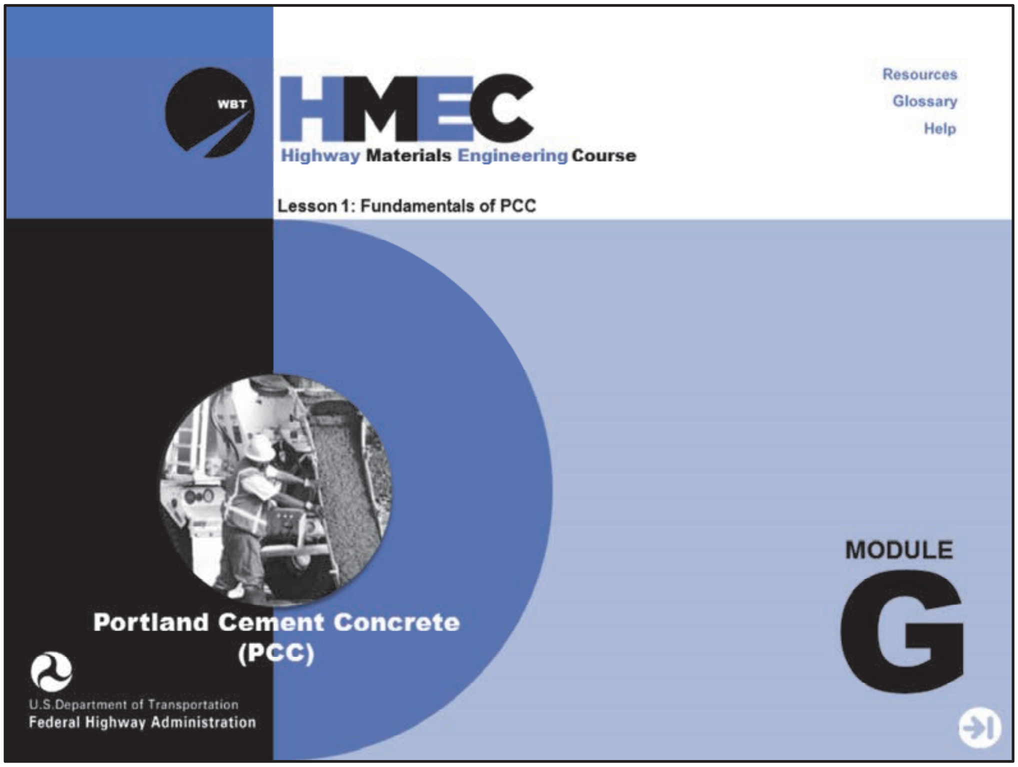
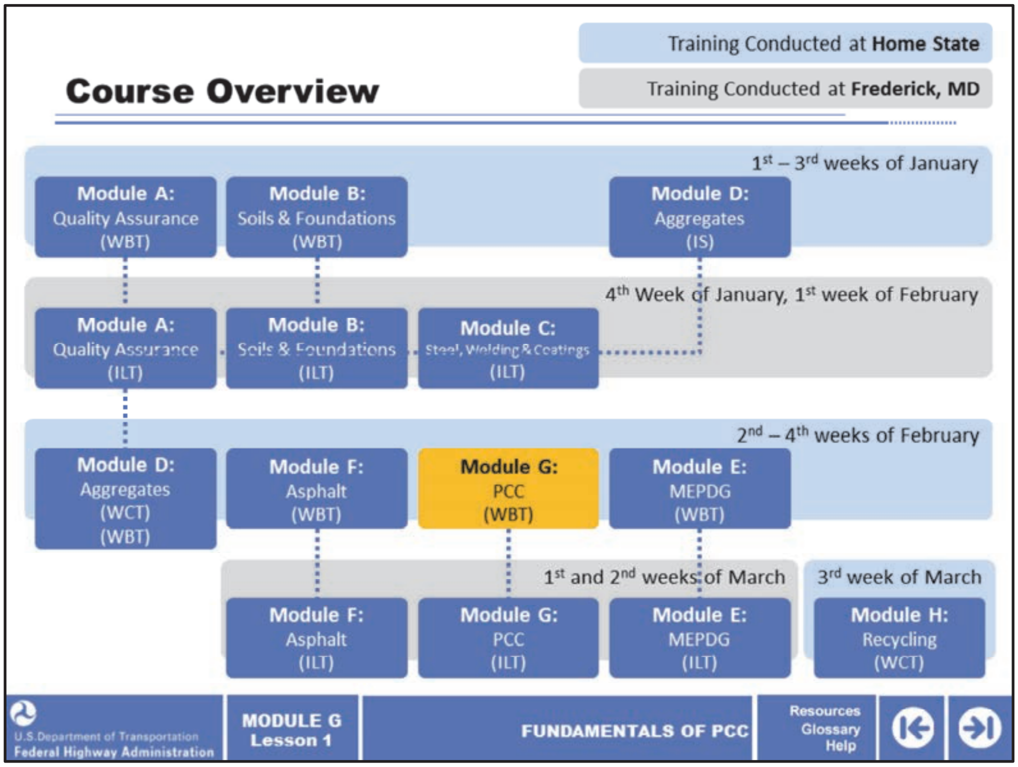


Welcome to the Highway Materials Engineering Course Module G, Lesson 1: Fundamentals of Portland Cement Concrete (PCC). In this lesson, we will look at the fundamental properties and the key factors that influence the mechanical properties of PCC as well as typical durability issues of PCC.

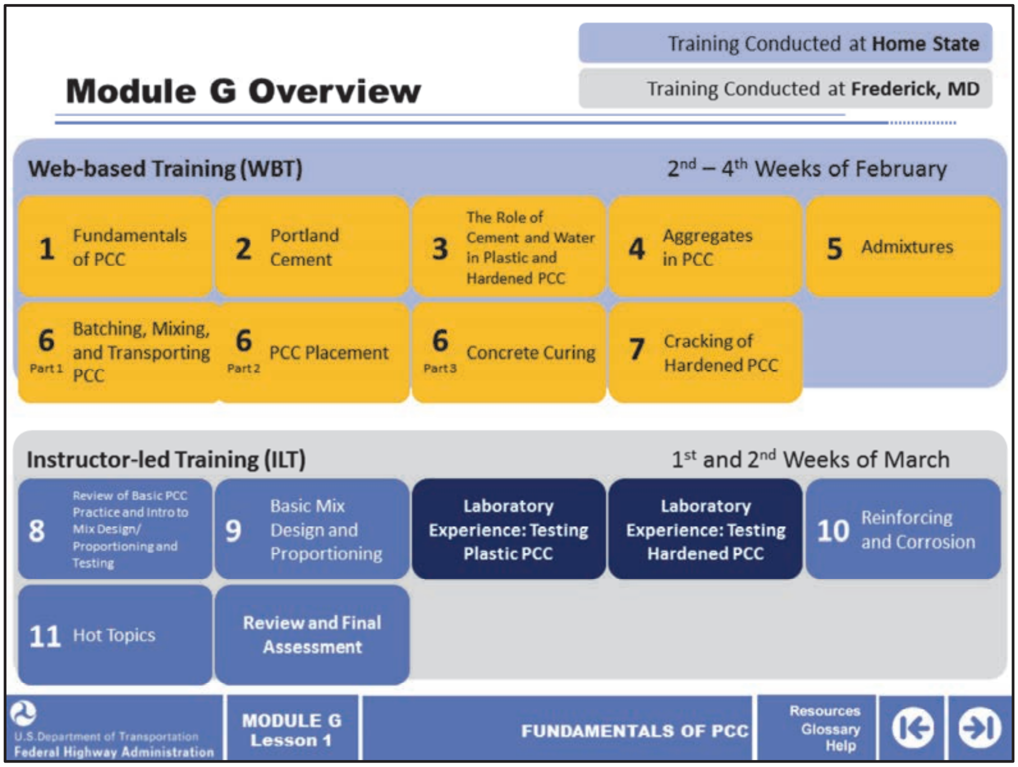
A printer-friendly version of the lesson materials can be downloaded by selecting the paperclip icon. A copy of the slides and narration are provided for download.

If you need technical assistance during the training, please select the Help link in the upper right-hand corner of the screen.



The Highway Materials Engineering Course (HMEC) is a comprehensive, six-week training event. Module G: Portland Cement Concrete is the sixth module in this course.

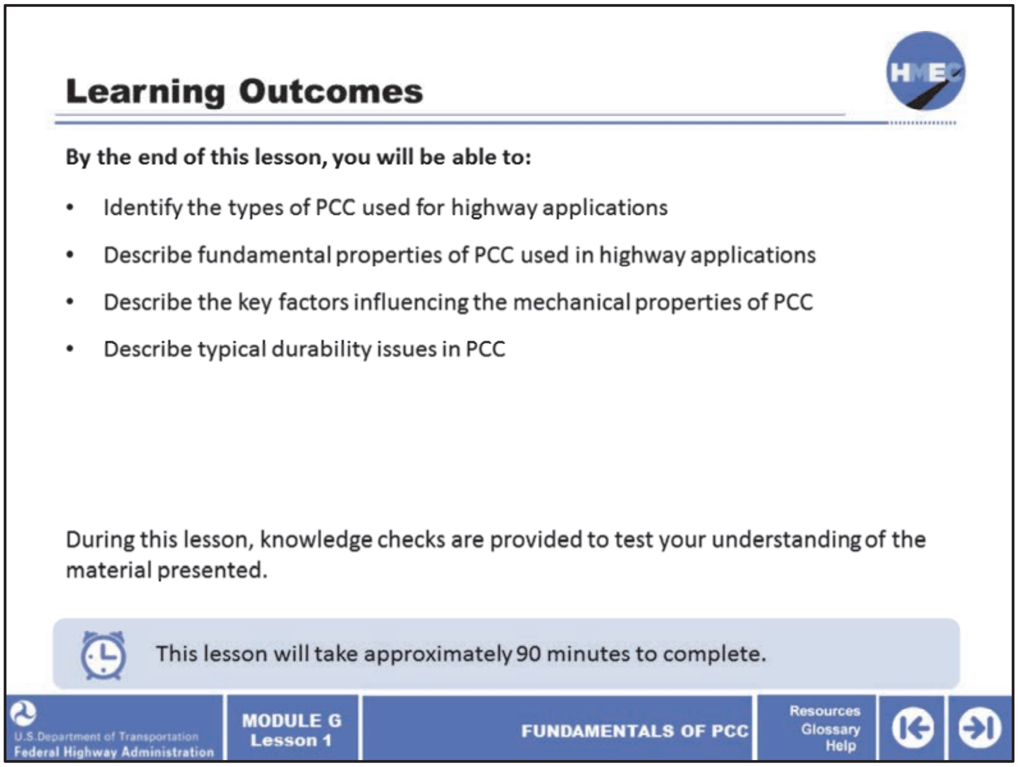
On the next screen, we'll review the lesson structure of this module.



Module G consists of 11 lessons. Lessons 1–7 are completed in the introductory Web-based training (WBT) portion of the module. Lessons 8–11 and the final assessment are completed during the instructor-led training (ILT) portion of the module.

The estimated duration for the WBT portion of the module is 10 hours. The estimated duration for the ILT portion of the module is 13 hours. Laboratory experiences and debriefing are estimated to take 10 hours.

The total commitment from participants is estimated to take 33 hours.

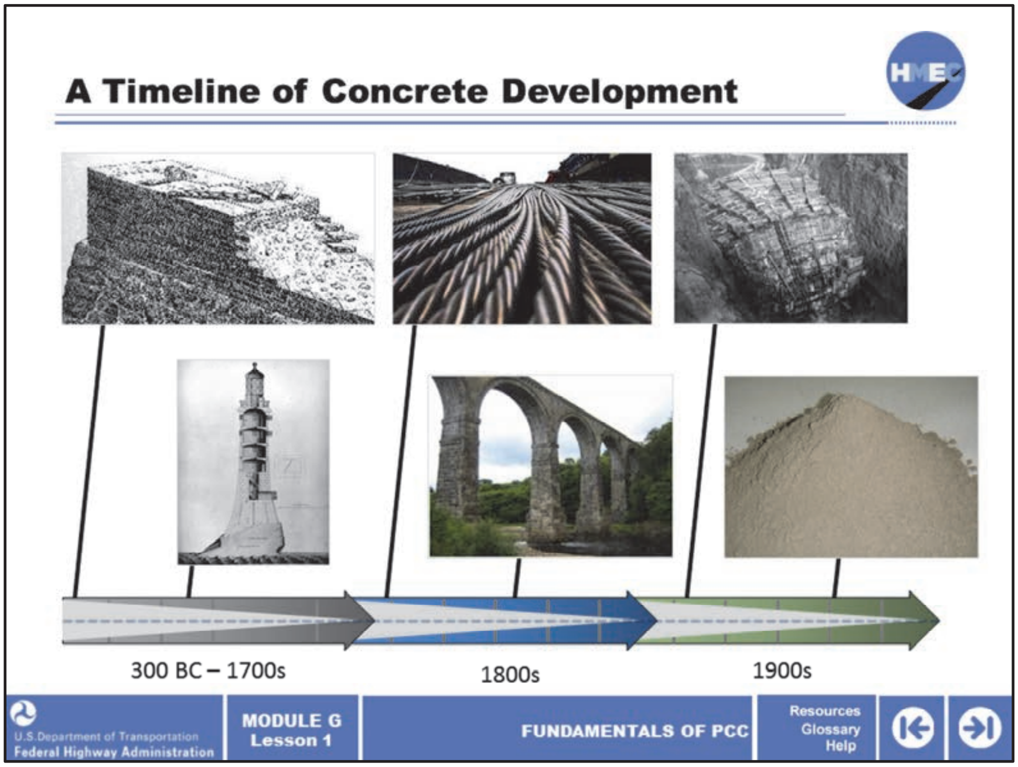


By the end of this lesson, you will be able to:

- Identify the types of PCC used for highway applications;
- Describe fundamental properties of PCC used in highway applications;
- Describe the key factors influencing the mechanical properties of PCC; and
- Describe typical durability issues in PCC.

During this lesson, knowledge checks are provided to test your understanding of the material presented.

This lesson will take approximately 90 minutes to complete.



Concrete is one of the oldest building materials as it dates back to the Roman times, as shown at the beginning of this timeline. The next three slides will show the historical development and major advances that has resulted in modern-day Portland cement concrete. Events in the timeline that are of significant importance have an asterisk.

Image description: Photo of Pozzuolana.

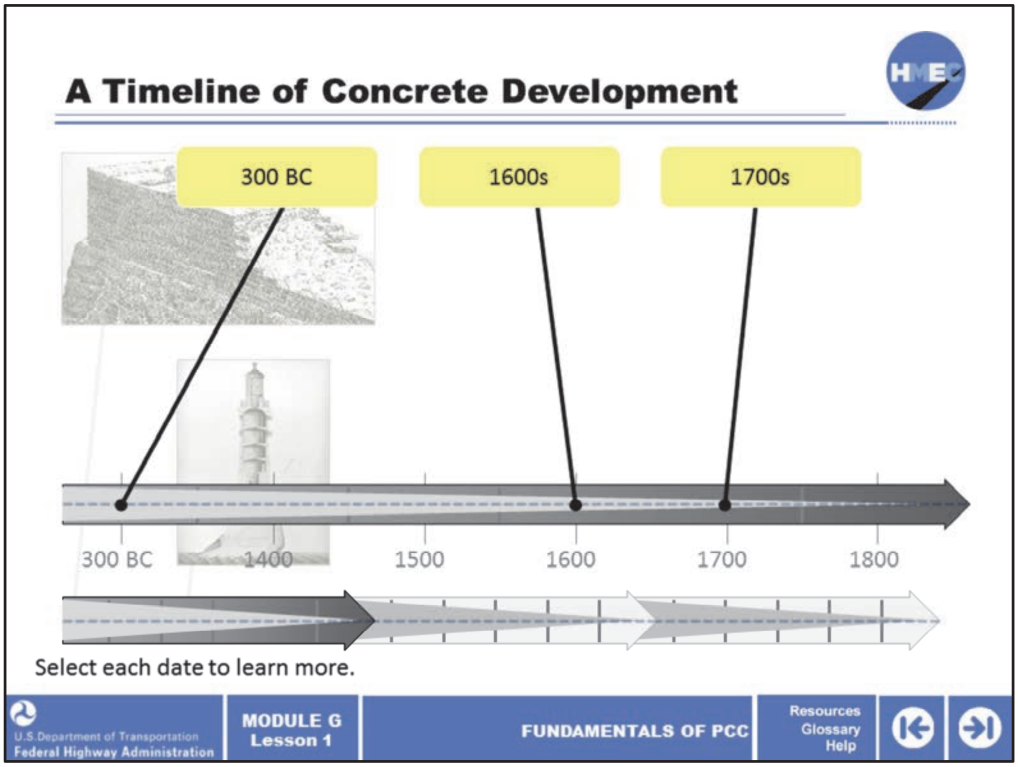
Image description: Photo of Twisted rods.

Image description: Photo of Hoover dam.

Image description: Photo of Eddystone Lighthouse in Cornwall, England.

Image description: Photo of Hydraulic lime bridge.

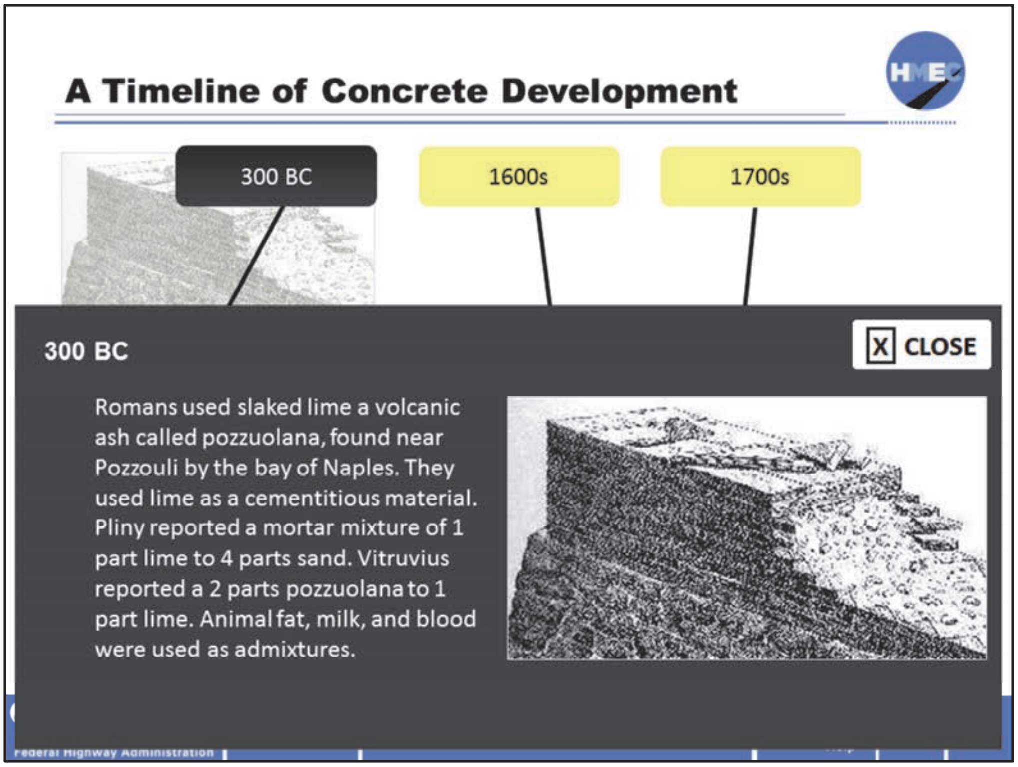
Image description: Photo of Portland cement.



Let's take a look at early concrete development from 300 BC until the 18th century. Select each date to learn more.

Image description: Photo of Pozzuolana.

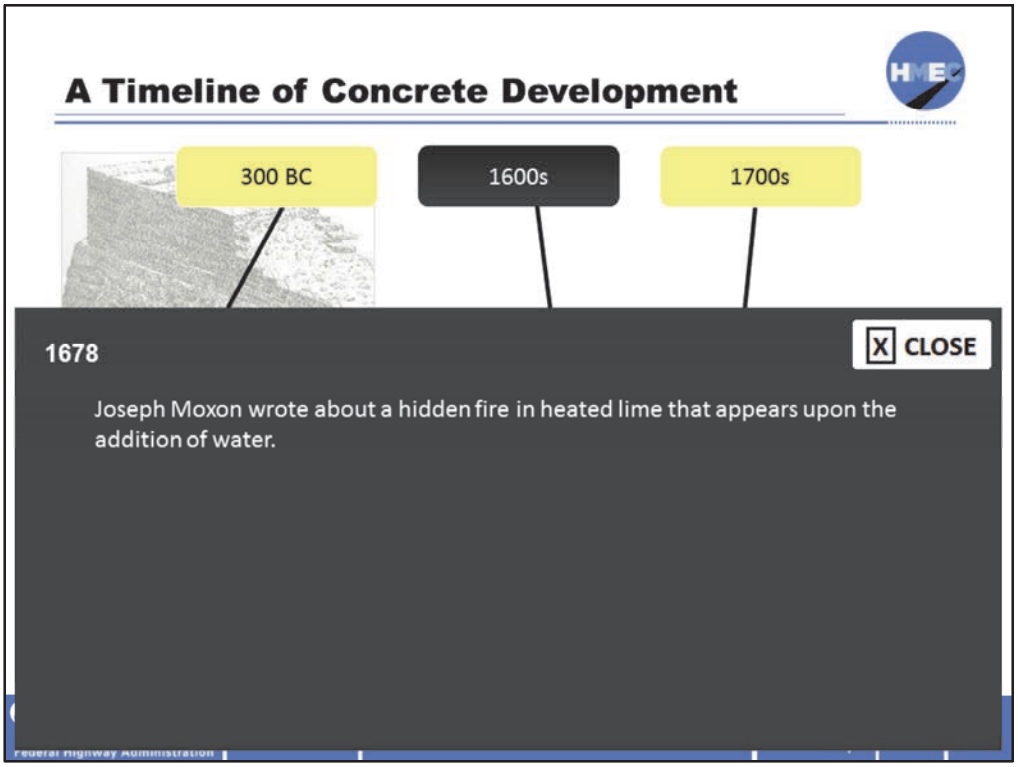
Image description: Photo of Eddystone Lighthouse in Cornwall, England.



300 B.C.: Romans used slaked lime, a volcanic ash called pozzuolana, found near Pozzouli by the bay of Naples. They used lime as a cementitious material. Pliny reported a mortar mixture of 1 part lime to 4 parts sand. Vitruvius reported a 2 parts pozzuolana to 1 part lime. Animal fat, milk, and blood were used as admixtures.

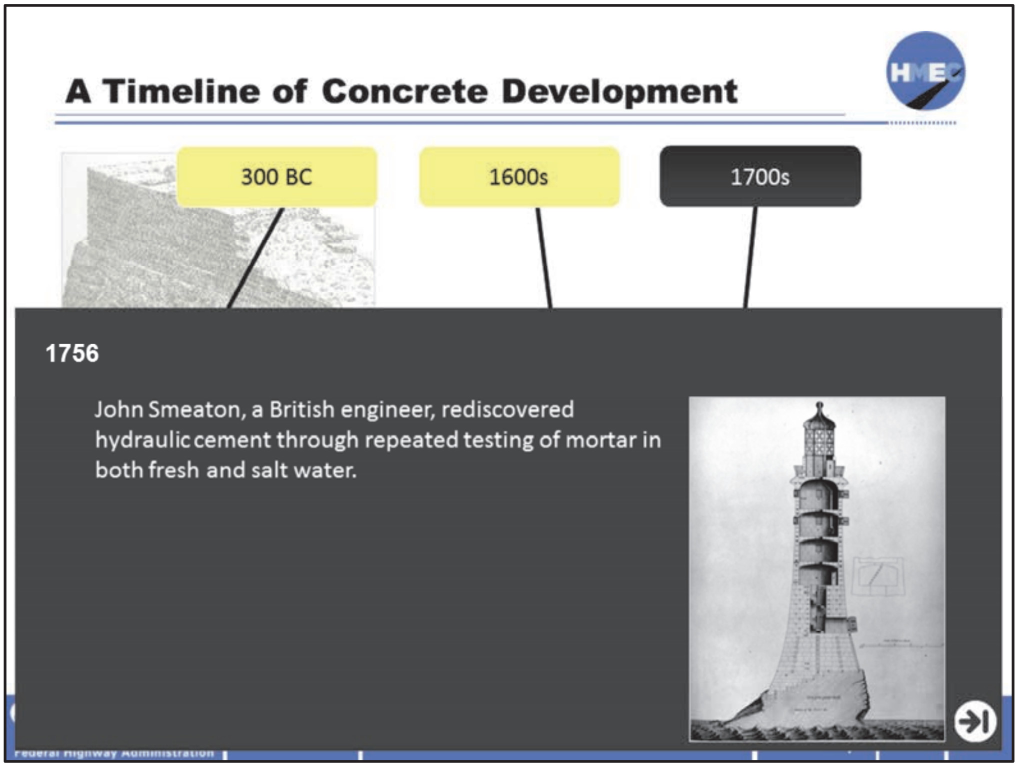
Image description: Photo of Pozzuolana.

Image description: Photo of Pozzuolana.



1678: Joseph Moxon wrote about a hidden fire in heated lime that appears upon the addition of water.

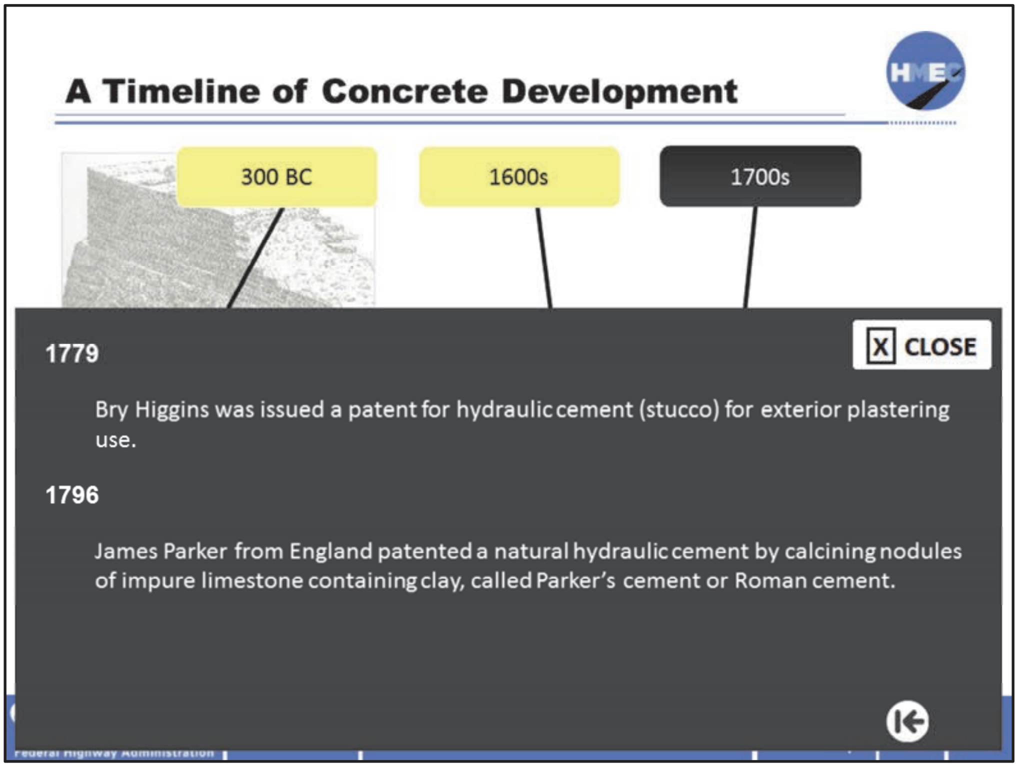
Image description: Photo of Pozzuolana.



1756: John Smeaton, a British engineer, rediscovered hydraulic cement through repeated testing of mortar in both fresh and salt water.

Image description: Photo of Pozzuolana.

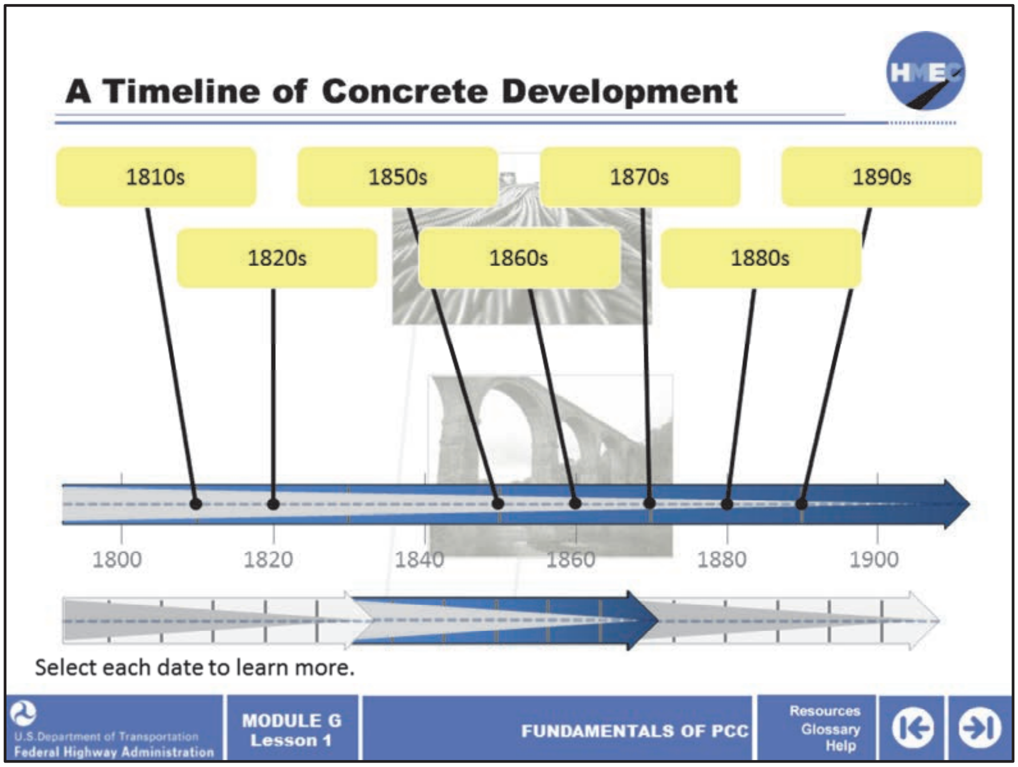
Image description: Photo of Eddystone Lighthouse in Cornwall, England.



1779: Bry Higgins was issued a patent for hydraulic cement (stucco) for exterior plastering use.

1796: James Parker from England patented a natural hydraulic cement by calcining nodules of impure limestone containing clay, called Parker's cement or Roman cement.

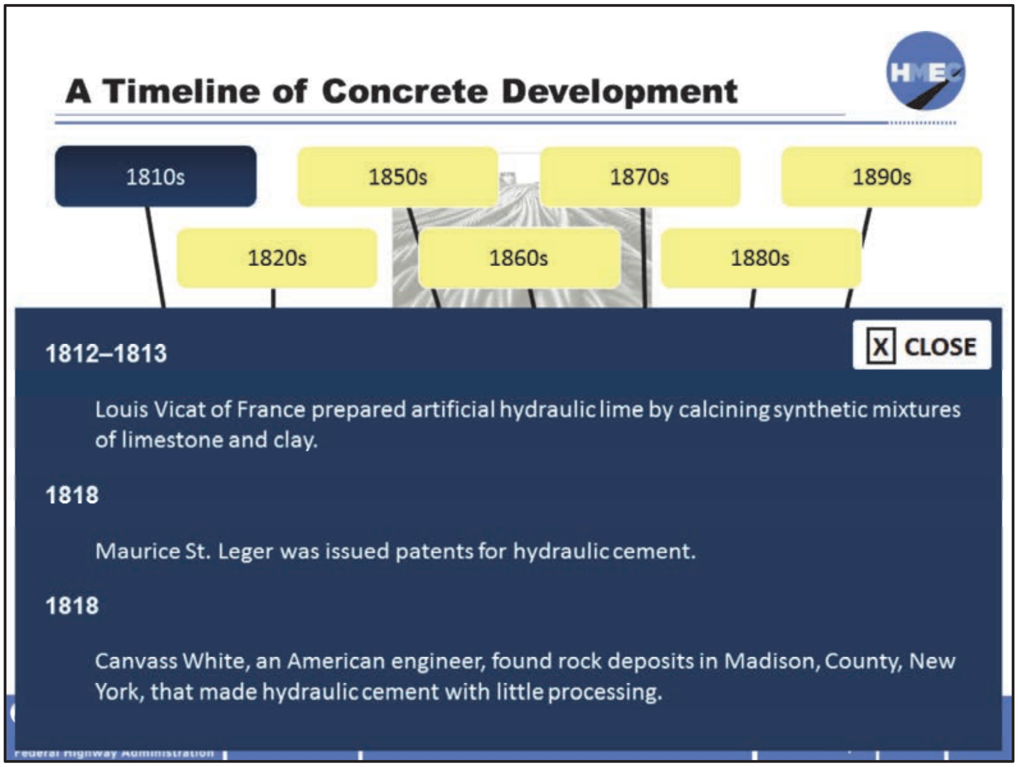
Image description: Photo of Pozzuolana.



Let's take a look at concrete development in the 19th century. Select each date to learn more.

Image description: Photo of Twisted rods.

Image description: Photo of Hydraulic lime bridge.

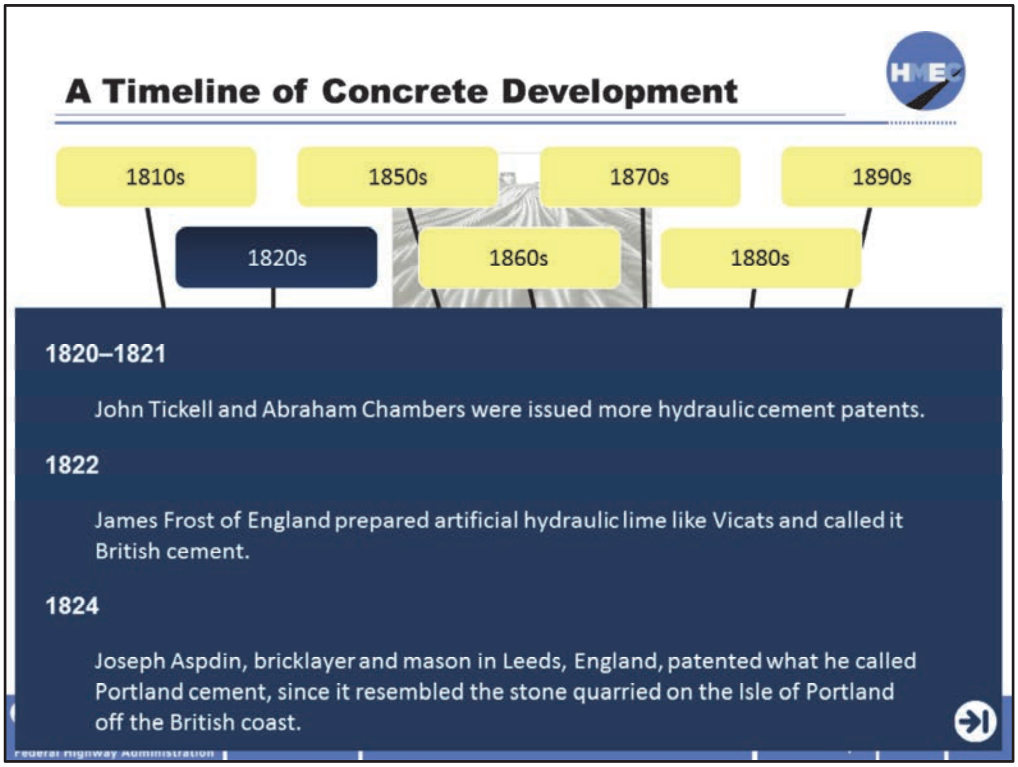


1812–1813: Louis Vicat of France prepared artificial hydraulic lime by calcining synthetic mixtures of limestone and clay.

1818: Maurice St. Leger was issued patents for hydraulic cement.

1818: Canvass White, an American engineer, found rock deposits in Madison, County, New York, that made hydraulic cement with little processing.

Image description: Photo of Twisted rods.

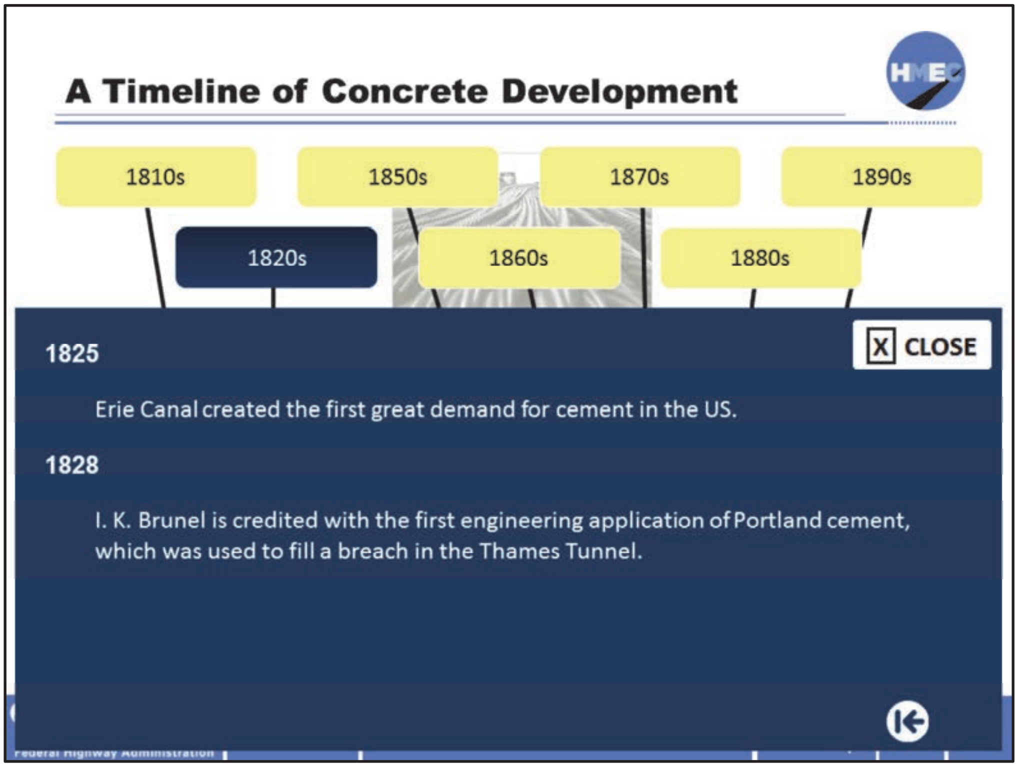


1820-1821: John Tickell and Abraham Chambers were issued more hydraulic cement patents.

1822: James Frost of England prepared artificial hydraulic lime like Vicats and called it British cement.

1824: Joseph Aspdin, bricklayer and mason in Leeds, England, patented what he called Portland cement, since it resembled the stone quarried on the Isle of Portland off the British coast.

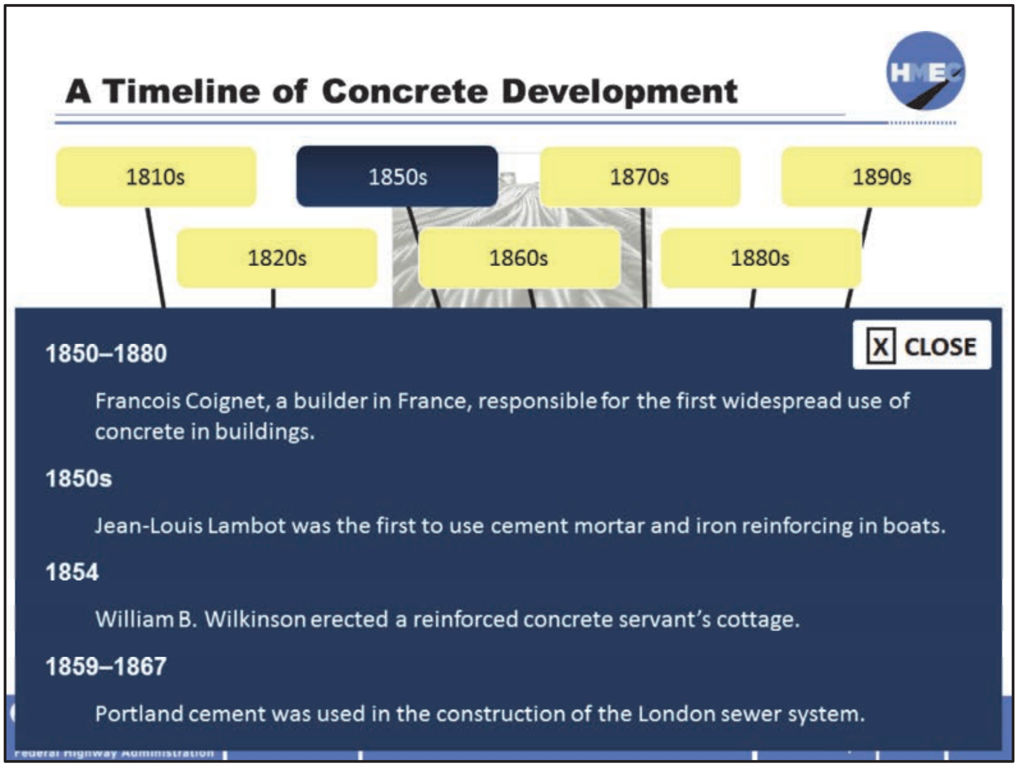
Image description: Photo of Twisted rods.



1825: Erie Canal created the first great demand for cement in the US.

1828: I. K. Brunel is credited with the first engineering application of Portland cement, which was used to fill a breach in the Thames Tunnel.

Image description: Photo of Twisted rods.



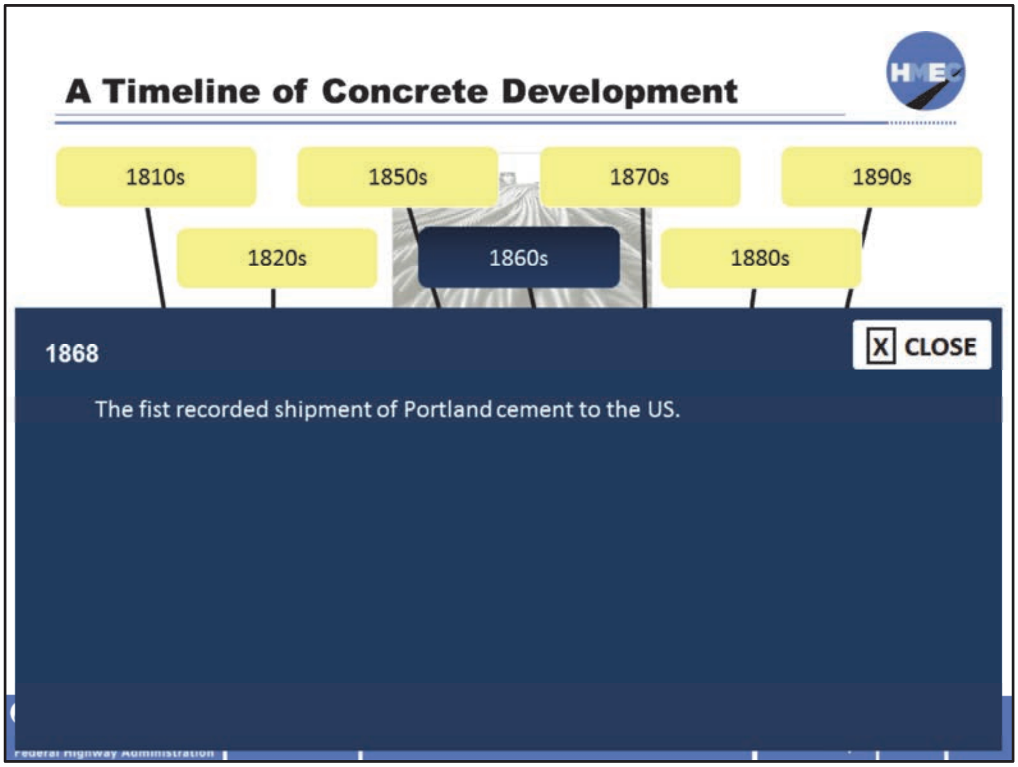
1850-1880: Francois Coignet, a builder in France, responsible for the first widespread use of concrete in buildings.

1850s: Jean-Louis Lambot was the first to use cement mortar and iron reinforcing in boats.

1854: William B. Wilkinson erected a reinforced concrete servant's cottage.

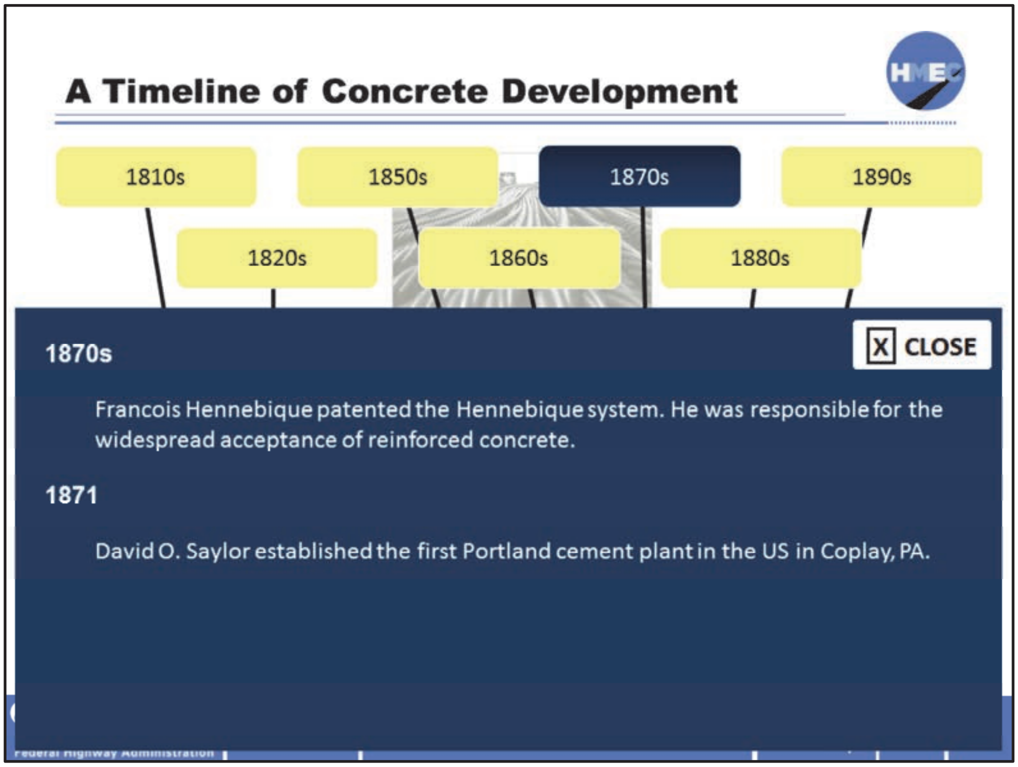
1859-1867: Portland cement was used in the construction of the London sewer system.

Image description: Photo of Twisted rods.



1868: The fist recorded shipment of Portland cement to the US.

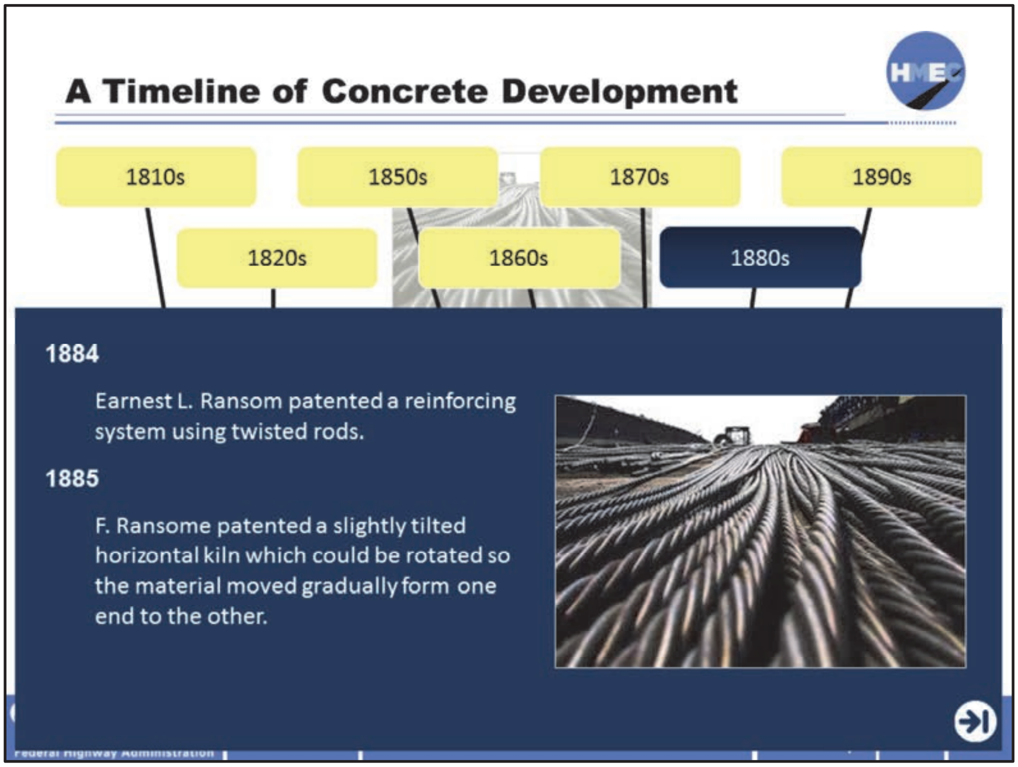
Image description: Photo of Twisted rods.



1870s: Francois Hennebique patented the Hennebique system. He was responsible for the widespread acceptance of reinforced concrete.

1871: David O. Saylor established the first Portland cement plant in the US in Coplay, PA.

Image description: Photo of Twisted rods.

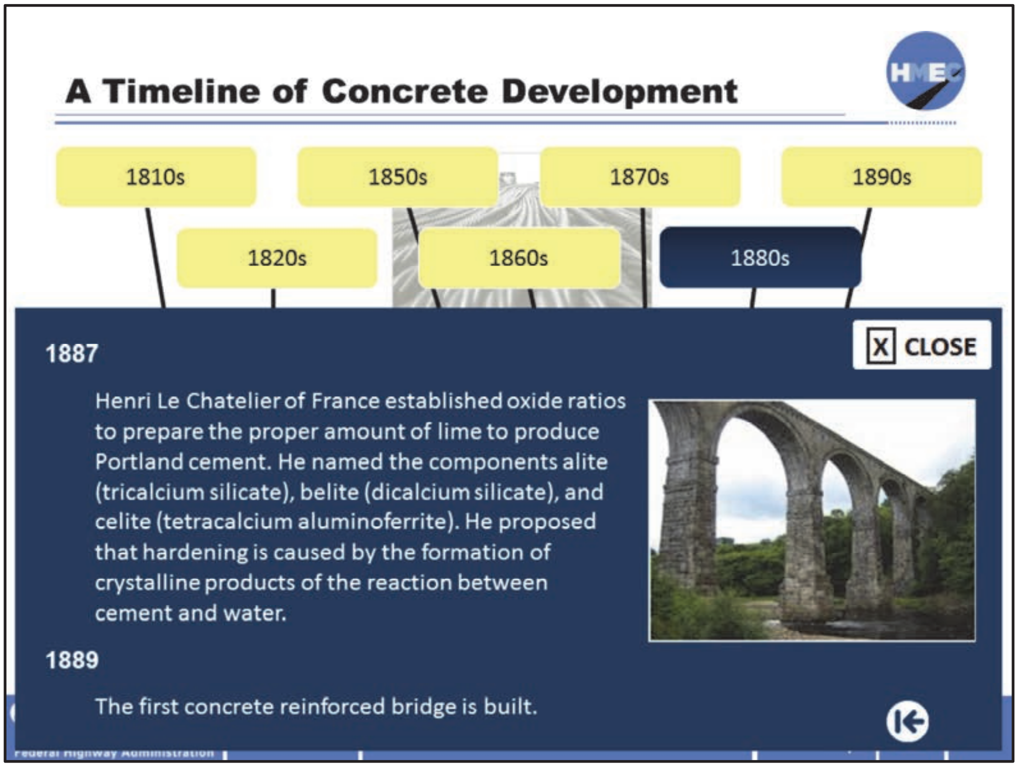


1884: Earnest L. Ransom patented a reinforcing system using twisted rods.

1885: F. Ransome patented a slightly tilted horizontal kiln which could be rotated so the material moved gradually from one end to the other.

Image description: Photo of Twisted rods.

Image description: Photo of Twisted rods.

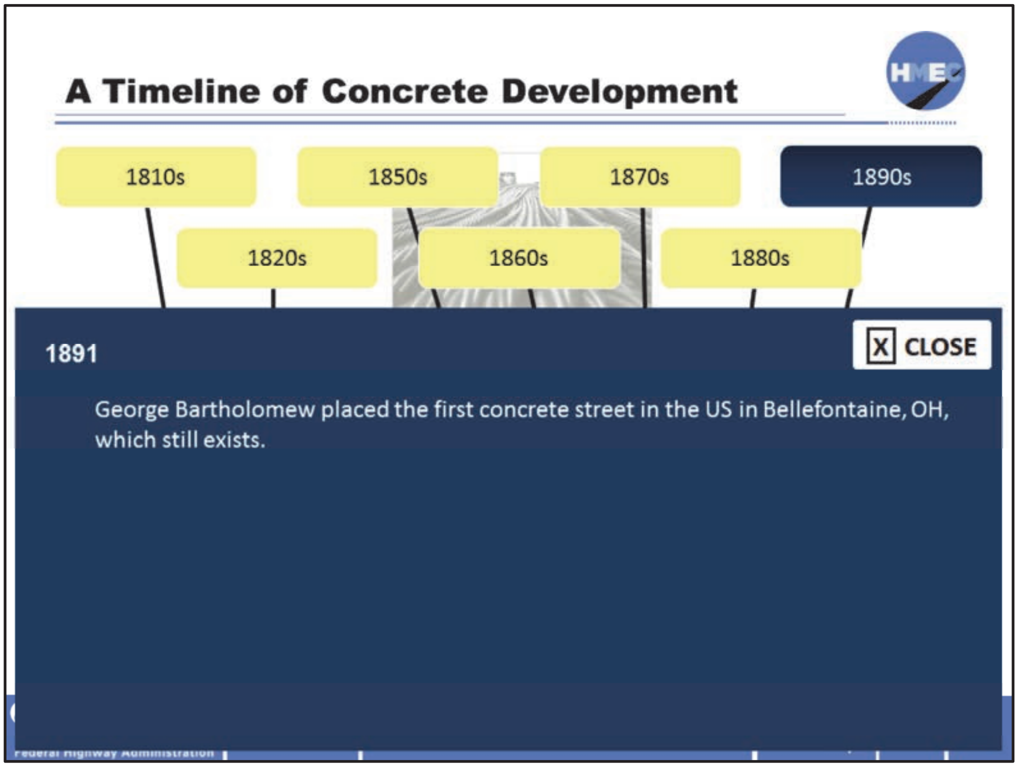


1887: Henri Le Chatelier of France established oxide ratios to prepare the proper amount of lime to produce portland cement. He named the components alite (tricalcium silicate), belite (dicalcium silicate), and celite (tetracalcium aluminoferrite). He proposed that hardening is caused by the formation of crystalline products of the reaction between cement and water.

1889: The first concrete reinforced bridge is built.

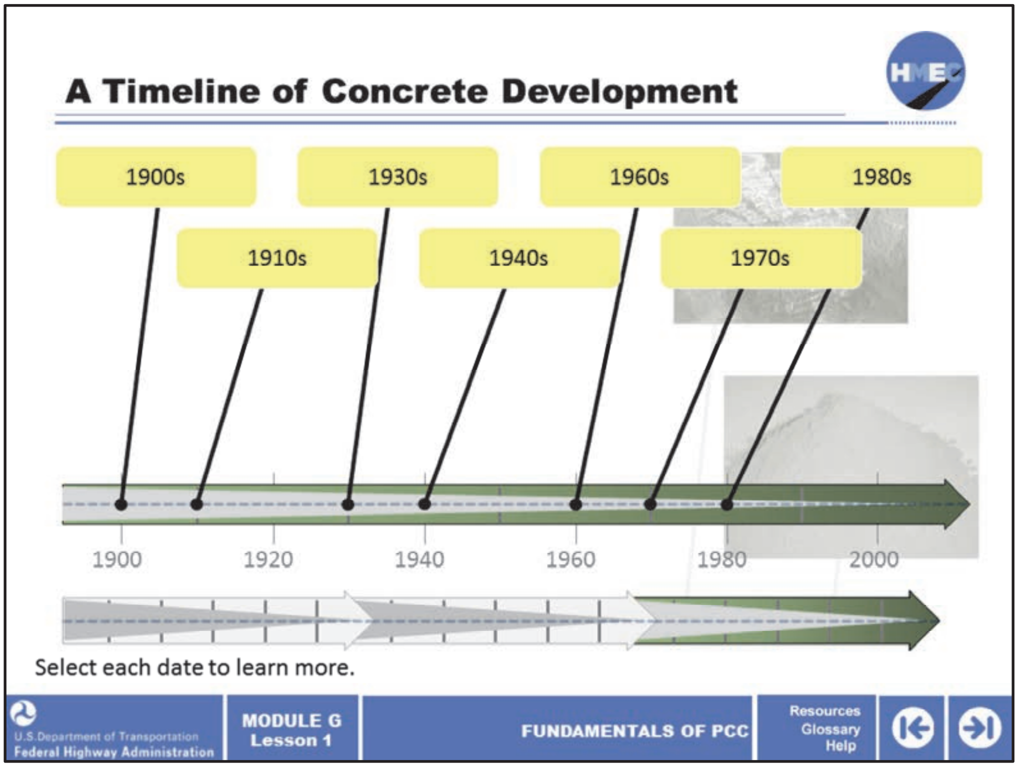
Image description: Photo of Twisted rods.

Image description: Photo of Hydraulic lime bridge.



1891: George Bartholomew placed the first concrete street in the USA in Bellefontaine, OH, which still exists.

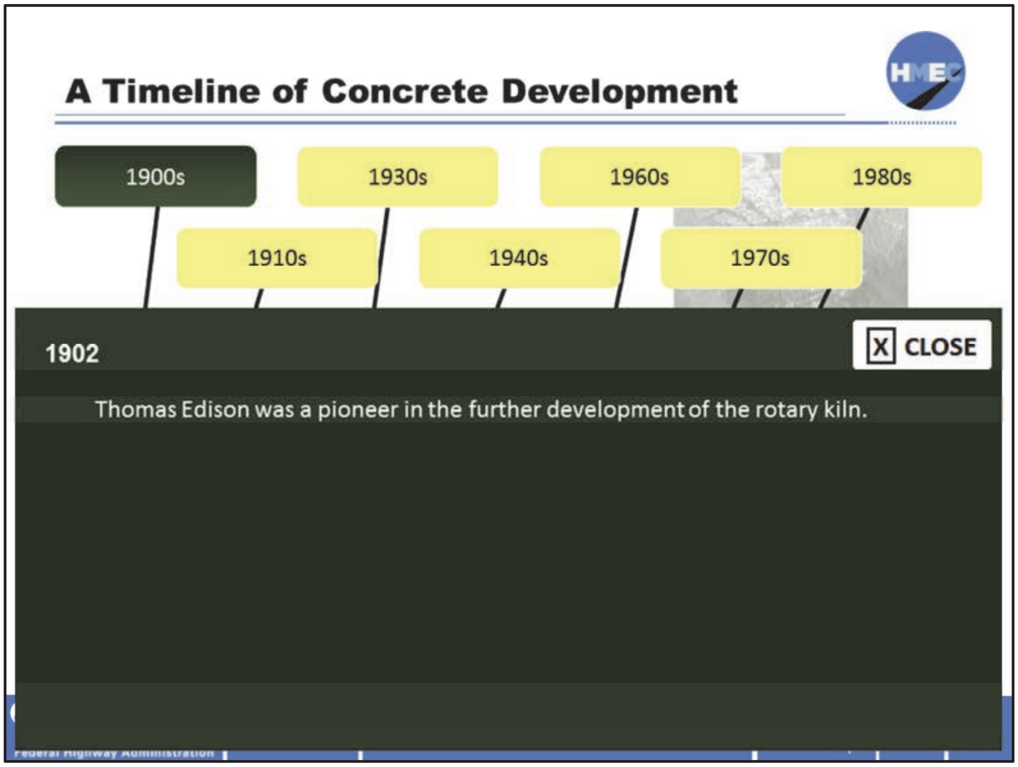
Image description: Photo of Twisted rods.



Let's take a look at concrete development in the 20th century. Select each date to learn more.

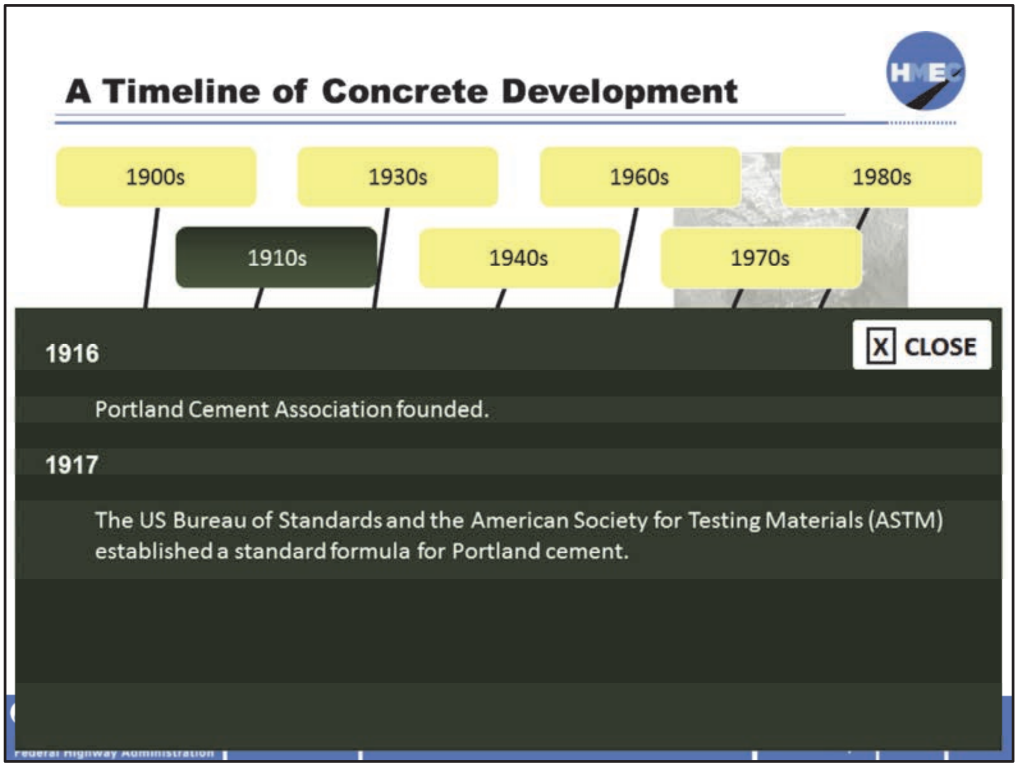
Image description: Photo of Hoover dam.

Image description: Photo of Portland cement.



1902: Thomas Edison was a pioneer in the further development of the rotary kiln.

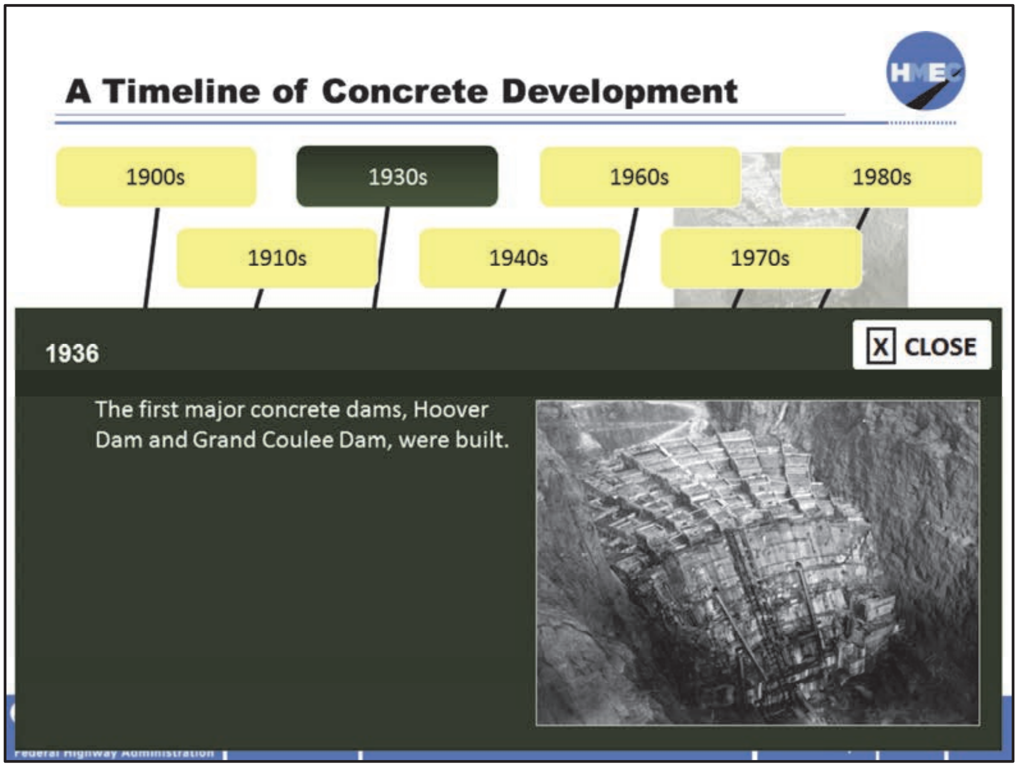
Image description: Photo of Hoover dam.



1916: Portland Cement Association founded.

1917: The US Bureau of Standards and the American Society for Testing Materials (ASTM) established a standard formula for Portland cement.

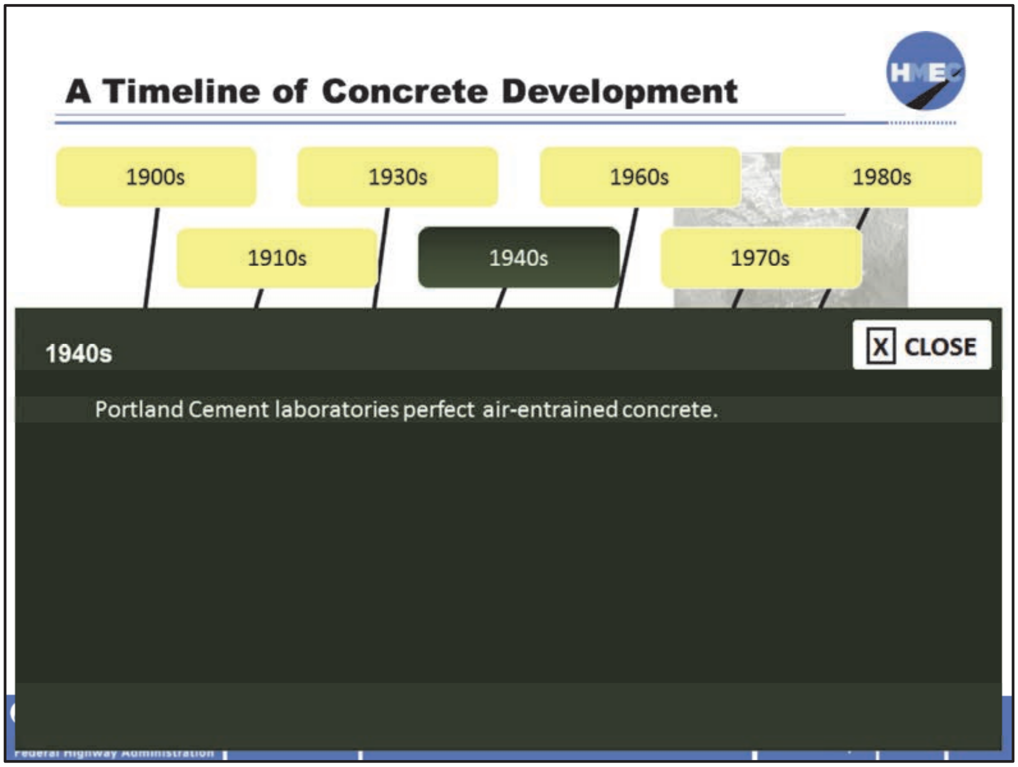
Image description: Photo of Hoover dam.



1936: The first major concrete dams, Hoover Dam and Grand Coulee Dam, were built.

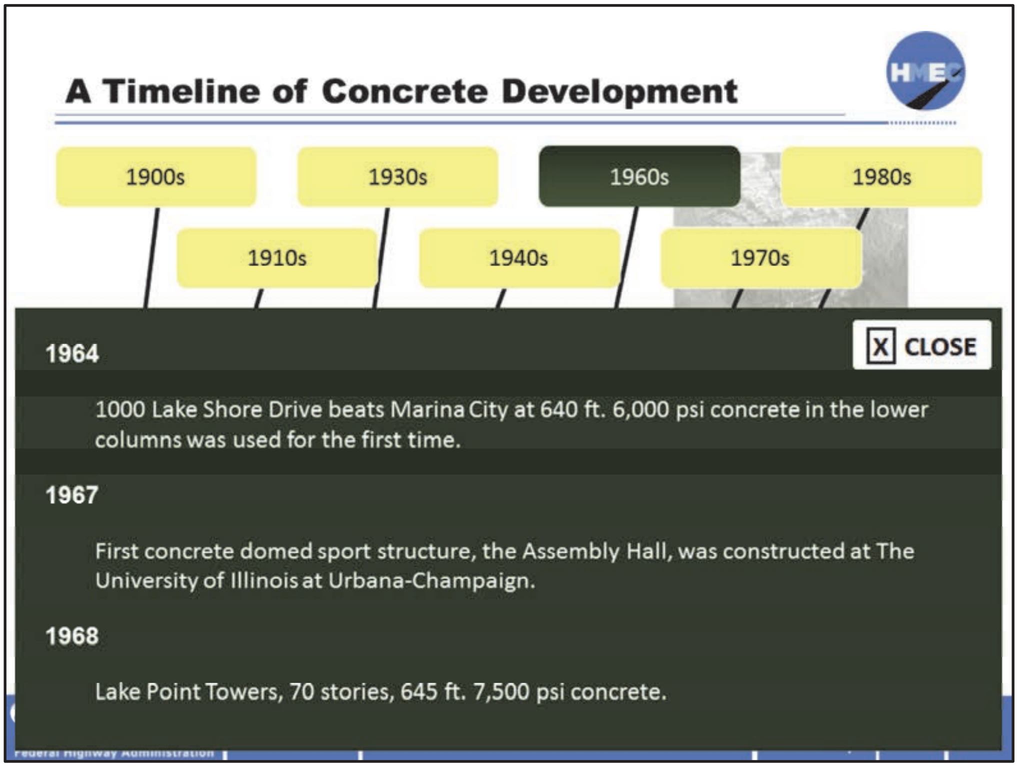
Image description: Photo of Hoover dam.

Image description: Photo of Hoover dam.



1940s: Portland Cement laboratories perfect air-entrained concrete.

Image description: Photo of Hoover dam.

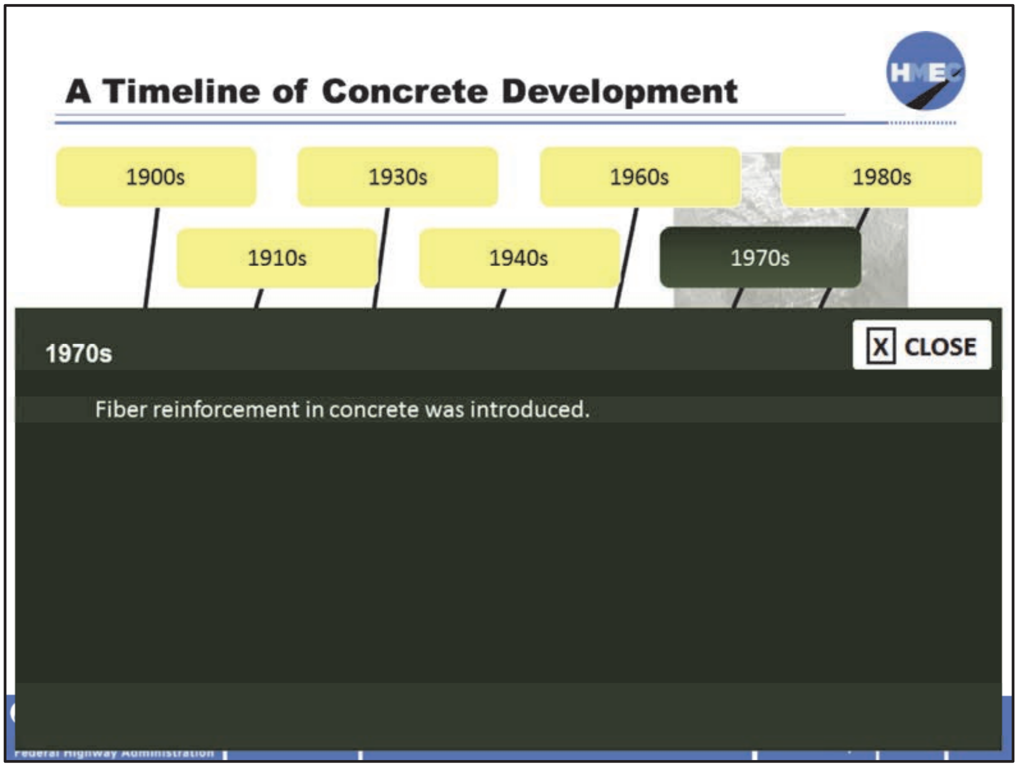


1964: 1000 Lake Shore Drive beats Marina City at 640 ft. 6,000 psi concrete in the lower columns was used for the first time.

1967: First concrete domed sport structure, the Assembly Hall, was constructed at The University of Illinois at Urbana-Champaign.

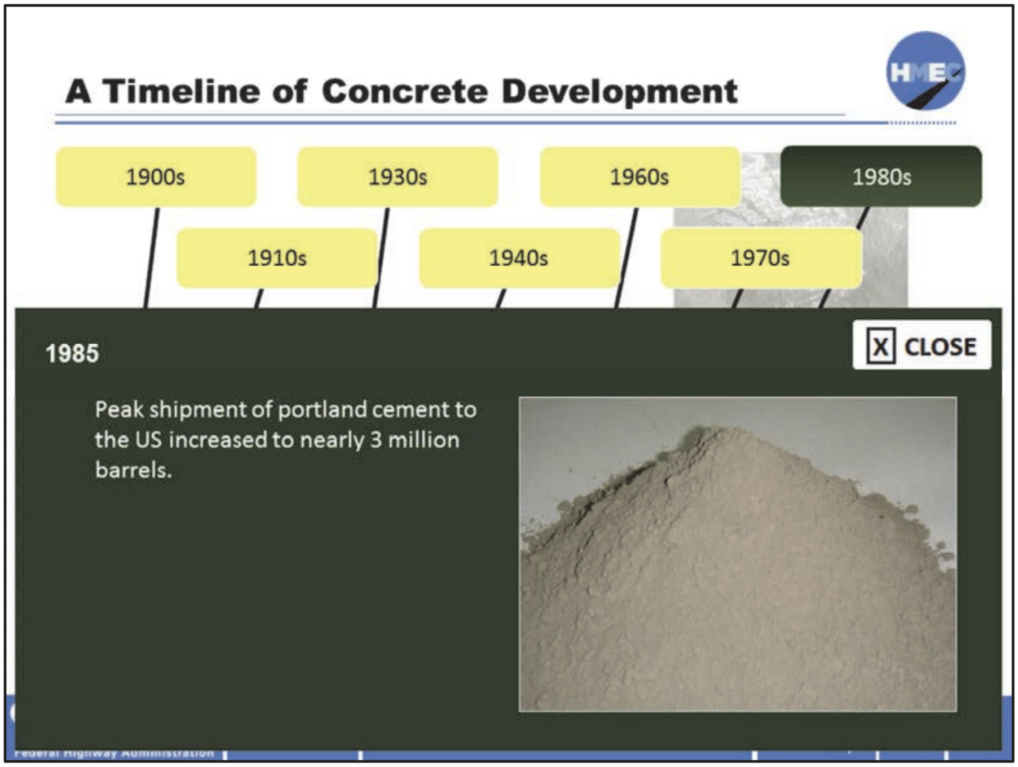
1968: Lake Point Towers, 70 stories, 645 ft. 7,500 psi concrete.

Image description: Photo of Hoover dam.



1970s: Fiber reinforcement in concrete was introduced.

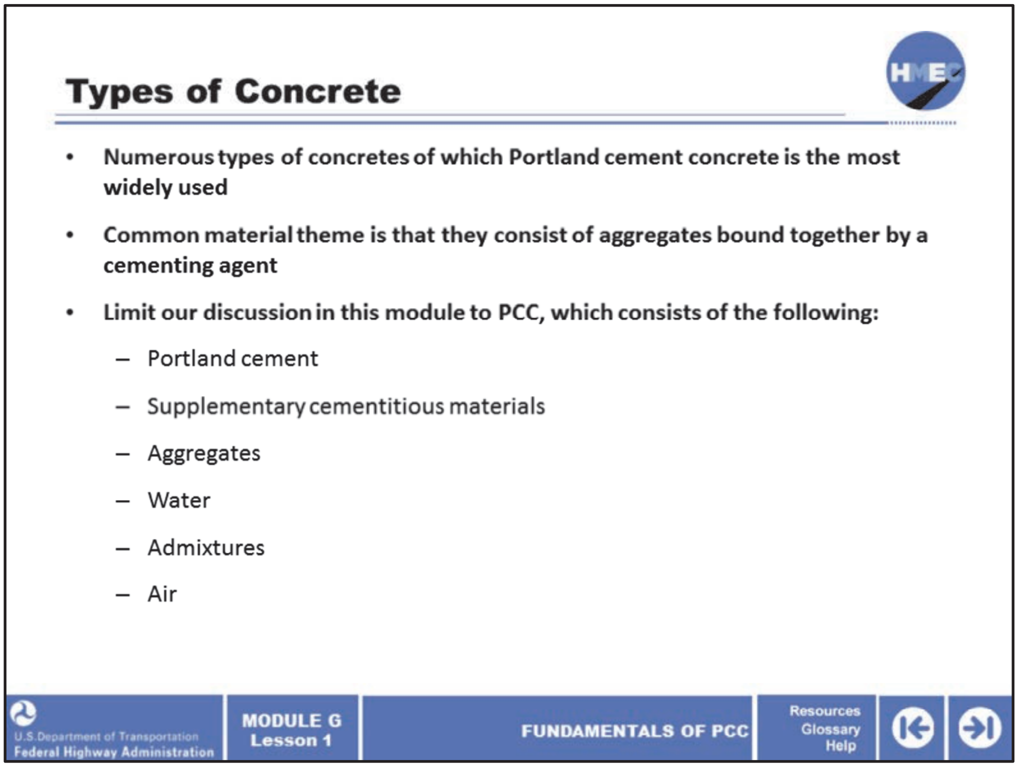
Image description: Photo of Hoover dam.



1985: Peak shipment of Portland cement to the US increased to nearly 3 million barrels.

Image description: Photo of Hoover dam.

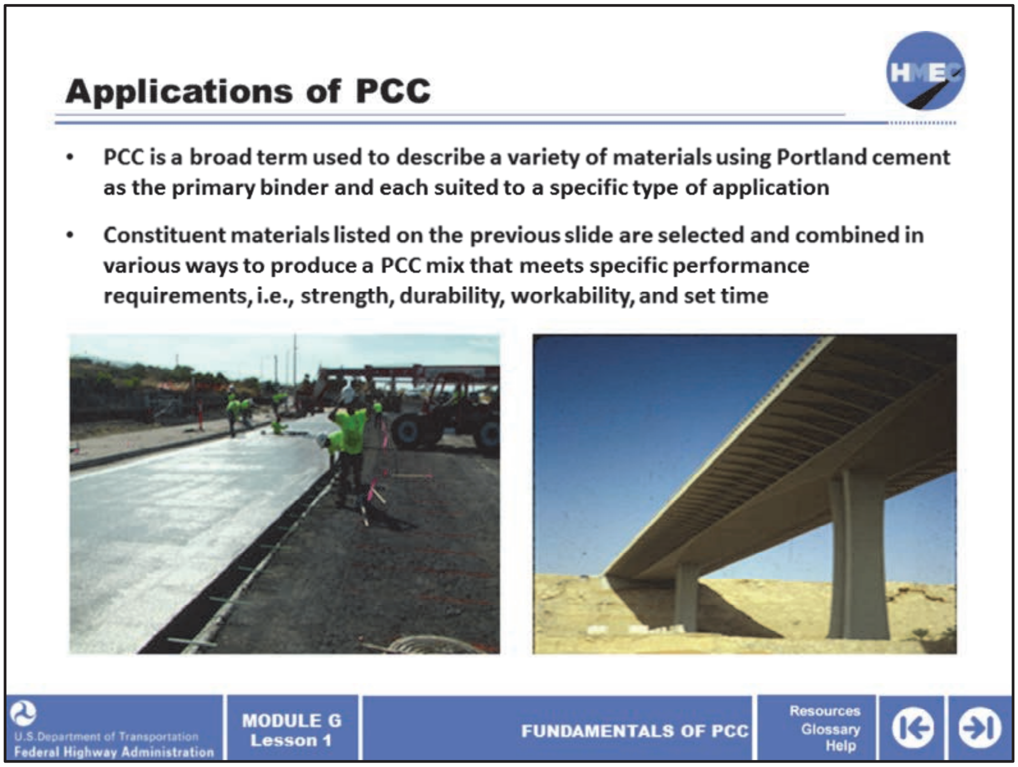
Image description: Photo of Portland cement.



Now let’s move onto the types of concrete. There are numerous types of concretes including Portland cement concrete, those made with calcium aluminate cements, magnesium phosphate cements, numerous proprietary cements, and many other variations.

The common theme in all of these materials is that they consist of aggregates bound together by a cementing agent. We are going to limit our discussion in this module to PCC, which consists of various types of Portland cement, supplementary cementitious materials, aggregates, water, admixtures, and air.

We are only going to concentrate on Portland cement concrete in this module although some of the others listed, primarily calcium aluminate, magnesium phosphate, and some of the proprietary concretes, are often used as repair materials during pavement restoration.,



PCC is often simply termed concrete but as we saw on the previous slide, that is not always an accurate description. For the remainder of this module, we will use the term PCC except in instances where the terminology is used by others in describing PCC.

The photo on the left shows a just-placed PCC pavement.

The photo on the right shows PCC for structural applications. Concrete for structural applications can have significantly different specified characteristics. However, many of the same properties including drying shrinkage, thermal movement, batch consistency, closely controlled set times and rate of strength gain, ability to be easily placed, consolidated and finished are somewhat similar although less stringent for highway applications.

Image description: Photo of just-placed PCC pavement.

Image description: Photo of PCC for structural applications.

PCC is often used in transportation structures and can have many different performance requirements based on end use.

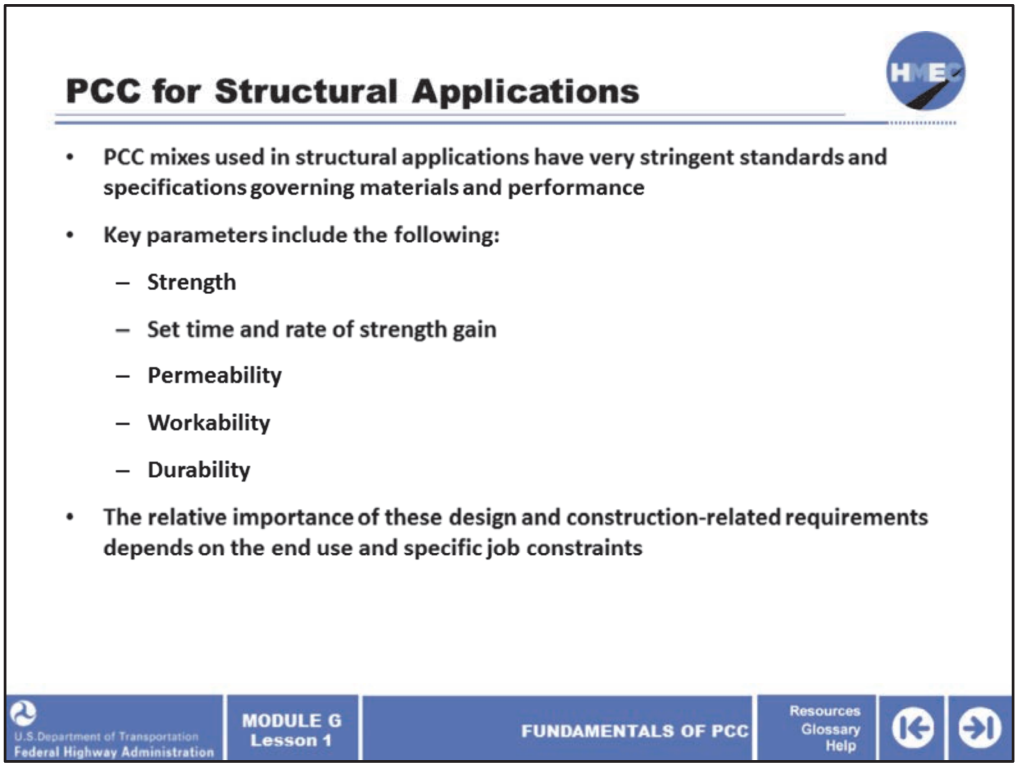
Structural applications generally have little or no tolerance for error, particularly bridges, retaining walls, and structures where failure would place the traveling public at high risk. The list included on this screen is by no means all inclusive, but it does provide some broad categorization of the primary uses of PCC in structures.

The specifications for each of these applications are likely different based on the requirements for strength, durability, and workability. For instance, the PCC used for bridge elements needs to be of extremely high quality (strength and durability) with minimal material variability throughout the structure. Whereas, sound walls have far fewer requirements related to strength but must still retain a moderately high degree of durability.

Image description: Photo of a bridge pier.

Image description: Photo of a bridge construction site.

Image description: Photo of a concrete drainage culvert.



PCC mixes used in structural applications have very stringent standards and specifications governing materials and performance.

The following key parameters are introduced here and will be discussed in detail later in this module:

- Strength is generally the primary criteria used for overall quality assurance.
- Set time and rate of strength gain are particularly important to permit form stripping and loading at the earliest possible time. Note that form stripping and the ability to apply construction loads at an early age are important on more and more projects as our window to construct is being reduced with early completion deadlines.
- Lower permeability is important to reduce corrosion of embedded steel.
- Good workability is crucial for timely placement and adequate consolidation, particularly when there is heavy reinforcement or the pour is large.
- Durability is important for all PCC but particularly for structural applications due to safety issues and repair difficulty.

The relative importance of these design and construction-related requirements depends on the end use and specific job constraints.

PCC is used for a variety of paving applications ranging from new construction to pavement rehabilitation with overlays.

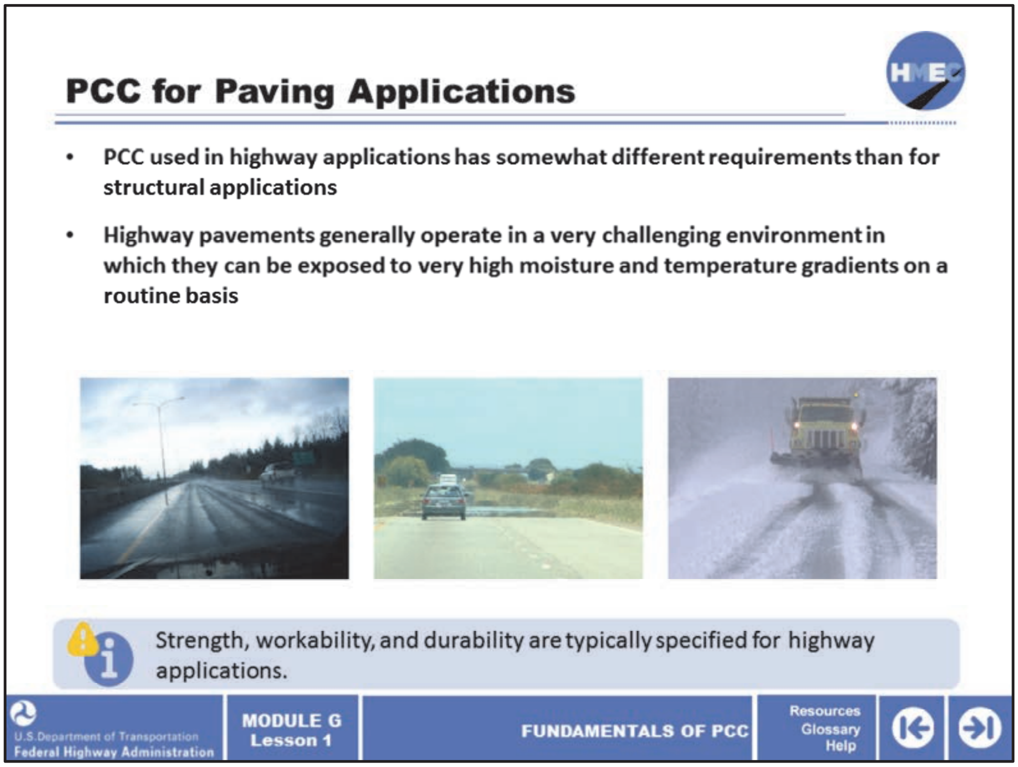
PCC paving requirements emphasize durability although strength, set time and the parameters listed for structural applications are still very important. The list included on this screen is not intended to represent all of the paving-related applications but does provide the primary categories of use.

The specifications for each of these applications may be slightly different based on the requirements for strength, durability, and workability, all of which are influenced by the mix characteristics and construction operations.

Image description: Photo of a bridge deck being patched.

Image description: Photo of a highway paving operation.

Image description: Photo of a highway paving operation.



The PCC used for highway applications has the same general quality assurance criteria as for structural applications.

Highway pavements generally operate in a challenging environment in which they can be exposed to high moisture and temperature gradients on a routine basis. They may also be exposed to deicing salts and other corrosive chemicals, sulfate attack from groundwater or the supporting soil, and a high number of dynamic load cycles.

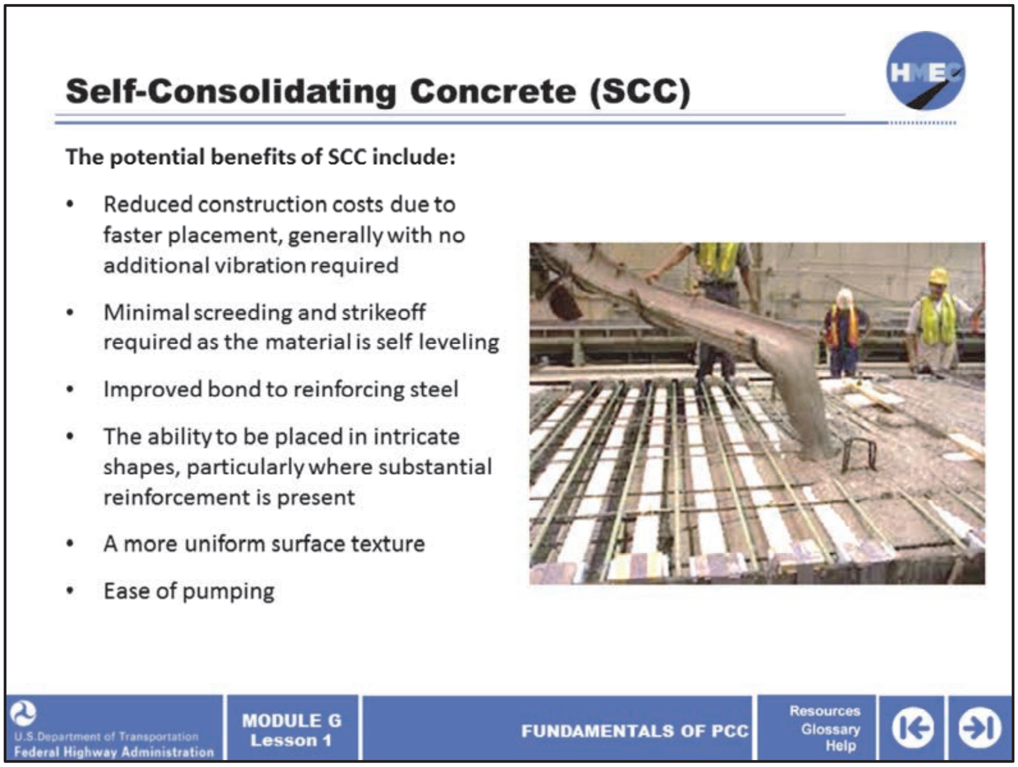
Strength, workability, and durability are typically specified for highway applications. The parameters mentioned for structural applications are applicable here as well although the range of acceptable values may differ.

Note that the PCC used for bridge elements and decks are subject to many of the same conditions as highway pavements.

Image description: Photo of a rainy wet highway.

Image description: Photo of heat rising from a highway.

Image description: Photo of a snowy road being plowed.

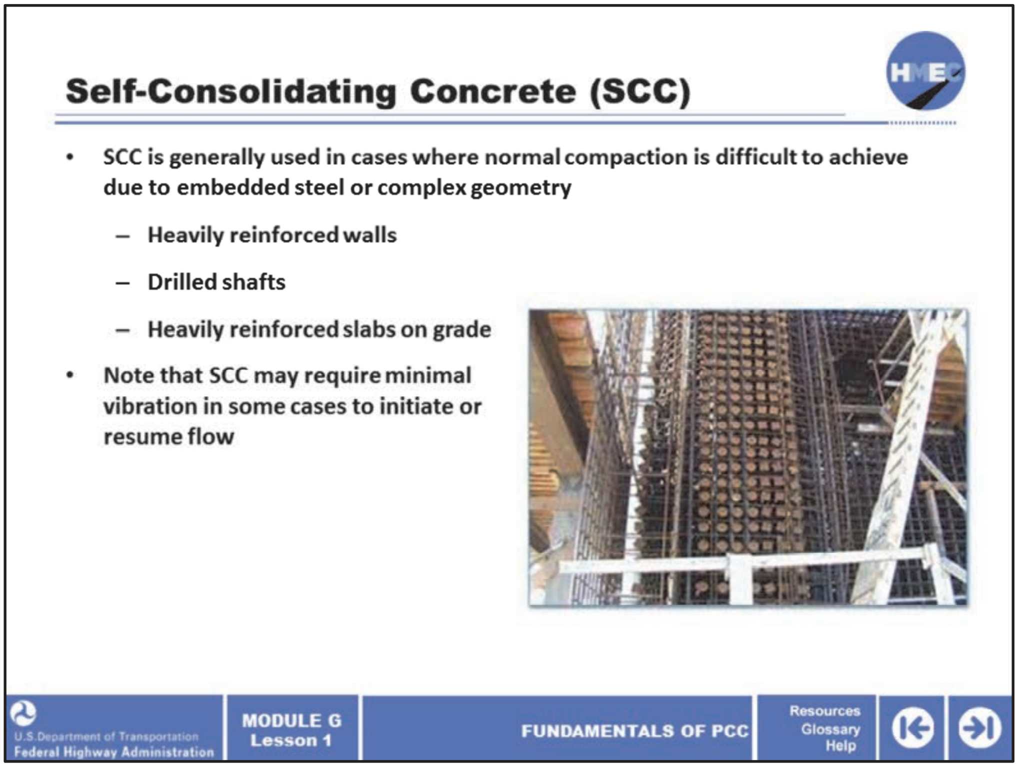


Self-consolidating concrete (SCC), as the name implies, is a self-leveling and self-consolidating PCC that does not require external vibration for effective consolidation. The high flowability and stability of SCC is generally achieved through the use of high range water reducers (superplaticizers) and a higher fines content than regular PCC. Through careful mix design and batching processes, SCC has been shown not to segregate and can greatly simplify construction under certain circumstances as shown in the photo.

The potential benefits of SCC include:

- Reduced construction costs due to faster placement, generally with no additional vibration required;
- Minimal screeding and strikeoff required as the material is self leveling;
- Improved bond to reinforcing steel;
- The ability to be placed in intricate shapes, particularly where substantial reinforcement is present;
- A more uniform surface texture; and
- Ease of pumping.

Image description: Photo of SCC concrete being poured.



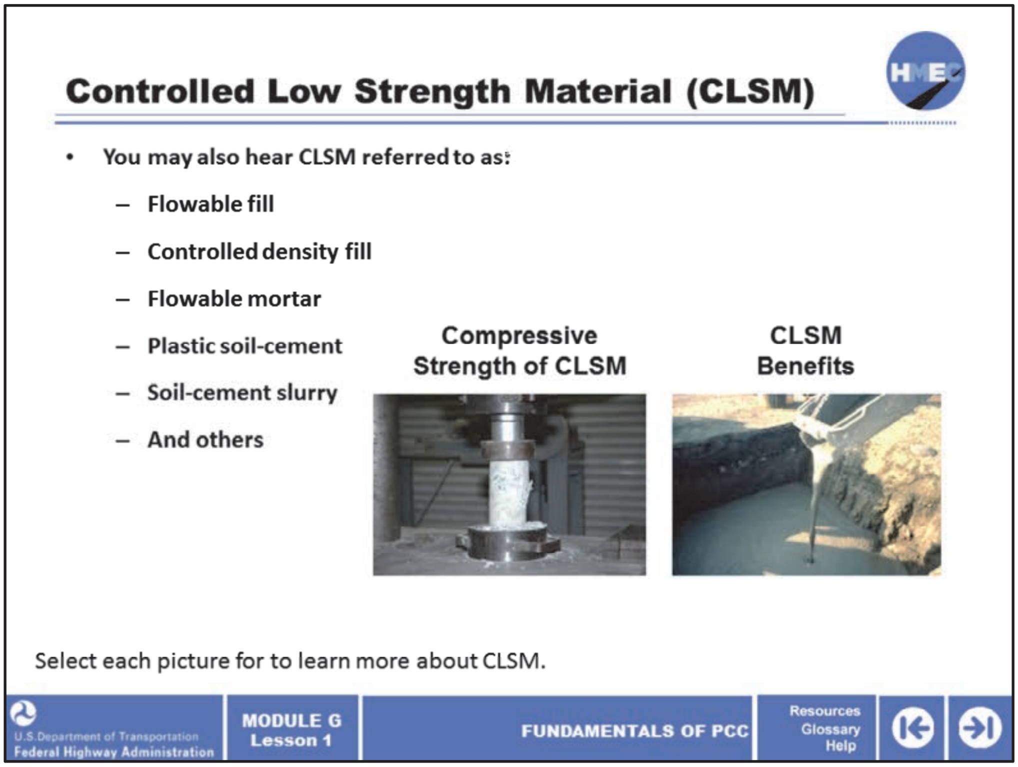
SCC is generally used in cases where normal compaction is difficult to achieve due to embedded steel or complex geometry, such as heavily reinforced walls, drilled shafts, or heavily reinforced slabs on grade.

Note that SCC may require minimal vibration in some cases to initiate or resume flow.

Due to its higher cost of production, use has been somewhat limited other than in cases where uniform and thorough compaction is not achievable by other means.

SCC has been evaluated for slipform paving applications but has been shown to be problematic due to edge slump.

Image description: Photo of a heavily enforced wall.



Controlled low strength material (CLSM), commonly known as flowable fill, is a self-compacting, self-leveling cementitious material used primarily as a backfill in lieu of compacted granular backfill. CLSM contains Portland cement, fine aggregate, fly ash, and water. The CLSM is a very fluid material and typically has a slump of 10 inches or more.

You may also hear CLSM referred to as flowable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry, and others.

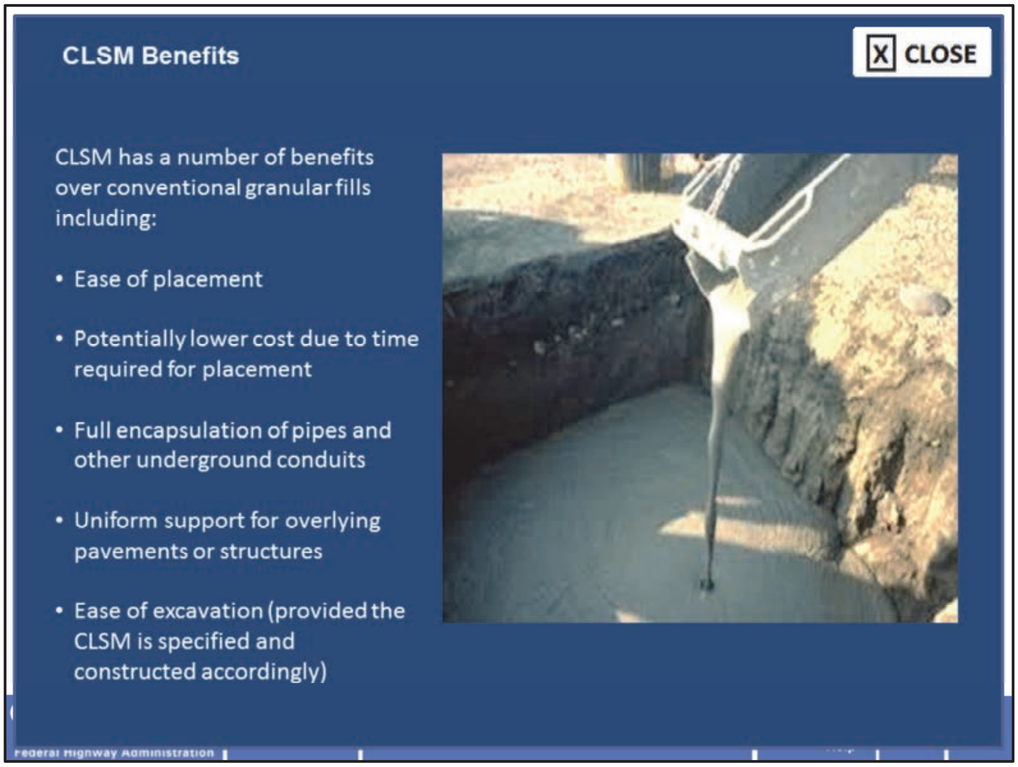
Select each picture to learn more about CLSM.

Image description: Photo of a concrete sample under compression.

Image description: Photo of concrete being poured from a truck.

The compressive strength of CLSM is generally in the range of approximately 200 psi where future excavation may be required (such as utility bedding) to approximately 1,200 psi for installations unlikely to require future excavation.

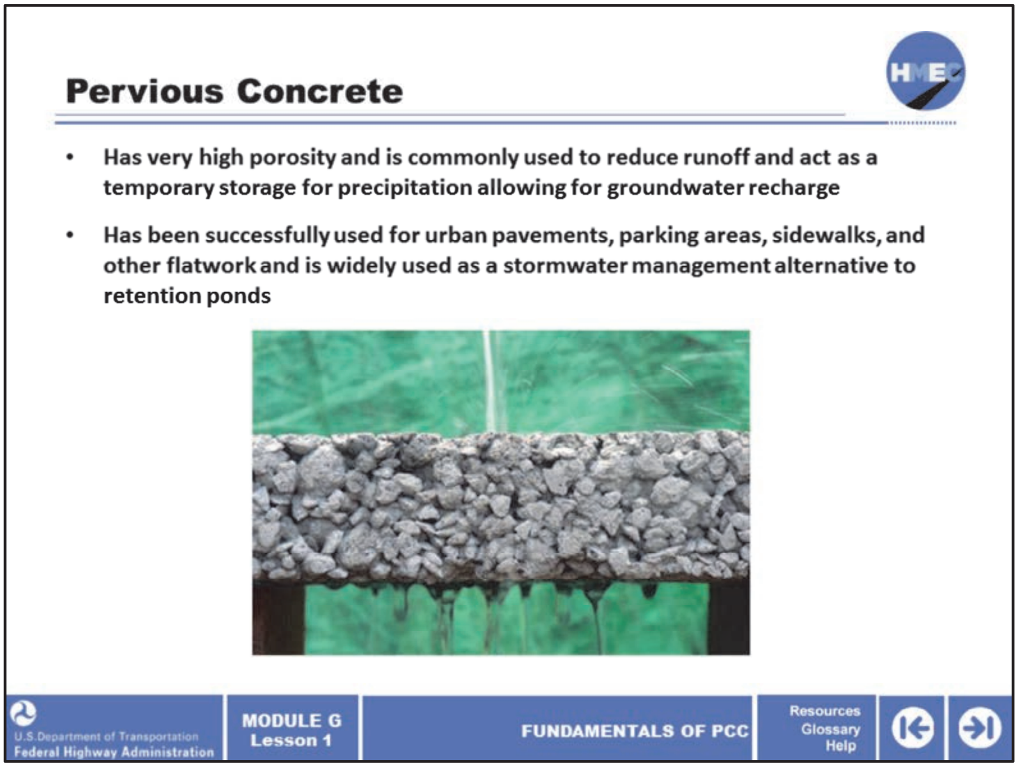
Image description: Photo of a concrete sample under compression.



CLSM has a number of benefits over conventional granular fills including:

- Ease of placement;
- Potentially lower cost due to time required for placement;
- Full encapsulation of pipes and other underground conduits;
- Uniform support for overlying pavements or structures; and
- Ease of excavation (provided the CLSM is specified and constructed accordingly).

Image description: Photo of concrete being poured from a truck.

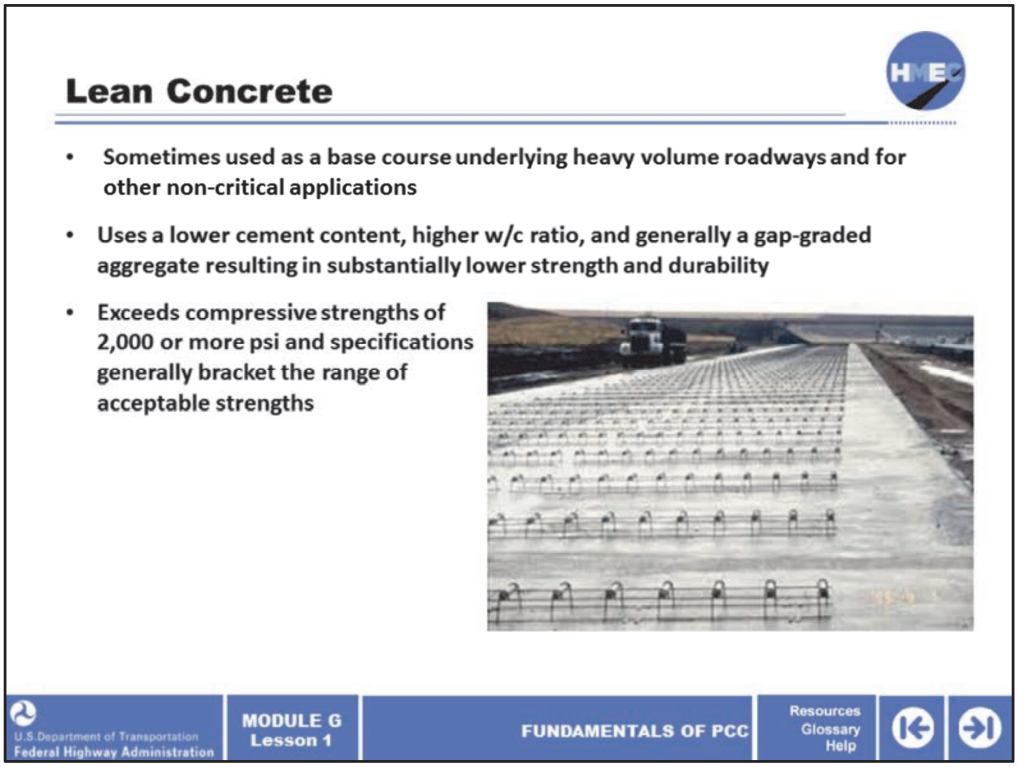


Pervious concrete is a type of concrete with very high porosity and is commonly used to reduce runoff and act as a temporary storage for precipitation allowing for groundwater recharge. This material has been successfully used for urban pavements, parking areas, sidewalks, and other flatwork and is widely used as a stormwater management alternative to retention ponds.

Pervious concrete has no appreciable fines content and relies solely on the Portland cement binder to hold the aggregates in place. Pervious pavements and parking areas have a proven level of performance but must be selected carefully based on anticipated traffic volume, loadings, and speed as well as turning movements. Use of pervious concrete has been recognized as a low impact development strategy in urban areas and is often referred to as a sustainable construction alternative.

Note that in some cases, an open graded base may be used in addition to the pervious pavement to add storage capacity and to facilitate drainage.

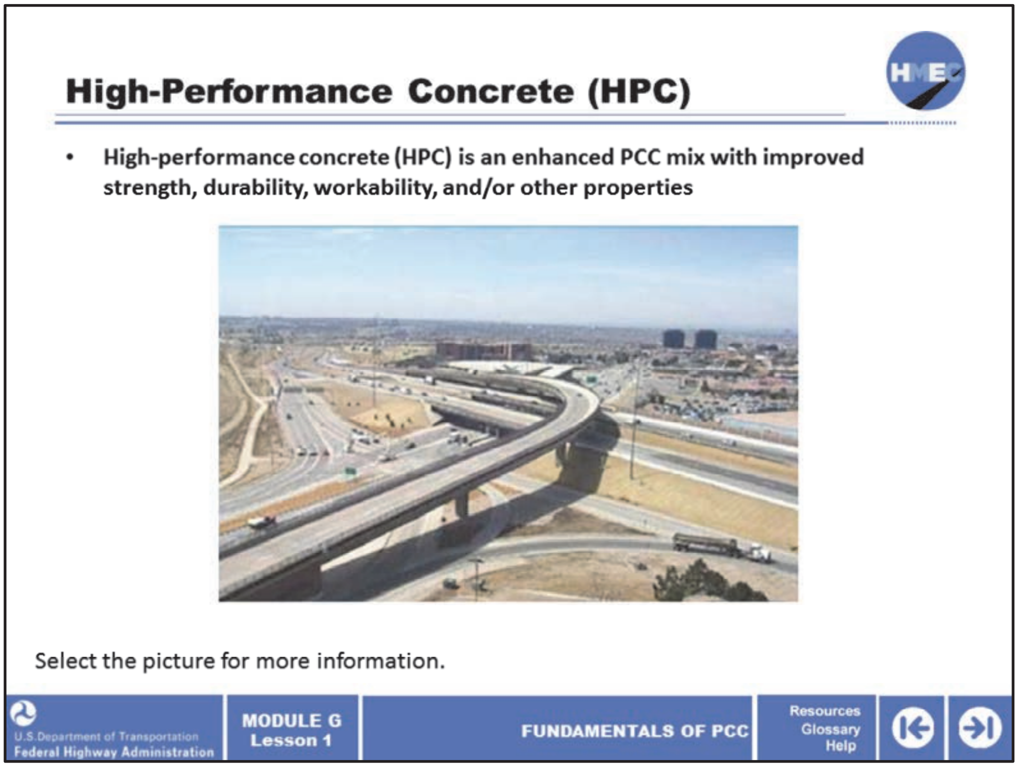
Image description: Photo of water flowing through pervious concrete.



Lean concrete is sometimes used as a base course underlying heavy volume roadways and for other non-critical applications. This variation of PCC uses a lower cement content, higher w/c ratio, and generally a gap-graded aggregate resulting in substantially lower strength and durability. However, lean concrete can still exceed compressive strengths of 2,000 or more psi and specifications generally bracket the range of acceptable strengths.

The issue with higher strengths is that the lean concrete behaves similarly to PCC with drying shrinkage cracks forming at random locations during hydration. When a new PCC pavement is placed on a lean concrete base without a physical separation, the materials will bond and the random cracking in the base may propagate into the new pavement. Another issue with a “too strong” base is that the curling and warping in the overlying pavement is more detrimental to performance compared with a slightly less rigid base. For these reasons, lean concrete bases are not widely used. Note that lean concrete bases should not be confused with cement treated bases (CTB) that work very well as a support layer and are in widespread use.

Image description: Photo of base course of concrete with rebar structure.



There are a number of different ways to characterize high-performance concrete. This designation does not have to mean only ultra-high strength PCC. It also is used to describe PCC with a high level of durability.

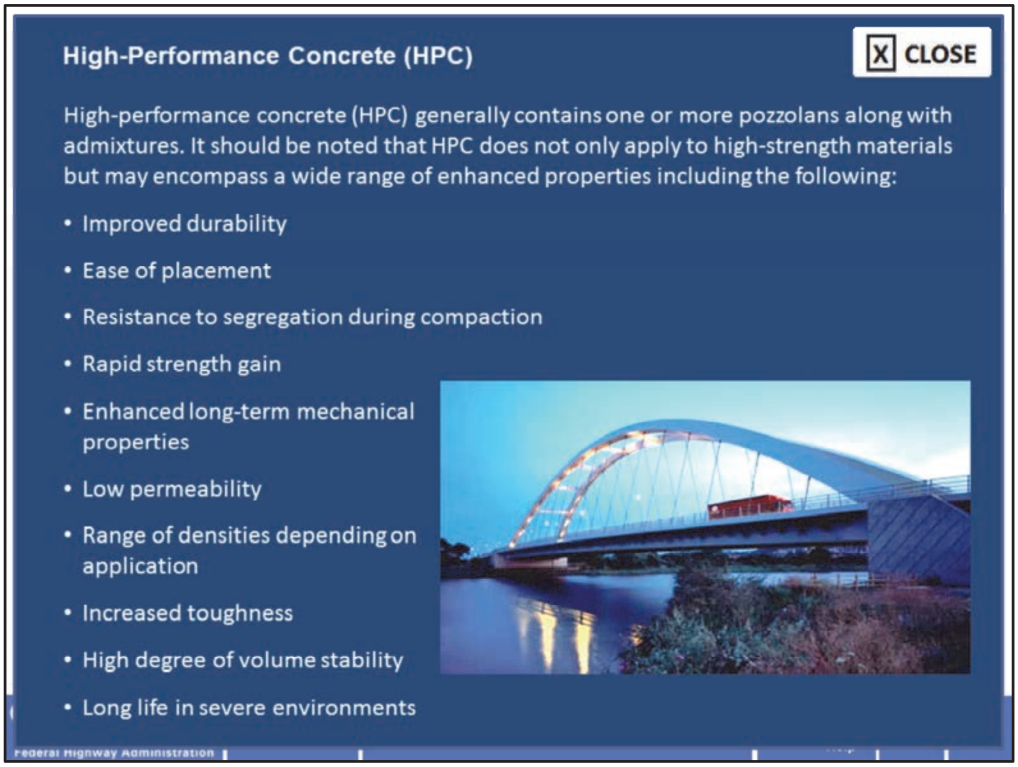
HPC uses modern materials, methods, specifications, and test procedures designed to provide better performance and more durable concrete than traditional PCC. HPC implementation became widespread in the US in the 1990s and early 2000s.

This photograph shows an off-ramp from Parker road to southbound I225 in Denver, CO. This structure used a ternary mix that included 6% silica fume, 20% fly ash class F, and less than 500 lbs. of cement with a 56-day strength of 4,500 psi.

Note that HPC is not necessarily more expensive to produce than conventional PCC. By using locally available materials and optimizing the mix design, the costs between HPC and conventional PCC are minimal, particularly when life cycle costs and performance are considered.

Select the picture for more information.

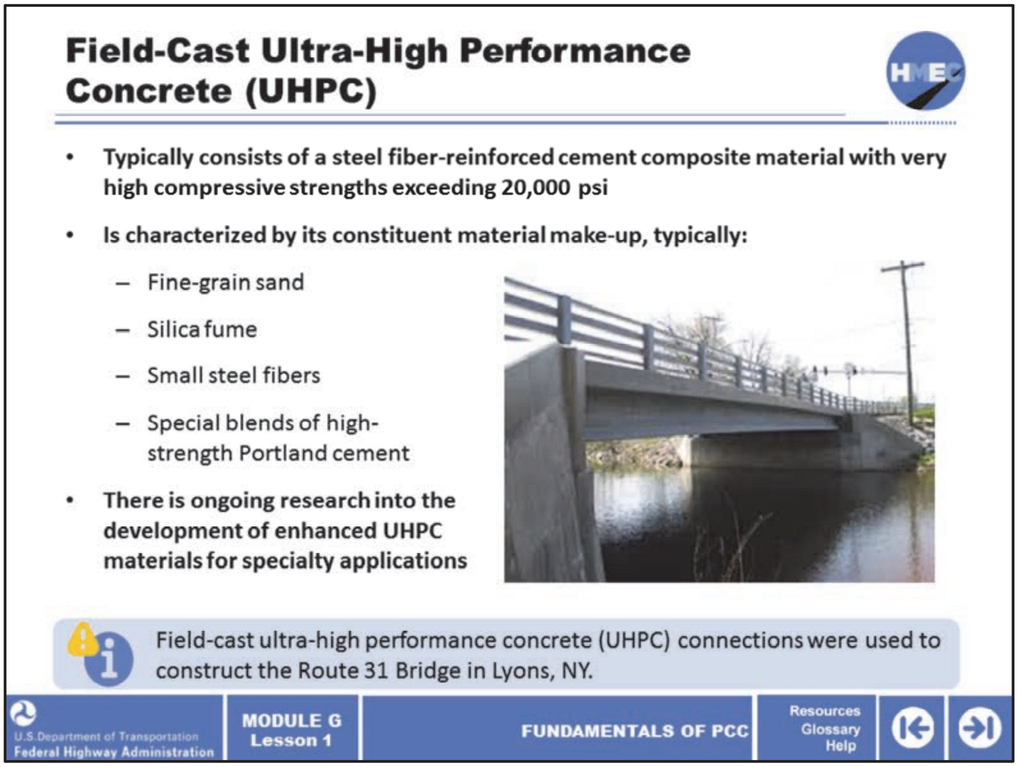
Image description: Photo of freeway stack.



High-performance concrete (HPC) generally contains one or more pozzolans along with admixtures. It should be noted that HPC does not only apply to high-strength materials but may encompass a wide range of enhanced properties including the following:

- Improved durability;
- Ease of placement;
- Resistance to segregation during compaction;
- Rapid strength gain;
- Enhanced long-term mechanical properties;
- Low permeability;
- Range of densities depending on application;
- Increased toughness;
- High degree of volume stability; and
- Long life in severe environments.

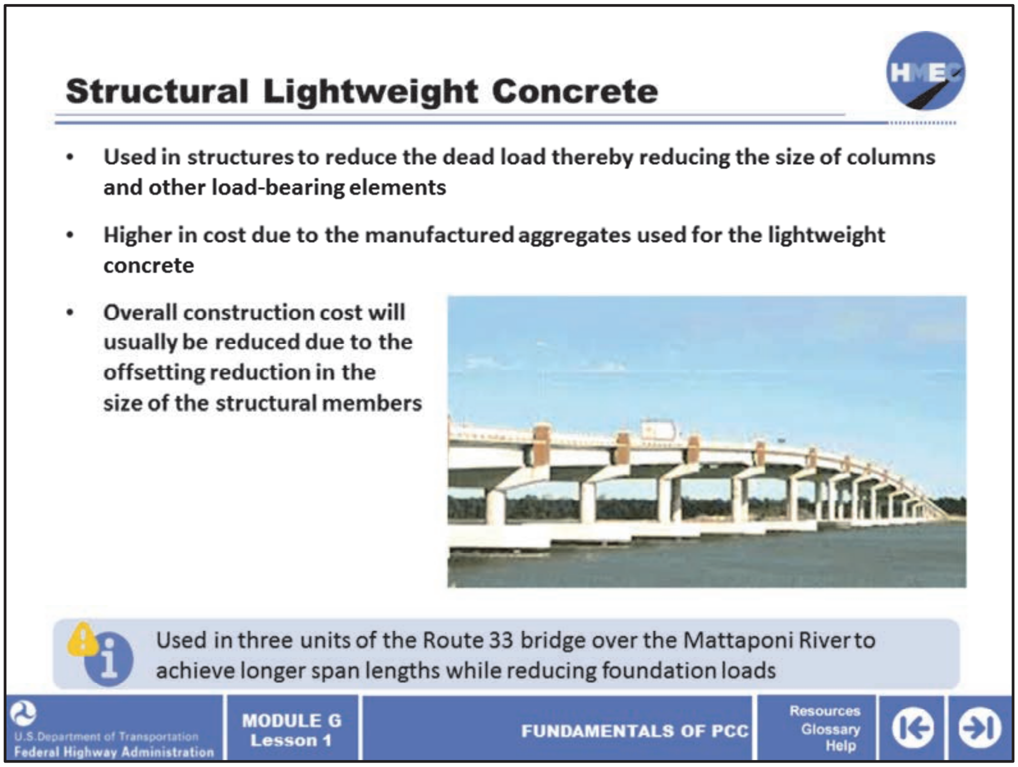
Image description: Photo of a bridge over a river.



Field-cast ultra-high performance concrete (UHPC) connections were used to construct the Route 31 Bridge in Lyons, NY. UHPC typically consists of a steel fiber-reinforced cement composite material with very high compressive strengths exceeding 20,000 psi.

UHPC is also characterized by its constituent material make-up: typically fine-grain sand, silica fume, small steel fibers, and special blends of high-strength Portland cement. There is ongoing research into the development of enhanced UHPC materials for specialty applications.

Image description: Photo of a bridge over a river.



Structural lightweight concrete was specified for use in three units of the Route 33 bridge over the Mattaponi River in order to achieve longer span lengths while reducing foundation loads.

Lightweight concrete is used in structures to reduce the dead load thereby reducing the size of columns and other load-bearing elements. Although higher in cost due to the manufactured aggregates used for the lightweight concrete, the overall construction cost will usually be reduced due to the offsetting reduction in the size of the structural members.

Structural lightweight concrete is produced using lightweight aggregates (both coarse and fine in most cases) in place of conventional aggregates. The unit weight of lightweight concrete is generally 90–115 pounds per cubic foot (pcf) as compared with 140 to 150 pcf for conventional PCC. Lightweight structural concrete can be designed with strengths comparable to traditional PCC mixes.

Image description: Photo of a bridge over a river.

Portland Cement Grout

Portland cement grout uses:

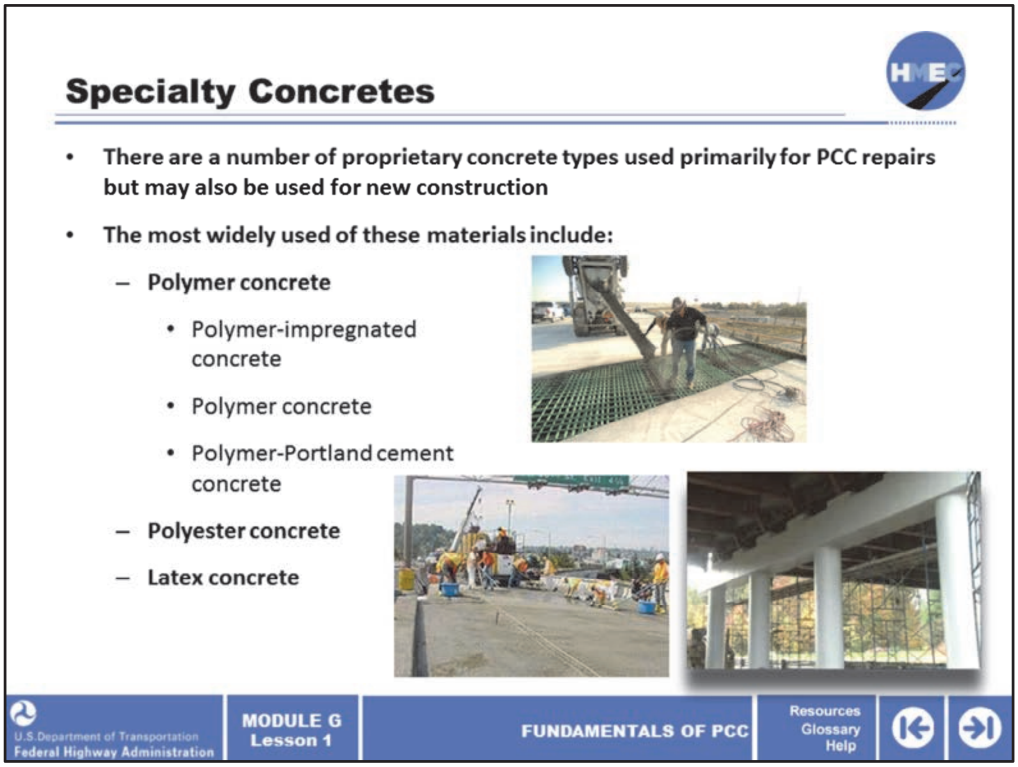
- Underpinning structures
- Anchoring
- Crack repair
- Slab jacking and stabilization
- Many others

Sand-cement grout mix being used for a piling.

Portland cement grout has widespread uses including underpinning structures, anchoring, crack repair, slab jacking and stabilization, and many others. This photograph shows sand-cement grout mix being used for a piling.

Grout consists of Portland cement, fine aggregate, water, potentially fly ash, and one or more chemical admixtures. The properties are highly variable and depend on the intended use.

Image description: Photo of sand-cement grout mix being used for piling.



Polymer concrete is part of a group of concretes that use polymers to supplement or replace cement as a binder. The types include polymer-impregnated concrete, polymer concrete, and polymer-Portland cement concrete.

Polymer concrete may be used for new construction or repairing existing concrete. The adhesive properties of polymer concrete allow patching of both polymer and conventional cement-based concretes. Polyester concrete has an additional binding agent of polyester resin. Polyester concrete can be used in concrete as (Poly) methyl meth Acrylate (PMMA), epoxy pre-polymer, and furfuryl alcohol.

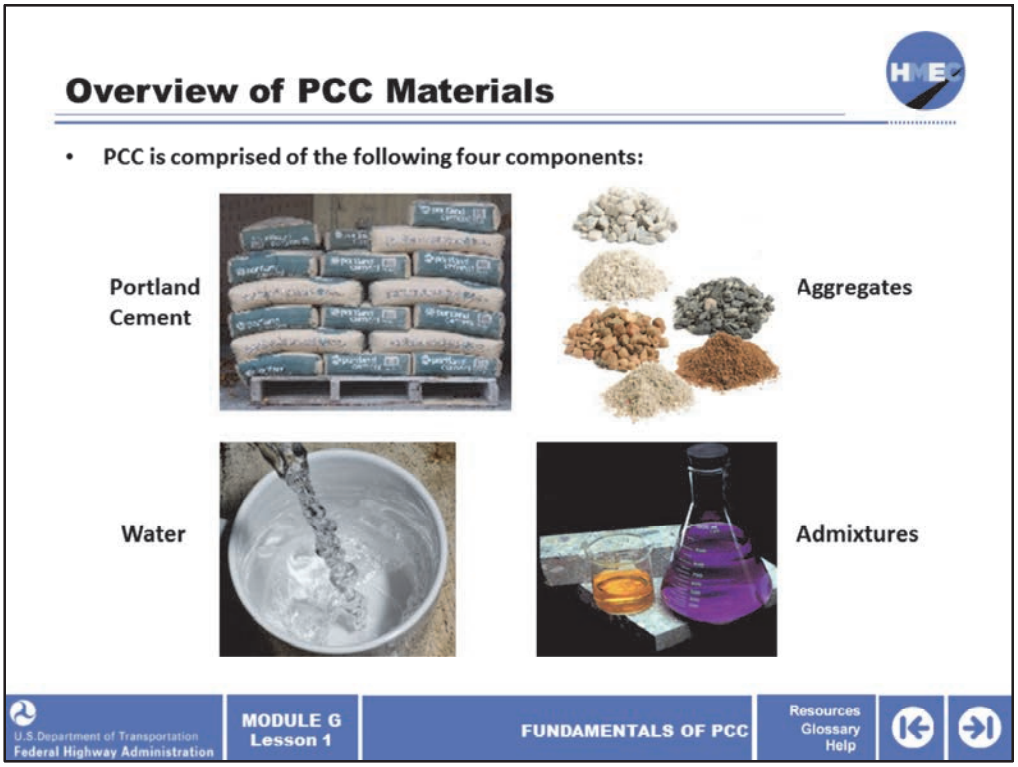
The benefits of polyester concrete bridge deck overlays include shorter lane closures, increased live load capacity, higher tensile strength, and a greater resistance to impact. A polyester concrete overlay can be placed as thin as ¾ inch up to 12 inches thick in a single lift. Priming the bridge deck with high molecular weight methacrylate (HMWM) allows for superior adhesion, permitting a wide variety of applications.

Detailed coverage of these materials is beyond the scope of this Module. However, additional information may be obtained through an internet search or by contacting the specialty cement manufacturers.

Image description: Photo of a truck pouring concrete.

Image description: Photo of a highway paving operation.

Image description: Photo of concrete supports under a highway bridge.



PCC is comprised of four primary components: Portland cement, aggregates, water, and admixtures.

The proportion and properties of each of these constituents determines the strength characteristics, workability, durability, and all other physical properties of the PCC.

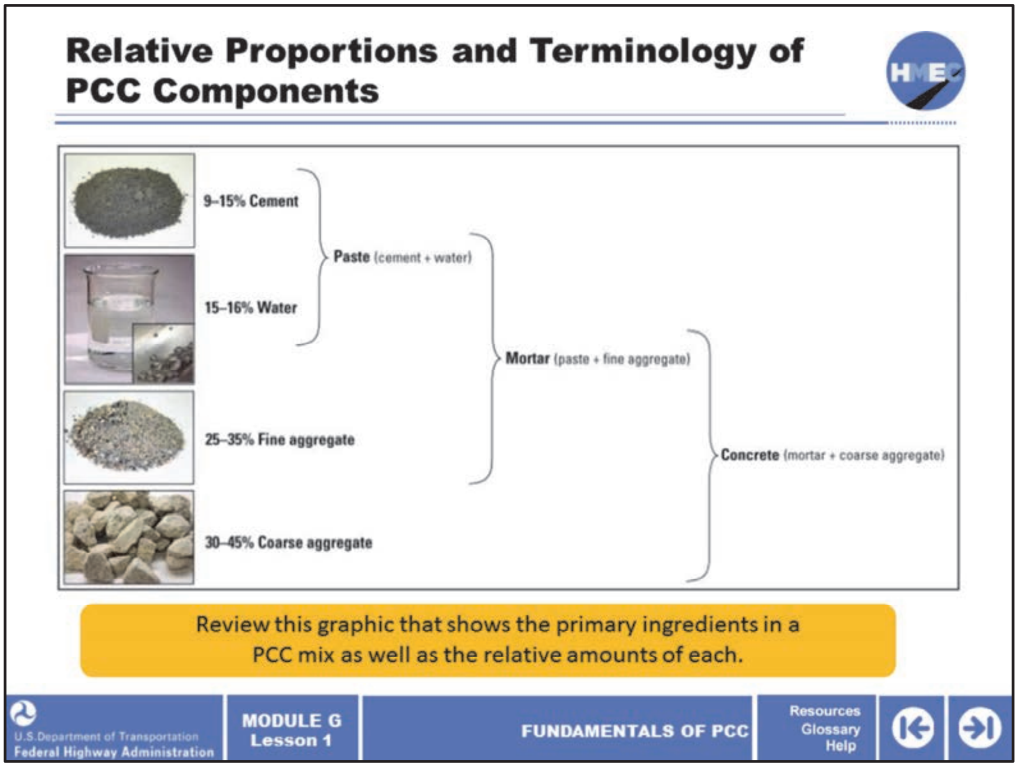
Each of these components will be addressed in-depth in upcoming lessons.

Image description: Photo of a stack of Portland cement on pallet.

Image description: Photo of aggregates.

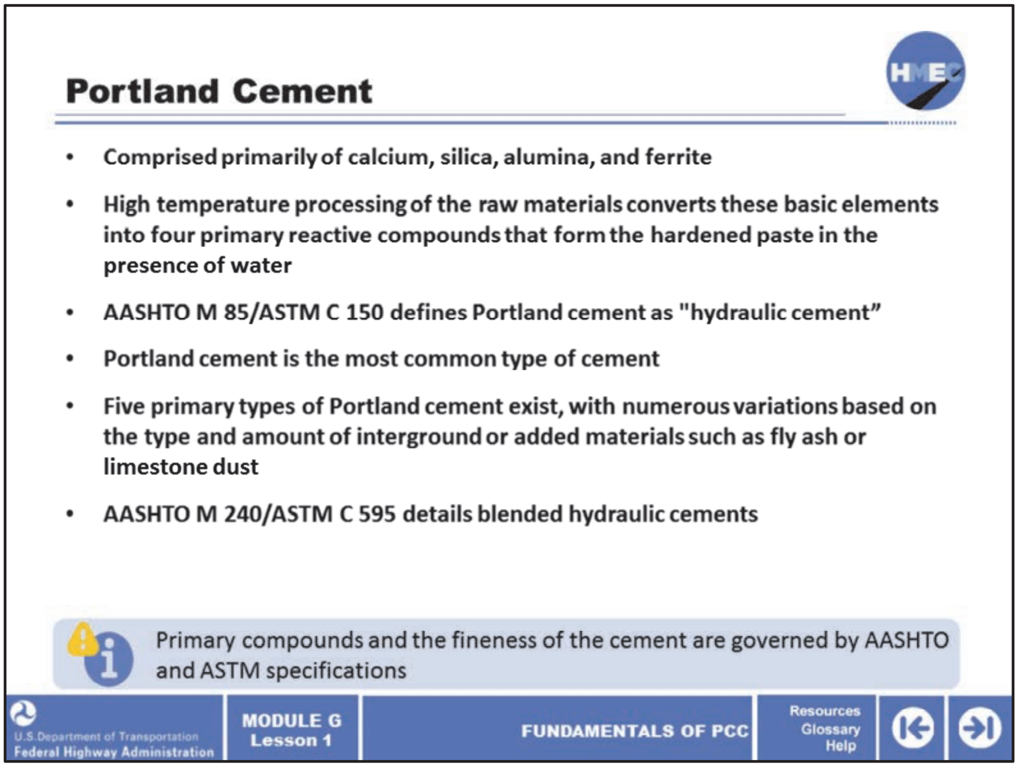
Image description: Photo of water pouring into bucket.

Image description: Photo of various admixture chemicals.



This graphic shows the primary ingredients in a PCC mix as well as the relative amounts of each. The combination of cement and water is referred to as paste. Combining paste and fine aggregate results in what is referred to as the mortar. The combination of the coarse aggregate with the mortar to complete the entire mixture is referred to as concrete or PCC.

Image description: Graphic showing the primary ingredients in a PCC mix as well as the relative amounts of each.



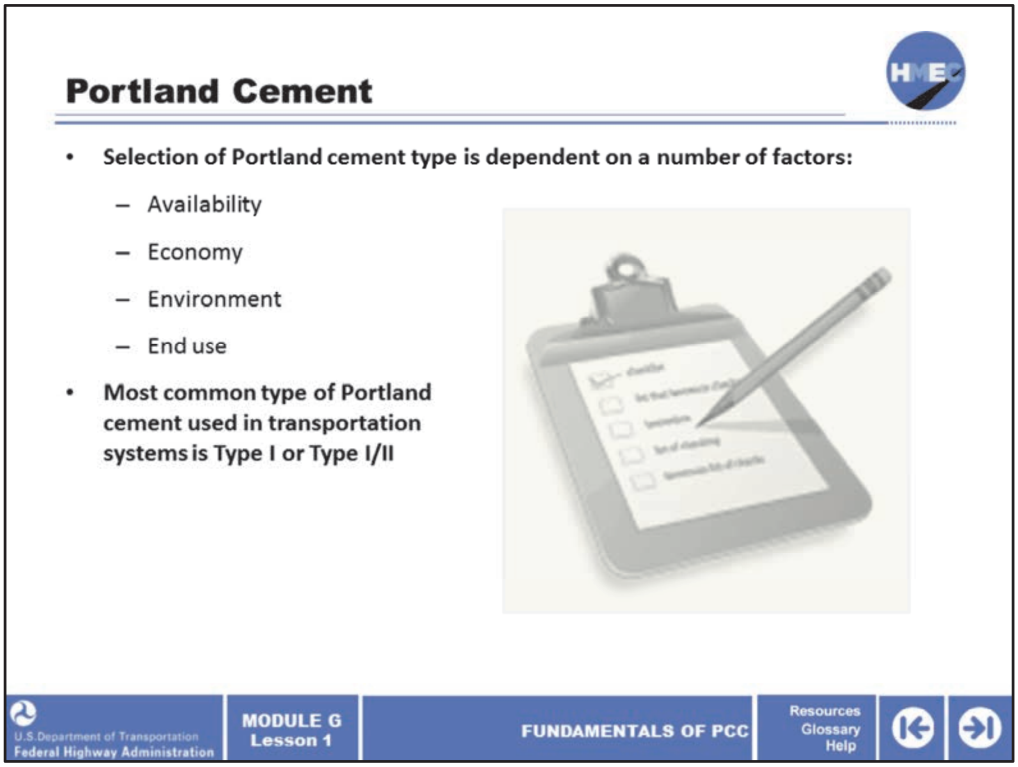
Portland cement is comprised primarily of calcium, silica, alumina, and ferrite. The high temperature processing of the raw materials (kiln operations) converts these basic elements into four primary reactive compounds that form the hardened paste in the presence of water.

AASHTO M 85 and ASTM C 150 defines Portland cement as "hydraulic cement," or cement that not only hardens by reacting with water but also forms a water-resistant product. Portland cement (often referred to as OPC or ordinary Portland cement) is the most common type of cement in general use around the world.

There are five primary types of Portland cement with numerous variations based on the type and amount of interground or added materials, such as fly ash or limestone dust. The primary compounds and the fineness of the cement are governed by AASHTO and ASTM specifications.

AASHTO M 240/ASTM C 595 lists four primary types of blended cements including IS, IP, IL and IT depending on the material that is blended with the Portland cement. Details on Portland and blended hydraulic cements are provided in Lesson 2.

Portland cement is a highly engineered material that controls the short- and long-term performance of the PCC. The specifications governing the individual cement types are sufficiently broad to allow for subtle differences in performance of the fresh and hardened PCC between manufacturers and even batches from the same manufacturer.



The selection of Portland cement type is dependent on a number of factors, such as availability, economy, environment, and end use.

The most common type of Portland cement used in transportation systems is Type I or Type I/II and under most circumstances is well suited to both structural and highway applications.

Note that Type I/II is not actually an AASHTO or ASTM designation but is commonly used to describe a Portland cement that falls within either the Type I or II specification. This type of cement is commonly used where a lower alkali cement is desired.

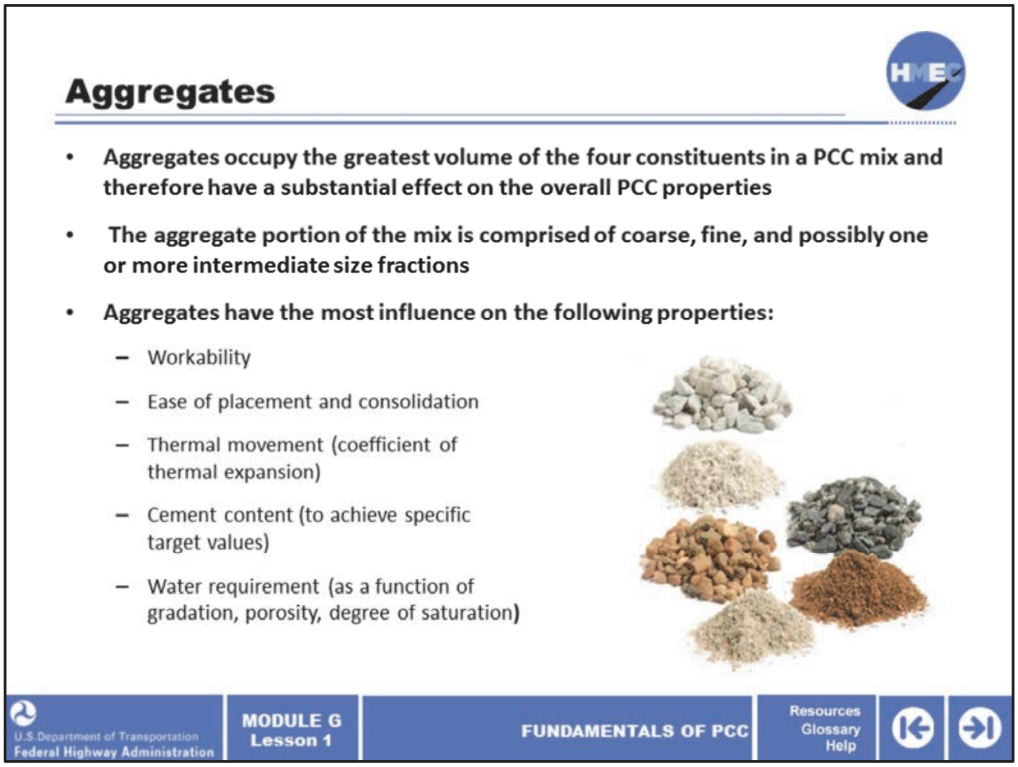
The majority of transportation projects will make use of Type I or Type I/II Portland cements, which are produced by all of the major cement manufacturers.

These cement types are suited for most applications where there is not a high sulfate content in the soil or groundwater or the PCC is not to be used for a mass concreting operation such as a dam structure.

The differences in cement types are due to the relative proportion of the calcium, silica, iron, and alumina compounds comprising the cement clinker and the fineness of the ground clinker. Relatively small changes in these two variables does not translate to significant changes in performance of the PCC.

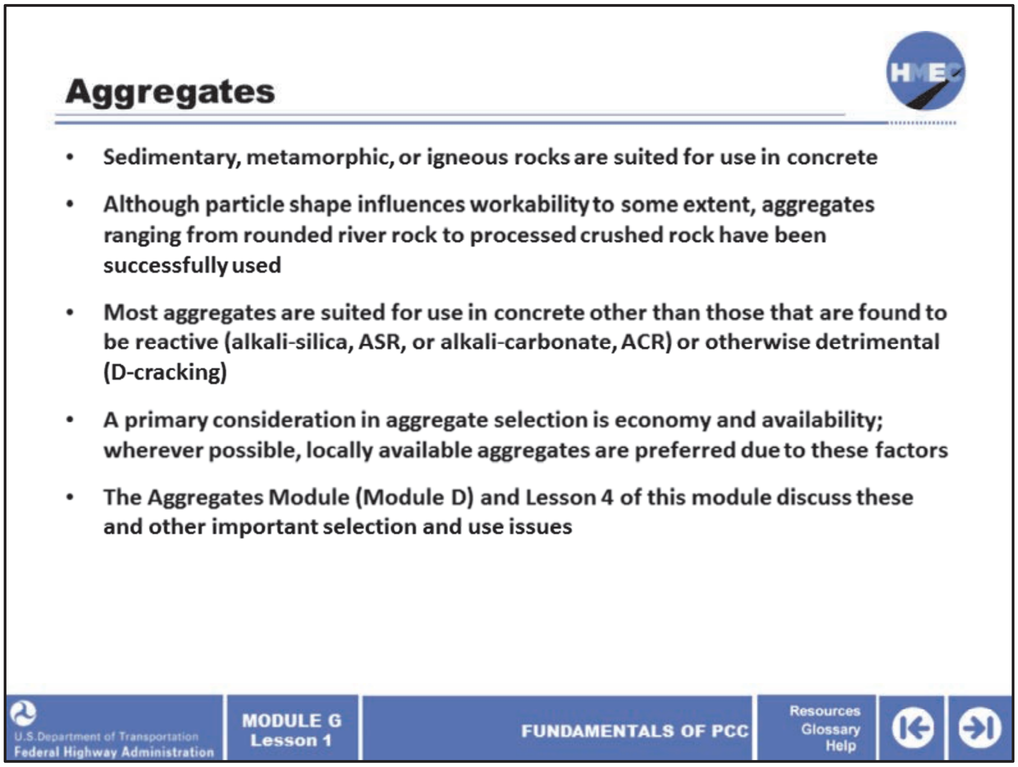
We will focus on Portland cement in Lesson 2 of this module.

Image description: Photo of a clipboard.



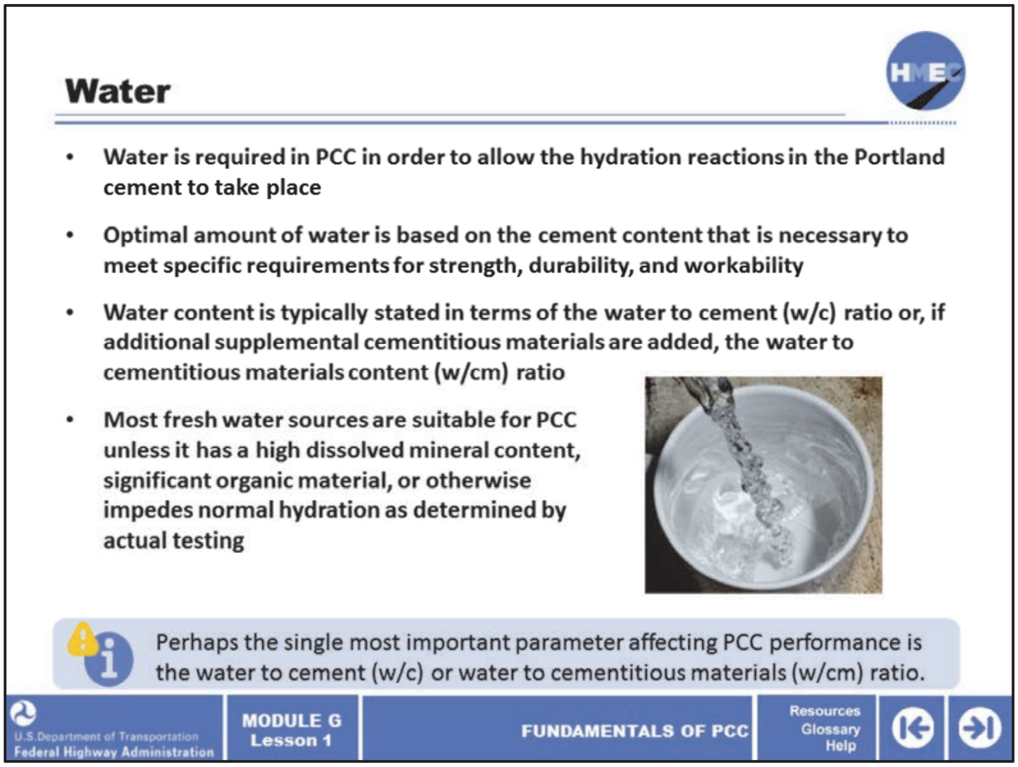
Aggregates play an important role in the performance of the fresh and hardened PCC. PCC mix optimization begins with the aggregates, more specifically the maximum aggregate size and the combined gradation. A well-graded (rather than the gap-graded) aggregate has a number of benefits, including lowering the required cement content (thereby lowering cost), reducing water demand, minimizing volumetric changes (particularly drying shrinkage), more batch to batch consistency, and other factors to be discussed in Lesson 4.

Image description: Photo of aggregates.



As discussed on the previous screen, aggregates play a vital role in predicting the behavior of fresh and hardened PCC. Rounded aggregates tend to reorient easily during placement and therefore result in a high degree of workability. Crushed stone has a higher degree of macro and micro roughness thereby enhancing the mechanical bond with the paste. In other words, each type of aggregate has benefits and drawbacks and the selection must consider all aspects.

One of the most important issues in aggregate selection is the potential reactivity. Adequate characterization or historical performance of a specific aggregate source is very important in assuring a durable PCC mix.



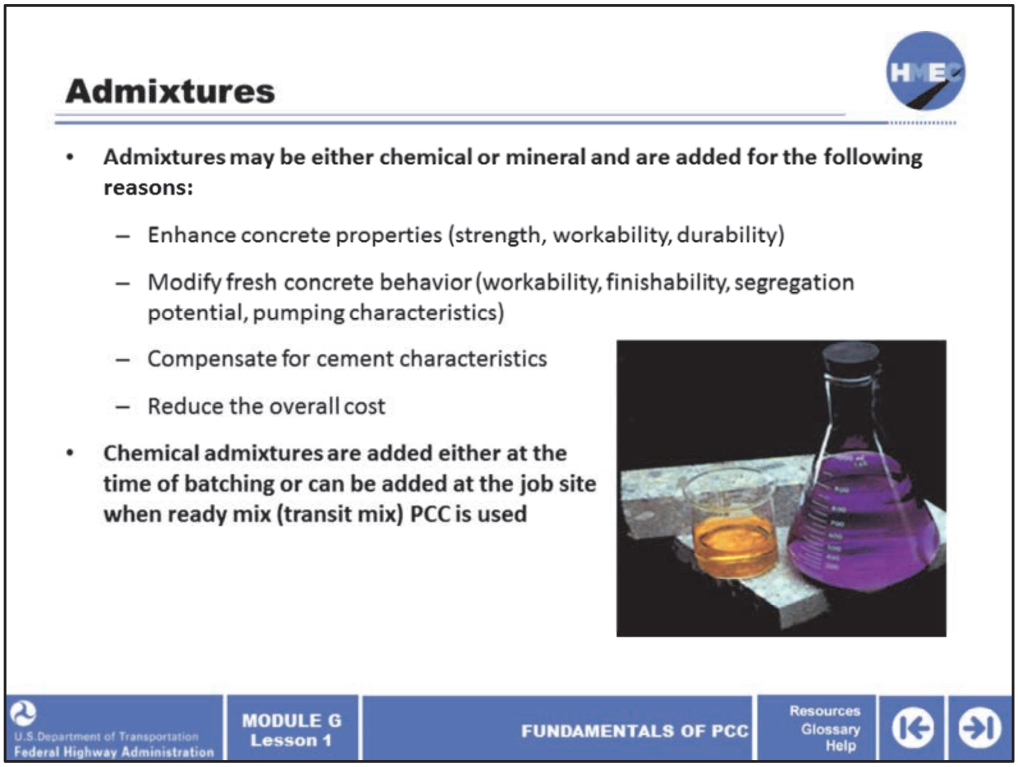
Water is required in PCC in order to allow the hydration reactions in the Portland cement to take place. The optimal amount of water is based on the cement content that is necessary to meet specific requirements for strength, durability, and workability.

The water content is typically stated in terms of the water to cement (w/c) ratio or, if additional supplemental cementitious materials are added, the water to cementitious materials (w/cm) ratio.

Most fresh water sources are suitable for PCC unless it has a high dissolved mineral content, significant organic material, or otherwise impedes normal hydration as determined by actual testing.

A common perception is that all potable water is suitable for use in PCC and, in most cases, that is true. However, when dealing with a new and untried water source, it is a good idea to actually perform trial batch tests to assess initial set time and rate of strength development as these are the two most affected parameters. Perhaps the single most important parameter effecting PCC performance is the water to cement or water to cementitious materials ratio.

Image description: Photo of water pouring into bucket.

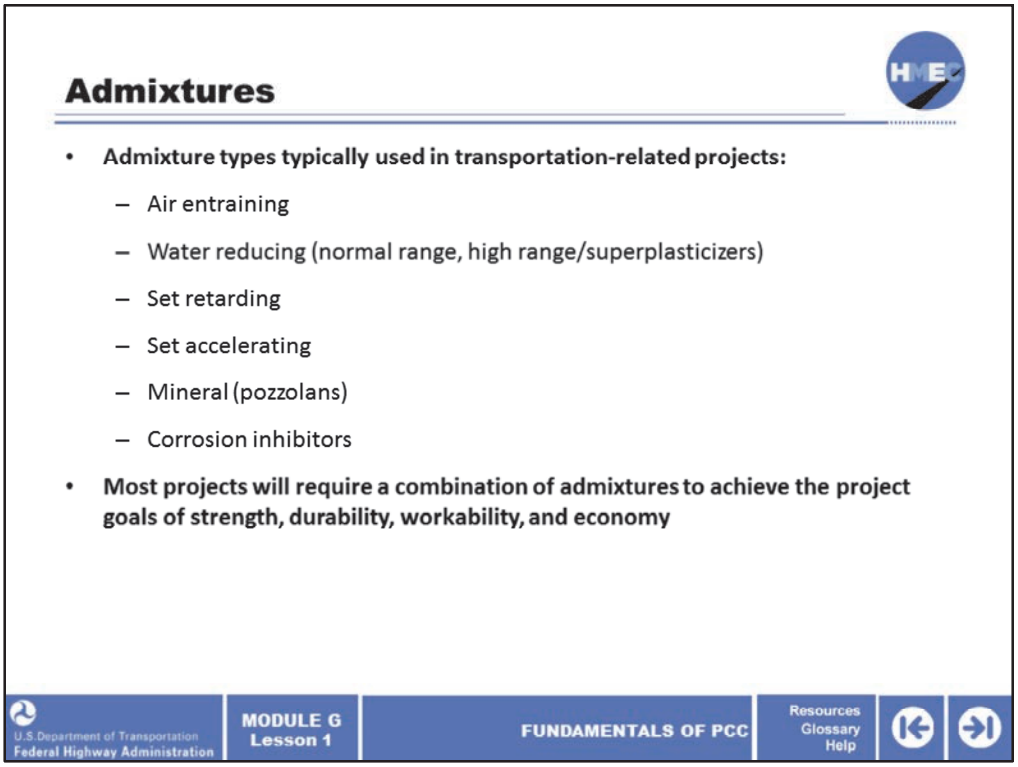


Admixtures may be either chemical or mineral and are added to enhance concrete properties, modify fresh concrete behavior, compensate for cement characteristics, or reduce the overall cost.

Chemical admixtures are added either at the time of batching or can be added at the job site when ready mix PCC is used.
SCMs are typically added to the PCC mix at the time of production. Note that blended cements combine SCMs and Portland cement at the time of manufacture.

Admixtures are used in virtually all PCC mixes designated for use in transportation-related projects. They are used to enhance performance in both the fresh and hardened concrete and can overcome many placement issues.

Image description: Photo of various admixture chemicals.



Air entraining admixtures (AEA) are used to provide freeze/thaw resistance for PCC placed in that type of environment. The addition of an AEA results in the formation of stabilized microscopic bubbles uniformly distributed throughout the cement paste.

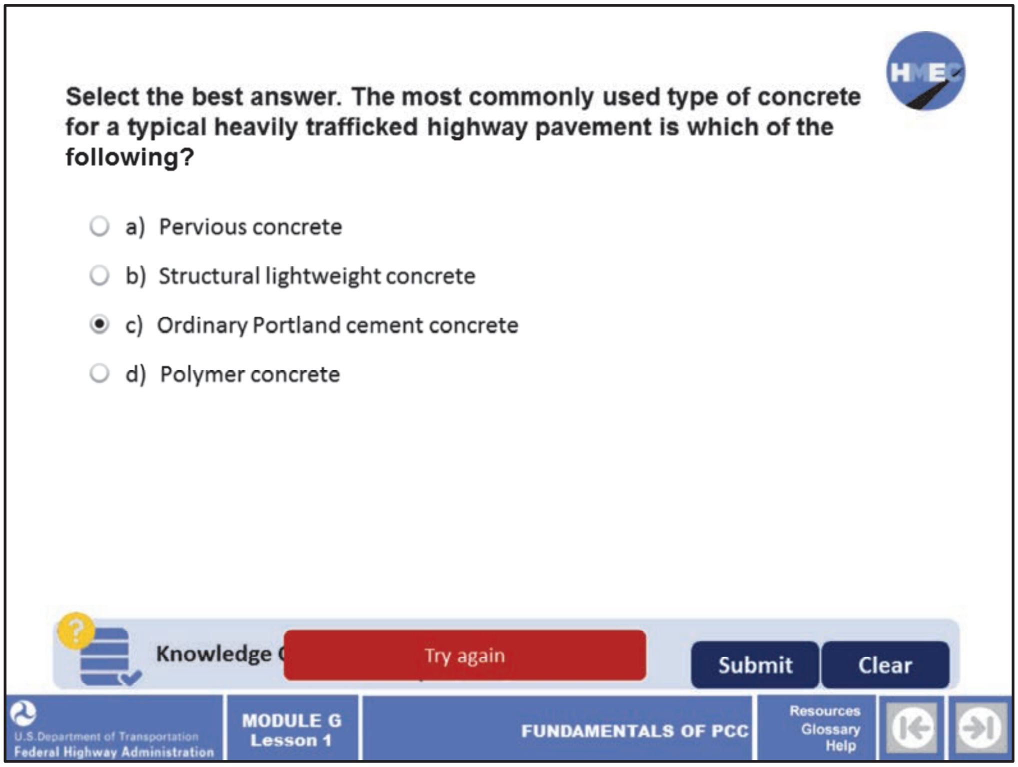
Water reducing admixtures are used to increase workability at a fixed w/c ratio or lower the w/c ratio at a fixed workability, thereby increasing strength and durability of the PCC.

Set retarding admixtures are used for hot weather concreting to slow the onset or rate of hydration thereby allowing placement, consolidation, and finishing operations.

Set accelerating admixtures are used in cold weather concreting to speed up the onset and rate of hydration. Accelerators are also sometimes used to reduce the time to opening or loading.

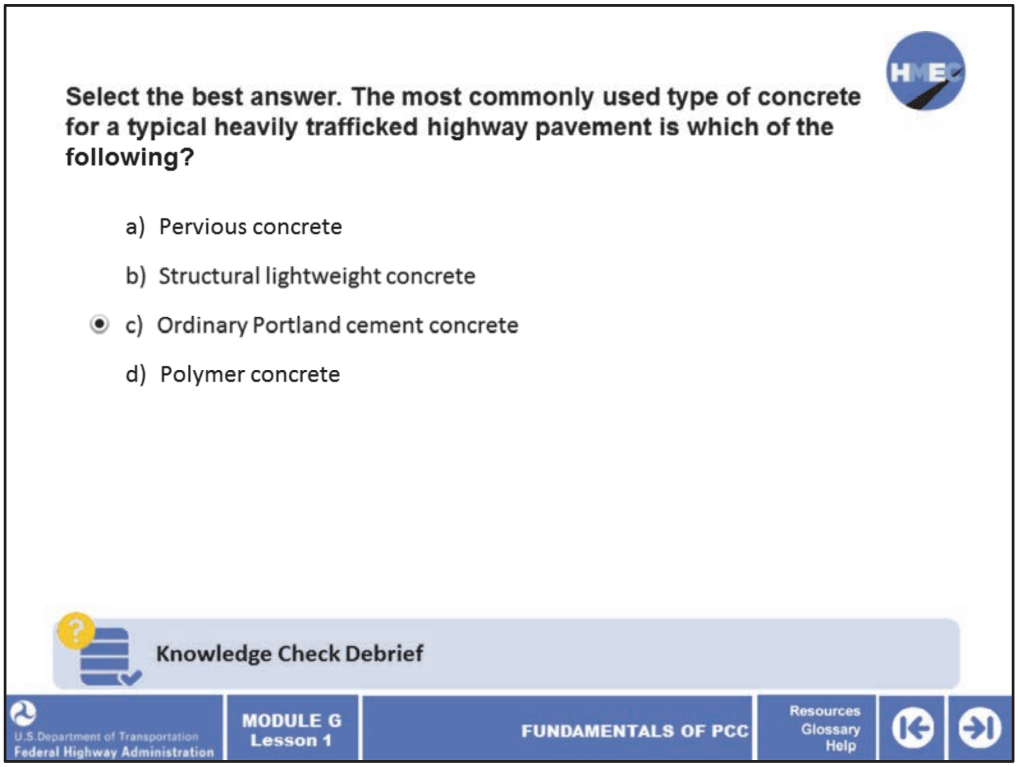
Mineral admixtures are frequently added to PCC mixes as a supplement to the Portland cement. These pozzolans are also referred to as supplemental cementitious materials (SCMs) and have a number of benefits that will be discussed in Lesson 5. Mineral admixtures can also be used as a replacement for a portion of the Portland cement to either enhance performance or to reduce cost.

Corrosion inhibitors are sometimes used when there is the possibility of embedded steel corrosion due to environmental conditions. Note that corrosion inhibitors are often accelerators.

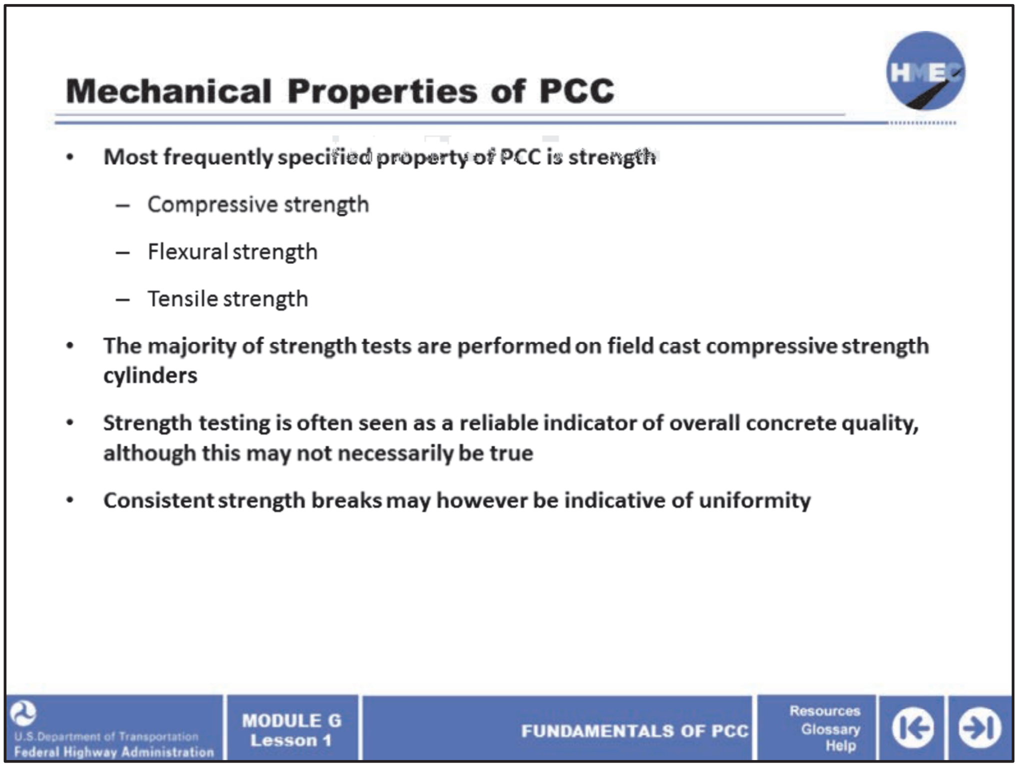


Select the best answer. The most commonly used type of concrete for a typical heavily trafficked highway pavement is which of the following?

a) Pervious concrete;
b) Structural lightweight concrete;
c) Ordinary Portland cement concrete; or
d) Polymer concrete.



The correct answer is c) Ordinary Portland cement concrete.



The most frequently specified property of PCC is strength. There are three types of strength: compressive strength, flexural strength, and tensile strength.

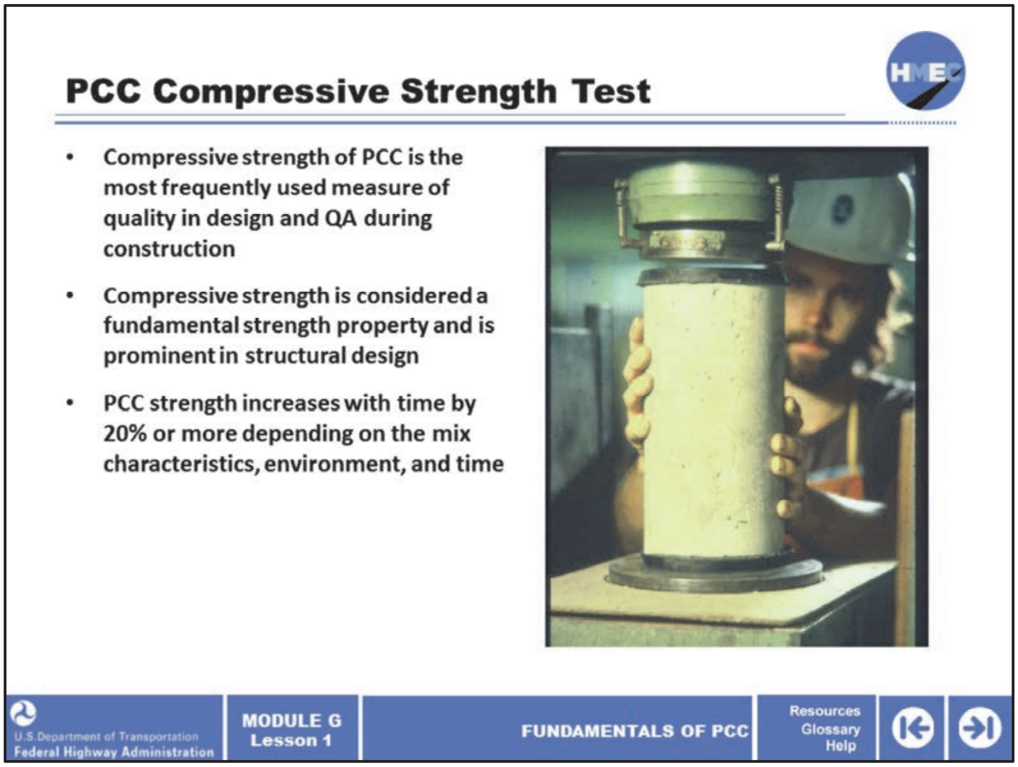
The majority of strength tests are performed on field cast compressive strength cylinders. The primary reason for this method of testing is that cylinders are relatively easy to cast uniformly at the job site and testing variability is significantly lower than flexural strength beam breaks.

Field cured cylinders can provide a more realistic estimate of real-time strength than laboratory cured specimens assuming they are stored correctly at the job site. Laboratory cured cylinders represent the ideal curing environment and may not always reflect field conditions. Refer to the discussion on maturity later in this module.

Strength testing is often seen as a reliable indicator of overall concrete quality. However, this is somewhat misleading because even high strength PCC is subject to durability issues if not designed and placed correctly.

Strength is a design element for both structural and highway applications and is specified for almost all projects. Compressive strength tests are the standard measure somewhat as a matter of convenience. For example, all highway design methods require a PCC modulus of rupture (MR) as the design strength parameter. Since determining MR requires beam breaks, it is far simpler to determine the compressive strength and then correlate that value to MR.

A number of agencies are beginning to use field-measured maturity and lab-derived maturity curves to determine the strength parameter of choice.

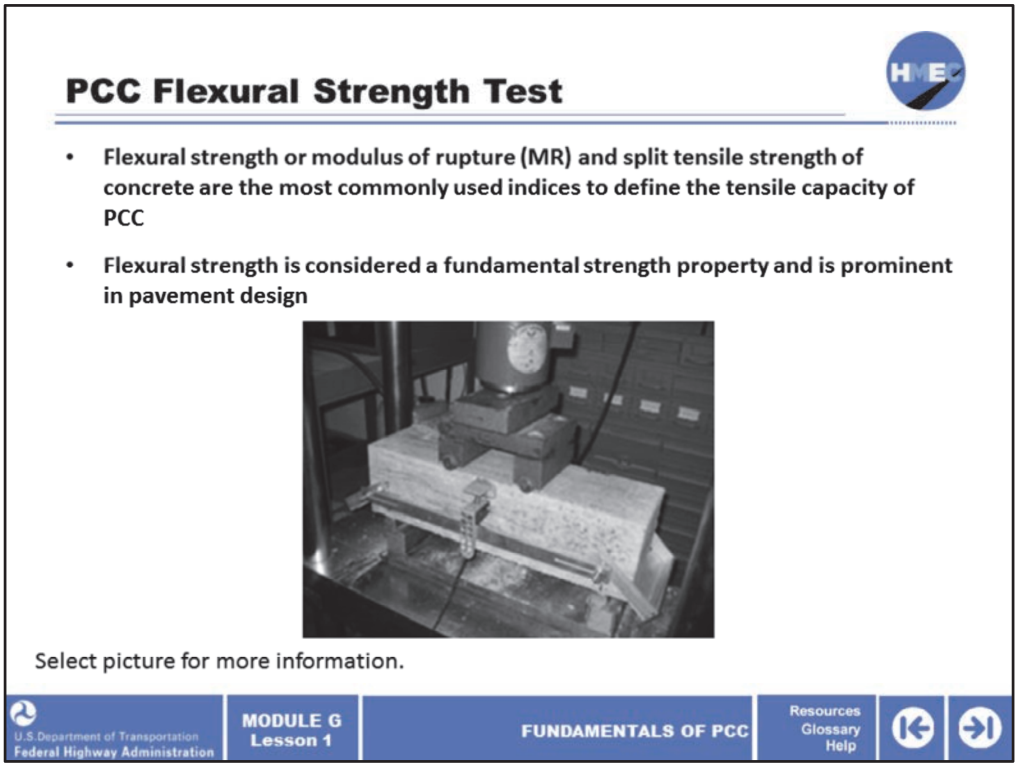


The compressive strength of PCC is the most frequently used measure of quality in design and quality assurance (QA) during construction. This parameter is easily determined through a laboratory uniaxial compressive loading test as described in the ASTM C 39 standard. Compressive strength is considered a fundamental strength property and is prominent in structural design. The 28-day compressive strength is a widely accepted strength index, especially for initial design purposes. It is now recognized that PCC strength increases with time by 20% or more depending on the mix characteristics, environment, and time.

Due to the widespread use and acceptance of this test, it is frequently correlated to other parameters including flexural and tensile strengths and is consistently used to predict the elastic modulus of PCC. Although the compressive strength of PCC may be specified for highway design, the MR is the basis for analysis.

The compressive strength of PCC is most strongly influenced by mix design parameters including w/c ratio, cement type, cement content, and aggregate properties (aggregate type, maximum size, gradation, and surface texture) as well as timely and adequate curing.

Image description: Photo of a concrete sample in compression testing machine.

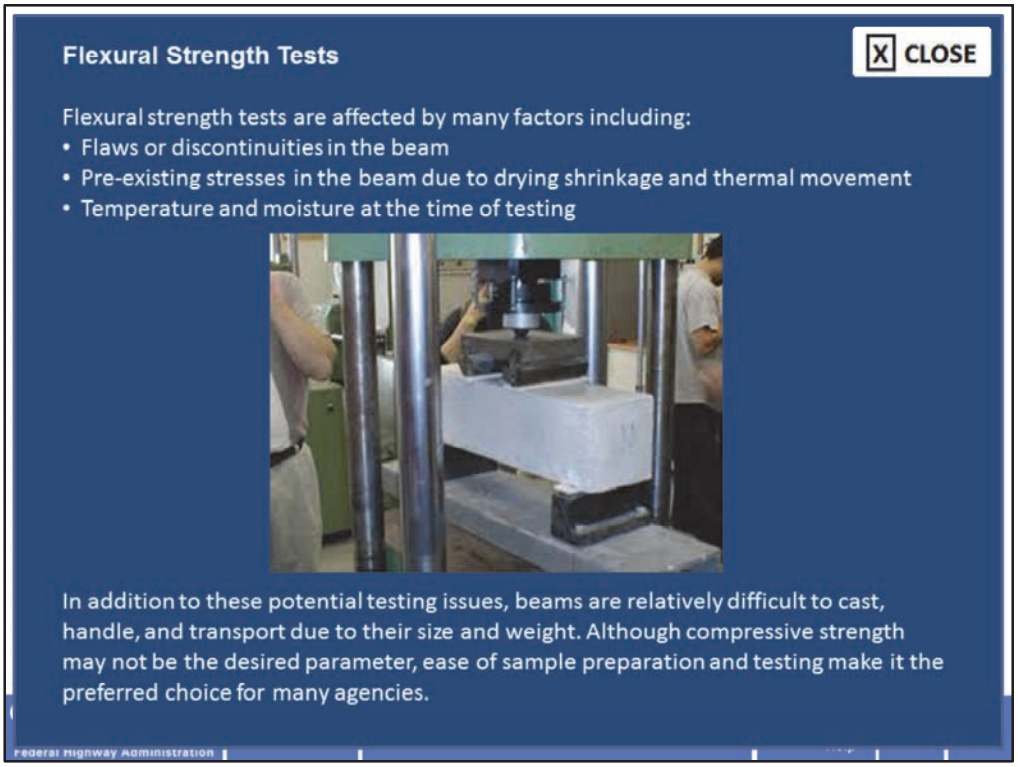


The flexural strength or modulus of rupture (MR) and split tensile strength of concrete are the most commonly used indices to define the tensile capacity of PCC. MR is influenced by mix design parameters including w/c ratio, cement type, cement content, and aggregate properties (aggregate type, maximum size, gradation, and surface texture) and curing as was compressive strength. In general, the material characteristics affect MR in the same manner as compressive strength. It has been determined in numerous laboratory-based studies that the most important factor governing concrete tensile capacity is the aggregate matrix bond. In a study by Kaplan, it was concluded that the elastic modulus of the aggregates has the greatest influence on the flexural strength of PCC.

The flexural strength of concrete is defined as the maximum tensile strength at rupture at the bottom of a simply supported PCC beam during a flexural test with third point loading, as standardized in ASTM C 78-02. This test measures the tensile capacity of the material in bending or flexure. Keep in mind that the MR of a fully supported slab is far greater than the flexural strength of a simply supported beam. Consider the implication to pavement design methodologies that use the MR value based on a simple beam break (incidentally, they all do at the present time).

Select the picture for more information.

Image description: Photo of a concrete under flexural testing.

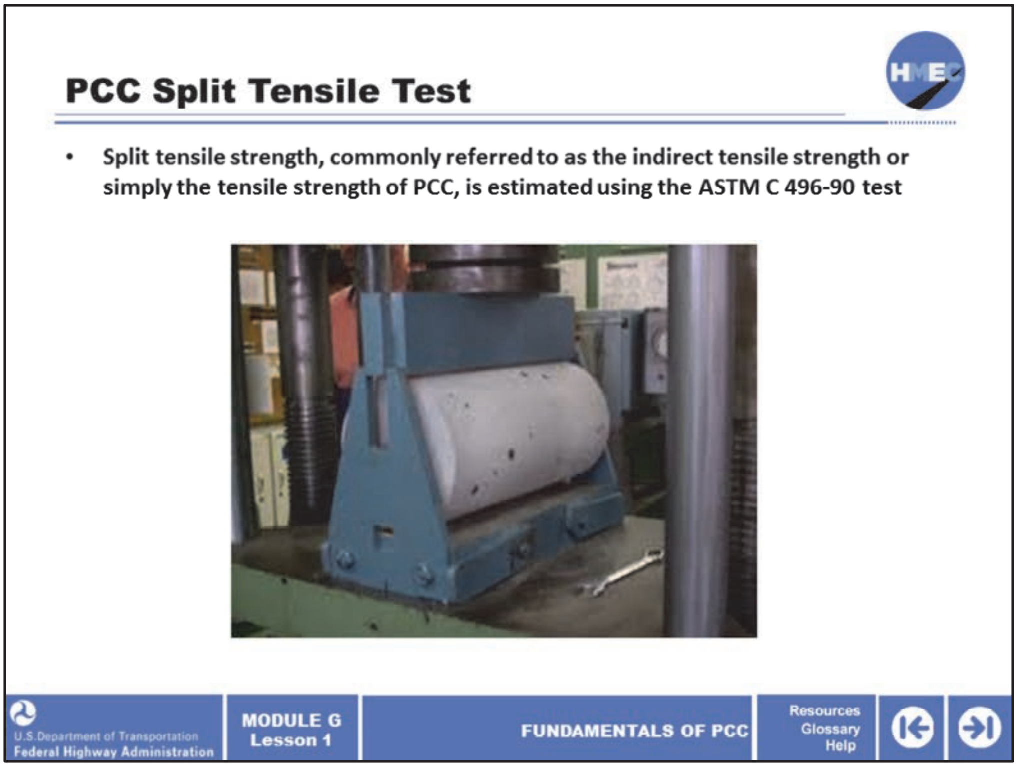


Flexural strength tests are affected by many factors including:

- Flaws or discontinuities in the beam;
- Pre-existing stresses in the beam due to drying shrinkage and thermal movement; and
- Temperature and moisture at the time of testing.

In addition to these potential testing issues, beams are relatively difficult to cast, handle, and transport due to their size and weight. Although compressive strength may not be the desired parameter, ease of sample preparation and testing make it the preferred choice for many agencies.

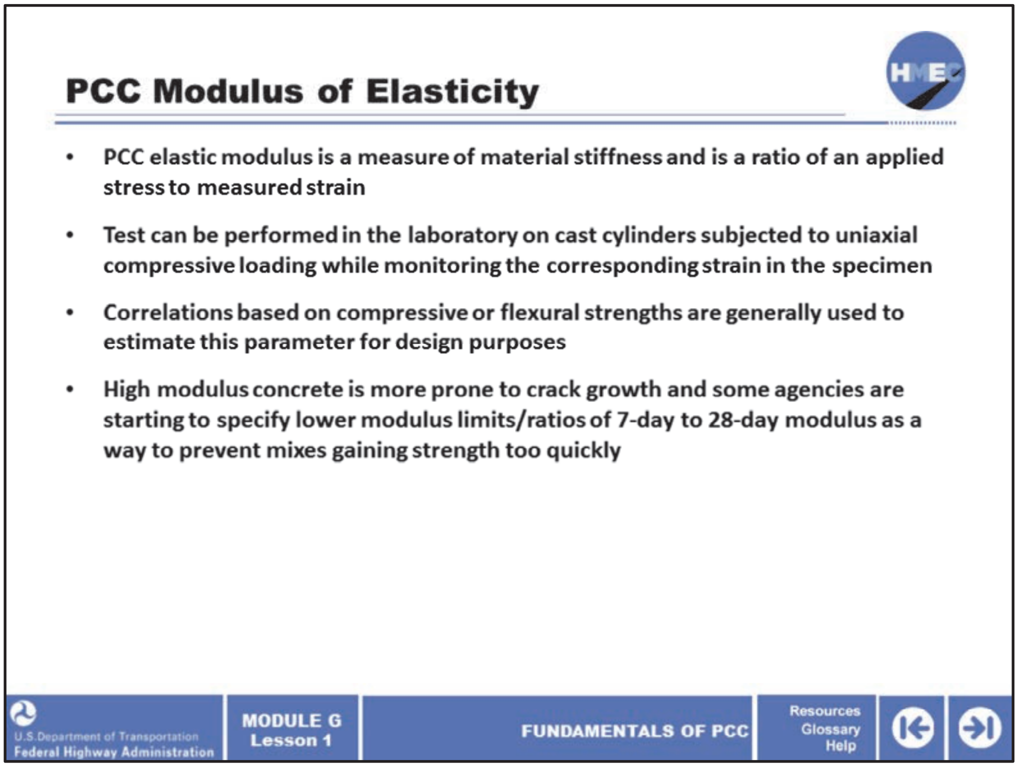
Image description: Photo of a concrete sample under Flexural testing.



The split tensile strength, commonly referred to as the indirect tensile strength or simply the tensile strength of PCC, is estimated using the ASTM C 496-90 test. The test consists of subjecting a concrete cylinder to compressive loads along two diametrically opposite axial lines. The compressive load applied on the side of a cylindrical specimen causes a uniform tensile stress along the vertical diameter until the specimen fails.

The indirect tensile strength is used in the continuously reinforced concrete pavement (CRCP) distress prediction models of Pavement ME design. This strength parameter has a direct influence on the transverse crack spacing, which, in turn, affects the crack widths, the load transfer efficiency of the crack, and eventually damage leading to punchout development.

Image description: Photo of a concrete sample under Split Tensile Strength testing machine.

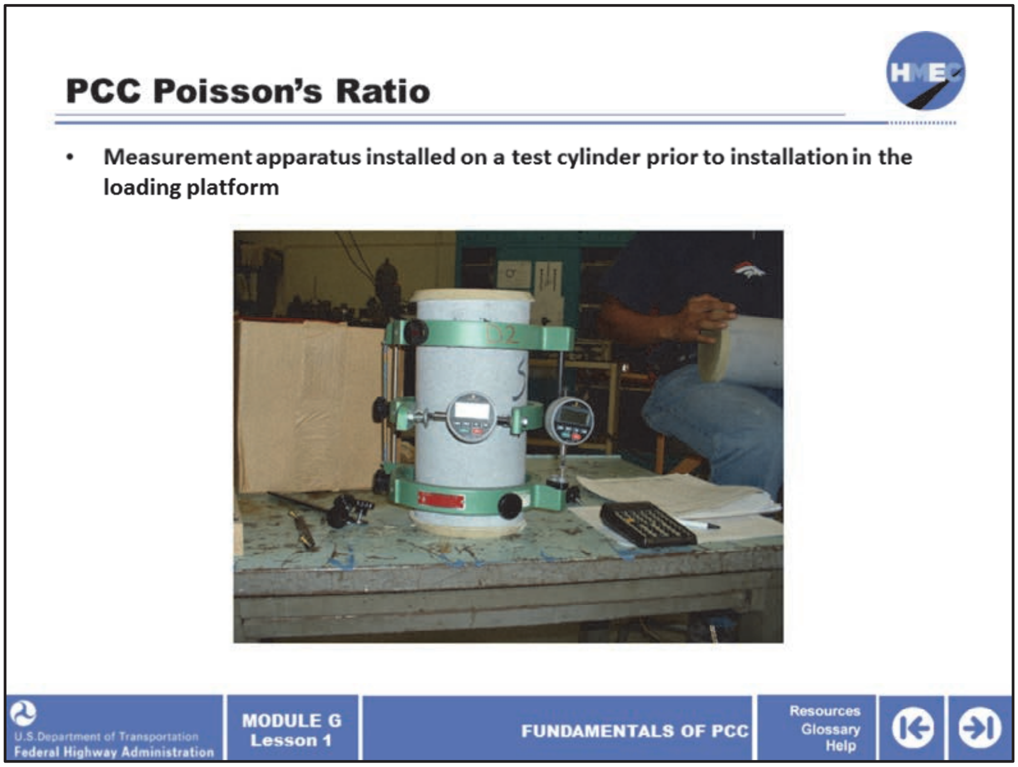


The PCC elastic modulus is a measure of material stiffness and is a ratio of an applied stress to measured strain. This test can be performed in the laboratory on cast cylinders subjected to uniaxial compressive loading while monitoring the corresponding strain in the specimen. However, modulus of elasticity tests are not routinely performed by most agencies. Correlations based on compressive or flexural strengths are generally used to estimate this parameter for design purposes.

The elastic modulus of PCC is determined using the ASTM C 496-90 test procedure, wherein the chord modulus is measured in a concrete cylinder loaded in longitudinal compression at a relatively slow constant rate. This test procedure also is used to determine Poisson's ratio.

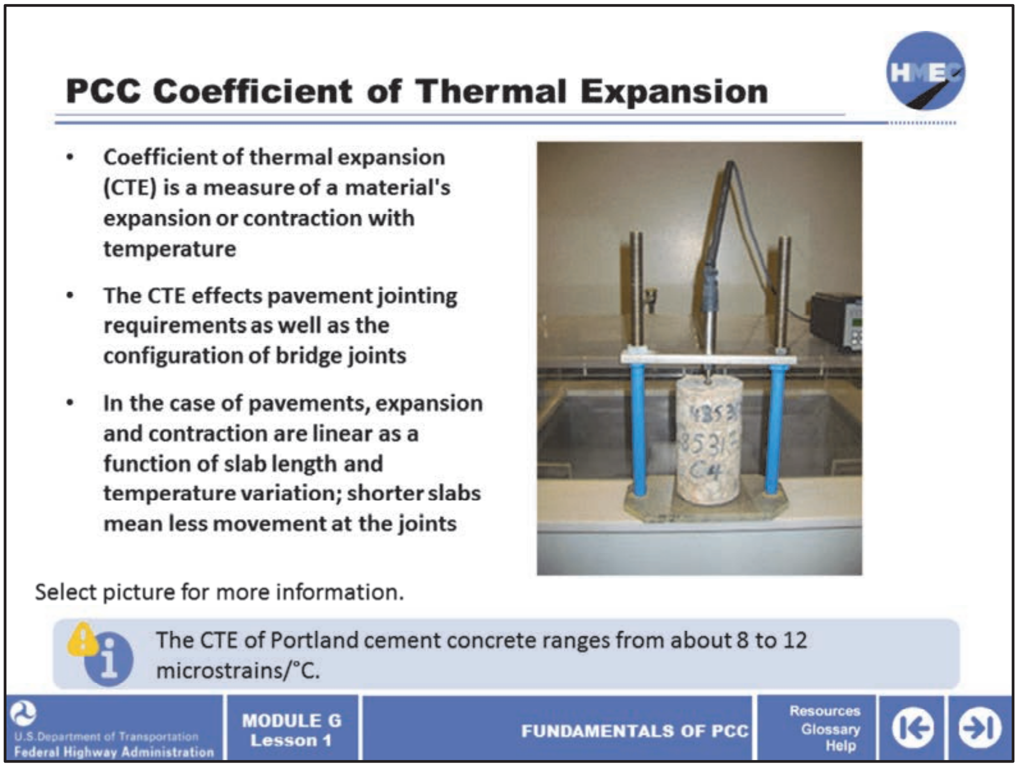
The concrete elastic modulus is an important variable in pavement design, as it controls the overall slab deflections from traffic loading and slab curling stresses. Historically, for pavement applications, this value has not been tested in the laboratory; typical values are assumed or correlated because it is perceived to have little effect. However, newer design methods such as the MEPDG (Pavement ME) have brought the importance of this parameter to the forefront. Generally, PCC elastic modulus increases as compressive strength increases, and it was found that, in general, the material characteristics affect the elastic modulus in the same manner as the compressive strength. However, elastic modulus is more sensitive to aggregate characteristics and volumes.

High modulus concrete is more prone to crack growth (more brittle) and some agencies are starting to specify lower modulus limits and/or ratios of 7-day to 28-day modulus as a way to prevent mixes gaining strength too quickly and being more crack-prone.



Poisson's ratio is defined as the ratio of transverse to longitudinal strains of a loaded specimen. The photo shows the measurement apparatus installed on a test cylinder prior to installation in the loading platform. As discussed in the previous screen, a similar setup is used in the determination of elastic modulus. Similar to the elastic modulus, Poisson's ratio is typically estimated rather than actually measured and is generally in the range of 0.15 to 0.20.

Image description: Photo of a measurement apparatus on test cylinder.



The coefficient of thermal expansion (CTE) is a measure of a material's expansion or contraction with temperature. Because the length changes associated with thermal expansion are very small, the CTE is usually expressed in microstrains per unit of temperature change. The CTE of Portland cement concrete ranges from about 8 to 12 microstrains/°C.

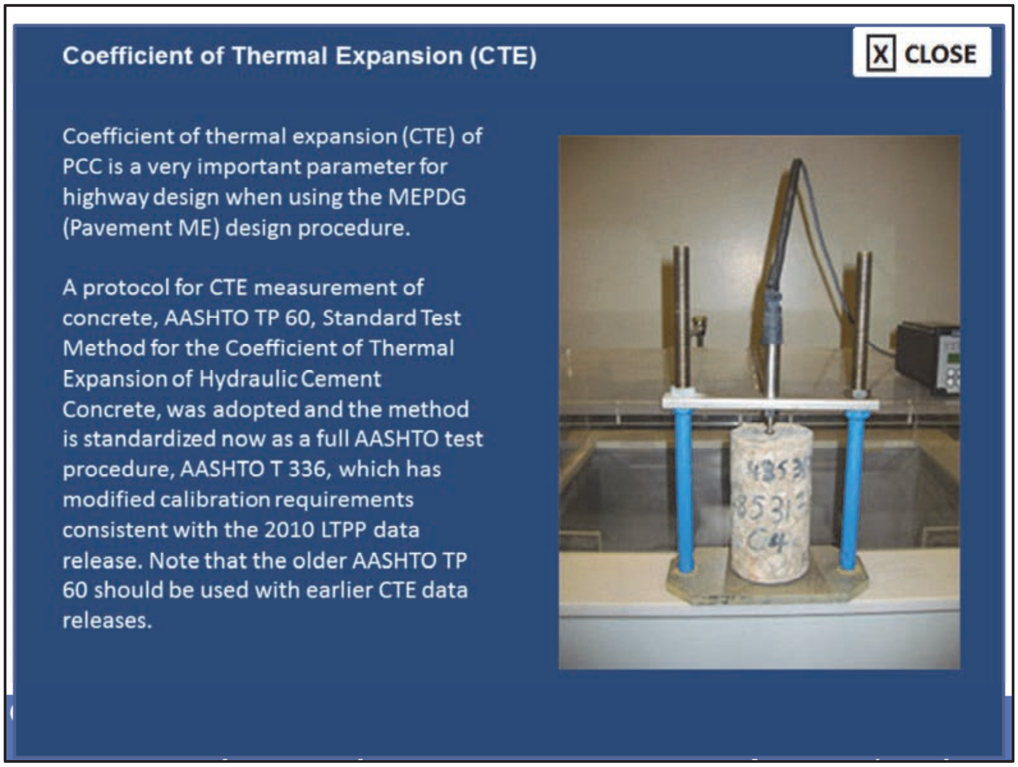
The range of CTE values for different concretes reflects the variation in CTE of concrete's component materials. For example, concrete containing limestone aggregate has a lower CTE than concrete containing siliceous aggregate. Because aggregate comprises about 70% of the volume of PCC, aggregate type has the greatest effect on the CTE of all the PCC constituents. The CTE of hardened cement paste, which is a function of factors such as w/c ratio, cement fineness, cement composition, and age, also affects the CTE.

The CTE effects pavement jointing requirements as well as the configuration of bridge joints.

In the case of pavements, expansion and contraction are linear as a function of slab length and temperature variation. Shorter slabs mean less movement at the joints.

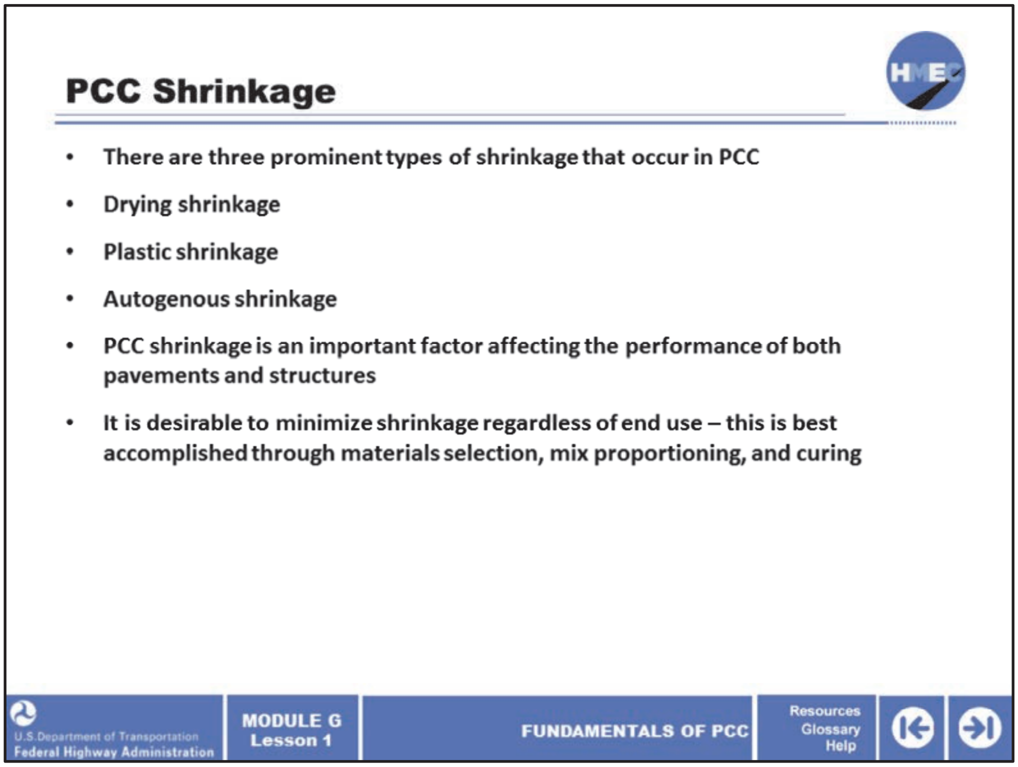
Select the picture for more information.

Image description: Photo of concrete under thermal testing for expansion.



The coefficient of thermal expansion (CTE) of PCC is a very important parameter for highway design when using the MEPDG (Pavement ME) design procedure. A protocol for CTE measurement of concrete, AASHTO TP 60, Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete, was adopted and the method is standardized now as a full AASHTO test procedure, AASHTO T 336, which has modified calibration requirements consistent with the 2010 LTPP data release. Note that the older AASHTO TP 60 should be used with earlier CTE data releases.

Image description: Photo of concrete under thermal testing for expansion.



PCC shrinkage is due to many factors, including the chemical transformation taking place during the hydration process. The hydration products occupy less volume than the unreacted compounds thereby leading to shrinkage as a function of the amount of cement paste (i.e. more paste equates to more shrinkage, all other factors being equal).

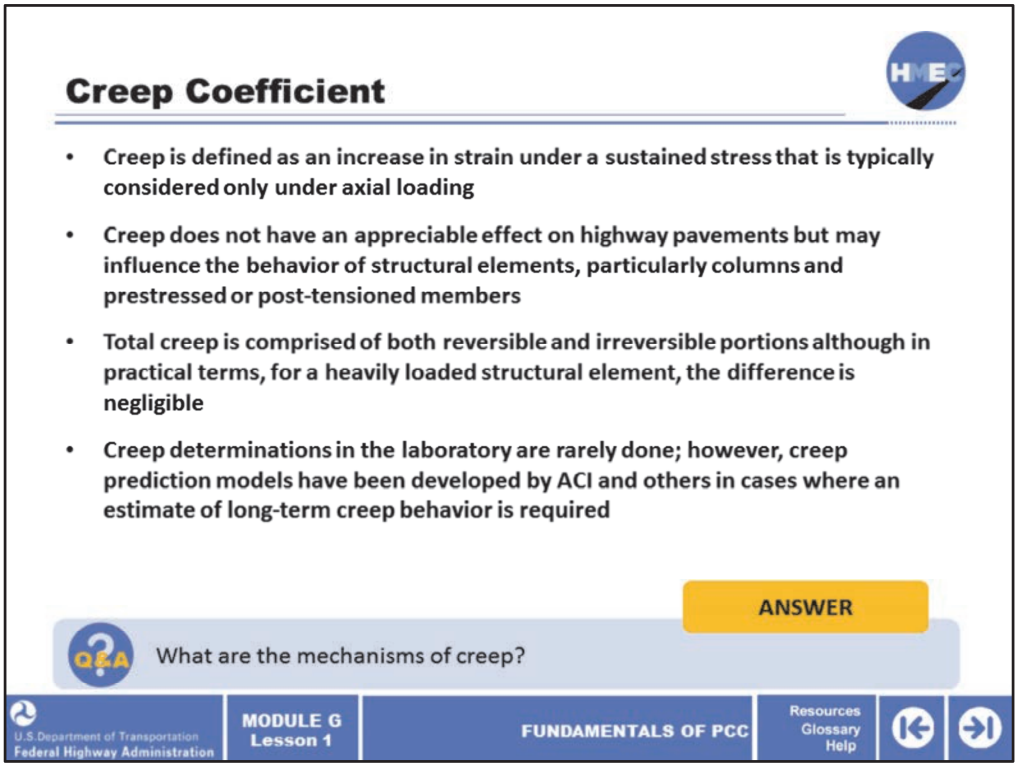
Magnitude of shrinkage depends on numerous factors including:

- Cement type and content;
- Water content;
- Aggregate characteristics and proportions; and
- Placement conditions and curing.

Restrained shrinkage leads the development of cracks and, in conjunction with thermal movement, is the primary reason for jointing PCC.

Drying shrinkage is generally the most significant of the three types listed. Aggregates have a bearing on drying shrinkage in two ways. A dense-graded aggregate helps minimize paste content, thereby reducing the drying shrinkage. The aggregates help restrain the drying shrinkage internally.

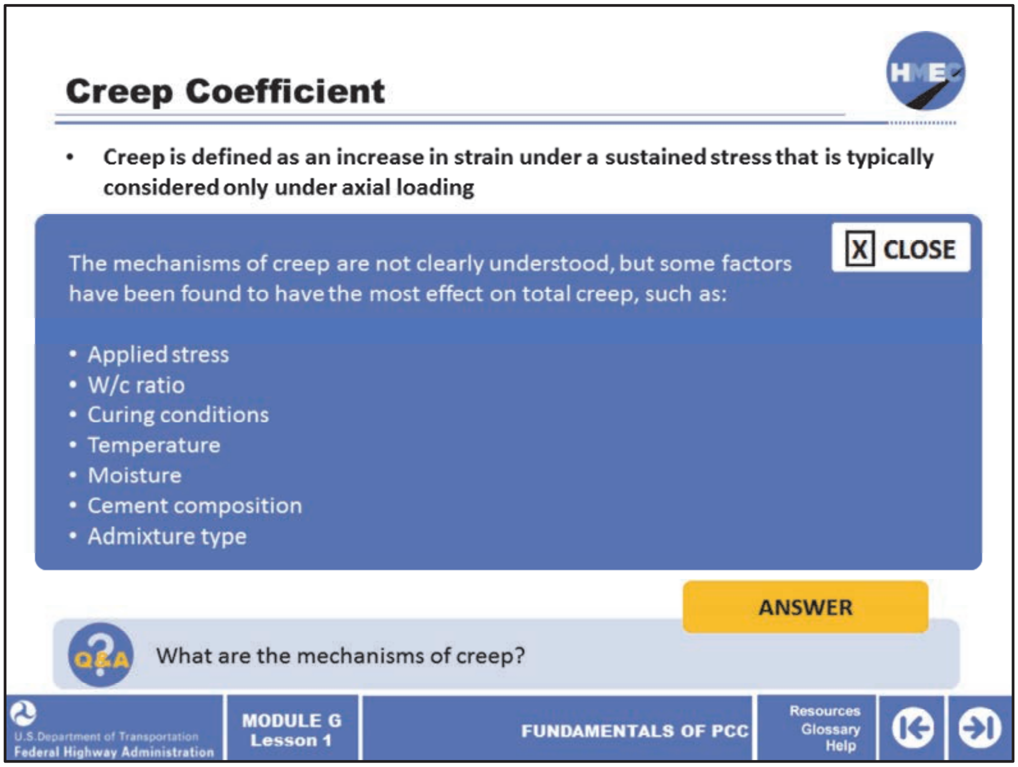
The placement conditions also influence the amount of drying shrinkage. Timely and sufficient application of curing compound (or alternative) as soon after placement as possible is key. This is particularly true for hot, dry, and windy placement conditions.



Creep is defined as an increase in strain under a sustained stress. This is typically considered only under axial loading. Creep does not have an appreciable effect on highway pavements but may influence the behavior of structural elements, particularly columns and prestressed or post-tensioned members.

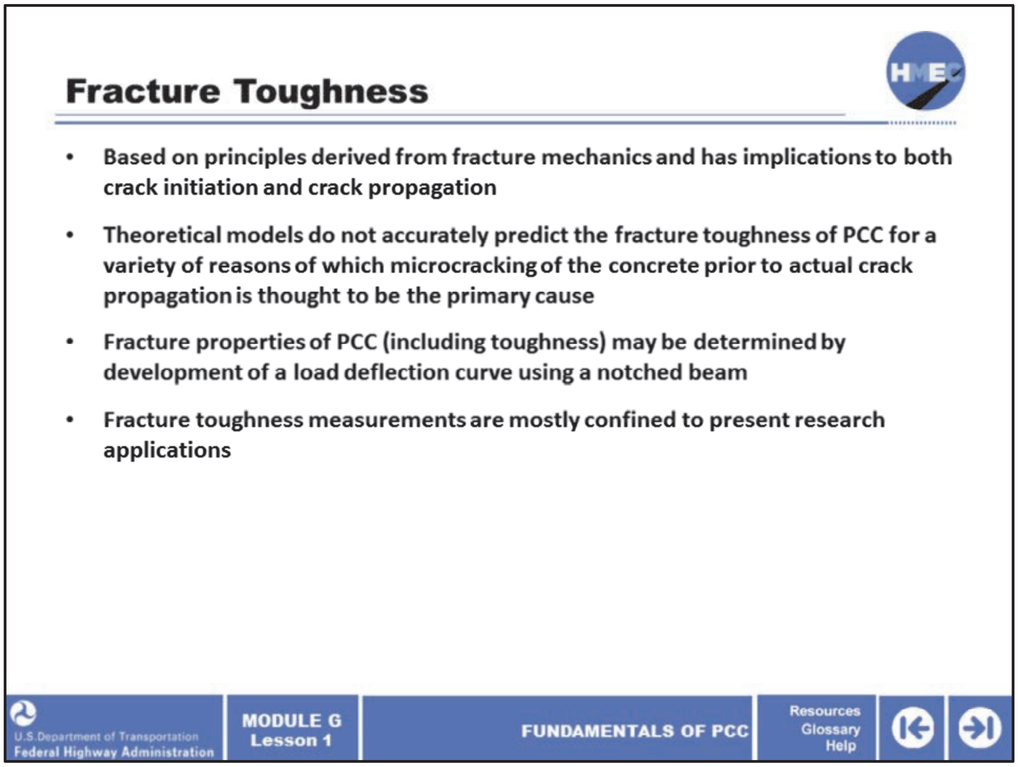
Total creep is comprised of both reversible and irreversible portions although in practical terms, for a heavily loaded structural element, the difference is negligible. Creep determinations in the laboratory are rarely done. Creep prediction models have been developed by the American Concrete Institute (ACI) and others in cases where an estimate of long-term creep behavior is required.

What are the mechanisms of creep? Select the answer button for more information.



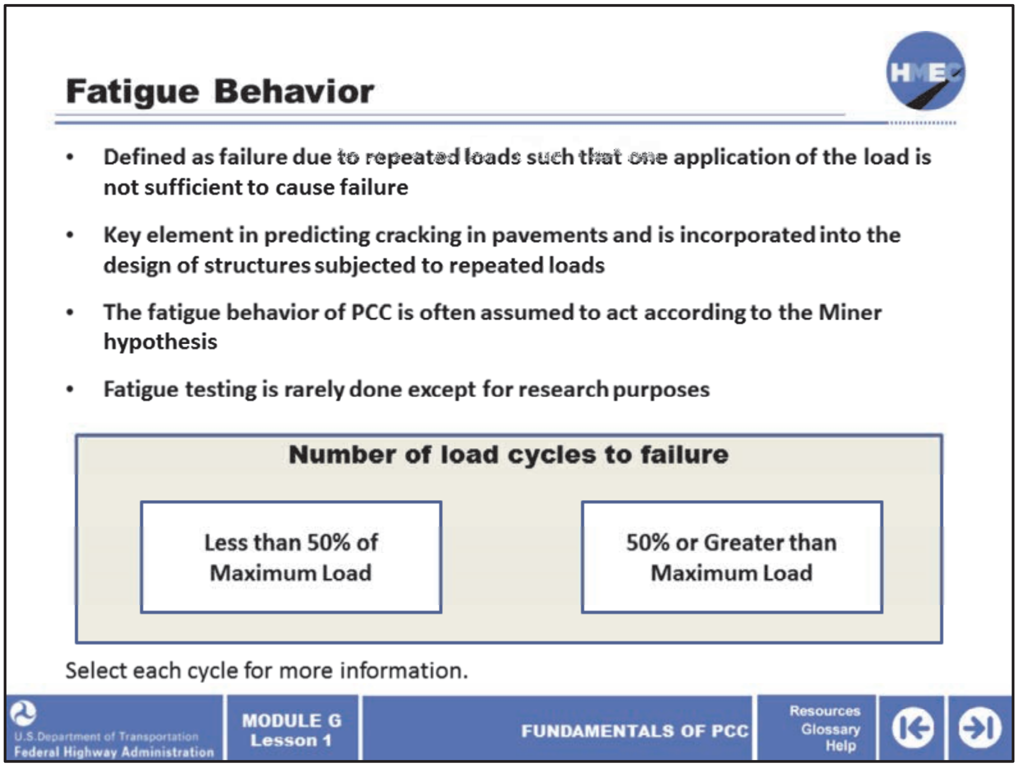
The mechanisms of creep are not clearly understood, but some factors have been found to have the most effect on total creep, such as:

- Applied stress;
- W/c ratio;
- Curing conditions;
- Temperature;
- Moisture;
- Cement composition; and
- Admixture type.



The fracture toughness of PCC is based on principles derived from fracture mechanics and has implications to both crack initiation and crack propagation. Theoretical models do not accurately predict the fracture toughness of PCC for a variety of reasons of which microcracking of the concrete prior to actual crack propagation is thought to be the primary cause.

Fracture properties of PCC (including toughness) may be determined by development of a load deflection curve using a notched beam. Fracture toughness measurements are mostly confined to present research applications. Although many of the mechanisms governing fracture toughness are unknown, it seems to be most closely related to PCC strength. The addition of fibers in PCC has been reported to increase the fracture toughness by varying amounts.



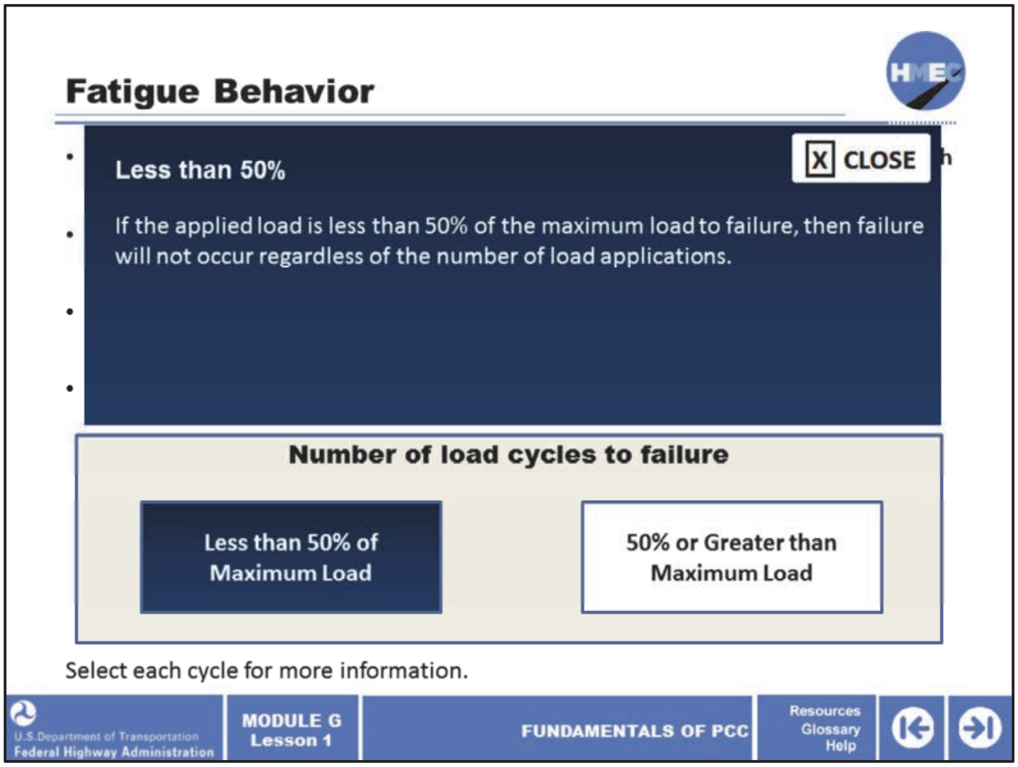
The fatigue behavior of a material is defined as failure due to repeated loads such that one application of the load is not sufficient to cause failure. Fatigue behavior is a key element in predicting cracking in pavements and is incorporated into the design of structures subjected to repeated loads.

The fatigue behavior of PCC is often assumed to act according to the Miner hypothesis. The Miner hypothesis relates the number of load cycles to failure and load. If a critical failure inducing load is applied to a sample, it takes 1 load cycle to failure. If the load is minute, it would take infinite loads to fail the sample in fatigue. This hypothesis basically states that if up to 50% of the failure load is applied to a sample, it will have infinite load cycles to failure. After 50% is reached there is a finite number of load cycles to failure.

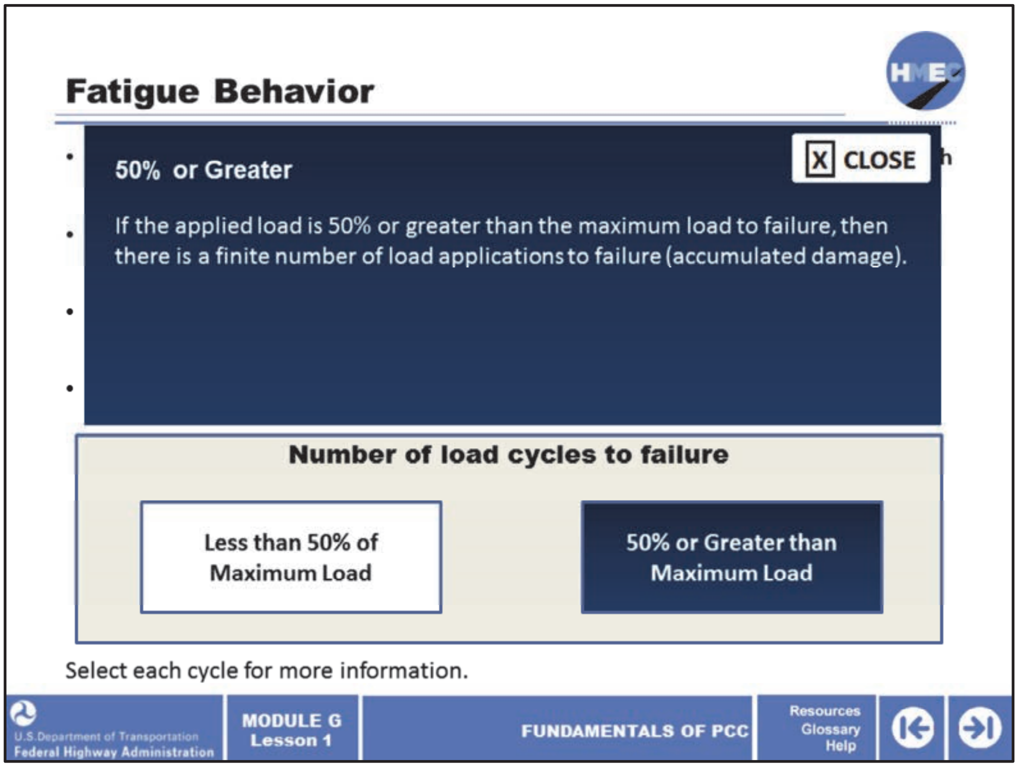
Note that fatigue testing is rarely done except for research purposes.

Fatigue behavior is at the heart of all pavement design methods. It assumes that accumulated damage in the pavement will ultimately lead to cracking. The cracking potential can be controlled however by PCC strength and slab thickness. The fatigue behavior of PCC also has a significant effect on any structure subjected to repeated loads and is implicit in the design calculations.

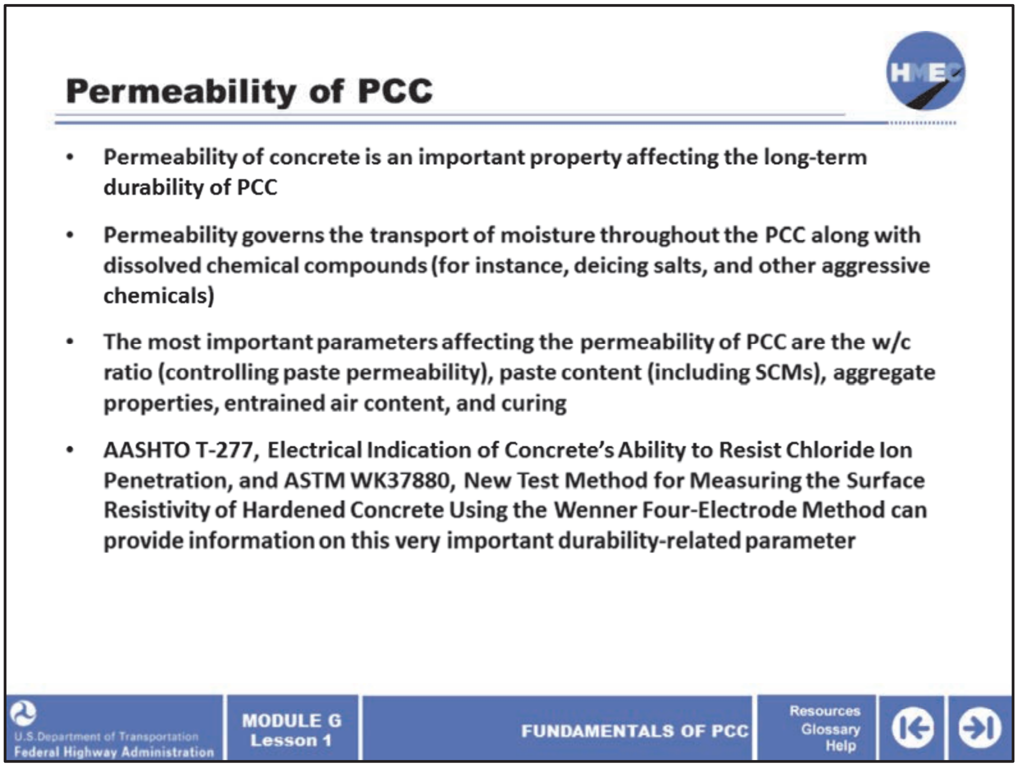
Select each cycle for more information.



If the applied load is less than 50% of the maximum load to failure, then failure will not occur regardless of the number of load applications.



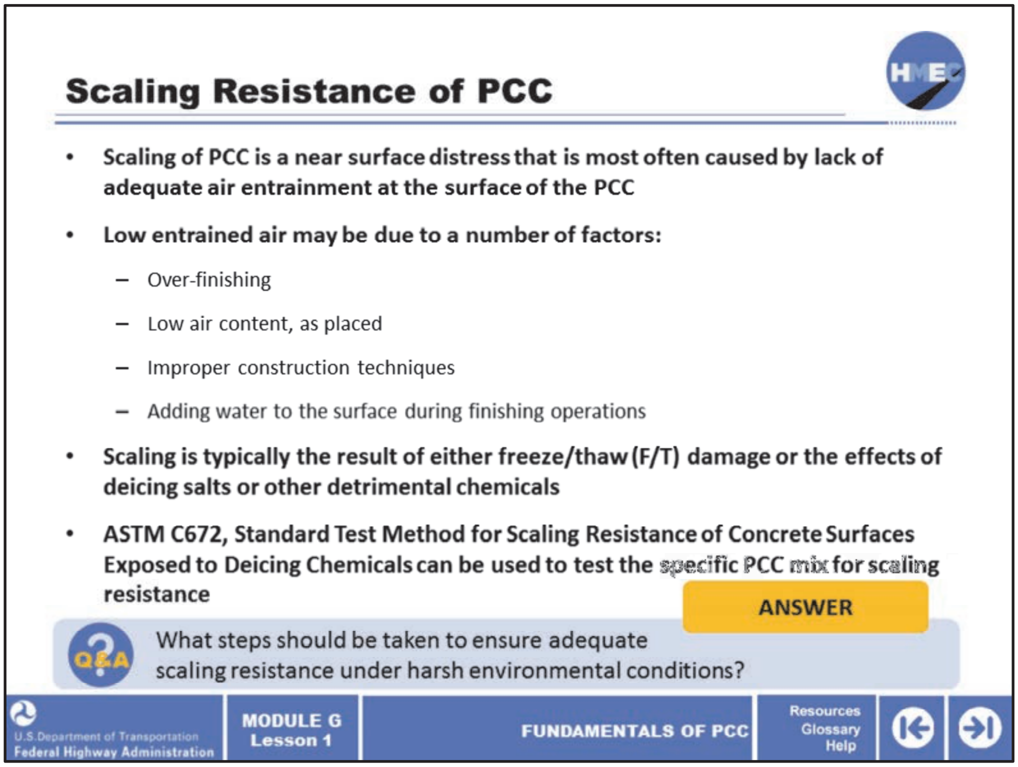
If the applied load is 50% or greater than the maximum load to failure, then there is a finite number of load applications to failure (accumulated damage).



The permeability of concrete is an important property affecting the long-term durability of PCC. The permeability governs the transport of moisture throughout the PCC along with dissolved chemical compounds (for instance, deicing salts, and other aggressive chemicals).

The most important parameters affecting the permeability of PCC are the w/c ratio (controlling paste permeability), paste content (including SCMs), aggregate properties, entrained air content and curing.

AASHTO T-277, Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, and ASTM WK37880, New Test Method for Measuring the Surface Resistivity of Hardened Concrete Using the Wenner Four-Electrode Method can provide information on this very important durability-related parameter.

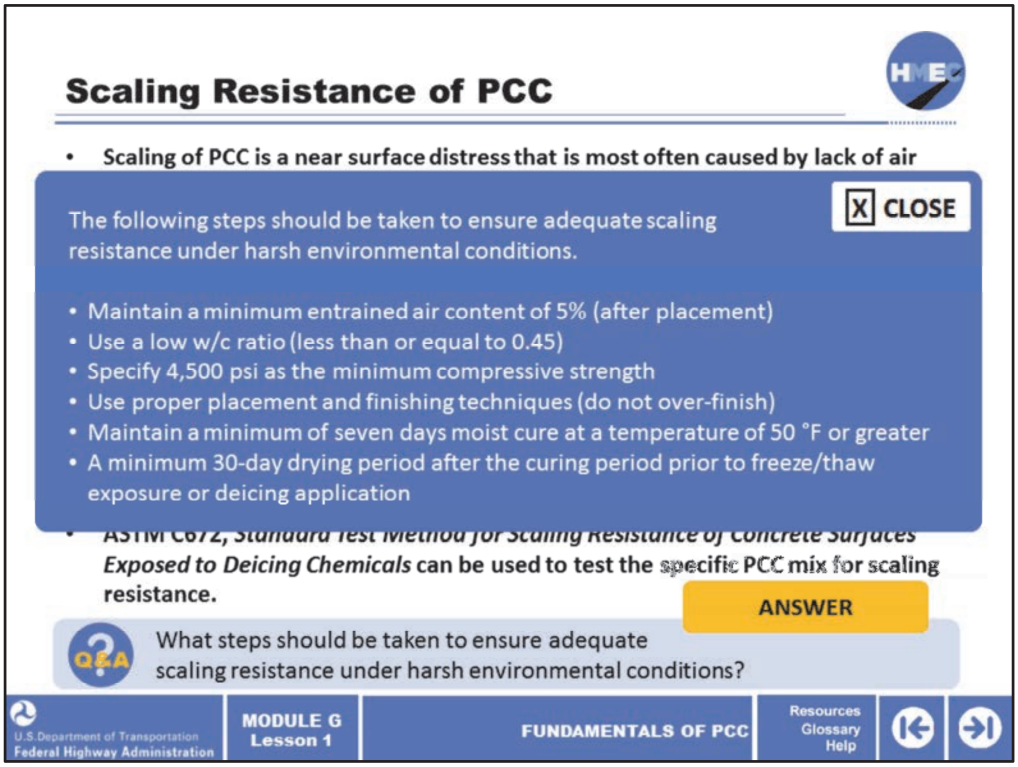


Scaling of PCC is a near surface distress that is most often caused by lack of adequate air entrainment at the surface of the PCC. The low entrained air may be due to a number of factors:

- Over-finishing;
- Low air content, as placed;
- Adding water to the surface during finishing operations; and
- Improper construction techniques.

The scaling is typically the result of either freeze/thaw damage or the effects of deicing salts or other detrimental chemicals. ASTM C672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals can be used to test the specific PCC mix for scaling resistance.

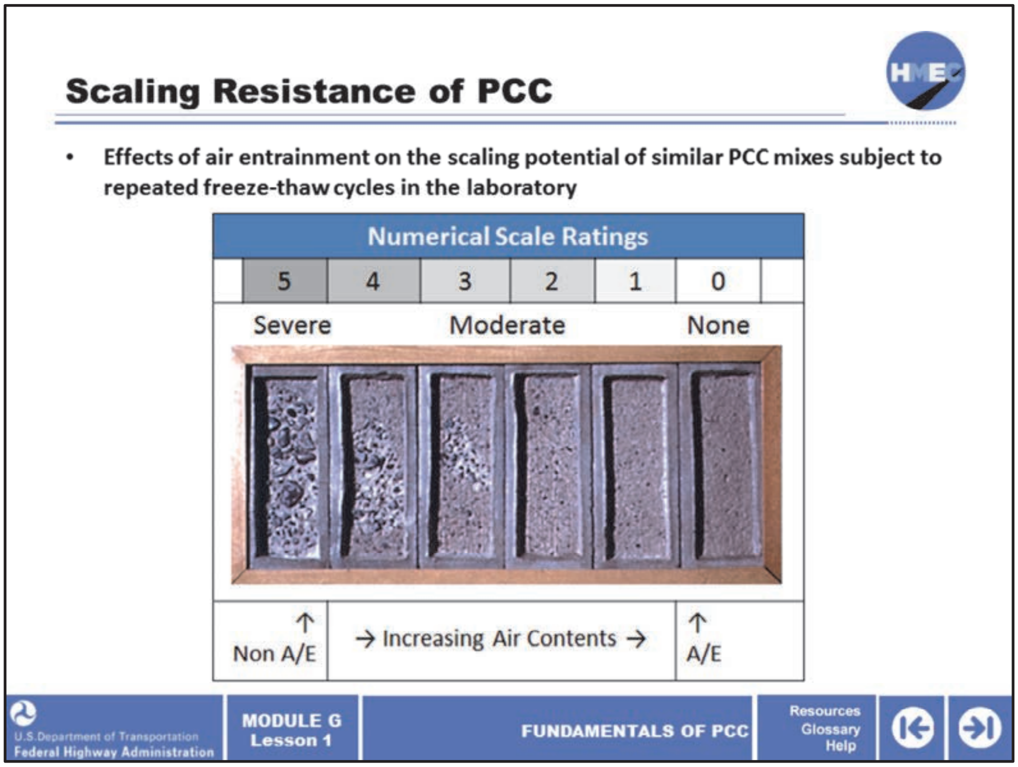
What steps should be taken to ensure adequate scaling resistance under harsh environmental conditions? Select the answer button for more information.



The following steps should be taken to ensure adequate scaling resistance under harsh environmental conditions.

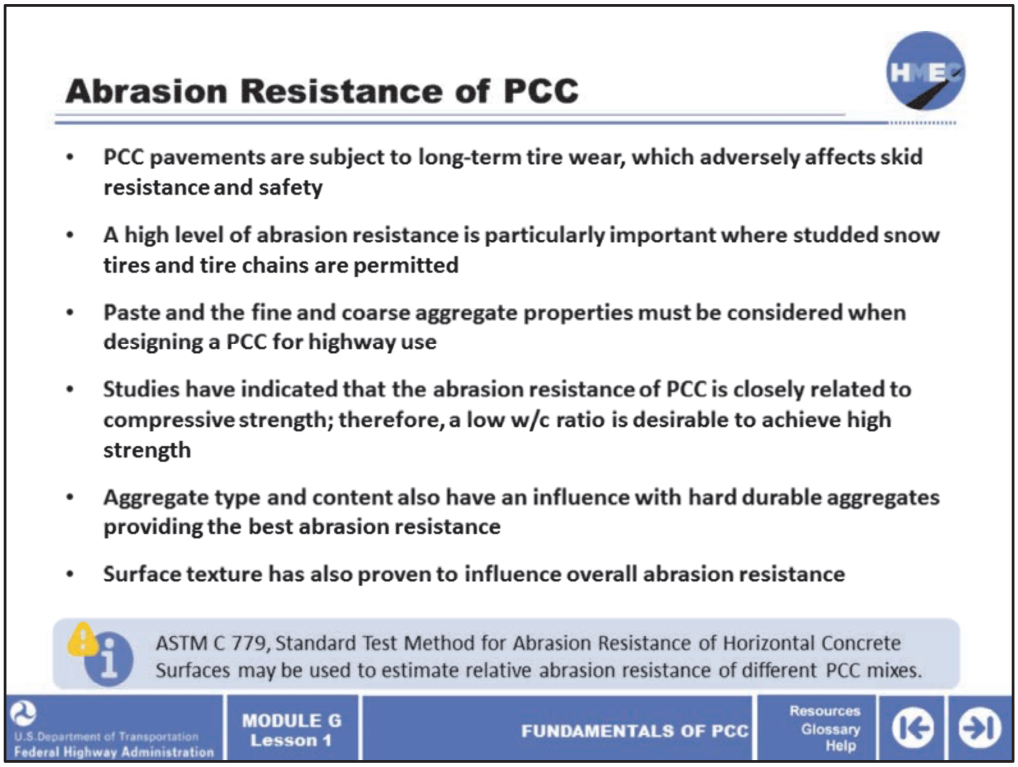
• Maintain a minimum entrained air content of 5% (after placement);
• Use a low w/c ratio (less than or equal to 0.45);
• Specify 4,500 psi as the minimum compressive strength;
• Use proper placement and finishing techniques (do not over-finish);
• Maintain a minimum of seven days moist cure at a temperature of 50 °F or greater; and
• A minimum 30-day drying period after the curing period prior to freeze/thaw exposure or deicing application.

Note that the use of SCMs is generally beneficial to PCC performance and have not been shown to adversely affect scaling.



The photo illustrates the effects of air entrainment on the scaling potential of similar PCC mixes subject to repeated freeze-thaw cycles in the laboratory. As can be clearly seen, effective air entrainment is key to minimizing or eliminating scaling potential of PCC.

Image description: Photo illustrating the effects of air entrainment on the scaling potential of similar PCC mixes subject to repeated freeze-thaw cycles in the laboratory.

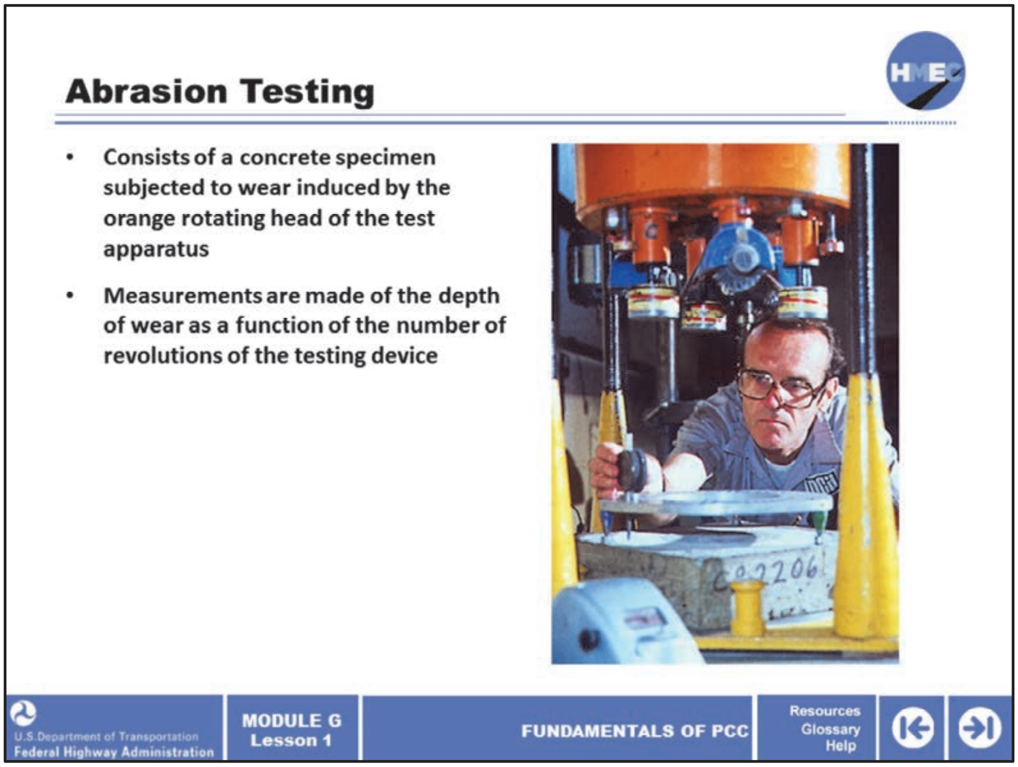


PCC pavements are subject to long-term tire wear, which adversely affects skid resistance and safety. A high level of abrasion resistance is particularly important where studded snow tires and tire chains are permitted.

The paste and the fine and coarse aggregate properties must be considered when designing a PCC for highway use. Studies have indicated that the abrasion resistance of PCC is closely related to compressive strength. Therefore, a low w/c ratio is desirable to achieve high strength.

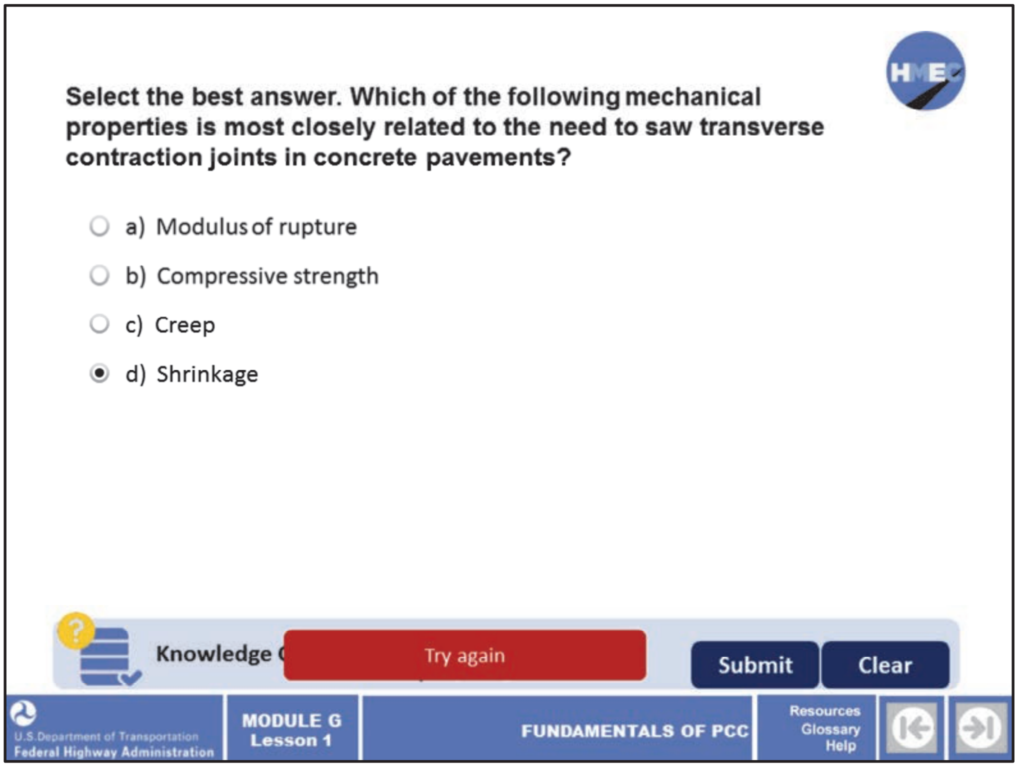
The aggregate type and content also have an influence with hard durable aggregates providing the best abrasion resistance. Surface texture has also proven to influence overall abrasion resistance.

ASTM C 779, Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces may be used to estimate relative abrasion resistance of different PCC mixes.



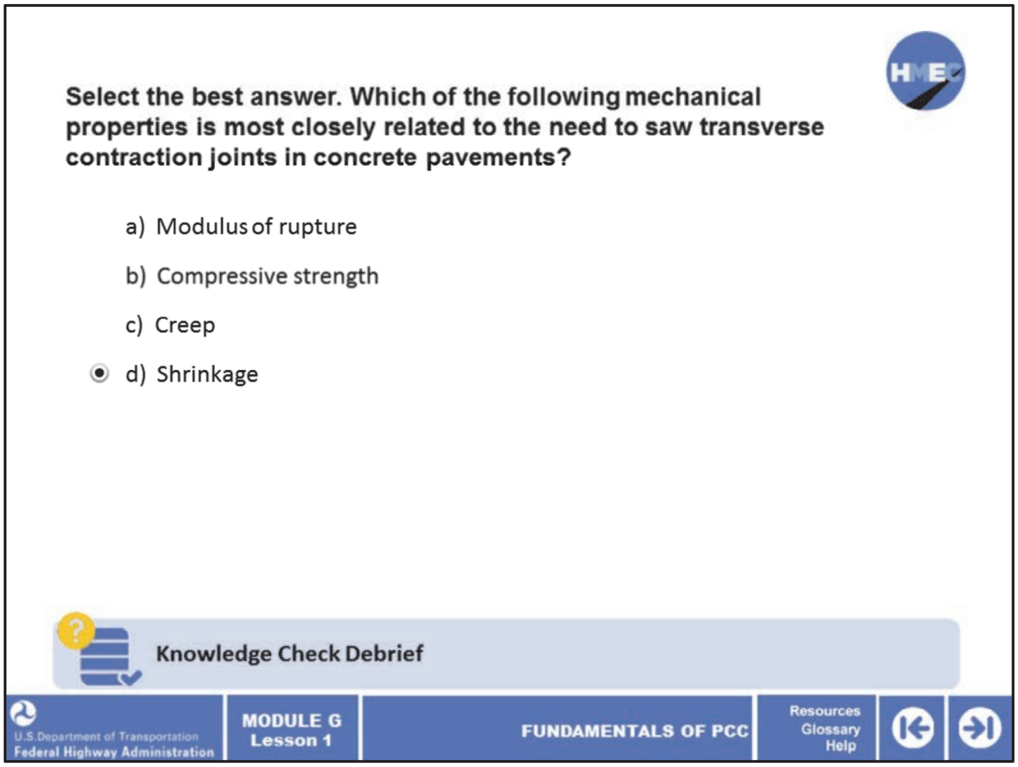
Let's look at an abrasion testing device. This device consists of a concrete specimen subjected to wear induced by the orange rotating head of the test apparatus. Measurements are made of the depth of wear as a function of the number of revolutions of the testing device. Although this is a relatively easy test to perform, correlation to field performance has been somewhat problematic. Perhaps the best use is to compare the characteristics of various mix designs prior to selection.

Image description: Photo of a concrete specimen in an abrasion testing machine.

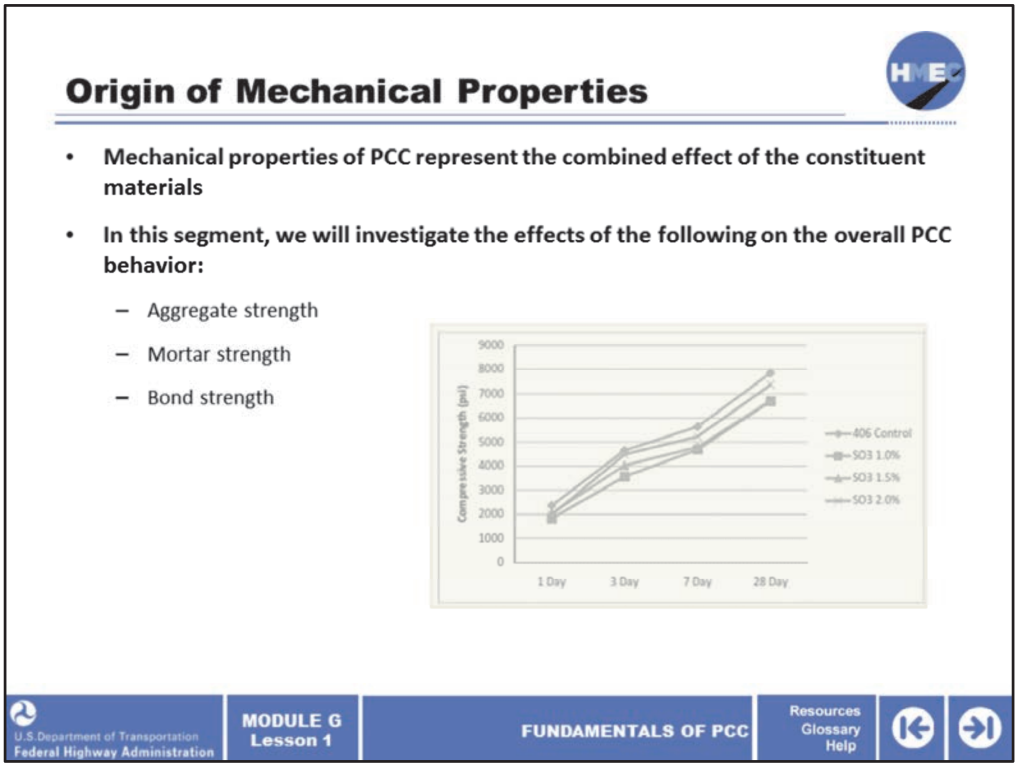


Select the best answer. Which of the following mechanical properties is most closely related to the need to saw transverse contraction joints in concrete pavements?

a) Modulus of rupture;
b) Compressive strength;
c) Creep; or
d) Shrinkage.



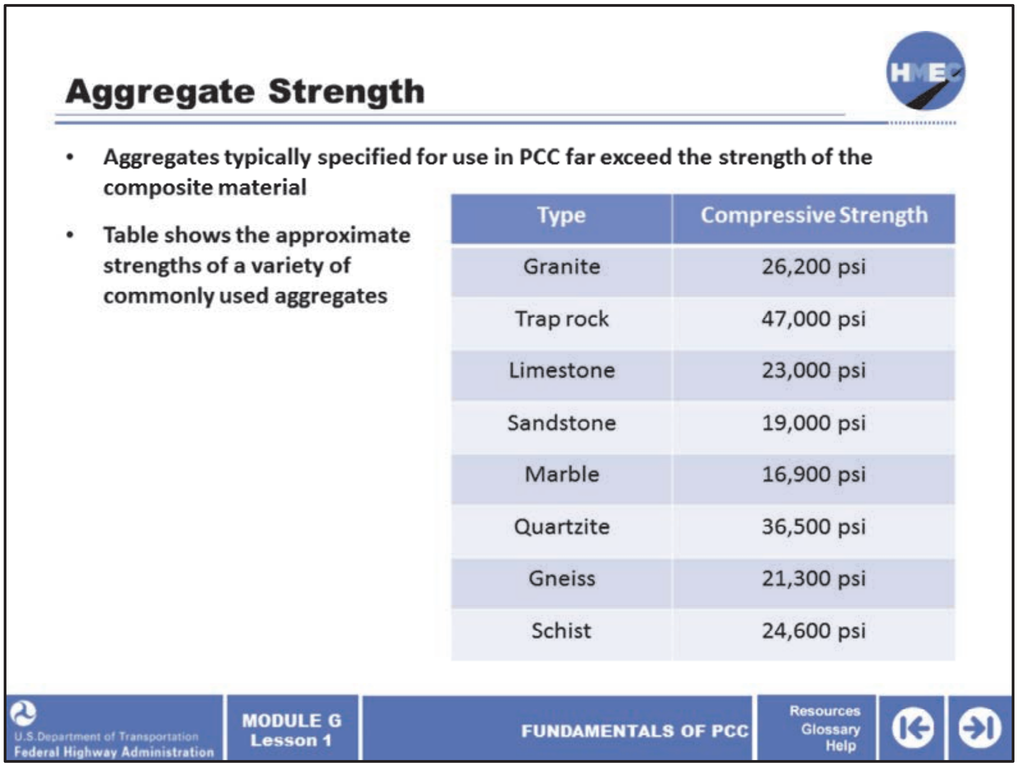
The correct answer is d) Shrinkage.



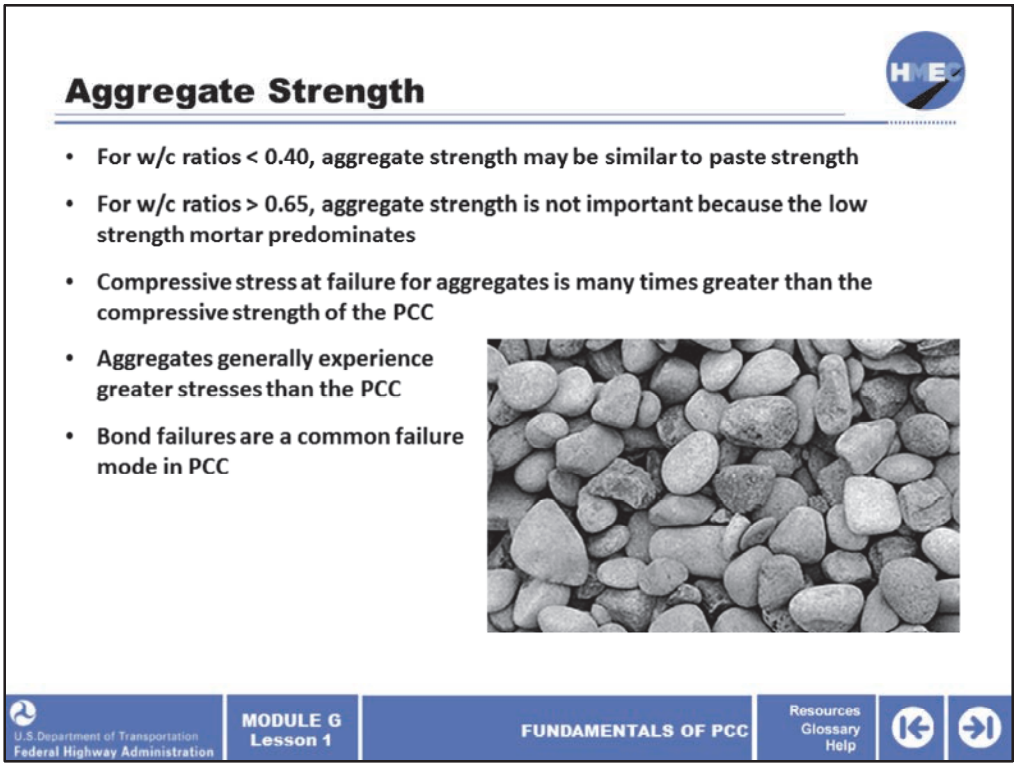
The mechanical properties of PCC represent the combined effect of the constituent materials. In this segment, we will investigate the effects of the following on the overall PCC behavior:

- Aggregate strength;
- Mortar strength; and
- Bond strength.

Image description: Graph of mechanical properties of PCC.



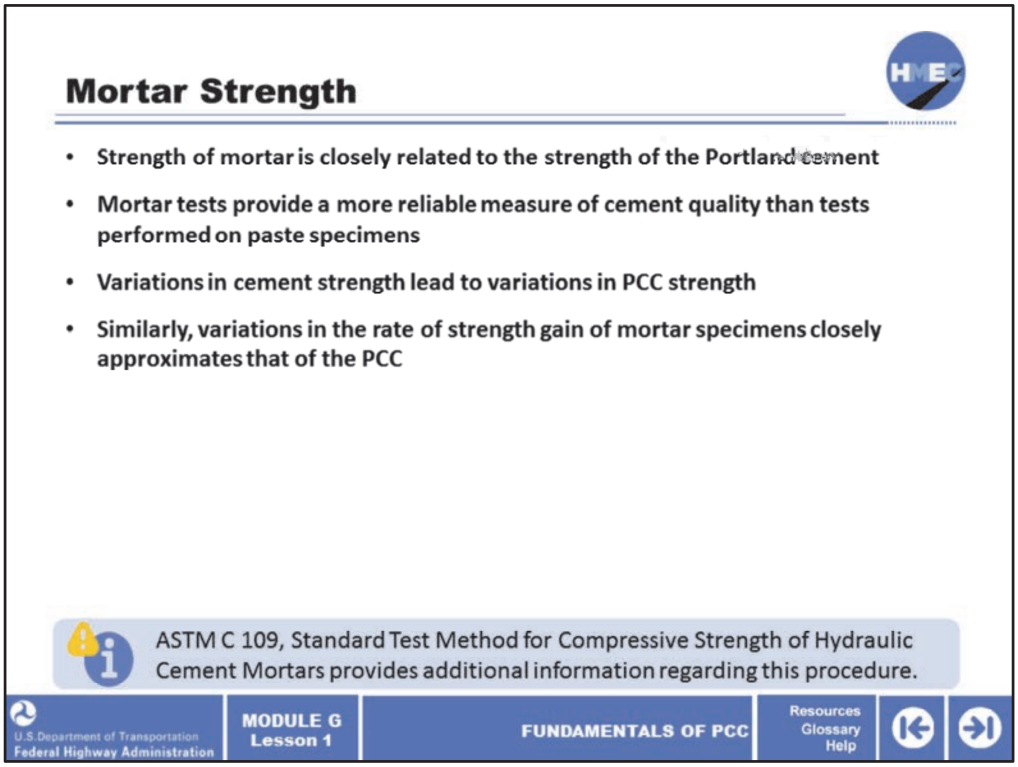
The aggregates typically specified for use in PCC far exceed the strength of the composite material. The table shows the approximate strengths of a variety of commonly used aggregates. A typical PCC mix using limestone aggregate might have a target strength of 3,500 to 4,500 psi.



For water to cement ratios less than 0.40, aggregate strength may be similar to paste strength. For water to cement ratios greater than 0.65, aggregate strength is not important because the low strength mortar predominates.

The compressive stress at failure for aggregates is many times greater than the compressive strength of the PCC. Aggregates generally experience greater stresses than the PCC. Bond failures are a common failure mode in PCC.

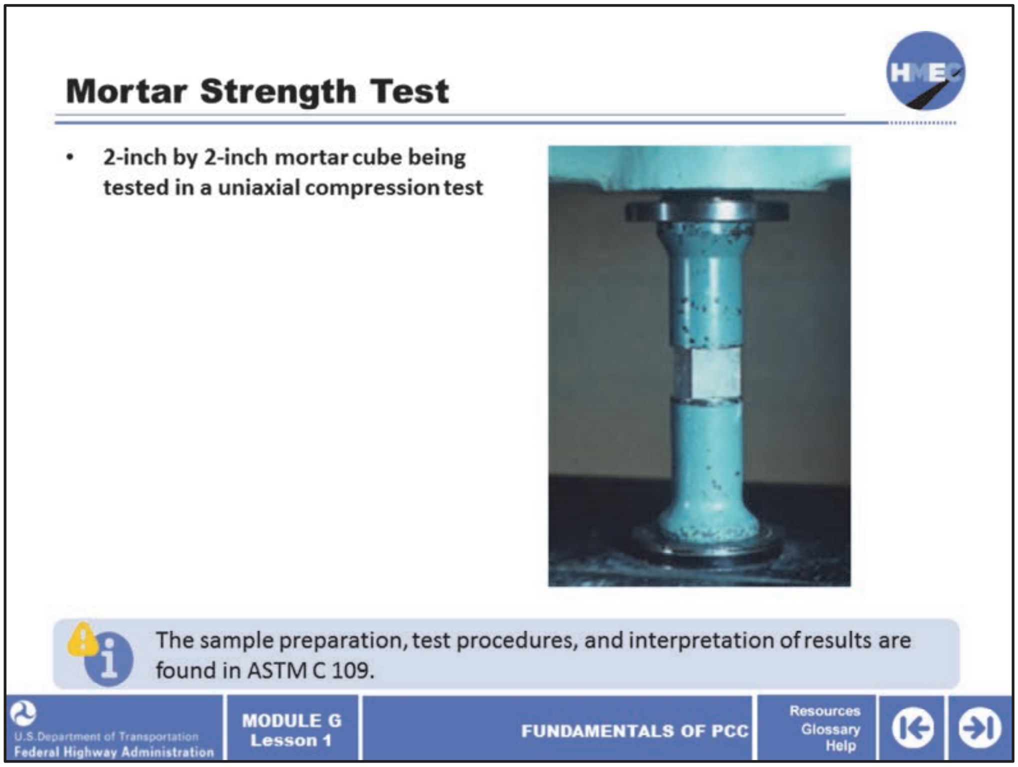
Image description: Photo of aggregate.



The strength of mortar is closely related to the strength of the Portland cement. Mortar tests provide a more reliable measure of cement quality than tests performed on paste specimens.

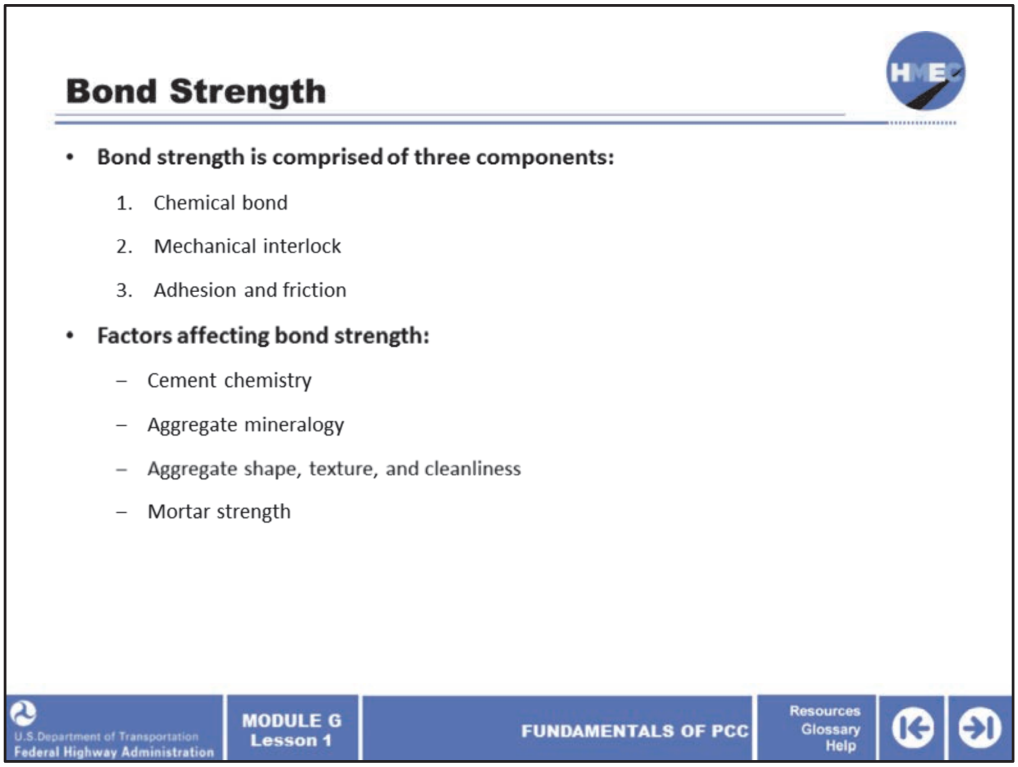
Variations in cement strength lead to variations in PCC strength. Similarly, variations in the rate of strength gain of mortar specimens closely approximates that of the PCC.

ASTM C 109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars provides additional information regarding this procedure.



The photo shows a 2-inch by 2-inch mortar cube being tested in a uniaxial compression test. The sample preparation, test procedures, and interpretation of results are found in ASTM C 109.

Image description: Photo showing a 2-inch by 2-inch mortar cube being tested in a uniaxial compression test.

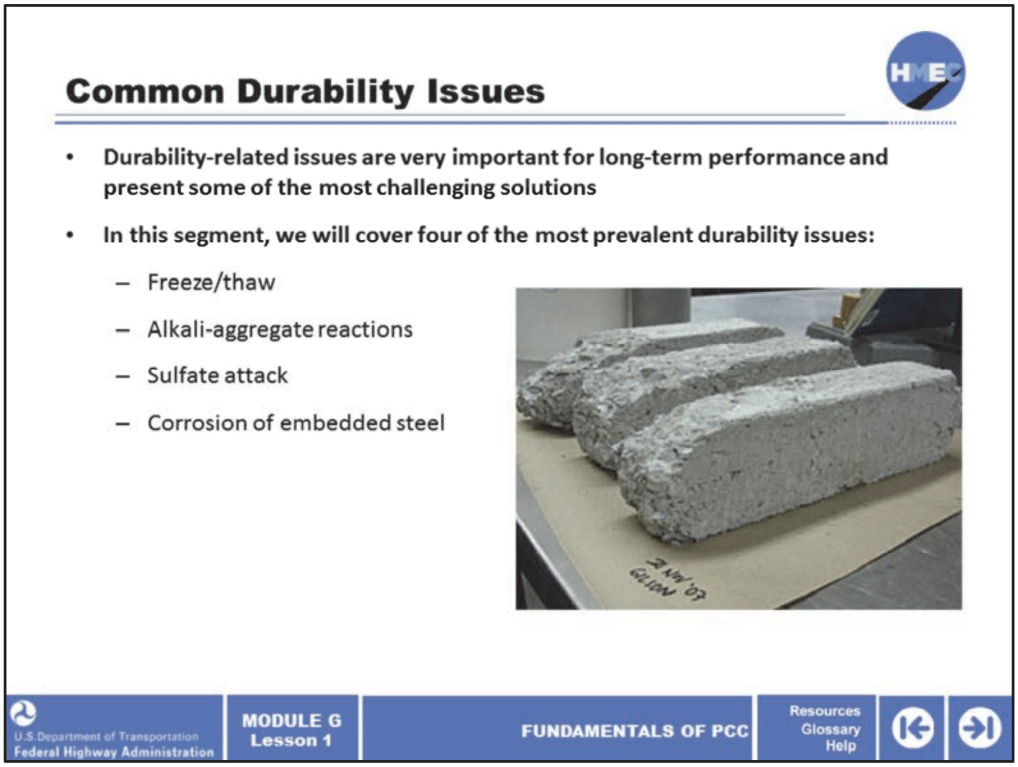


Bond strength is comprised of three components:

1. Chemical bond;
2. Mechanical interlock; and
3. Adhesion and friction.

Factors affecting bond strength are:

- Cement chemistry;
- Aggregate mineralogy;
- Aggregate shape, texture, and cleanliness; and
- Mortar strength, based on w/c ratio, time, temperature, and curing.

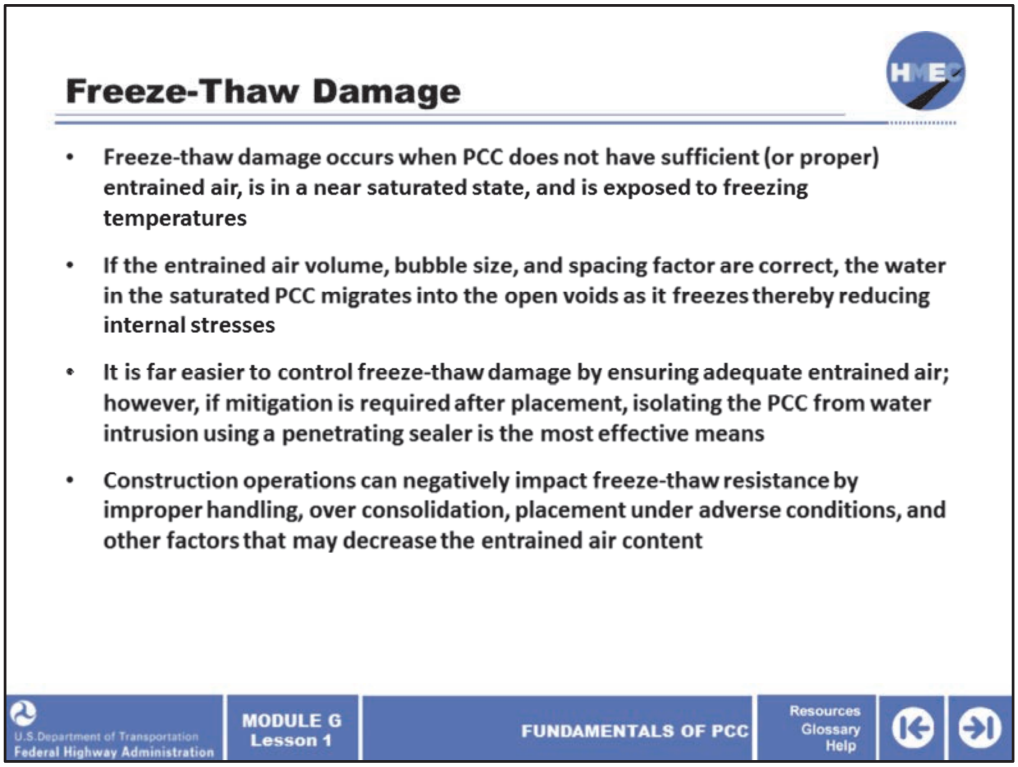


Durability-related issues are very important for long-term performance and present some of the most challenging solutions. In this segment, we will cover four of the most prevalent durability issues:

- Freeze/thaw;
- Alkali-aggregate reactions;
- Sulfate attack; and
- Corrosion of embedded steel.

This is not an all-inclusive list but does represent the majority of the issues you are likely to encounter.

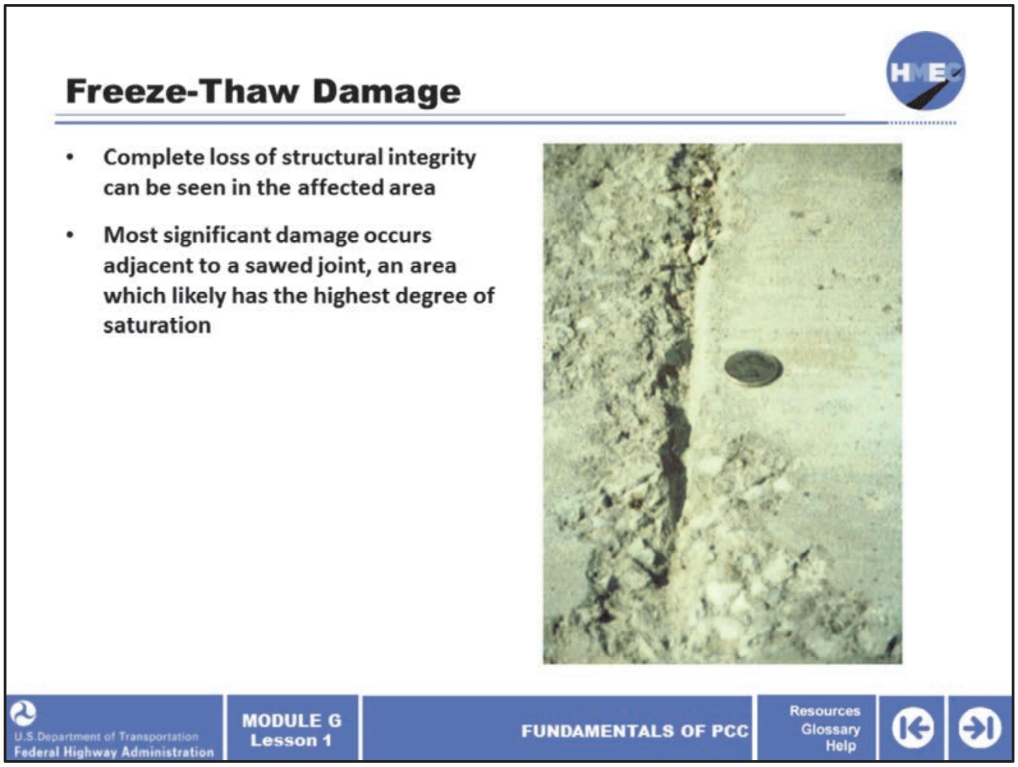
Image description: Photo of multiple concrete samples in various stages of decay.



Freeze-thaw damage occurs when PCC does not have sufficient (or proper) entrained air, is in a near saturated state, and is exposed to freezing temperatures. If the entrained air volume, bubble size, and spacing factor are correct, the water in the saturated PCC migrates into the open voids as it freezes thereby reducing internal stresses.

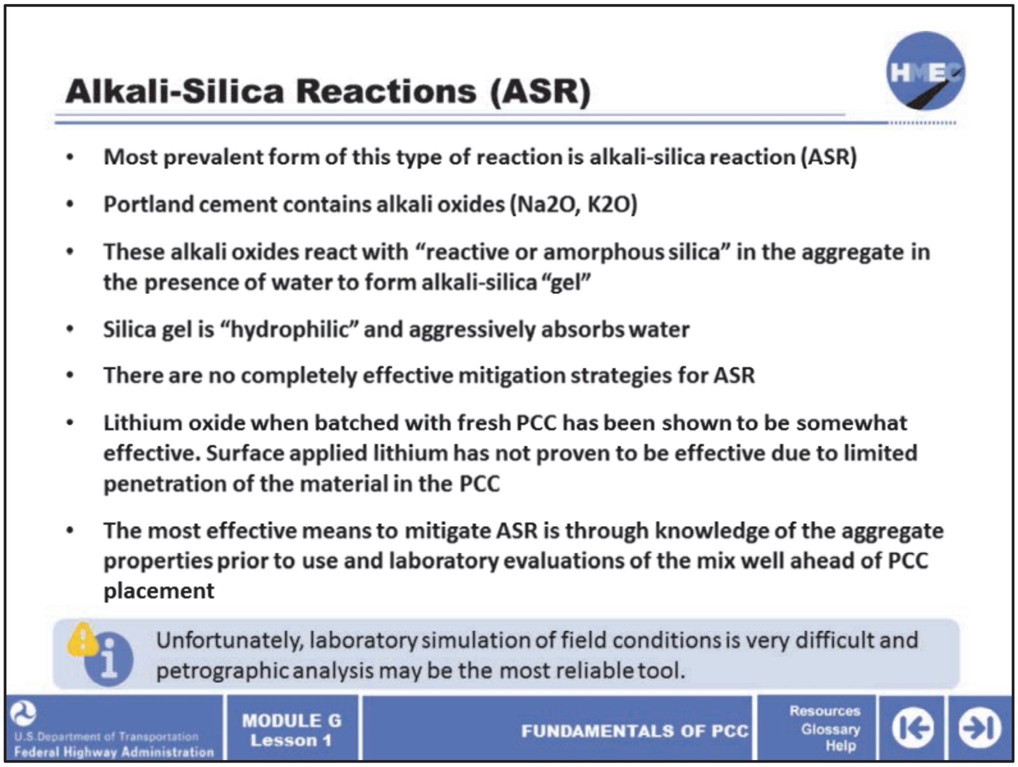
It is far easier to control freeze-thaw damage by ensuring adequate entrained air. However, if mitigation is required after placement, isolating the PCC from water intrusion using a penetrating sealer is the most effective means.

Construction operations can negatively impact freeze-thaw resistance by improper handling, over consolidation, placement under adverse conditions, and other factors that may decrease the entrained air content.



This photo illustrates the effects of freeze-thaw damage. The complete loss of structural integrity can be seen in the affected area. Note that the most significant damage occurs adjacent to a sawed joint, an area which likely has the highest degree of saturation.

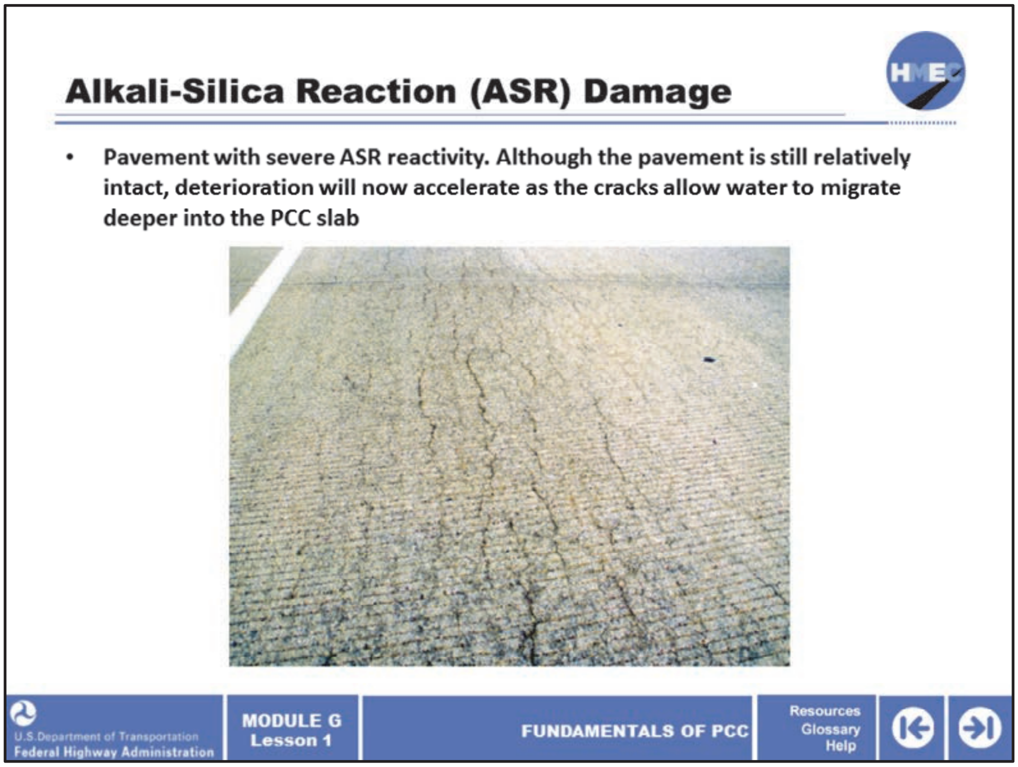
Image description: Photo illustrating the effects of freeze-thaw damage.



The most prevalent form of an alkali-aggregate reaction is alkali-silica reaction (ASR). Portland cement contains alkali oxides, such as Na_2O, K_2O.

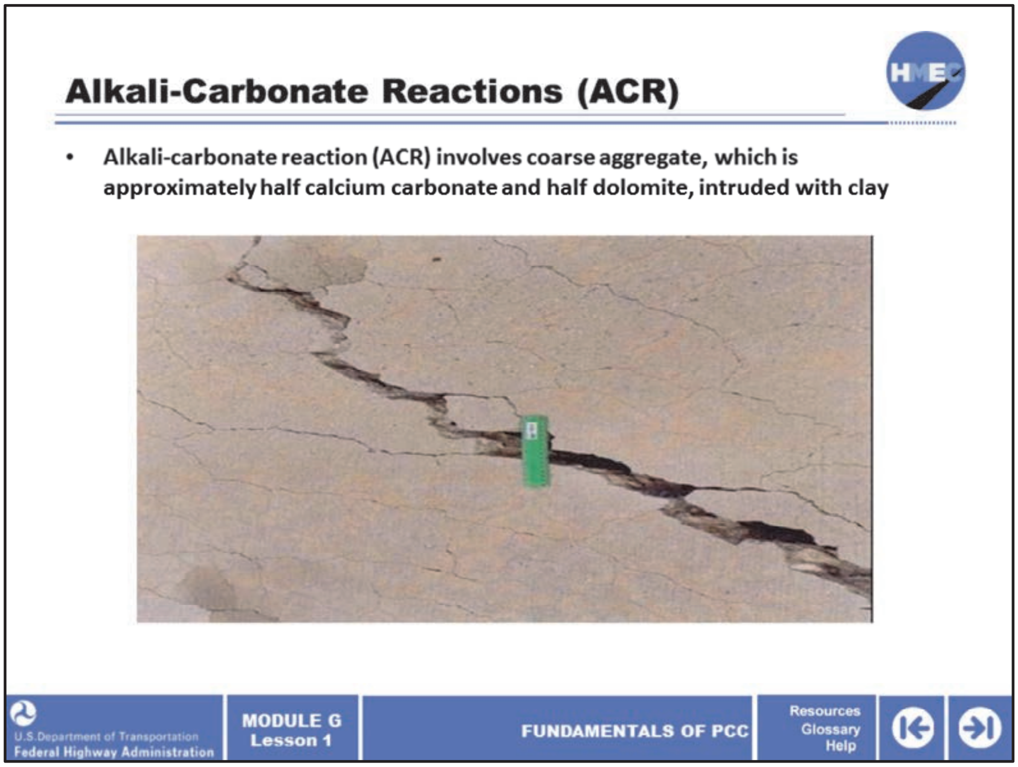
These alkali oxides react with “reactive or amorphous silica” in the aggregate in the presence of water to form alkali-silica “gel.“ Silica gel is “hydrophilic” and aggressively absorbs water.

Since the silica gel is more viscous than water, the water cannot diffuse back through pores. Osmotic pressure develops, causing cracking. There are no completely effective mitigation strategies for ASR although lithium oxide treatments have been used on occasion. The most effective means to mitigate ASR is through laboratory evaluations well ahead of PCC placement. Unfortunately, the laboratory simulation of field conditions is very difficult (considerable research has been conducted in this area) and petrographic analysis may be the most reliable tool.



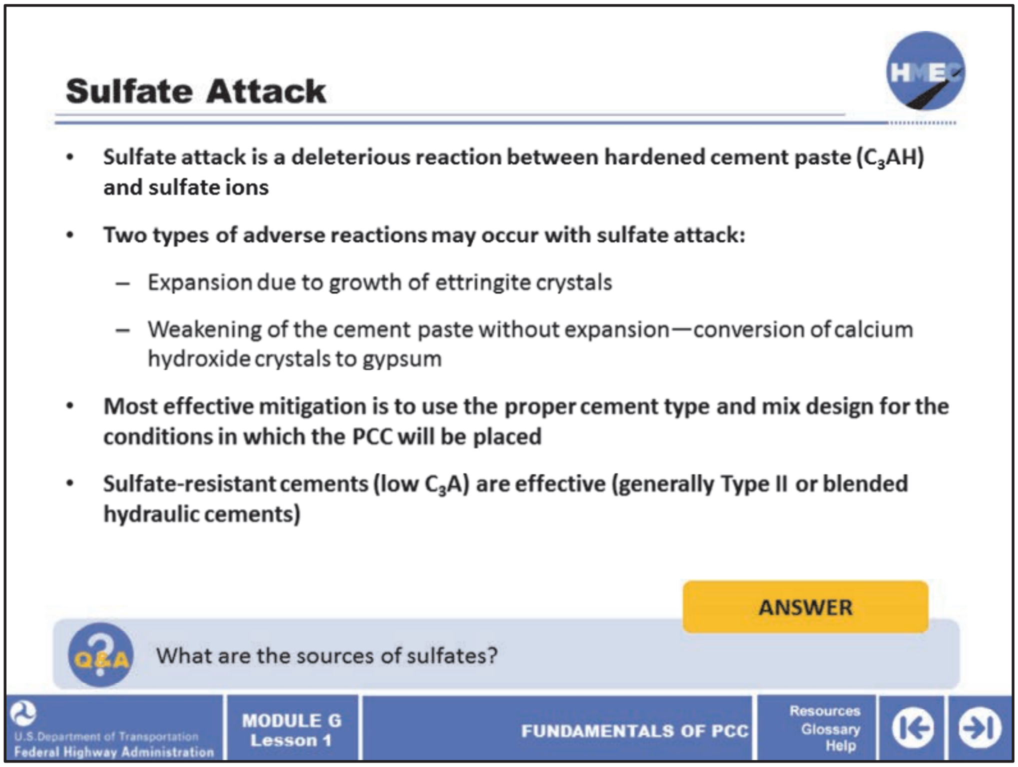
This photo shows a pavement with severe ASR reactivity. Although the pavement is still relatively intact, deterioration will now accelerate as the cracks allow water to migrate deeper into the PCC slab.

Image description: Photo of pavement with ASR reactivity (cracks in pavement).



The alkali-carbonate reaction (ACR) involves coarse aggregate, which is approximately half calcium carbonate and half dolomite, intruded with clay. Although not prevalent, this reaction can occur if proper testing is not conducted on the sample using the aggregate and cement that will be used during construction according to ASTM C 586.

Image description: Photo of ACR.



Sulfate attack is a deleterious reaction between hardened cement paste and sulfate ions.

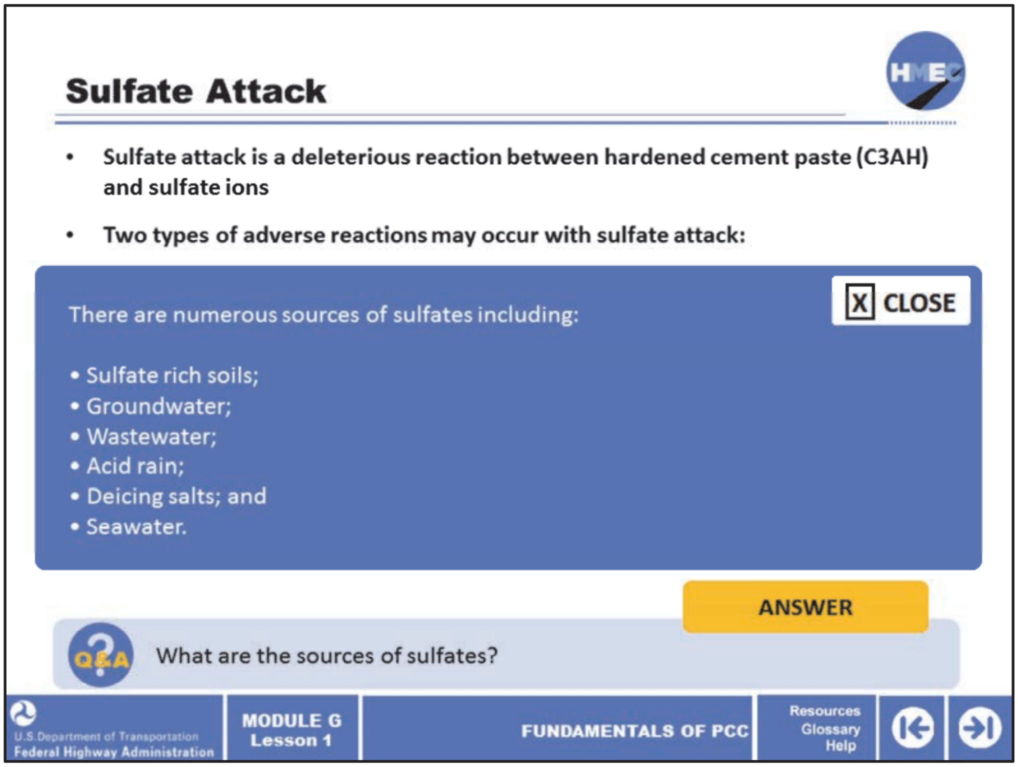
Two types of adverse reactions may occur with sulfate attack:

- Expansions due to growth of ettringite crystals; and
- Weakening of the cement paste without expansion, or conversion of calcium hydroxide crystals to gypsum.

The most effective mitigation is to use the proper cement type and mix design for the conditions in which the PCC will be placed.

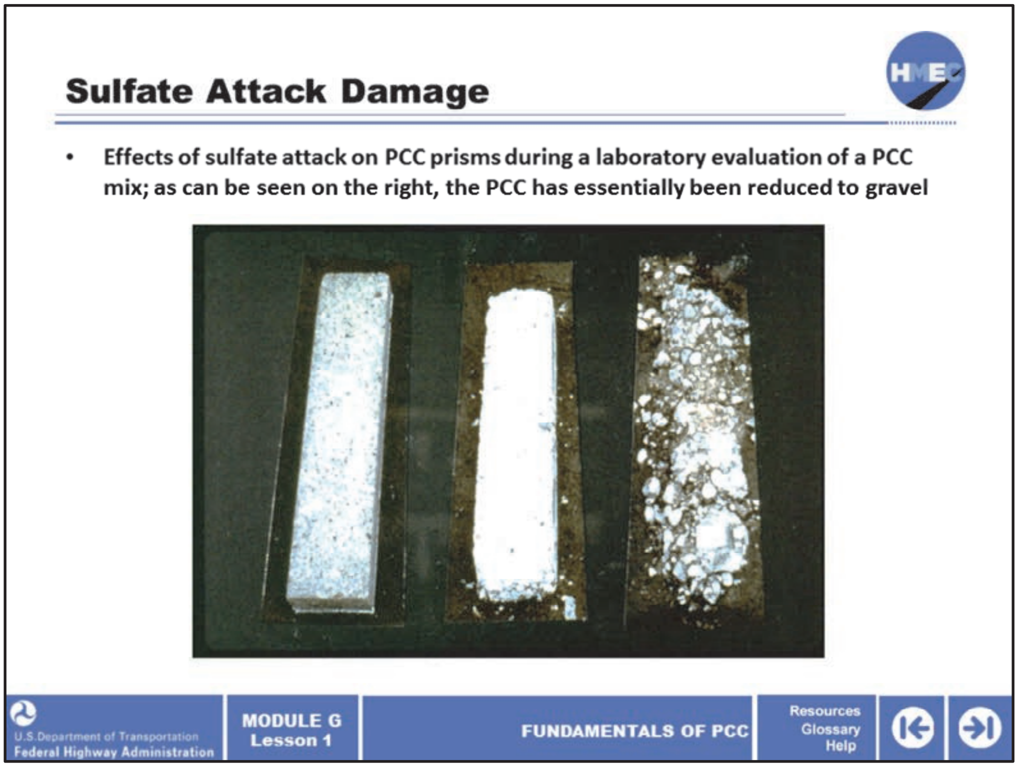
Sulfate-resistant cements (low C_3A) are effective (generally Type II or blended hydraulic cements). However, tests have shown paste permeability may be more important than cement chemistry. The most effective means to reduce paste permeability is by lowering the w/c ratio.

What are the sources of sulfates? Select the answer button for more information.



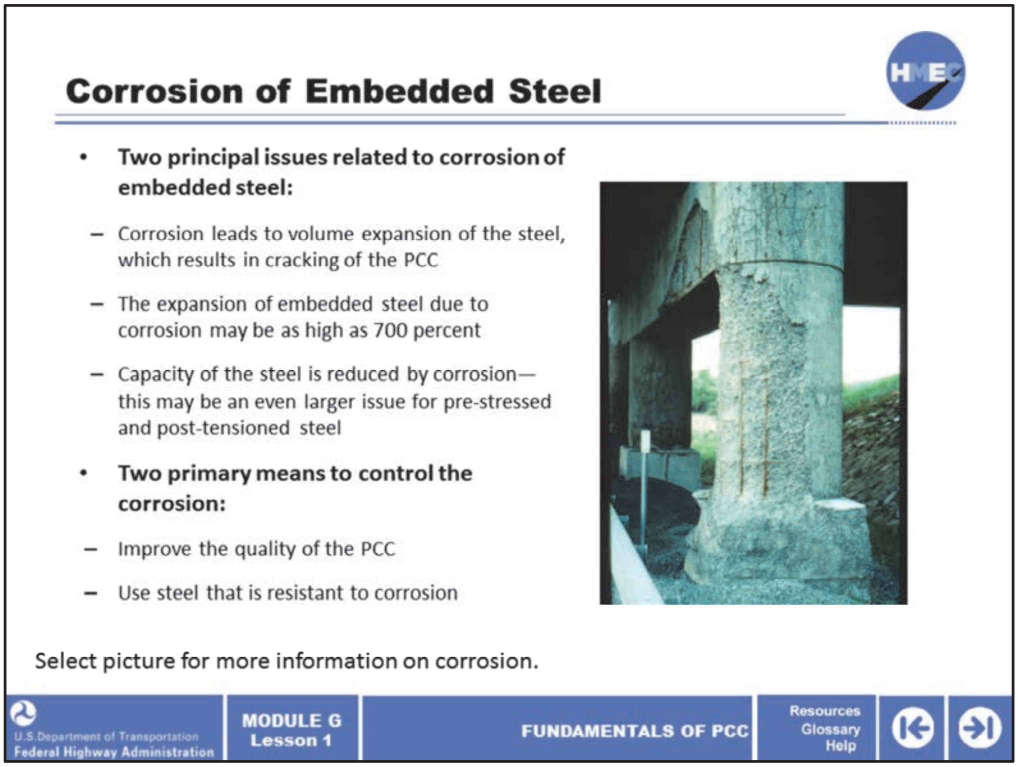
There are numerous sources of sulfates including:

• Sulfate rich soils;
• Groundwater;
• Wastewater;
• Acid rain;
• Deicing salts; and
• Seawater.



This photo illustrates the effects of sulfate attack on PCC prisms during a laboratory evaluation of a PCC mix. As can be seen on the right, the PCC has essentially been reduced to gravel.

Image description: Photo of different phases of sulfate attack on PCC prisms.



The photo illustrates severe PCC damage as a result of corrosion of the reinforcing steel.

There are three principal issues related to corrosion of embedded steel:

- The corrosion leads to volume expansion of the steel, which results in cracking of the PCC;
- Note that the expansion of embedded steel due to corrosion may be as high as 700 percent; and
- The capacity of the steel is reduced by corrosion. This may be an even larger issue for pre-stressed and post-tensioned steel.

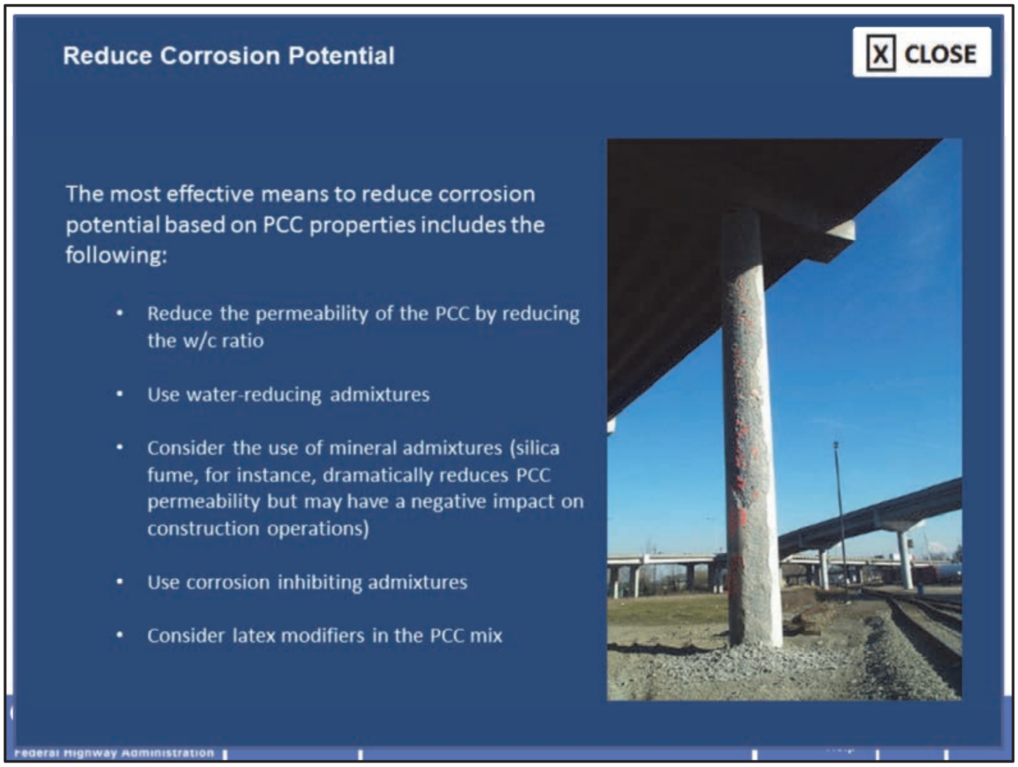
The corrosion may be due to chloride-induced corrosion, such as deicing salts, seawater, chloride admixtures, and carbonation effects.

There are two primary means to control the corrosion:

- Improve the quality of the PCC; and
- Use steel that is resistant to corrosion.

Select the picture for more information on corrosion.

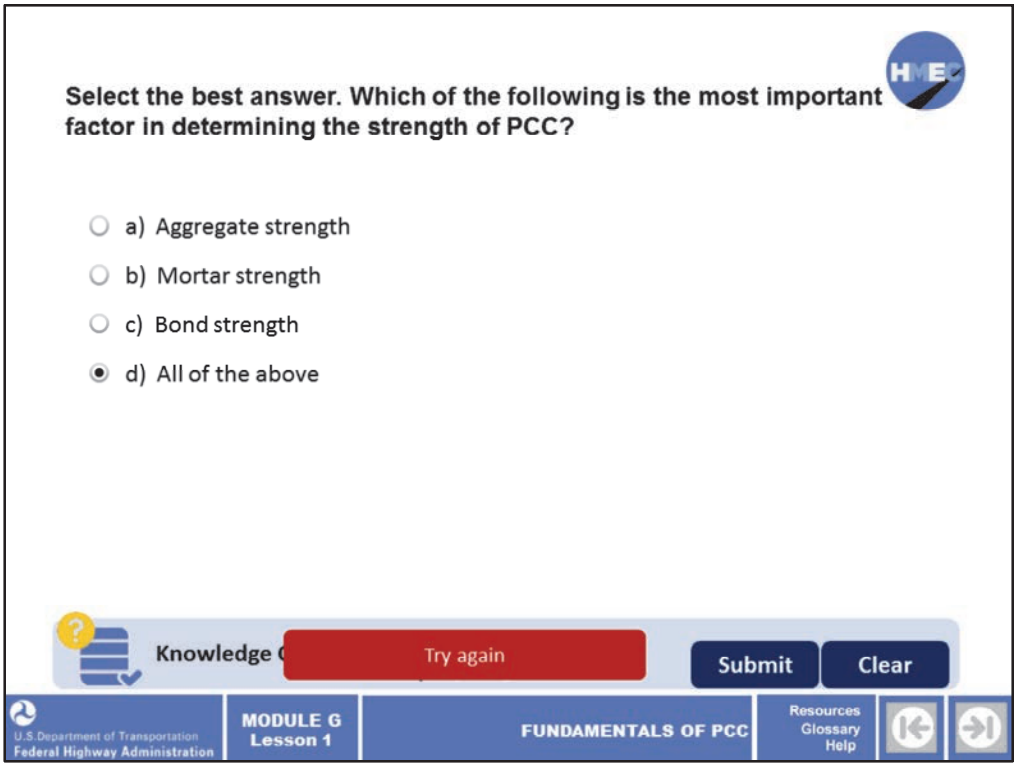
Image description: Photo of a corroded bridge pier.



The most effective means to reduce corrosion potential based on PCC properties includes the following:

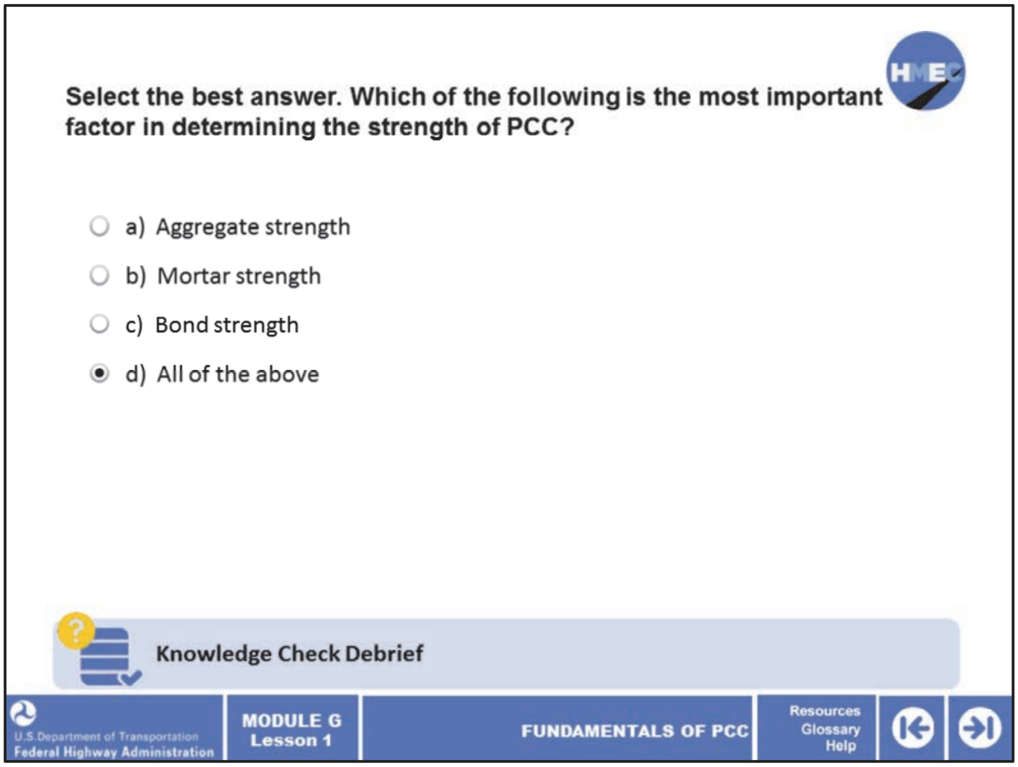
- Reduce the permeability of the PCC by reducing the w/c ratio;
- Use water-reducing admixtures;
- Consider the use of mineral admixtures (silica fume, for instance, dramatically reduces PCC permeability but may have a negative impact on construction operations);
- Use corrosion inhibiting admixtures; and
- Consider latex modifiers in the PCC mix.

Image description: Photo of a corroded bridge pier.

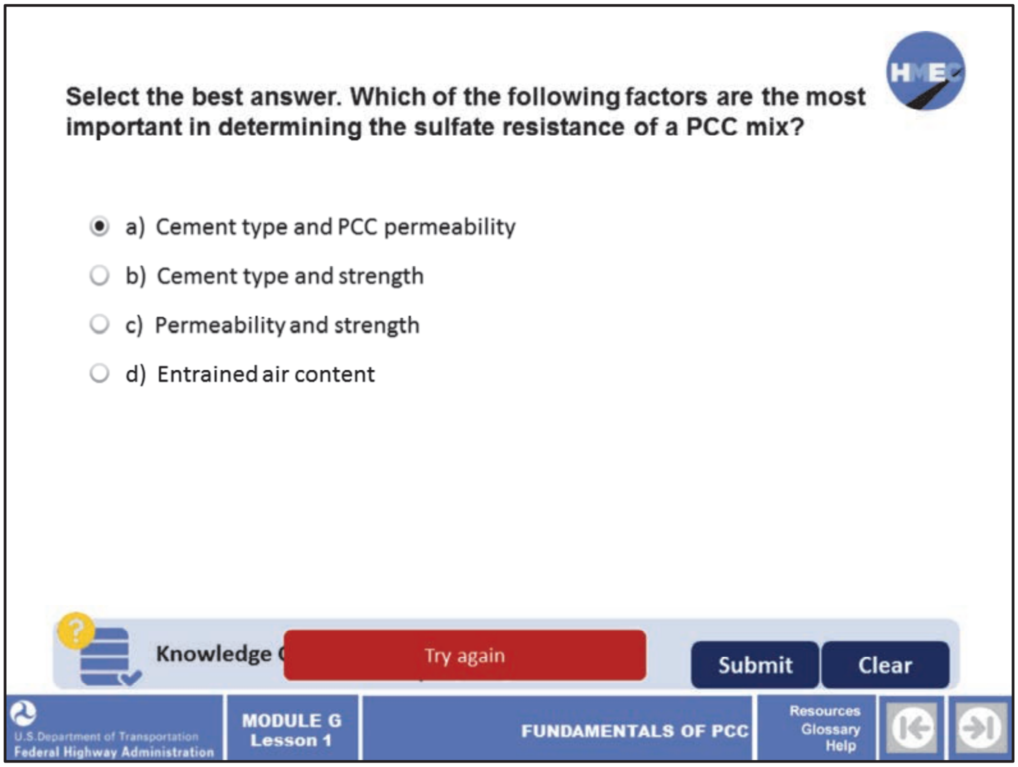


Select the best answer. Which of the following is the most important factor in determining the strength of PCC?

a) Aggregate strength;
b) Mortar strength;
c) Bond strength; or
d) All of the above.

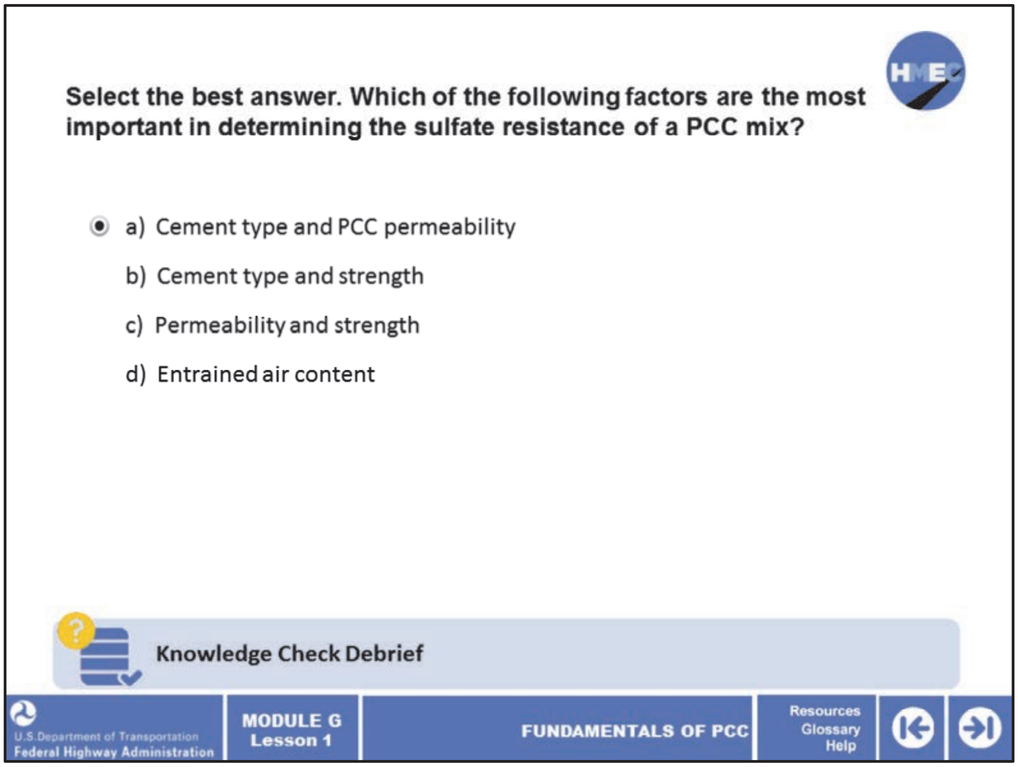


The correct answer is d) All of the above.

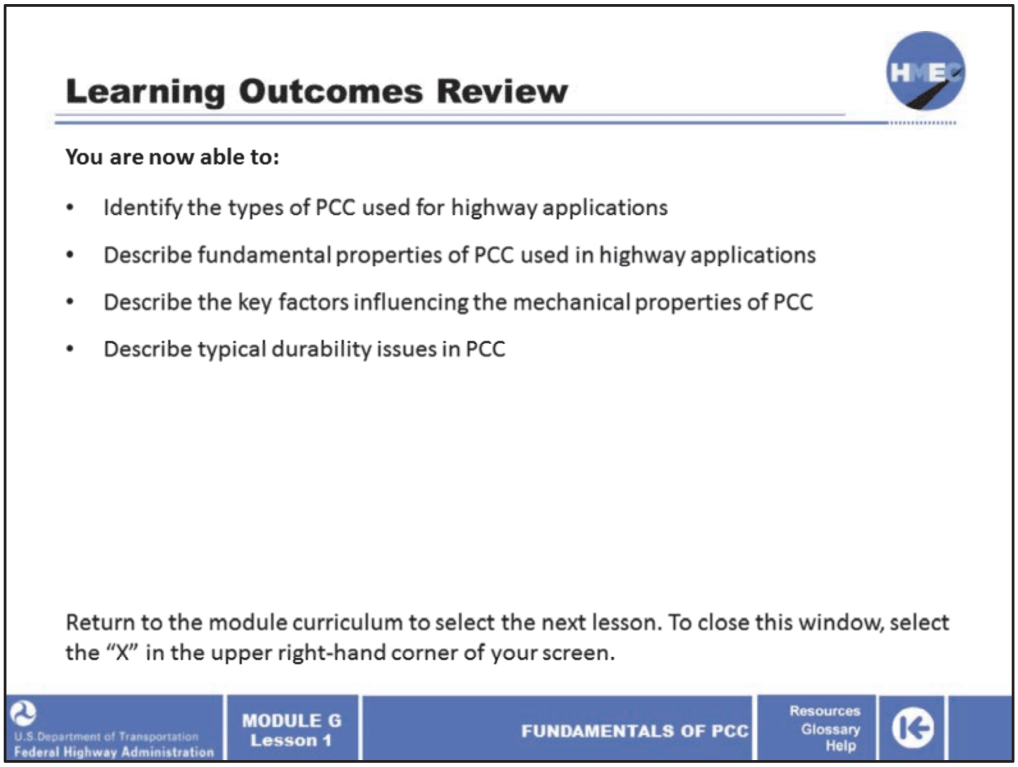


Select the best answer. Which of the following factors are the most important in determining the sulfate resistance of a PCC mix?

a) Cement type and PCC permeability;
b) Cement type and strength;
c) Permeability and strength; or
d) Entrained air content.



The correct answer is a) Cement type and PCC permeability.



You have completed Module G, Lesson 1: Fundamentals of PCC.

You are now able to:

- Identify the types of PCC used for highway applications;
- Describe fundamental properties of PCC used in highway applications;
- Describe the key factors influencing the mechanical properties of PCC; and
- Describe typical durability issues in PCC.

Close this lesson, and return to the module curriculum to select the next lesson. To close this window, select the "X" in the upper right-hand corner of your screen.