slide 39

Re-evaluation of Baseline Mix

- Based on the new exposure conditions (severe sulfate exposure), the revised w/c ratio will be lowered from the current 0.45 to 0.40
- Are there other changes that will need to be evaluated?
 - Slump
 - Air
 - Others
- What impact does this have on the mix proportions?




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Slide 40



Requirements for Exposure Conditions

Exposure Condition	Maximum W/C Ratio, by Mass	Minimum Strength, f'_c , psi
No freeze-thaw, deicers, aggressive substances	Select for strength, workability, and finishing needs	Select for structural requirements
Concrete with low permeability, exposed to water	0.50	4,000
Concrete exposed to freezing and thawing in a moist condition or deicers	0.45	4,500
For corrosion protection for reinforced concrete exposed to chlorides	0.40	5,000


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Sulfate Exposure	Sulfate (SO ₄) in Soil, % by Mass	Sulfate (SO ₄) in Water, ppm	Cement Type	Maximum W/C Ratio, by Mass	Minimum Strength, f'c, psi
Negligible	Less than 0.10	Less than 150	No special type required	—	—
Moderate	0.10 to 0.20	150 to 1,500	II, MS, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	4,000
Severe	0.20 to 2.00	1,500 to 10,000	V, HS	0.45	4,500
Very severe	Over 2.00	Over 10,000	V, HS	0.40	5,000

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Note the lower w/c requirement and the increased strength due to the more severe sulfate exposure.

Slide 42


Relationship Between W/C Ratio and Strength



Compressive Strength at 28 Days, psi	Water-Cementitious Materials Ratio by Mass	
	Non-air-entrained concrete	Air-entrained concrete
7,000	0.33	—
6,000	0.41	0.32
5,000	0.48	0.40
4,000	0.57	0.48
3,000	0.68	0.59
2,000	0.82	0.74



Based on the revised mix, what is the appropriate value for the w/c ratio?



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Slide 43



Recommended Slump Ranges

Concrete Construction	Slump, in.	
	Maximum	Minimum
Reinforced foundation walls and footings	3	1
Plain footings, caissons, and substructure walls	3	1
Beams and reinforced walls	4	1
Building columns	4	1
Pavements and slabs	3	1
Mass concrete	3	1

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The recommended slump range for pavements also has not changed, as shown by the highlighted portion of this slide.

Slide 44

Discussion: Baseline Mix and New Exposure Conditions



- Is the w/c ratio for the baseline mix adequate for the new exposure conditions?
- Is the strength adequate for the stated conditions?
- What changes could be done to make the baseline mix suitable?



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Slide 45

Effects of Proportioning on the Engineering Properties of PCC




- Each of the eight primary steps listed in the ACI 211.1 procedure can affect the engineering properties of PCC, including:
 - Workability
 - Shrinkage
 - Permeability
 - Strength
 - Others

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Slide 46

Workability



- Workability requirements are based on the method and type of placement (i.e., heavily reinforced walls have significantly different requirements than slipform pavements)
- Based on previous lessons, we know that workability is influenced in large part by the following factors:
 - Cement (or cementitious materials) content
 - W/c ratio
 - Aggregate size and combined grading
 - Admixtures


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Emphasize that without adequate workability, effective placement, and consolidation are difficult, if not impossible, to achieve.


Slide 47

Shrinkage

- Shrinkage is not expressly considered in the ACI 211.1 procedure, although several of the steps effect this parameter
- Shrinkage is a function of the paste content and characteristics but is primarily controlled by the overall water content







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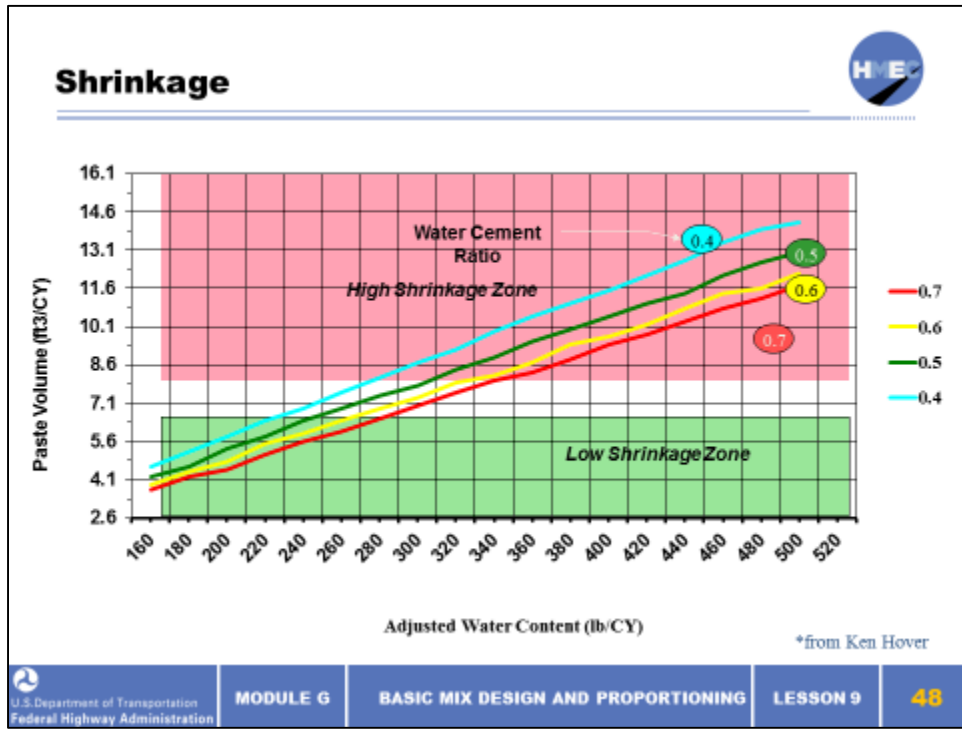
LESSON 9

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Shrinkage is not directly considered in ACI 211.1. However, the shrinkage is affected by the cement content, w/c ratio, water content, and aggregate volume—all of which are accounted for in mix design.

It is important to note that the mix design and proportioning should result in a mix that is resistant to shrinkage cracking. However, there are many factors that also influence shrinkage cracking including admixtures, curing, evaporation rate, and ambient conditions.


Slide 48



Slide 49

Permeability (Water)

- Permeability is not expressly considered in the ACI 211.1 procedure, although several of the steps affect this parameter
- Permeability is a function of the paste content and characteristics but is primarily controlled by the w/c ratio



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The permeability of PCC is a primary durability-related property and is implicitly considered in the paste content and w/c ratio.

The photo shows a surface resistivity device being used to measure the hardened PCC permeability.

Slide 50

Strength

- An assumed strength is the initial step in determining the mix proportions according to ACI 211.1



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The strength is directly considered in the ACI procedure.

Slide 51

Effects of Batching Tolerances

- Batching tolerances are designed to account for differences in the weighing and metering precision of PCC production plants
- The scales, load cells, aggregate gates, conveyor systems, and other components found in PCC plants cannot be precisely controlled due to mechanical considerations and the types of materials we are batching

Batch Weight / Cubic Yard	
Aggregate	nearest 10 lbs.
Cement	nearest 5 lbs.
Water	nearest 5 lbs.
Volumes/Cubic Yard	2 decimal places

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The batching tolerances shown (previously shown in this lesson) are not sufficient to cause substantial changes in any of the mix properties we have considered. The effects on the performance characteristics for fresh and hardened PCC are minimal based on the tolerances shown.

Slide 52


Group Activity

- What are the effects of mix proportions on the following PCC properties?
 - Strength
 - Durability
 - Dimensional stability
 - Others you may want to discuss

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Mix Proportioning Effects on Durability


- The durability of PCC is a function of the mix design and proportioning, materials, and construction practices
- Note that aggregate characteristics (reactivity), cement characteristics, and construction practices are not addressed in the mix proportioning
- In this section, we are going to look at the effects of the following mix parameters on durability:
 - Cement content
 - Supplemental cementitious materials content
 - Water-cementitious material (w/cm) ratio
 - Aggregate/paste volume
 - Entrained air content and structure

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The variables listed on this slide are very important in achieving adequate durability.

Slide 54

Cement Content and Durability



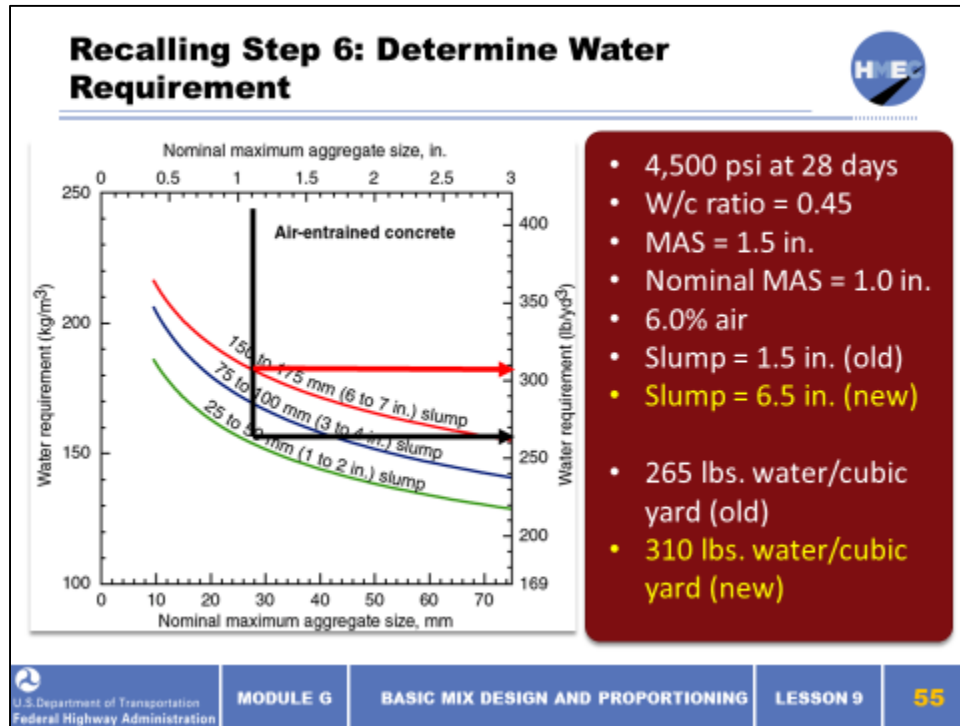
- In order to illustrate the effects of changing cement content, let's look at the baseline mix developed earlier:
 - According to the ACI procedure, the cement content is a function of desired slump and the nominal maximum aggregate size
 - For this example, assume that we are going to hold the aggregate size constant but change the slump to 6–7 in. as might be required for certain placement conditions
 - Note that we are not going to use a superplasticizer, but instead increase the water content

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Lower cement contents generally result in a more economical mixes with improved durability and dimensional stability.

To illustrate the point, we are going to modify the original baseline mix proportions, as shown in the following slides.


Slide 55



We are increasing the slump of the PCC to 6–7 in. without the use of a water reducer. The new water requirement for the increased slump is approximately 310 lbs./cy versus 265 lbs./cy for the baseline mix.

Slide 56

Recalling Step 7: Determine Cement Content



Cement Content =

$$= \frac{\text{Required Water Content}}{\text{Water-Cement Ratio}}$$
$$= \frac{310 \text{ lb./yd}^3 \text{ water}}{0.45 \text{ w/c ratio}}$$

= 689 lb. cement per yd³ of concrete

- 4,500 psi at 28 days
- W/c ratio = 0.45
- MAS = 1.5 in.
- Nominal MAS = 1.0 in.
- 6.0% air
- Slump = 6.5 in.
- 310 lbs. water


- 589 lbs. cement (old)
- **689 lbs. cement (new)**

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Based on the new water requirement and the w/c ratio (which did not change since the strength didn't change), 689 lbs. of cement/cy are now required versus 589 lbs./cy for the baseline mix.

Slide 57


Absolute Volume Computation for Fine Aggregate Content			
Water	=	$\frac{310}{1 \cdot 62.4} = 4.97 \text{ ft}^3$	
Coarse Aggregate	=	$\frac{1930}{2.65 \cdot 62.4} = 11.67 \text{ ft}^3$	
Air	=	$\frac{6.0 \cdot 27}{100} = 1.62 \text{ ft}^3$	
Cement	=	$\frac{689}{3.15 \cdot 62.4} = 3.50 \text{ ft}^3$	
Subtotal = 21.76 ft³			
Fine Aggregate Volume = 27.00 - 21.76 = 5.24 ft³			
Fine Aggregate Mass = 5.24 • 2.65 • 62.4 = 866 lbs.			

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The water and cement changed but the air and coarse aggregates did not. In order to compensate, the fine aggregate will have to change since we are dealing with a 1 cy fixed volume. The revised amount of fine aggregate is shown on this slide.

Slide 58

Mix Proportioning Example Summary



- The following weights (mass) of materials form the basis for a trial batch

Coarse Aggregate	=	1,930 lbs./cy	vs.	1,930 lbs./cy
Fine Aggregate	=	1,068 lbs./cy	vs.	866 lbs./cy
Cement	=	589 lbs./cy	vs.	689 lbs./cy
Water	=	265 lbs./cy	vs.	310 lbs./cy
Air Content	=	6%	vs.	6%

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Slide 59



Group Discussion

- What are the implications of the changed mix proportions in terms of the following?
 - Economy
 - Segregation potential
 - Bleed water
 - Overall durability
 - Permeability
 - Other factors you think are important

 Let's have a discussion and answer some questions.

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Slide 62


W/C Ratio and Durability



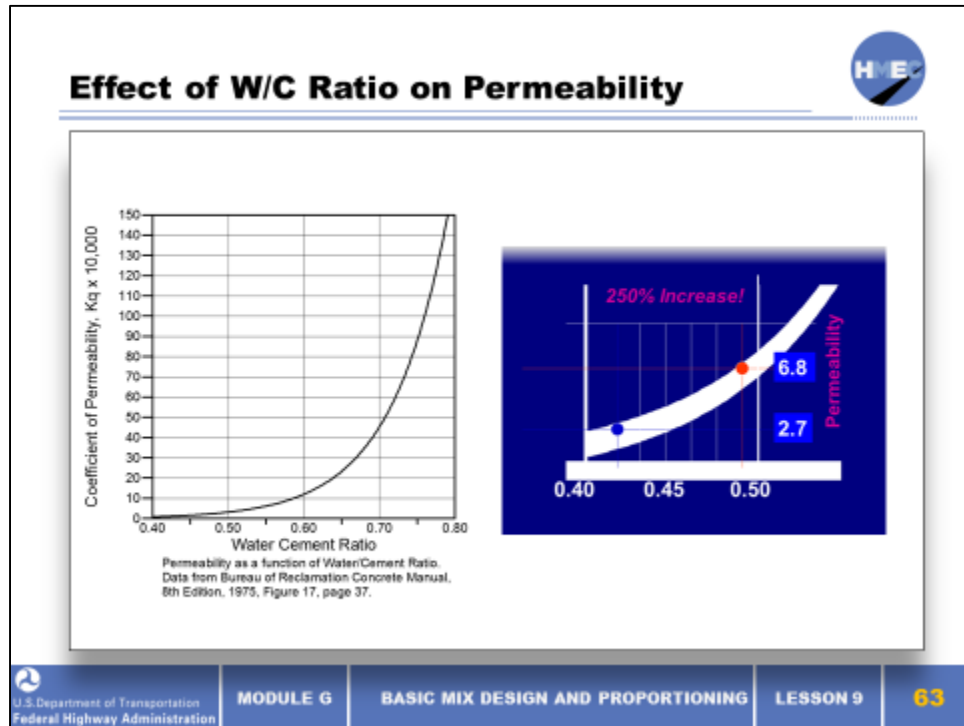
- The w/cm ratio is treated as the w/c ratio in the ACI procedure
- Step 2 of the mix proportioning process is the selection of the w/c ratio based on a target strength requirement
- In terms of durability considerations, the durability is closely linked to the permeability of the PCC (i.e. lower permeability equates to improved durability)
- Note that the water requirements for the mixes containing a large amount of SCMs may be different due to the particle size distribution and increased surface area



The w/c ratio is perhaps the single most important parameter controlling the strength and durability of PCC.


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Slide 63



Permeability is a key factor in durability as it limits the amount of moisture and damaging chemicals that can intrude into the hardened PCC. Note that w/c ratios above 0.55 are unusual for transportation facilities work. Therefore the graph on the right is more indicative of the actual effect.

Slide 65




Aggregate/Paste Volume and Durability

- In general, aggregates are the most dimensionally stable and durable component in the hardened PCC
- The previous example, where we varied the slump, illustrates the effect of increasing the paste volume

Coarse Aggregate	=	1,930 lbs./cy	vs.	1,930 lbs./cy
Fine Aggregate	=	1,068 lbs./cy	vs.	866 lbs./cy
Cement	=	589 lbs./cy	vs.	689 lbs./cy
Water	=	265 lbs./cy	vs.	310 lbs./cy
Air Content	=	6%	vs.	6%


- The baseline paste/aggregate ratio was .28 while the increased slump mix was .36
- The increase in the paste/aggregate ratio will result in decreased dimensional stability, increased permeability, decreased durability, and increased cracking potential


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Compare the cement and water content in particular. As a rule, lowering the paste/aggregate ratio is desirable.

Slide 66



Entrained Air and Durability


- The target entrained air content of a mix based on ACI 211.1 (Step 4) is a function of aggregate size and exposure conditions and typically ranges from 5 to 7%
- Increasing the entrained air content has the effect of decreasing strength but improving durability (to a point)
- Reducing the entrained air content has the effect of increasing the fine aggregate content and therefore effects workability in addition to durability and strength

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Slide 67


Absolute Volume Computation for Fine Aggregate Content

Water	= $\frac{310}{1 \bullet 62.4}$	= 4.97 ft ³
Coarse Aggregate	= $\frac{1930}{2.65 \bullet 62.4}$	= 11.67 ft ³
Air	= $\frac{6.0 \bullet 27}{100}$	= 1.62 ft ³
Cement	= $\frac{689}{3.15 \bullet 62.4}$	= 3.50 ft ³
Subtotal = 21.76 ft³		
Fine Aggregate Volume = 27.00 - 21.76 = 5.24 ft³		
Fine Aggregate Mass = 5.24 • 2.65 • 62.4 = 866 lbs.		


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Admixture dosages are too small to account for in the volumetric method, but they play a vital role in the mix.

Slide 68

Group Discussion 

- We have discussed a number of aspects of changing the mix proportions to achieve the higher required slump

Coarse Aggregate	=	1,930 lbs./cy	vs.	1,930 lbs./cy
Fine Aggregate	=	1,068 lbs./cy	vs.	866 lbs./cy
Cement	=	589 lbs./cy	vs.	689 lbs./cy
Water	=	265 lbs./cy	vs.	310 lbs./cy
Air Content	=	6%	vs.	6%

 What other steps could we have taken to increase slump? Are there other aspects of the changed mix you would like to discuss?

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Adding superplasticizer to increase slump is generally less expensive than adding cement and doesn't have the downsides of increasing paste content.

Slide 69


Implications of Substituting Materials

- Cement:
 - Substituting one type of cement for another does not have an effect on the mix proportioning calculations
 - Depending on the fineness and relative proportion of the compounds in the cement, set times, rate of strength gain, ultimate strength, and reactivity may be significantly impacted
- Cement manufacturer:
 - Cement manufacturers all produce cements to the same standards; however, significant variations may exist due to the processing
 - Mineralogical differences in the raw materials and changes in the kiln and final processing of the clinker can produce variations in the four primary cement compounds
 - Finally, differences in grinding (Blaine fineness) can alter the hydration rate and set time


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The impact of substituting materials on which a specific mix proportioning is based may have virtually no effect to completely changing the mix characteristics. The only sure way to access changes is to perform trial batches with the new materials.

Slide 70

Implications of Substituting Materials 


- **Water:**
 - Differences in water can affect set time and rate of hydration due to dissolved minerals or the presence of organic compounds




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Implications of Substituting Materials 

- Aggregate source:
 - The aggregate source can result in similarly graded aggregates that vary greatly in terms of mineralogy, potential reactivity, and durability-related issues
- Aggregate gradation:
 - The aggregate gradation (MAS, NMAS, and FM of the sand) has a large impact on the mix proportioning
 - The combined gradation also has a significant effect on the properties of the fresh concrete (workability, finishability) and the properties of the hardened PCC (strength, durability)

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Changing aggregate gradation can have a very significant impact on water requirements and workability.

Slide 72

Implications of Substituting Materials


- Aggregate mineralogy:
 - Aggregate mineralogy is a primary contributor to alkali-aggregate reactivity
 - Changed aggregate sources may result in changes to mineralogy
 - It is highly recommended that the aggregate mineralogy be verified prior to use




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Slide 73

Implications of Substituting Materials



- Admixture performance:
 - The performance of admixtures is highly dependent on the mix characteristics and the paste chemistry (cement, SCMs, admixtures, and water)
 - Changing admixture types or manufacturers may result in significantly different performance and effectiveness of the admixtures
- Admixture interaction:
 - As previously mentioned, the chemistry of the paste is the key to admixture performance and interaction between admixtures
 - Admixtures are added to the mix separately to limit the amount of interaction; however, it can still occur and changes to admixtures need to be verified by trial batching

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Changing one or more admixture types or manufacturers may lead to incompatibility due to changes in chemistry of the paste system.

Admixture interaction can be a non-issue or it can diminish the effects of one or more of the admixtures.


Point out that concrete mixes should be reviewed and potentially tested anytime there is a source change for cement, aggregates or admixtures.


Slide 74




Group Discussion

- What are some potential effects of substituting each of the following?
 - Cement
 - SCM
 - Admixtures
 - Aggregates




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Determining the Properties of Fresh PCC 

- The properties of fresh PCC should be assessed in order to determine if the mix design and proportioning criteria have been met
- In Lesson 8, we discussed the tests that are required to determine the following parameters:
 - Slump
 - Entrained air content
 - Unit weight and yield
 - Temperature
- These tests will be performed in the laboratory session
- The appropriate AASHTO and/or ASTM test specification designations should be reviewed prior to your laboratory visit


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These tests will be performed in the laboratory session and it is suggested you refer back to Lesson 8 for the appropriate ASTM or AASHTO specification.

Slide 76

Determining the Properties of Hardened PCC 

- The properties of hardened PCC should be assessed in order to determine if the mix design and proportioning criteria have been met
- In Lesson 8, we discussed the following tests:
 - Compressive strength
 - Flexural strength
- We will now look at a number of other tests that may be performed on hardened PCC to determine specific properties related primarily to strength and durability
- These tests will be performed in the laboratory session
- The appropriate AASHTO and/or ASTM test specification designations should be reviewed prior to your laboratory visit

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The properties of the hardened PCC are of great importance to in-service performance. The compressive and flexural strength tests have already been covered and we will now focus our attention on numerous other characterization tools.

Slide 77

Air Void System in Hardened PCC

- The hardened air void system can be assessed by:
 - ASTM C457, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
- This method is used to determine the bubble size distribution and the spacing factor of the entrained air in hardened PCC




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The bubble sizes, distribution, and spacing can all be determined with this test. This procedure is often used in forensic studies of distressed PCC.

Slide 78

Freeze-Thaw Resistance of Hardened PCC 

- The freeze-thaw resistance of hardened PCC can be assessed by:
 - AASHTO T 161 (ASTM C666), Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing
 - This method is used to determine the resistance to degradation of PCC due to rapid freeze-thaw cycling




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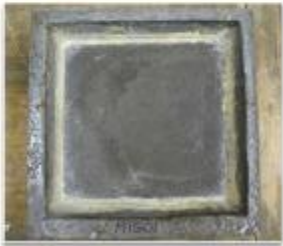

This test is suggested for new mix designs subjected to freeze-thaw cycles.


Slide 79

Scaling Resistance of Hardened PCC



- The scaling resistance of hardened PCC can be assessed by:
 - ASTM C672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
- This method is used to determine the resistance to scaling of horizontal surfaces of hardened PCC subjected to freeze-thaw cycling in the presence of deicing salts




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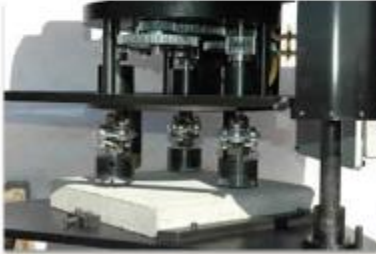
Scaling is oftentimes due to over-finishing, lack of adequate curing, and other construction practices. This test, however, will provide information regarding the material behavior assuming proper construction practices are followed.


Slide 80

Abrasion Resistance of Hardened PCC



- The scaling resistance of hardened PCC can be assessed by:
 - ASTM C779, Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces
 - ASTM C944, Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method





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The elastic modulus value is an important design variable for both structures and pavements. Although this value is often assumed based on correlation to compressive strength, testing new mixes is desirable.


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Modulus of Elasticity of Hardened PCC

- The modulus of elasticity of hardened PCC can be assessed by:
 - ASTM C469, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression



 **Q&A** Is this test performed in your State labs?


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Federal Highway Administration**MODULE G****BASIC MIX DESIGN AND PROPORTIONING****LESSON 9****81**

The elastic modulus value is an important design variable for both structures and pavements. Although this value is often assumed based on correlation to compressive strength, testing new mixes is desirable.

Slide 82

Creep of Hardened PCC

- The creep of hardened PCC can be assessed by:
 - ASTM C512, Standard Test Method for Creep of Concrete in Compression



(a)


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The creep, or long-term deformation, under load is important in structural analysis. The long-term creep apparatus is shown on the left while short-term creep testing is shown on the right.

Slide 83

Chloride Penetration of Hardened PCC

- The chloride penetration of hardened PCC can be assessed by:
 - AASHTO T 259, Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration




Is this test performed in your State labs?

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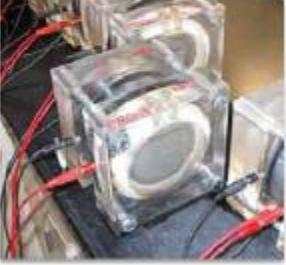
This test is slower to perform than other tests in determining chloride penetration.

Slide 84

Rapid Chloride Permeability of Hardened PCC



- The permeability of hardened PCC can be assessed by:
 - AASHTO T 277 (ASTM C1202), Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

?
Q&A
Is this test performed in your State labs?

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This test can be used to determine this property for new mixes.

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Surface Resistivity of Hardened PCC 

- The surface resistivity of hardened PCC can be determined by:
 - AASHTO TP 95, Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration




 Is this test performed in your State labs?

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The surface resistivity is another test procedure aimed at determining chloride ion penetration in hardened PCC.


Slide 86

Rebound Testing of Hardened PCC



- The compressive strength of PCC can be estimated by use of the Schmidt hammer
- This device measures the surface hardness that can be used to estimate strength through a correlation with the rebound of the hammer or piston



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This apparatus measures the surface hardness of PCC, which is then correlated to strength. Testing with this device is very quick, although there are many parameters that affect its accuracy, including surface finish, PCC moisture, and aggregates. This test is not used for acceptance testing and is typically used for forensic analysis.

Slide 87

Penetration Resistance of Hardened PCC

- The penetration resistance of hardened PCC can be determined by:
 - ASTM C803, Standard Test Method for Penetration Resistance of Hardened Concrete




Q&A Is this test performed in your State labs?

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MODULE G BASIC MIX DESIGN AND PROPORTIONING LESSON 9 87


This test is not used for acceptance testing and is typically used for forensic analysis.


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Ultrasonic Pulse Velocity of Hardened PCC 

- The ultrasonic pulse velocity of hardened PCC can be determined by:
 - ASTM C597, Standard Test Method for Pulse Velocity Through Concrete



 Is this test performed in your State labs?

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MODULE G BASIC MIX DESIGN AND PROPORTIONING LESSON 9 88

This test is not used for acceptance testing and is typically used for forensic analysis.

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Pullout Strength of Hardened PCC

- The pullout strength of concrete can be determined by:
 - ASTM C900 Standard Test Method for Pullout Strength of Hardened Concrete



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This test is not used for acceptance testing and is typically used for forensic analysis.

Maturity of Hardened PCC


- The maturity of hardened PCC can be determined by:
 - AASHTO T 325 (ASTM C1074), Standard Method of Test for Estimating the Strength of Concrete in Transportation Construction by Maturity Tests





Is this test performed in your State labs?


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Maturity Monitoring

- The concrete maturity method is a technique that accounts for the effects of time and temperature on the strength development of in-place concrete
- Maturity monitoring provides a procedure for estimating concrete strength in relation to time and temperature from very early ages
- The maturity relationship can be developed with cylinders or beams for virtually any type of PCC mix
- The overview presented in this lesson is greatly abbreviated and you are encouraged to read the ASTM C1074 procedure or consult the manufacturer’s literature for complete details

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Maturity monitoring (ASTM C1074) provides a procedure for estimating concrete strength in relation to time and temperature from very early ages (less than 1 day). The maturity relationship can be developed with cylinders or beams (compressive strength or flexural strength) for virtually any type of PCC mix.

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Advantages of Maturity

- Provides instant predictions of in-place strength
- Reduces cost and time
- Not operator dependent
- Not specimen dependent
- Accurate, efficient, and consistent
- Simple test method
- Portable equipment
- Field implementation of the concept and procedures is simple
- Ensures that strength of concrete meets specifications
- Applicable to field and lab specimens regardless of their shape
- The pavement or structure can be opened to loading at the optimal time based on maturity readings


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Limitations of Maturity

- Maturity measures only time and temperature, so other factors that could affect strength are not considered
- The PCC mix proportions and materials being monitored cannot deviate from the ones used to develop the strength-maturity relationship, such as:
 - Brand or type of cement
 - Source and type of fly ash
 - Source of aggregates
 - Water to cement ratio
- Maturity does not directly measure concrete strength
- Maturity does not eliminate test breaks
- It is important to note that while maturity is a very useful tool for early loading considerations, it does not reduce the need for adequate curing for both continued strength development and durability

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Maturity does not measure concrete strength, it estimates it. Maturity does not eliminate test breaks, but it can significantly reduce the number required. Maturity is most applicable to predicting the strength of the concrete over the early ages of the concrete while hydration is still progressing.


It is important to note that while maturity is a very useful tool for early loading considerations, it does not reduce the need for adequate curing for both continued strength development and durability.


Slide 94

Learning Outcomes Review

You are now able to:

- Describe the steps involved in mix design and mix proportioning using ACI 211.1
- Evaluate an existing mix design to ensure it meets a given set of criteria
- Describe how proportioning affects the engineering properties of PCC
- Relate mix proportions to distress and durability issues
- Explain the consequences of substituting materials in terms of mix performance and behavior
- Describe the most common tests used for determining the properties of plastic and hardened PCC
- Describe the tests used for determining the properties of plastic PCC and their use in controlling the quality of PCC
- Describe the tests used for determining the properties of hardened PCC and their use in controlling the quality of PCC





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Slide 1

The slide features a blue and black color scheme. In the top left, the ILT logo is displayed. To its right, the HMEC logo is prominently shown, with 'HMEC' in large, bold letters and 'Highway Materials Engineering Course' in a smaller font below it. Underneath the HMEC logo, the text 'Lesson 10: Reinforcing and Corrosion' is visible. A circular inset image shows two construction workers in hard hats and safety vests working with a large piece of rebar. Below this image, the text 'Portland Cement Concrete (PCC)' is written. In the bottom left corner, the U.S. Department of Transportation Federal Highway Administration logo is present. On the right side of the slide, the word 'MODULE' is positioned above a large, bold letter 'G'. The background consists of a solid blue area on the right and a black area on the left, separated by a vertical line.


Slide 2




Learning Outcomes

By the end of this lesson, you will be able to:

- Compare reinforcement types and the appropriate uses of each
- Describe the primary reasons for corrosion of steel in PCC
- Relate mix design properties to corrosion potential
- Describe the selection of reinforcement types based on environmental conditions and corrosion potential
- Recommend an appropriate corrosion mitigation technique for a given scenario
- Describe the necessary elements for an acceptance plan for reinforcing materials



This lesson will take approximately 2 hours to complete.

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REINFORCING AND CORROSION

LESSON 10


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Slide 3



Reinforcement Types

- There are a number of reinforcement types used in PCC construction
 - Mild steel
 - High-strength steel
 - Fiber reinforced polymer (FRP)
 - Stainless steel
 - Corrosion-resistant alloy steel (MMFX)
- The selection of the most appropriate type of reinforcement is based on several factors, including:
 - Intended function
 - Environmental conditions
 - Cost


Are you familiar with reinforcing and corrosion?


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Slide 4

Mild Steel Reinforcement

- Mild steel is produced in many forms depending on its intended use, including smooth bars, deformed bars, and welded wire mesh
- Steel reinforcement is typically graded by the minimum yield strength
- Common grades include 40, 60, and 75, which correspond to yield strengths of 40,000, 60,000, and 75,000 psi respectively




Q&A What grades of mild steel are used in your State and for what applications?

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Steel reinforcement is typically graded by the minimum yield strength. Common grades include 40, 60, and 75, which correspond to yield strengths of 40,000, 60,000, and 75,000 pounds per square inch (psi) respectively.


The photo on the left is of round steel bars as would be used for round dowels.
The photo in the center shows deformed bars, commonly termed rebars.
The photo on the right shows wire mesh, also termed wire fabric.

Slide 5



Mild Steel Reinforcement

- The intended use often dictates the shape of the reinforcement
 - Smooth bars are used for dowel bars in pavements or other applications where slip between the bar and PCC is desirable
 - Deformed bars, commonly termed rebar, are used where it is desirable to have a strong mechanical bond between the steel and the PCC, which results in a high resistance to “pull out”
 - Welded wire fabric or mesh is designed to provide reinforcement in two directions and is used primarily to restrain crack movements in slabs
- Mild steel reinforcement is subject to corrosion (rusting) and is frequently coated with epoxy, galvanizing, or other material depending on the service environment
- Additional corrosion-inhibiting measures may also be used, including corrosion-inhibiting admixtures, low permeability PCC, and in some cases, galvanic anodes

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Smooth bars are used for dowel bars in pavements or other applications where slip between the bar and PCC is desirable. Deformed bars, commonly termed rebar, are used where it is desirable to have a strong mechanical bond between the steel and the PCC, which results in a high resistance to “pull out.” Welded wire fabric or mesh is designed to provide reinforcement in two directions and is used primarily to restrain crack movements in slabs.

Mild steel reinforcement is subject to corrosion (rusting) and is frequently coated with epoxy or other material, depending on the service environment.

Additional corrosion-inhibiting measures may also be used. Including corrosion-inhibiting admixtures, low permeability PCC, and in some cases, galvanic anodes.

Note that the “Buy America” mandate can, in some cases, impact the selection of reinforcing steel, which will be discussed in the next lesson.

Slide 6

High-Strength Steel Reinforcement 

- High-strength steel, grade 100, with a yield strength of 100,000 psi has been approved by AASHTO for use in bridges and other structures
- The increase in yield strength of the steel will result in less steel being required for an equivalent structural section
- The cost savings in both materials and the potential for reduced sectional dimensions make this a viable option for many applications



 Is high-strength steel used in your State, and if so, in what applications?

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MODULE G REINFORCING AND CORROSION LESSON 10 6


The increase in yield strength of the steel will result in less steel being required for an equivalent structural section. The cost savings in both materials and the potential for reduced sectional dimensions make this a viable option for many applications.


Both photos shown here illustrate high-strength steel. The photo on the top shows deformed and round smooth bars. The photo on the bottom shows high-strength rebar bent into a very complex shape for column reinforcement.

Slide 7

FRP Reinforcement

- FRP reinforcement is comprised of a binder (a resin or polymer material such as polyester, vinyl ester, or epoxy) and a reinforcing material (typically fiberglass, carbon fiber, or aramid fiber)
- FRP reinforcement is available in a variety of shapes, including deformed and smooth bars
- The primary advantages of FRP are the resistance to corrosion, reduced weight, and potentially lower cost





What is your experience with FRP bars?

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FRP reinforcement is available in a variety of shapes, including deformed and smooth bars. The primary advantages of FRP are the resistance to corrosion, reduced weight, and potentially lower cost.

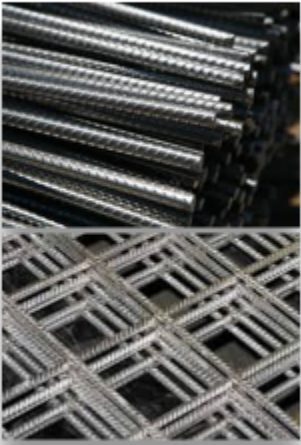
The potential for lower cost is based primarily on reduced hauling and installation costs. However, there is an economy of scale and in order to realize these savings, more widespread adoption is likely needed.

The photo on the top shows that FRP deformed bars are available in the same general range of sizes as steel bars. The photo on the bottom shows smooth round FRP dowel bars. FRP dowels have not seen widespread acceptance at this time but have been placed in numerous highway test installations.

Slide 8

Stainless Steel Reinforcement

- Stainless steel reinforcement is highly corrosion resistant and as such is typically used for long-life structures in harsh environments
- As with conventional mild steel, it is available in a variety of configurations (deformed bars, smooth bars, and mesh) and in a wide range of yield strengths (some exceeding 100,000 psi)
- Traditionally, the high cost of stainless steel has limited its use although this is changing.



Q&A What is your experience with stainless steel reinforcement?

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MODULE G REINFORCING AND CORROSION LESSON 10 8

As with conventional mild steel, it is available in a variety of configurations (deformed bars, smooth bars, and mesh) and in a wide range of yield strengths (some exceeding 100,000 psi).

Stainless steel reinforcement is available in various grades, which may correspond to yield strength as well as corrosion resistance. The lower grades may be economically viable when coupled with additional measures, such as corrosion-inhibiting admixtures, particularly for critical applications, such as bridge decks.


The photos on the screen show stainless steel deformed bars. Note that smooth round bars are also available and are used for dowels in some long-life pavements.

The cost of stainless steel is dependent on the type (grade). Although it has traditionally been expensive compared to conventional steel, when considered from a performance or life cycle standpoint, it may actually be the lowest long-term cost (particularly for bridge decks).

Slide 9

MMFX Steel Reinforcement

- MMFX steel is a highly corrosion-resistant alloy steel resulting from a proprietary manufacturing process
- The yield strength of MMFX rebar corresponds to the requirements of grades 60 or 75 steel, although it far exceeds that value and is generally in the range of high-strength steel at 100,000 to 120,000 psi or greater
- MMFX is typically used in harsh environments (particularly structures) where long service lives are required
- MMFX is available in similar shapes to those shown for mild steel



Q&A Is MMFX steel used in your State, and if so, in what application?

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The yield strength of MMFX rebar corresponds to the requirements of grades 60 or 75 steel, although it far exceeds that value and is generally in the range of high-strength steel at 100,000 to 120,000 psi or greater. MMFX is typically used in harsh environments (particularly structures) where long service lives are required. MMFX is available in similar shapes to those shown for mild steel.

Although the initial cost is higher for MMFX steel and stainless steel, their use can frequently be justified on the basis of life cycle cost.

Note that every agency has policies related to steel selection for specific applications. These guidelines are based upon performance histories as well as cost and availability.

The photos here illustrate some of the available shapes of MMFX steel.

Slide 10



Reinforcement Coatings

- Coatings are applied to reinforcing steel primarily to minimize or eliminate corrosion
- The most common types of coatings include:
 - Epoxy
 - Hot-dipped galvanized
 - Stainless cladding

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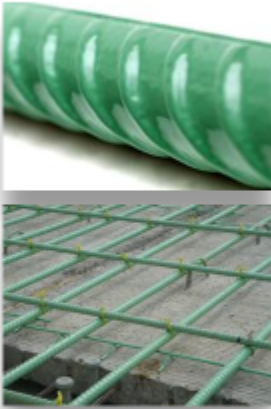
LESSON 10


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Slide 11

Epoxy Coating

- Epoxy coating is used to protect embedded steel from corrosion
- This multi-step process involves cleaning the steel, heating, powder application, and cooling; note that the powder melts to form the coating
- Epoxy can be an effective corrosion barrier as long as the surface is not damaged during handling and installation and the coating forms a continuous film of the required thickness





What is your experience with epoxy coatings? Have they been successful at eliminating corrosion problems?

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Note that the powder melts to form the coating. Epoxy can be an effective corrosion barrier as long as the surface is not damaged during handling and installation and the coating forms a continuous film of the required thickness.

Note that there are different types of epoxy coatings and coating processes (including green and purple coatings). Consult the manufacturer’s literature for specific information regarding these factors.

The photos on the screen show typical epoxy coated rebar. It is very important that this coating not be damaged prior to or during installation.

Slide 12

Hot Dip Galvanized Coating

- Hot dip galvanizing consists of a zinc or zinc alloy coating on the surface of the reinforcement to prevent corrosion
- The prepared steel is dipped in molten zinc or zinc alloy to produce the desired coating thickness
- Galvanized coatings are durable but, like epoxy, must not be damaged in handling and installation



Q&A What types of projects is galvanized steel used for in your State?

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MODULE G REINFORCING AND CORROSION LESSON 10 12

The prepared steel is dipped in molten zinc or zinc alloy to produce the desired coating thickness. Galvanized coatings are durable but, like epoxy, must not be damaged in handling and installation.


Note that in some instances, the galvanized coating may react with the cement, resulting in hydrogen outgassing.

The photo shown on top illustrates the placement of the prepared bars into the molten zinc bath. The photo on the bottom shows the zinc or galvanized coating.

Slide 13

Stainless Steel Cladding


- Stainless steel cladding is a stainless steel layer covering a mild steel bar
- Stainless cladding is used for long-term corrosion protection but at a lower initial cost compared with solid stainless steel bars
- To ensure the optimal functionality, the bars should be completely encapsulated





?

Have stainless steel clad bars been used in your State?



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Stainless cladding is used for long-term corrosion protection but at a lower initial cost compared with solid stainless steel bars. To ensure the optimal functionality, the bars should be completely encapsulated. It is very important that the cladding be integrated with the mild steel so that it doesn't delaminate during installation, particularly if bending is required during fabrication.

Note that stainless clad bars are not widely available and may be precluded from use due to the Buy American Act.


The photo shows stainless steel clad dowel bars installed in basket assemblies. Note that the ends are not clad but have been coated with epoxy.

Slide 14

Additional Types of Coatings



- Development of improved coatings to prevent corrosion of embedded steel is ongoing
- Various polymers, paints, metallic coatings, and others have been, and will continue to be, evaluated
- The key to good performance is to encapsulate the steel with an impenetrable barrier that cannot be damaged during transport or installation
- The primary obstacles for widespread use and implementation of a new product is cost and lack of performance history

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14


Various polymers, paints, metallic coatings, and others have been, and will continue to be, evaluated. The key to good performance is to encapsulate the steel with an impenetrable barrier that cannot be damaged during transport or installation. The primary obstacles for widespread use and implementation of a new product is cost and lack of performance history.

Slide 15

PCC Mix Considerations for Corrosion Protection




- In conjunction with, or as an alternative to, specialty steel coatings, the PCC mix can significantly impact corrosion potential
- Corrosion of embedded steel in PCC requires moisture for the basic electrochemical reactions to occur
- The presence of chloride ions greatly increases the corrosion potential; high chloride concentrations are commonly found in deicing salts and seawater
- Access to CO₂ can lead to carbonation that drives corrosion of embedded steel



Carbonated Area
indicates below pH 8.2 colorless

Sound Area
indicates above pH 10 pink

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15

Corrosion of embedded steel in PCC requires moisture for the basic electrochemical reactions to occur.

The presence of chloride ions greatly increases the corrosion potential; high chloride concentrations are commonly found in deicing salts and seawater. Access to CO₂ can lead to carbonation that drives corrosion of embedded steel.

The figure shown on the screen illustrates the migration of carbon dioxide into the hardened PCC. Note that the carbonation reduces the pH and the effectiveness of the passive coating on the reinforcing steel, thereby facilitating corrosion.

Slide 16

PCC Mix Considerations for Corrosion Protection




- In order to limit the amount of moisture and chloride intrusion, the permeability of the PCC can be lowered through proper mix design
- We have previously discussed the impact of various mix design parameters in terms of lowering permeability
- The use of a low w/c ratio mix, the addition of SCMs, and possibly a corrosion inhibiting admixture greatly improves the effectiveness of coated steel and may actually eliminate the need for coatings in some circumstances

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Emphasize that w/c ratio, more complete hydration, and denser hydration products lower permeability. If permeability can be lowered substantially, the need for many of the other topics we are about to discuss is greatly reduced.

Slide 17

Reinforcing Applications




- Reinforcing steel has a number of functions depending on the application
 - In reinforced PCC structural applications, the deformed bars (rebars) carry the majority of the tensile stresses developed in-service thereby improving the overall strength and load carrying capacity of the member
 - Wire mesh or fabric is intended to hold random cracks together in slabs on grades and can act to increase the tensile strength of structural members
 - In continuously reinforced PCC pavements, the rebar essentially holds the cracks together, thereby facilitating load transfer

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In continuously reinforced PCC pavements, the rebar essentially holds the cracks together, thereby facilitating load transfer.


Wire mesh or fabric is intended to hold random cracks together and can act to increase the tensile strength of structural members.

Slide 18



Rebar Splices

- Reinforcing bars must be continuous in order to provide uniform tensile reinforcement
- Due to the logistics of shipping and placement considerations, rebar typically must be spliced
 - Mechanical splices
 - Welded splices
 - Lap splices





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Slide 19


Mechanical Splices

- Specifications govern the pullout strength of these splices and, in most cases, they exceed the tensile strength of the rebar
- Mechanical splices are a rapid and effective means of splicing, although they cost more than simple lap splices





? **Q&A** What types of splices are used in your State?

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Specifications govern the pullout strength of these splices and, in most cases, they exceed the tensile strength of the rebar. Mechanical splices are a rapid and effective means of splicing, although they cost more than simple lap splices. Note that mechanical splices are typically proprietary products.

The photos shown on the screen illustrate three types of mechanical splices. Note that there are dozens of variously sized and differently configured splices available.

Slide 20

Welded Splices and Joints

- Reinforcing steel may be welded for some applications; however, the procedure requires a skilled welder and appropriate equipment
- Three types of welding processes may be used, including tungsten inert gas (TIG), arc welding using specialty rods, and metal inert gas (MIG)
- Only certain types and grades of reinforcing steel may be welded
- If welded splices are allowed by specification, it is best to consult with the steel supplier as to the viability of welding versus other options



Q&A Are welded splices allowed in your State? If so, for what applications?

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If done improperly, welding can significantly change the properties of the adjacent steel by either increasing ductility or brittleness, depending on the process used. In other words, the yield strength and fracture toughness of the steel is changed.

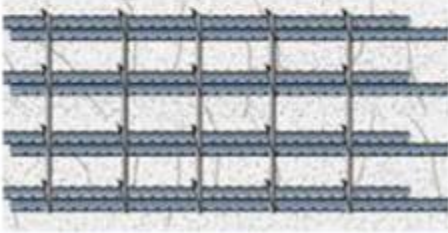
Note that reinforcing steel should not be cut on site using a cutting torch as this can reduce the yield strength of the steel.

Slide 21

Lap Splices

- Lap splices are the simplest means to connect rebar sections
- They rely solely on the amount of overlap for effective use
- Lap splices may be either contact splices (preferred), as shown in the photo, or non-contact splices where there is an offset between the bars
- The amount of overlap is based on the bar diameter





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The amount of overlap is based on the bar diameter and is generally a minimum of 40 times the bar diameter.

Slide 22

Dowels

- The primary function of a dowel is to provide load transfer across pavement joints (typically transverse joints)
- Dowel bars are available in a variety of configurations, including smooth round bars, elliptical bars, diamond-shape plates, rectangular plates, and others
- Dowels are generally mild steel but may also be FRP
- Dowels are designed to permit movement horizontally but not vertically



Q&A What types of dowels are used in your State?

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MODULE G REINFORCING AND CORROSION LESSON 10 **22**

Dowel bars are available in a variety of configurations including smooth round bars, vertically.

Slide 23

Wire Mesh

- Wire mesh or welded wire fabric is basically designed to hold cracks together tightly, thereby facilitating load transfer across the cracks or joints
- Mesh is used for irregularly shaped slabs, occasionally in full-depth repairs of pavements and other applications where crack restraint is important




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Mesh is used for irregularly shaped slabs, occasionally in full-depth repairs of pavements and other applications where crack restraint is important. In order to assure proper depth of the mesh in the slab, the mesh should be placed on chairs or other supports, as shown in the photo.

Slide 24

Acceptance of Reinforcing Materials



- We have discussed many options for reinforcement in this lesson, including mild steel, high-strength steel, fiber reinforced composites, as well as a number of different materials and coatings to prevent corrosion
- State specifications regarding rebar, dowel bars, and other embedded steel consider the following aspects of performance (at a minimum):
 - Grade of steel (based on minimum yield strength)
 - Coating type


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Discussion: Acceptance of Reinforcing Materials



- What are the acceptance procedures in your State?
 - Who performs the tests?
 - How frequently are tests performed?
 - What happens in the case of noncompliance?
 - Are there other issues?

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Note that the AASHTO NTPEP (National Transportation Product Evaluation Program) has a Reinforcing Steel/Welded Wire Reinforcement (REBAR/WWR) technical committee to evaluate new and existing products.

Slide 26

Mechanisms of Corrosion

- Corrosion of embedded steel in PCC is extremely detrimental to performance and can result in complete failure due to cracking and spalling
- The key issue that leads to failure is the expansion of steel during the corrosion process
- Corrosion is caused by various electrochemical reactions that can be driven by moisture, chlorides, and atmospheric carbon dioxide
- We will discuss the basic elements of corrosion in this section




Q&A Have you witnessed any corrosion approaching the severity shown in these photos?

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This screen serves as an introduction to corrosion of embedded steel. The photos are simply to illustrate the effects of steel corrosion in reinforced structures. The key issue that leads to failure is the expansion of the steel during the corrosion process.


Carbon dioxide from the atmosphere can react with calcium oxide present in the concrete to form calcium carbonate. The effect of this is that the alkalinity of the concrete is reduced. When the pH of the concrete falls below 9.0 adjacent to the steel, the passive corrosion protection is diminished and corrosion begins.


Slide 27




Reversal of Corrosion

- Corrosion may be slowed or stopped by one of several techniques including cathodic protection and sealants to prevent moisture and chloride intrusion
- However, the damage to the PCC is not reversible, although in many cases, the damage can be repaired satisfactorily
- The first step in the repair process is a thorough evaluation of the existing damage and identification as to probable cause for the corrosion
- The next step is to determine the structural implications of the deterioration and whether repairs are feasible



 Would this inspection process in your State document this type of deterioration?

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The damage to the PCC is not reversible, although in many cases, the damage can be repaired satisfactorily. The first step in the repair process is a thorough evaluation of the existing damage and identification as to probable cause for the corrosion. The next step is to determine the structural implications of the deterioration and whether repairs are feasible.


The photo is a time series of the progression of corrosion on the Route 438 overpass over the New York State Thruway.

Slide 28


PCC Repairs



- PCC repairs can take many forms depending on the type and severity of the distress and the purpose of the repair
- In the case of isolated, near-surface spalling on highways, a short-lived but simple repair may be made with asphalt; a long-lasting repair would rely on established partial-depth slab repair techniques using PCC or proprietary patching materials
- Crack repairs typically involve sealing with epoxy, MMA, or other products to prevent further moisture and chemical intrusion
- In some cases epoxy injection, can be used to restore structural integrity



Q&A What are your experiences repairing PCC due to corrosion? What was the application, what products were used, was the repair successful?

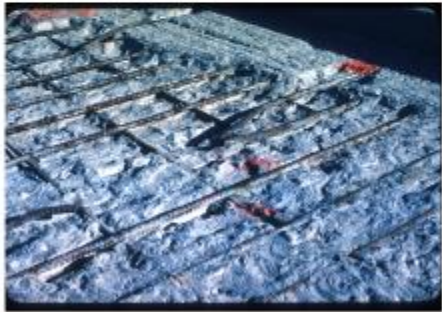
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For instance, in the case of isolated, near-surface spalling on highways, a short-lived but simple repair may be made with asphalt. A long-lasting repair would rely on established partial-depth slab repair techniques using PCC or proprietary patching materials. The simplest repairs involve crack sealing with epoxy, MMA, or other products to prevent further moisture and chemical intrusion. In some cases, epoxy injection, as pictured, can be used to restore structural integrity.

Slide 29

PCC Repairs

- More significant repairs begin with removal of the damaged PCC and either cleaning (removal of corrosion) or removal and replacement of the embedded steel
- A number of repair materials are available, ranging from PCC to proprietary materials (typically polymeric concrete)




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A number of repair materials are available, ranging from PCC to proprietary materials (typically polymeric concrete). The overall goals are to restore structural or functional performance and minimize or eliminate recurrence of the problem.


Slide 30

Use of Different PCC Mixes



- The use of different PCC mixes than were originally placed is generally unavoidable since repairs are hopefully required many years after initial construction
- The new material should be selected on the basis of compatibility and performance
 - Compatibility issues include the ability to provide a long-lasting bond and a comparable coefficient of thermal expansion
 - Performance issues include providing a barrier to limit further damage to the steel and restoring structural or functional capacity
- A primary consideration in using different repair materials is the possibility of creating concentration cells that may drive continued steel corrosion

 Would a non-Portland cement-based repair material experience the same issue?

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In order to minimize this effect, commonly referred to as ring corrosion, the use of corrosion-inhibiting admixtures and low permeability materials should be considered. In addition, the use of galvanic anodes may be required in very corrosive environments, such as bridge decks subjected to routine deicing applications.

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Factors Leading to Steel Corrosion in PCC

- PCC cracks
- PCC permeability
- Controlling PCC properties
- Electrical currents



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PCC Cracking 

- PCC cracking provides an avenue for moisture, chloride, and carbon dioxide intrusion, oftentimes extending to the reinforcing steel
- Regardless of the cause of the cracking, the effect on the onset and progression of corrosion is the same
- Note that effective crack sealing would delay but not stop progression



Before corrosion Build-up of corrosion products Further corrosion, surface cracks, stains Eventual spalling, corroded bar, exposed


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Regardless of the cause of the cracking, the effect on the onset and progression of corrosion is the same. The diagram displayed shows the steps involved in the process. Note that effective crack sealing would delay but not stop progression.

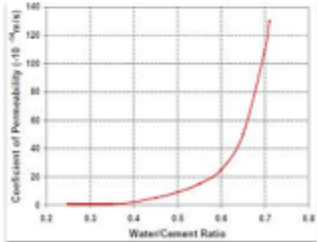
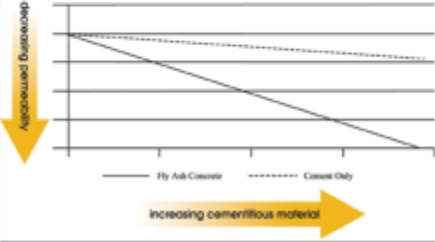
Also note that as more cracking develops, the faster the rate of corrosion will be.


Slide 33

PCC Permeability



- The permeability of PCC has a very significant effect on the corrosion potential of embedded steel
- The higher the PCC permeability, the easier it is for water and chlorides to infiltrate to the level of the steel
- Permeability is most effectively controlled by lowering the w/c ratio, adding SCMs, and ensuring adequate curing


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The higher the PCC permeability, the easier it is for water and chlorides to infiltrate to the level of the steel. Permeability is most effectively controlled by lowering the w/c ratio, adding supplementary cementitious materials (SCMs), and ensuring adequate curing.


The graph on the left shows the effect of the w/c ratio on the permeability of the paste. The graph on the right shows the effect of adding SCMs on permeability. Note that both of these graphs are intended to show trends in behavior.

Slide 34

Controlling Relevant PCC Properties




- The primary mix considerations are based on limiting the permeability of the PCC
- There are two approaches to achieve this goal:
 1. Lowering the w/c ratio lowers permeability
 2. If necessary to achieve adequate workability, a water-reducing admixture may be used
- The addition of SCMs to the PCC mix can also lower permeability by increasing the amount and density of the hydration products
- The most commonly added SCMs include the following:
 - Fly ash (type F or C)
 - Ground granulated blast furnace slag (GGBFS)
 - Note that silica fume can also be used to dramatically lower the permeability but with additional effects, as noted in earlier lessons

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Silica fume can also be used to dramatically lower the permeability but with additional effects, as noted in earlier lessons. These effects include increased water demand, higher risk of drying shrinkage cracks, difficulty in finishing, and others.

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Selection of Reinforcement Based on Corrosion Potential



- Steel selection is based on the intended application and the environmental conditions expected
- Reinforcing steel is graded based on the minimum tensile strength
- The following general steel categories will be discussed in this section:
 - Mild steel
 - Coated
 - Uncoated
 - High-strength steel
 - Vapor phase inhibitor

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The environment in which the reinforced PCC is placed has a major effect on the selection of coating or type of steel. The decision as to mild or high-strength steel is made for other reasons, such as reducing the amount of steel required in a structure. A reduction in steel can lower the dead weight and reduce the size of the structural members.


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Mild Steel



- Mild steel is the most commonly used type of steel and is available in shapes and sizes suited to virtually all applications
- Uncoated mild steel is subject to fairly rapid corrosion in harsh environments
 - If placed in a dry environment with no chlorides present, uncoated steel is acceptable and can provide a long life
- Coated mild steel is suitable for use in harsh conditions, assuming that the coating forms an impenetrable barrier to chlorides and moisture
 - The most common coating for mild steel is epoxy


 **Q&A** What is the most commonly used steel type in your State?

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Uncoated mild steel is subject to fairly rapid corrosion in harsh environments. If placed in a dry environment with no chlorides present, uncoated steel is acceptable and can provide a long life. Coated mild steel is suitable for use in harsh conditions, assuming that the coating forms an impenetrable barrier to chlorides and moisture. The most common coating is epoxy.


Note that the coating must completely encapsulate the steel and be free from defects that will permit corrosion. The coating must remain intact through placement.


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High-Strength Steel

- High-strength steel has yield strength of 100,000 psi and above
- However, the majority of high-strength steel materials are not inherently corrosion resistant and require the use of a corrosion barrier
 - Coatings such as epoxy, galvanizing, or cladding are frequently used
 - Use of a vapor phase inhibitor may also be a viable option, although this technology is generally more useful for smaller-scale corrosion protection
- Stainless steel or MMFX steel are corrosion resistant based on their metallurgical properties and do not require additional protection
- Another option for corrosion prevention with high-strength steel, particularly with bridge decks and structural members, is a cathode protection system, as will be discussed later in this lesson

 What is your experience with high-strength steel? In your experience, what corrosion prevention measures were used?


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However, the majority of high-strength steel materials are not inherently corrosion resistant and require the use of a corrosion barrier. Coatings such as epoxy or cladding are frequently used. Use of a vapor phase inhibitor may also be a viable option. Stainless steel or MMFX steel are corrosion resistant based on their metallurgical properties and do not require additional protection.


Vapor corrosion inhibitors (VCIs) are also known as vapor phase corrosion inhibitors (VPCIs). These corrosion-inhibiting compounds release molecules into the air. When these compounds come in contact with metal surfaces, they form a very thin molecular layer. This thin layer effectively inhibits corrosion on the metal surface by preventing air and moisture from coming in contact with the surface. Unlike other methods of rust prevention, the corrosion-inhibiting vapors have the ability to reach into intricate surfaces that would be otherwise hard to reach with traditional rust prevention products.

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Methods of Corrosion Detection




- Corrosion detection is the best defense against potential damage
- Early detection allows remedial measures to be taken prior to the onset of moderate to severe damage
- Early detection can save a significant amount of money due to the level of remediation required at early stages of distress
- There are three categories of corrosion detection and monitoring that will be discussed in this section:
 - Electrical potentials (half-cell potentials)
 - Chloride content
 - Condition monitoring

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Early detection allows remedial measures to be taken prior to the onset of moderate to severe damage. Early detection can save a significant amount of money due to the level of remediation required at early stages of distress.

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Electrical Potentials

- Measuring electrical potentials (half-cell potentials) in PCC is a common method to estimate the corrosion
- The rate at which corrosion can occur is affected by the electrical resistivity of the concrete
- A variety of devices can be used to measure the resistivity of the PCC but generally consist of measurements using two to four electrical probes placed on the surface of the PCC
- Threshold values are used to determine the likelihood of corrosion
- Examples of threshold values include:
 - When $\rho \geq 120 \Omega\text{-m}$ corrosion is unlikely
 - When $\rho = 80$ to $120 \Omega\text{-m}$ corrosion is possible
 - When $\rho \leq 80 \Omega\text{-m}$ corrosion is fairly certain

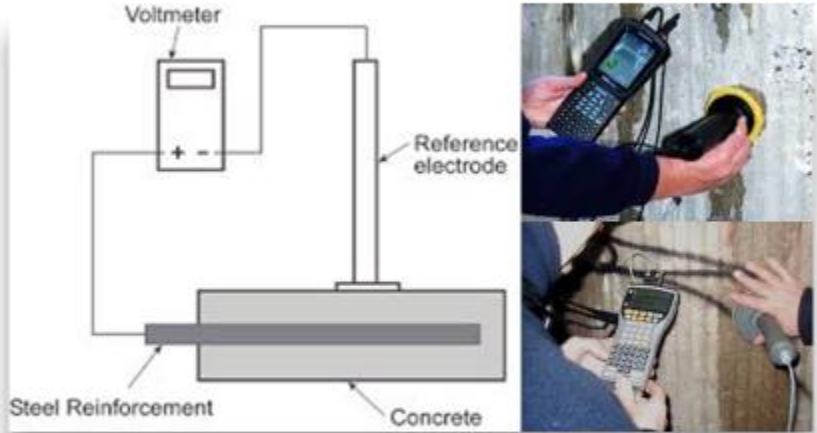
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Remember that corrosion is an electro-chemical process and as such has a defined rate of flow of electrons (ions) between the anode and cathode areas. The rate at which corrosion can occur is affected by the electrical resistivity of the concrete.

Slide 40

Measuring Electrical Potentials in PCC



The diagram on the left shows a cross-section of a concrete slab with a steel reinforcement bar. A reference electrode is inserted into the concrete, and a voltmeter is connected to both the reference electrode and the steel reinforcement. The photo on the right shows a person using a handheld device to measure the potential of a steel reinforcement bar in a concrete slab.

Q&A What is your experience in performing this type of test?

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The figure on the left illustrates the basic concept behind the measurement of resistivity. Note that half-cell potentials require an electrical contact to be established with the reinforcement. If epoxy coated bars are used, the epoxy coating must be removed in a small area to allow the connection to the device.

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Chloride Content

- The standard method for determining chloride content in hardened PCC uses chemical titration
 - This method is somewhat complex and relatively slow, generally requiring an extracted core specimen
- Equipment, such as the device pictured, requires less sample preparation and is more convenient since it is intended for field application





?

Q&A What is your experience in determining in-situ chloride content?

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This method is somewhat complex and relatively slow, generally requiring an extracted core specimen. Equipment, such as the device pictured, requires less sample preparation and is more convenient since it is intended for field application.

This test determines the amount of chloride present at the time of the test and is not the same as the chloride permeability test.


Note that the laboratory results are typically more reliable than the rapid field determinations due in large part to the controlled conditions in laboratory testing.


Slide 42

Condition Monitoring




- Condition monitoring can take many forms, ranging from measuring electrical potential as a function of time to detailed observations of distresses
- Time series data, regardless of the type, is useful to determine the rate of progression of corrosion
- Used with “predetermined trigger values” that set in motion one or more remedial strategies, condition monitoring is a very useful tool
- Condition monitoring may be used on an individual project or for managing multiple projects on a network level

 What type of testing is performed in your State, how often is it performed, and what is the data used for?


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Time series data, regardless of the type, is useful to determine the rate of progression of corrosion. Used with “predetermined trigger values” that set in motion one or more remedial strategies, condition monitoring is a very useful tool. Condition monitoring may be used on an individual project or for managing multiple projects on a network level.

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Methods for the Prevention and Mitigation of Corrosion 


- Corrosion prevention and mitigation strategies are widely employed in reinforced concrete structures
- There are numerous strategies that can be used, such as:
 - Reducing the penetrability of the PCC (in addition to permeability)
 - Providing adequate PCC cover to protect the steel
 - Developing a comprehensive, total system approach incorporating various elements

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Reducing Penetrability of PCC



- Penetrability refers to all the possible avenues, such as moisture, chlorides, carbon dioxide, and other corrosive materials
- Although the permeability of the PCC plays a vital role, penetrability also includes cracking and discontinuities such as joints
- Cracking and joints, unless adequately sealed, provide a ready access for corrosive agents
- The permeability of the PCC may be measured using a variety of methods ranging from essentially soaking samples to determine the rate of absorption to electrical resistivity measurements
- Recall that permeability may be reduced by lowering the w/c ratio and/or adding SCMs to the mix

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Although the permeability of the PCC plays a vital role, penetrability also includes cracking and discontinuities, such as joints.


Cracking and joints, unless adequately sealed, provide a ready access for corrosive agents.

The permeability of the PCC may be measured using a variety of methods ranging from essentially soaking samples to determine the rate of absorption to electrical resistivity measurements.

Recall that permeability may be reduced by lowering the w/c ratio and/or adding SCMs to the mix. The photos on the following screen illustrate some of the more common procedures for determining the permeability of the PCC as well as chloride penetration.

Slide 45

Permeability and Rapid Chloride Test Methods



Q&A What type of testing is performed in your State, how often is it performed, and what is the data used for?

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The implications to corrosion have been addressed in this lesson and are shown to be a factor in developing an effective mitigation strategy.


The photo on the top left illustrates an ASTM-designated test to determine the permeability of PCC through soaking and determining the uptake of water on a timed basis.

The photo on the lower left shows one on many types of permeability apparatus.

The photo on the upper right shows a surface resistivity test.


The photo on the lower right shows a rapid chloride permeability test.

Slide 46



Protecting the Steel

- In addition to lowering the PCC penetrability as previously described, a number of other options should be considered
 - Provide adequate PCC cover
 - Use coated steel (epoxy coated, galvanized, other)
 - Use corrosion-resistant steel (stainless steel, MMFX)
 - Utilize corrosion-inhibiting admixtures
 - Cathodic protection
 - Galvanic anodes
 - Penetrating sealers/impermeable coatings


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Other methods to reduce corrosion include corrosion-inhibiting admixtures or topical applications, galvanic anodes, cathodic protection, penetrating/coating type sealers on the concrete surface—some mention of these should also be made with the pros and cons of each.

Slide 47

Depth of Cover



- Adequate depth of cover slows the penetration of chloride ions and can significantly improve corrosion resistance, assuming low permeability PCC is used
- A secondary issue, but equally important, is the intrusion of carbon dioxide
- The steel is naturally protected from corrosion by a passive coating that is due to the high pH of the pore solution in the PCC
- This coating becomes less effective with decreasing pH and completely ineffective at a pH of approximately 10.5
- Intrusion of carbon dioxide effectively lowers the pH of the pore solution by means of the carbonation reaction
- Adequate depth of cover requirements vary by application but are typically in the range of 2 in.

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A secondary issue, but equally important, is the intrusion of carbon dioxide.


The steel is naturally protected from corrosion by a passive coating that is due to the high pH of the pore solution in the PCC. This coating becomes less effective with decreasing pH and completely ineffective at a pH of approximately 10.5. Intrusion of carbon dioxide effectively lowers the pH of the pore solution by means of the carbonation reaction. Adequate depth of cover requirements vary by application but are typically in the range of 2 in.

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Coatings


- The effectiveness of either type depends on the integrity and thickness of the coating and the level of encapsulation
- The most widely used coatings used for corrosion protection of embedded steel include:
 - Epoxy
 - Galvanizing (zinc or zinc alloy)
 - Stainless steel cladding
- Regardless of the type, care must be exercised during handling and installation to prevent damaging the coating, thereby leading to corrosion
- Stainless steel cladding is an option for very corrosive environments but is not widely used due to its high cost

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Poorly applied epoxy coatings may have minute pores that allow the intrusion of corrosive agents. Regardless of the type, care must be exercised during handling and installation to prevent damaging the coating, thereby leading to corrosion. Stainless steel cladding is an option for very corrosive environments but is not widely used due to its high cost.

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Comprehensive Total Systems Approach



- In order to achieve the maximum corrosion resistance, a number of the previously discussed options are typically combined
- For instance, in a highly corrosive environment (i.e., a bridge deck with frequent applications of deicing salt), low permeability PCC combined with adequate cover and coated steel may be required to achieve desirable results
- Historical data on the performance of various corrosion prevention options in a specific environment can prove very useful in determining the best overall strategy



What would constitute a total systems approach? Is this current practice or is it considered on a project basis?

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For instance, in a highly corrosive environment (i.e., a bridge deck with frequent applications of deicing salt), low permeability PCC combined with adequate cover and coated steel may be required to achieve desirable results.

Historical data on the performance of various corrosion prevention options in a specific environment can prove very useful in determining the best overall strategy.

Slide 50

Life-365 Software 

- Life-365 is software designed to estimate the service life and life cycle costs of alternative concrete mix designs
 - It follows a methodology, created by the Life-365 Consortium I and II groups of companies, that gives research-based estimates of the effects of concrete design, chloride exposure, environmental temperature, concrete mixes and barriers, and steel types on service life and life cycle cost

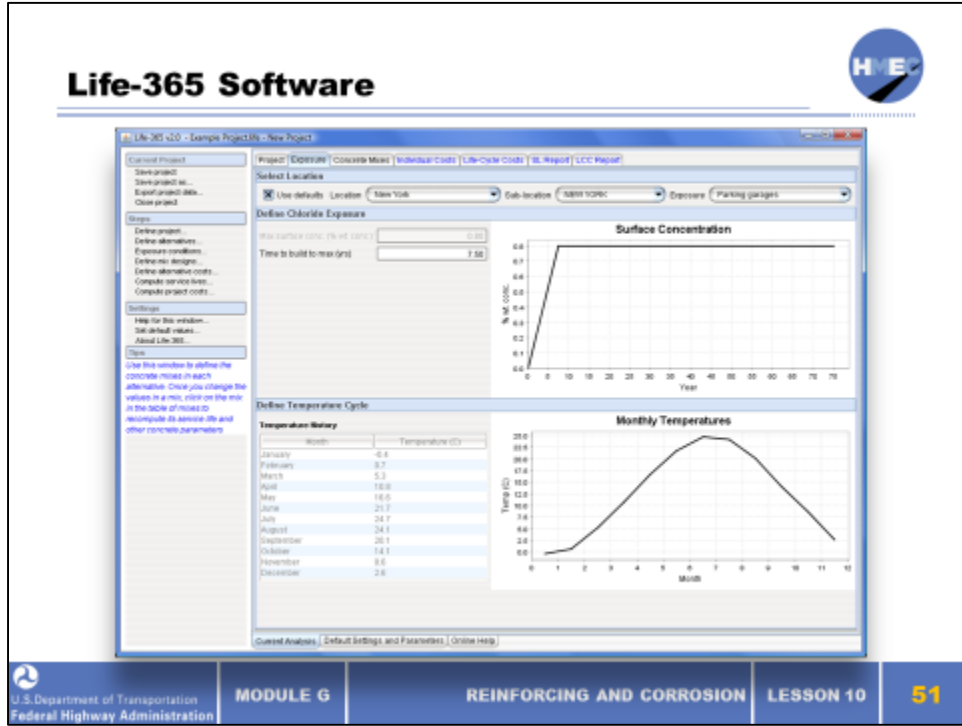


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Life-365 is software designed to estimate the service life and life cycle costs of alternative concrete mix designs. It follows a methodology, created by the Life-365 Consortium I and II groups of companies that gives research-based estimates of the effects of concrete design, chloride exposure, environmental temperature, concrete mixes and barriers, and steel types on service life and life cycle cost.


The software has been reviewed and widely distributed by the FHWA.

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Note that the surface concentration of chloride is a key parameter, as would be expected based on our discussion.

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Mitigating Active Corrosion 

- Active corrosion may be mitigated by disrupting the electrochemical reactions leading to corrosion or preventing access to corrosive chemicals and water
- The primary mitigation strategies include:
 - Cathodic protection
 - Overlays
 - Surface coatings



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Active corrosion may be mitigated by disrupting the electrochemical reactions leading to corrosion or preventing access to corrosive chemicals and water.

The photo shows cathodic protection being installed on a structural component.

It is important to note that the techniques listed for mitigating active corrosion are also applicable to new construction as a preventative measure. This is in addition to the use of corrosion inhibiting admixtures, low permeability PCC, corrosion resistant steel, and so on.

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Cathodic Protection

- Cathodic protection is an active electrical process in which a sacrificial metal grid acts as an anode while the reinforcing steel acts as a cathode and is therefore protected from corrosion
- An external direct current (DC) is applied to the circuit to provide the drive to the electrochemical process

The diagram illustrates a cross-section of a concrete slab. At the top is a 'Concrete overlay' layer. Below it is a 'Ti mesh' layer. The bottom layer is 'ORIGINAL CONCRETE' containing 'Rebars'. A 'Rectifier/Control Unit' is connected to the Ti mesh (positive terminal) and the Rebars (negative terminal).

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Cathodic protection is an active electrical process in which a sacrificial metal grid acts as an anode while the reinforcing steel acts as a cathode and is therefore protected from corrosion.


An external direct current (DC) is applied to the circuit to provide the drive to the electrochemical process.


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Overlays

- Overlays can be used on new structures to minimize or eliminate corrosion by preventing intrusion of moisture, chlorides, carbon dioxide, or other chemicals
- They can also be used on moderately distressed structures to minimize further damage and to provide a structural and/or functional repair
- A number of options are available depending on the intended purpose of the overlay:
 - Low-slump, high-density PCC
 - Latex-modified concrete overlays
 - Silica fume (microsilica)
 - GGBFS





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They can also be used on moderately distressed structures to minimize further damage and to provide a structural and/or functional repair.


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Low-Slump, High-Density PCC Overlay



- Low-slump, high-density PCC overlays can be used to repair bridge decks where corrosion is a concern
- These overlays are intended to mitigate chloride intrusion and corrosion and have been shown to be effective when intact
 - They are prone to plastic shrinkage cracking during construction so adequate curing is critical
 - The effectiveness of the overlay is dependent on the extent and severity of cracking
- The mix design relies on a low w/c ratio and the addition of SCMs to achieve low permeability
- These overlays are typically 2 in. thick and must be carefully constructed as a bonded overlay



Q&A What is your experience with low-slump, high-density overlays?


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The mix design relies on a low w/c ratio and the addition of SCMs to achieve low permeability. These overlays are typically 2 in. thick and must be carefully constructed as a bonded overlay.


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Latex-Modified Concrete Overlays



- Conventional latex-modified overlays are based on Portland cement mixes enhanced with latex
- Rapid-set, latex-modified mixes are also available and are based on either proprietary or high early strength Portland cements
- These overlays are usually placed on bridge decks to reduce the infiltration of water and chloride ions
- The performance of this type of overlay has generally been good due partially to the enhanced bonding capabilities
- This type of overlay is typically 1.5 in. thick

 What is your experience with latex-modified overlays?

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Rapid-set, latex-modified mixes are also available and are based on either proprietary or high early strength Portland cements. These overlays are usually placed on bridge decks to reduce the infiltration of water and chloride ions.

The performance of this type of overlay, which is typically 1.5 in. thick, has generally been good due partially to the enhanced bonding capabilities.

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Latex-Modified Concrete Overlays



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Latex-modified concrete typically exhibits higher tensile strength, lower elastic modulus, increased wear resistance, and enhanced bond relative to normal PCC.

The added cost of this material may be justified based on life cycle cost.

Placement should be avoided when hot, windy, low humidity conditions are expected as the material is prone to plastic shrinkage cracking unless adequate measures are taken very soon after placement.


The use of fogging to maintain high relative humidity at the surface, expedited curing application, the use of soaker hoses after initial set, etc. to prevent surface cracking are options to consider.


Note that mobile mixers are required to place latex concrete. These mixers must be calibrated for the specific mix and may require adjustments as the ambient conditions change.

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Silica fume (microsilica)

- Microsilica, commonly referred to as silica fume, is a SCM added to PCC mixes to increase strength, durability, and reduce permeability
- The fineness of the silica fume increases water demand in the mix and can lead to plastic shrinkage cracking and reduced workability
- Timely and adequate curing are critical to prevent plastic shrinkage cracking, which can occur soon after placement
- The use of water reducers, particularly superplasticizers, is generally needed to produce a workable mix and promote a good bond to the existing PCC
- Microsilica overlays are typically 2 in. thick





What is your experience with microsilica overlays?



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Silica fume or silica dioxide is approximately 1/100th of the size of cement grains and its use results in a very dense packing of reactive particles in the cement paste.


The fineness of the silica fume increases water demand in the mix and can lead to plastic shrinkage cracking and reduced workability. Timely and adequate curing are critical to prevent plastic shrinkage cracking, which can occur soon after placement. The use of water reducers, particularly superplasticizers, is generally needed to produce a workable mix and promote a good bond to the existing PCC. Microsilica overlays are typically 2 in. thick.


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Ground Granulated Blast Furnace Slag



- GGBFS is another SCM that can be added to PCC to promote a denser, less permeable mix
- As with the addition of other SCMs, the reduction in permeability may allow a reduction in the depth of cover while still providing adequate corrosion mitigation
- According to an FHWA report, the substitution of GGBFS for Portland cement should be limited to approximately 25% in applications where deicing salts are used. However, some agencies have used substitutions as high as 50% with no performance-related issues
- GGBFS overlays are typically 2 to 3 in. thick

 What is your experience with GGBFS supplemented overlays?

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As with the addition of other SCMs, the reduction in permeability may allow a reduction in the depth of cover while still providing adequate corrosion mitigation. According to an FHWA report, the substitution of GGBFS for Portland cement should be limited to approximately 25% in applications where deicing salts are used. However, some agencies have used substitutions as high as 50% with no performance-related issues.


GGBFS overlays are typically 2 to 3 in. thick.

Note that GGBFS, as with fly ash, can enhance the workability and finishability of the PCC.

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PCC Surface Coatings and Crack Sealing


- Surface coatings encompass a wide range of products that can be used to alter the appearance and performance of PCC
 - Pigmented sealants
 - Penetrating sealants
 - Crystalline waterproofing
- The primary function of these materials is to seal the surface of the PCC and prevent the intrusion of water and chlorides
- Crack sealing, while not generally applied like surface coatings, is also used to prevent the intrusion of corrosive materials

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Pigmented Sealants

- Pigmented sealers come in a wide variety of formulations and available colors
- Their use is twofold:
 1. To seal the PCC surface to prevent the intrusion of water and chlorides
 2. To add color to delineate areas such as crosswalks or simply for aesthetic reasons



Q&A Does your State use pigmented sealants?


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The use of pigmented sealants is to prevent the intrusion of water and chlorides and to add color to delineate areas such as crosswalks or simply for aesthetic reasons.


Care must be exercised in selecting a product. The primary criteria for selection includes durability of the sealant, effectiveness in reducing permeability, colorfastness, cost, and any potential reduction in skid resistance.


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Penetrating Sealants



- Penetrating sealers include silanes, siloxanes, and silicates
- They function by penetrating the PCC surface to form a chemical barrier that prevents moisture and chloride intrusion



 What is your experience with penetrating sealants?

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They function by penetrating the PCC surface to form a chemical barrier that prevents moisture and chloride intrusion.


The majority of these products are breathable, allowing water vapor to escape. These materials are generally applied to the surface of the PCC with a high-volume, low-pressure sprayer or roller.


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Crystalline Waterproofing


- Crystalline waterproofing technology improves the durability of PCC structures by filling the pores, capillaries, and micro-cracks with a non-soluble, highly weather-resistant crystalline formation
- The byproducts of cement hydration (calcium hydroxide, sodium carbonate, etc.) and the crystalline chemicals are brought together in the presence of moisture; a chemical reaction occurs and the end product of this reaction is a non-soluble crystalline formation







What is your experience with crystalline waterproofing in your State?



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The waterproofing effect is based on two simple reactions—one chemical and one physical. Concrete is chemical in nature. When a cement particle hydrates, the reaction between water and the cement causes the concrete to become a hard, solid mass. The reaction also generates chemical byproducts such as calcium hydroxide, sulfates, and carbonates of sodium potassium and calcium as well as not hydrated or partially hydrated cement particles—all of which reside in the capillary tracts of the concrete.

Crystalline waterproofing introduces another set of chemicals to the concrete. When these two chemical groups, the byproducts of cement hydration and the crystalline chemicals, are brought together in the presence of moisture and a chemical reaction occurs. The end product of this reaction is a non-soluble crystalline formation.


This crystalline formation can only occur where moisture is present, thus it will only form in the pores, capillary tracts, and shrinkage cracks of the concrete. Wherever water goes, crystalline waterproofing will form, filling the pores, voids, and cracks.

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Crack Repair and Sealing



- Crack repair is generally intended to immobilize the crack
- Crack sealing is intended to prevent the intrusion of water, chlorides, and incompressible materials into cracks
- There are several crack repair materials in common use, including epoxy and methyl methacrylate (MMA)
- Crack sealing may utilize silicone, bituminous, or a number of proprietary products
- In order to be effective and long lasting, crack preparation prior to installation is critical



What is your experience with crack repair and sealing procedures in your State?


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Crack repair is generally intended to immobilize the crack. Crack sealing is intended to prevent the intrusion of water, chlorides, and incompressible materials into cracks.


There are several crack repair materials in common use including epoxy and methyl methacrylate. Crack sealing may utilize silicone, bituminous, or a number of proprietary products. In order to be effective and long lasting, crack preparation prior to installation is critical. Each material has specific installation requirements and performance characteristics.


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Discussion: Other Options for Corrosion Mitigation




- Please share your experiences regarding corrosion mitigation techniques used in your State
 - Type of treatment or procedure
 - Where it is used
 - Whether or not there are any issues regarding construction or performance

 What have your experiences been regarding corrosion mitigation?

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Learning Outcomes Review



You are now able to:

- Compare reinforcement types and the appropriate uses of each
- Describe the primary reasons for corrosion of steel in PCC
- Relate mix design properties to corrosion potential
- Describe the selection of reinforcement types based on environmental conditions and corrosion potential
- Recommend an appropriate corrosion mitigation technique for a given scenario
- Describe the necessary elements for an acceptance plan for reinforcing materials

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Appendix A: Acronyms

The following are acronyms referenced throughout the course that are important agencies or organizations:

Acronym	Proper Name
AASHTO	American Association of State Highway and Transportation
ACAA	American Coal Ash Association
ACI	American Concrete Institute
ACPA	American Concrete Paving Association
AI	Asphalt Institute
ASTM	American Society for Testing and Materials
AWS	American Welding Society
CFR	Code of Federal Regulations
DOT	U.S. Department of Transportation
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
NACE	National Association of Corrosion Engineers
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NEPCOAT	North East Protective Coating
NHI	National Highway Institute
NRC	National Recycling Coalition
NRMCA	National Ready Mixed Concrete Association
NSA	National Slag Association
NSBA	National Steel Bridge Alliance

Acronym	Proper Name
NTPEP	National Transportation Product Evaluation Program
OSHA	Occupational Safety and Health Administration
RCSC	Research Council on Structural Connections
SSPC	Society for Protective Coatings
TRB	Transportation Research Board
USGS	U.S. Geological Survey

Appendix B: Resources

Additional information regarding Module G can be found in the following sources.

Design and Control of Concrete Mixtures, 14th edition. By S. Kosmatka, B. Kerkhoff, W. Panarese. The book is available from the Portland Cement Association, 5420 Old Orchard Road, Skokie, IL 60077 or online at <http://www.cement.org/bookstore/index.asp>.

Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete (American Concrete Institute Publication ACI 221 R-96, 2001) or later version.

Distress Identification Manual for the Long-Term Pavement Performance Program, June 2003 (US Department of Transportation Federal Highway Administration Publication No. FHWA-RD-03-031).

Portland Cement Concrete Pavement Construction Field Inspection Manual for Project No. STMAAF-I059.

(342) PCCP Overlay Project in Etowah County, AL (FHWA/Alabama DOT publication, 2009) is strongly suggested as a resource for developing best practices and a case study.

The Life-365 Program and associated software: www.life-365.org and www.nrmca.org/research/Life365_instructions.asp.

FHWA/ACI seminar: “Chemical Admixtures for Concrete”.

Mindess, Sidney J. and Young, Francis. *Concrete*. Prentice-Hall, 1981.

Neville, A.M. *Properties of Concrete*. Prentice Hall, 2012.

Current Research on ASR: <https://www.fhwa.dot.gov/pavement/concrete/asr.cfm>

Past Research on ASR: <http://onlinepubs.trb.org/onlinepubs/shrp/SHRP-C-342.pdf>

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