HMEC

Highway Materials Engineering Course

PARTICIPANT WORKBOOK

Portland Cement Concrete

MODULE

G

U.S.Department of Transportation
Federal Highway Administration

Table of Contents

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:

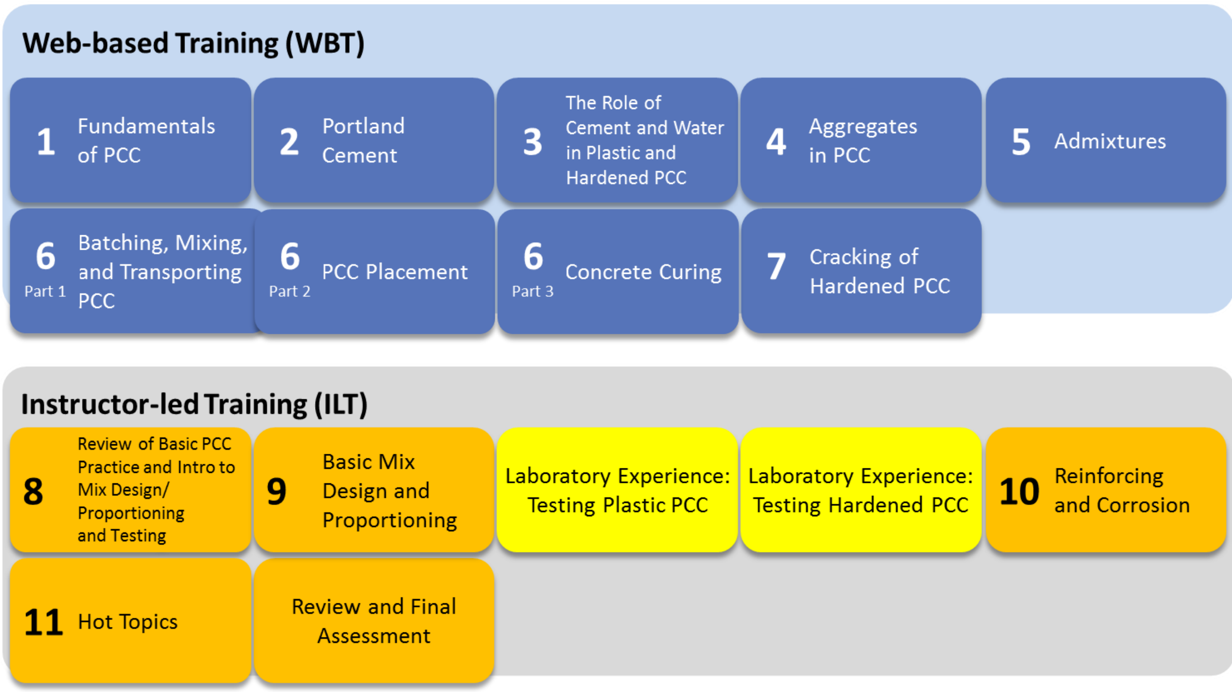
- Module A: Quality Assurance
- Module B: Soils and Foundations
- Module C: Steel, Welding, and Coatings
- Module D: Aggregates for Transportation Construction Projects
- Module E: Mechanistic Empirical Pavement Design Guide
- Module F: Asphalt Materials and Paving Mixtures
- Module G: Portland Cement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



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

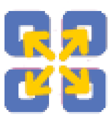
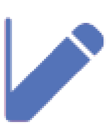
- LO 10.1: Compare reinforcing types and the appropriate uses of each
- LO 10.2: Describe the primary reasons for corrosion of steel in PCC
- LO 10.3: Relate mix design properties to corrosion potential
- LO 10.4: Describe the selection of reinforcement types based on environmental conditions and corrosion 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:

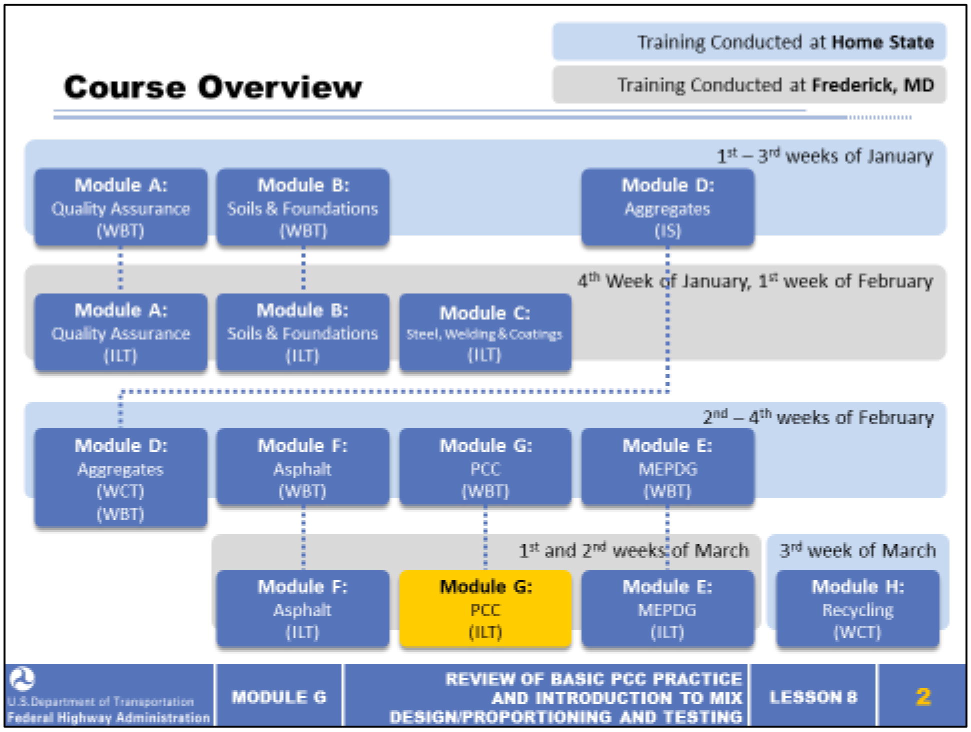
Icon	Icon Name	Typical Use
	Timer	▪ Call out the estimated time for the lesson
	Important Information	▪ Call out important information.
	Q & A	▪ Check for understanding or agreement. ▪ Survey participants. ▪ Solicit feedback.
	Breakout/Small Group Exercise	▪ Break participants into groups. ▪ Provide directions for exercise.
	Video/Sound	▪ Show a video.
	Reference	▪ Reference another document or resource.
	Links	▪ Share a Web link for additional resources.
	Whiteboard	▪ Draw or document something on a whiteboard or easel pad.

Icon	Icon Name	Typical Use
	Safety	▪ Call out important safety information.
	Common Error	▪ Call out a system or process that is often misused.

Slide 1


HMEC
Highway Materials Engineering Course
Lesson 8: Review of Basic PCC Practice and Introduction to Mix Design/Proportioning and Testing
Portland Cement Concrete
(PCC)
U.S.Department of Transportation
Federal Highway Administration
MODULE
G

Slide 2



Training Conducted at Home State
Training Conducted at Frederick, MD
Course Overview
1st – 3rd weeks of January
Module A: Quality Assurance (WBT)
Module B: Soils & Foundations (WBT)
Module D: Aggregates (IS)
4th Week of January, 1st week of February
Module A: Quality Assurance (ILT)
Module B: Soils & Foundations (ILT)
Module C: Steel, Welding & Coatings (ILT)
2nd – 4th weeks of February
Module D: Aggregates (WCT) (WBT)
Module F: Asphalt (WBT)
Module G: PCC (WBT)
Module E: MEPDG (WBT)
1st and 2nd weeks of March
3rd week of March
Module F: Asphalt (ILT)
Module G: PCC (ILT)
Module E: MEPDG (ILT)
Module H: Recycling (WCT)
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
2

____

____

____

____

____

____

____

____

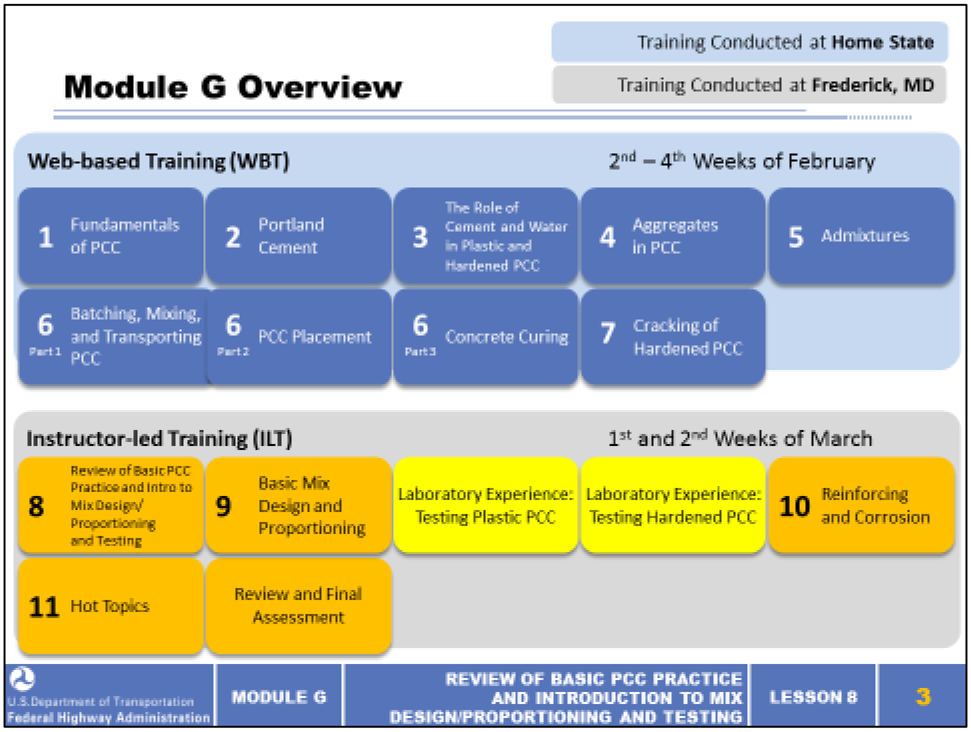
____

____

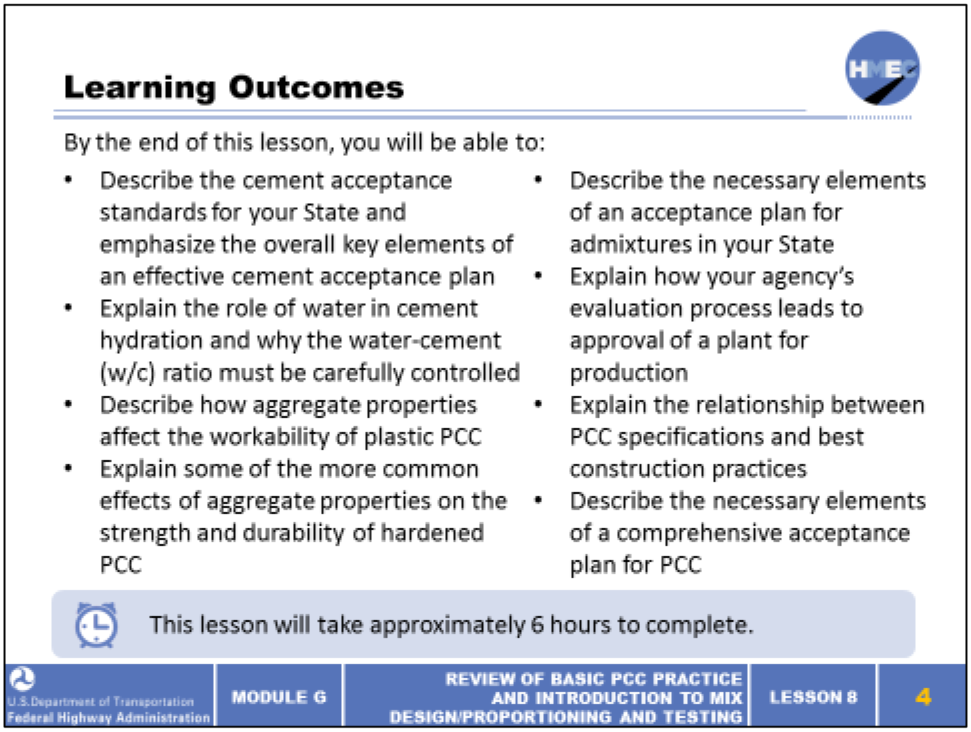
____

____

Slide 3


Training Conducted at Home State
Training Conducted at Frederick, MD
Module G Overview
Web-based Training (WBT)
2nd – 4th Weeks of February
1 Fundamentals of PCC
2 Portland Cement
3 The Role of Cement and Water in Plastic and Hardened PCC
4 Aggregates in PCC
5 Admixtures
6 Part 1 Batching, Mixing, and Transporting PCC
6 Part 2 PCC Placement
6 Part 3 Concrete Curing
7 Cracking of Hardened PCC
Instructor-led Training (ILT)
1st and 2nd Weeks of March
8 Review of Basic PCC Practice and Intro to Mix Design/ Proportioning and Testing
9 Basic Mix Design and Proportioning
Laboratory Experience: Testing Plastic PCC
Laboratory Experience: Testing Hardened PCC
10 Reinforcing and Corrosion
11 Hot Topics
Review and Final Assessment
U.S. Department of Transportation Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
3

Slide 4


Learning Outcomes
HMEC
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.
U.S. Department of Transportation Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
4

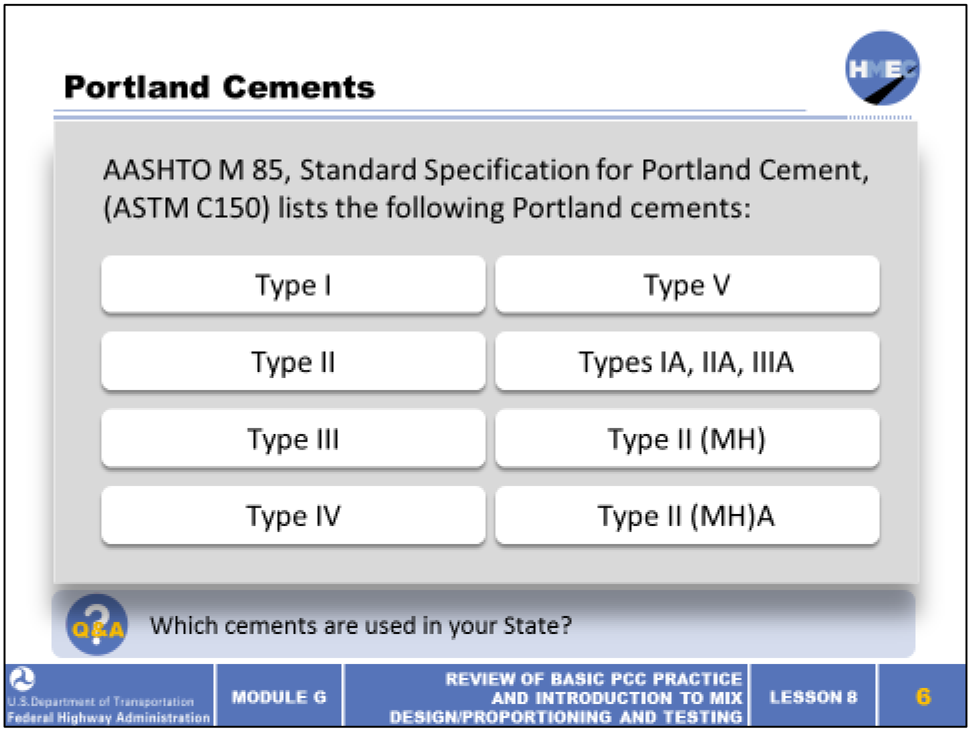
Slide 5

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

U.S. Department of Transportation Federal Highway Administration | MODULE G | REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING | LESSON 8 | 5

Slide 6



The cement types listed and discuss their availability and use.

____

____

____

____

____

____

____

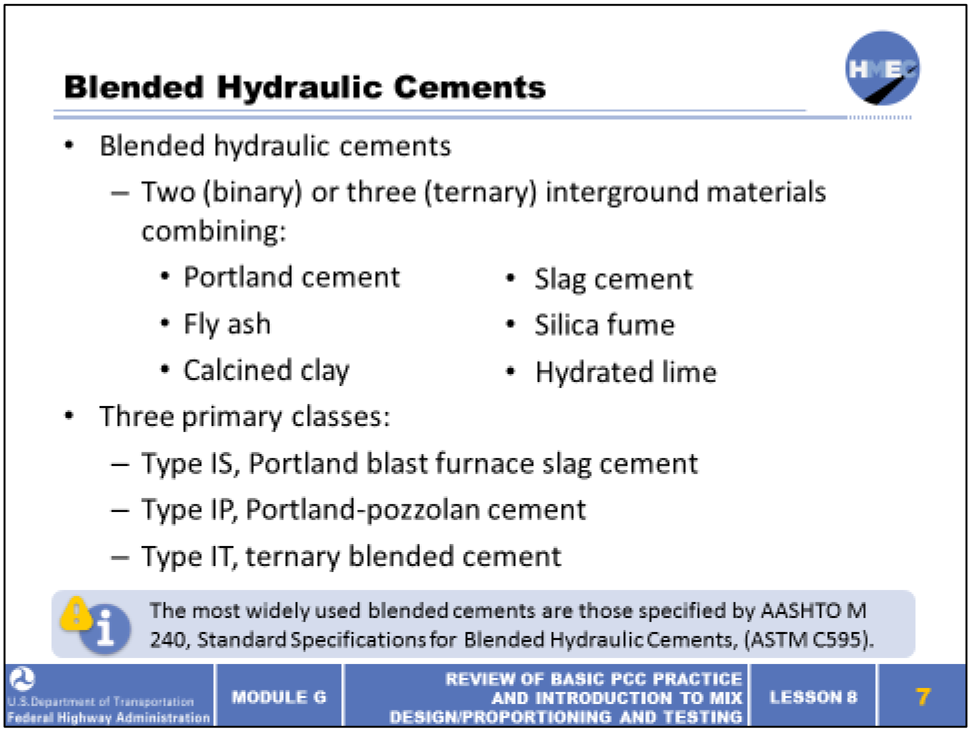
____

____

____

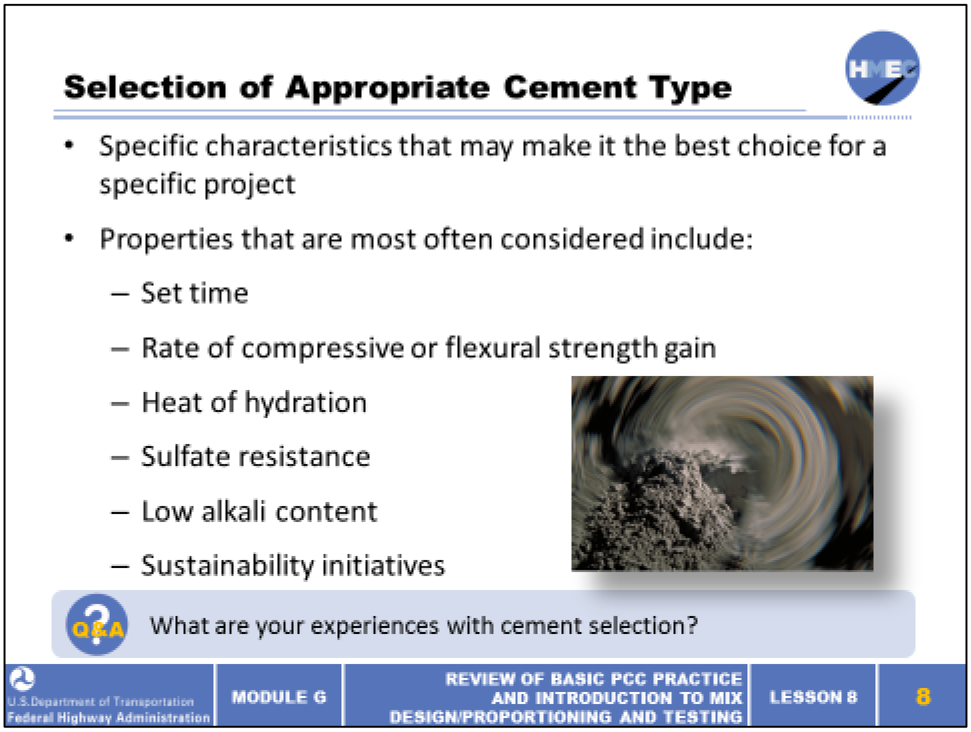
____

Slide 7



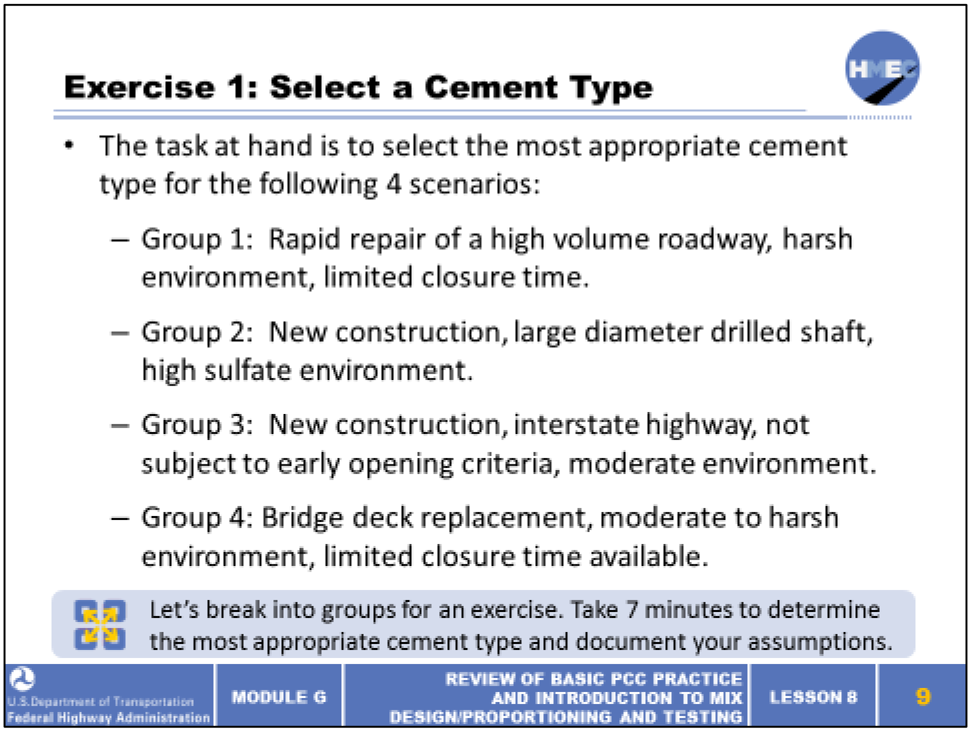
The blended hydraulic cements are becoming increasingly popular because they offer the benefit of complete and uniform blending of the materials.

Slide 8

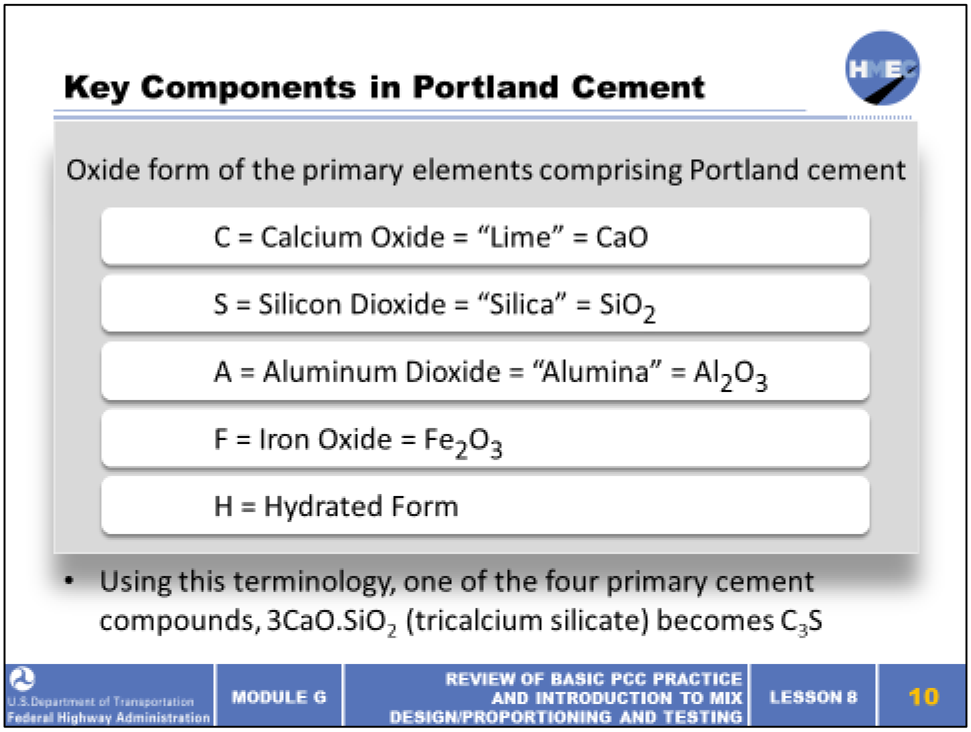


The availability and economy may figure strongly into the final decision as to the selected cement type.

Slide 9

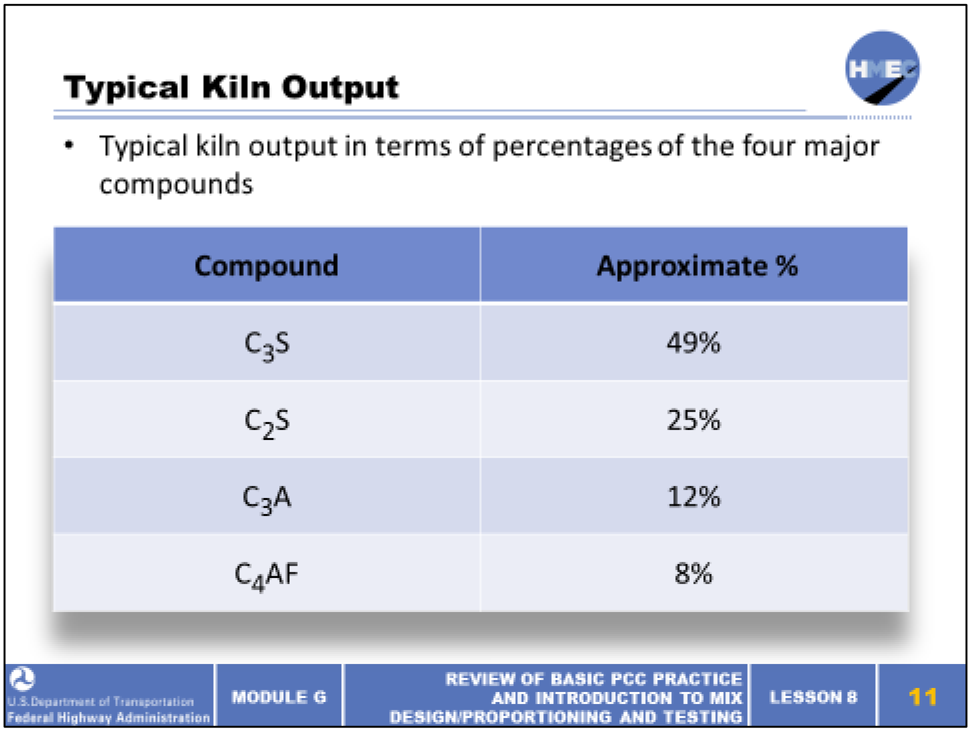

Exercise 1: Select a Cement Type
HMEC
The task at hand is to select the most appropriate cement type for the following 4 scenarios:
– Group 1: Rapid repair of a high volume roadway, harsh environment, limited closure time.
– Group 2: New construction, large diameter drilled shaft, high sulfate environment.
– 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.
U.S. Department of Transportation Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
9

Slide 10



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.

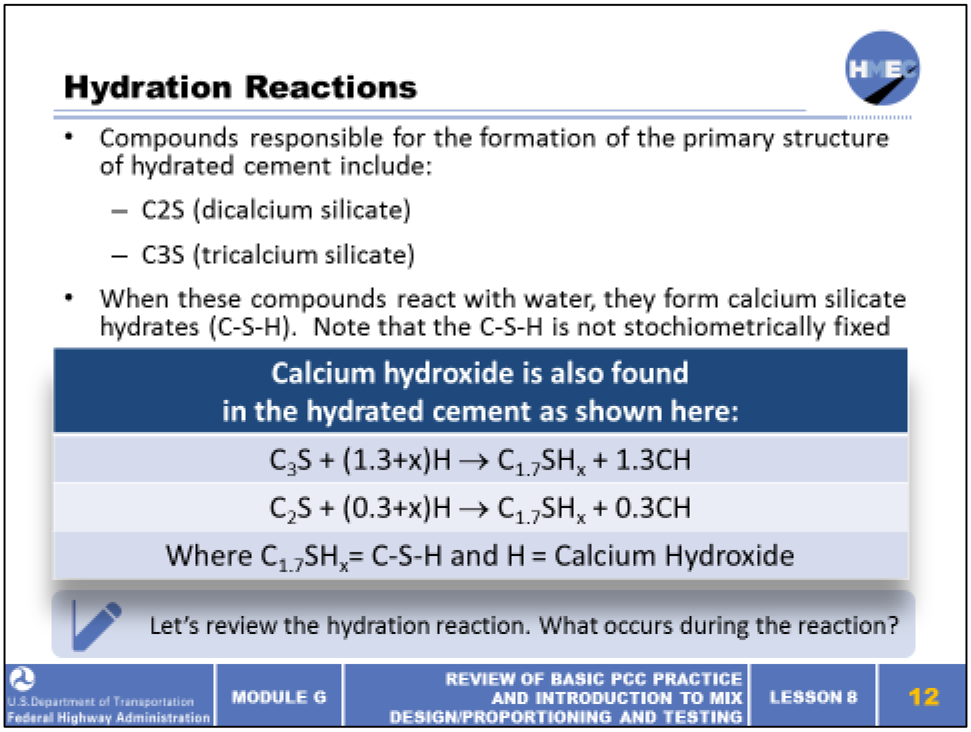
Slide 11



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.

Slide 12



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 C_3A). This is a reversible reaction with monosulfoaluminate.

____

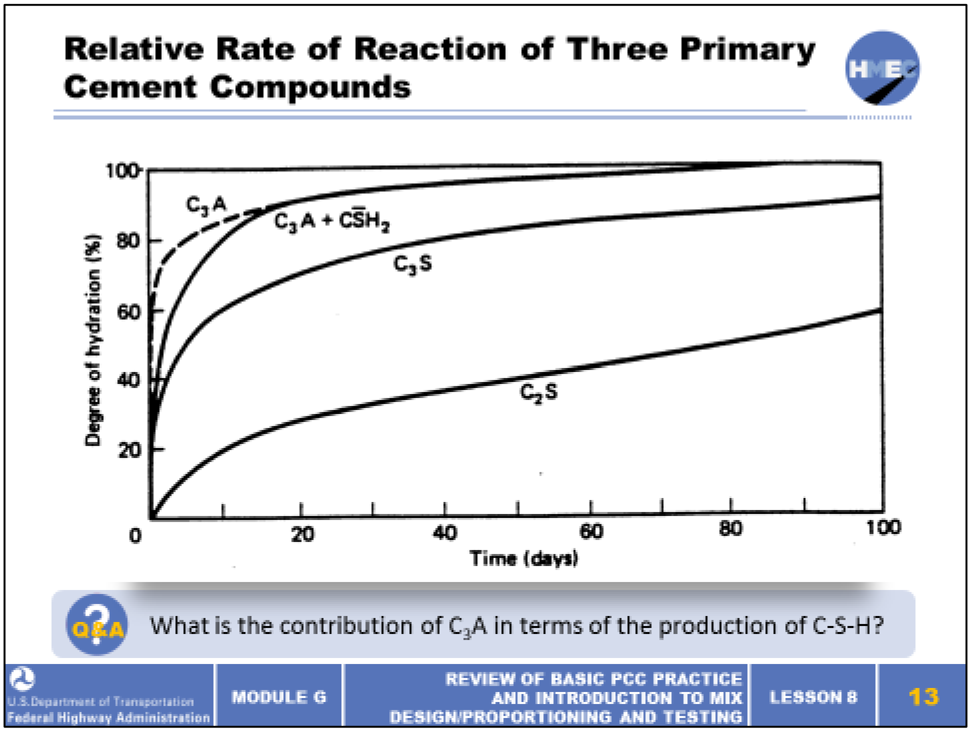
____

____

____

____

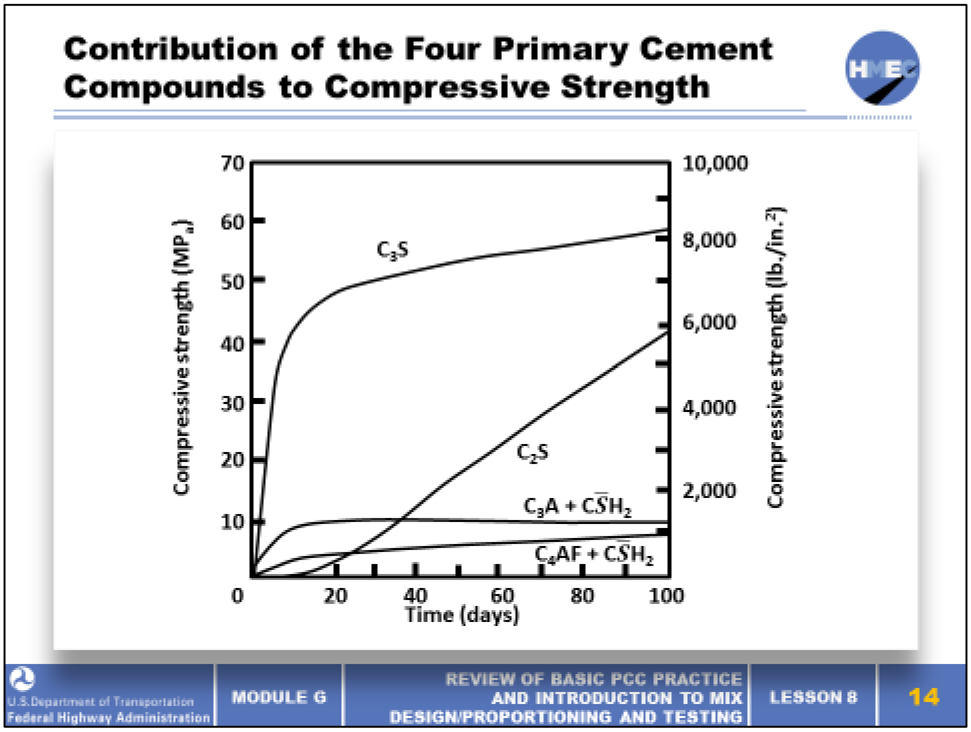
Slide 13



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.

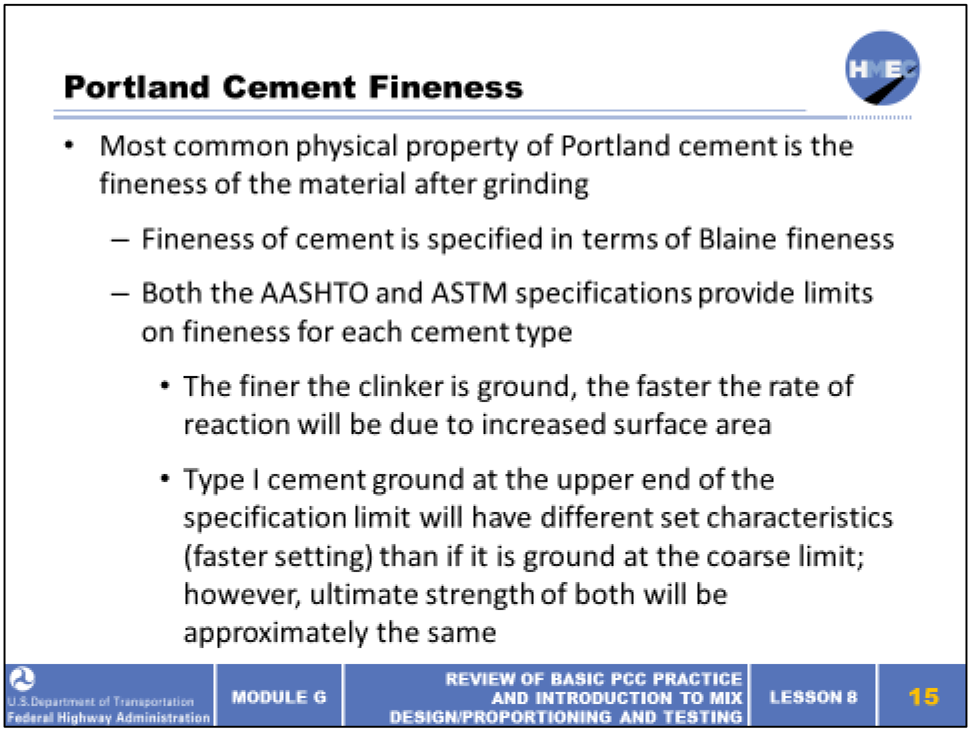
Note that C_4AF is not shown.

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

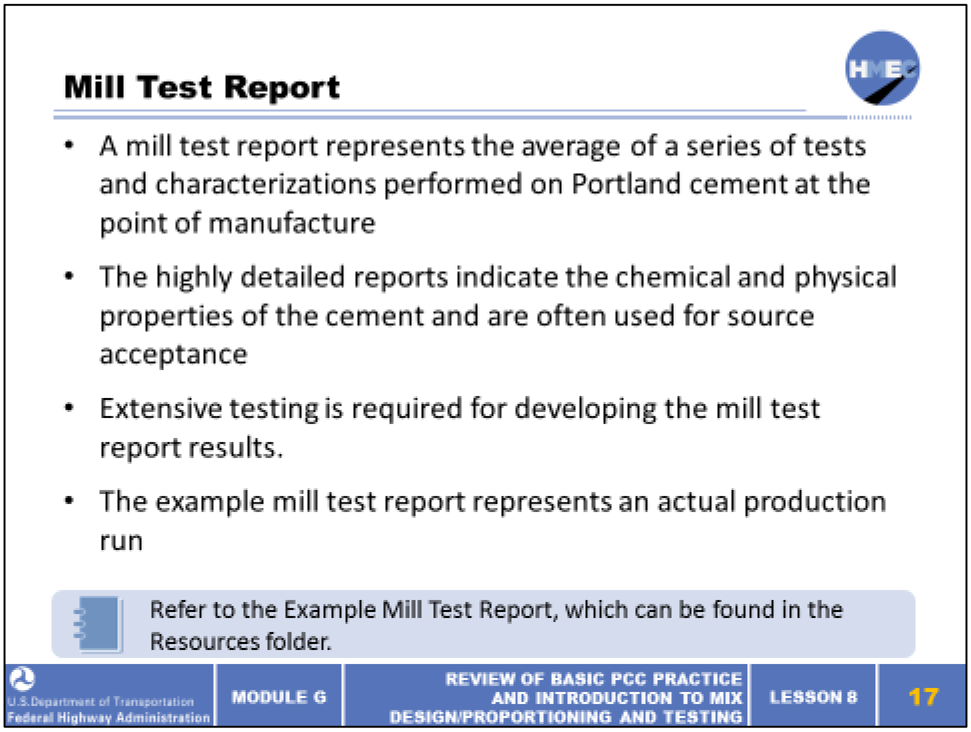


The most common physical property of Portland cement is the fineness of the material after grinding. The fineness of cement is specified in terms of the Blaine fineness. Both the AASHTO and ASTM specifications provide limits on fineness for each cement type. The reason that fineness is important is that 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

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

Slide 17



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 diffration, x-ray fluorescence and numerous others.

Slide 18

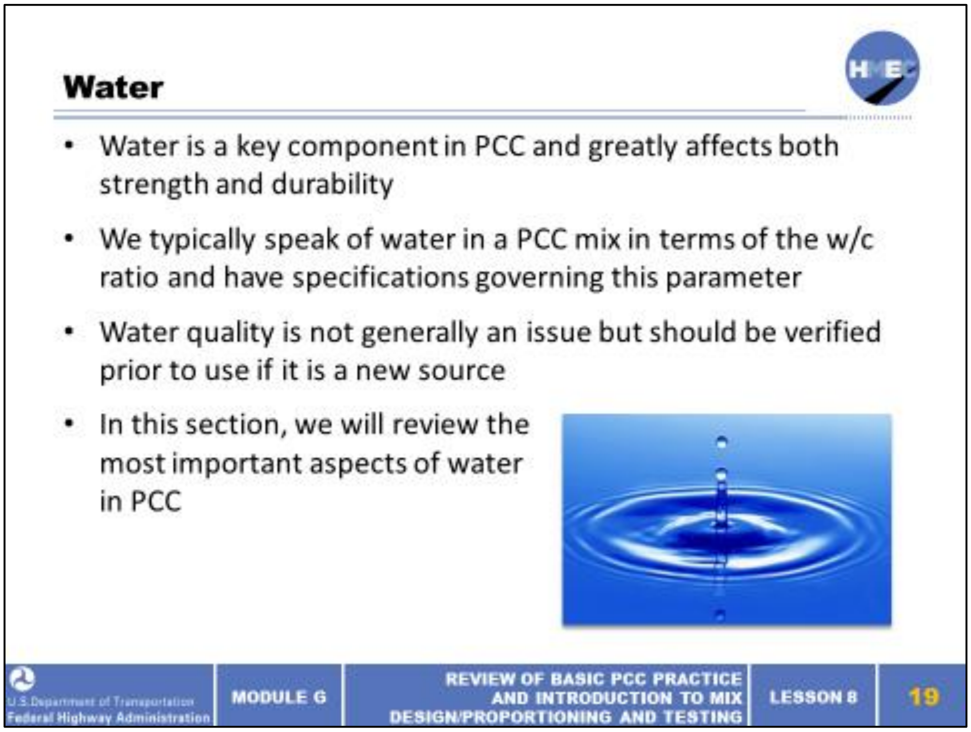
Exercise 2: Portland Cement Acceptance Plan by State

- 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?

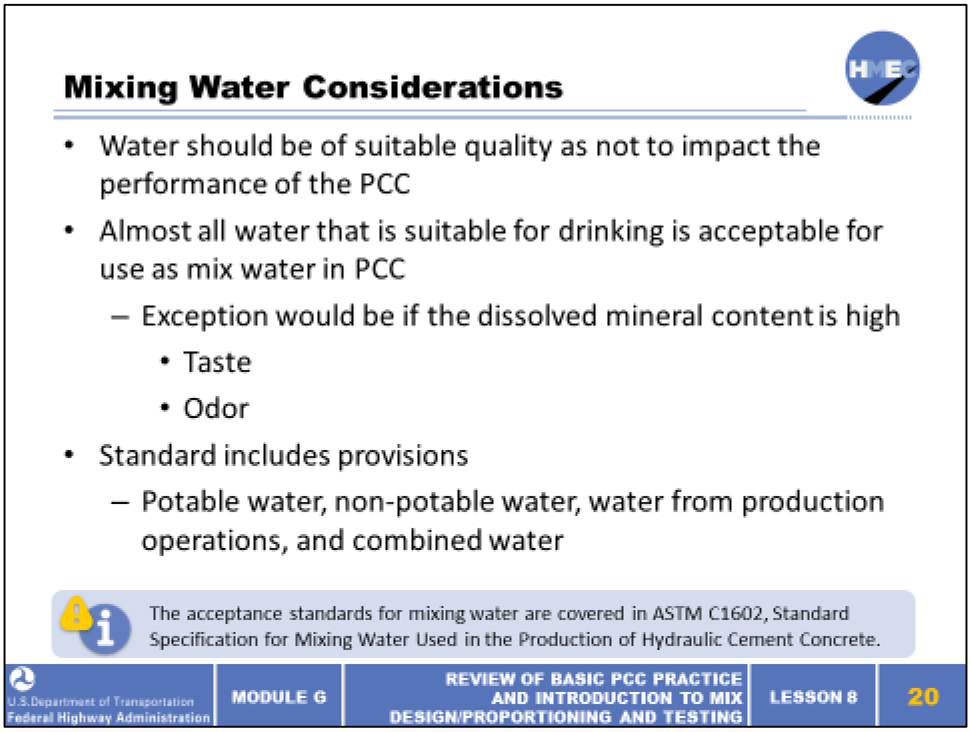
U.S. Department of Transportation Federal Highway Administration | MODULE G | REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING | LESSON 8 | 18

Slide 19



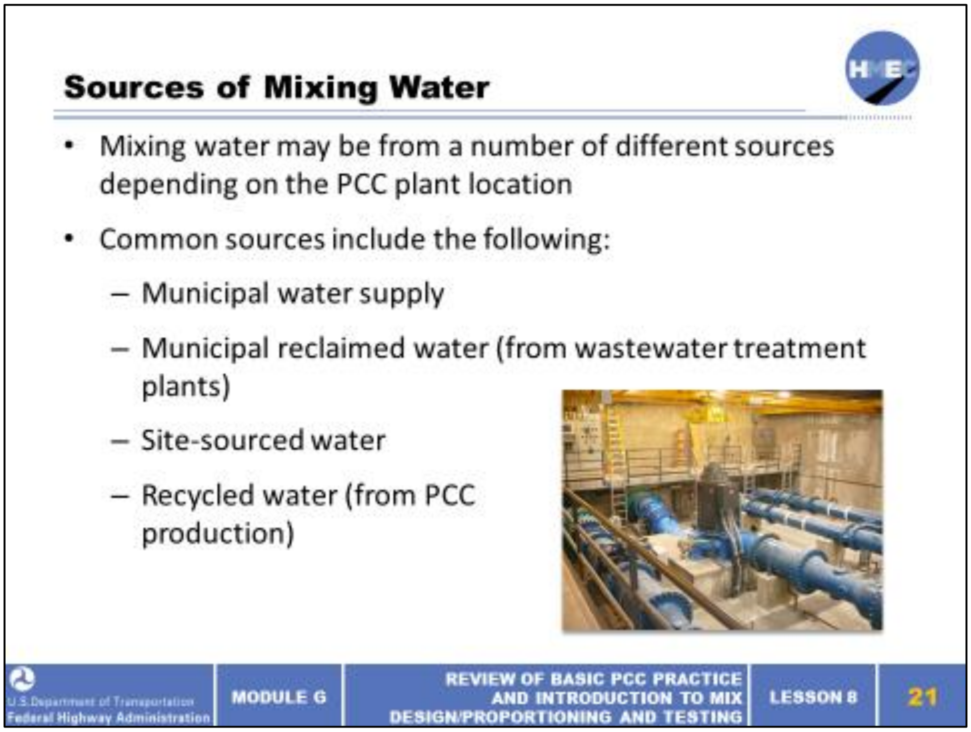
Water plays an important role in both fresh and hardened PCC.

Slide 20



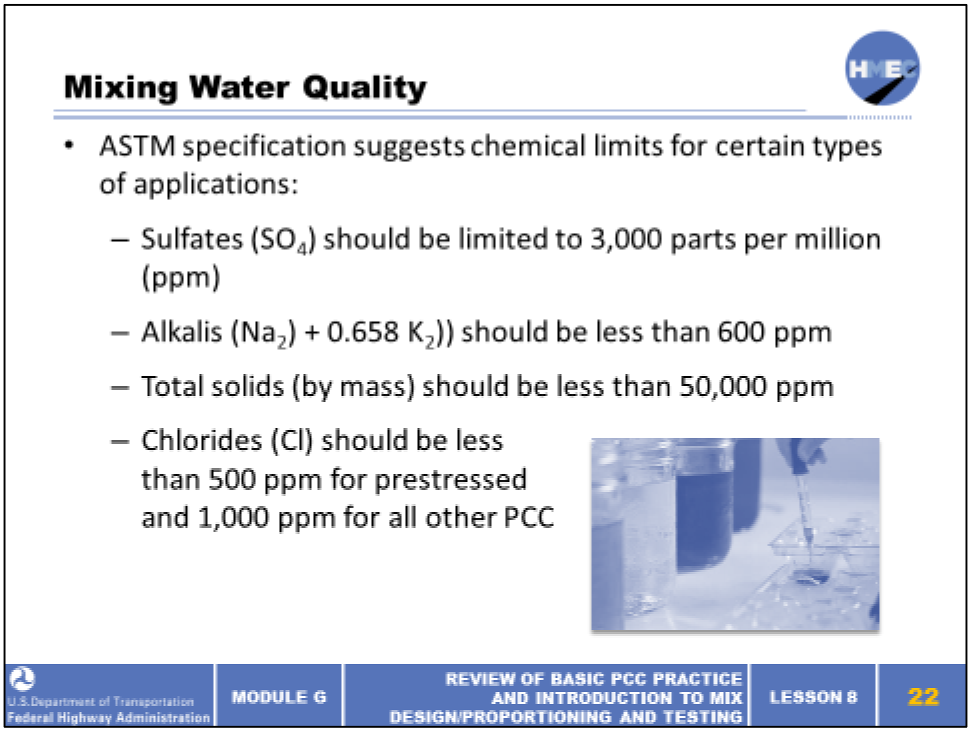
The ASTM standard includes provisions for potable water, non-potable water, water from production operations, and combined water. Under the specification guidelines, all potable water is automatically qualified for used in PCC production. If the water from the other sources is questionable, it should 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.

Slide 21



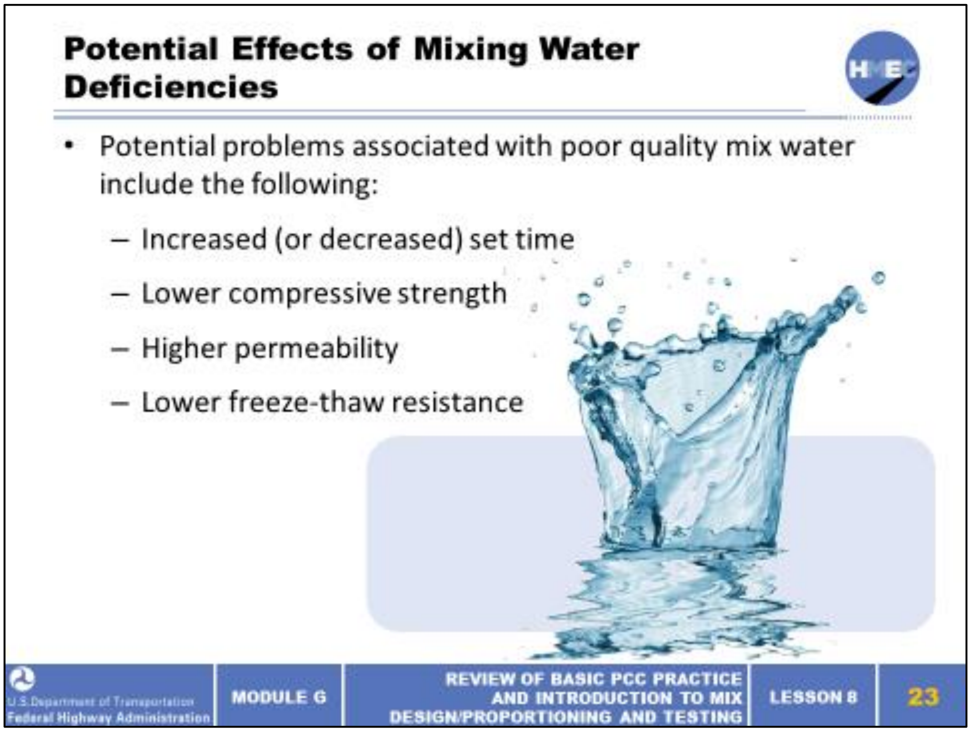
These water sources may be used with the limitations.

Slide 22



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.

Slide 23



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.

____

____

____

____

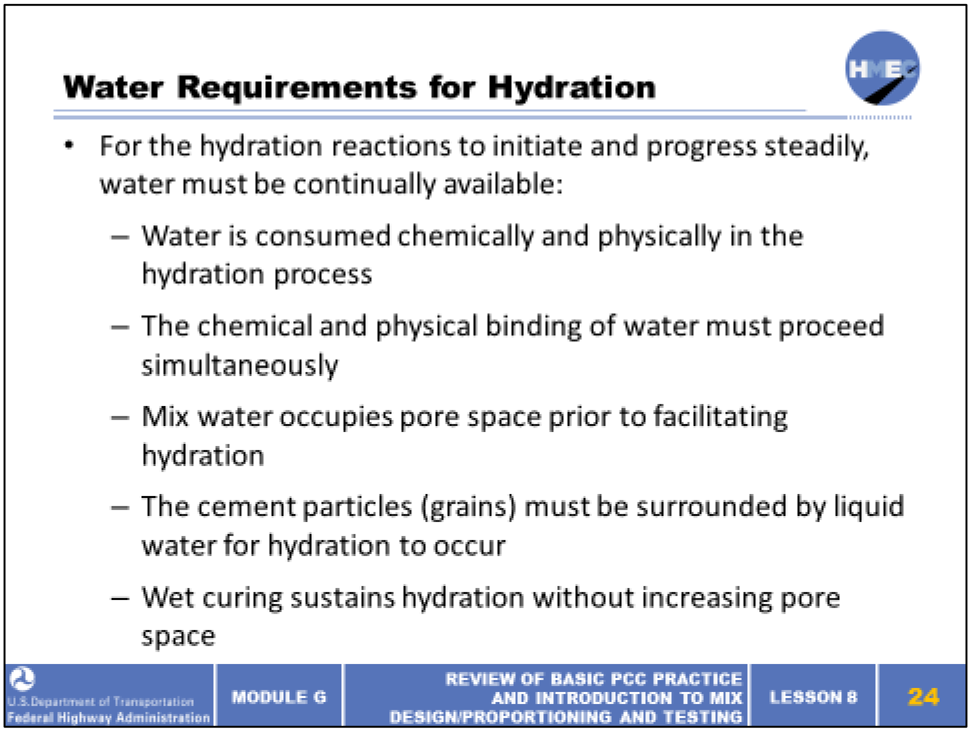
____

____

____

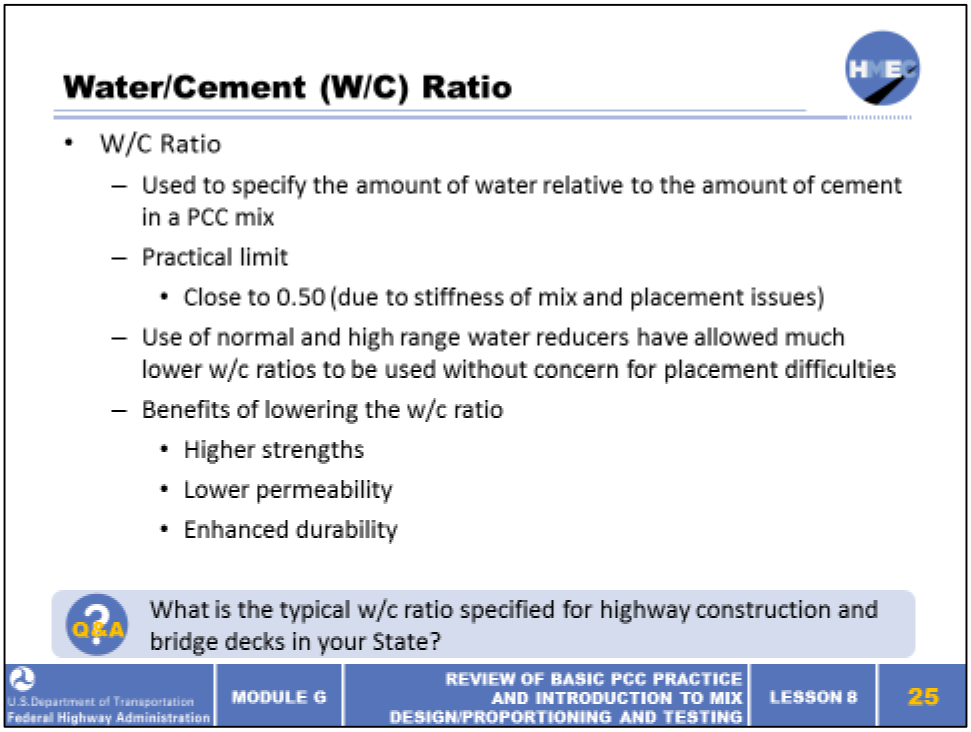
____

Slide 24



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.

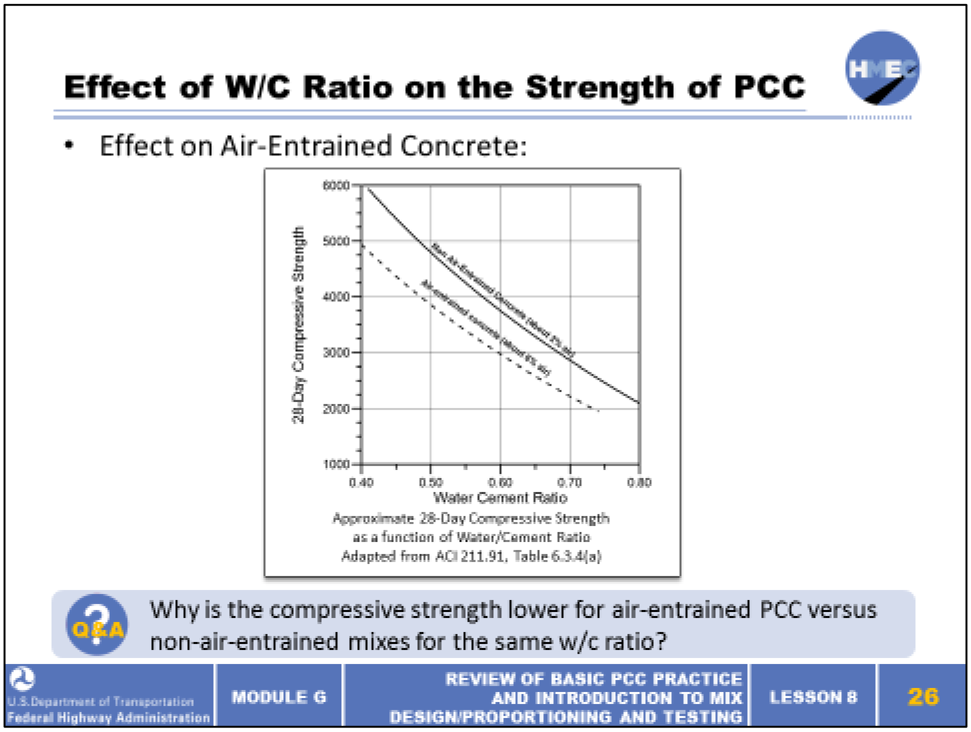
Slide 25

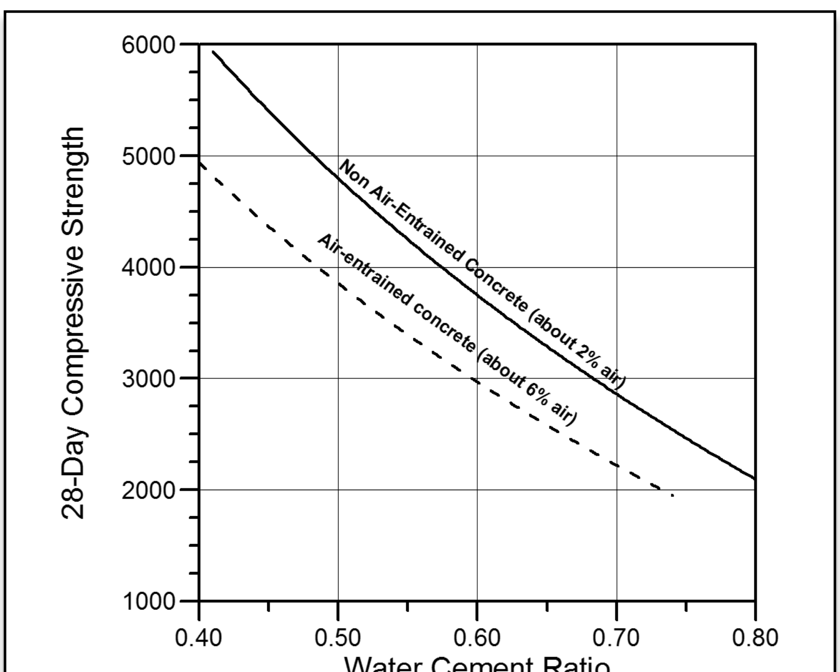


The term w/c ratio is used to specify the amount of water relative to the amount of cement in a PCC mix. We have equated higher strengths, lower permeability, enhanced durability, and other benefits with low w/c ratios.

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.

Slide 26





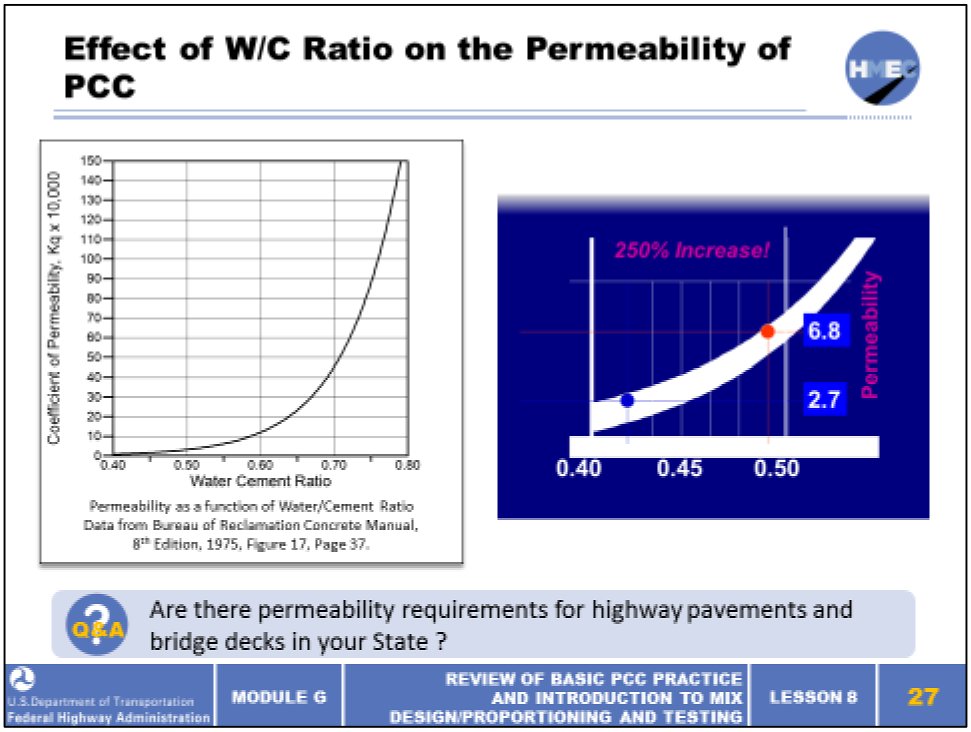
Approximate 28-Day Compressive Strength
as a function of Water/Cement Ratio
Adapted from ACI 211.91, Table 6.3.4(a)

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



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.

____

____

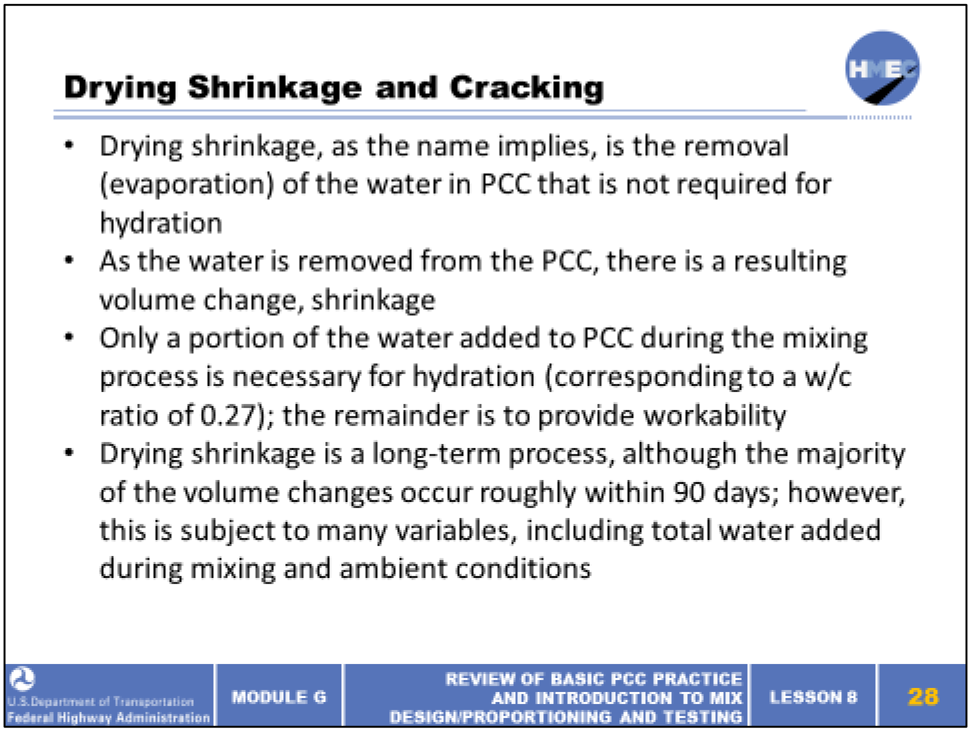
____

____

____

____

Slide 28

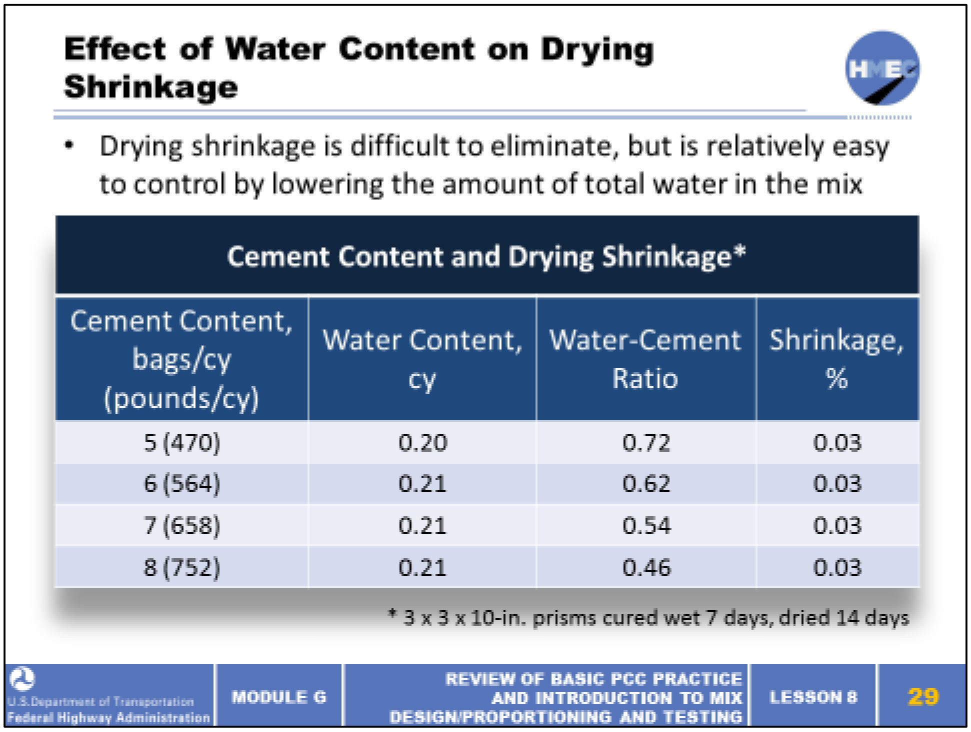


Drying shrinkage, as the name implies, is the removal (evaporation) of the water in PCC that is not required for hydration. As the water is removed from the PCC, there is a resulting volume change, shrinkage. Drying shrinkage refers to a volume change in PCC due to moisture loss.

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



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.

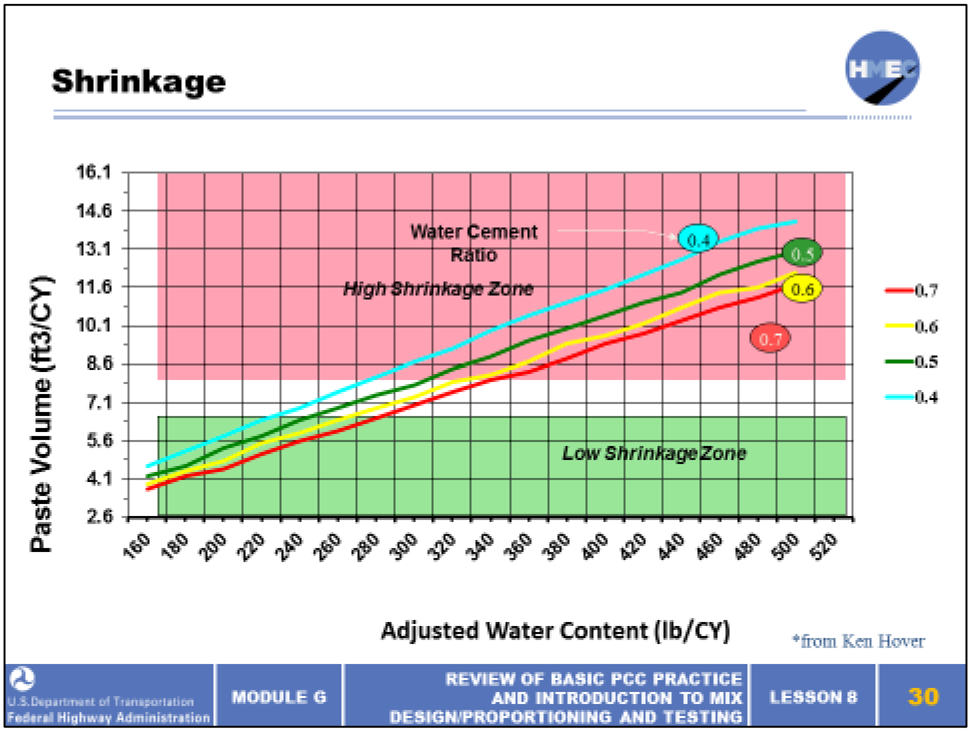
Taking this to the next level, you have to lower the cement content if you need to reduce the overall water content at an already low w/c ratio. We will discuss this in greater detail in the mix proportioning lesson.

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

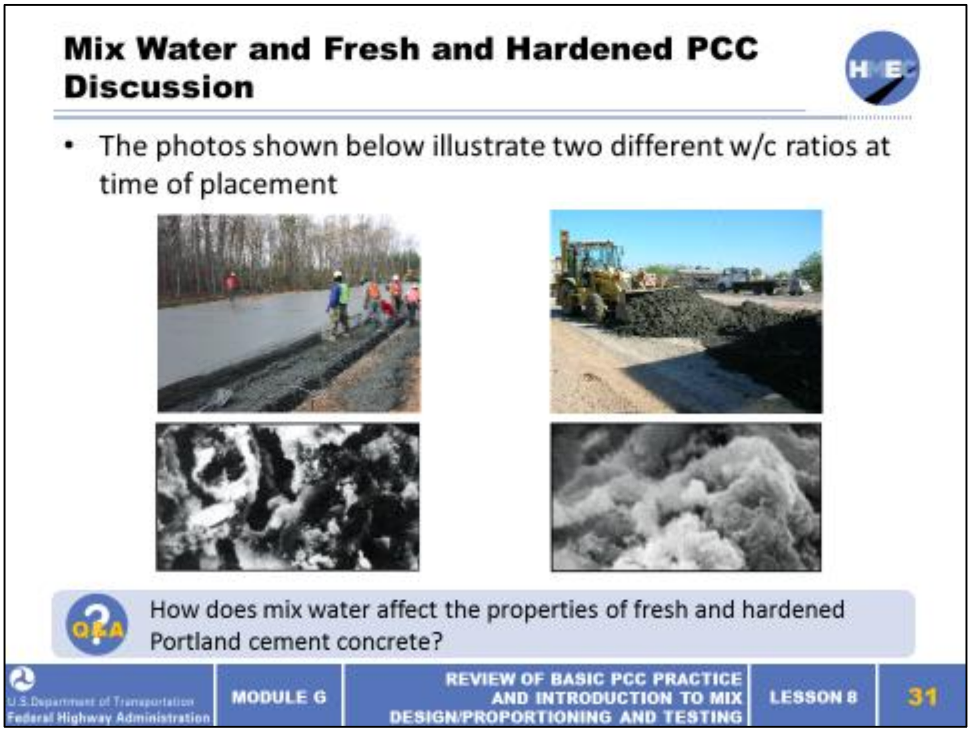
Note that 1 bag of cement weighs 94 lbs.

____

Slide 30


Shrinkage
HMEC
16.1
14.6
13.1
11.6
10.1
8.6
7.1
5.6
4.1
2.6
Paste Volume (ft3/CY)
Water Cement Ratio
High Shrinkage Zone
Low Shrinkage Zone
0.4
0.5
0.6
0.7
160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500 520
Adjusted Water Content (lb/CY)
*from Ken Hover
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
30

Slide 31



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.

____

____

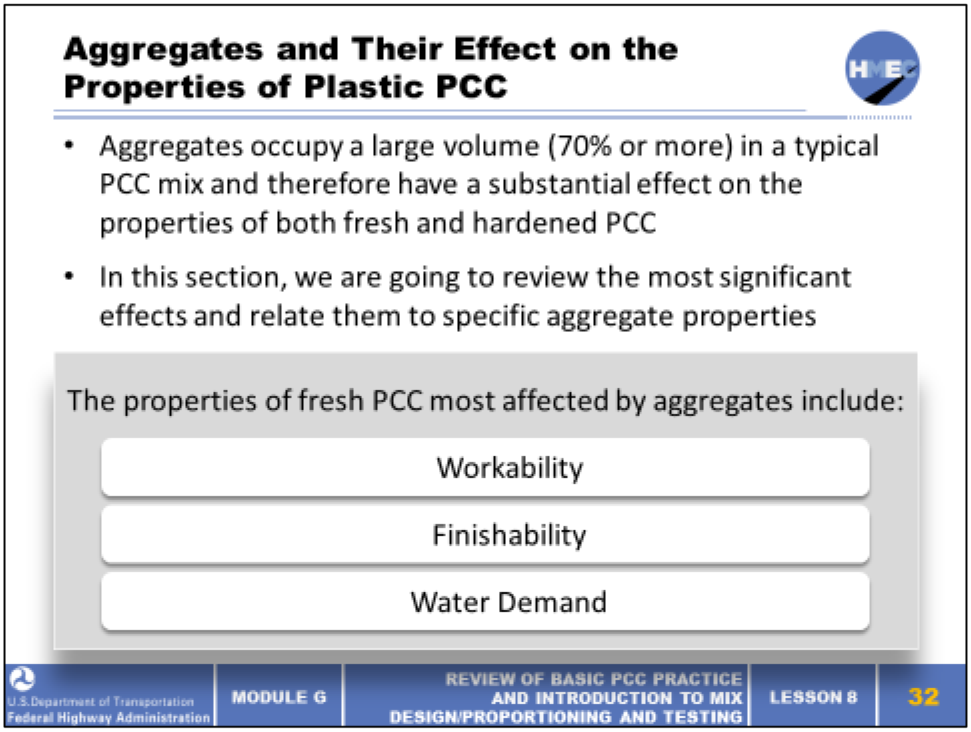
____

____

____

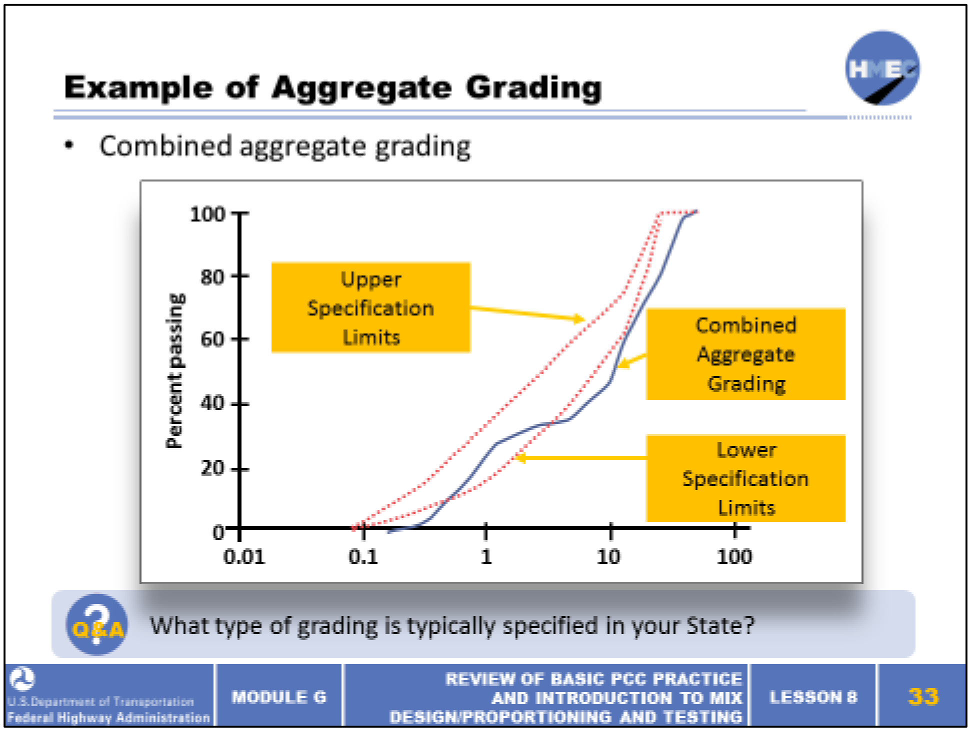
____

Slide 32



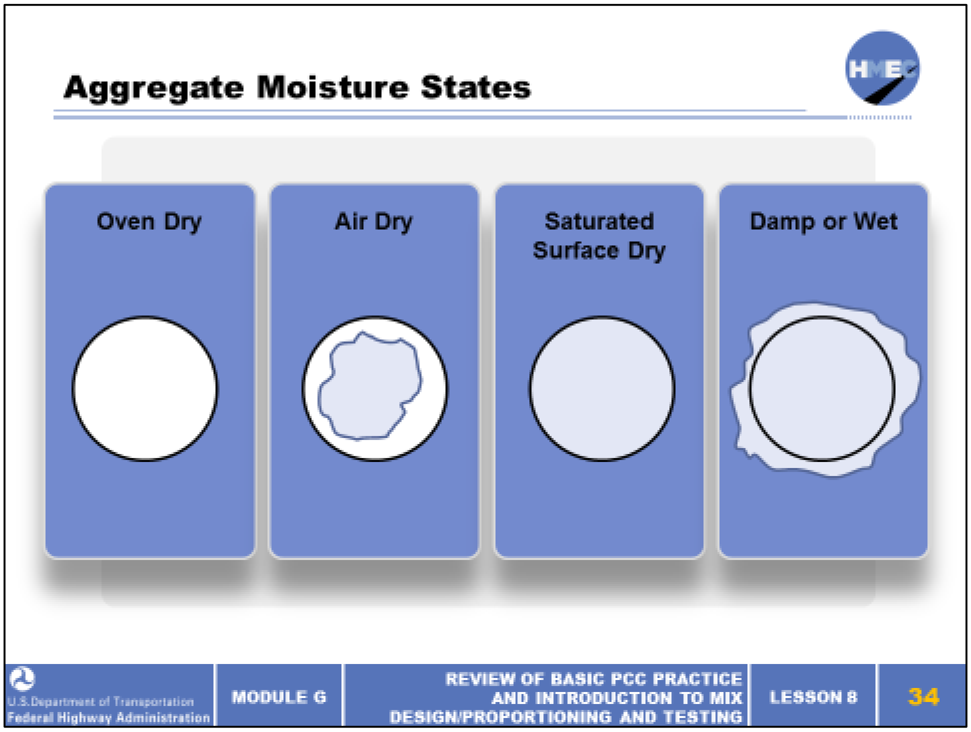
Aggregate properties along with w/c ratio, cement content, and admixtures are the primary factors controlling the properties of fresh PCC.

Slide 33



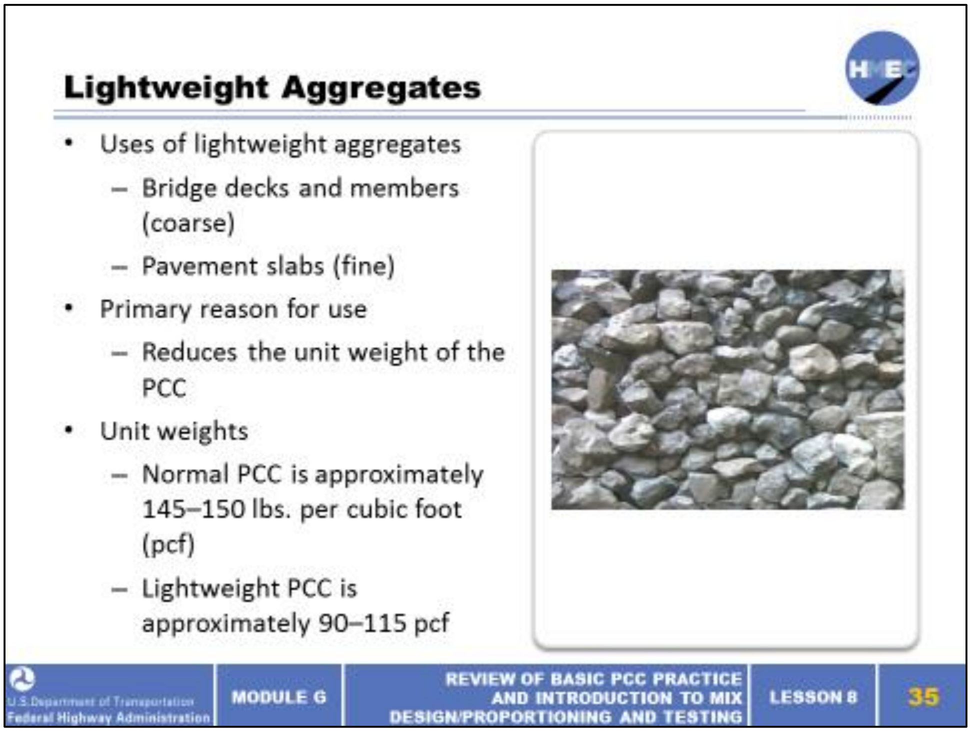
This example shows a combined aggregate grading, which is represented by the blue line. The upper and lower specification limits for this aggregate are shown by the two red dashed lines. Note that the gradation shown falls outside of the specifications on the lower bound.

Slide 34



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



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.

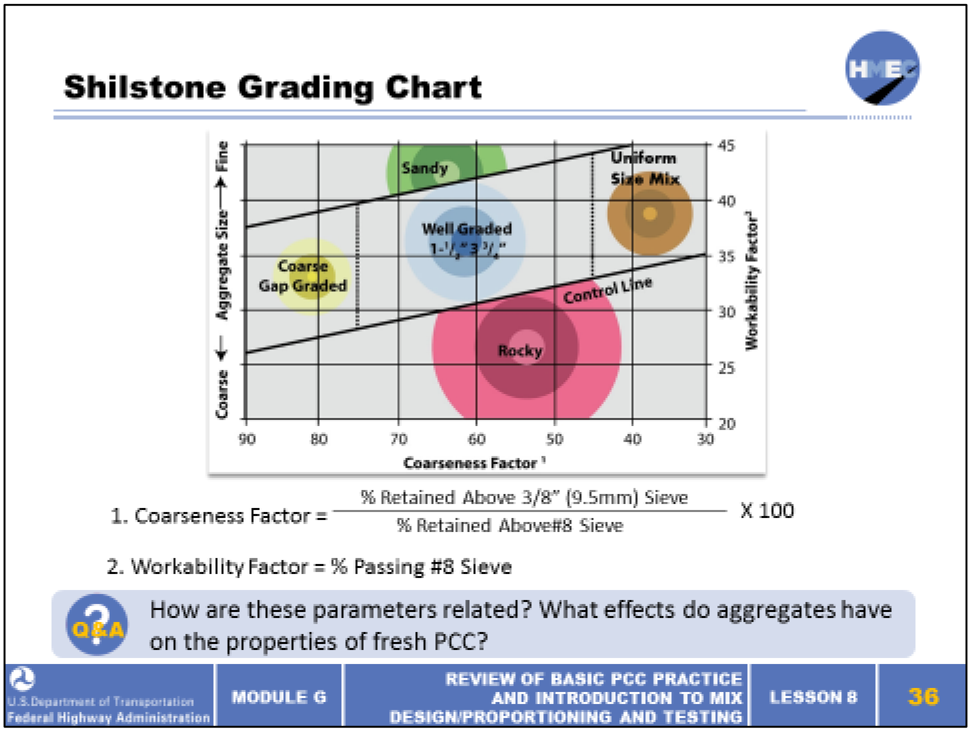
Lightweight aggregates are naturally occurring (volcanic) or manufactured products with a high degree of internal void space. Lightweight coarse aggregates are used primarily in structures to reduce the amount of dead load. Lightweight fine aggregates are sometimes used to provide internal curing by 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.

____

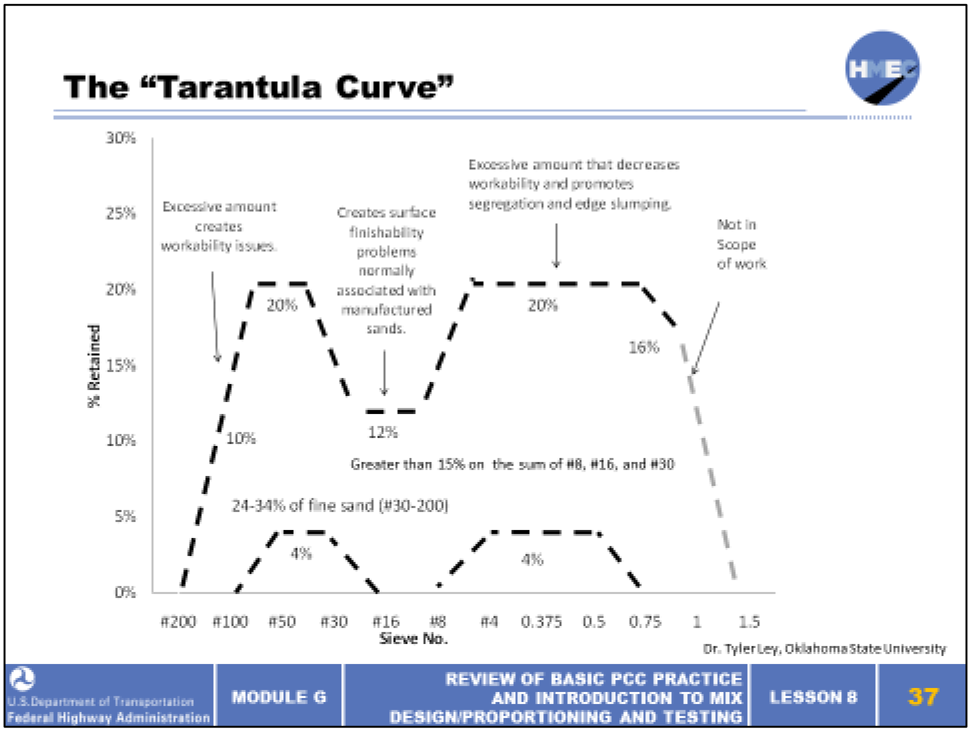
____

Slide 36

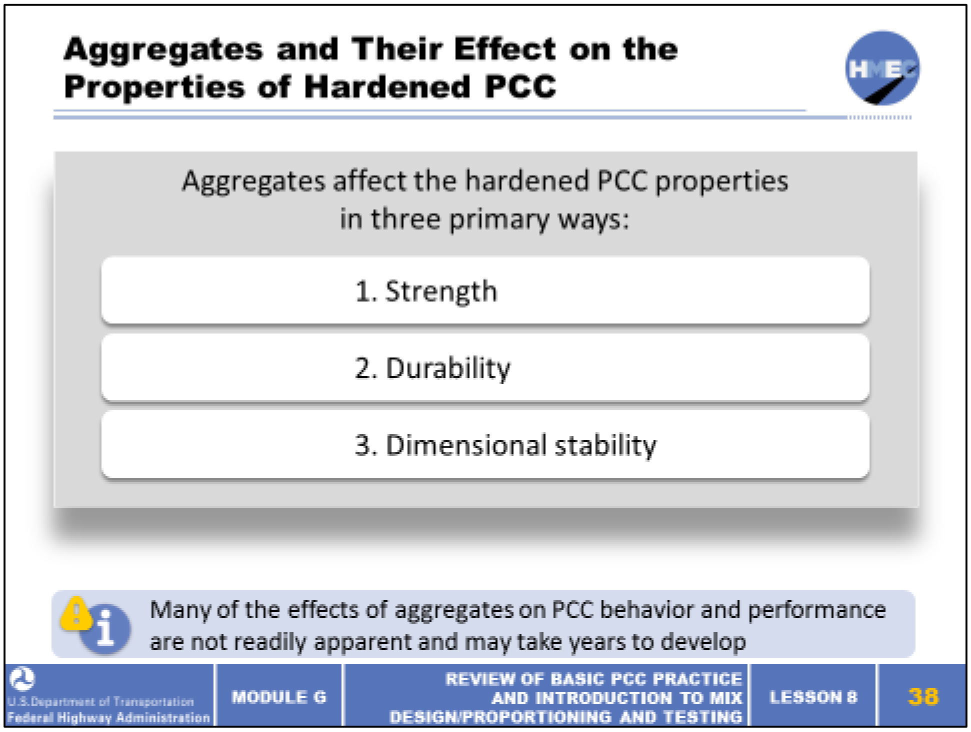


Shilstone Grading Chart
HMEC
Sandy
Uniform
Size Mix
Well Graded
1-1/2" 3/4"
Coarse
Gap Graded
Control Line
Rocky
Coarse ← Aggregate Size → Fine
Workability Factor 2
45
40
35
30
25
20
90
80
70
60
50
40
30
Coarseness Factor 1
1. Coarseness Factor = % Retained Above 3/8" (9.5mm) Sieve / % Retained Above#8 Sieve X 100
2. Workability Factor = % Passing #8 Sieve
Q&A
How are these parameters related? What effects do aggregates have on the properties of fresh PCC?
U.S.Department of Transportation
Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
36

Slide 37


The "Tarantula Curve"
HMEC
30%
25%
20%
15%
10%
5%
0%
% Retained
Excessive amount creates workability issues.
Creates surface finishability problems normally associated with manufactured sands.
Excessive amount that decreases workability and promotes segregation and edge slumping.
Not in Scope of work
20%
20%
16%
10%
12%
Greater than 15% on the sum of #8, #16, and #30
24-34% of fine sand (#30-200)
4%
4%
#200 #100 #50 #30 #16 #8 #4 0.375 0.5 0.75 1 1.5
Sieve No.
Dr. Tyler Ley, Oklahoma State University
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
37

Slide 38



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

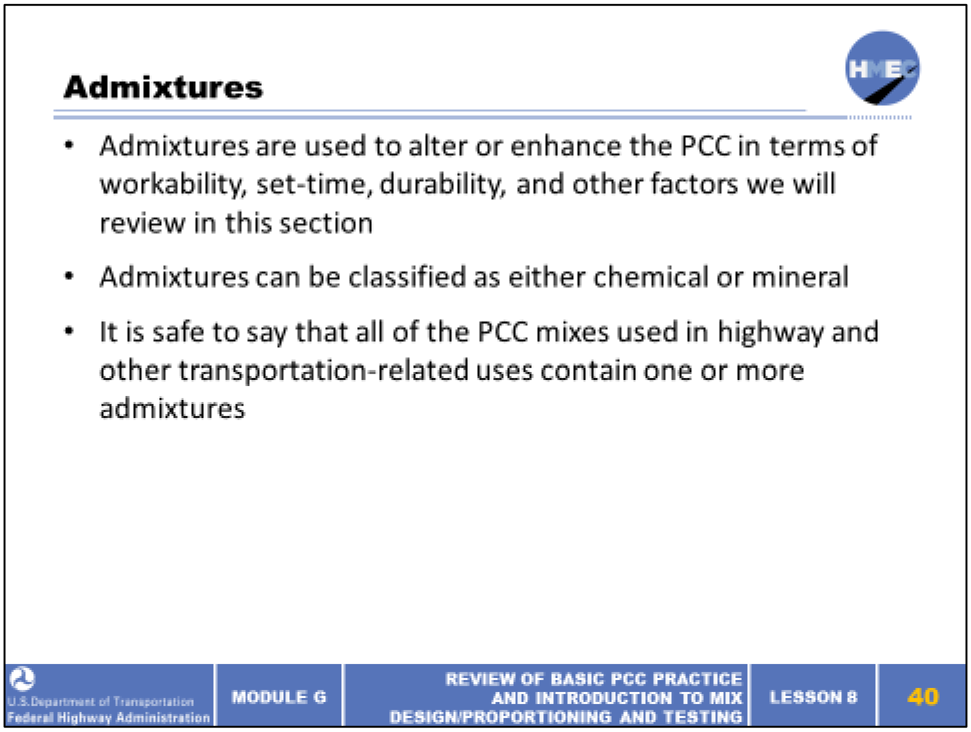
Factors Affecting Alkali-Silica Reactivity (ASR)

- 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

U.S. Department of Transportation Federal Highway Administration | MODULE G | REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING | LESSON 8 | 39

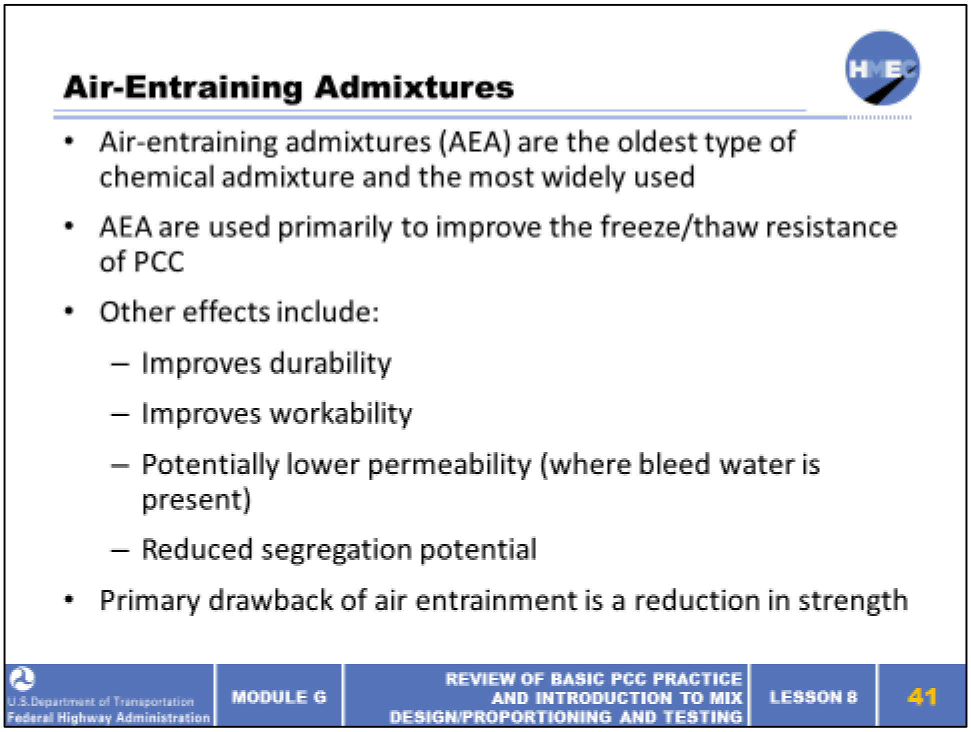
Aggregate selection, cement type, mix design, pozzolan additions, etc., all play a role in the potential for and the severity of ASR. Specifications should be written in such a way that one or more of these factors is controlled so as to eliminate ASR.

Slide 40



Admixtures 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.

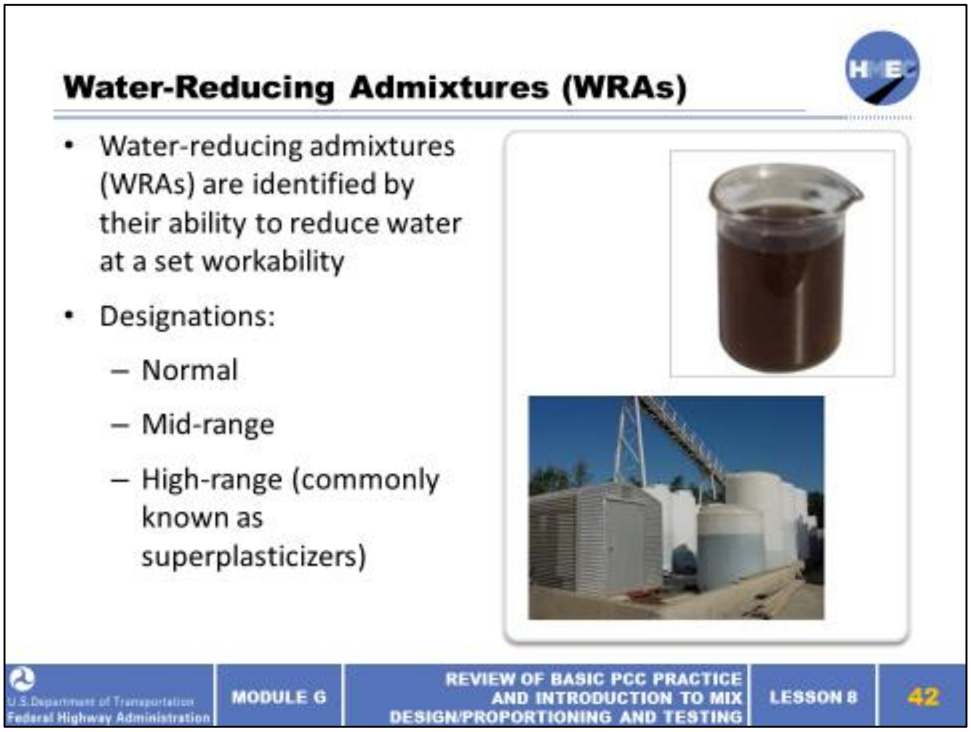
Slide 41



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.

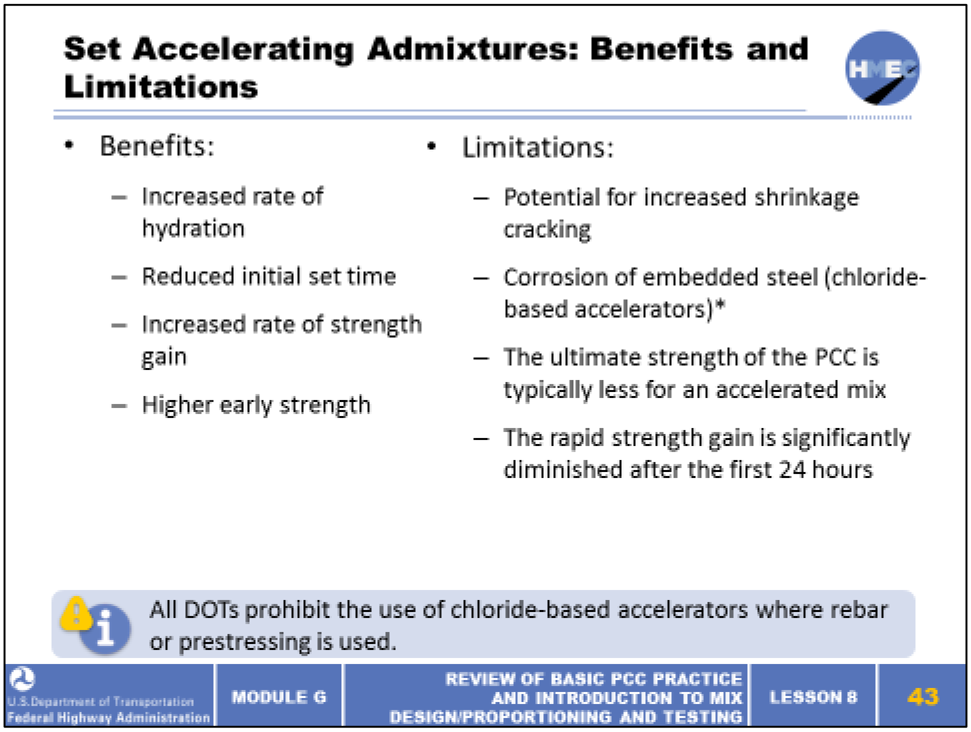
These benefits typically outweigh the loss in strength. The improved workability is due to the lubricating properties of entrained air. Consider the entrained air bubbles as acting similar to microscopic ball bearings, thereby allowing the aggregate particles to reorient more readily. If the workability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

Slide 42



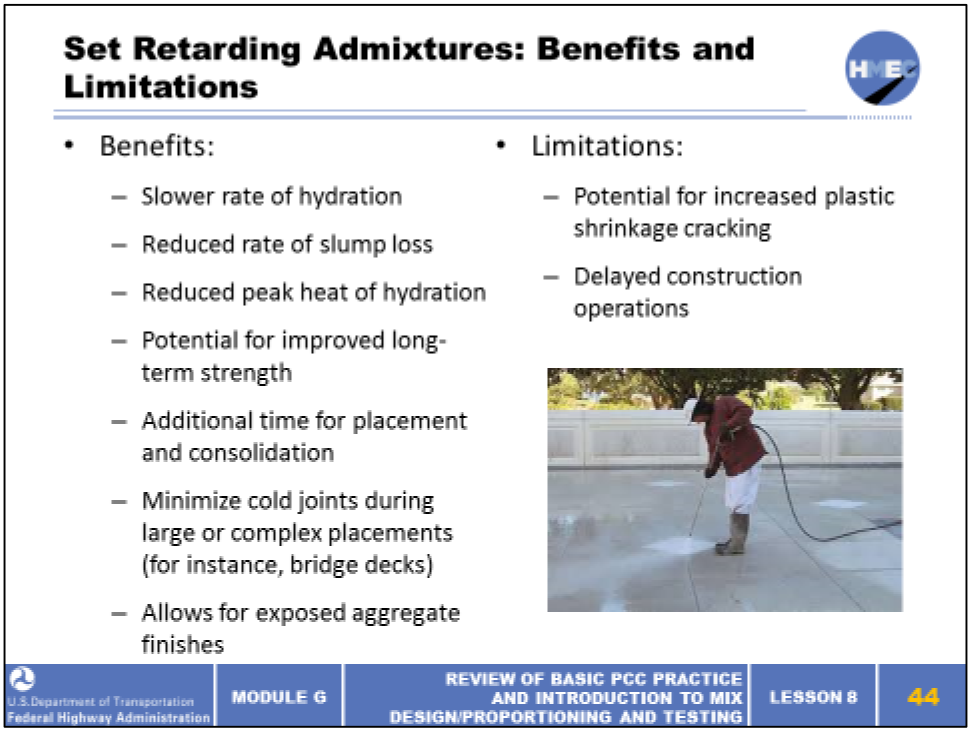
Water-reducing admixtures (WRAs) are identified by their ability to reduce water at a set workability. The three designations listed perform the same basic function of allowing the use of a reduced amount of water while maintaining workability.

Slide 43



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 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.

____

____

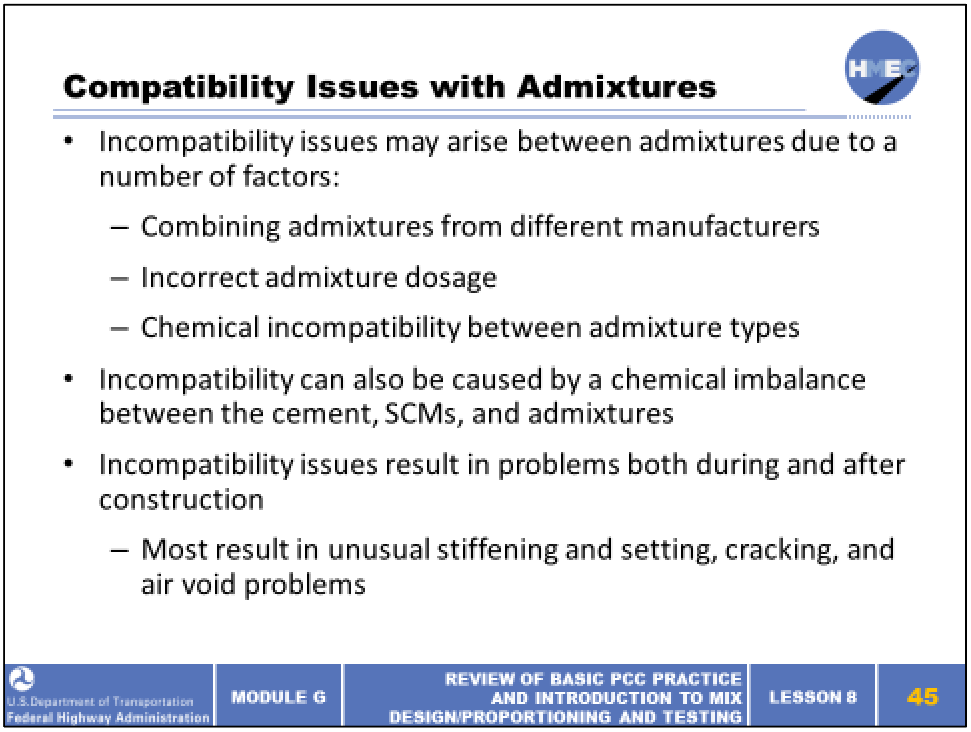
____

____

____

____

Slide 45



Compatibility issues 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.

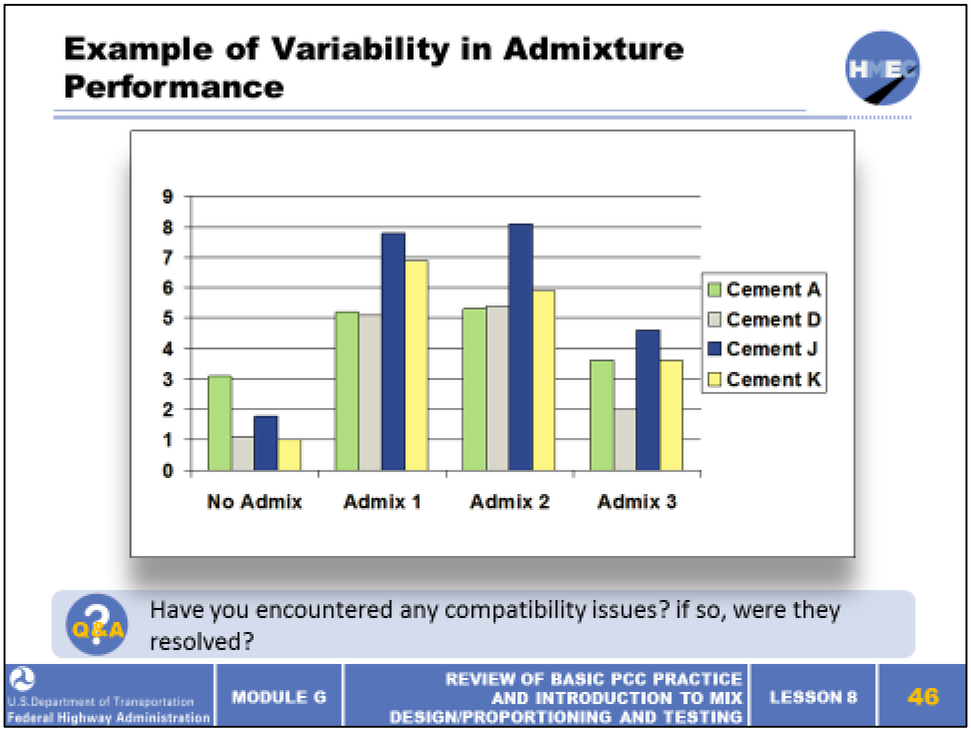
____

____

____

____

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

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.

____

____

____

____

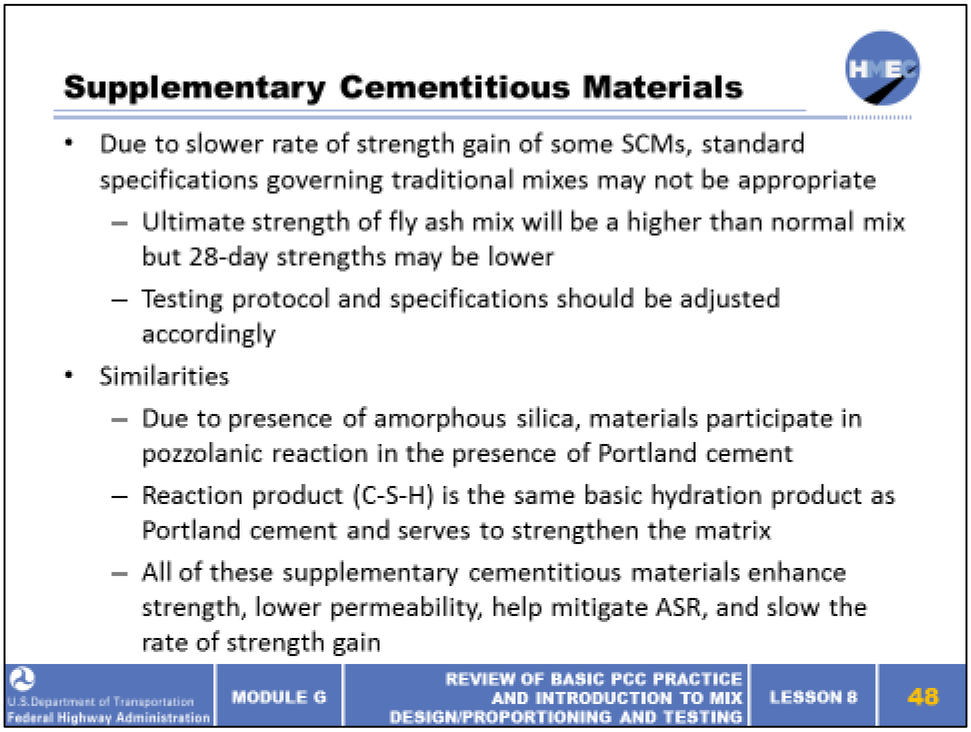
____

____

____

____

Slide 48



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 than 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

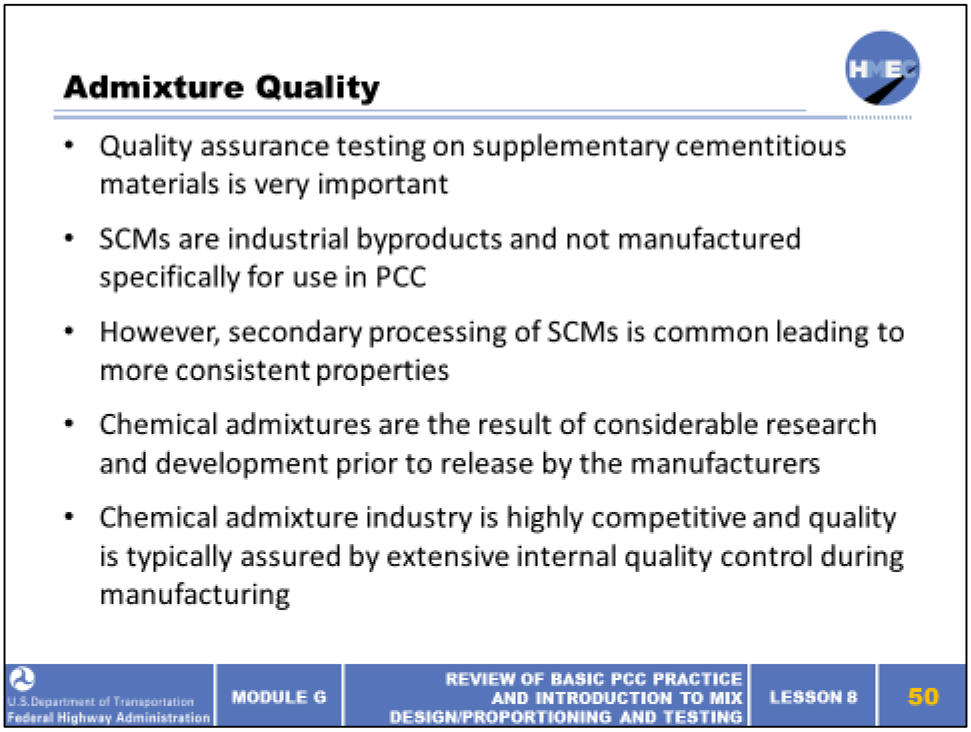
- In order to understand incompatibility issues, consider the chemical makeup and interaction of the compounds within the "chemical system"
- Fly ash in a mix containing Type I cement is often a desirable addition
  - If the C_3A content of the fly ash is too high, there will be insufficient sulfates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

Q&A: Have you encountered any compatibility issues? If so, what were they and were they resolved?

U.S. Department of Transportation Federal Highway Administration | MODULE G | REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING | LESSON 8 | 49

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



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.

____

____

____

____

____

____

____

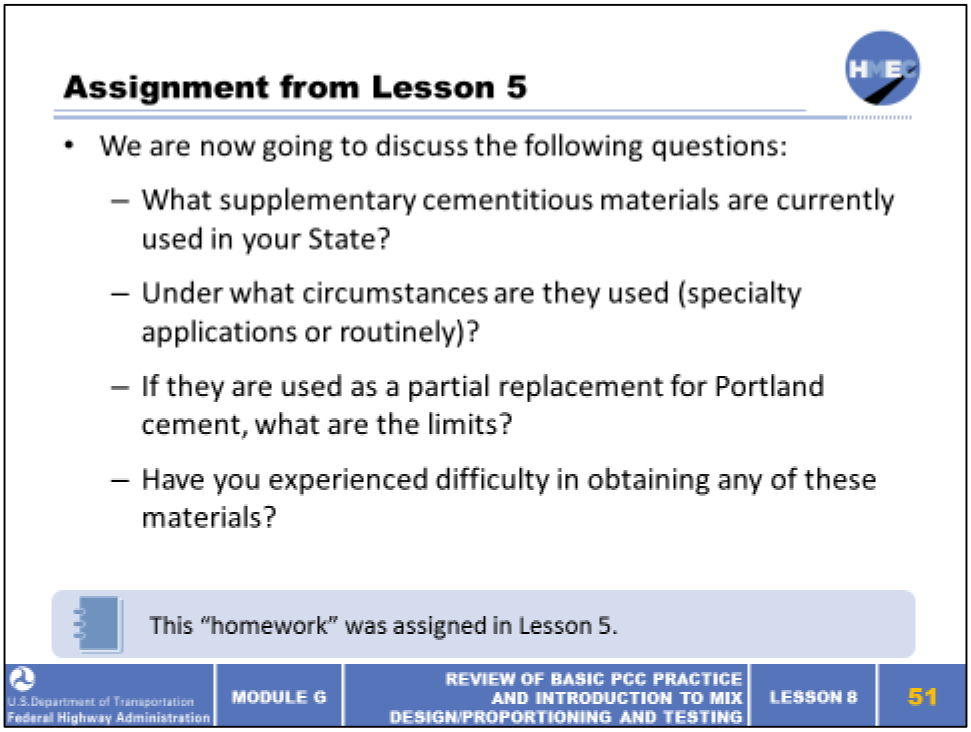
____

____

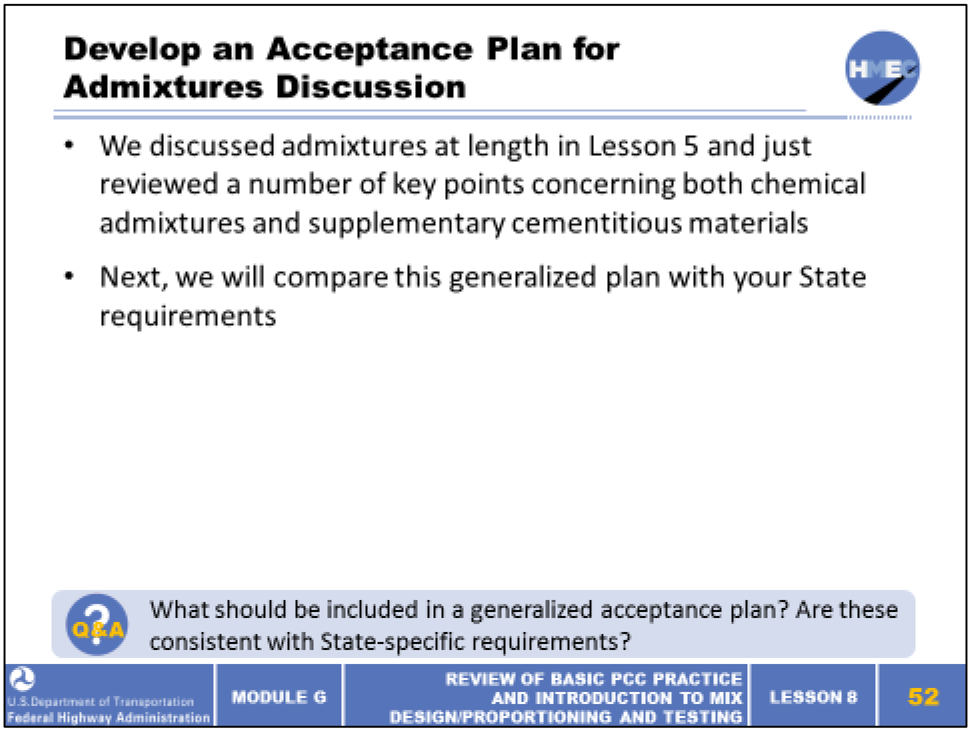
____

____

Slide 51

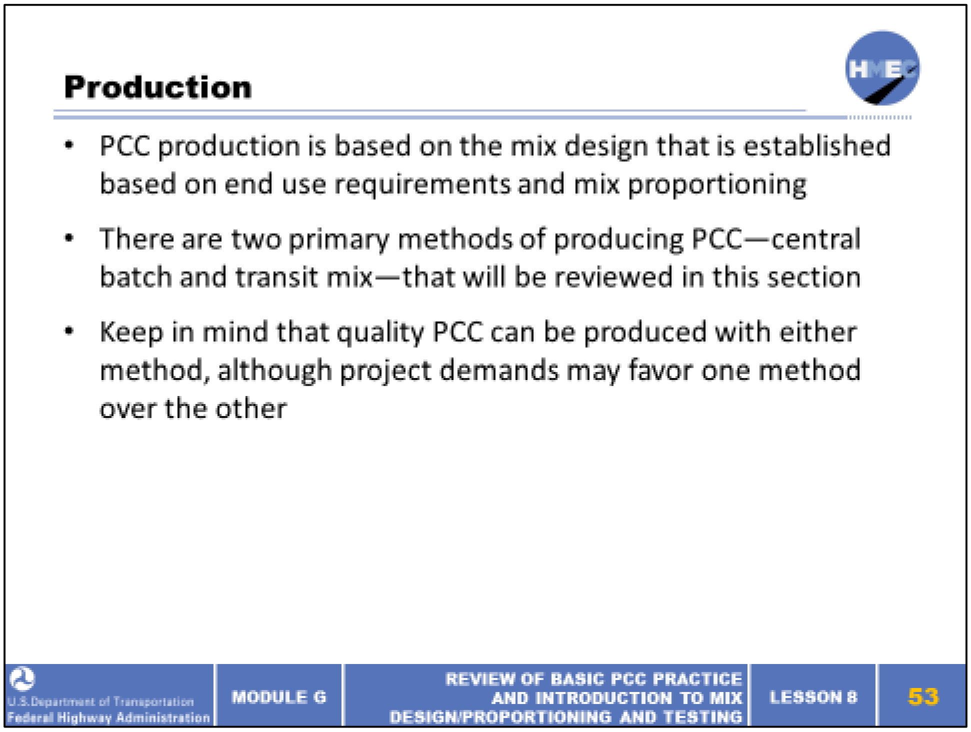

Assignment from Lesson 5
HMEC
• We are now going to discuss the following questions:
– What supplementary cementitious materials are currently used in your State?
– Under what circumstances are they used (specialty applications or routinely)?
– If they are used as a partial replacement for Portland cement, what are the limits?
– Have you experienced difficulty in obtaining any of these materials?
This "homework" was assigned in Lesson 5.
U.S. Department of Transportation Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
51

Slide 52



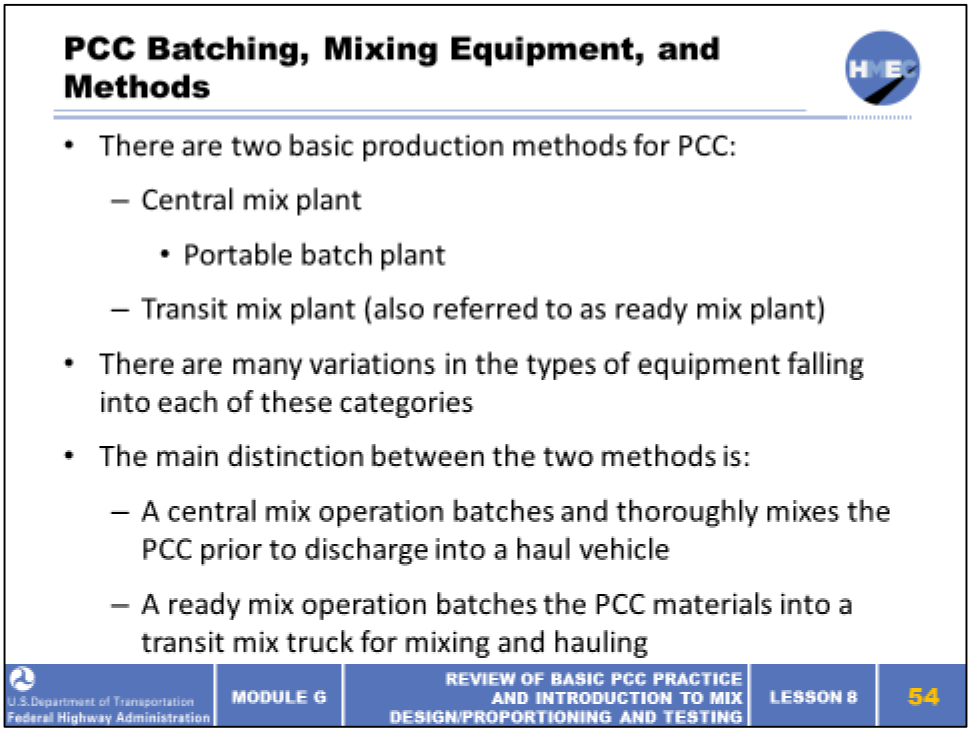
The objective is to discuss the necessary elements of a general acceptance plan for admixtures.

Slide 53



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



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.

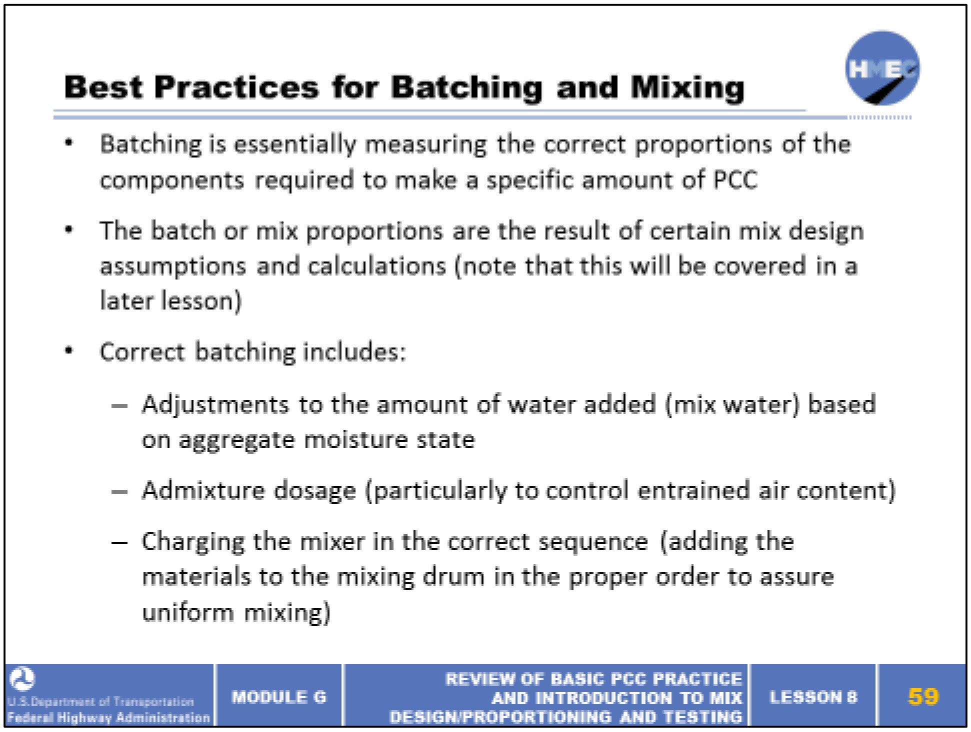
In this type of plant, all of the PCC constituents are charged into the transit trucks for mixing. Point out the key components of the plant, including the aggregate bin, conveyor, and silos. Also note the end loader that feeds aggregates to the plant where they are batched into the transit mix trucks 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.

Slide 58

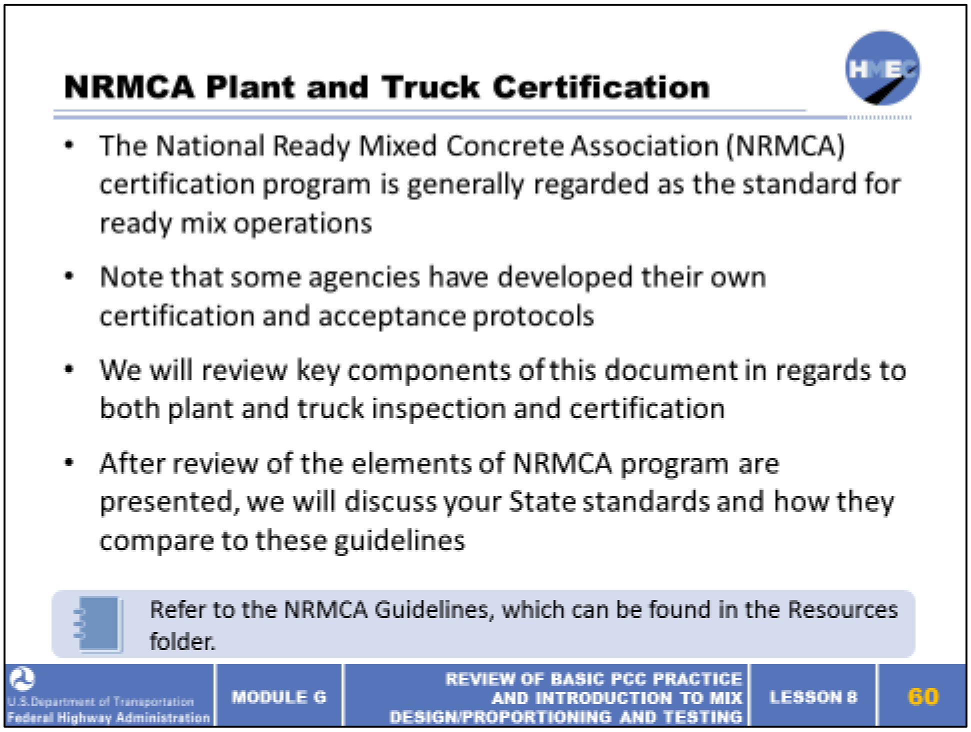
The photo shows a rear discharge transit mix truck. The mixing drum is visible as is the plant in the background. There are numerous variations in the configurations of these trucks, including front and rear discharge and a range of drum sizes.

Slide 59



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

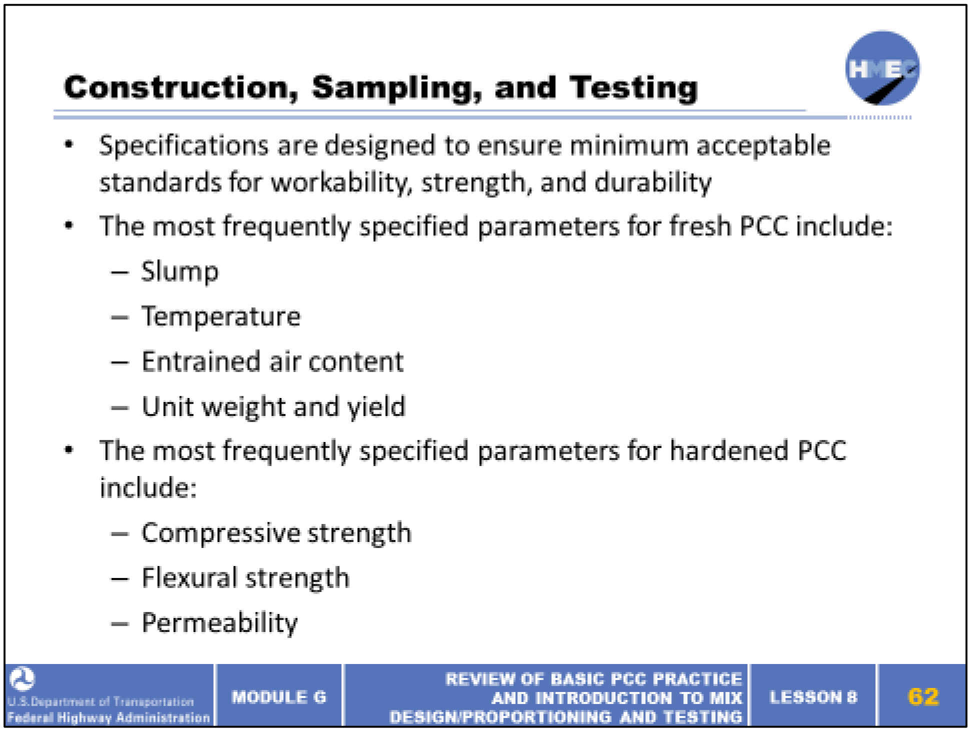


The NRMCA certification program covers all aspects of the production of PCC using ready mix facilities. Note that some agencies have developed their own certification and acceptance protocols.

Slide 61

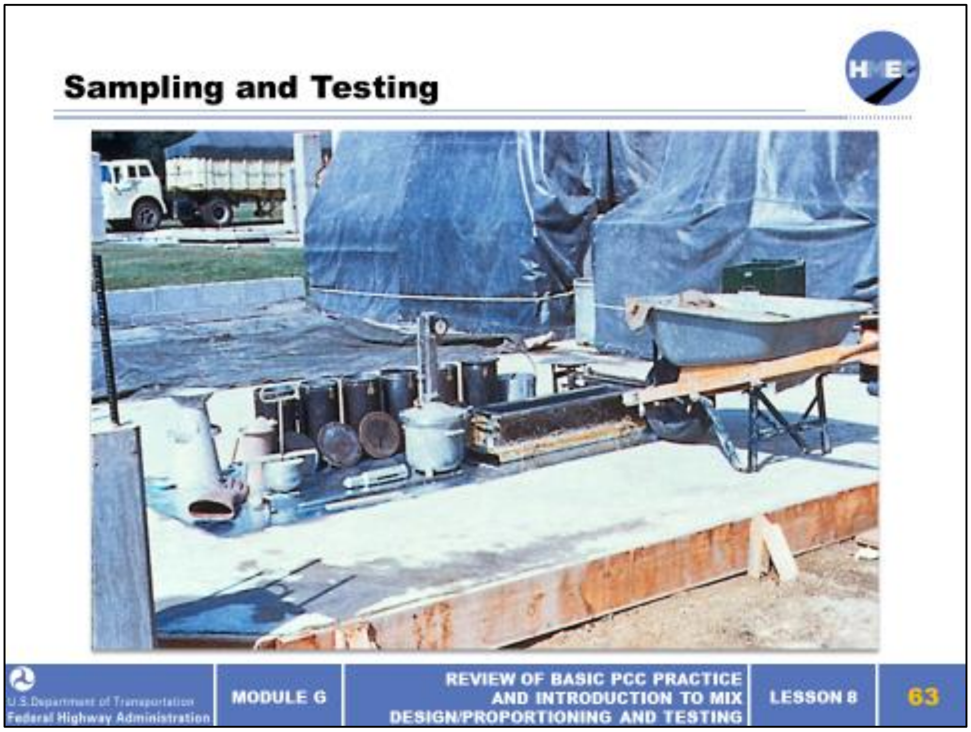

Developing an Acceptance Plan for
Production Facilities Discussion
NRMCA
How does your agency's evaluation process lead to approval of a plant for production?
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
61

Slide 62



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

Slide 63



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

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 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

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.

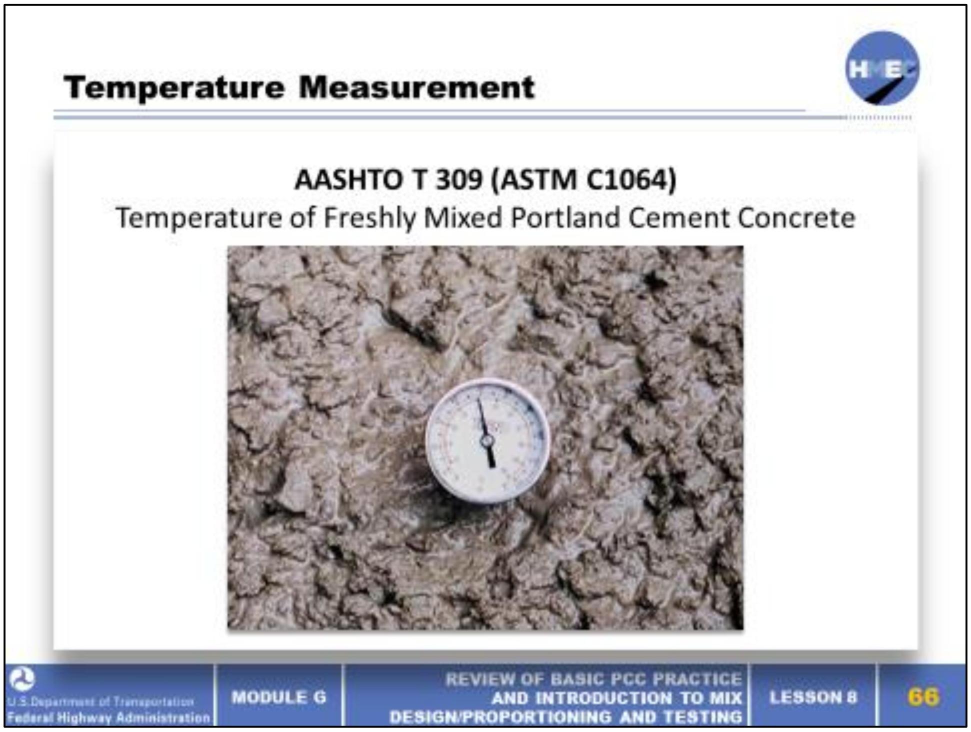
Frequency of testing:

- 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



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:

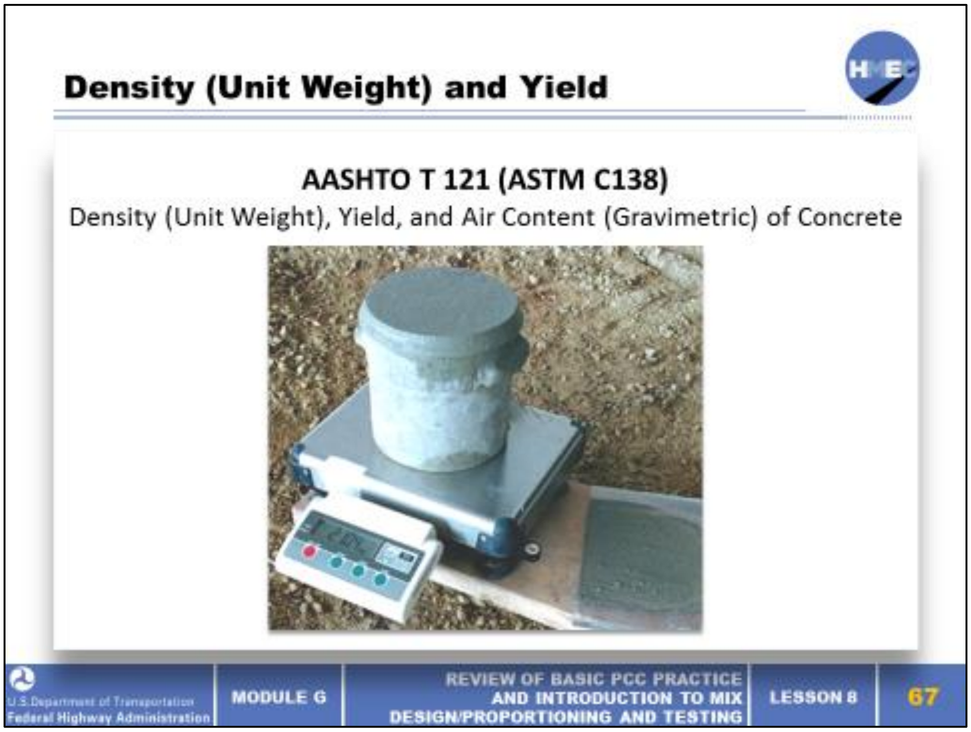
- First batch of concrete each day;
- Every 150 cy or as directed by the Engineer
- Whenever a slump test is performed; or
- Whenever strength-test cylinders are made at job site.

____

____

____

Slide 67



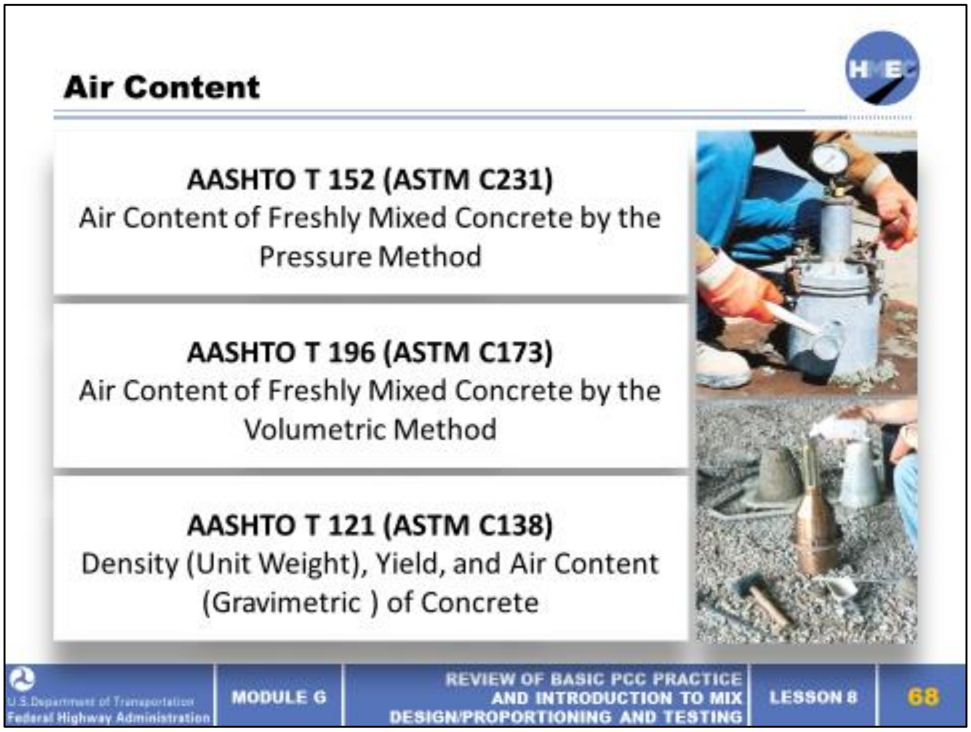
Fresh concrete is measured in a container of known volume to determine density (unit weight).

- 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-ft^3) air meter container for up to 25 mm (1 in.) nominal max. size aggregate: 14-L (0.5 ft^3) 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



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.

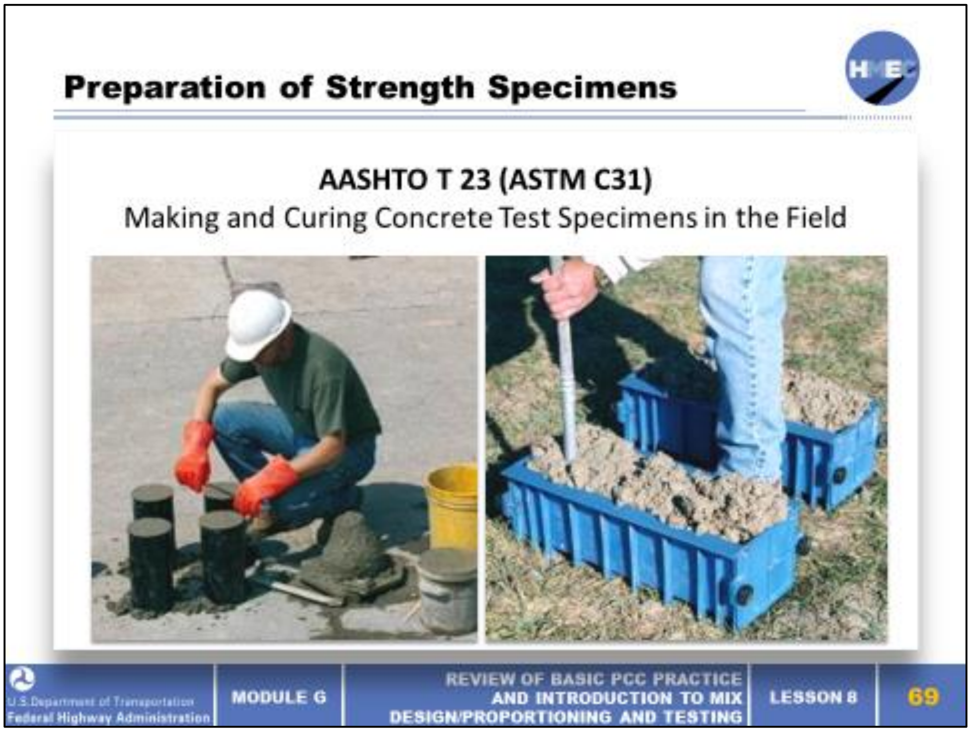
The photo on the upper right shows a pressure meter air test. This is the most commonly used device, but is not appropriate for lightweight or porous aggregates.

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



Time limit: start molding ≤ 15 minutes after sampling.

Frequency of testing:

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

____

____

____

____

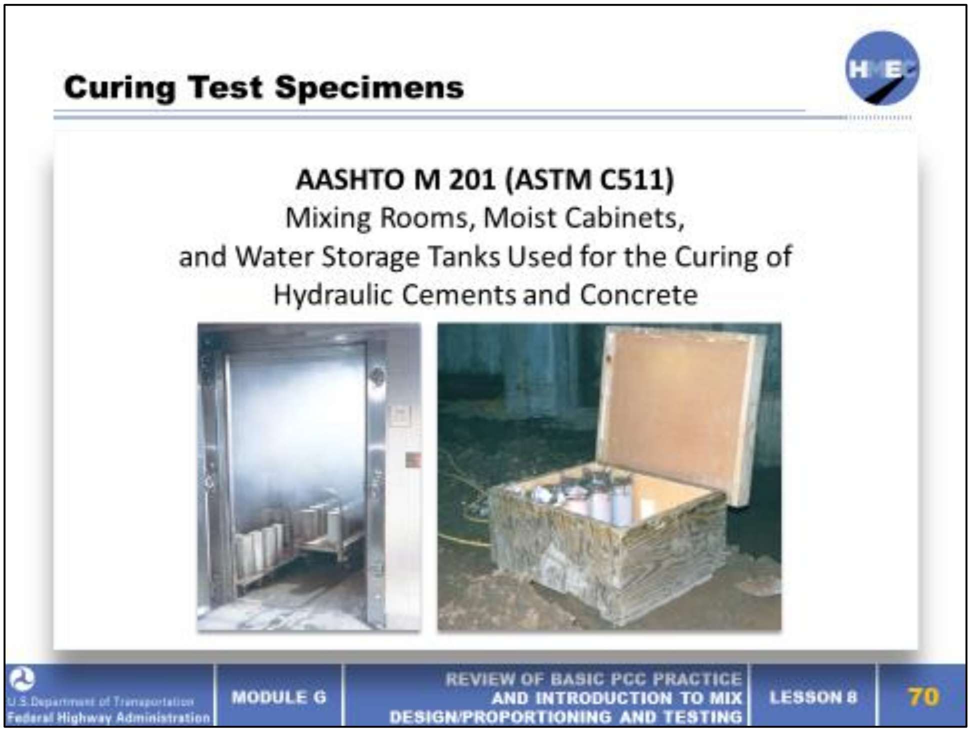
____

____

____

____

Slide 70



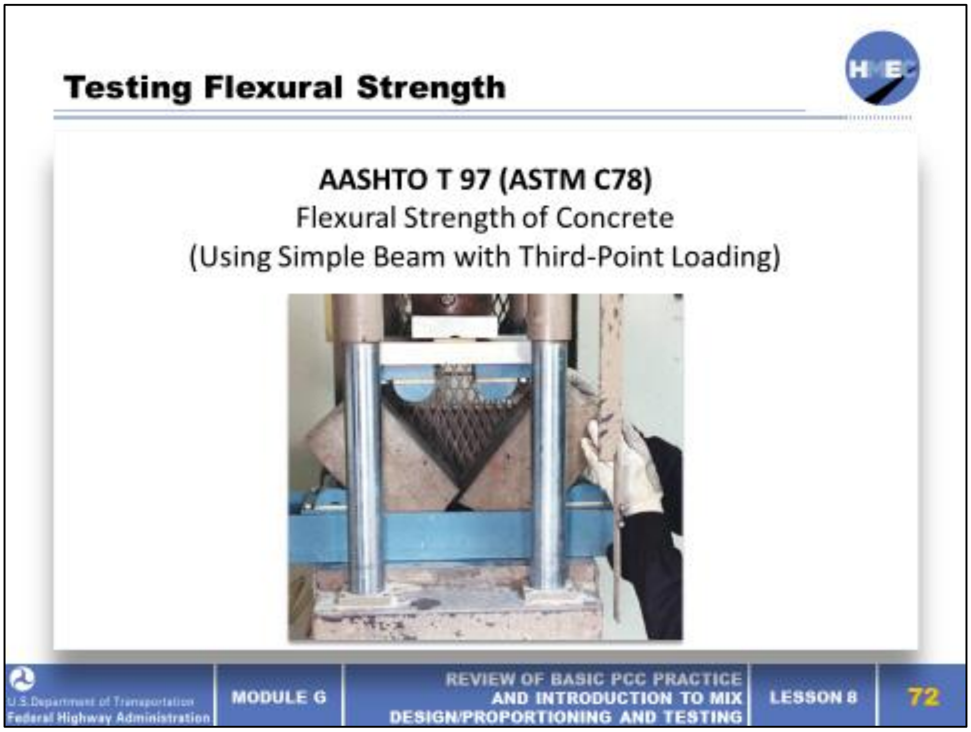
The temperature and moisture conditions are very important in terms of test results. The most representative curing approximates the conditions in the field. The photo in the upper left shows a field curing box with thermostat and heating pad for initial curing of PCC test cylinders. The photo on the 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

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

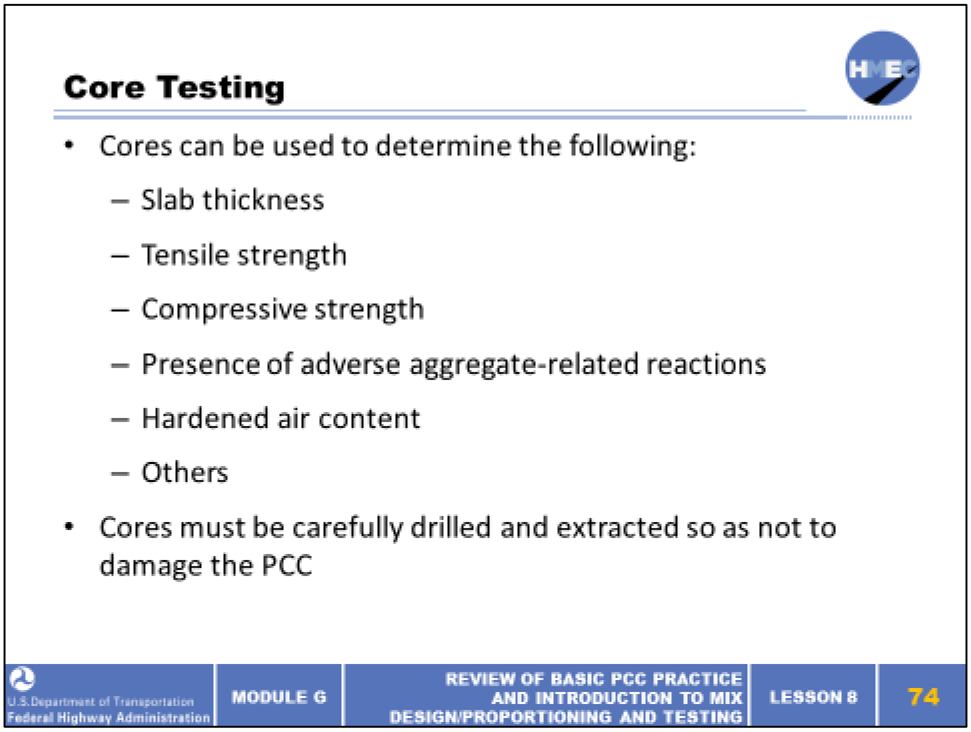


The flexural strength of PCC is a design input for pavement design. The third-point loading beam break, as pictured here, is used to assess that value. However, since beams are difficult to prepare and handle and even slight imperfections in the beam can result in significant strength variation, compressive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

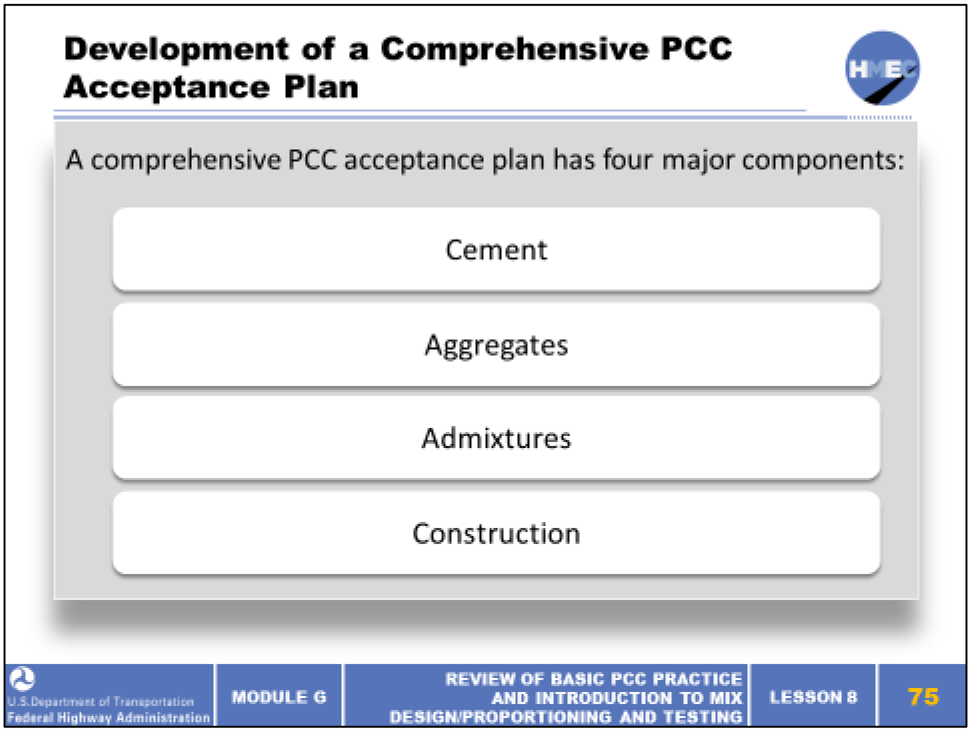
Cores are frequently taken from in-place pavements as a quality assurance measure for new pavements or to perform forensic analyses on deteriorated pavements. The photo on the right illustrates a split tensile test used to determine the tensile strength of PCC, as placed.

Slide 74



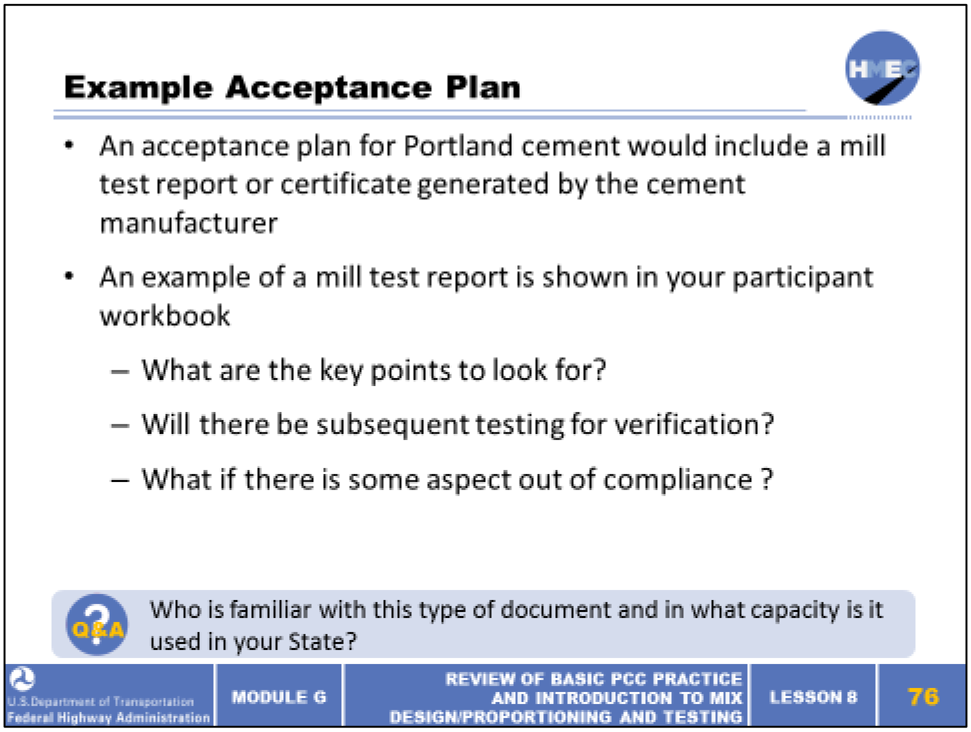
The information obtained for cores is highly dependent on the care used during drilling and extraction. For instance, an eccentric core bit or using too high of a down pressure during drilling can result in the formation of microcracks (thereby reducing strength).

Slide 75



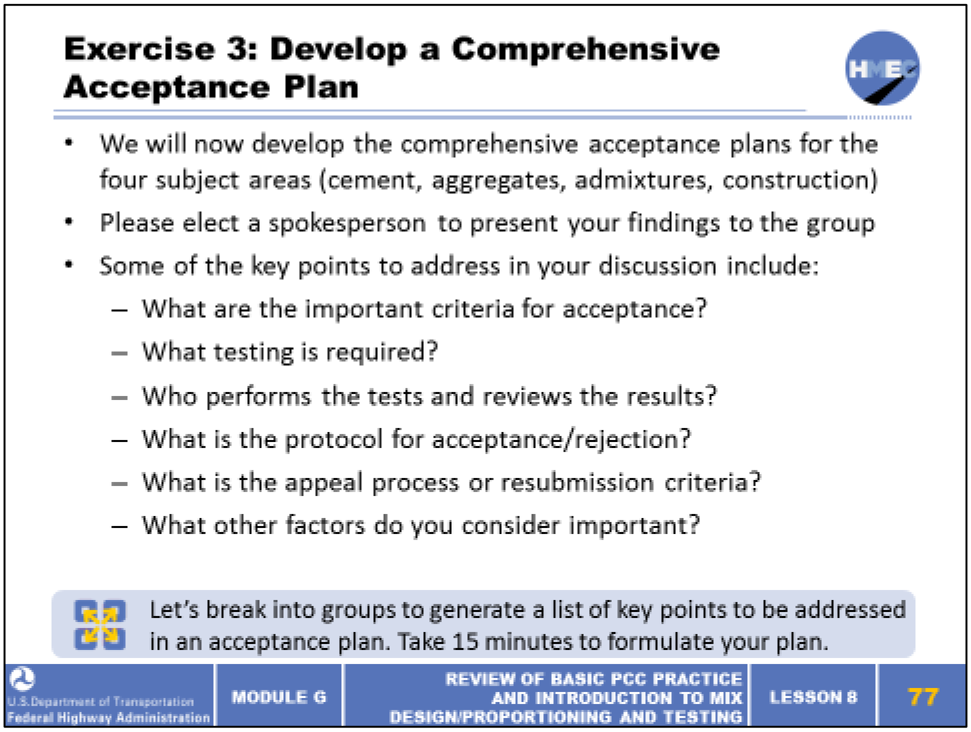
A comprehensive acceptance plan for PCC must include all of the major constituents: cement, aggregates, admixtures, and construction. In this section, we are going to develop a plan for each of these components as a group activity.

Slide 76

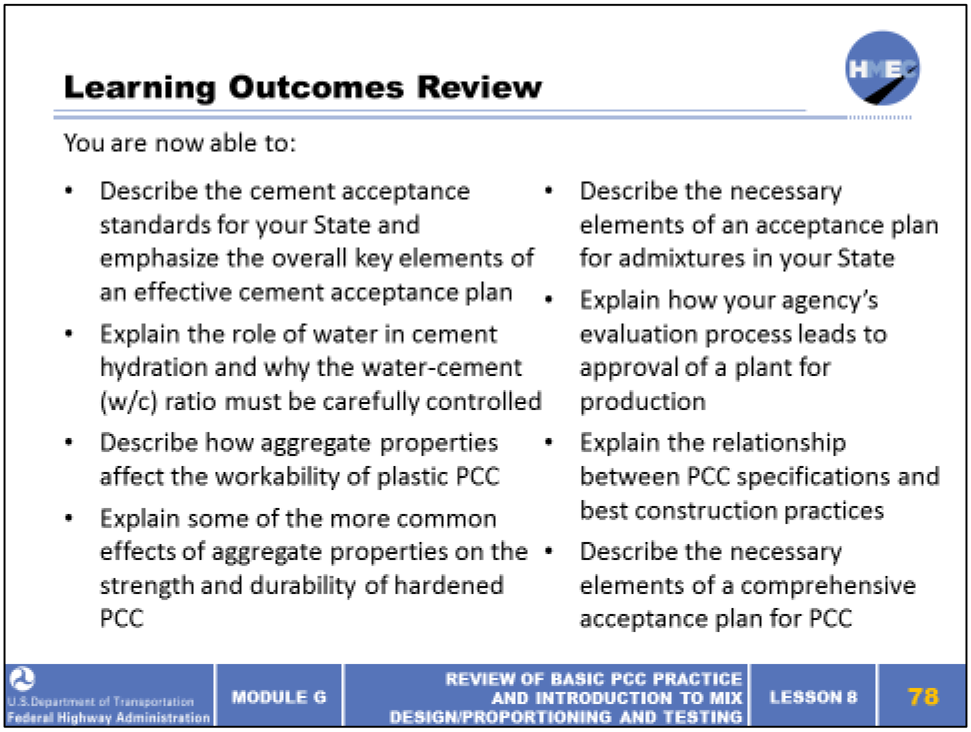


Note that there are numerous items that are tested that do not have to be covered in the plan.

Slide 77


Exercise 3: Develop a Comprehensive Acceptance Plan
HMEC
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.
U.S. Department of Transportation Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
77

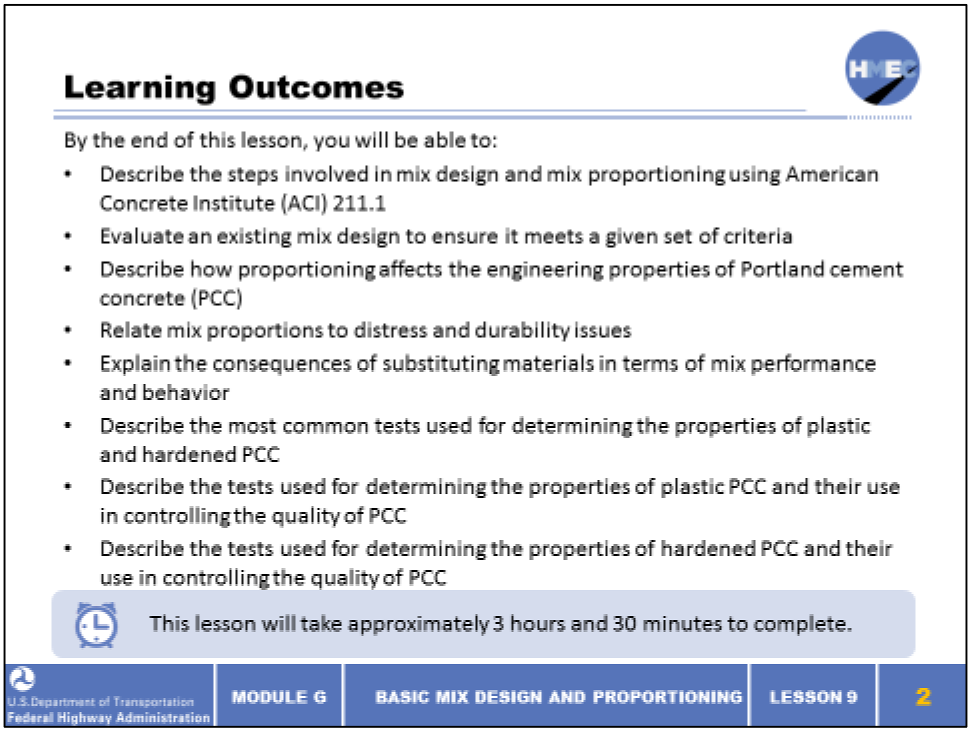
Slide 78


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
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REVIEW OF BASIC PCC PRACTICE AND INTRODUCTION TO MIX DESIGN/PROPORTIONING AND TESTING
LESSON 8
78

Slide 1


ILT
HMEC
Highway Materials Engineering Course
Lesson 9: Basic Mix Design and Proportioning
Portland Cement Concrete (PCC)
U.S.Department of Transportation
Federal Highway Administration
MODULE
G

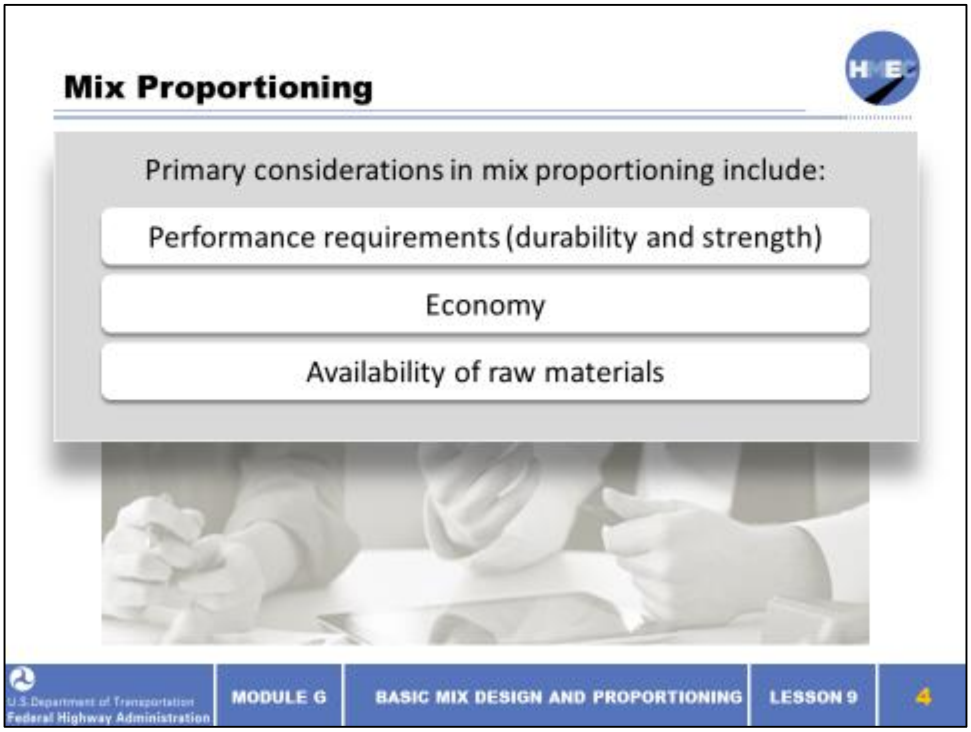
Slide 2


Learning Outcomes
HMEC
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.
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
2

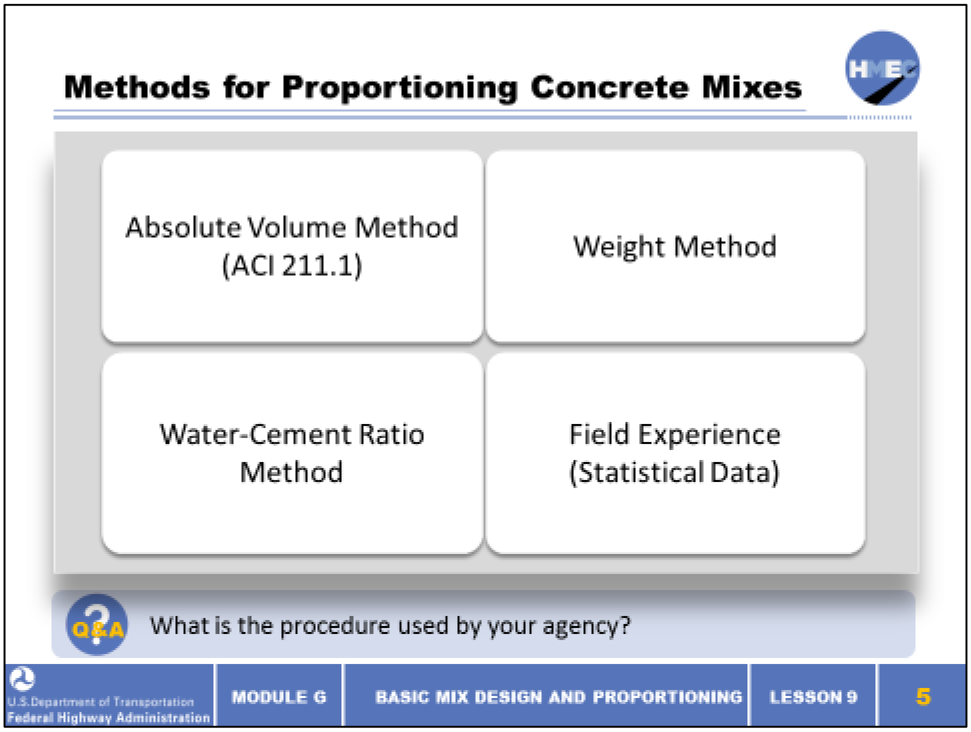
Slide 3

Design and proportioning are different activities, although they are sometimes incorrectly labeled.

Slide 4

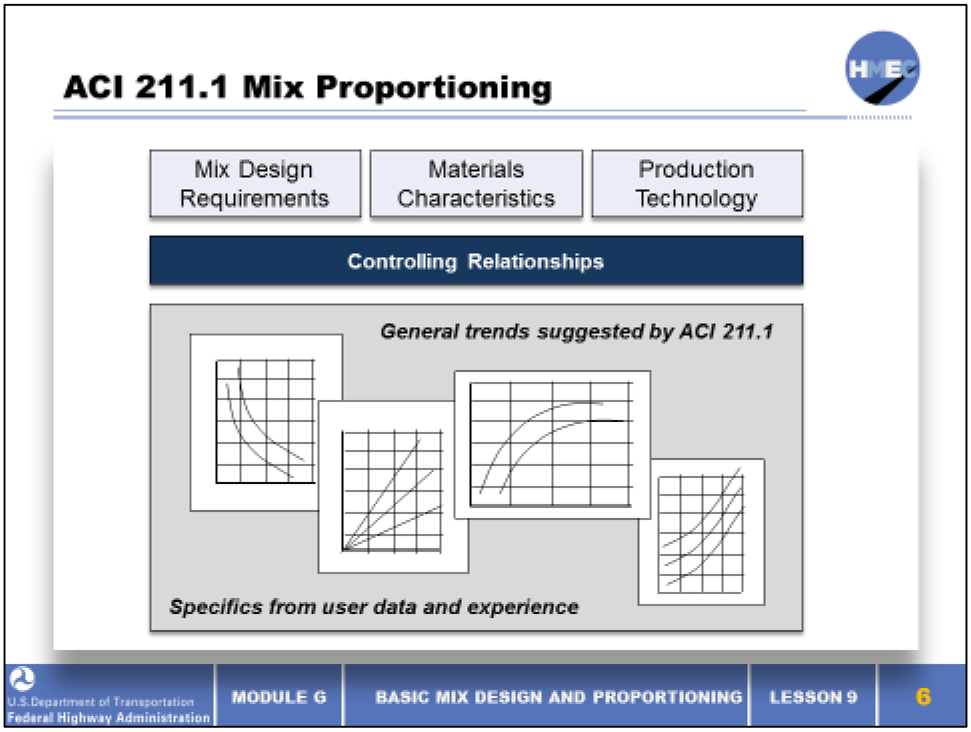

Mix Proportioning
Primary considerations in mix proportioning include:
Performance requirements (durability and strength)
Economy
Availability of raw materials
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
4

Slide 5



There are a number of methods to proportion PCC mixes although none is as widely used as ACI 211.1.

Slide 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.

____

____

____

____

____

____

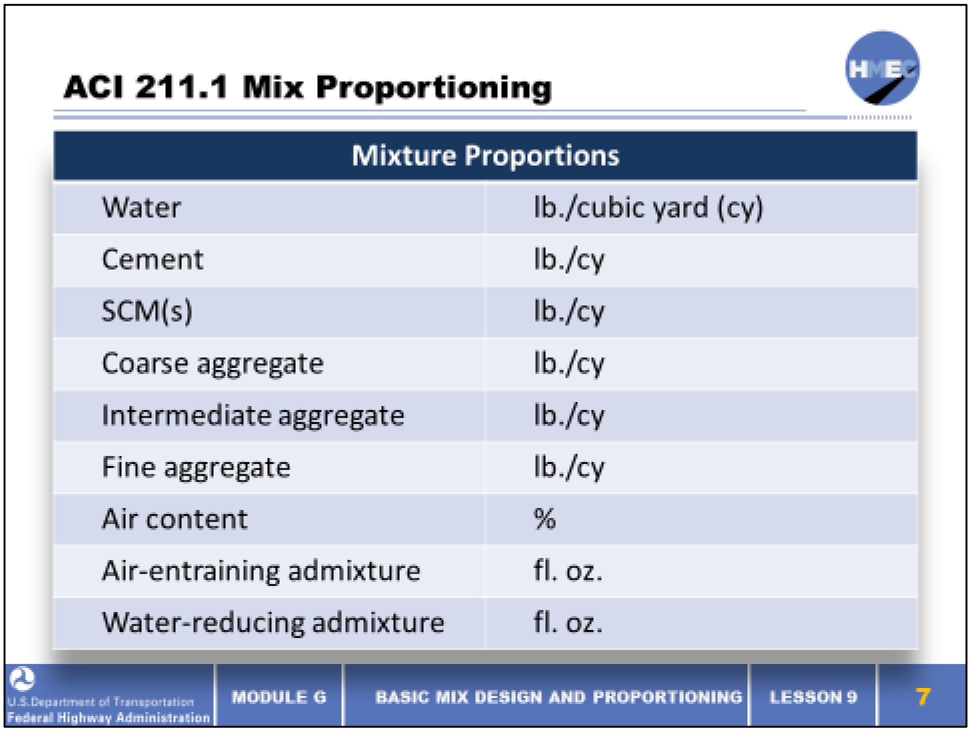
____

____

____

____

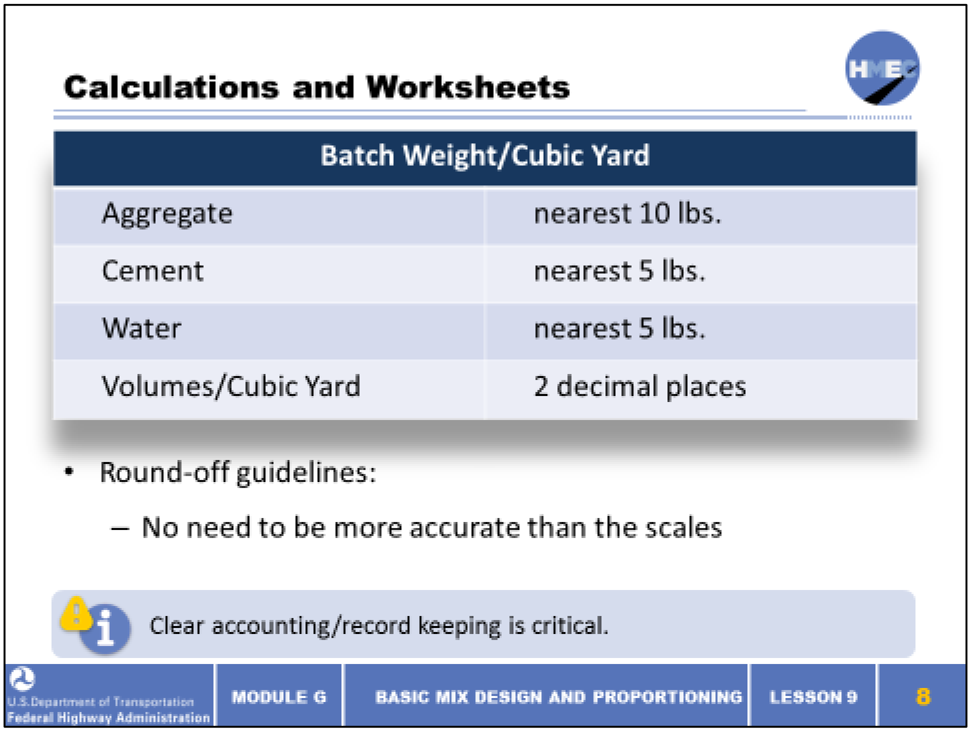
Slide 7



Mixture Proportions	
Water	lb./cubic yard (cy)
Cement	lb./cy
SCM(s)	lb./cy
Coarse aggregate	lb./cy
Intermediate aggregate	lb./cy
Fine aggregate	lb./cy
Air content	%
Air-entraining admixture	fl. oz.
Water-reducing admixture	fl. oz.

Note that not all of these materials are actually accounted for specifically in the calculations and some may not be used for a specific mix.

Slide 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

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 9

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

____

____

____

____

____

____

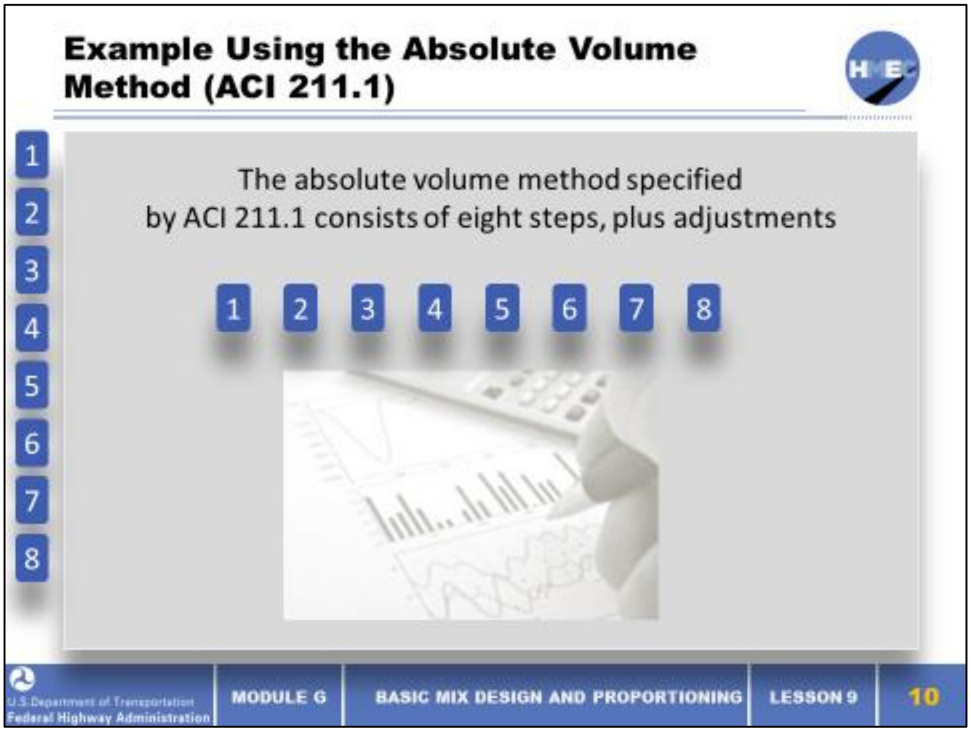
____

____

____

____

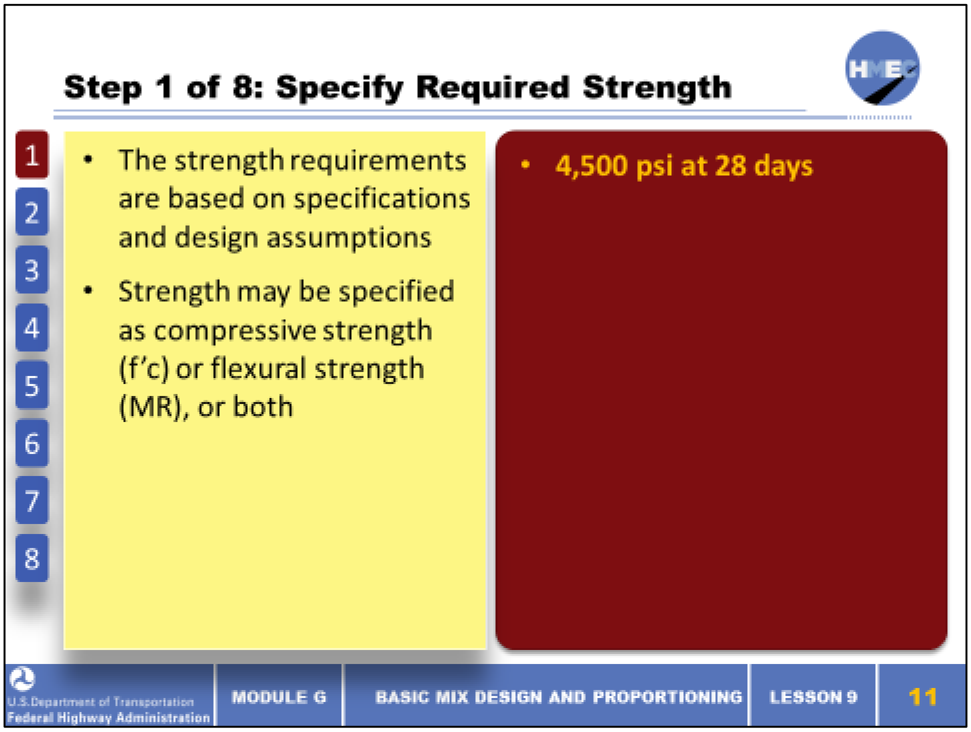
Slide 10



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.

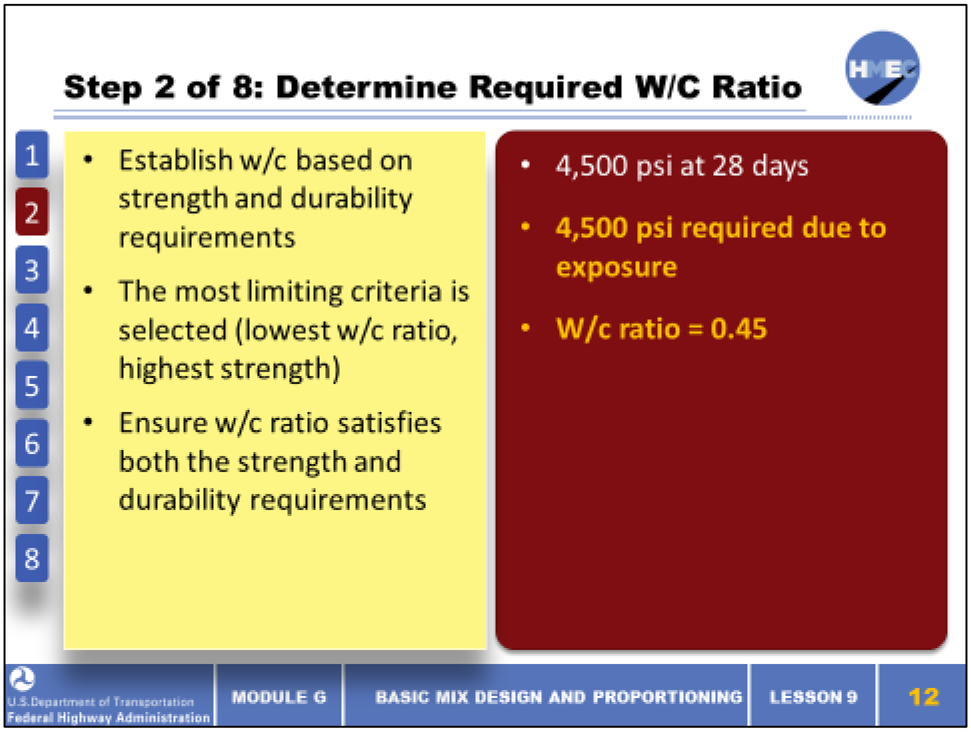
These calculations will be used to generate a baseline mix that will be used throughout this lesson.

Slide 11



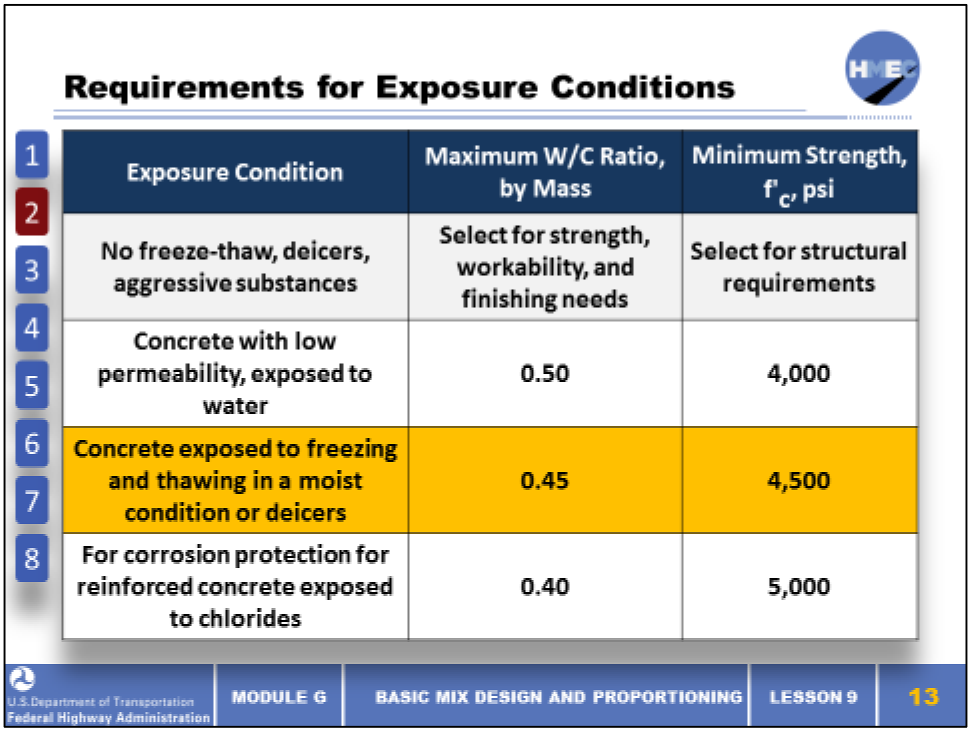
Keep in mind that variability exists in both materials and testing procedures. On the right side of the slide, we see an example, which will be carried out as we go through the steps.

Slide 12



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

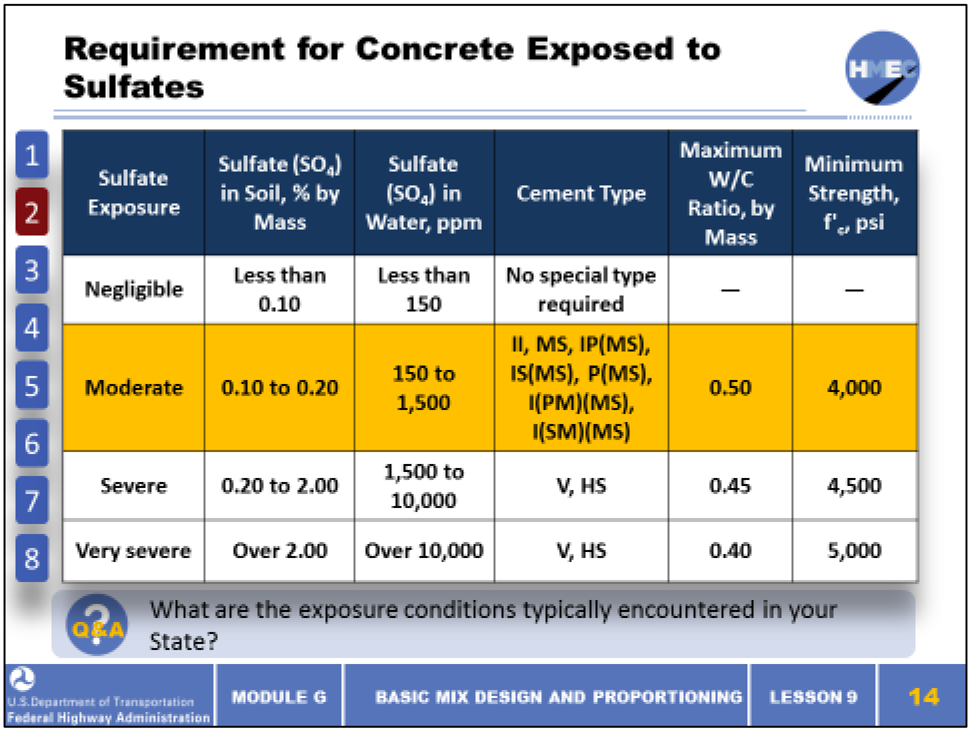


Requirements for Exposure Conditions

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

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

Slide 14



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

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

Slide 15

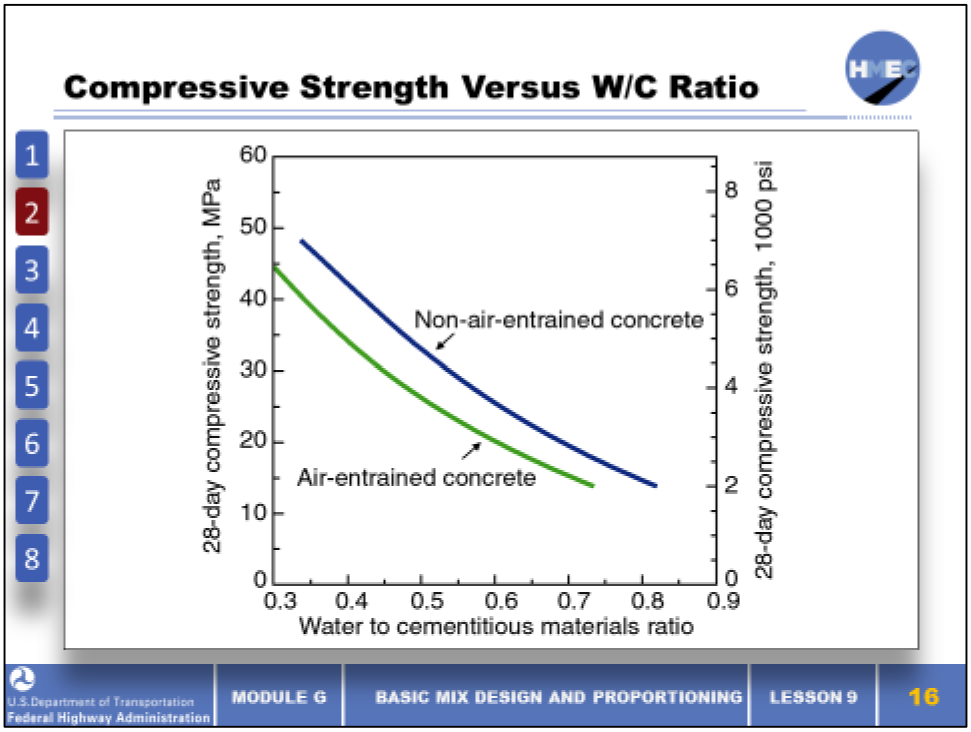
Relationship Between W/C Ratio and Strength

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

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 15

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 ¾ 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.

____

____

____

____

____

____

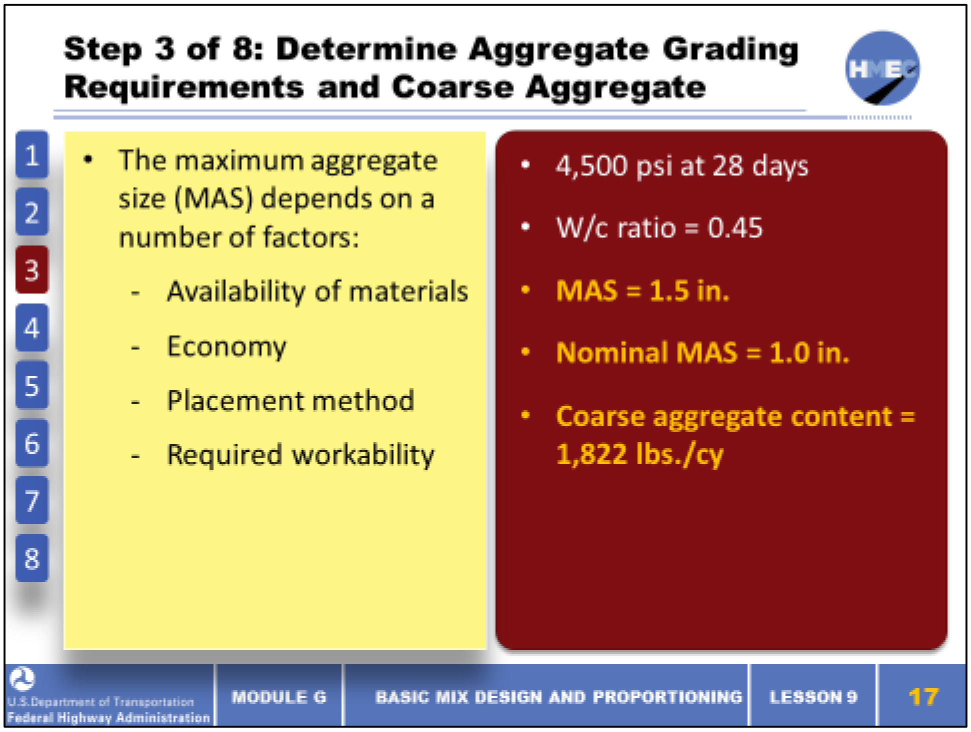
____

____

____

____

Slide 17



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

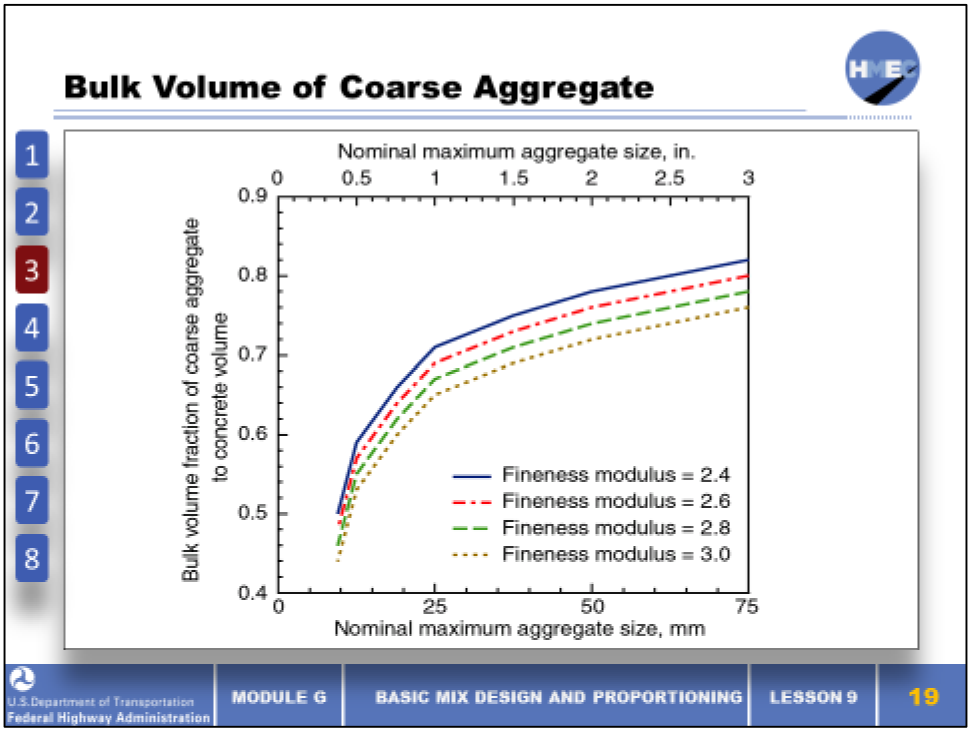
Bulk Volume of Coarse Aggregate

Nominal Maximum Aggregate Size (in.)	Fineness Modulus of Sand			
	2.40	2.60	2.80	3.00
⅜	0.50	0.48	0.46	0.44
½	0.59	0.57	0.55	0.53
¾	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

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 18

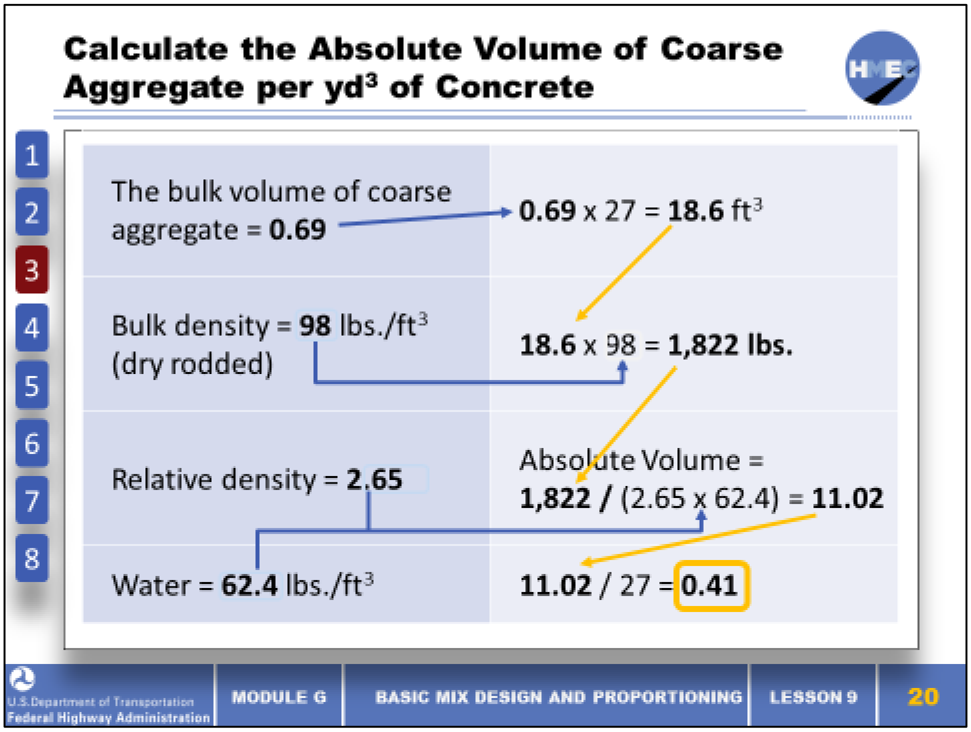
This value is representative of the void space in the coarse aggregates in the dry rodded state.

Slide 19



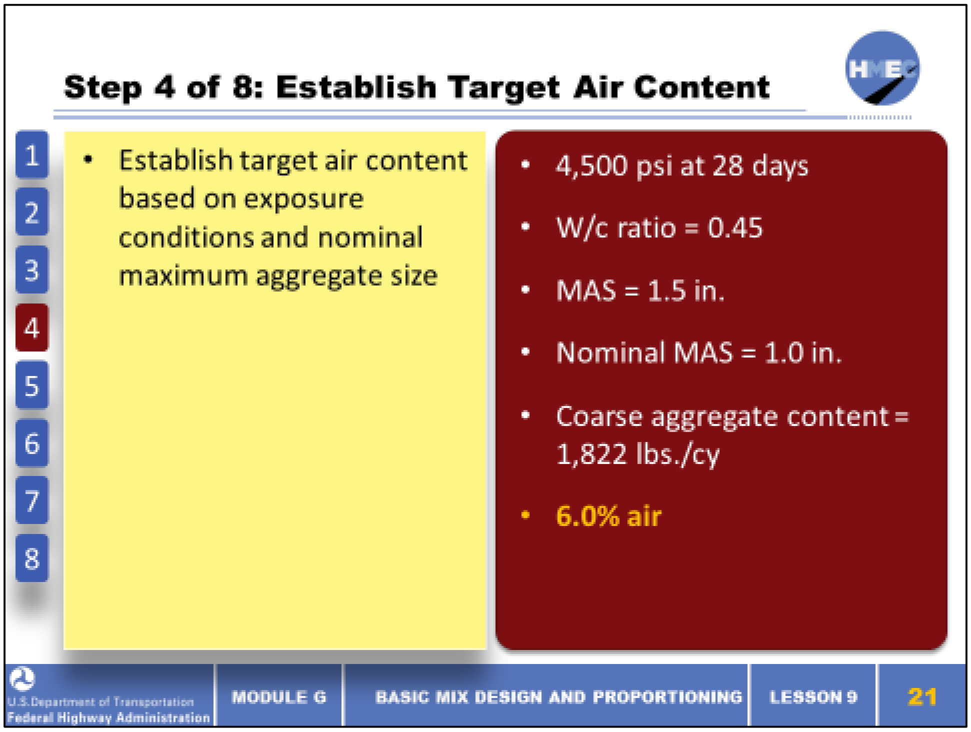
This graph shows the bulk volume of coarse aggregate per unit volume of concrete. For more workable concrete, such as may be required when placement is by pump, they may be reduced up to 10%.

Slide 20



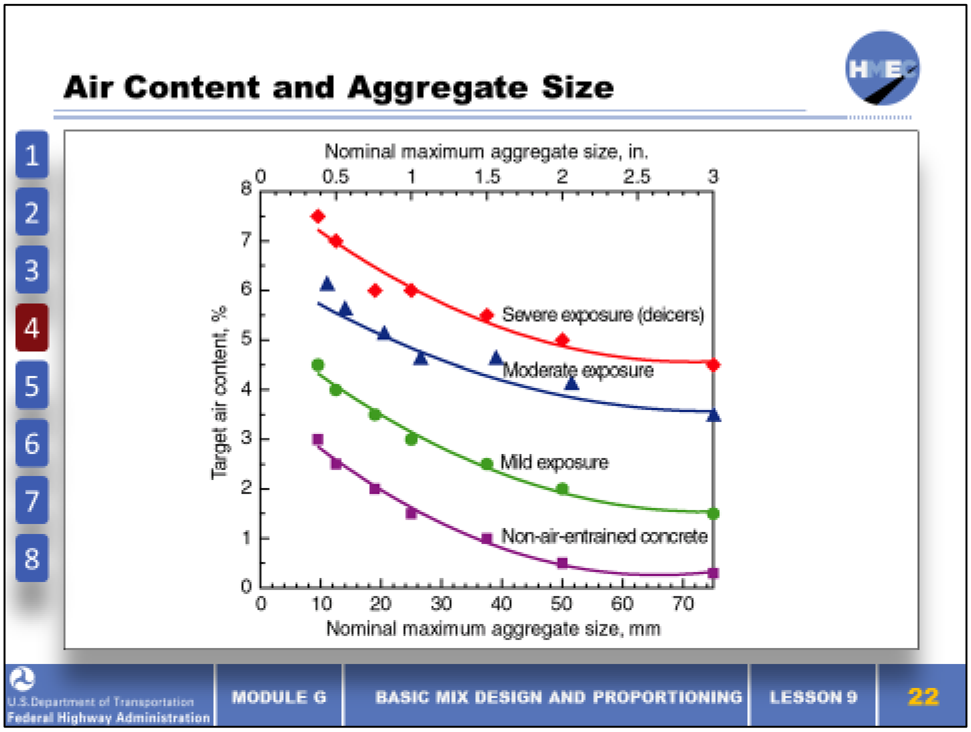
The bulk density and dry rodded weight were assumed in this example calculation.

Slide 21



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.

____

____

____

____

____

____

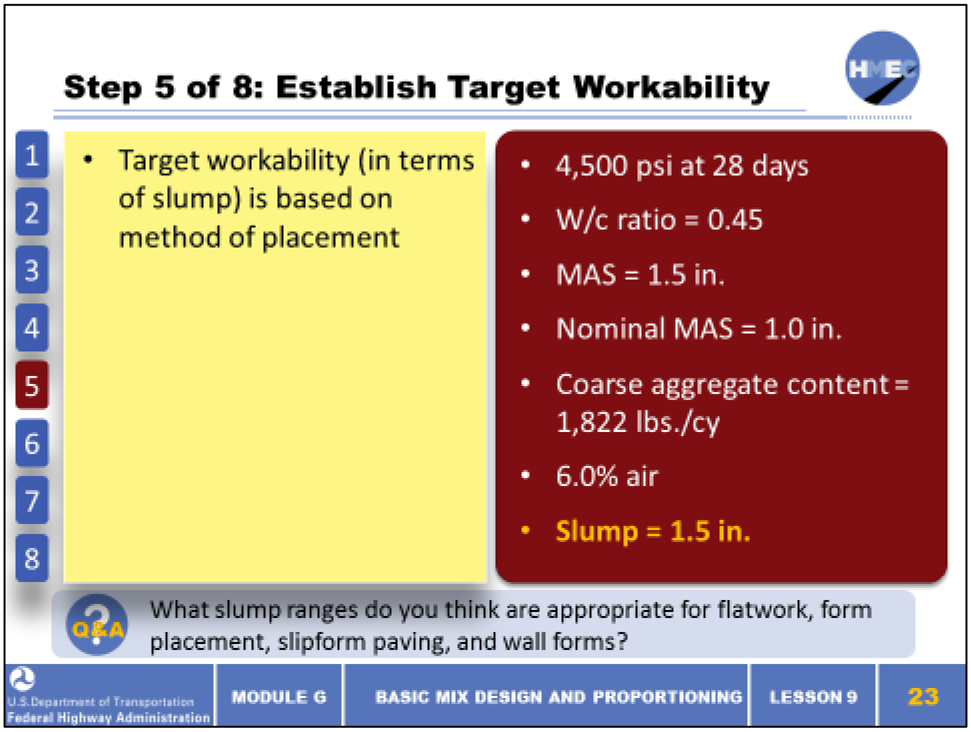
____

____

____

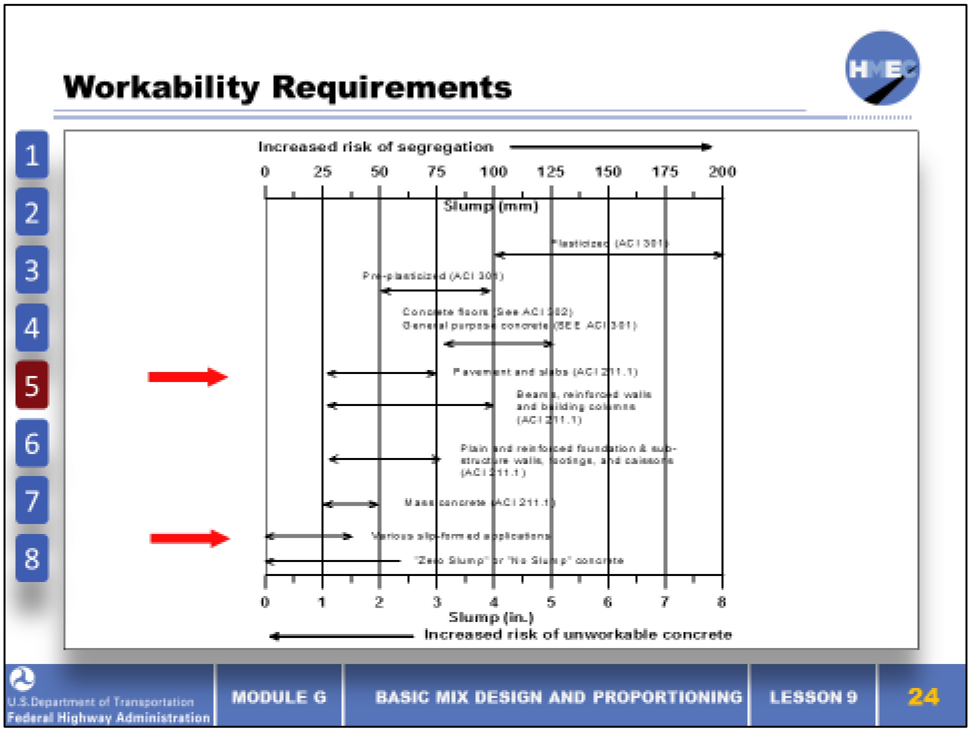
____

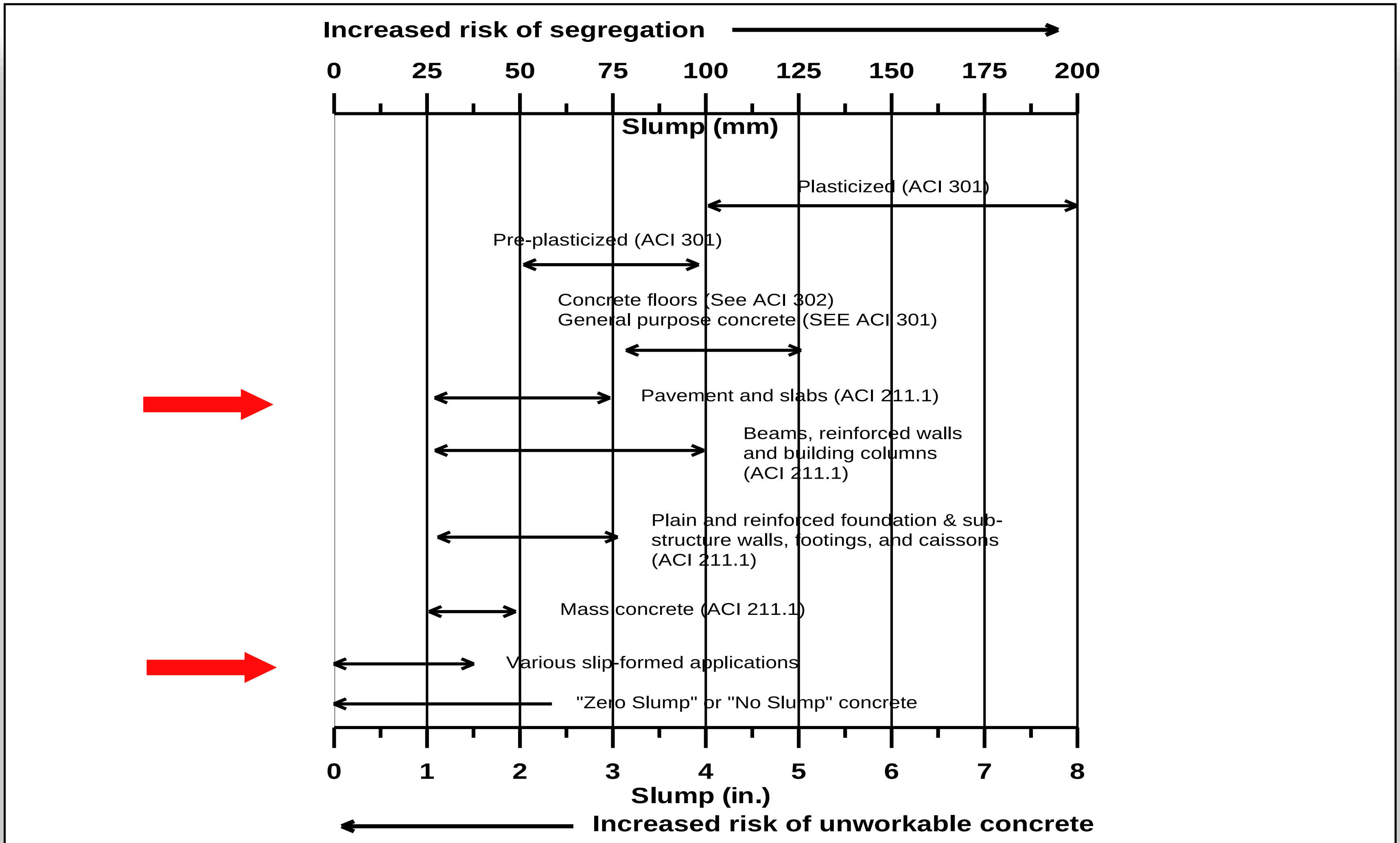
Slide 23



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

Slide 24


Workability Requirements
HMEC
1
2
3
4
5
6
7
8
Increased risk of segregation
0 25 50 75 100 125 150 175 200
Slump (mm)
Plasticized (ACI 301)
Pre-plasticized (ACI 301)
Concrete floors (See ACI 302)
General purpose concrete (SEE ACI 301)
Pavement and slabs (ACI 211.1)
Beams, reinforced walls
and building columns
(ACI 211.1)
Plain and reinforced foundation & sub-
structure walls, footings, and caissons
(ACI 211.1)
Mass concrete (ACI 211.1)
Various slip-formed applications
"Zero Slump" or "No Slump" concrete
0 1 2 3 4 5 6 7 8
Slump (in.)
Increased risk of unworkable concrete
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
24


Increased risk of segregation
0 25 50 75 100 125 150 175 200
Slump (mm)
Plasticized (ACI 301)
Pre-plasticized (ACI 301)
Concrete floors (See ACI 302)
General purpose concrete (SEE ACI 301)
Pavement and slabs (ACI 211.1)
Beams, reinforced walls and building columns (ACI 211.1)
Plain and reinforced foundation & sub-structure walls, footings, and caissons (ACI 211.1)
Mass concrete (ACI 211.1)
Various slip-formed applications
"Zero Slump" or "No Slump" concrete
0 1 2 3 4 5 6 7 8
Slump (in.)
Increased risk of unworkable concrete

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

____

____

____

____

____

____

____

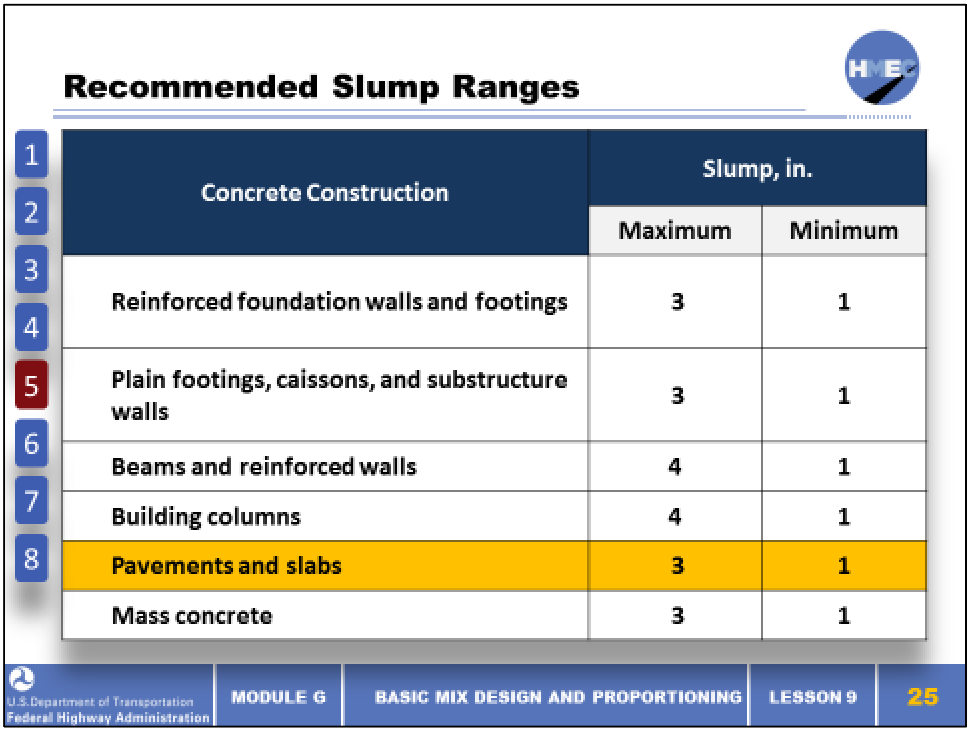
____

____

____

____

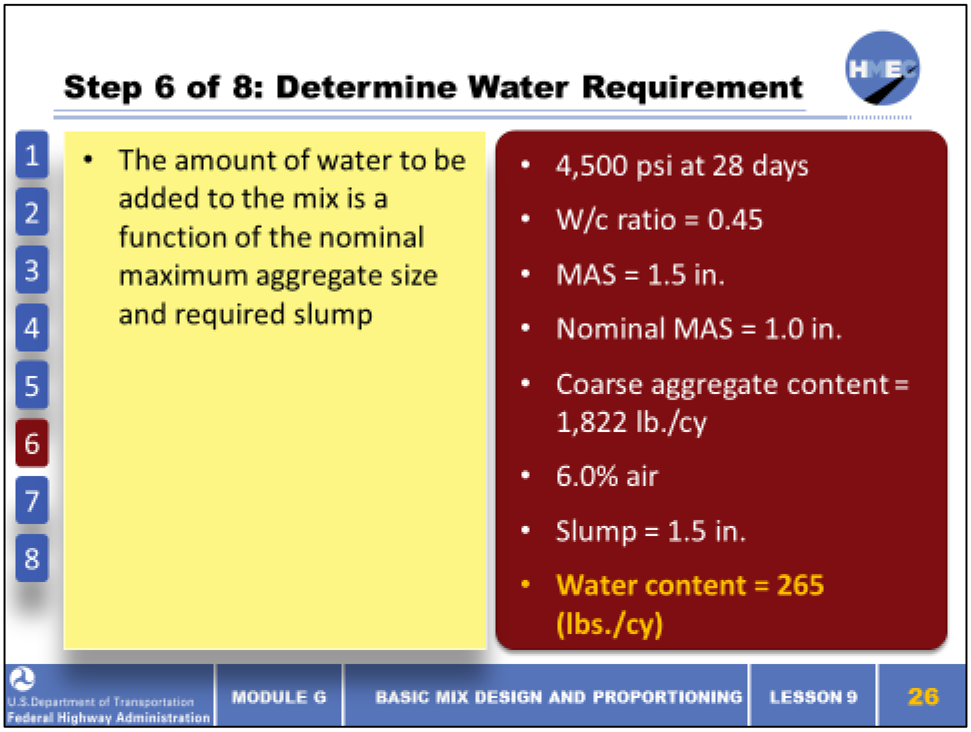
Slide 25



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

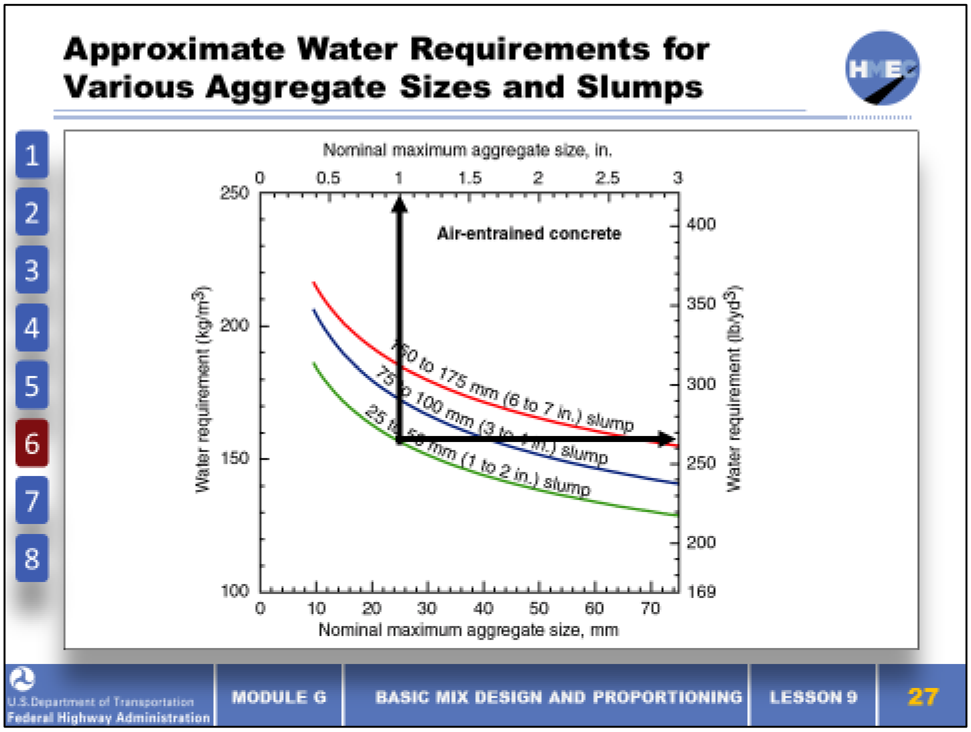
The example we are working on is highlighted in yellow. Maximum slump may be increased by 25 mm (1 in.) for consolidation by hand methods, such as rodding and spading. Plasticizers can safely provide higher slumps.

Slide 26

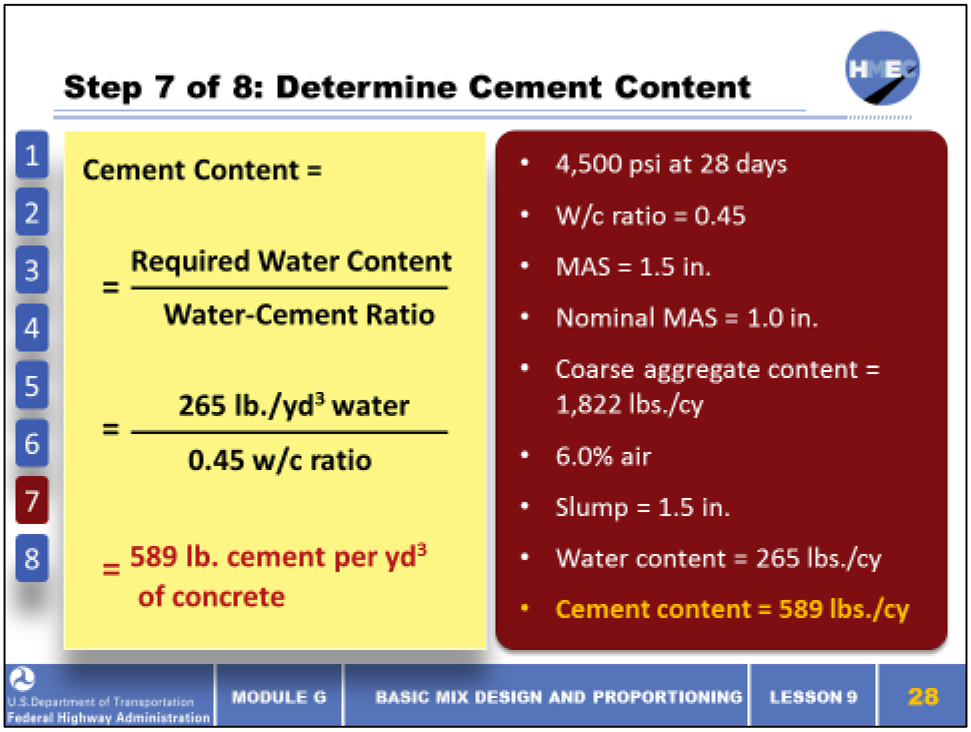


The water requirement is based on the nominal MAS and the desired slump.

Slide 27


Approximate Water Requirements for Various Aggregate Sizes and Slumps
HMEC
1
2
3
4
5
6
7
8
Nominal maximum aggregate size, in.
0
0.5
1
1.5
2
2.5
3
Air-entrained concrete
150 to 175 mm (6 to 7 in.) slump
75 to 100 mm (3 to 4 in.) slump
25 to 50 mm (1 to 2 in.) slump
Water requirement (kg/m3)
250
200
150
100
Water requirement (lb/yd3)
400
350
300
250
200
169
0
10
20
30
40
50
60
70
Nominal maximum aggregate size, mm
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
27

Slide 28



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

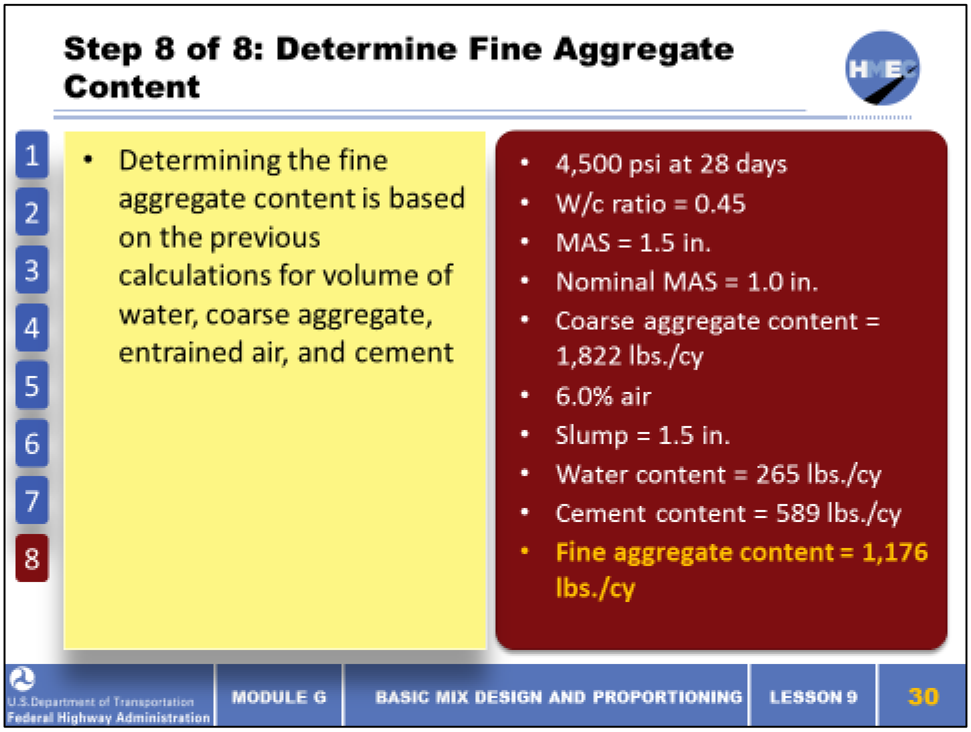
Minimum Cementing Materials Content for Flatwork

Nominal Maximum Size of Aggregate, in.	Cementing Materials, lbs./yd³
1½	470
1	520
¾	540
½	590
⅜	610

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 29

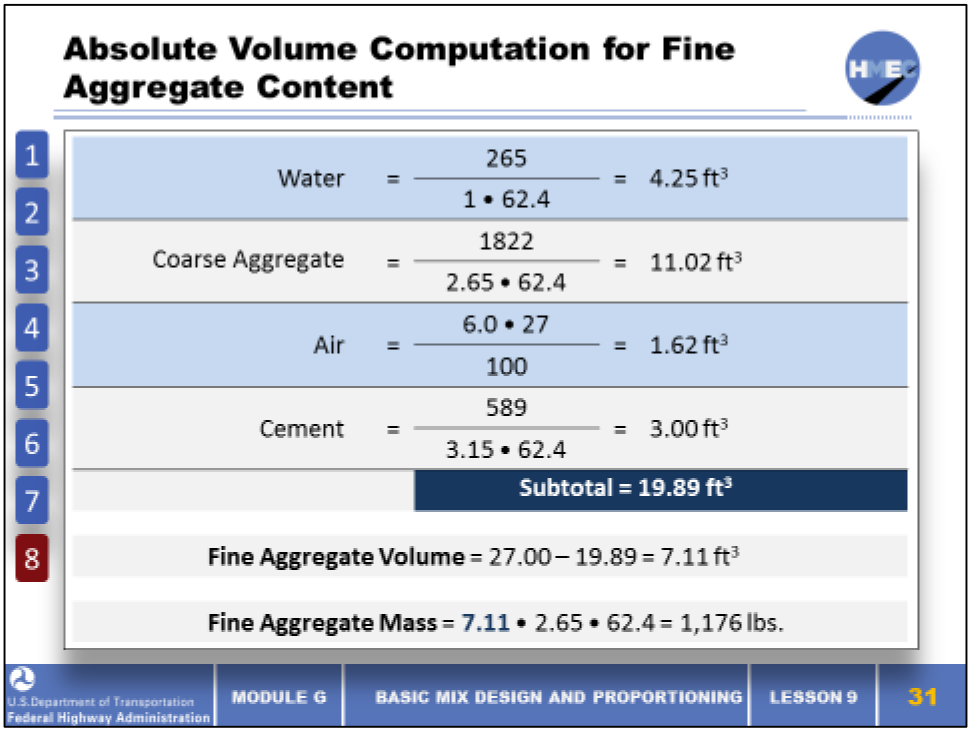
Cementing materials quantities may need to be greater for severe exposure. For example, for deicer exposures, concrete should contain at least 335 kg/m^3 (564 $lbs./yd^3$) of cementing materials.

Slide 30



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



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%

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 32

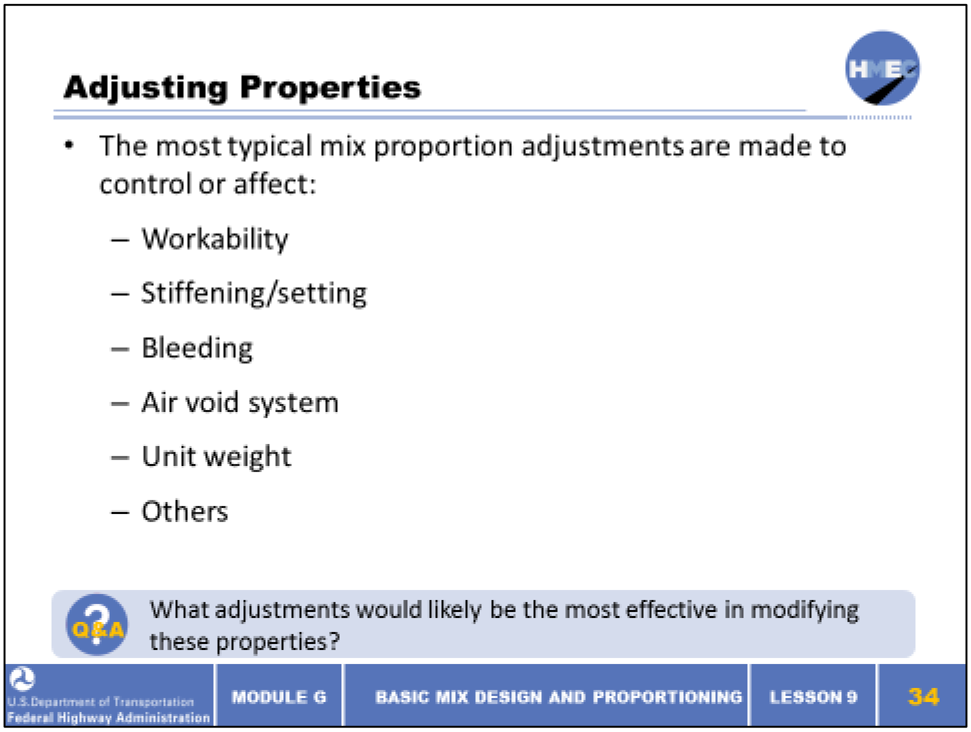
The long-standing relationship of three parts coarse aggregate, two parts fine aggregate and one part cement (by volume) can be used to get a rough idea as to the validity of your calculations.

Slide 33

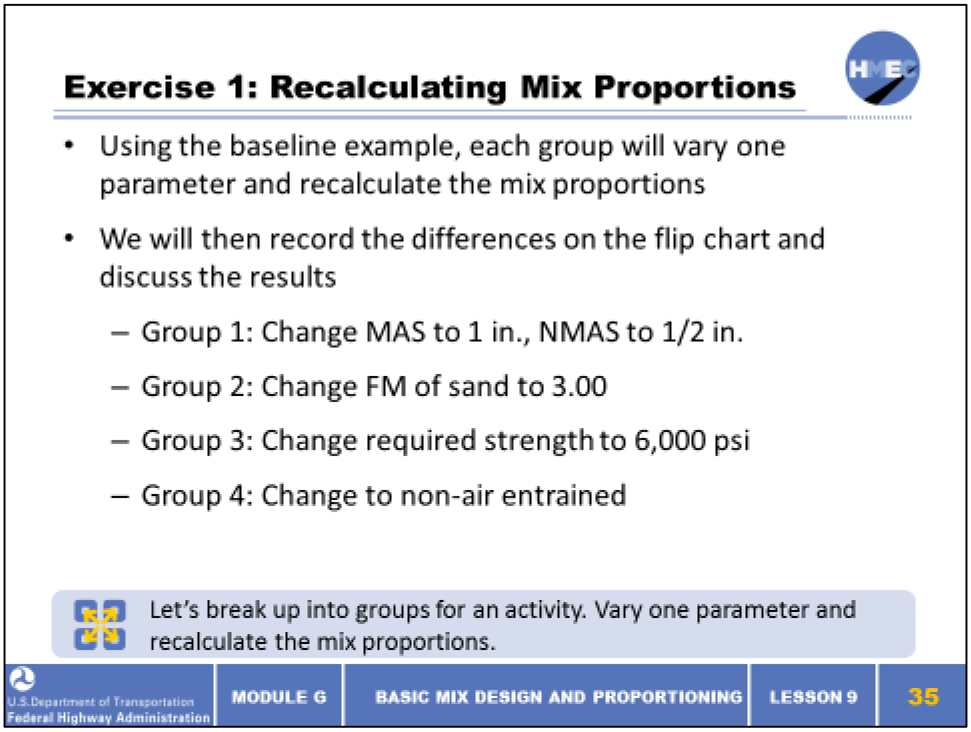
We now have the initial proportions of a trial batch. Remember that the job is not done until the batch is tested and adjusted.

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.

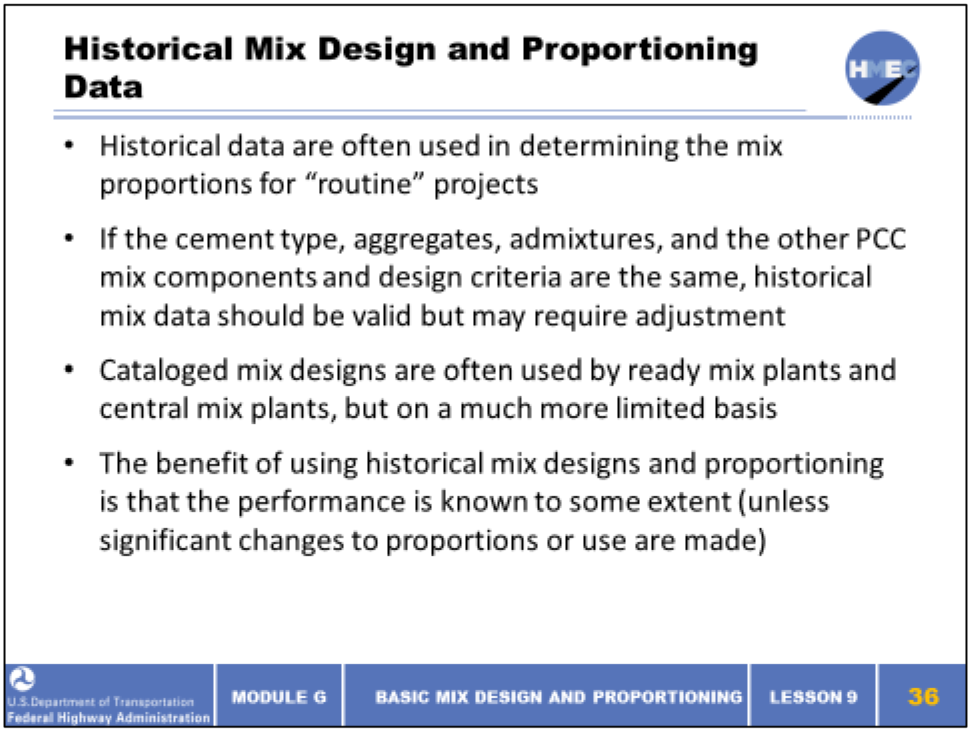
Slide 34


Adjusting Properties
HMEC
• The most typical mix proportion adjustments are made to control or affect:
– Workability
– Stiffening/setting
– Bleeding
– Air void system
– Unit weight
– Others
Q&A
What adjustments would likely be the most effective in modifying these properties?
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
34

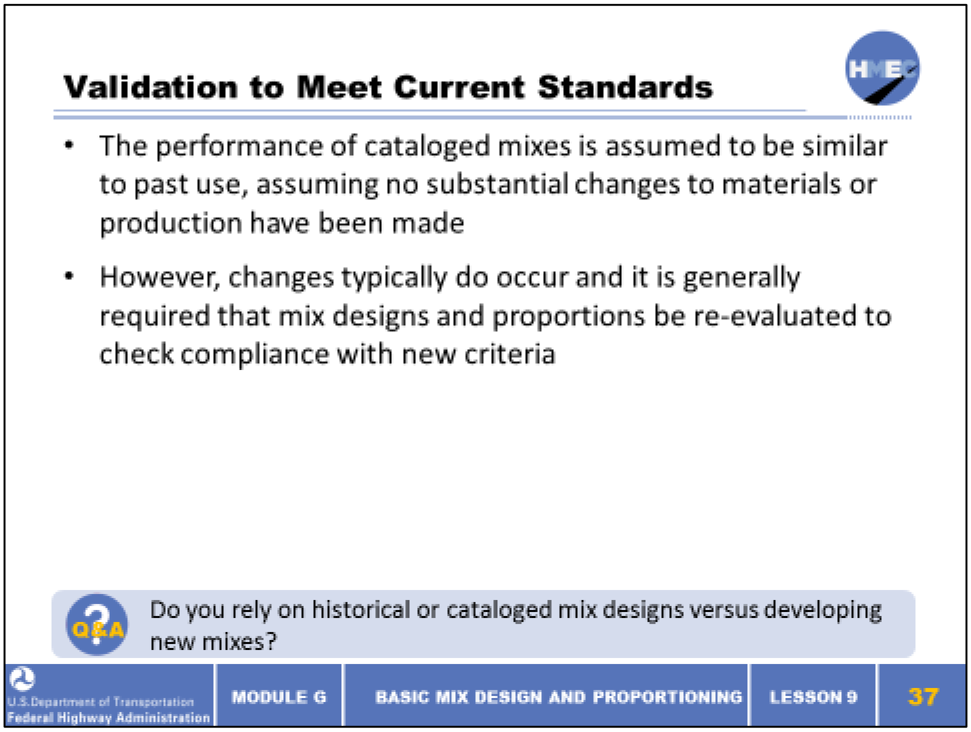
Slide 35


Exercise 1: Recalculating Mix Proportions
HMEC
• 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.
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
35

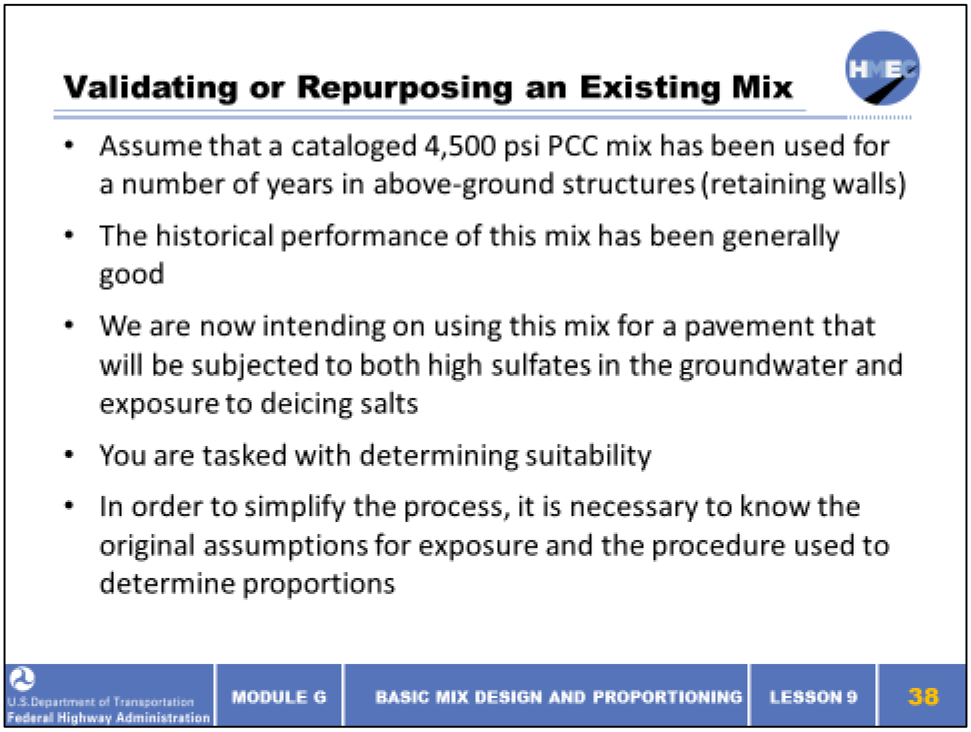
Slide 36


Historical Mix Design and Proportioning Data
HMEC
• 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)
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
36

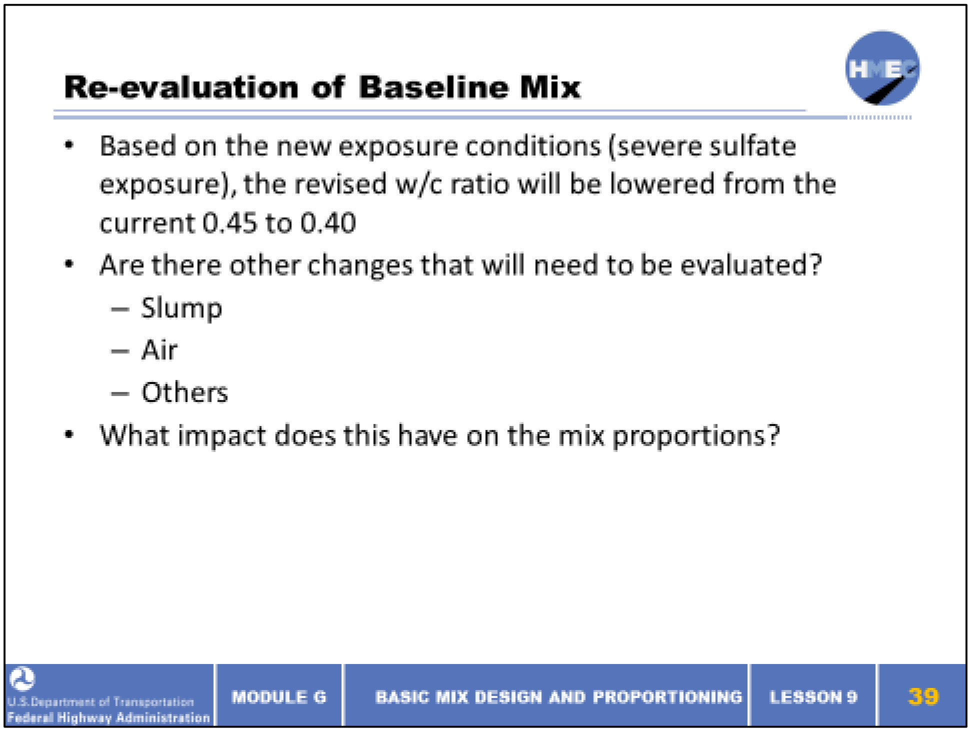
Slide 37


Validation to Meet Current Standards
HMEC
• 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
Q&A
Do you rely on historical or cataloged mix designs versus developing new mixes?
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
37

Slide 38


Validating or Repurposing an Existing Mix
HMEC
• 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
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
38

Slide 39


Re-evaluation of Baseline Mix
HMEC
• 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?
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
39

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

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 40

Slide 41

Requirements 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
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

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 41

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

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

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 42

Slide 43

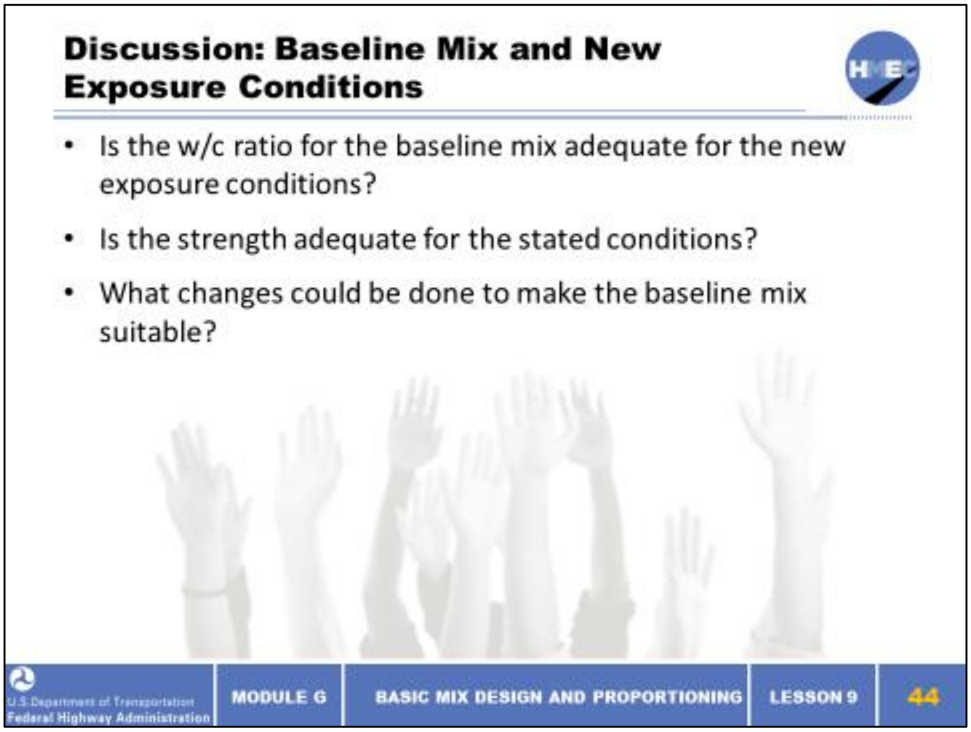
Recommended Slump Ranges

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

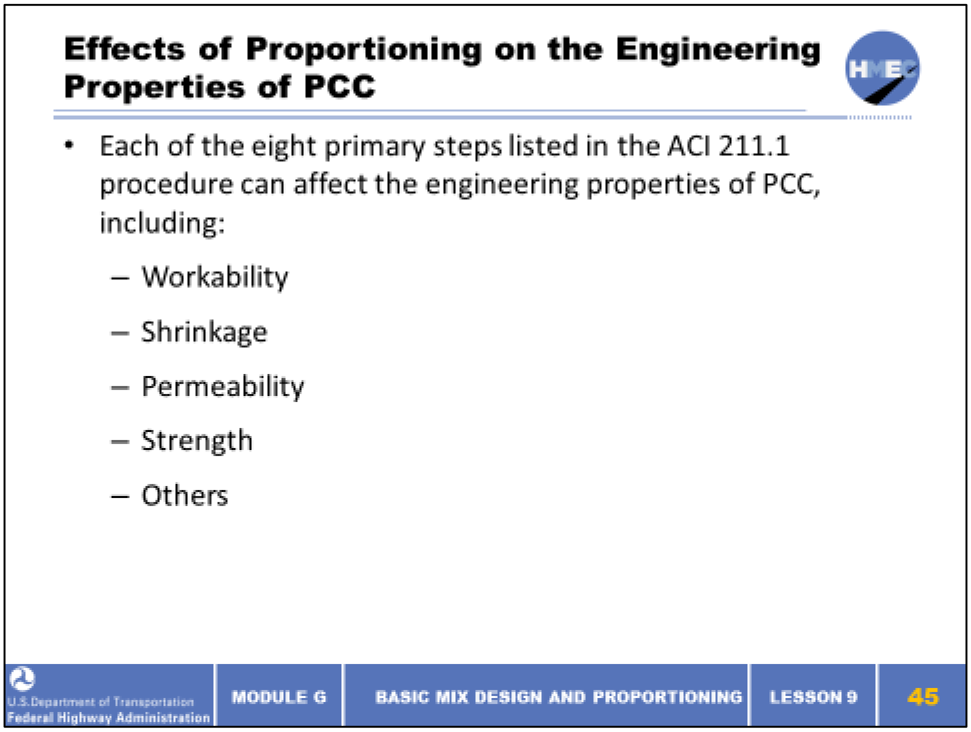
U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 43

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

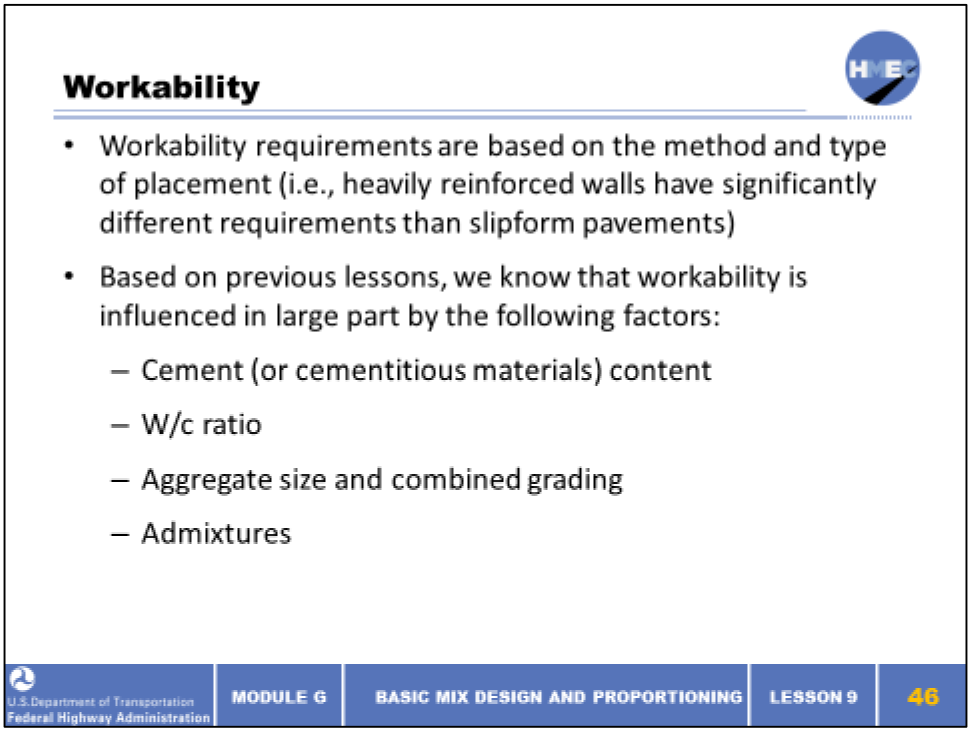
Slide 44


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?
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
44

Slide 45

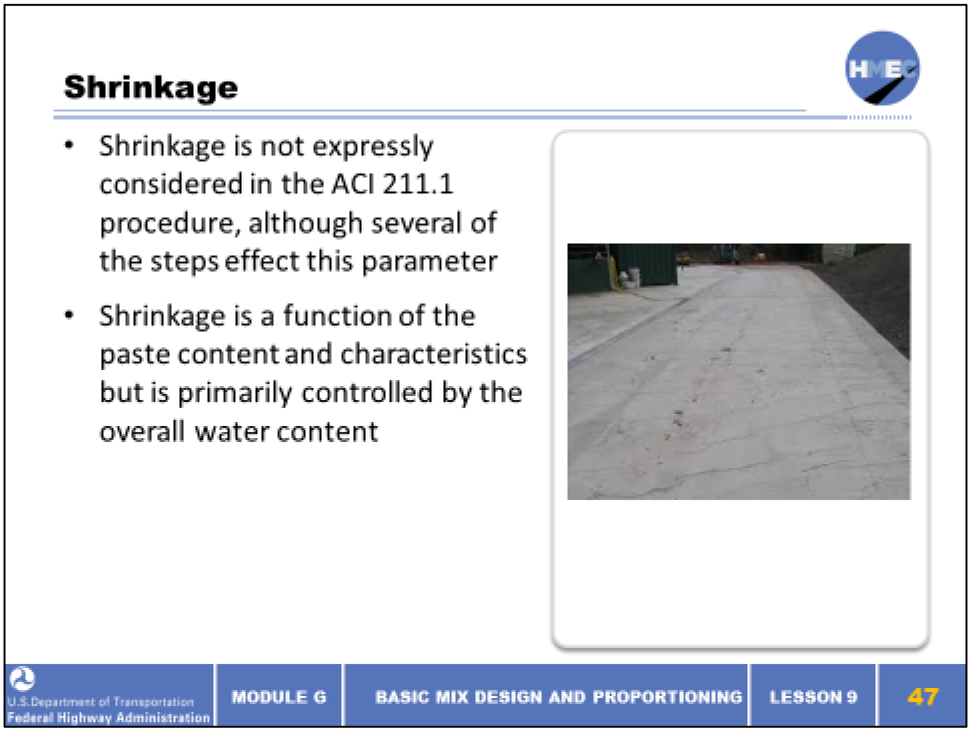

Effects of Proportioning on the Engineering Properties of PCC
HMEC
Each of the eight primary steps listed in the ACI 211.1 procedure can affect the engineering properties of PCC, including:
– Workability
– Shrinkage
– Permeability
– Strength
– Others
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
45

Slide 46



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

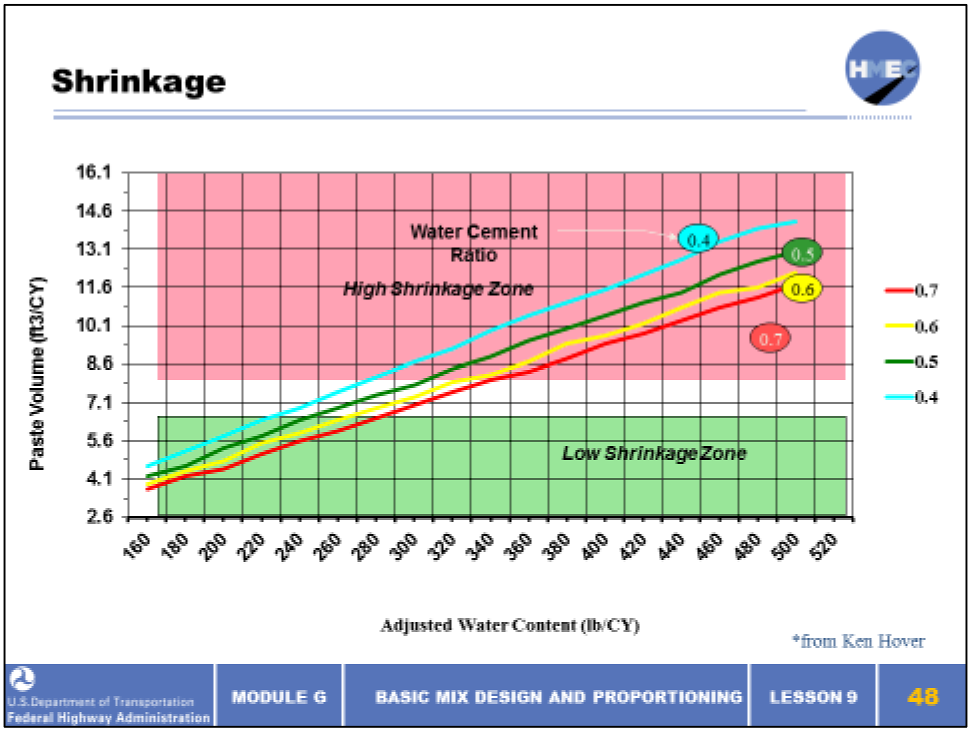
Slide 47



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



Shrinkage
HMEC
16.1
14.6
13.1
11.6
10.1
8.6
7.1
5.6
4.1
2.6
Paste Volume (ft3/CY)
Water Cement Ratio
High Shrinkage Zone
Low Shrinkage Zone
0.4
0.5
0.6
0.7
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
520
Adjusted Water Content (lb/CY)
*from Ken Hover
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
48

____

____

____

____

____

____

____

____

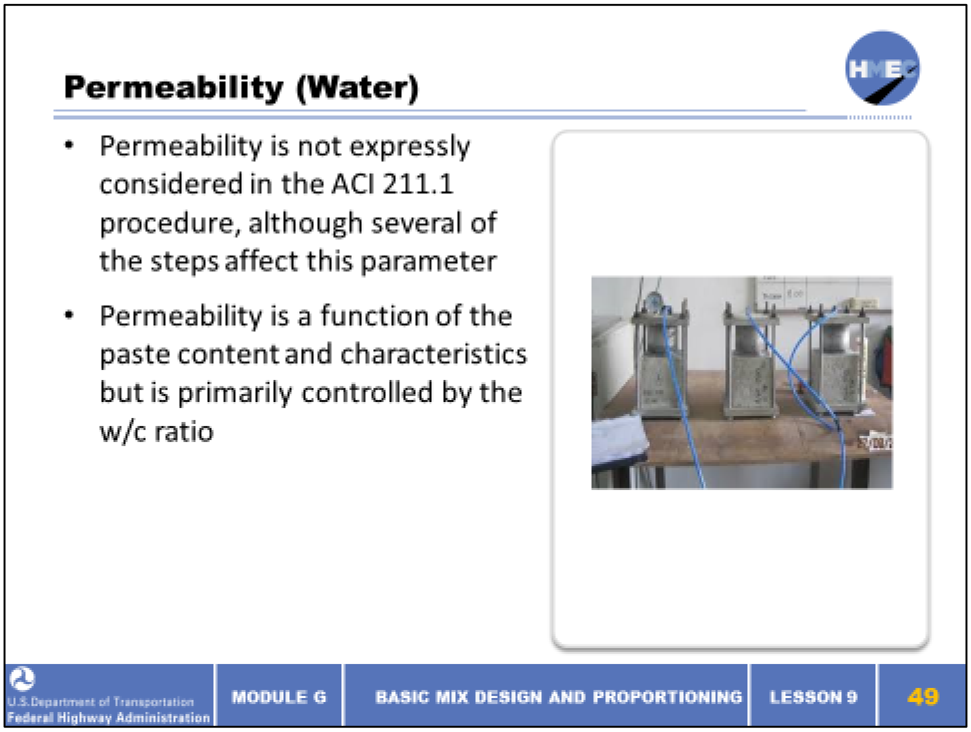
____

____

____

____

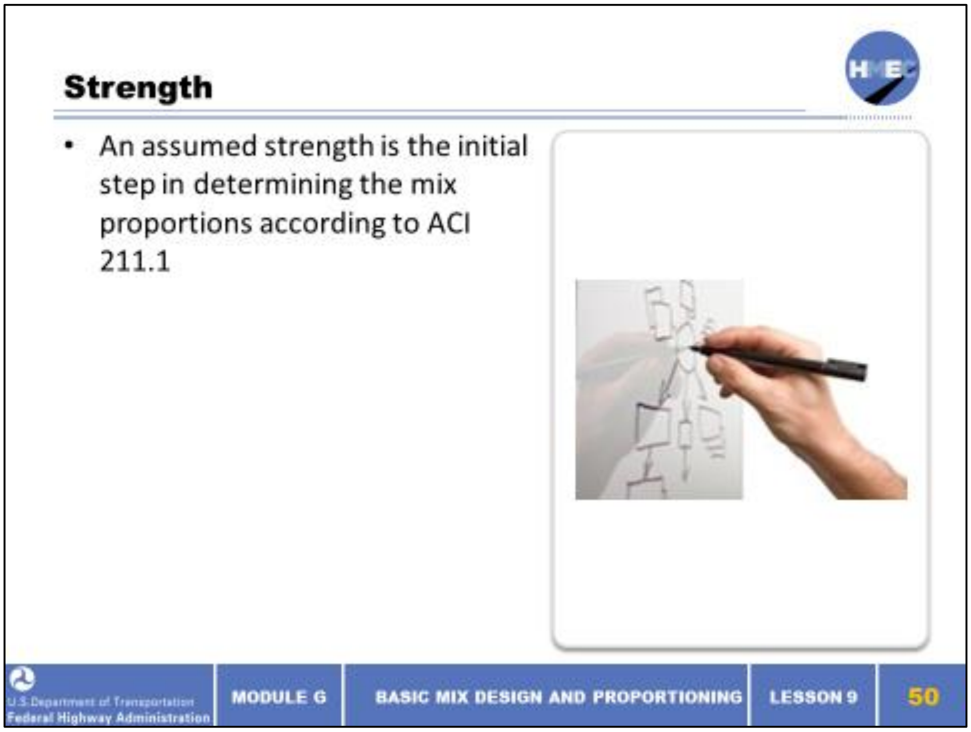
Slide 49



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

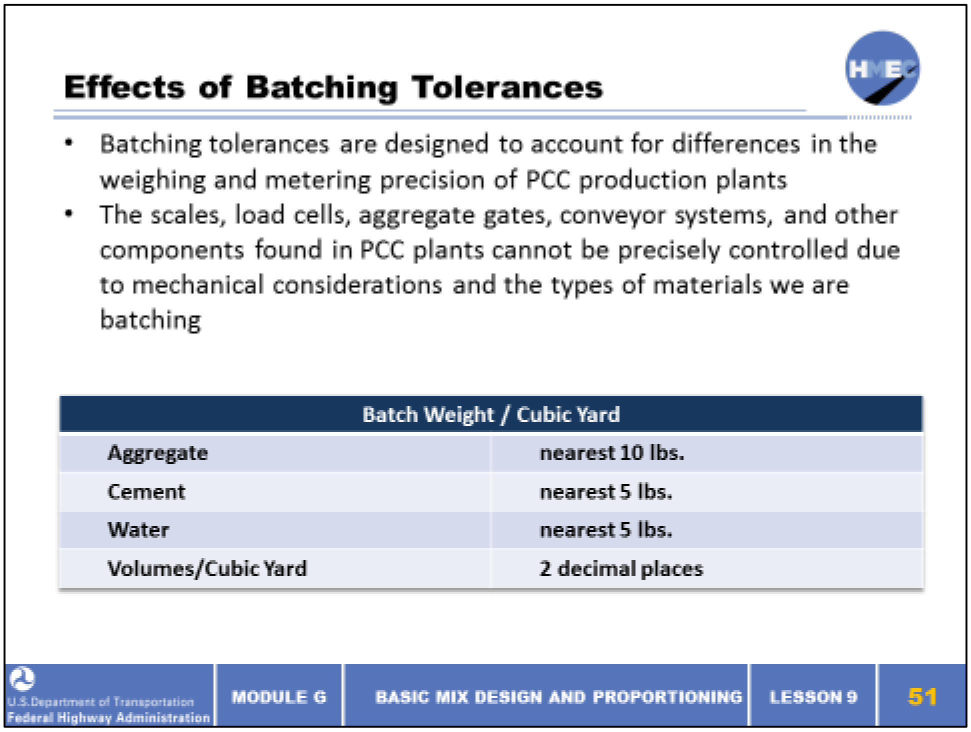
The photo shows a surface resistivity device being used to measure the hardened PCC permeability.

Slide 50



The strength is directly considered in the ACI procedure.

Slide 51



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.

____

____

____

____

____

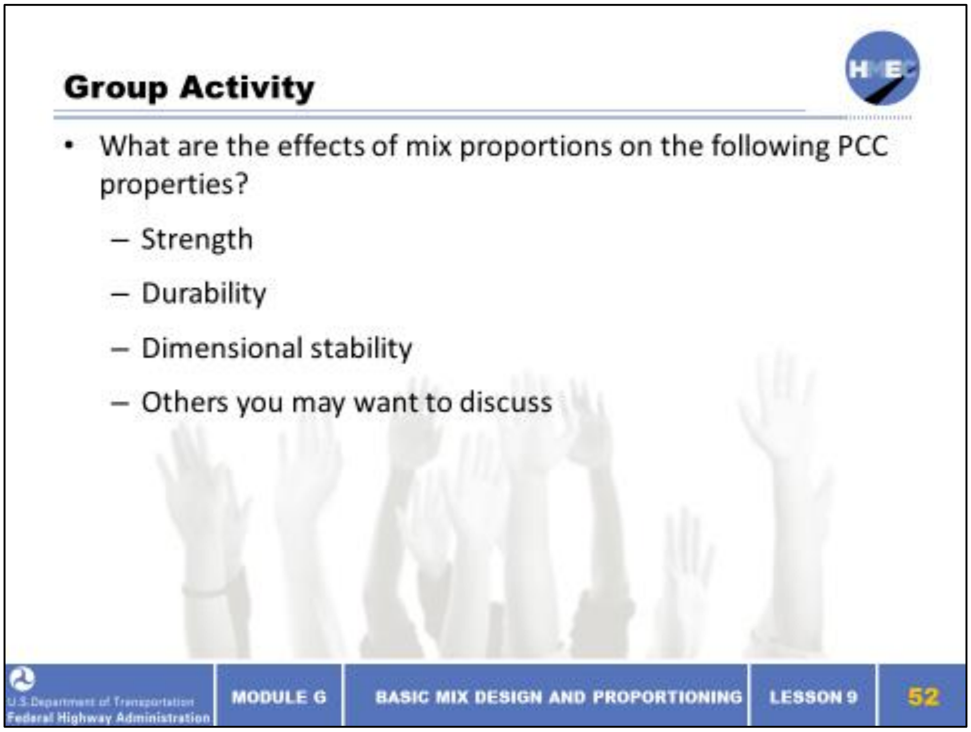
____

____

____

____

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
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
52

____

____

____

____

____

____

____

____

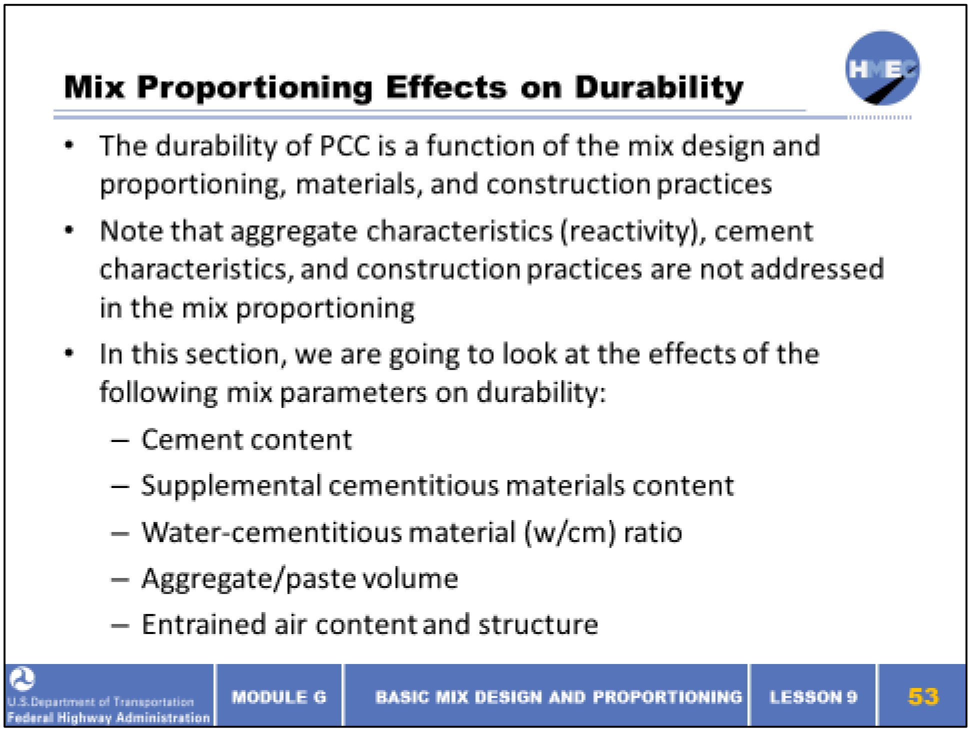
____

____

____

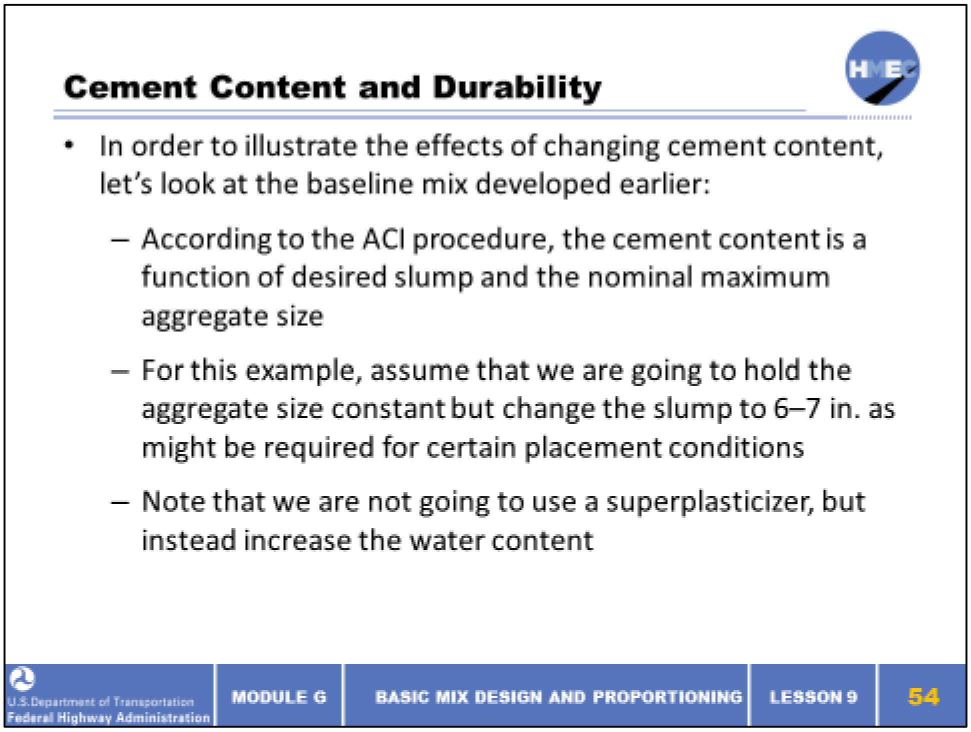
____

Slide 53



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

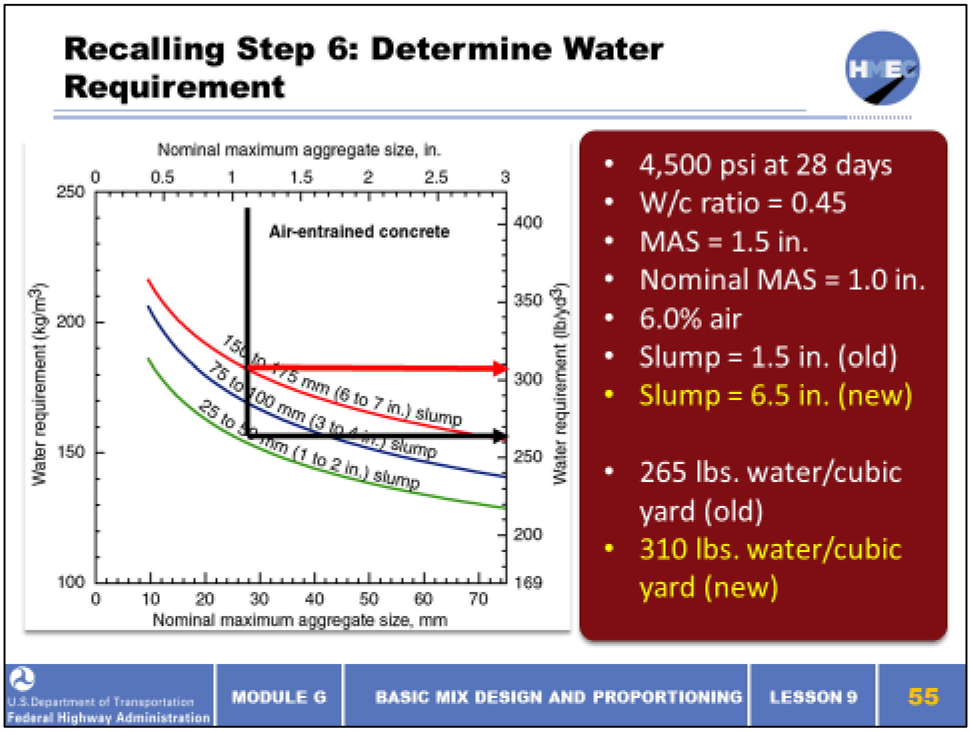
Slide 54



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

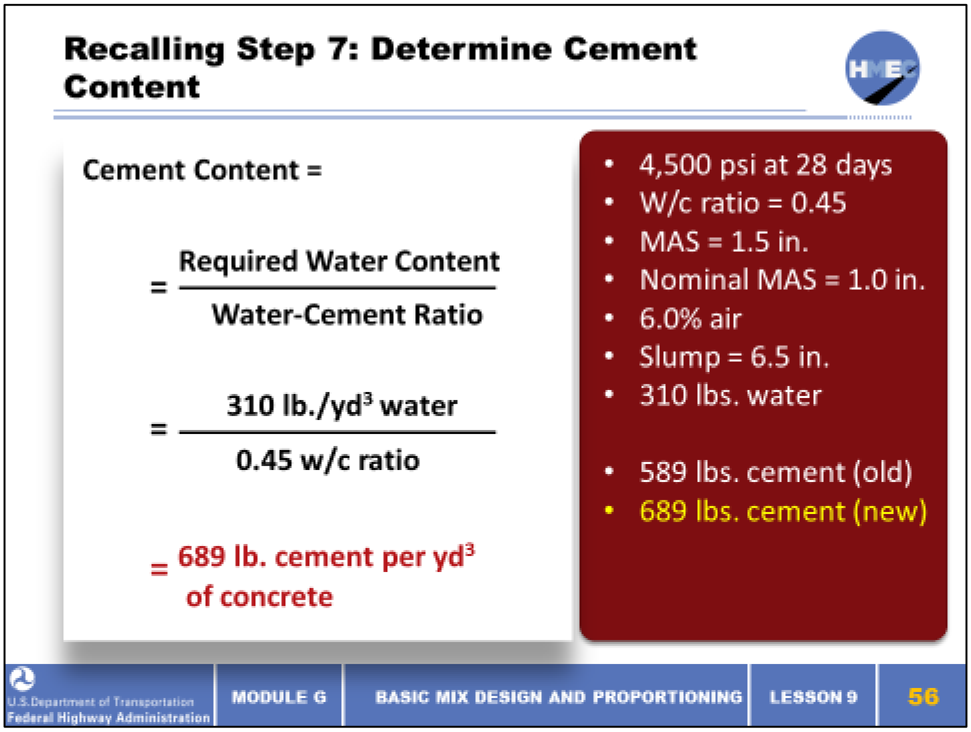
To illustrate the point, we are going to modify the original baseline mix proportions, as shown in the following slides.

Slide 55



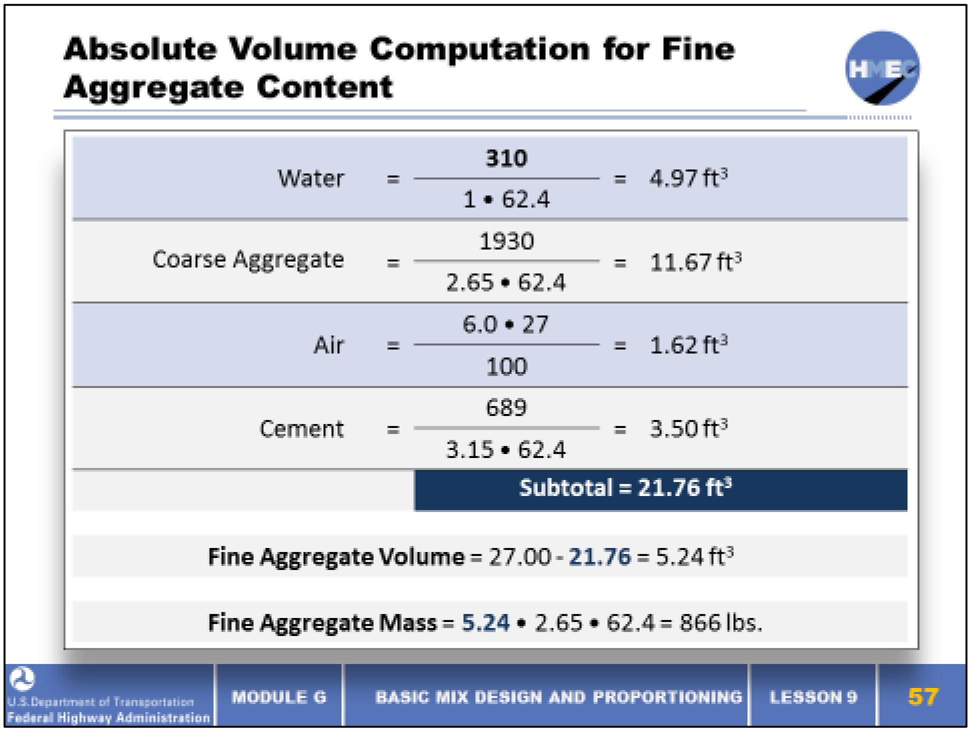
We are increasing the slump of the PCC to 6–7 in. without the use of a water reducer. The new water requirement for the increased slump is approximately 310 lbs./cy versus 265 lbs./cy for the baseline mix.

Slide 56



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



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

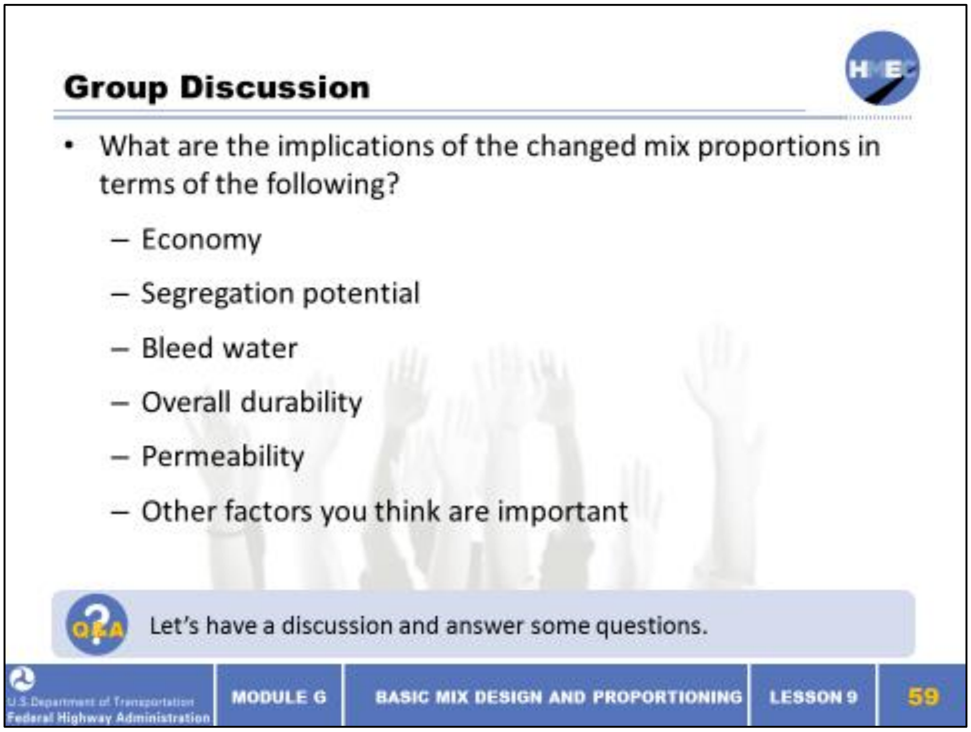
Mix Proportioning Example Summary

- 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%

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 58

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.
Q&A
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
59

Slide 60

Supplemental Cementitious Materials Content and Durability

- The cementitious materials content is not directly calculated in the ACI 211.1 procedure (the cement content is)
- However, if the cement content is actually viewed as the cementitious materials content and the w/c ratio as the w/cm ratio, the same mix design may be used
- Most agencies have established limits on SCMs based on past performance or specific goals related to performance or economy

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 60

Slide 61

Cementitious Materials Requirements for Concrete Exposed to Deicing Chemicals

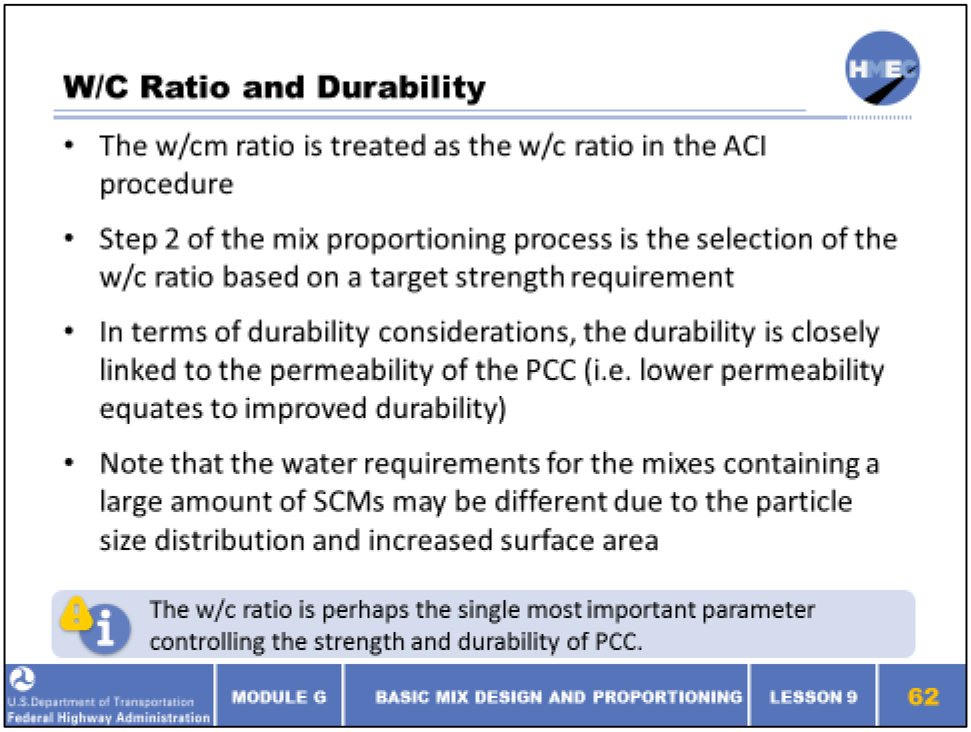
Cementitious Materials	Maximum of Cementitious Materials, %
Fly ash and natural pozzolans	25 (25)
Slag	40 (50)
Silica fume	0 (10)
Total of fly ash, slag, silica fume, and natural pozzolans	50 (50)
Total of natural pozzolans and silica fume	*(35)

Non-bracketed numbers are American Concrete Pavement Association recommendations
( ) denotes ACI recommendations

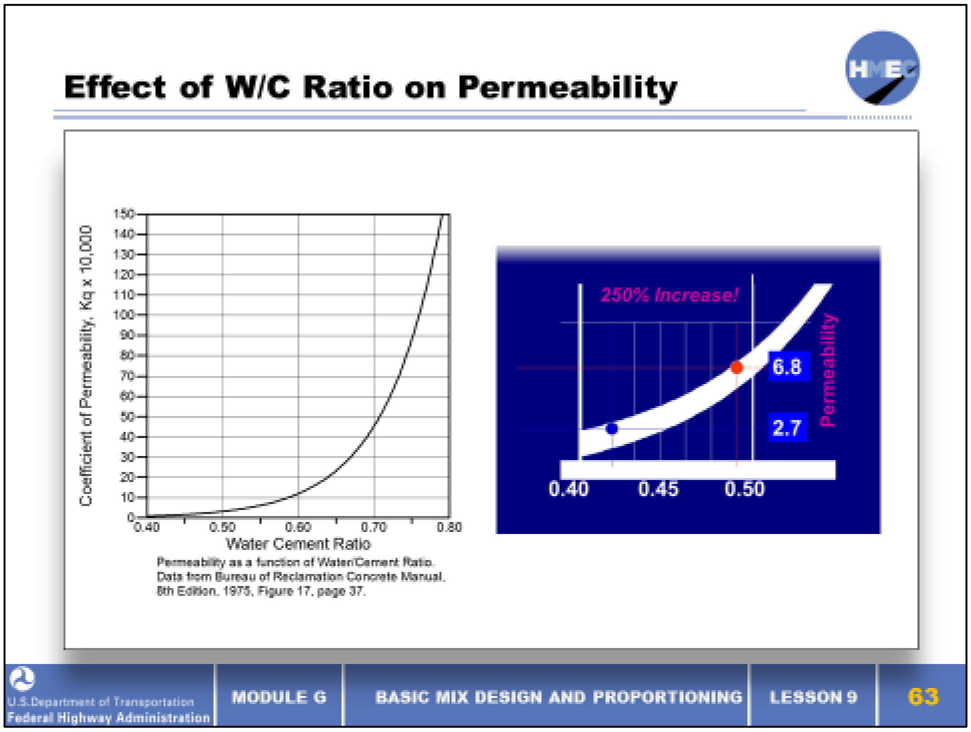
Q&A What is the range of addition that is allowed in your State?

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 61

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.
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
62

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 64

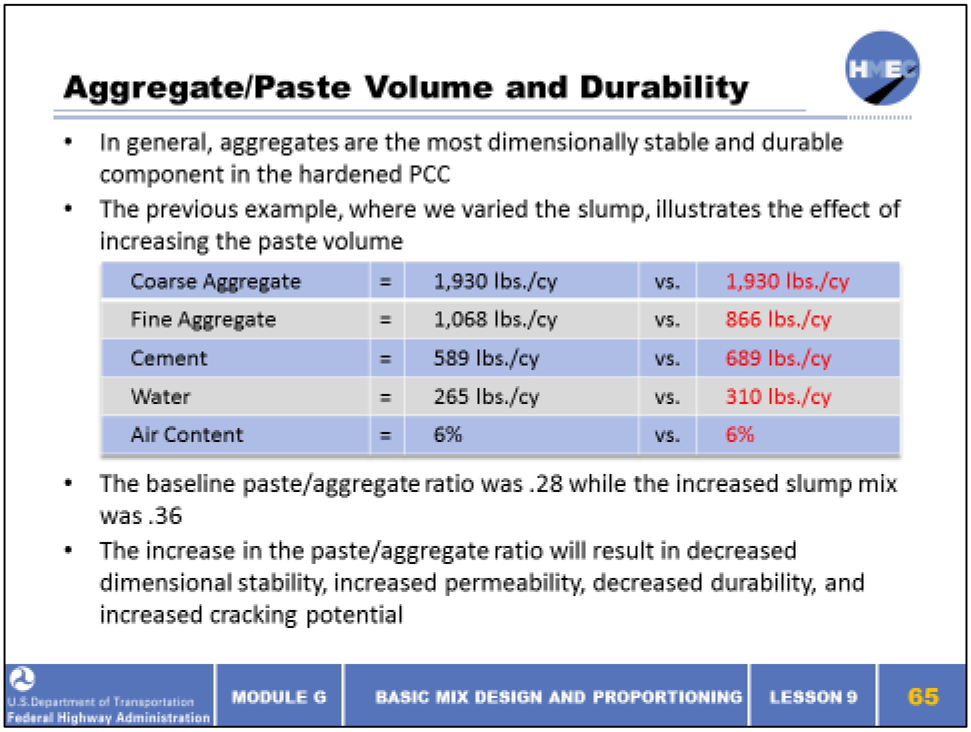
Adjustments to Mix Water

Water Adjustment	Water Adjustment Range
Aggregate shape and texture	-5 to +5%
Combined aggregate grading	-10 to +10%
Air entraining admixture	-10 to 0%
Water reducing admixtures	
Normal range	-10 to -5%
Mid-range	-15 to -8%
High-range	-30 to -12%
Supplementary cementitious materials	-10 to +15%
Other factors (w/c, fineness, temp)	-10 to +10%

Q&A What are some common practices in your State?

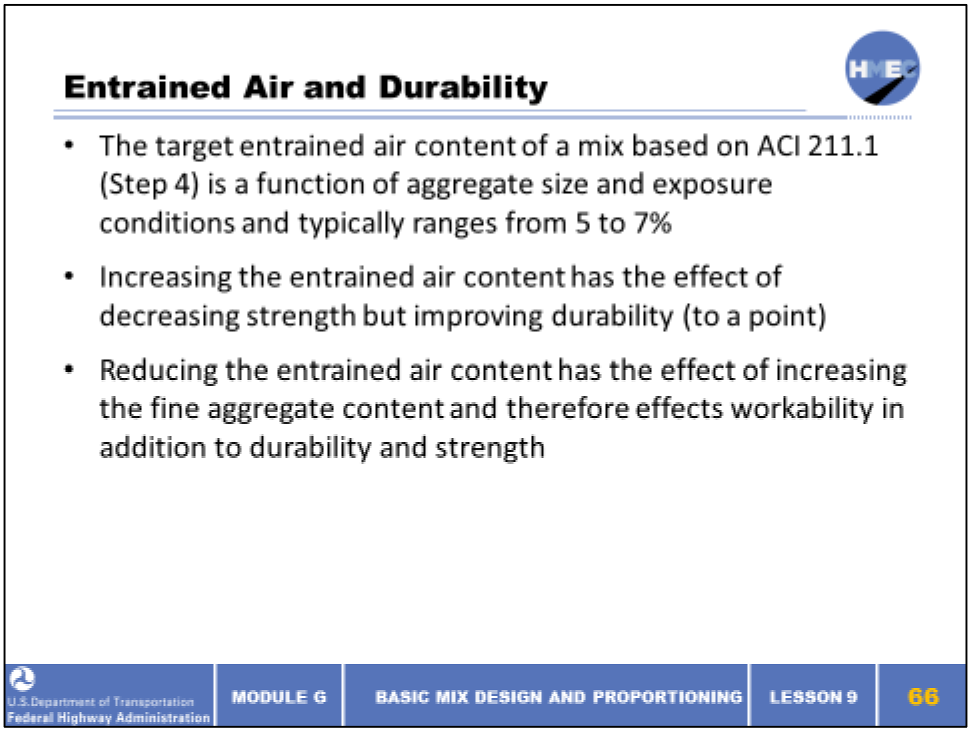
U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 64

Slide 65

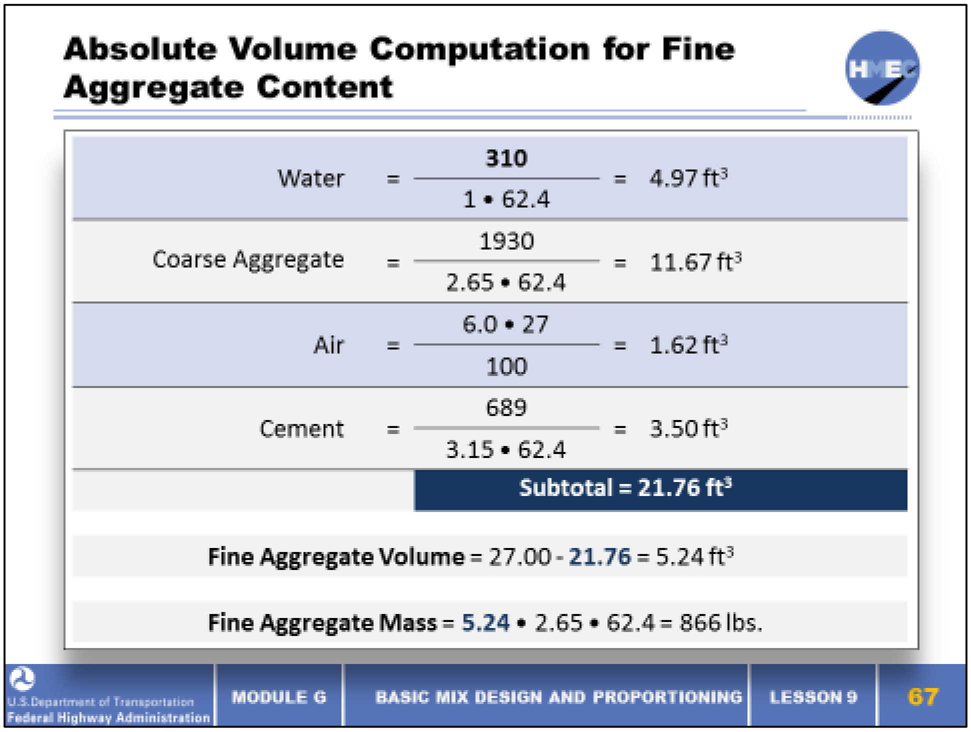


Compare the cement and water content in particular. As a rule, lowering the paste/aggregate ratio is desirable.

Slide 66

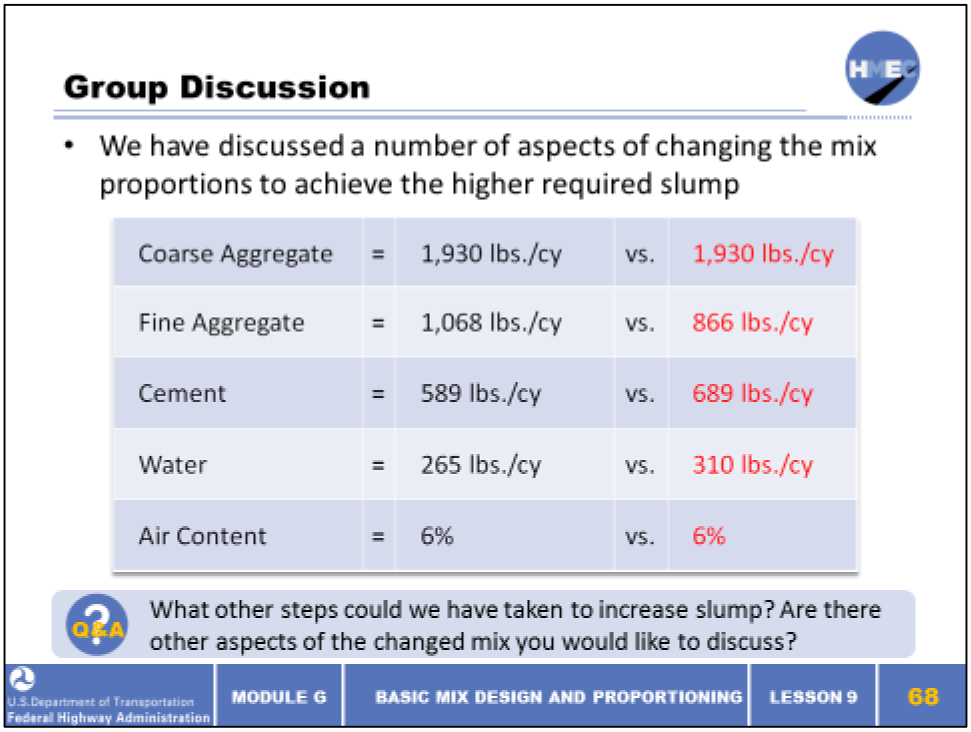

Entrained Air and Durability
• The target entrained air content of a mix based on ACI 211.1 (Step 4) is a function of aggregate size and exposure conditions and typically ranges from 5 to 7%
• Increasing the entrained air content has the effect of decreasing strength but improving durability (to a point)
• Reducing the entrained air content has the effect of increasing the fine aggregate content and therefore effects workability in addition to durability and strength
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
66

Slide 67



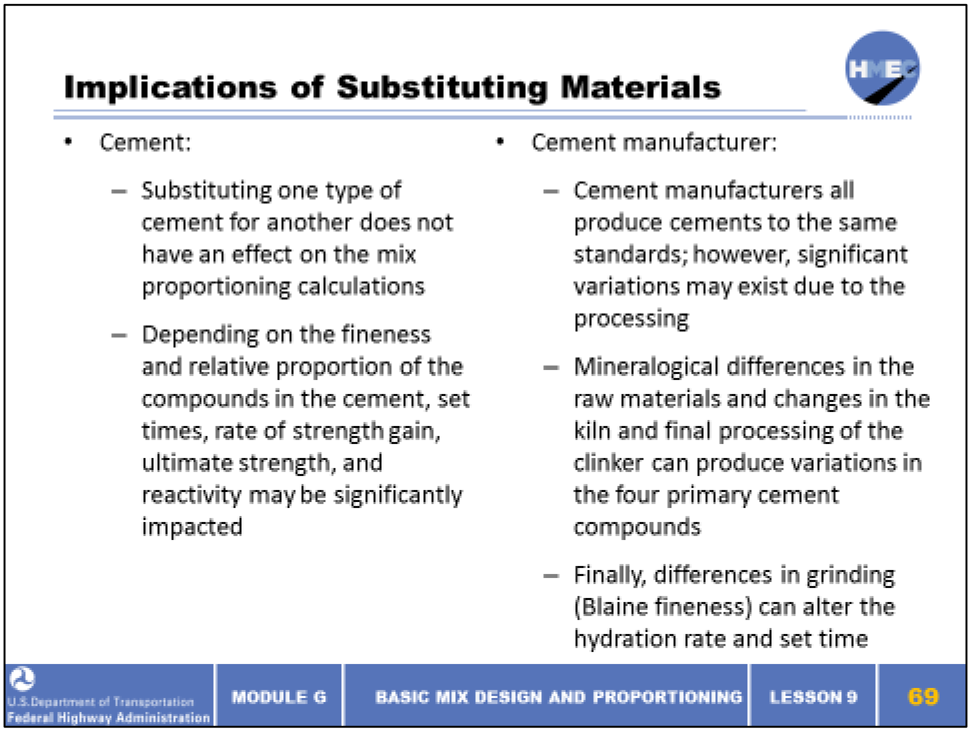
Admixture dosages are too small to account for in the volumetric method, but they play a vital role in the mix.

Slide 68



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

Slide 69



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.

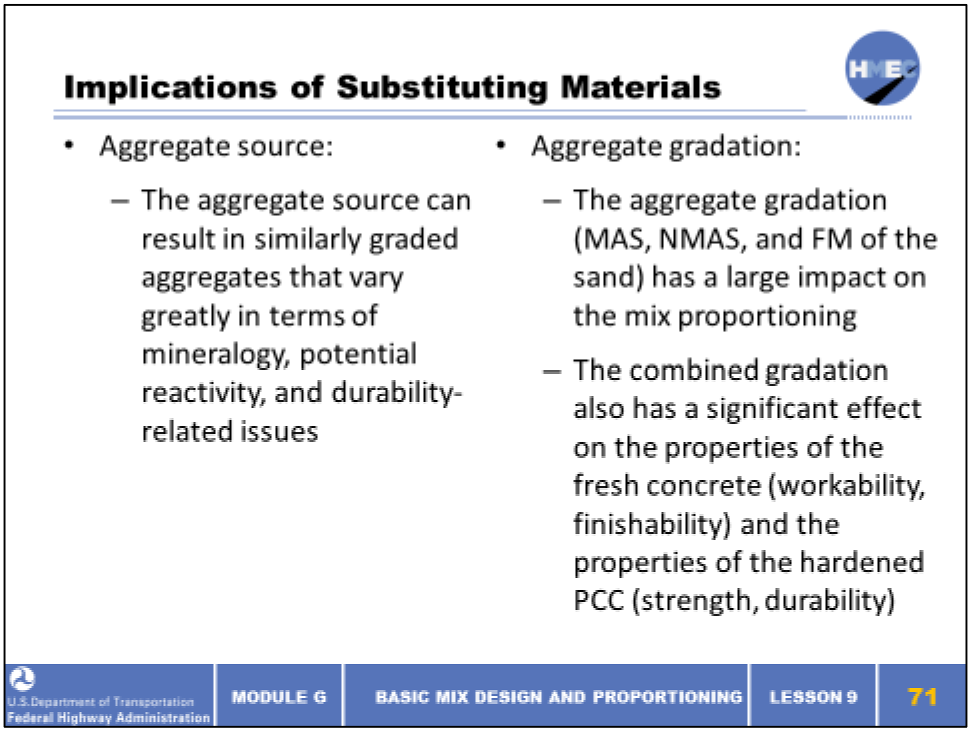
Slide 70

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

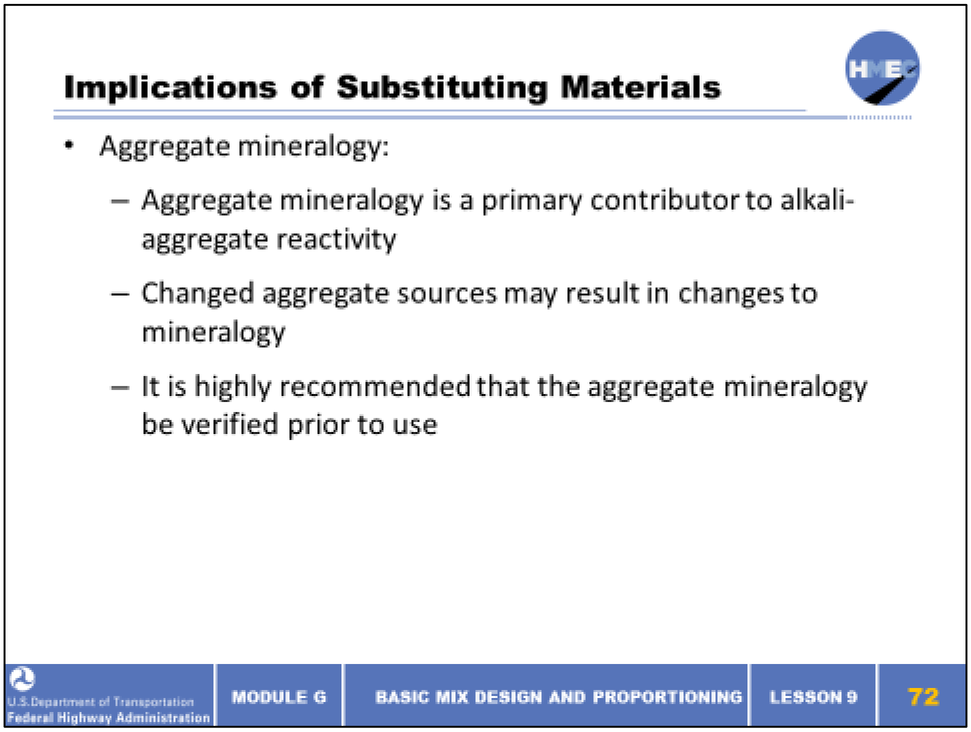
U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 70

Slide 71

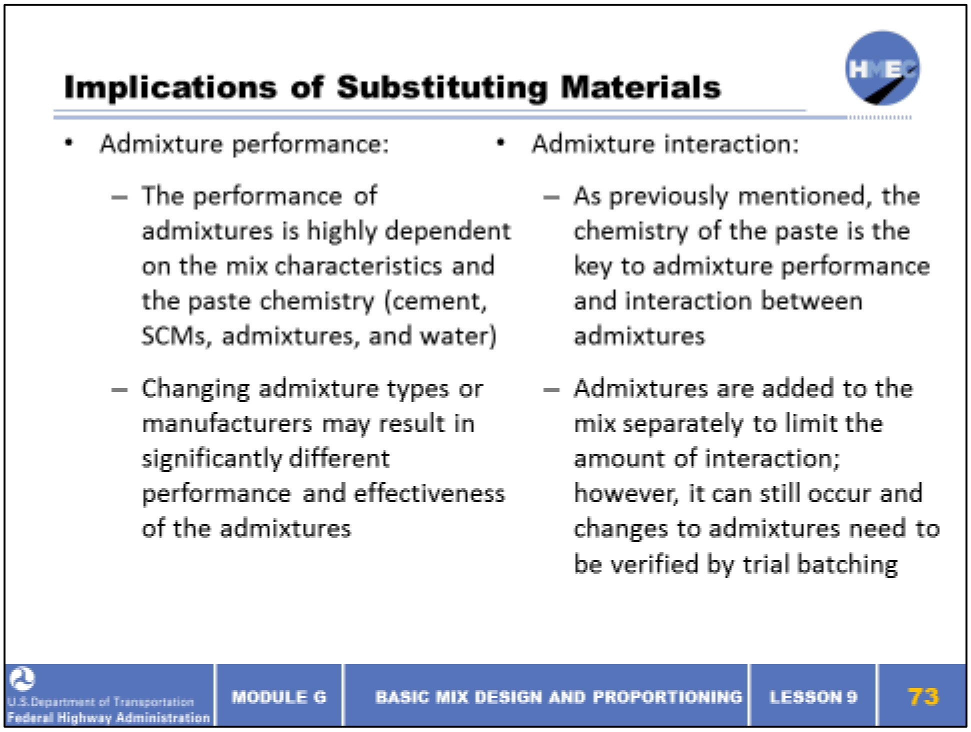


Changing aggregate gradation can have a very significant impact on water requirements and workability.

Slide 72


Implications of Substituting Materials
HMEC
• 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
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
72

Slide 73

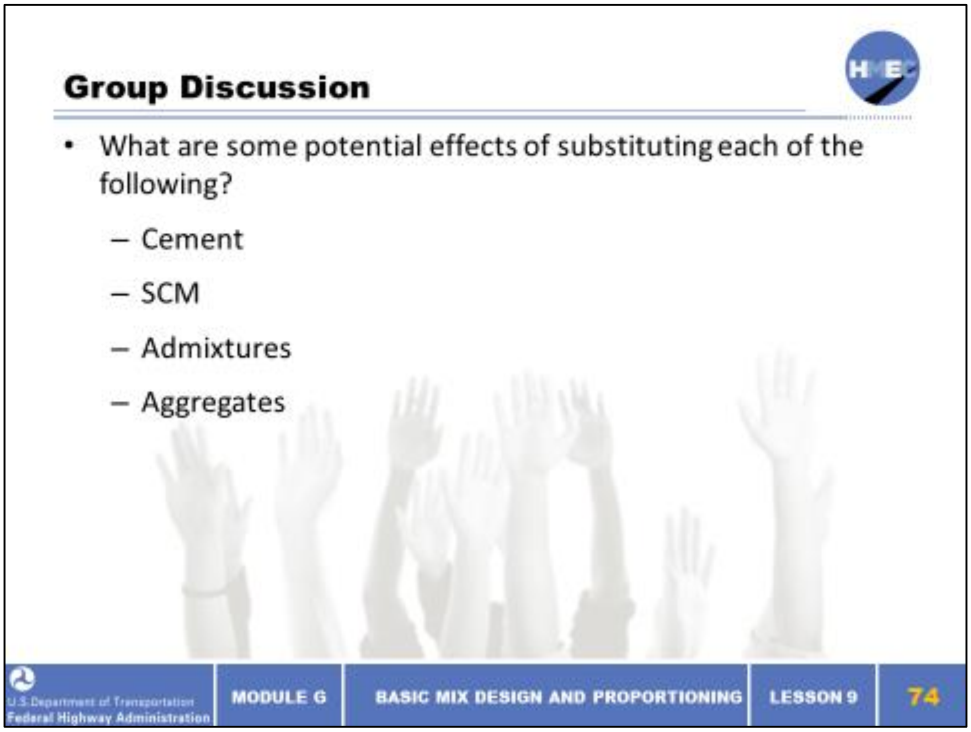


Changing one or more admixture types or manufacturers may lead to incompatibility due to changes in chemistry of the paste system.

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
HMEC
• What are some potential effects of substituting each of the following?
– Cement
– SCM
– Admixtures
– Aggregates
U.S. Department of Transportation Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
74

____

____

____

____

____

____

____

____

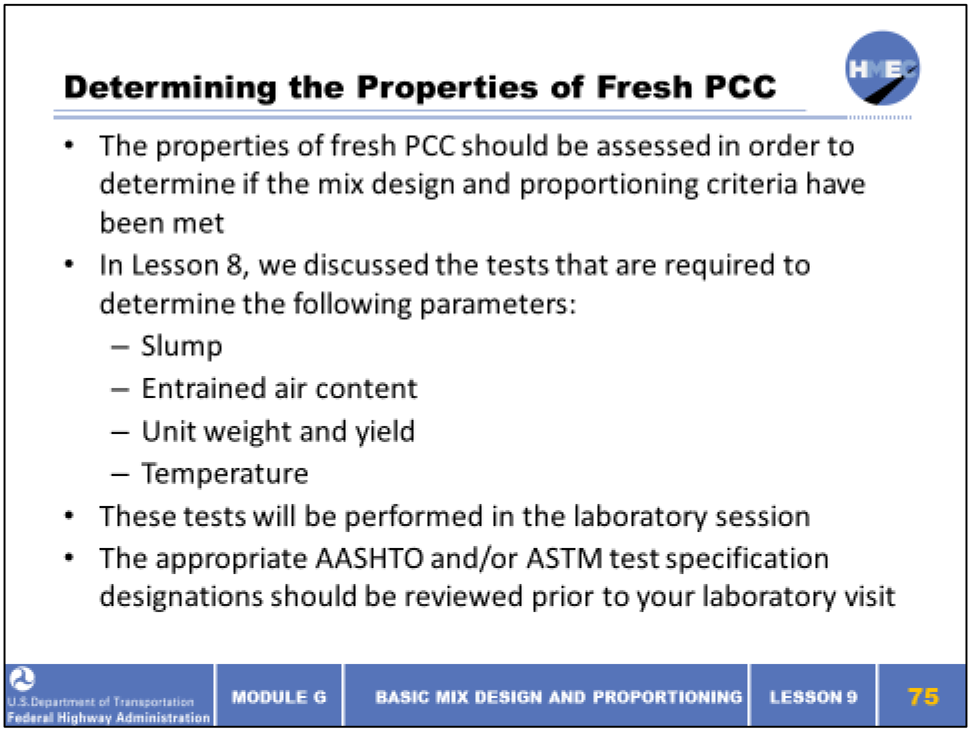
____

____

____

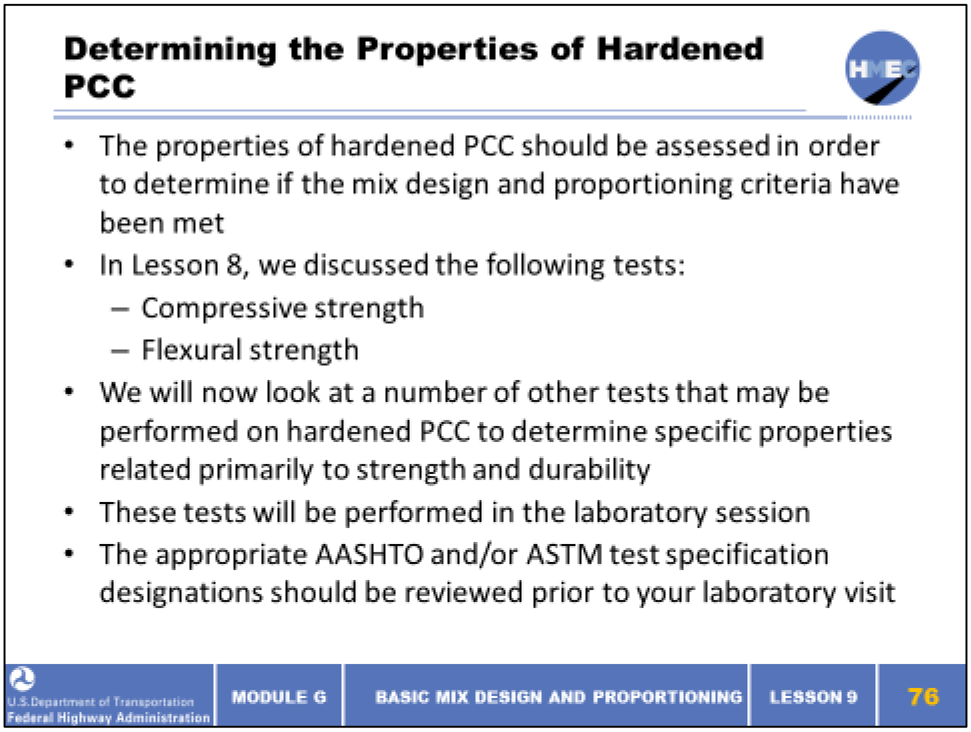
____

Slide 75



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



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.

____

____

____

____

____

____

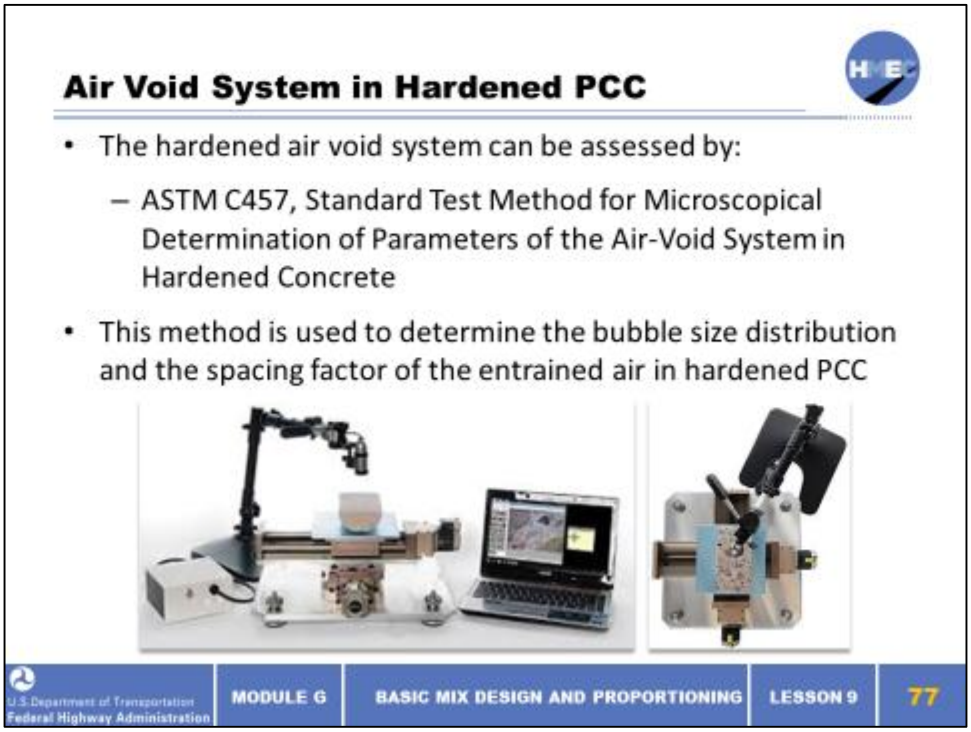
____

____

____

____

Slide 77

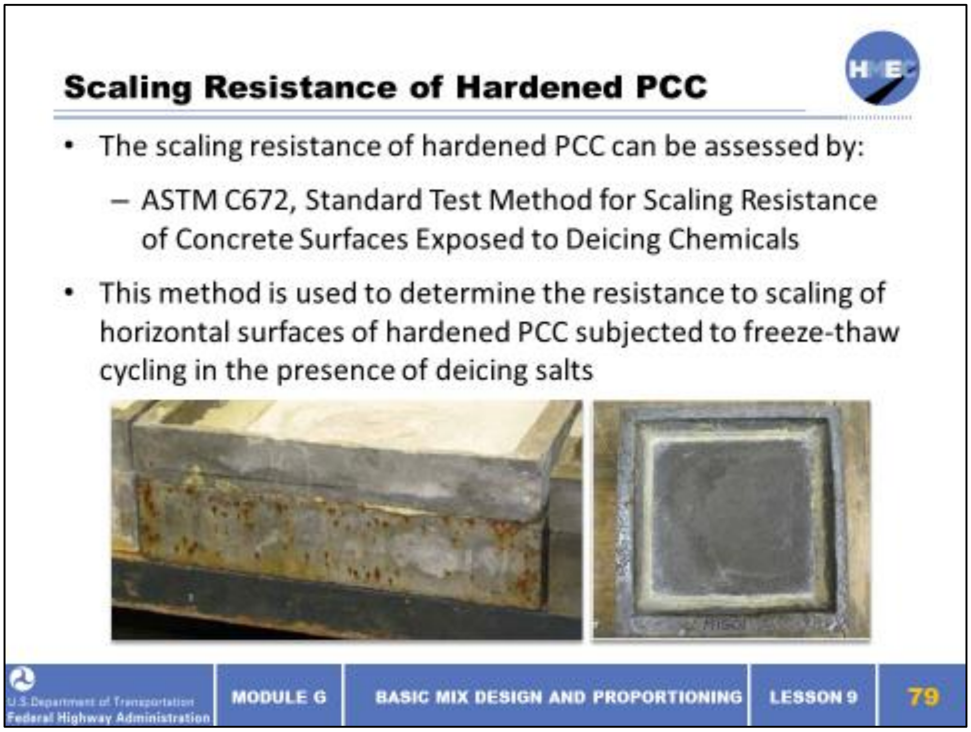


The bubble sizes, distribution, and spacing can all be determined with this test. This procedure is often used in forensic studies of distressed PCC.

Slide 78

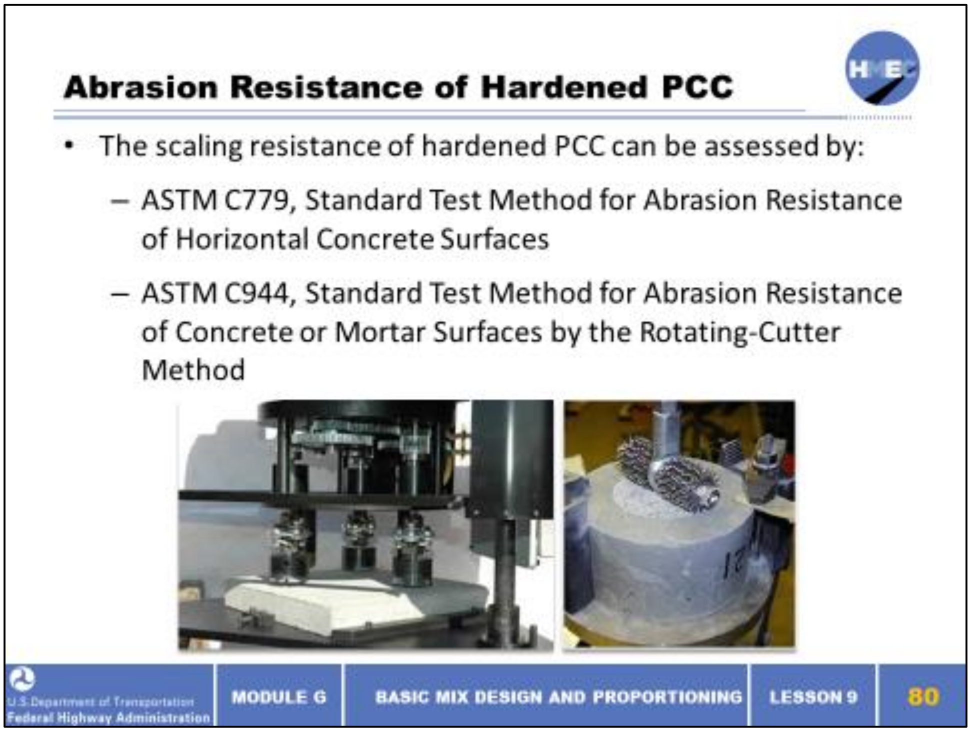
This test is suggested for new mix designs subjected to freeze-thaw cycles.

Slide 79



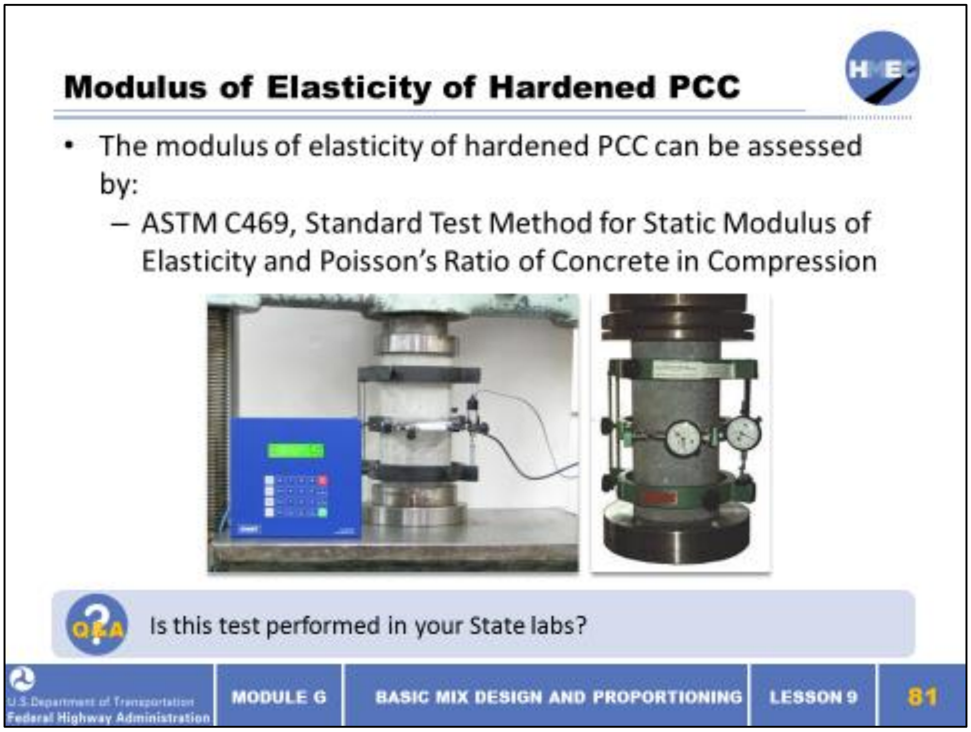
Scaling is oftentimes due to over-finishing, lack of adequate curing, and other construction practices. This test, however, will provide information regarding the material behavior assuming proper construction practices are followed.

Slide 80



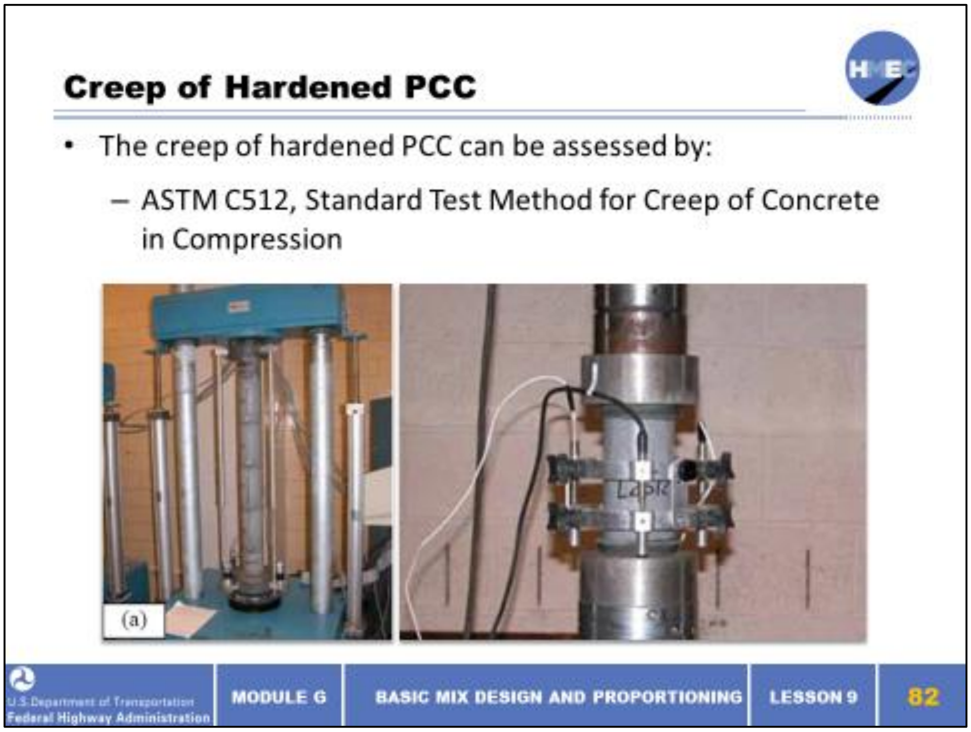
The elastic modulus value is an important design variable for both structures and pavements. Although this value is often assumed based on correlation to compressive strength, testing new mixes is desirable.

Slide 81



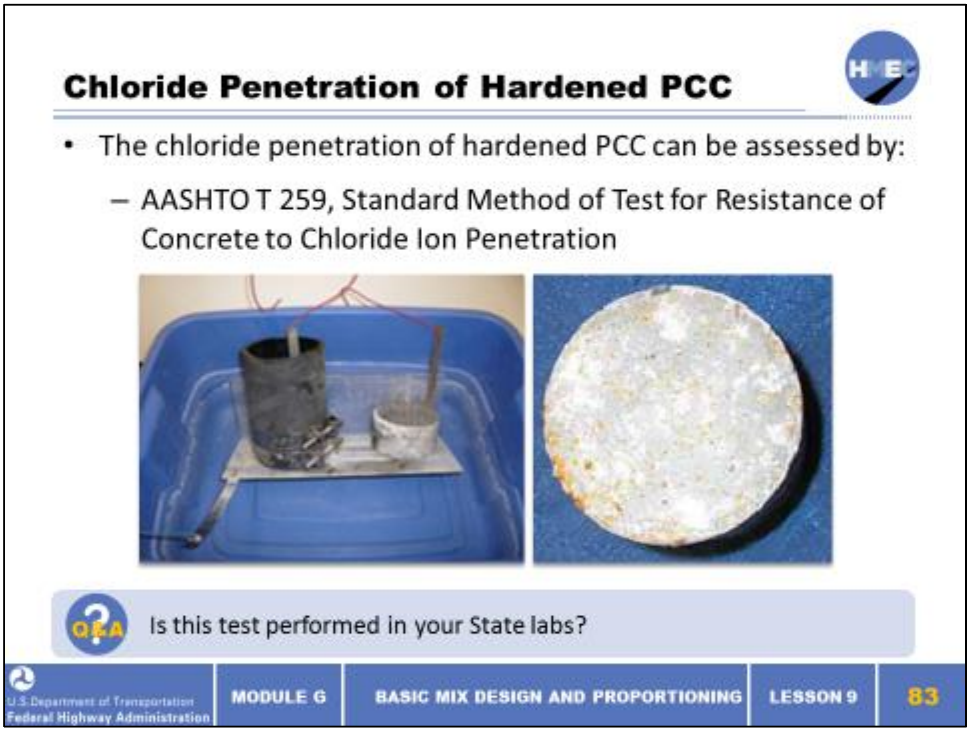
The elastic modulus value is an important design variable for both structures and pavements. Although this value is often assumed based on correlation to compressive strength, testing new mixes is desirable.

Slide 82



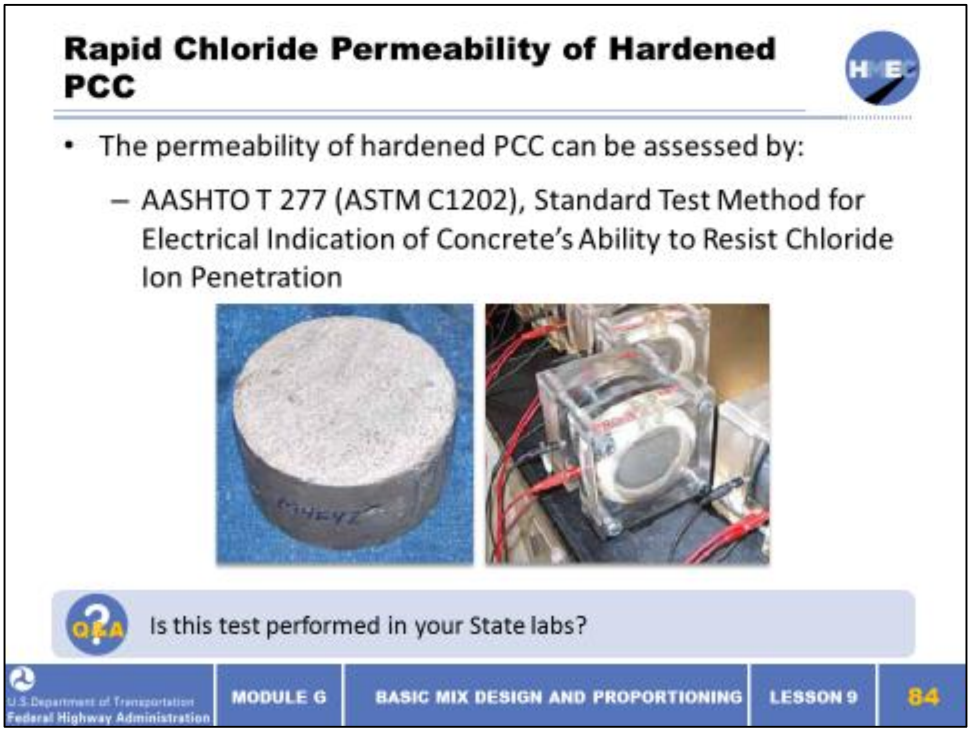
The creep, or long-term deformation, under load is important in structural analysis. The long-term creep apparatus is shown on the left while short-term creep testing is shown on the right.

Slide 83



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

Slide 84

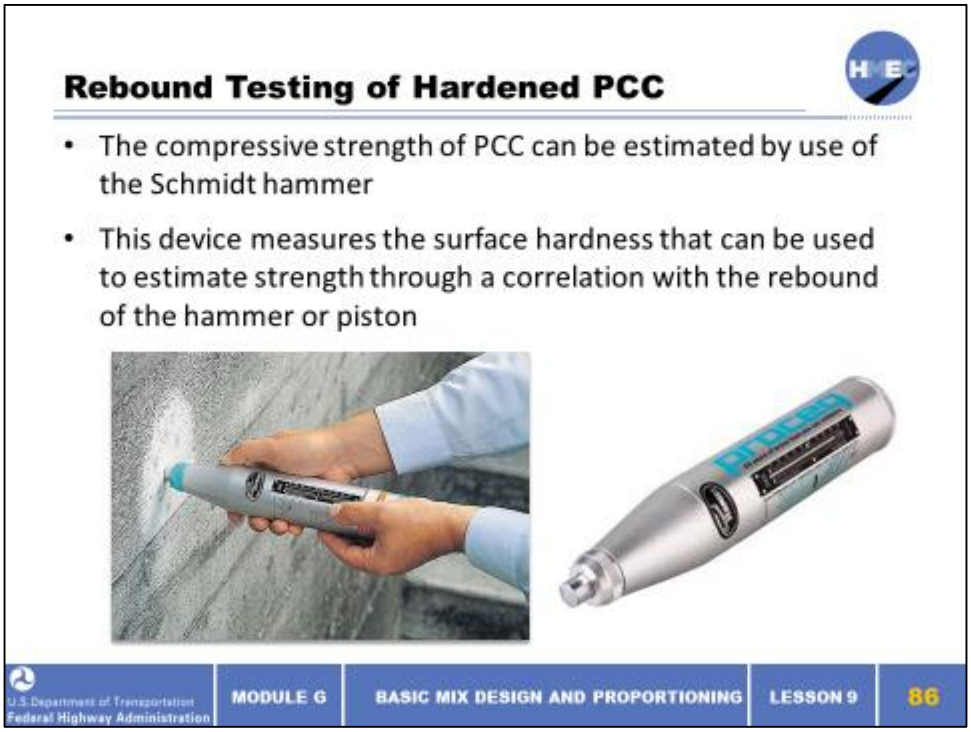


This test can be used to determine this property for new mixes.

Slide 85

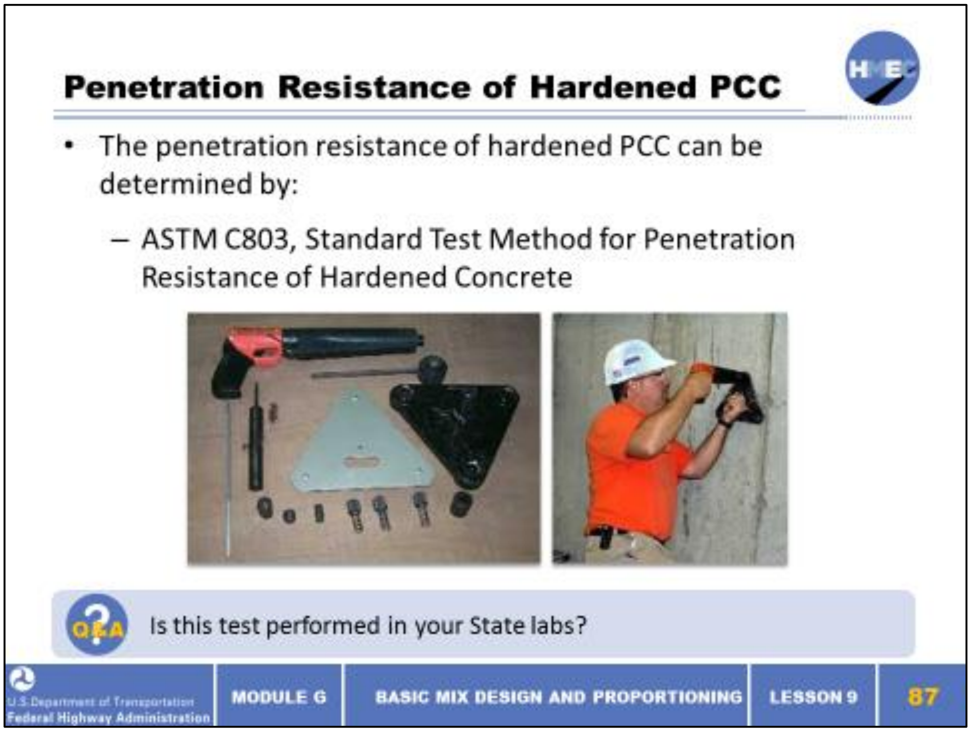
The surface resistivity is another test procedure aimed at determining chloride ion penetration in hardened PCC.

Slide 86



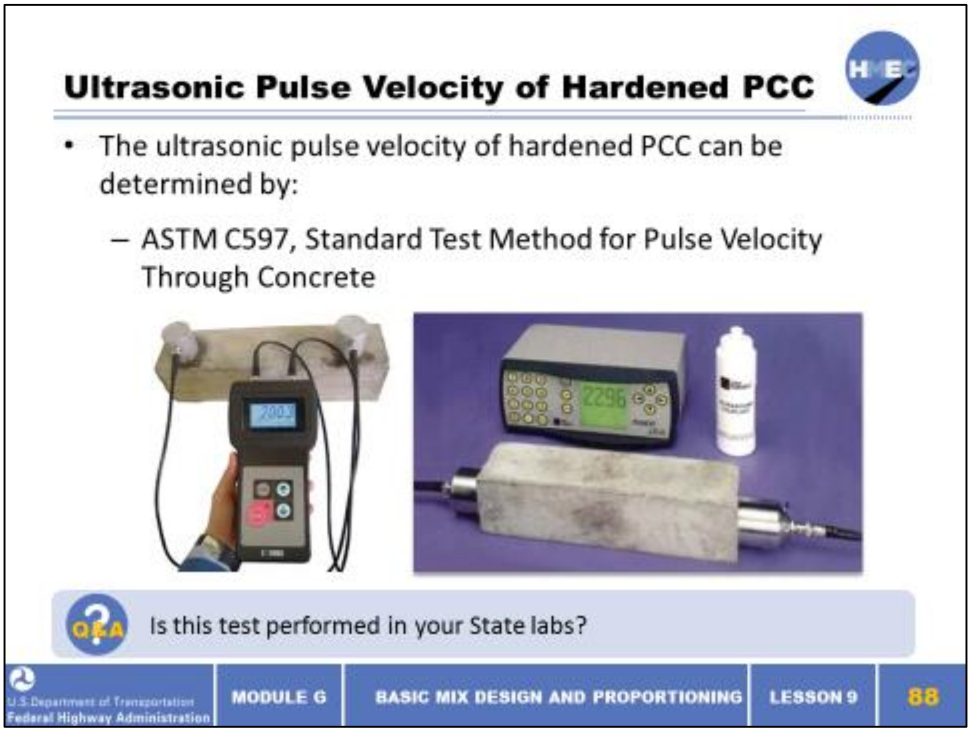
This apparatus measures the surface hardness of PCC, which is then correlated to strength. Testing with this device is very quick, although there are many parameters that affect its accuracy, including surface finish, PCC moisture, and aggregates. This test is not used for acceptance testing and is typically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

Slide 87



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

Slide 88



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

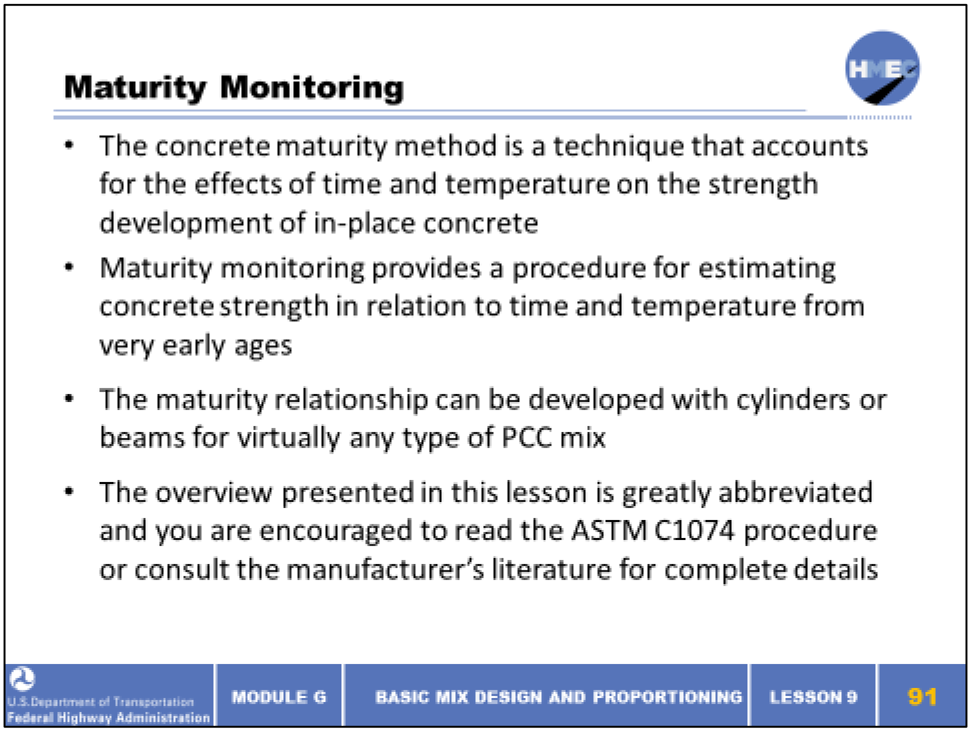
Slide 89

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

Slide 90

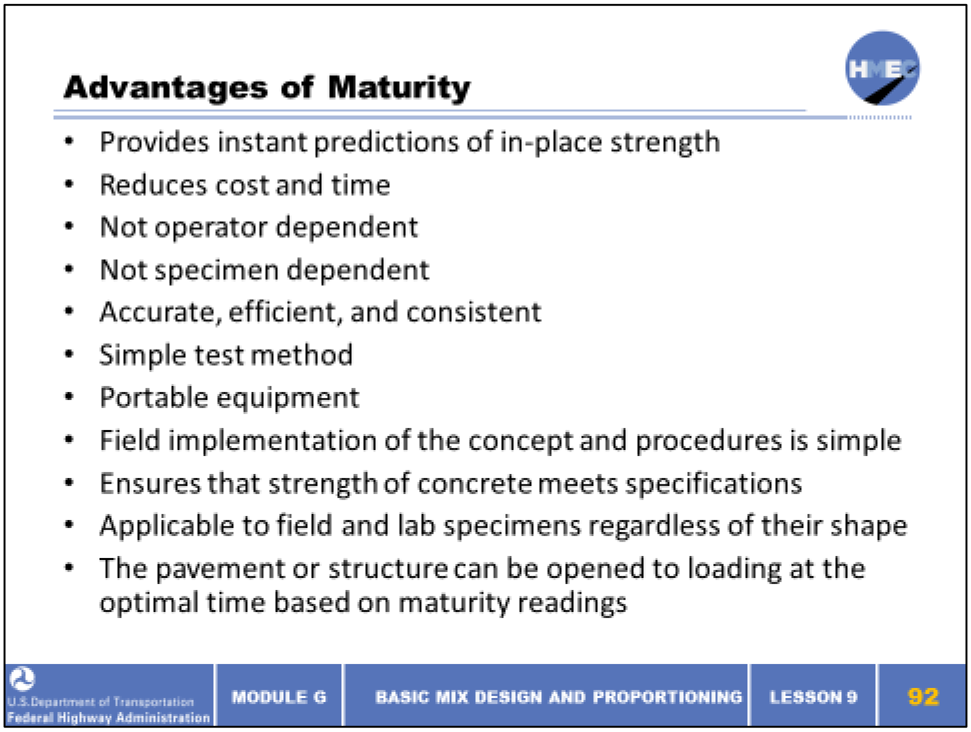

Maturity of Hardened PCC
• The maturity of hardened PCC can be determined by:
– AASHTO T 325 (ASTM C1074), Standard Method of Test for Estimating the Strength of Concrete in Transportation Construction by Maturity Tests
Is this test performed in your State labs?
U.S. Department of Transportation Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
90

Slide 91

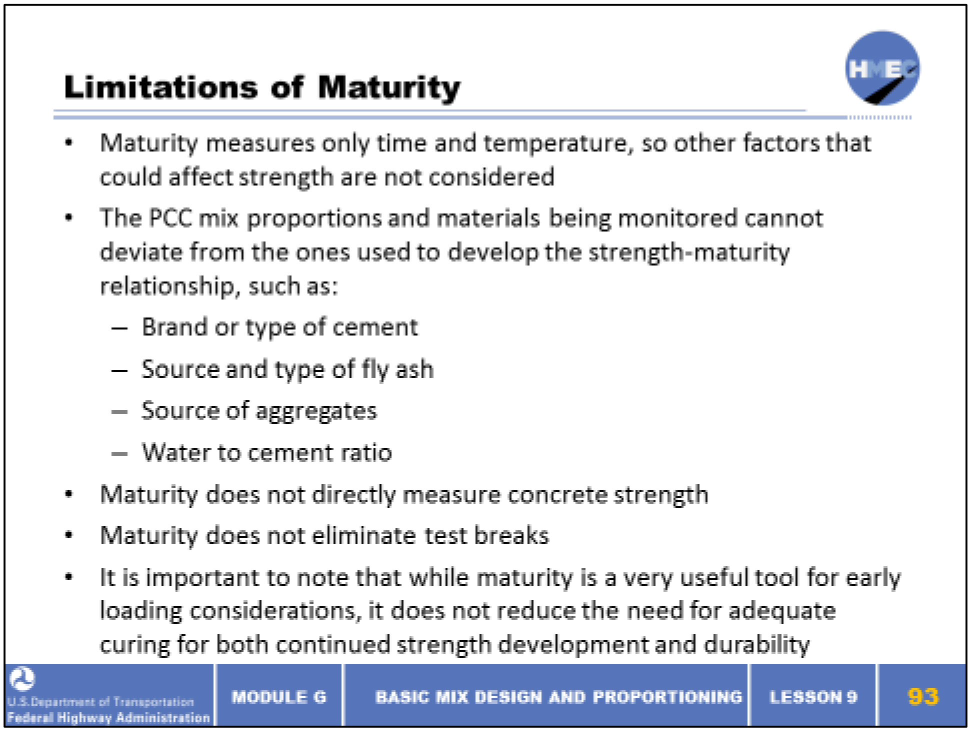


Maturity monitoring (ASTM C1074) provides a procedure for estimating concrete strength in relation to time and temperature from very early ages (less than 1 day). The maturity relationship can be developed with cylinders or beams (compressive strength or flexural strength) for virtually any type of PCC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

Slide 92


Advantages of Maturity
HMEC
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
U.S. Department of Transportation
Federal Highway Administration
MODULE G
BASIC MIX DESIGN AND PROPORTIONING
LESSON 9
92

Slide 93



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

U.S. Department of Transportation Federal Highway Administration | MODULE G | BASIC MIX DESIGN AND PROPORTIONING | LESSON 9 | 94

Slide 1


HMEC
Highway Materials Engineering Course
Lesson 10: Reinforcing and Corrosion
Portland Cement Concrete
(PCC)
U.S.Department of Transportation
Federal Highway Administration
MODULE
G

____

____

____

____

____

____

____

____

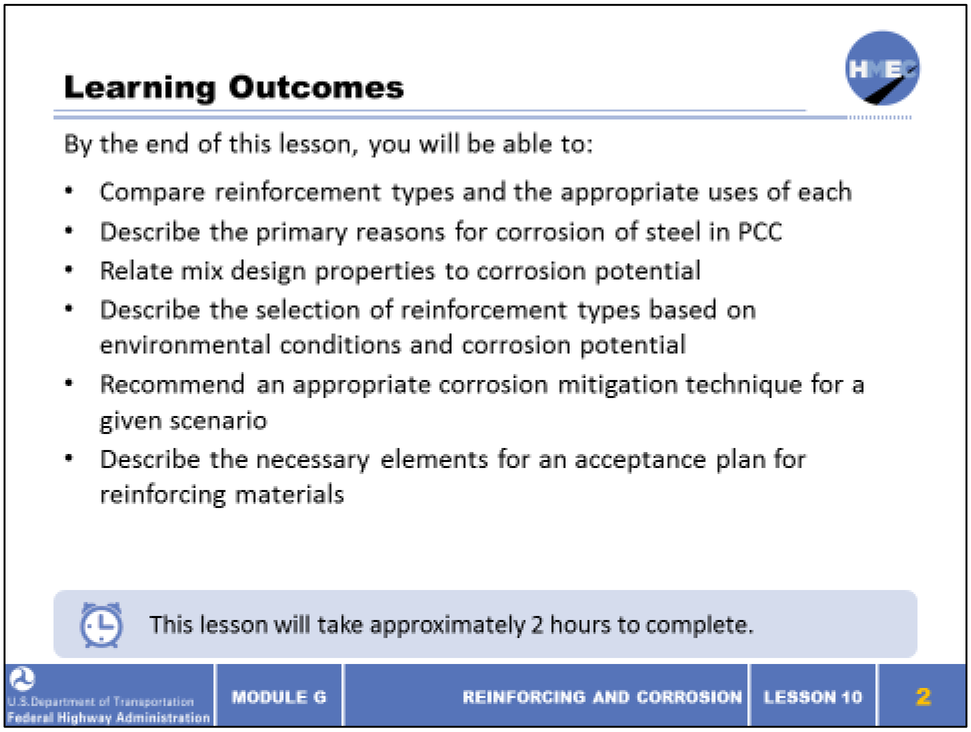
____

____

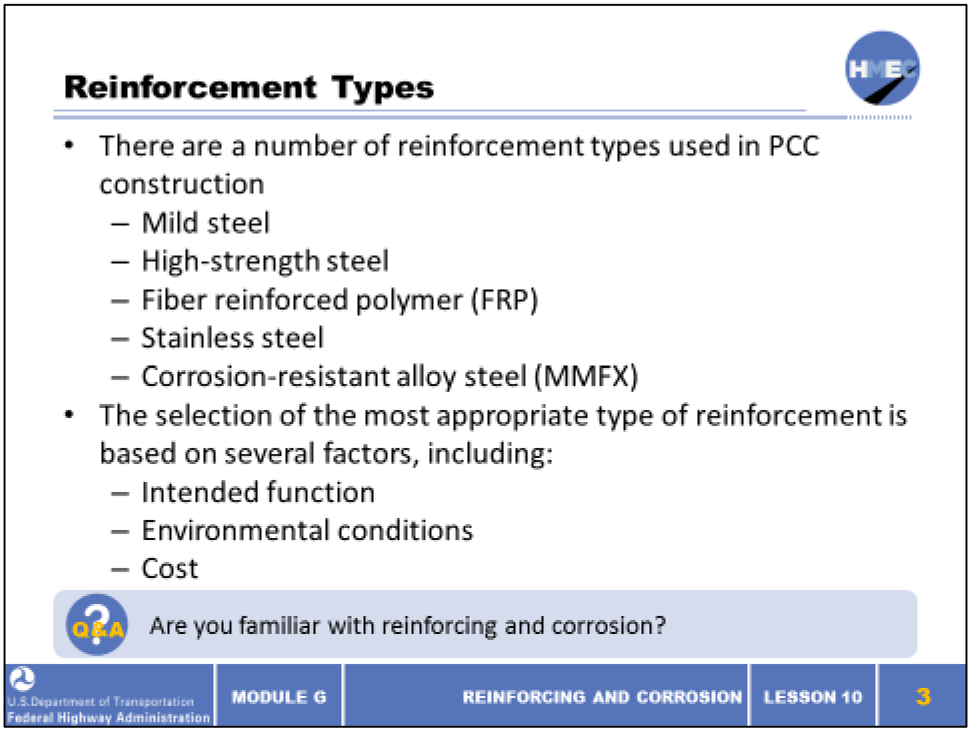
____

____

Slide 2


Learning Outcomes
HMEC
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.
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REINFORCING AND CORROSION
LESSON 10
2

Slide 3

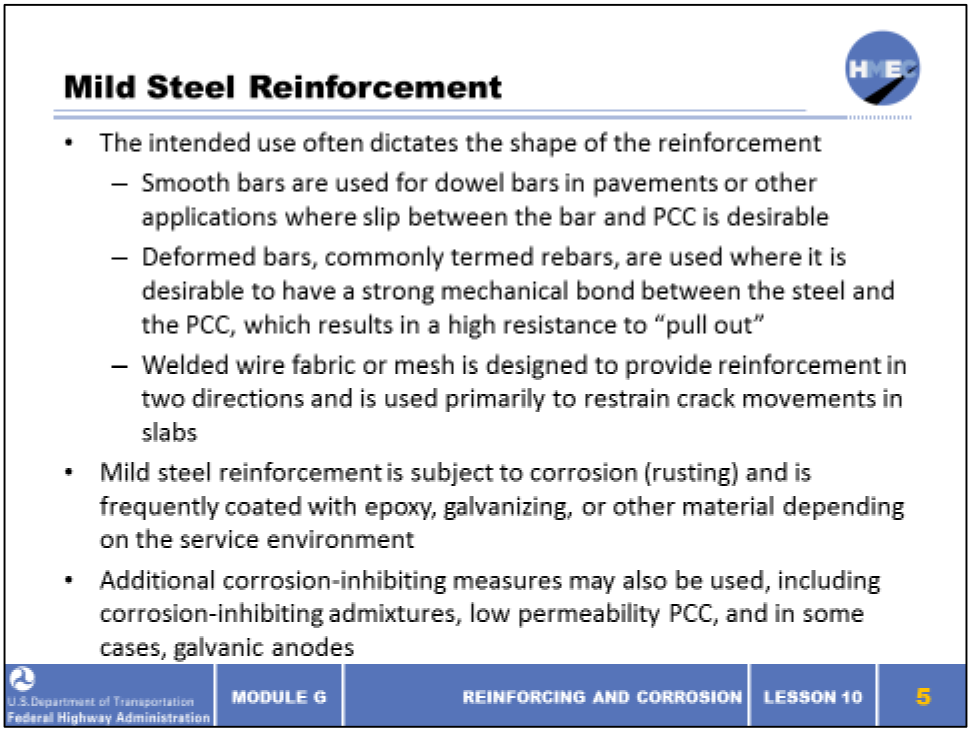

Reinforcement Types
HMEC
• There are a number of reinforcement types used in PCC construction
– Mild steel
– High-strength steel
– Fiber reinforced polymer (FRP)
– Stainless steel
– Corrosion-resistant alloy steel (MMFX)
• The selection of the most appropriate type of reinforcement is based on several factors, including:
– Intended function
– Environmental conditions
– Cost
Q&A
Are you familiar with reinforcing and corrosion?
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REINFORCING AND CORROSION
LESSON 10
3

Slide 4

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



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 rebars, 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.

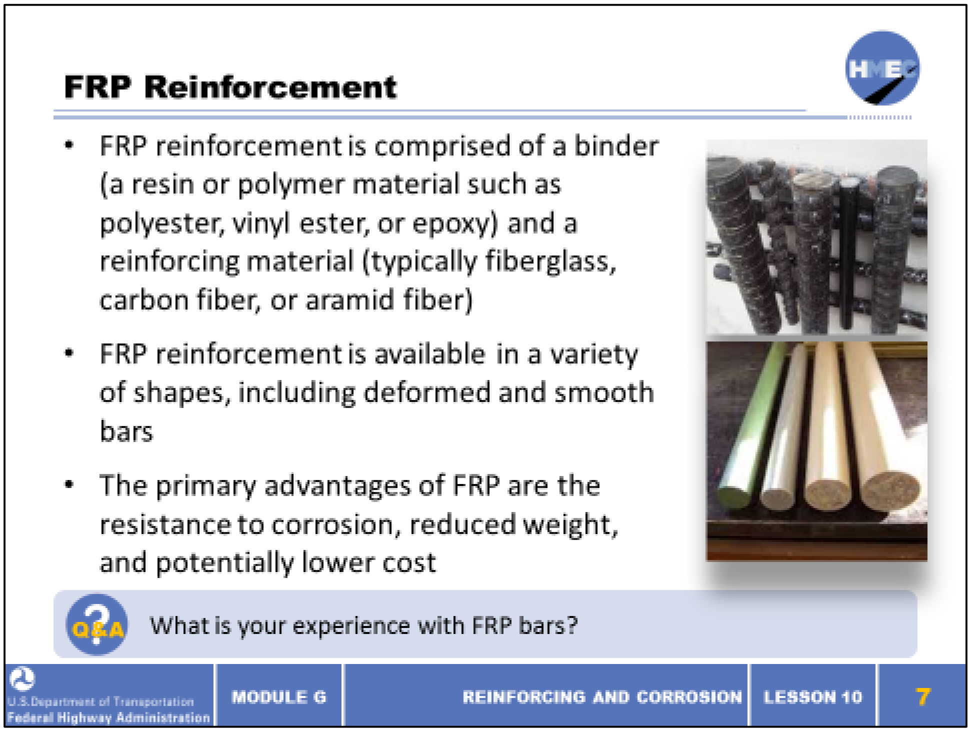
Note that the "Buy America" mandate can, in some cases, impact the selection of reinforcing steel, which will be discussed in the next lesson.

Slide 6

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

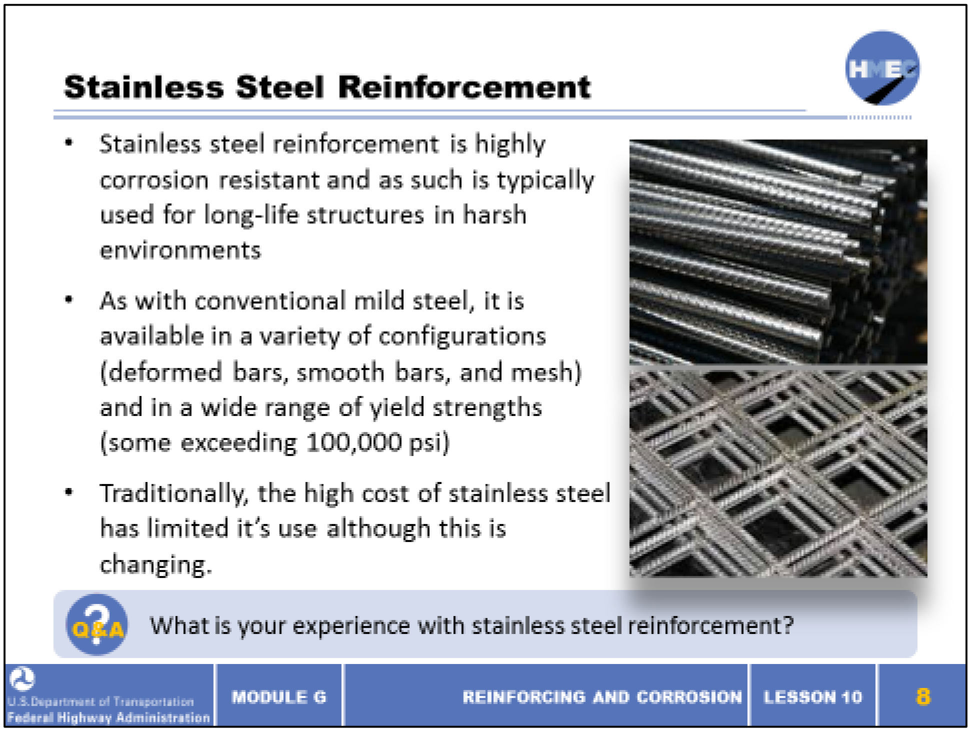


FRP reinforcement is available in a variety of shapes, including deformed and smooth bars. The primary advantages of FRP are the resistance to corrosion, reduced weight, and potentially lower cost.

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



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 make actually be the lowest long-term cost (particularly for bridge decks).

Slide 9

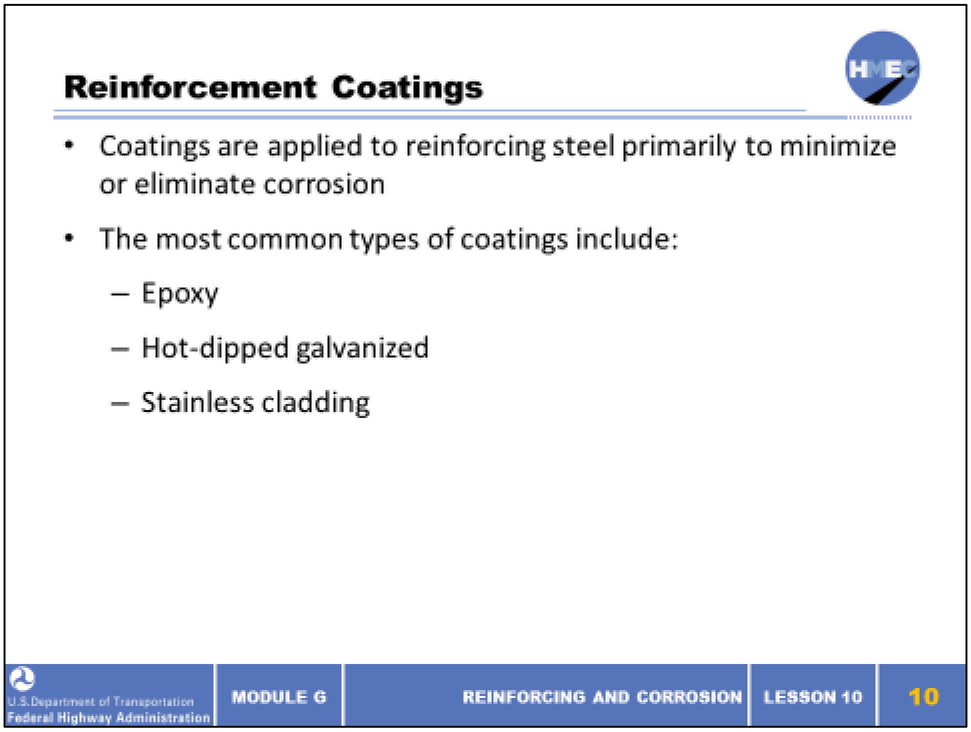
The yield strength of MMFX rebar corresponds to the requirements of grades 60 or 75 steel, although it far exceeds that value and is generally in the range of high-strength steel at 100,000 to 120,000 psi or greater. MMFX is typically used in harsh environments (particularly structures) where long service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

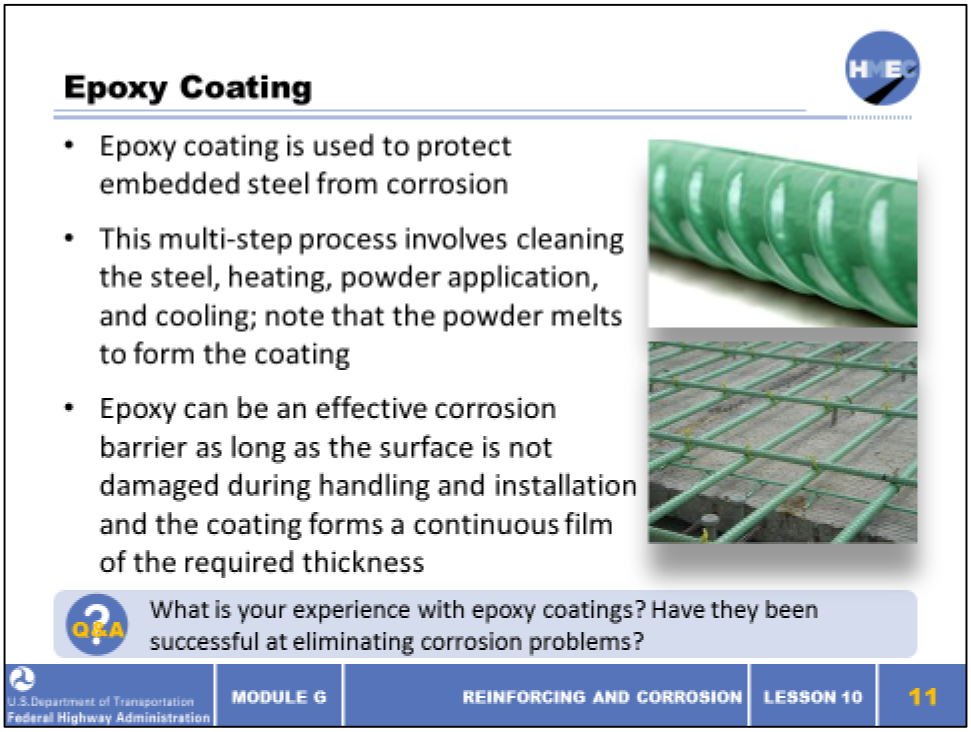
Note that every agency has policies related to steel selection for specific applications. These guidelines are based upon performance histories as well as cost and availability.

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

Slide 10


Reinforcement Coatings
HMEC
• 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
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REINFORCING AND CORROSION
LESSON 10
10

Slide 11

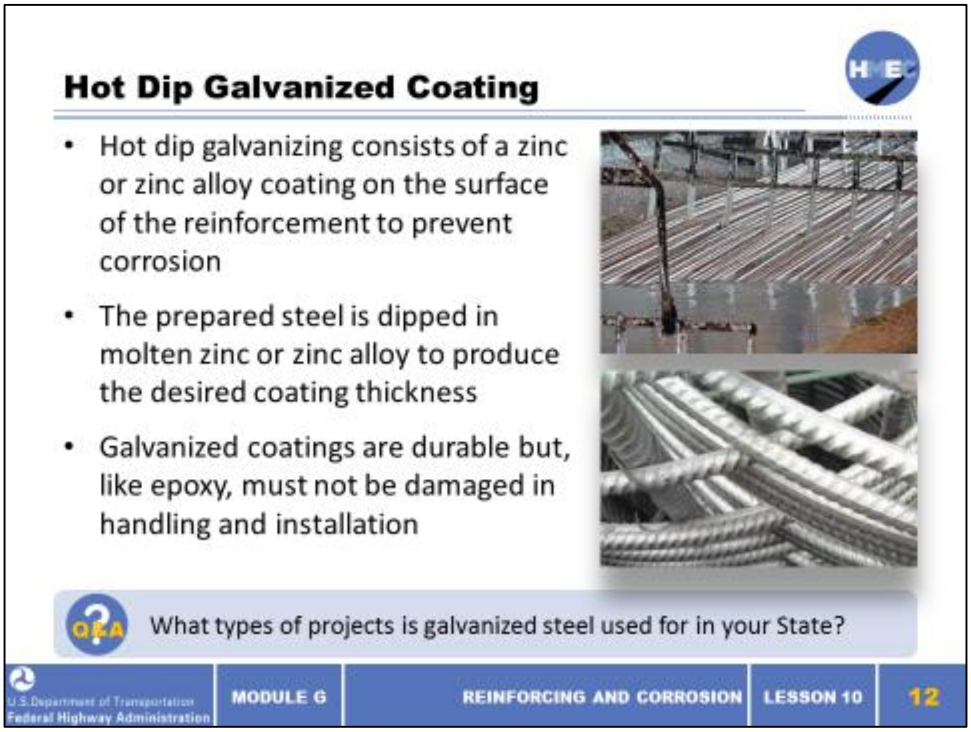


Note that the powder melts to form the coating. Epoxy can be an effective corrosion barrier as long as the surface is not damaged during handling and installation and the coating forms a continuous film of the required thickness.

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



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.

____

____

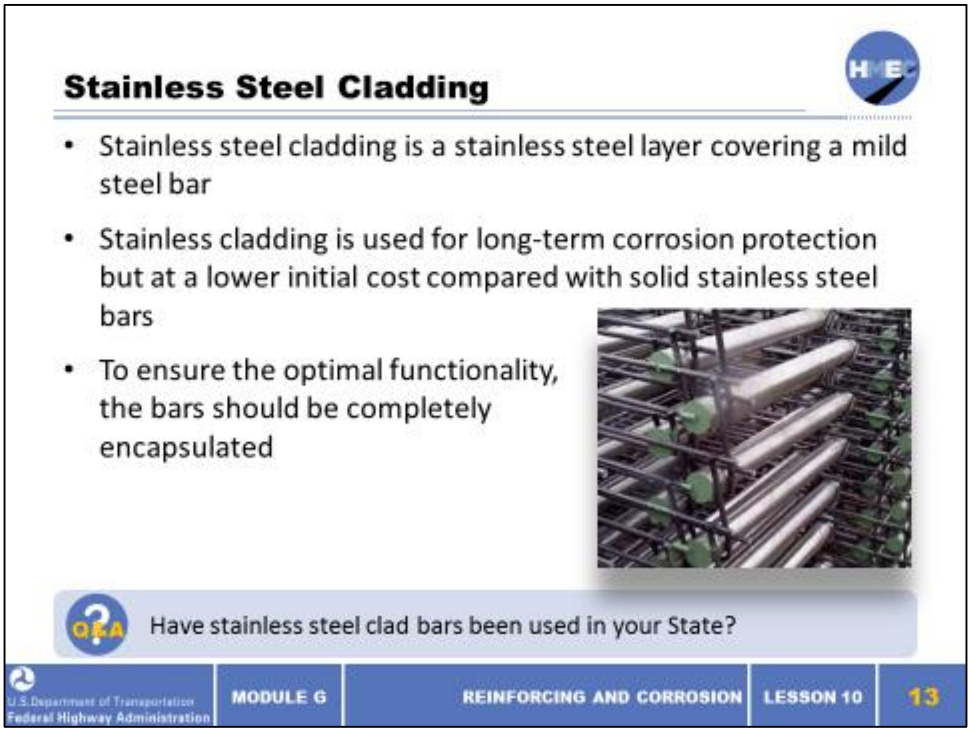
____

____

____

____

Slide 13

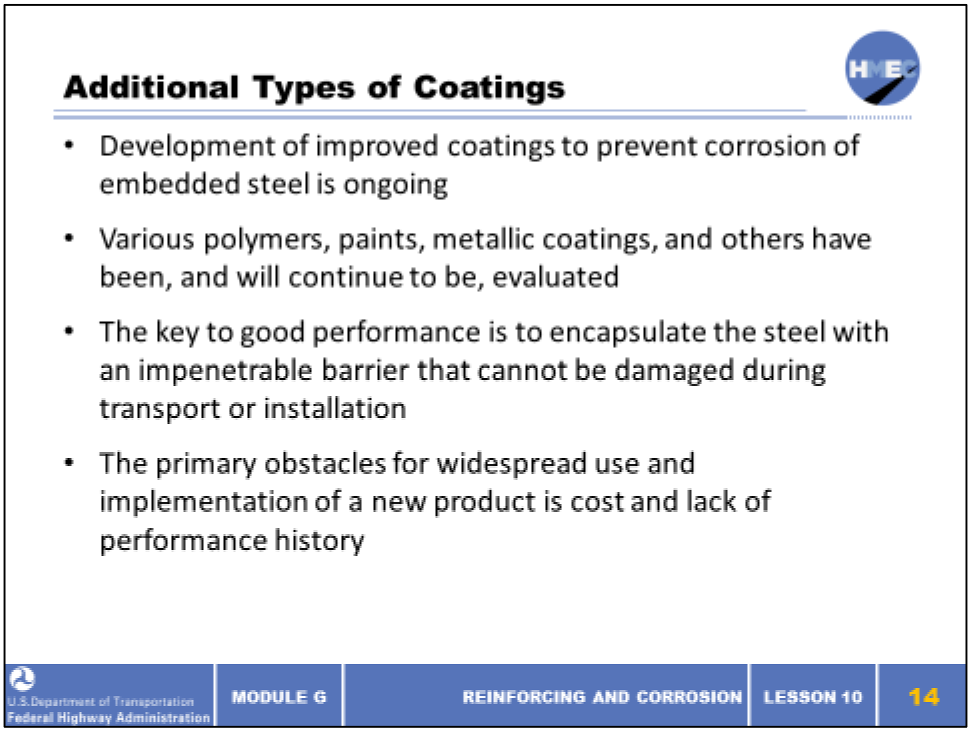


Stainless cladding is used for long-term corrosion protection but at a lower initial cost compared with solid stainless steel bars. To ensure the optimal functionality, the bars should be completely encapsulated. It is very important that the cladding be integrated with the mild steel so that it doesn't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

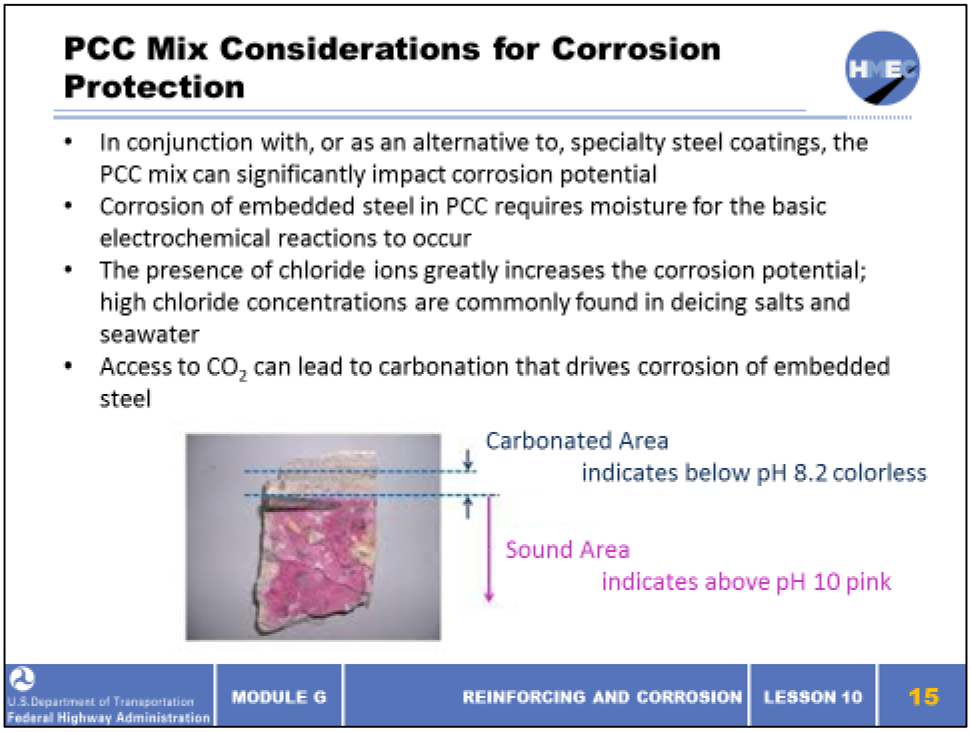
The photo shows stainless steel clad dowel bars installed in basket assemblies. Note that the ends are not clad but have been coated with epoxy.

Slide 14



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

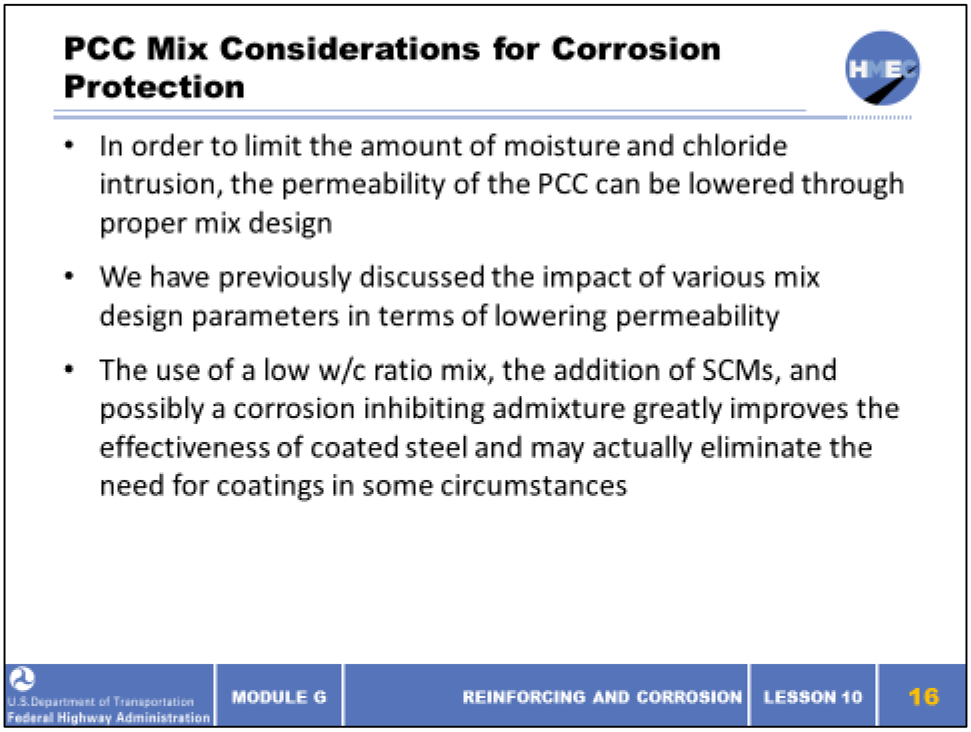


Corrosion of embedded steel in PCC requires moisture for the basic electrochemical reactions to occur.

The presence of chloride ions greatly increases the corrosion potential; high chloride concentrations are commonly found in deicing salts and seawater. Access to CO_2 can lead to carbonation that drives corrosion of embedded steel.

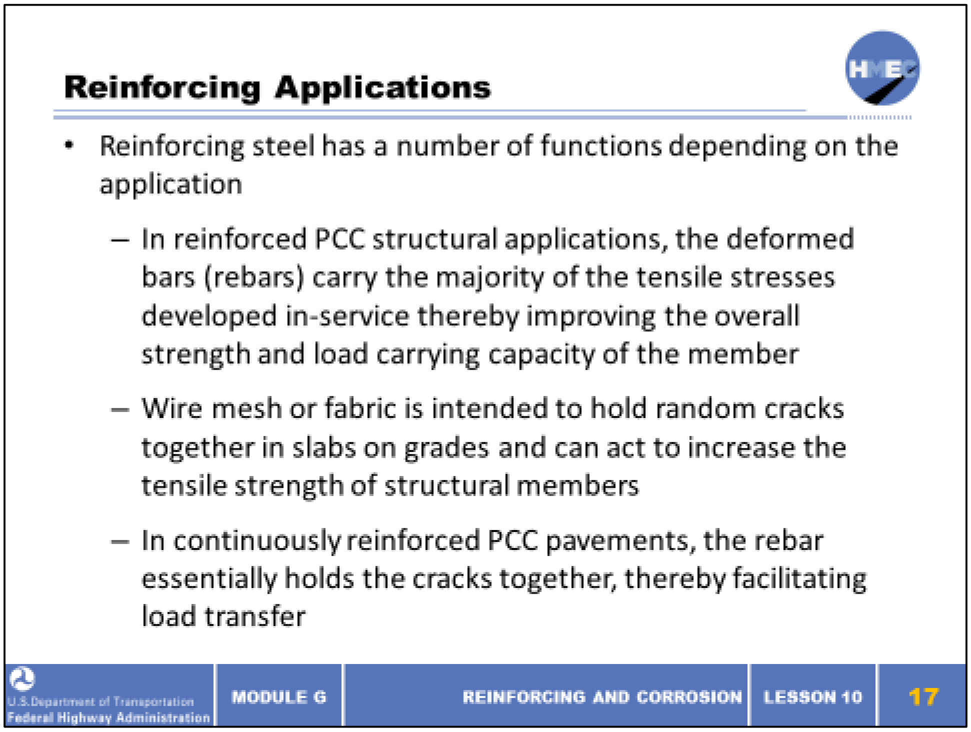
The figure shown on the screen illustrates the migration of carbon dioxide into the hardened PCC. Note that the carbonation reduces the pH and the effectiveness of the passive coating on the reinforcing steel, thereby facilitating corrosion.

Slide 16



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



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.

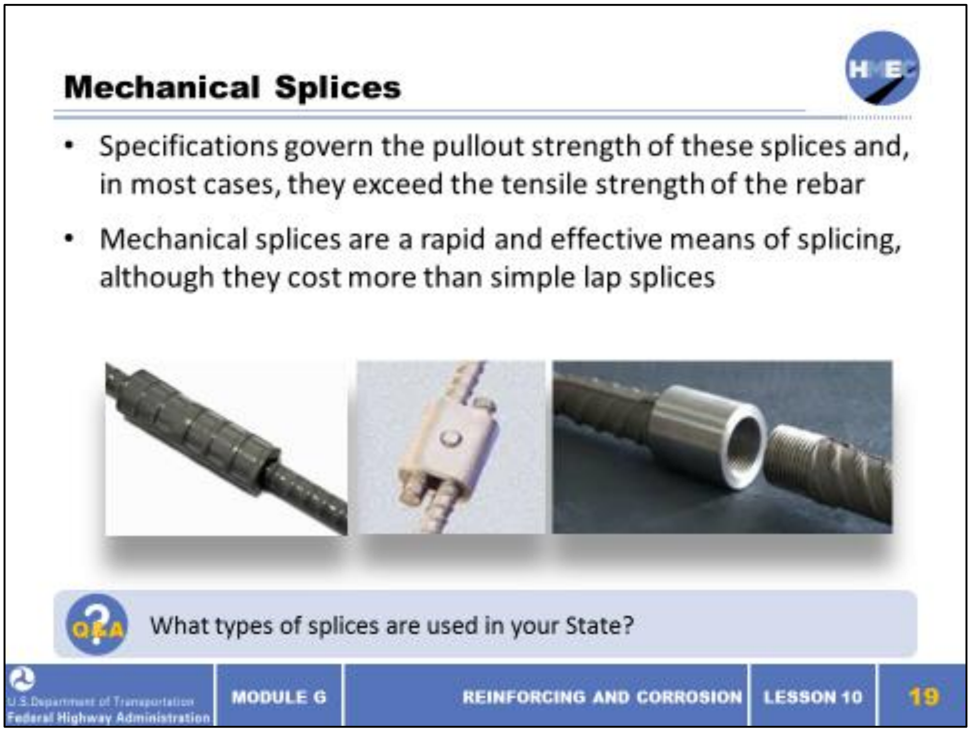
Slide 18

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

U.S. Department of Transportation Federal Highway Administration | MODULE G | REINFORCING AND CORROSION | LESSON 10 | 18

Slide 19



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.

____

____

____

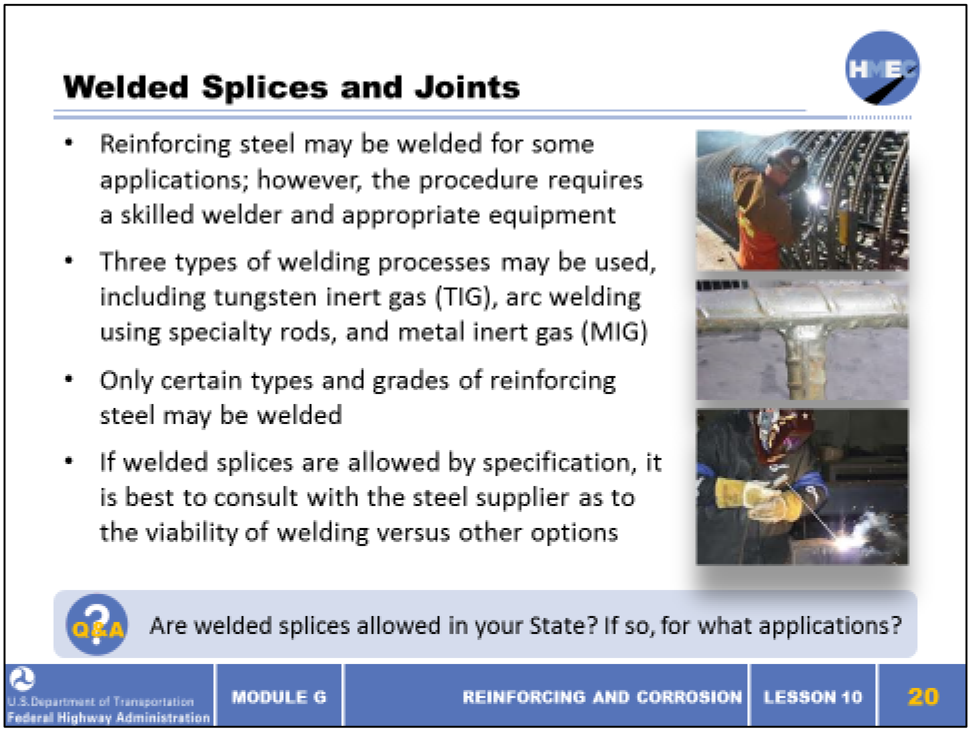
____

____

____

____

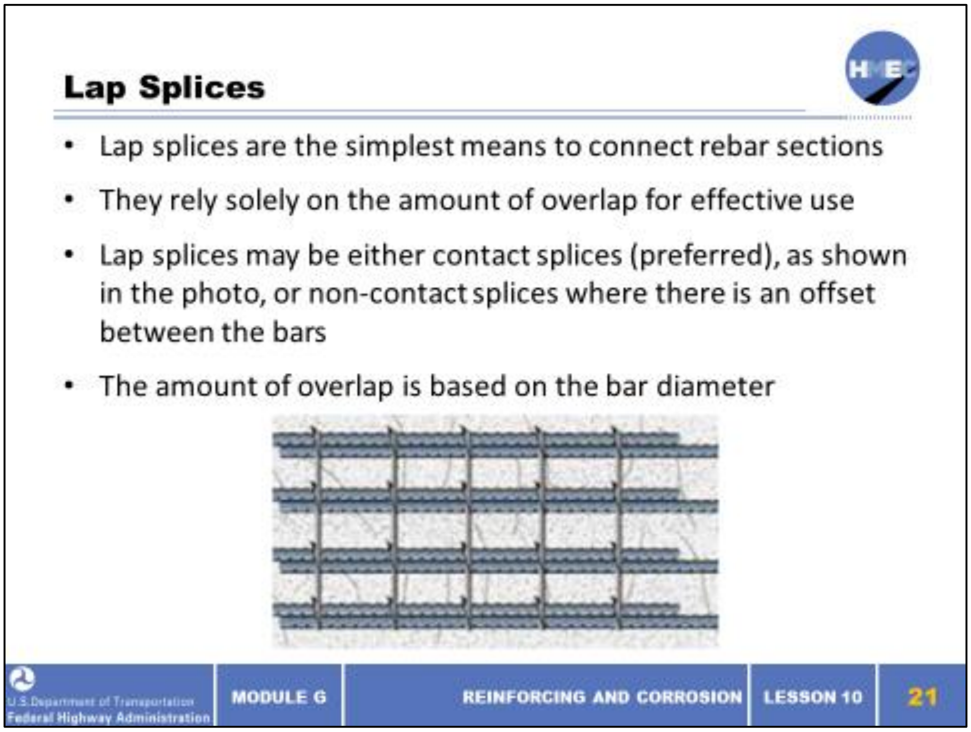
Slide 20



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.

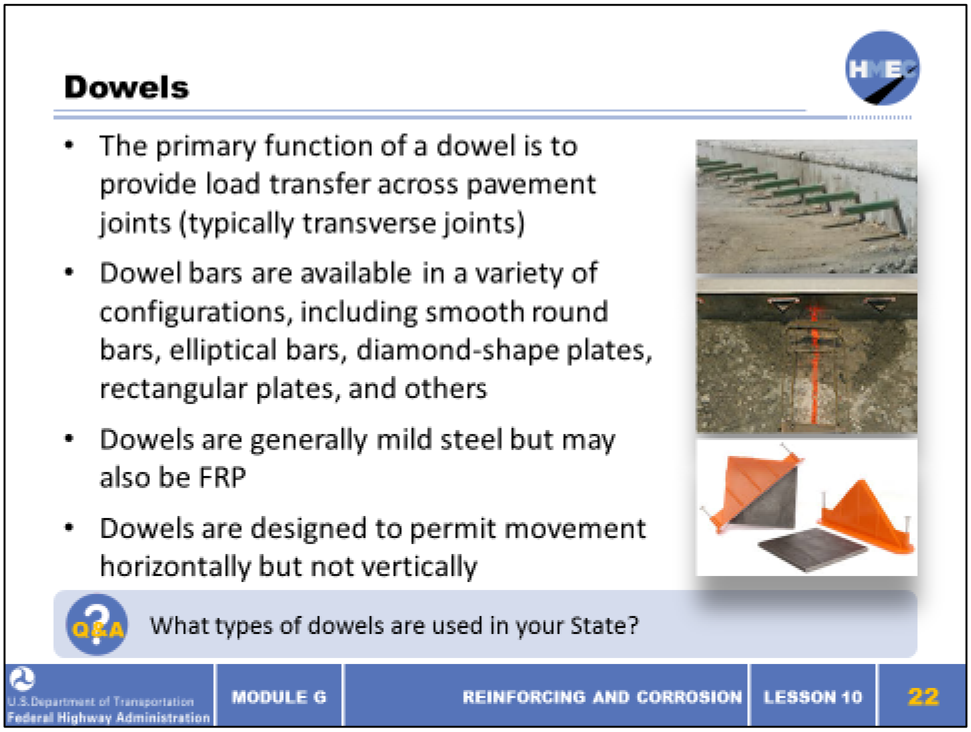
Note that reinforcing steel should not be cut on site using a cutting torch as this can reduce the yield strength of the steel.

Slide 21



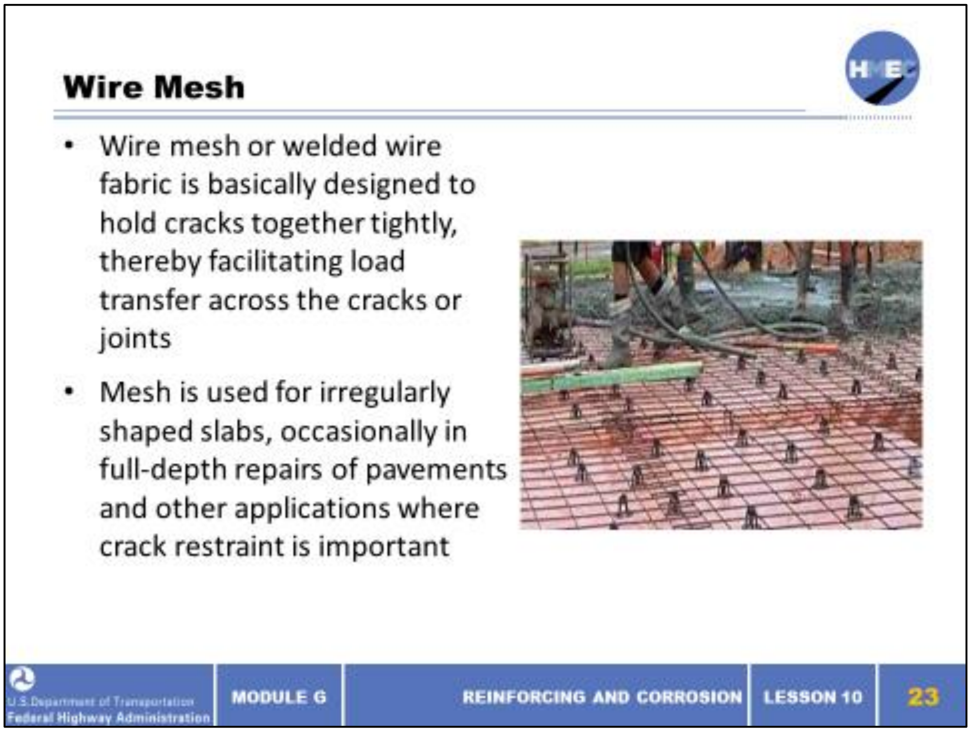
The amount of overlap is based on the bar diameter and is generally a minimum of 40 times the bar diameter.

Slide 22



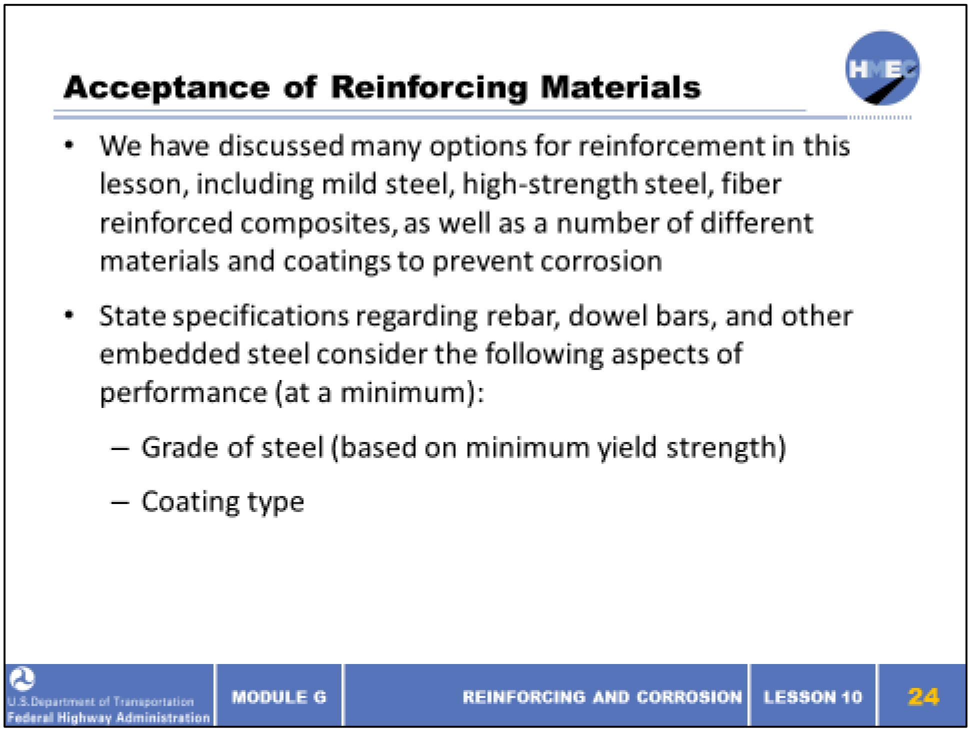
Dowel bars are available in a variety of configurations including smooth round bars, vertically.

Slide 23

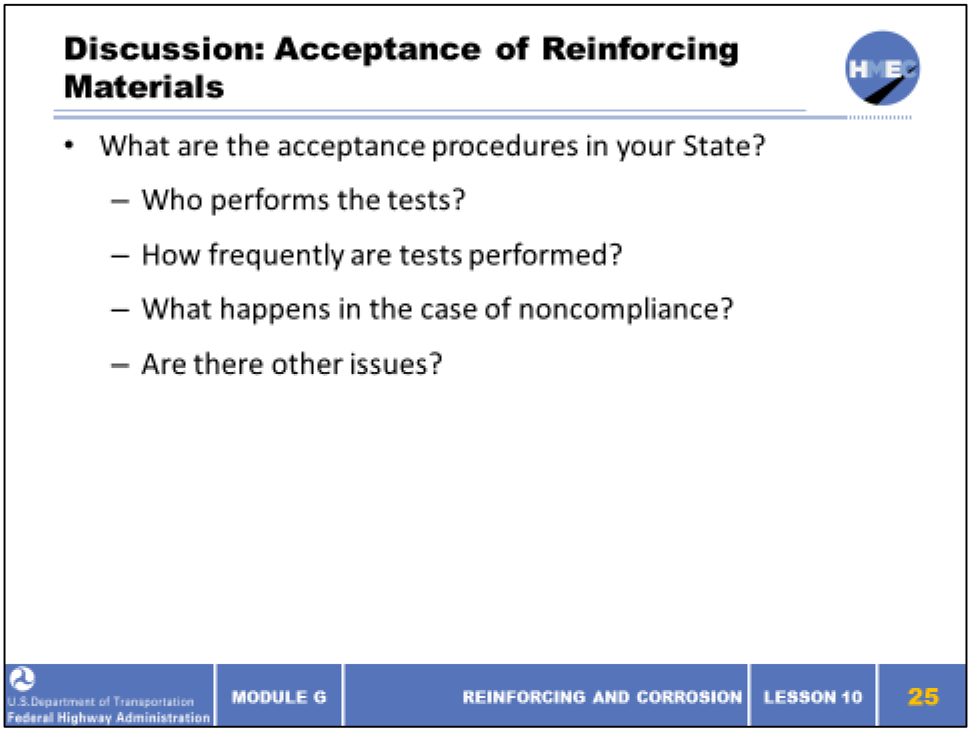


Mesh is used for irregularly shaped slabs, occasionally in full-depth repairs of pavements and other applications where crack restraint is important. In order to assure proper depth of the mesh in the slab, the mesh should be placed on chairs or other supports, as shown in the photo.

Slide 24

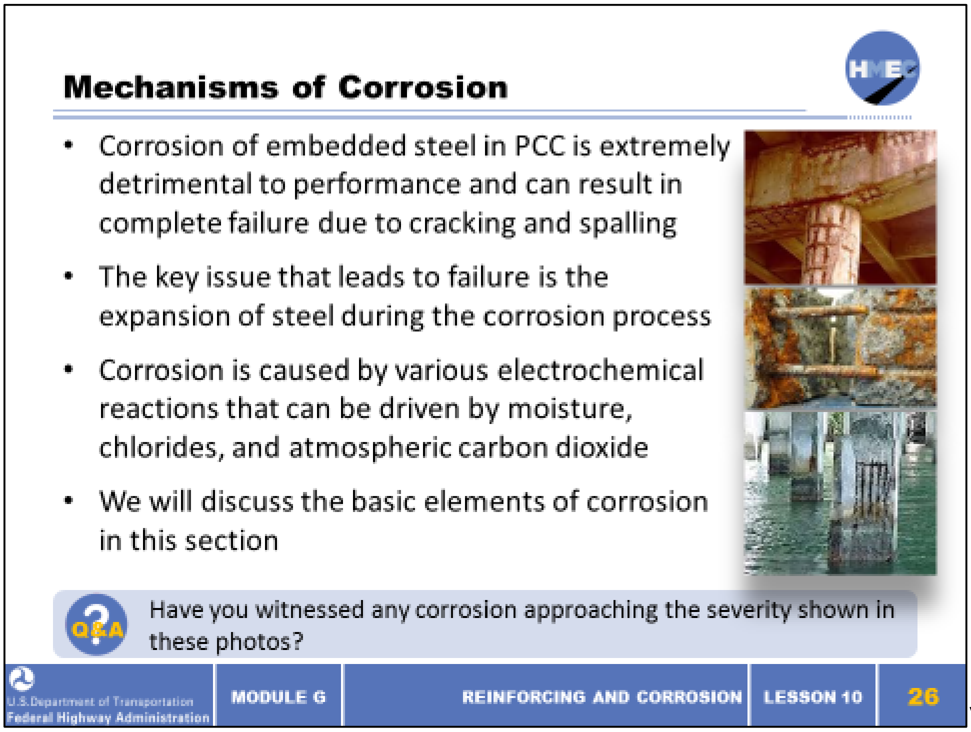

Acceptance of Reinforcing Materials
• We have discussed many options for reinforcement in this lesson, including mild steel, high-strength steel, fiber reinforced composites, as well as a number of different materials and coatings to prevent corrosion
• State specifications regarding rebar, dowel bars, and other embedded steel consider the following aspects of performance (at a minimum):
– Grade of steel (based on minimum yield strength)
– Coating type
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REINFORCING AND CORROSION
LESSON 10
24

Slide 25



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.

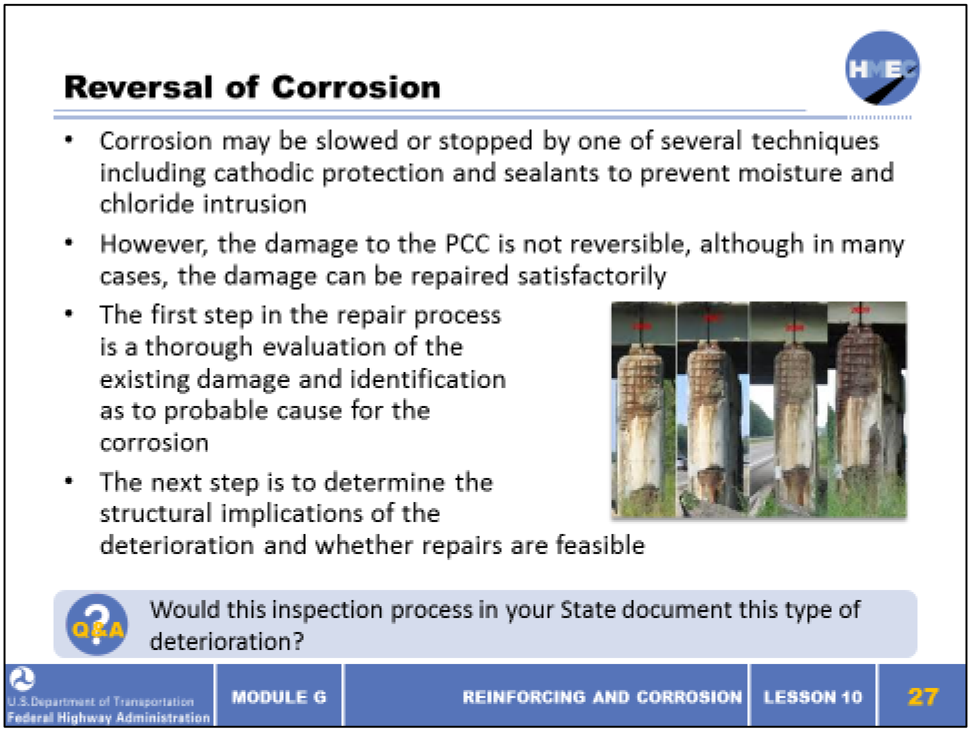
Slide 26



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.

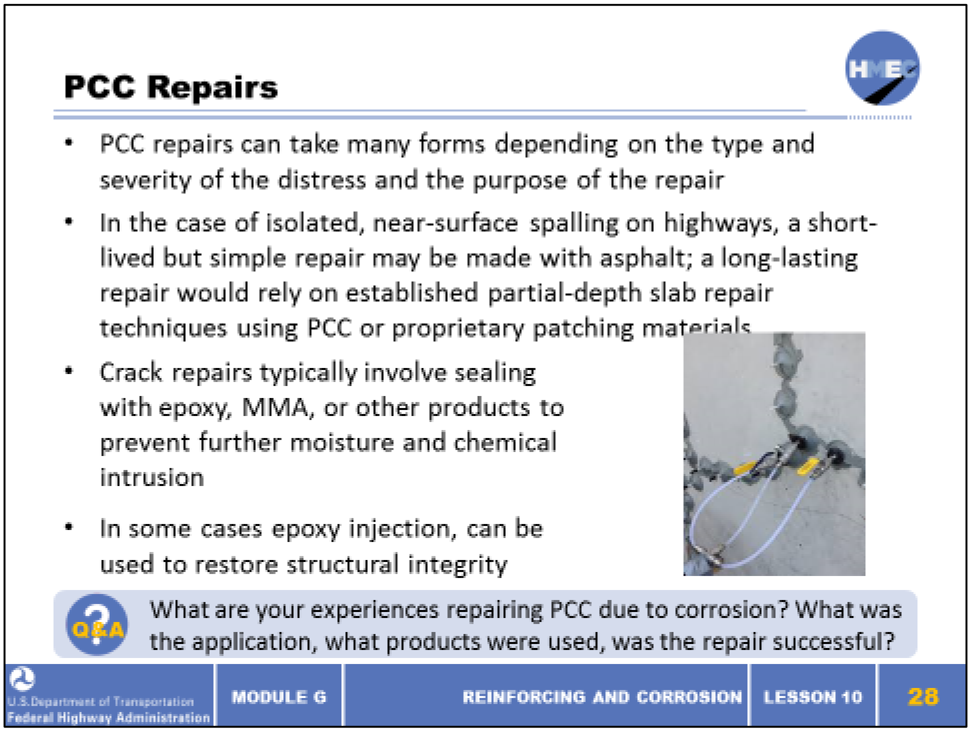
Slide 27



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

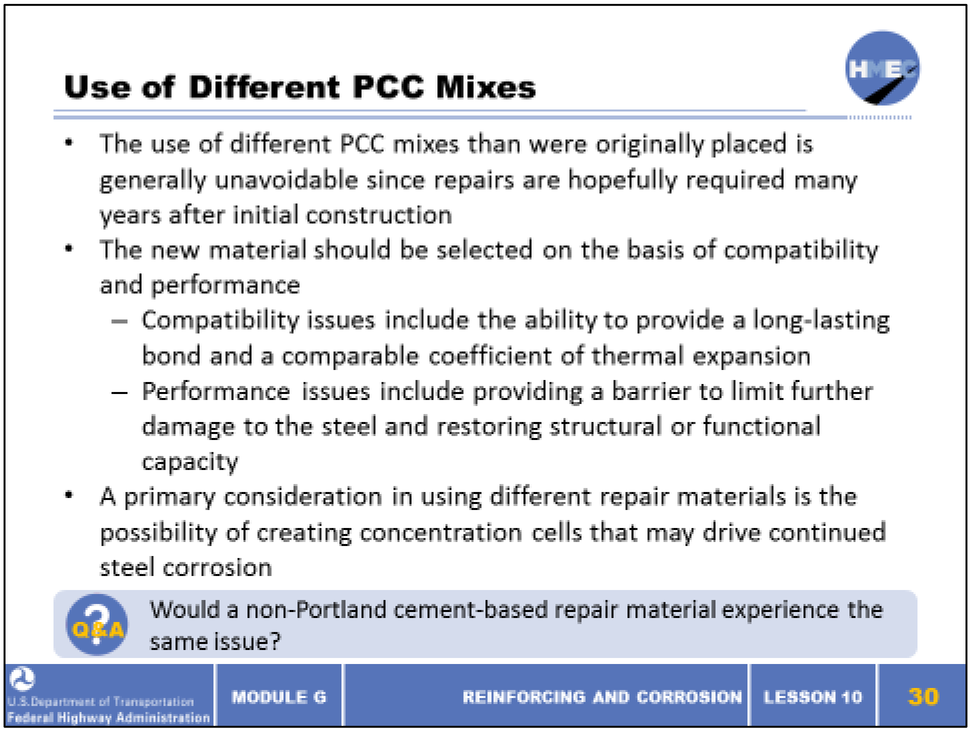


For instance, in the case of isolated, near-surface spalling on highways, a short-lived but simple repair may be made with asphalt. A long-lasting repair would rely on established partial-depth slab repair techniques using PCC or proprietary patching materials. The simplest repairs involve crack sealing 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

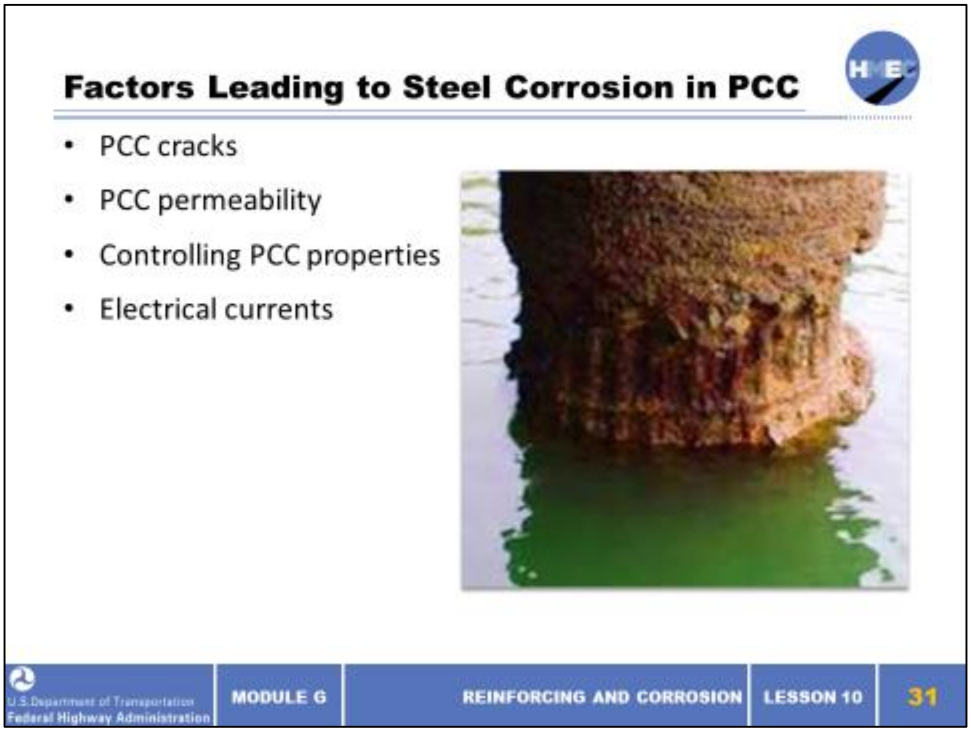
A number of repair materials are available, ranging from PCC to proprietary materials (typically polymeric concrete). The overall goals are to restore structural or functional performance and minimize or eliminate recurrence of the problem.

Slide 30

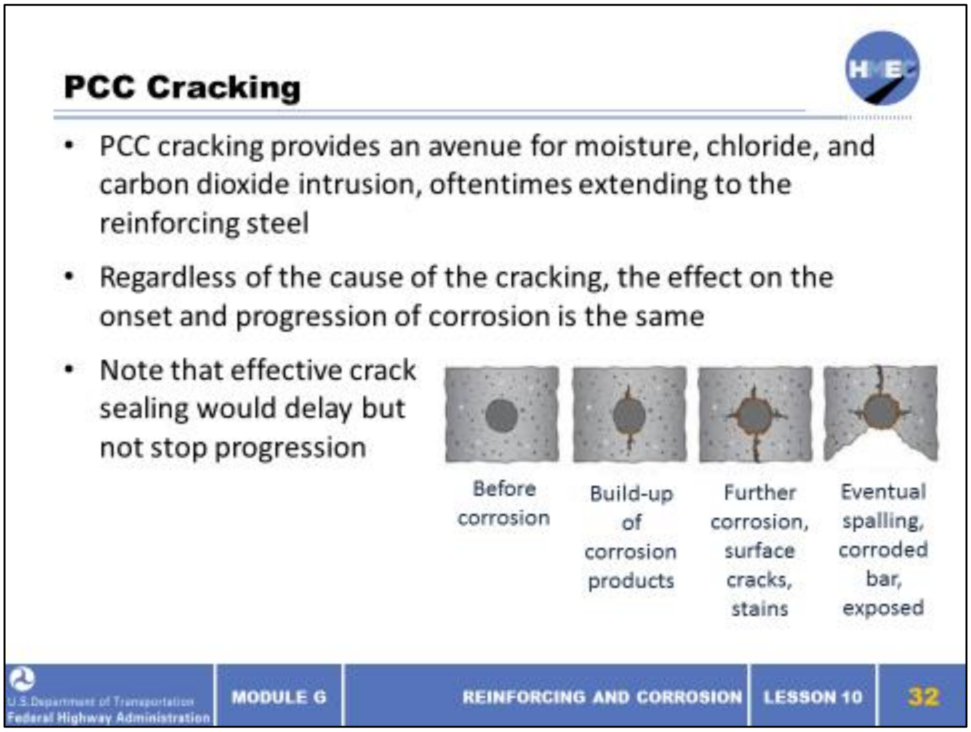


In order to minimize this effect, commonly referred to as ring corrosion, the use of corrosion-inhibiting admixtures and low permeability materials should be considered. In addition, the use of galvanic anodes may be required in very corrosive environments, such as bridge decks subjected to routine deicing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

Slide 31


Factors Leading to Steel Corrosion in PCC
PCC cracks
PCC permeability
Controlling PCC properties
Electrical currents
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REINFORCING AND CORROSION
LESSON 10
31

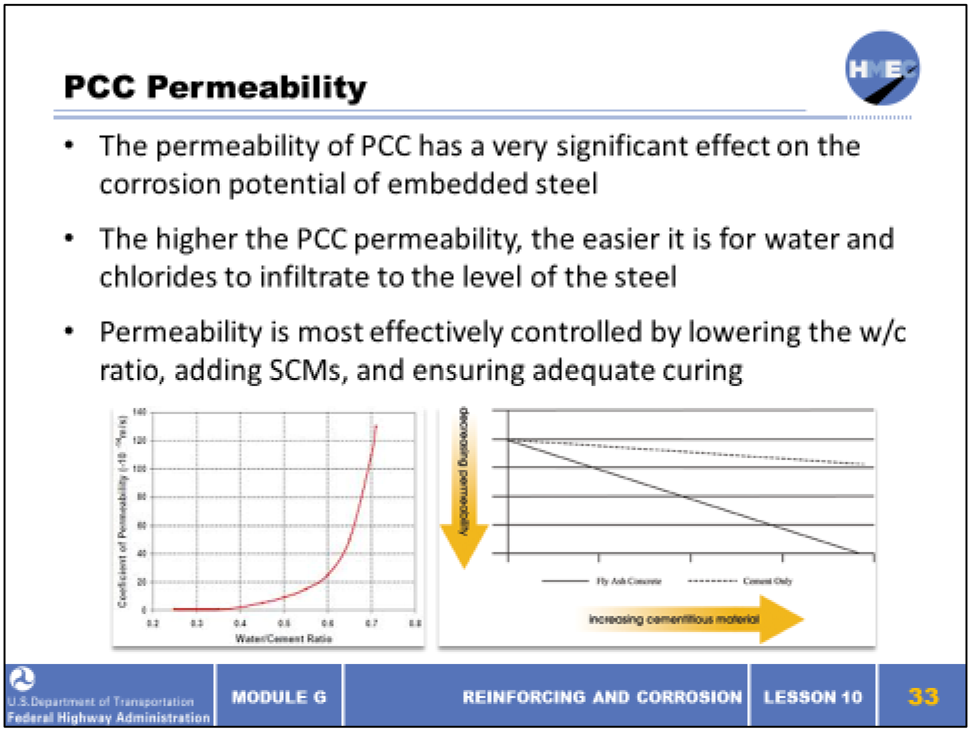
Slide 32



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



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.

____

____

____

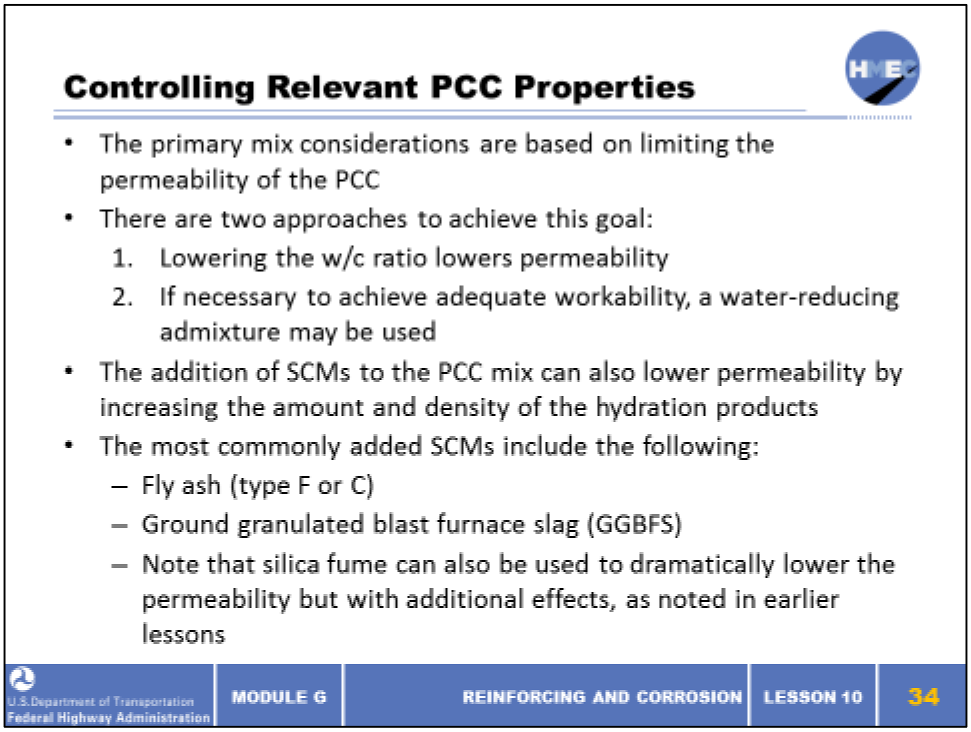
____

____

____

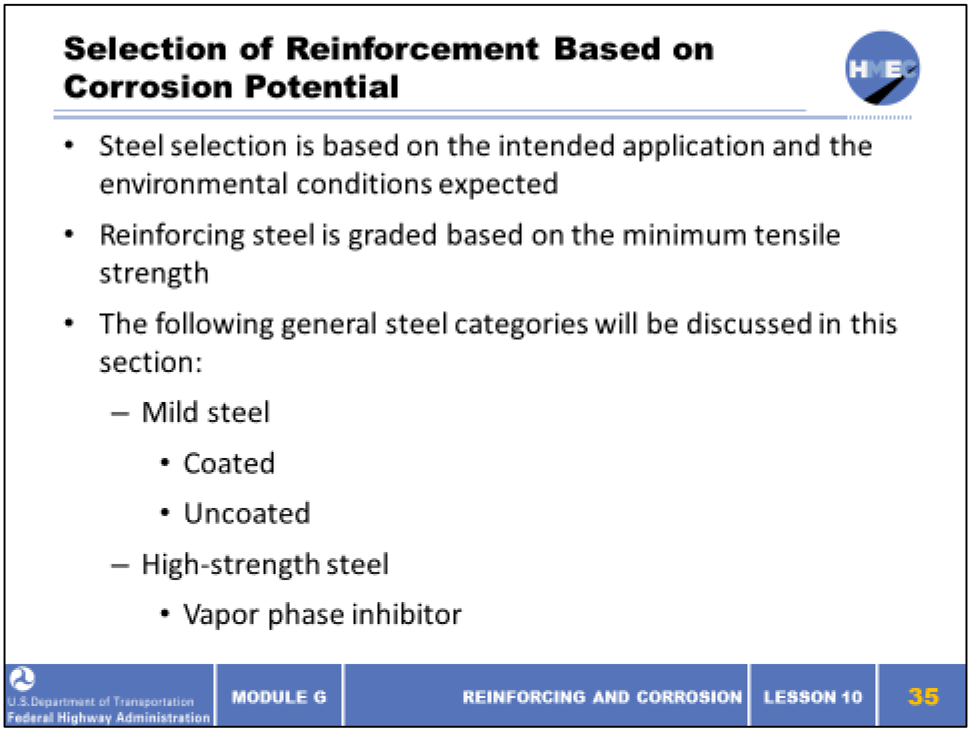
____

Slide 34



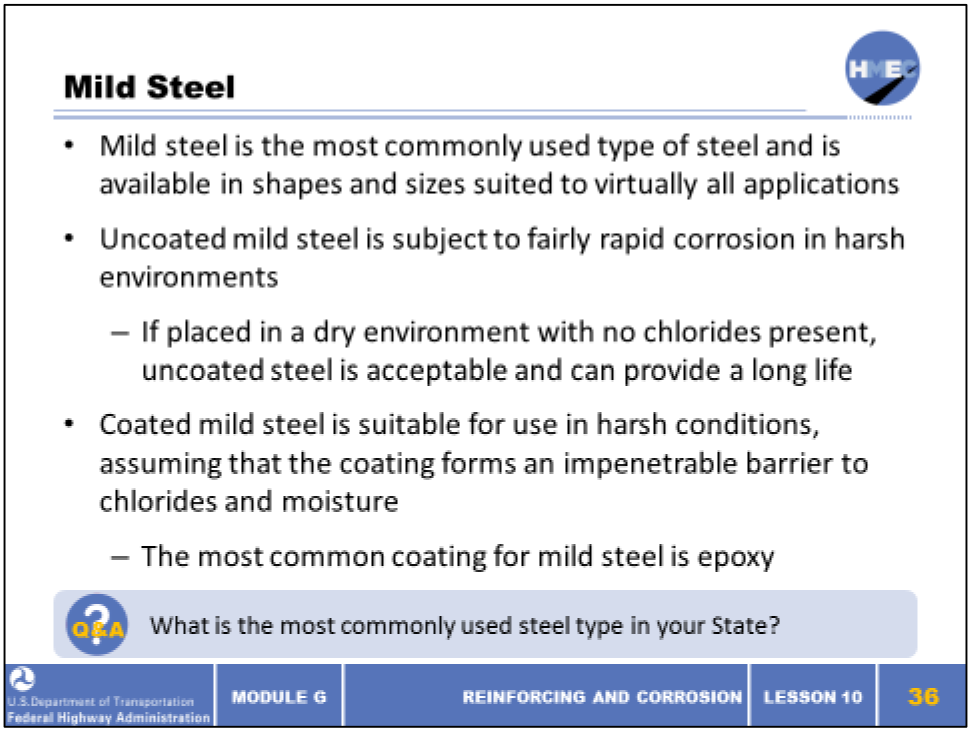
Silica fume can also be used to dramatically lower the permeability but with additional effects, as noted in earlier lessons. These effects include increased water demand, higher risk of drying shrinkage cracks, difficulty in finishing, and others.

Slide 35



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.

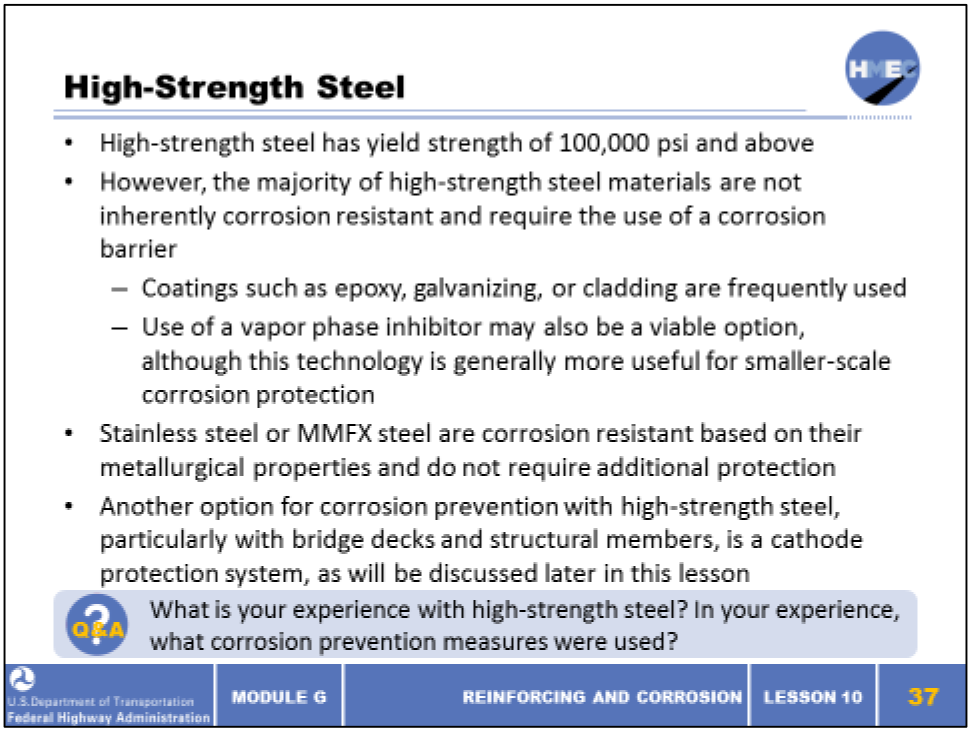
Slide 36



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.

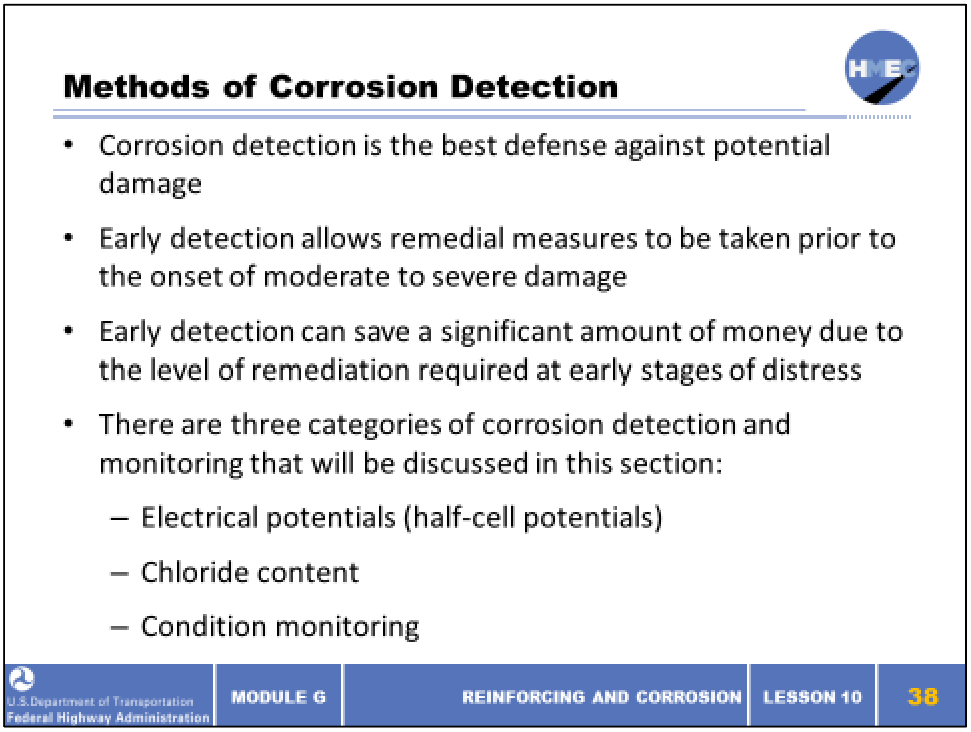
Slide 37



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.

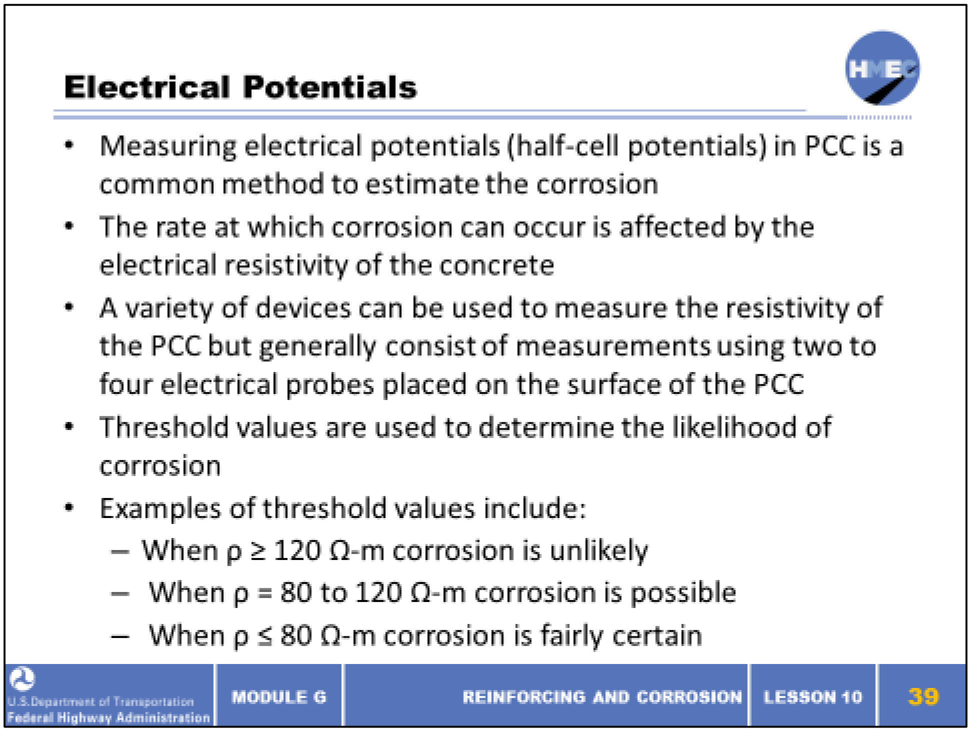
Vapor corrosion inhibitors (VCIs) are also known as vapor phase corrosion inhibitors (VPCIs). These corrosion-inhibiting compounds release molecules into the air. When these compounds come in contact with metal surfaces, they form a very thin molecular layer. This thin layer effectively inhibits corrosion 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.

Slide 38



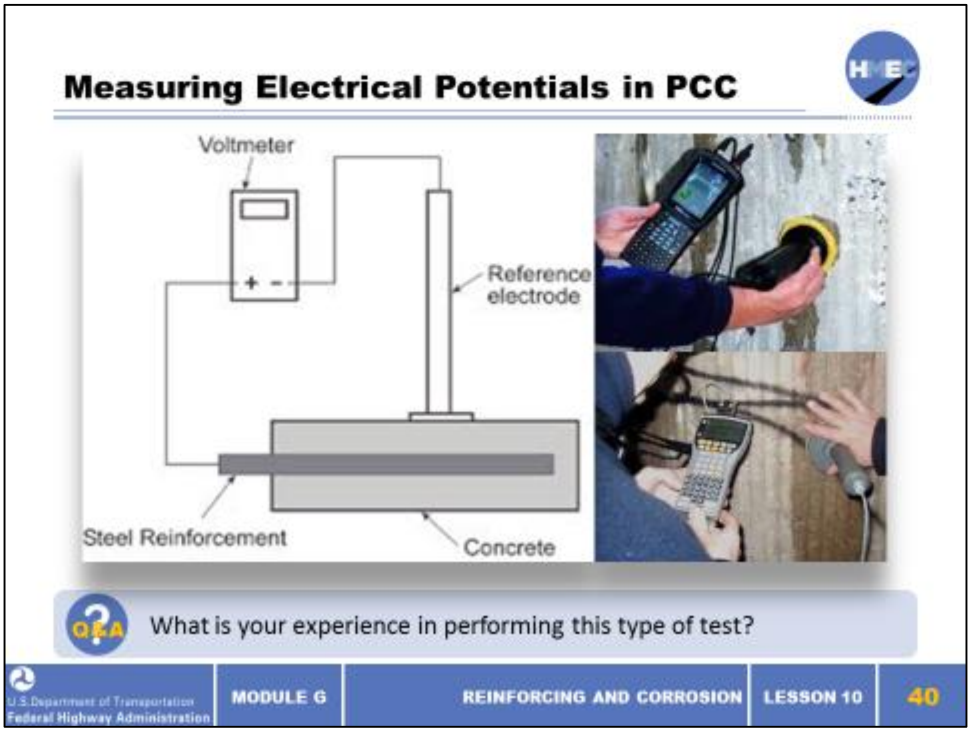
Early detection allows remedial measures to be taken prior to the onset of moderate to severe damage. Early detection can save a significant amount of money due to the level of remediation required at early stages of distress.

Slide 39



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.

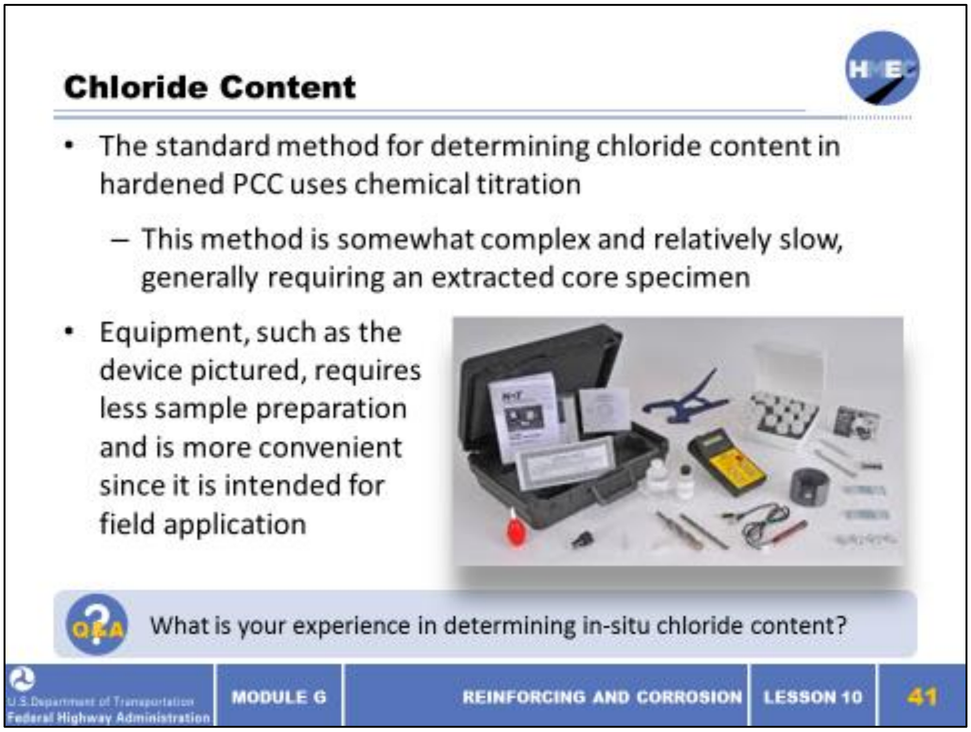
Slide 40



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.

____

Slide 41

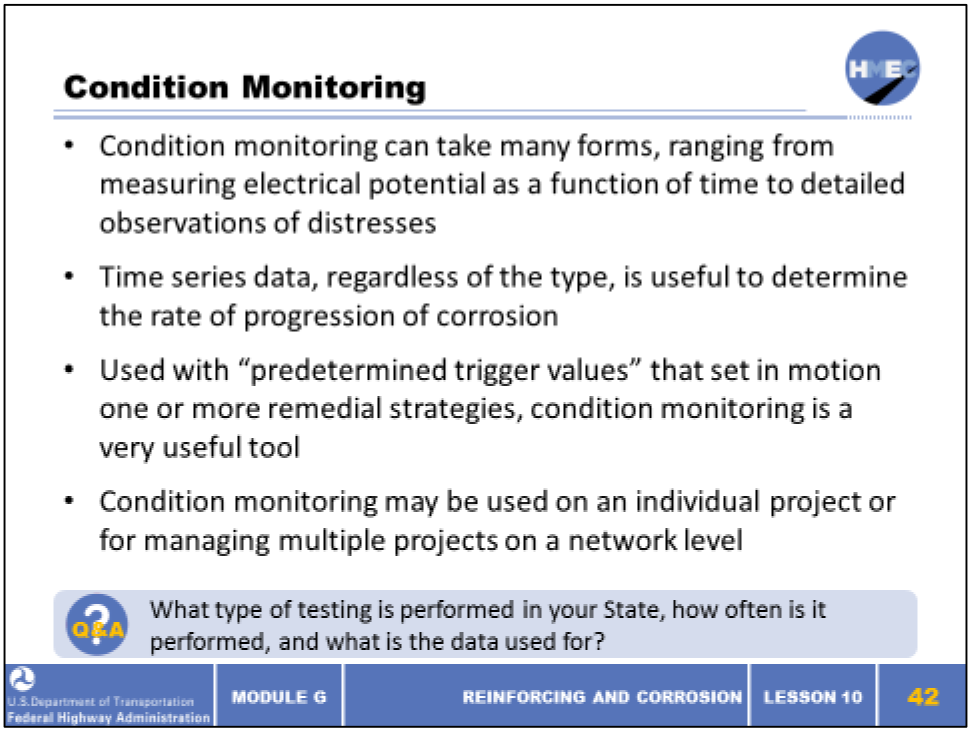


This method is somewhat complex and relatively slow, generally requiring an extracted core specimen. Equipment, such as the device pictured, requires less sample preparation and is more convenient since it is intended for field application.

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

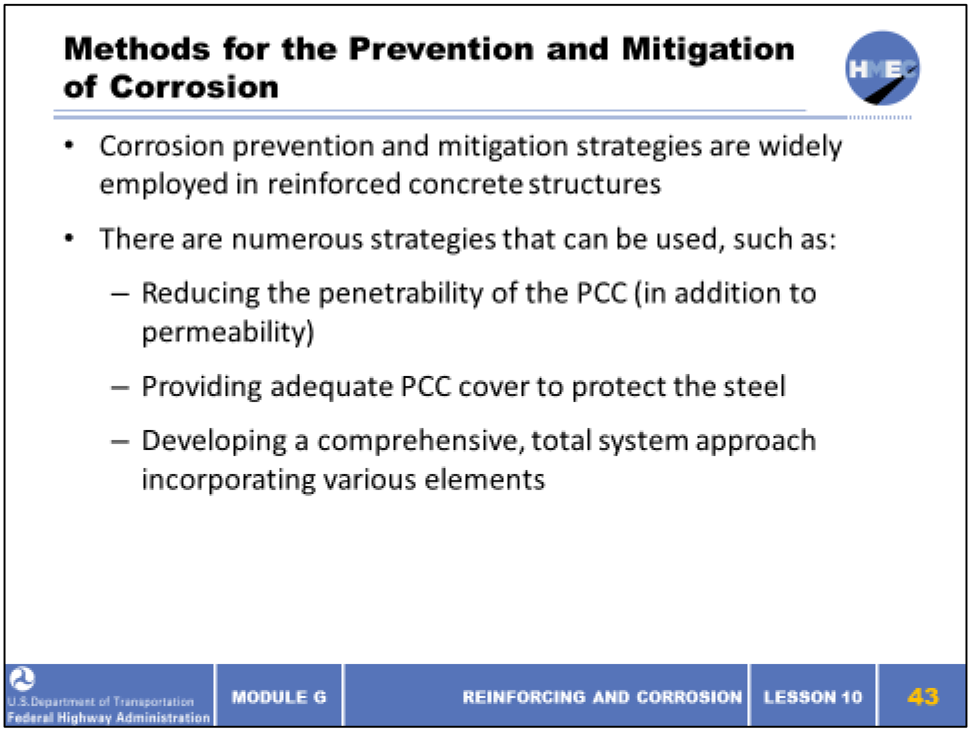
Note that the laboratory results are typically more reliable than the rapid field determinations due in large part to the controlled conditions in laboratory testing.

Slide 42

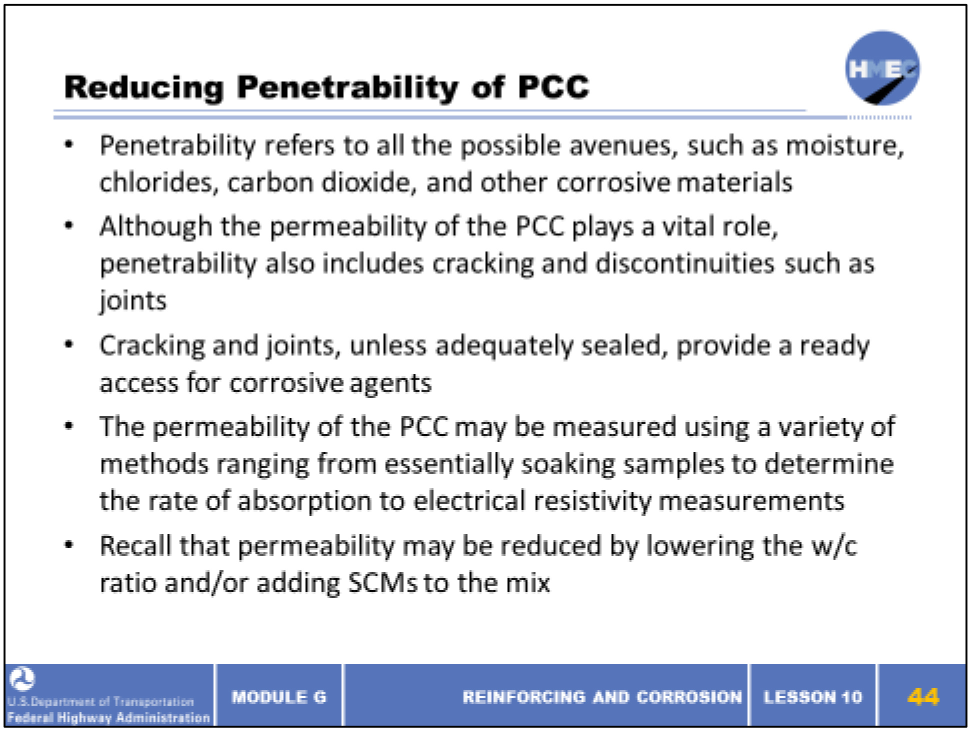


Time series data, regardless of the type, is useful to determine the rate of progression of corrosion. Used with "predetermined trigger values" that set in motion one or more remedial strategies, condition monitoring is a very useful tool. Condition monitoring may be used on an individual project or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

Slide 43


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
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REINFORCING AND CORROSION
LESSON 10
43

Slide 44



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.

____

____

____

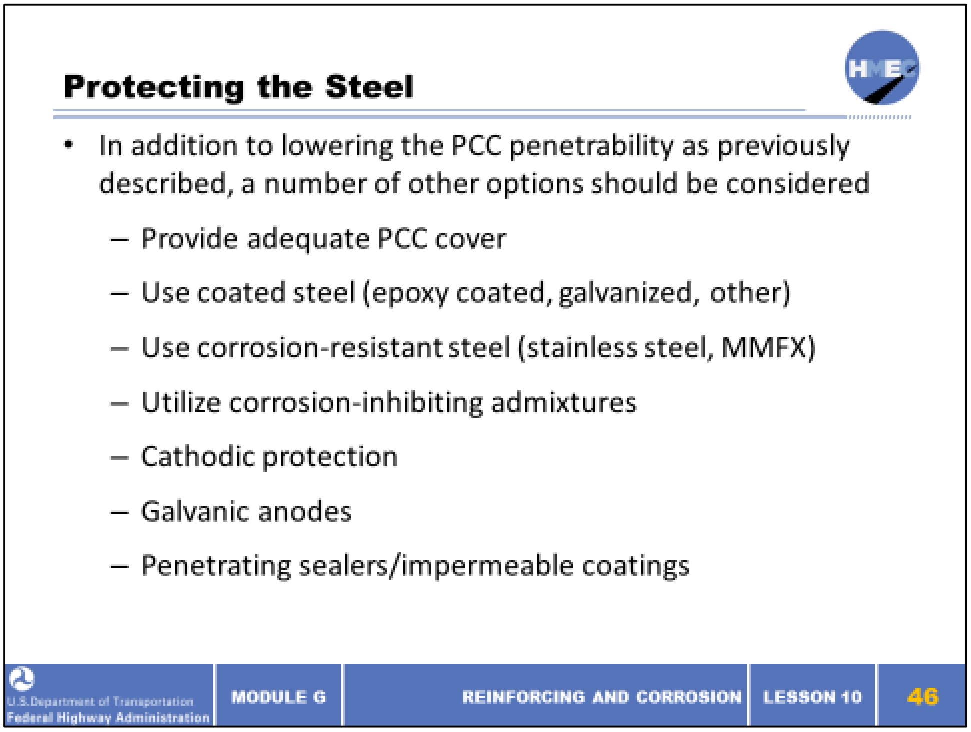
____

Slide 45

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

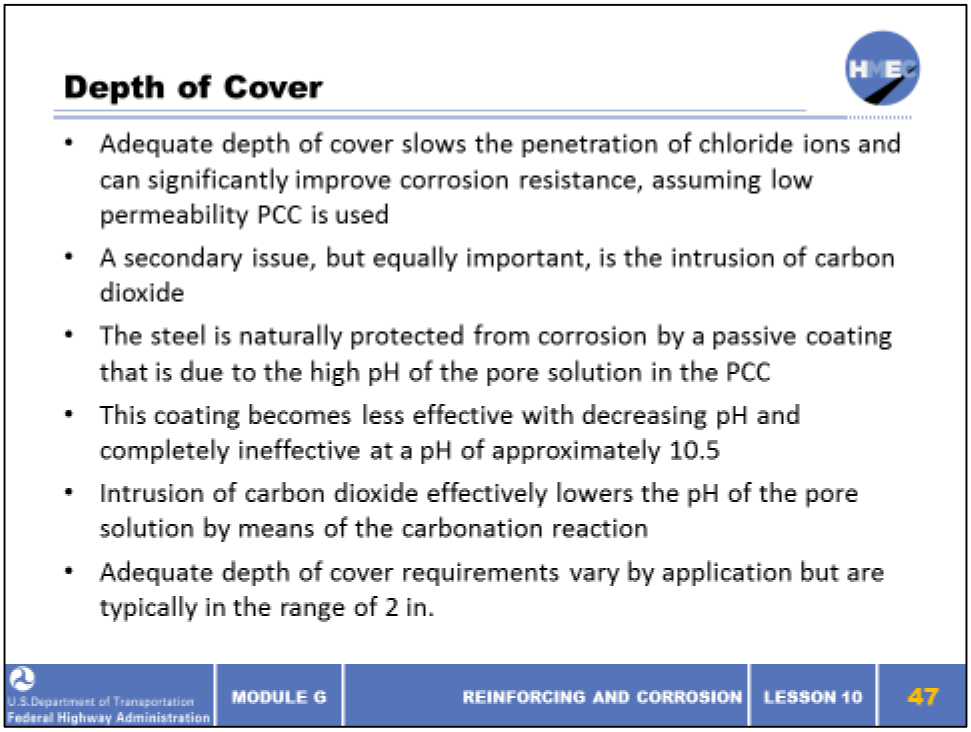
The photo on the top left illustrates an ASTM-designated test to determine the permeability of PCC through soaking and determining the uptake of water on a timed basis.
The photo on the lower left shows one on many types of permeability apparatus.
The photo on the upper right shows a surface resistivity test.
The photo on the lower right shows a rapid chloride permeability test.

Slide 46



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.

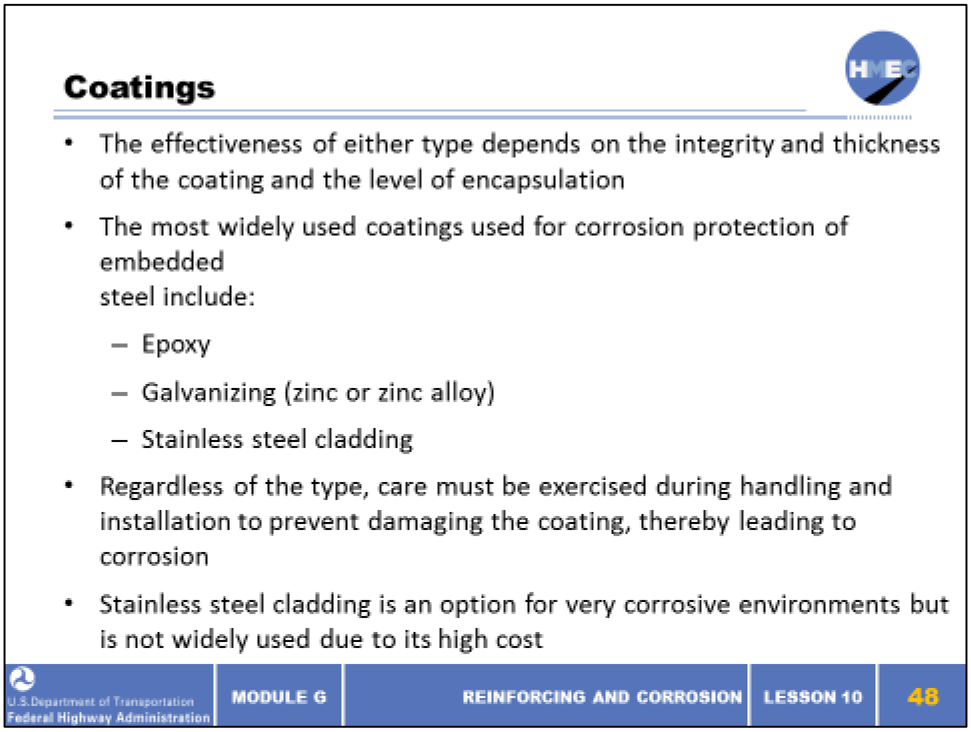
Slide 47



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

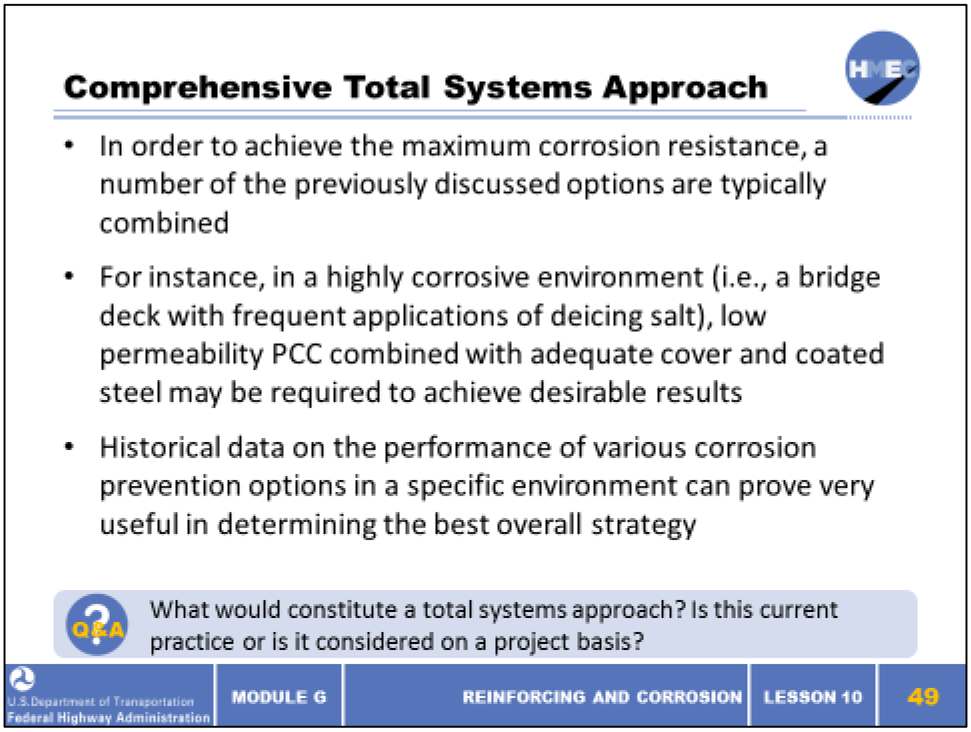
The steel is naturally protected from corrosion by a passive coating that is due to the high pH of the pore solution in the PCC. This coating becomes less effective with decreasing pH and completely ineffective at a pH of approximately 10.5. Intrusion of carbon dioxide effectively lowers the pH of the 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.

Slide 48



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.

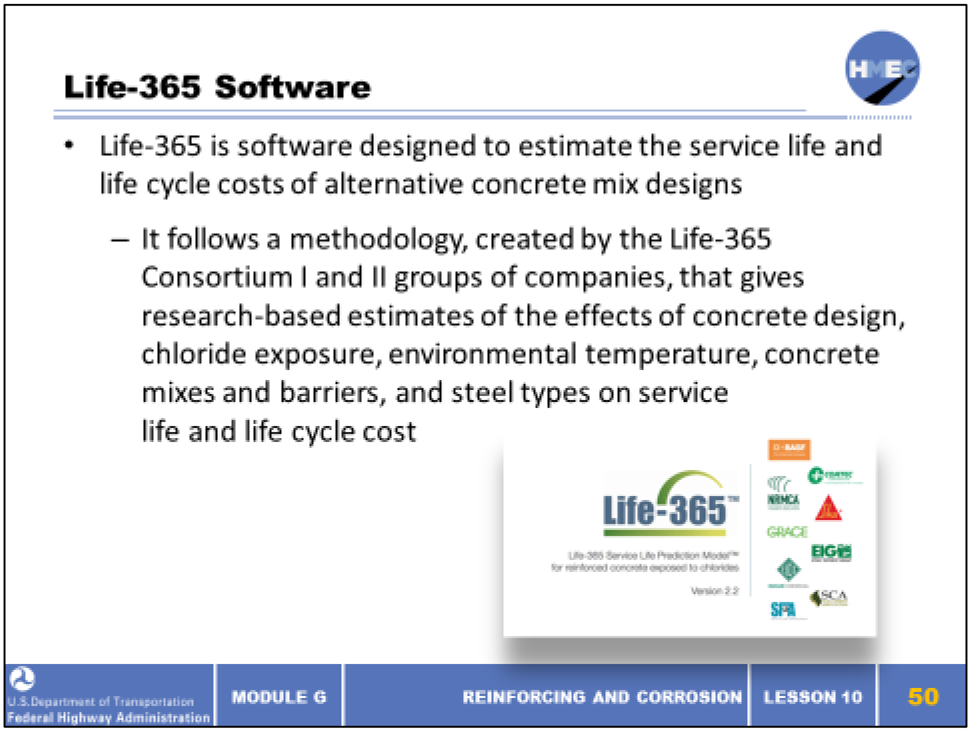
Slide 49



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.

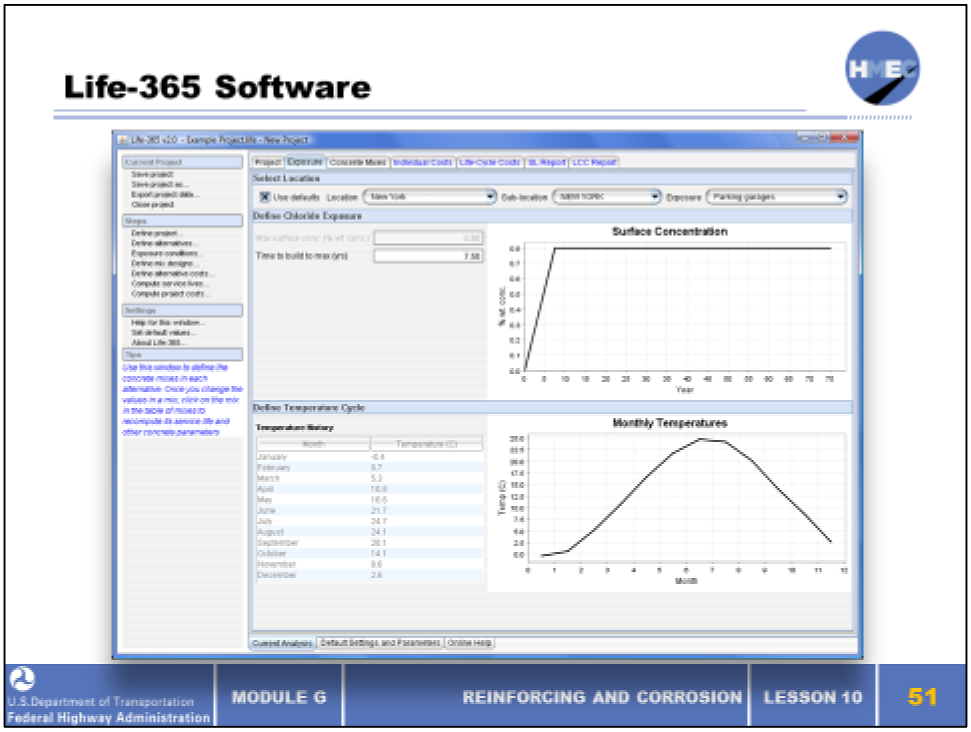
Slide 50



Life-365 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.

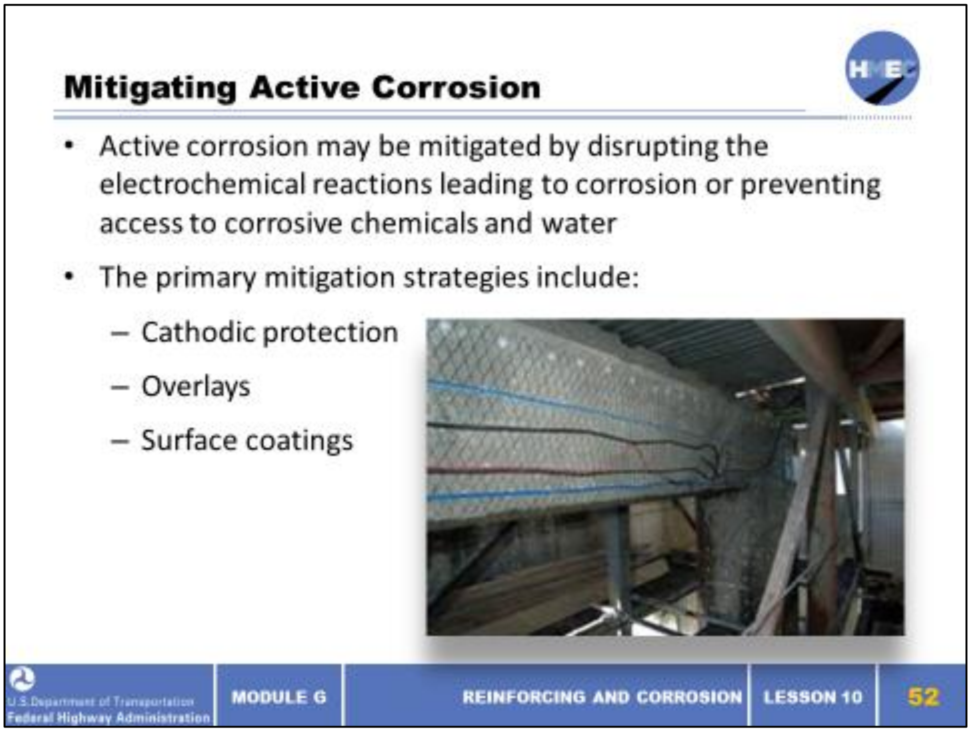
The software has been reviewed and widely distributed by the FHWA.

Slide 51



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

Slide 52

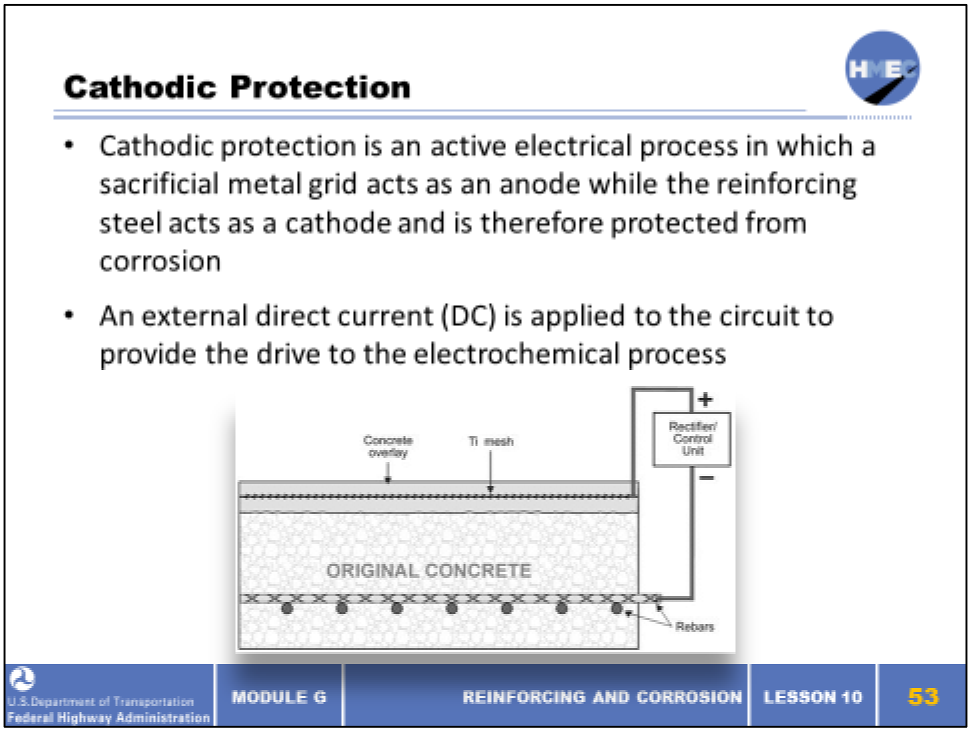


Active corrosion may be mitigated by disrupting the electrochemical reactions leading to corrosion or preventing access to corrosive chemicals and water.

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.

Slide 53



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.

____

____

____

____

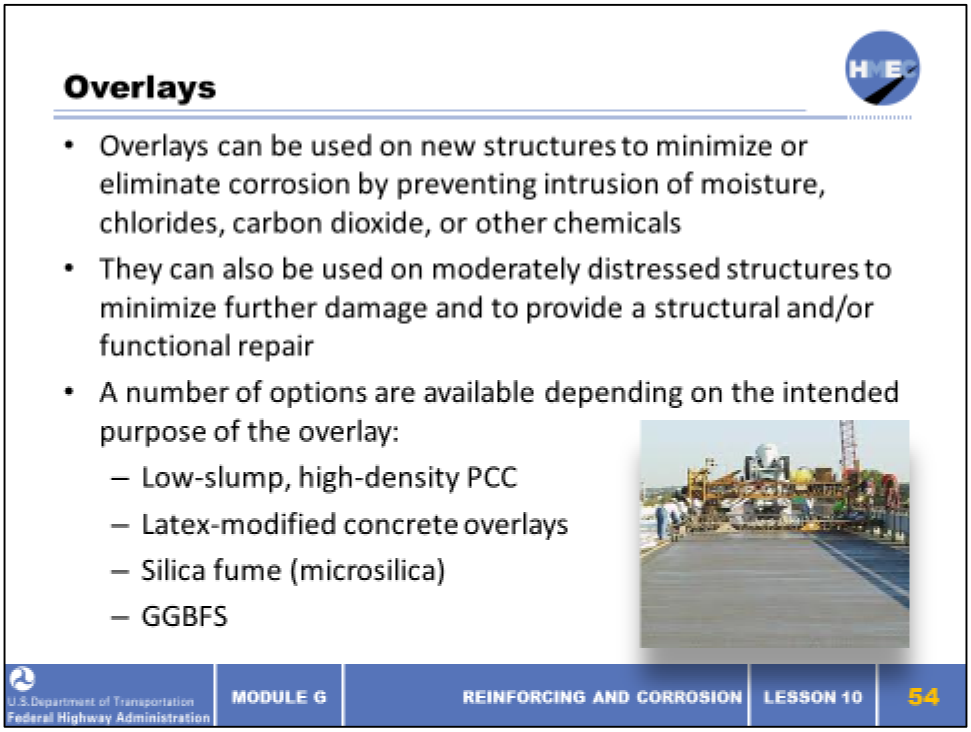
____

____

____

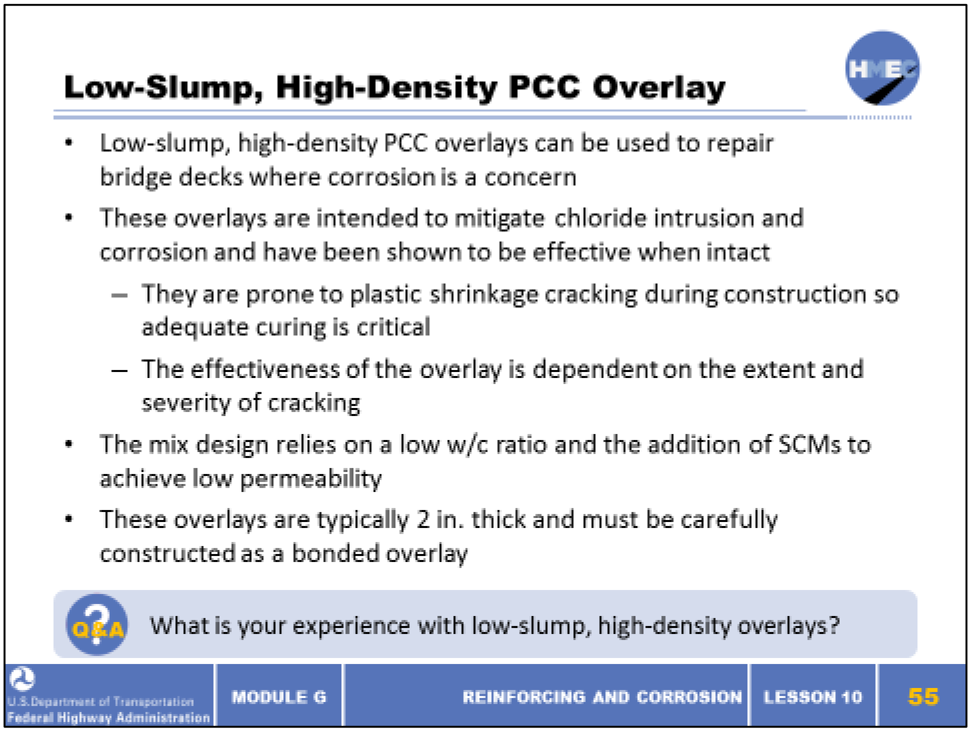
____

Slide 54



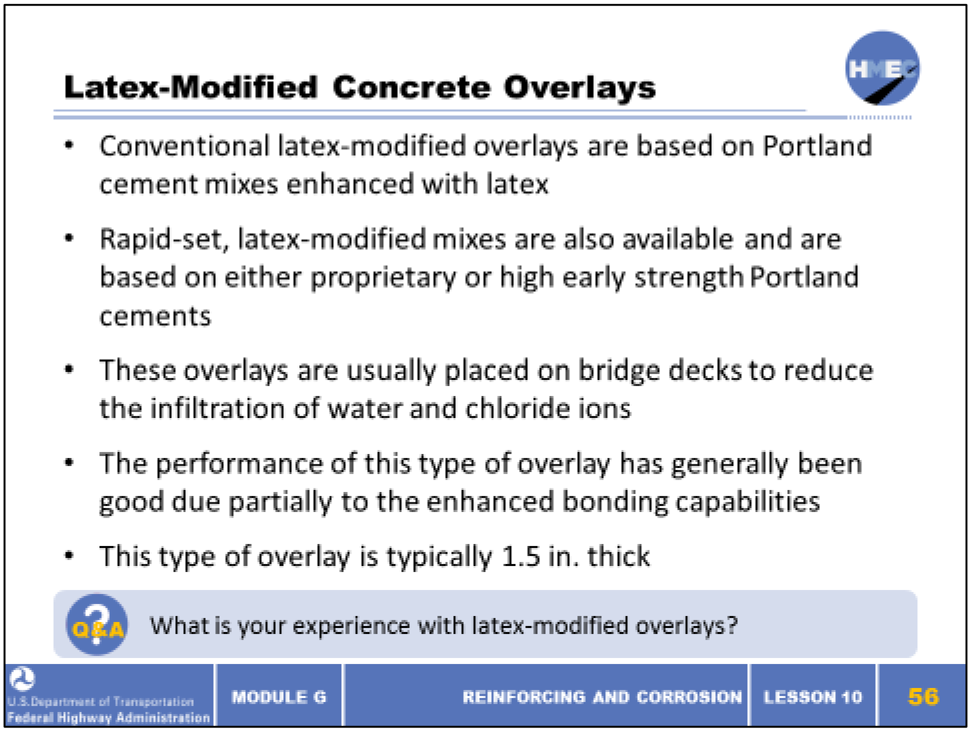
They can also be used on moderately distressed structures to minimize further damage and to provide a structural and/or functional repair.

Slide 55



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.

Slide 56



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.

Slide 57

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.

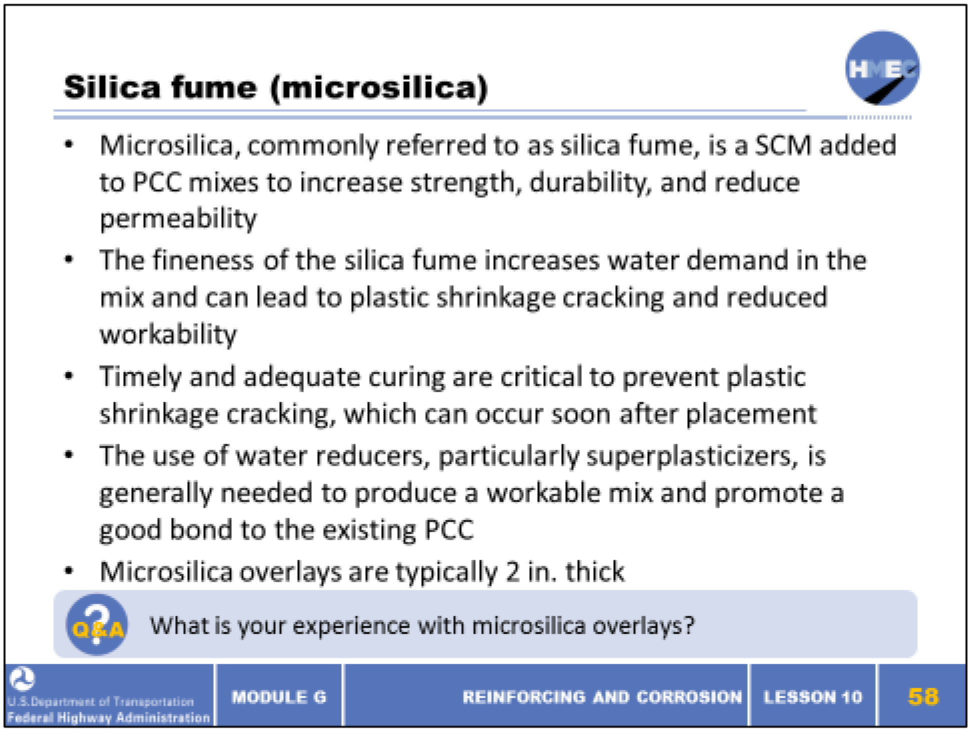
Placement should be avoided when hot, windy, low humidity conditions are expected as the material is prone to plastic shrinkage cracking unless adequate measures are taken very soon after placement.

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.

____
____
____
____
____
____
____
____
____
____
____

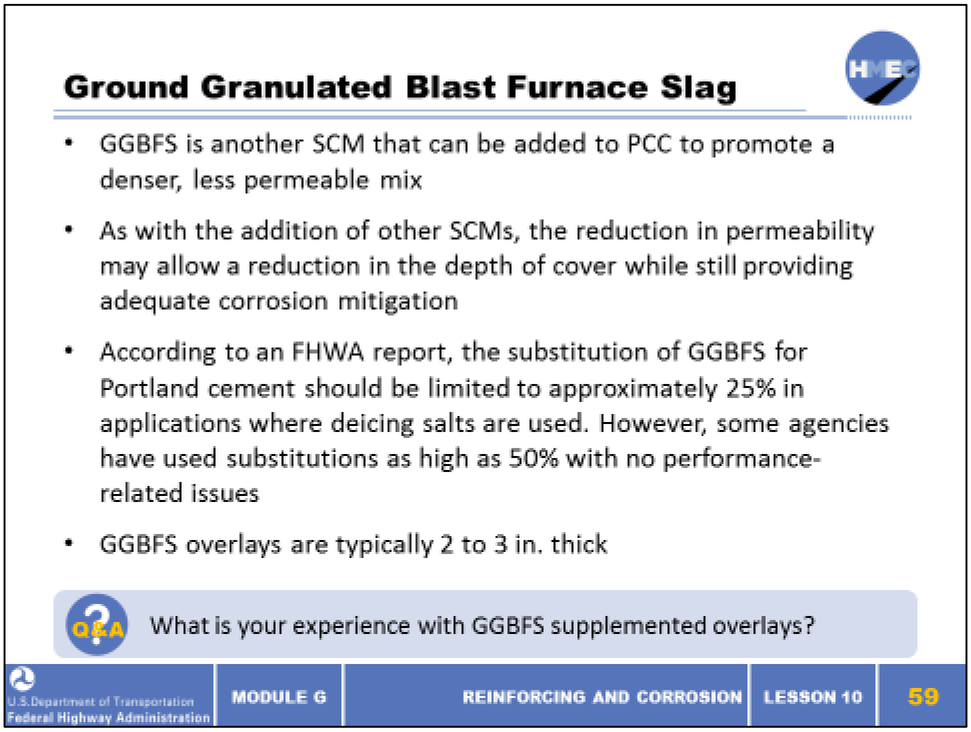
Slide 58



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.

Slide 59



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.

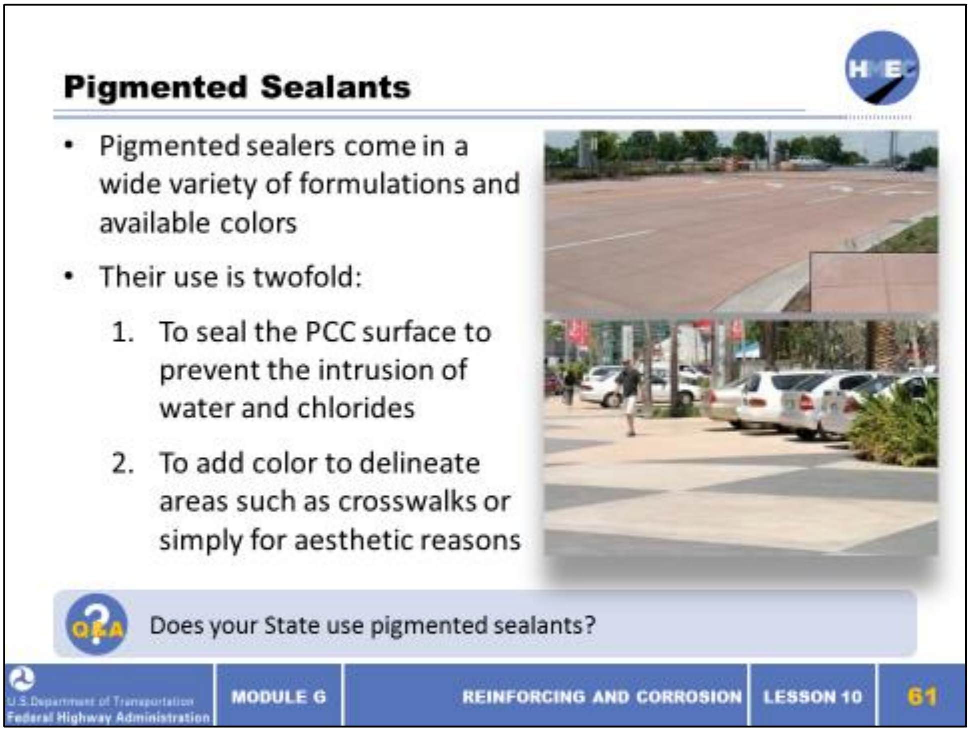
Slide 60

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

U.S. Department of Transportation Federal Highway Administration | MODULE G | REINFORCING AND CORROSION | LESSON 10 | 60

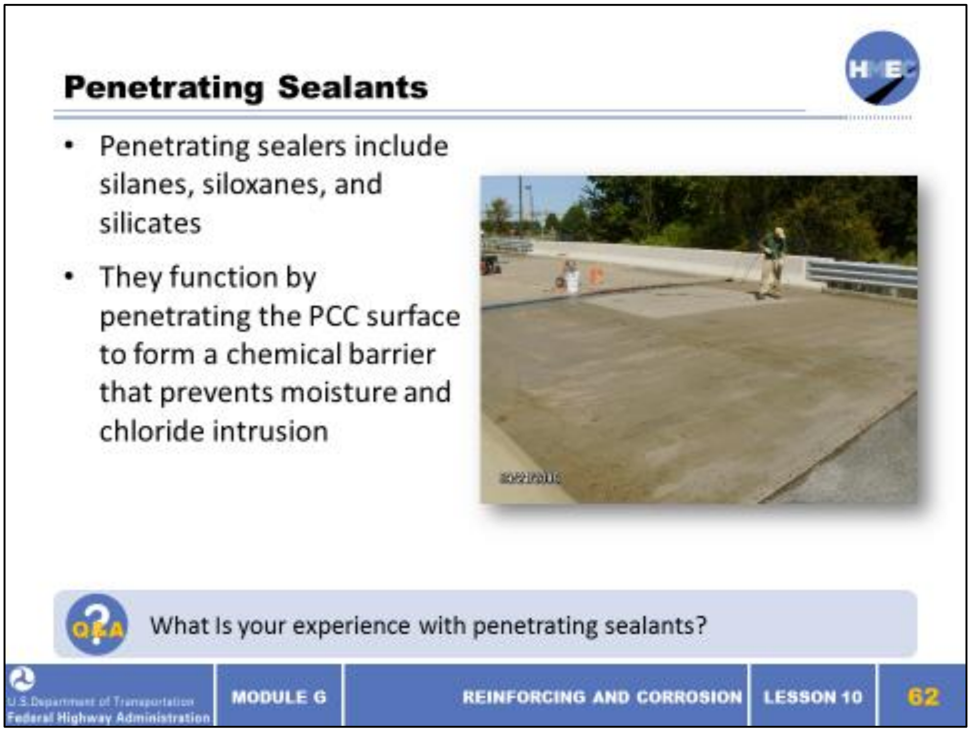
Slide 61



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.

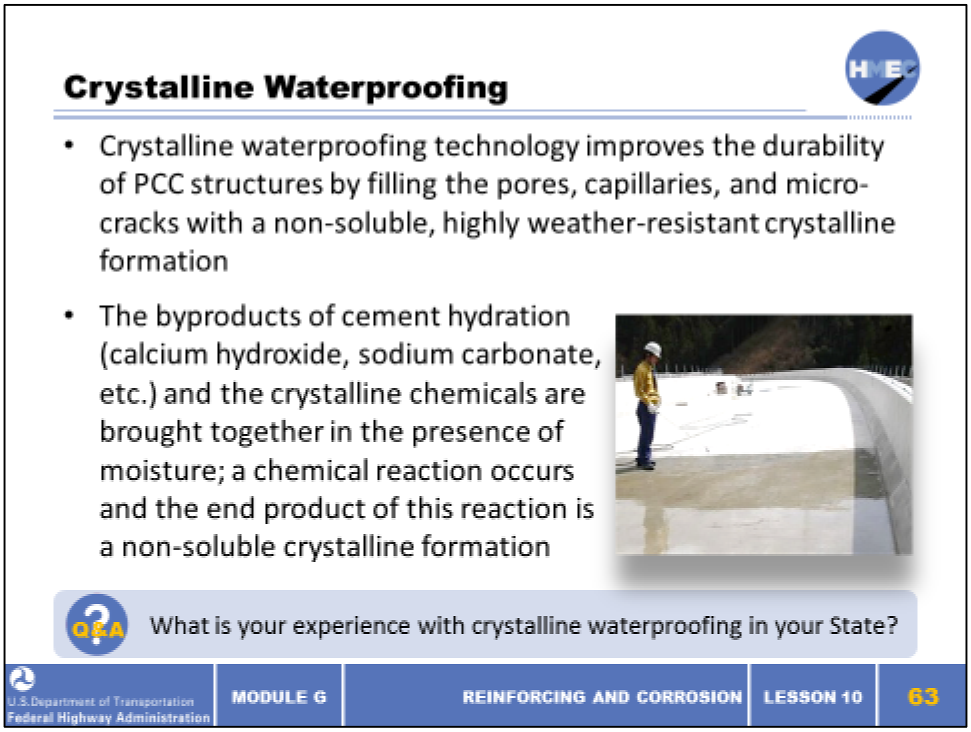
Slide 62



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.

Slide 63



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.

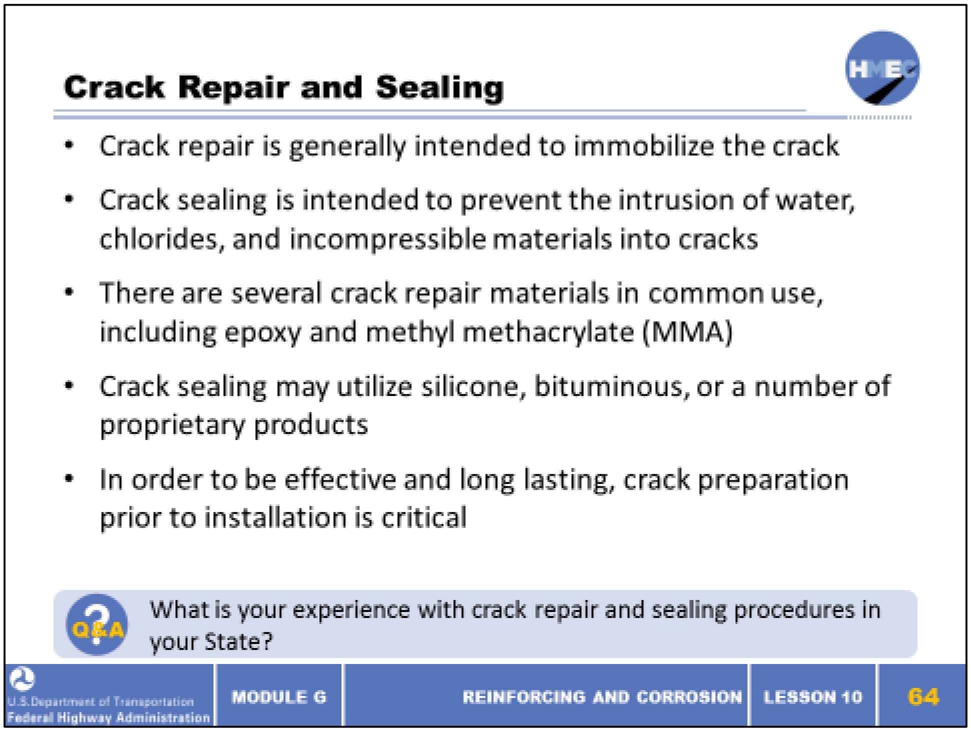
Crystalline waterproofing introduces another set of chemicals to the concrete. When these two chemical groups, the byproducts of cement hydration and the crystalline chemicals, are brought together in the presence of moisture and a chemical reaction occurs. The end product of this reaction is a non-soluble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

____

____

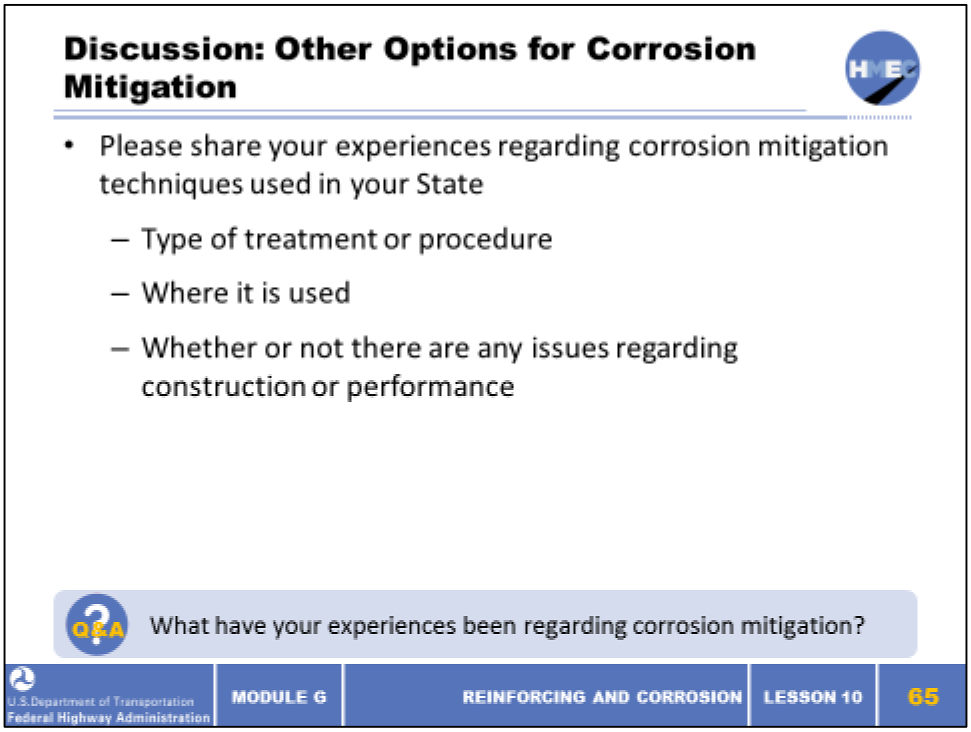
Slide 64



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.

Slide 65


Discussion: Other Options for Corrosion Mitigation
HMEC
• 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
Q&A
What have your experiences been regarding corrosion mitigation?
U.S. Department of Transportation
Federal Highway Administration
MODULE G
REINFORCING AND CORROSION
LESSON 10
65

Slide 66

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

U.S. Department of Transportation Federal Highway Administration | MODULE G | REINFORCING AND CORROSION | LESSON 10 | 66

This page is intentionally blank.

Slide 1


ILT
HMEC
Highway Materials Engineering Course
Lesson 11: Hot Topics
Portland Cement Concrete
(PCC)
U.S.Department of Transportation
Federal Highway Administration
MODULE
G

This page is intentionally blank.

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

This page is intentionally blank.