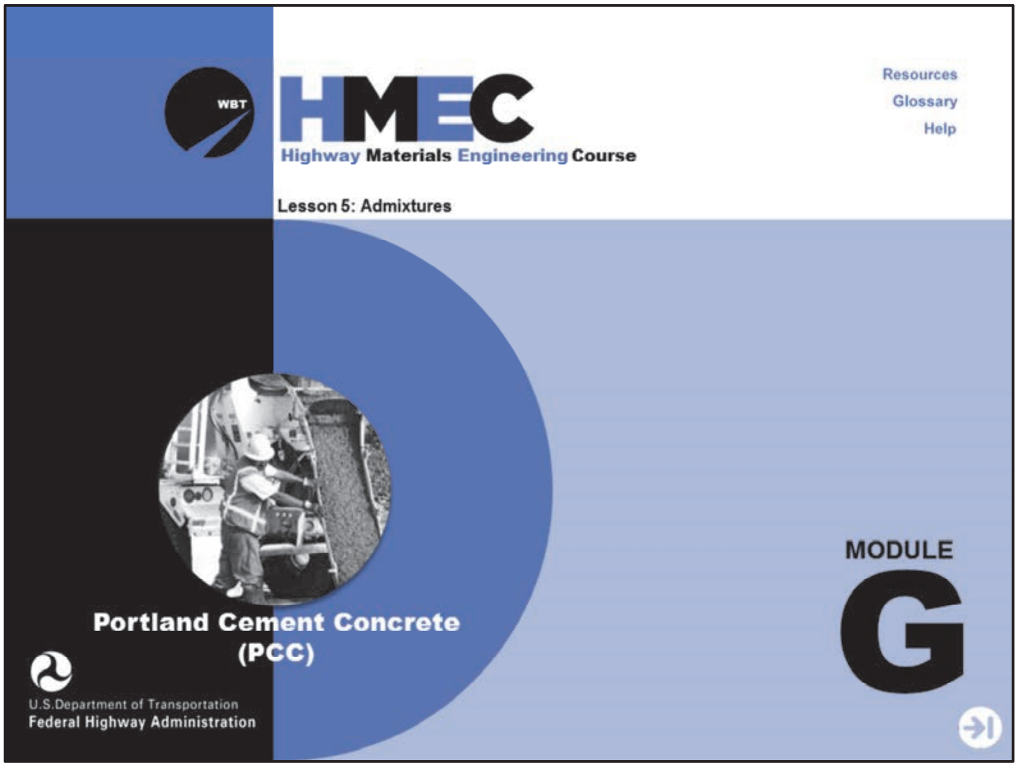
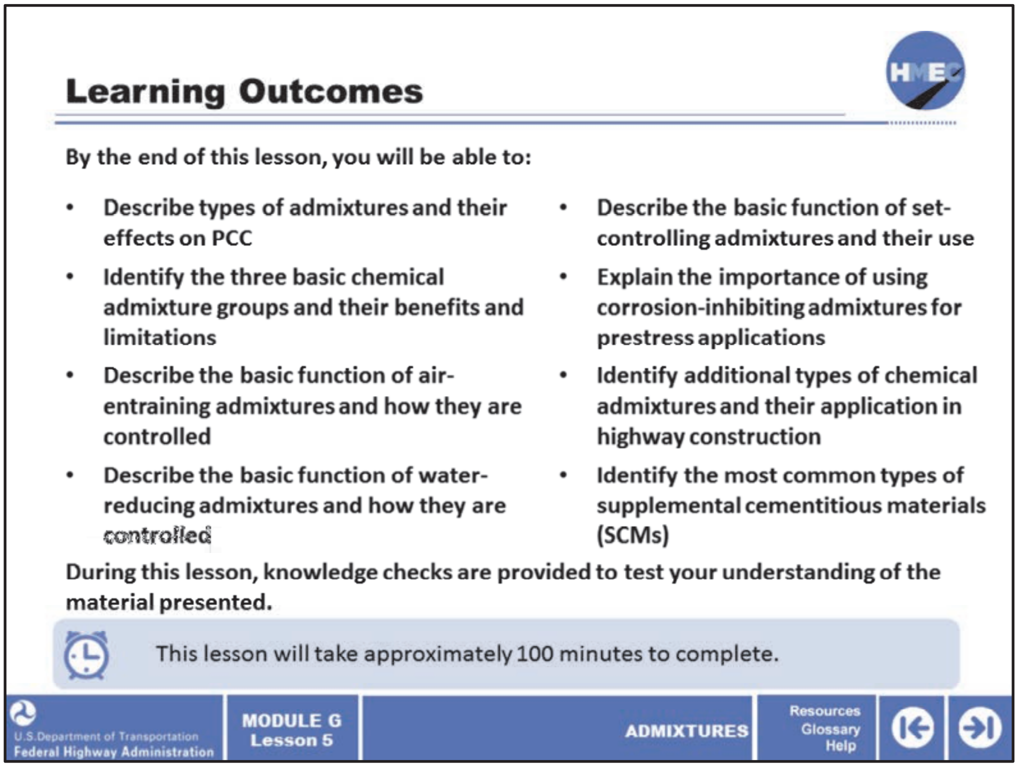


Welcome to the Highway Materials Engineering Course (HMEC) Module G, Lesson 5: Admixtures. This lesson will focus on the different types of admixtures.

A printer-friendly version of the lesson materials can be downloaded by selecting the paperclip icon. Only the slides for the this lesson are available.

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

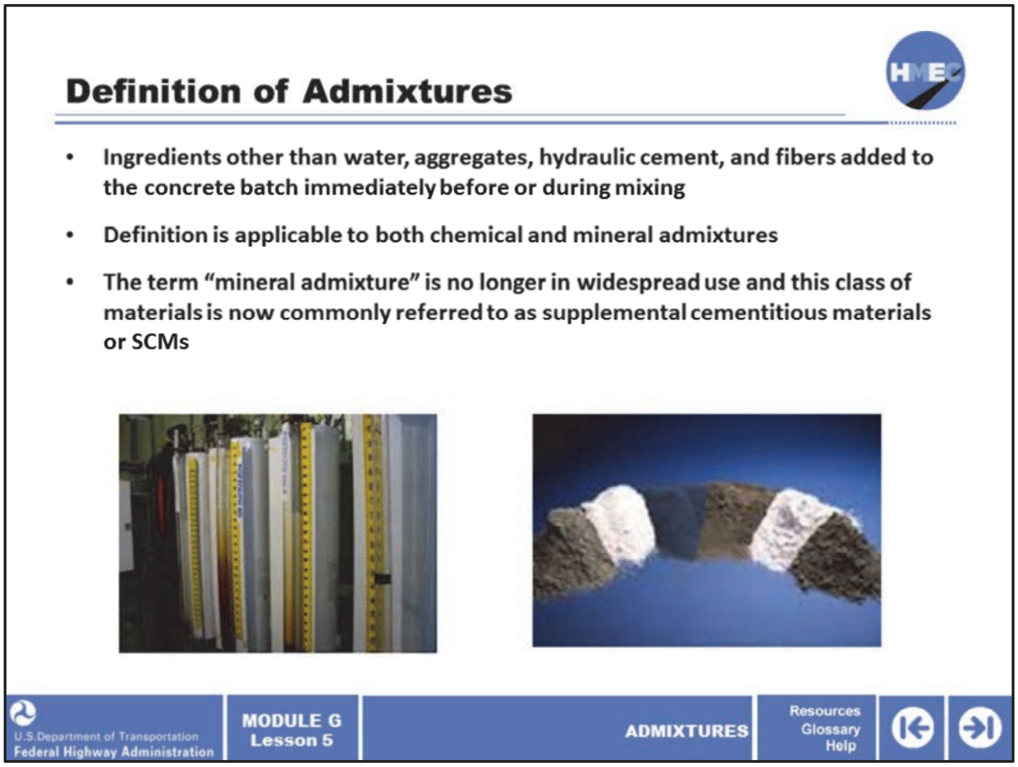


By the end of this lesson, you will be able to:

• Describe types of admixtures and their effects on Portland cement concrete (PCC);
• Identify the three basic chemical admixture groups and their benefits and limitations;
• Describe the basic function of air-entraining admixtures and how they are controlled;
• Describe the basic function of water-reducing admixtures and how they are controlled;
• Describe the basic function of set-controlling admixtures and their use;
• Explain the importance of using corrosion-inhibiting admixtures for prestress applications;
• Identify additional types of chemical admixtures and their application in highway construction; and
• Identify the most common types of supplemental cementitious materials (SCMs).

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

This lesson will take approximately 100 minutes to complete.



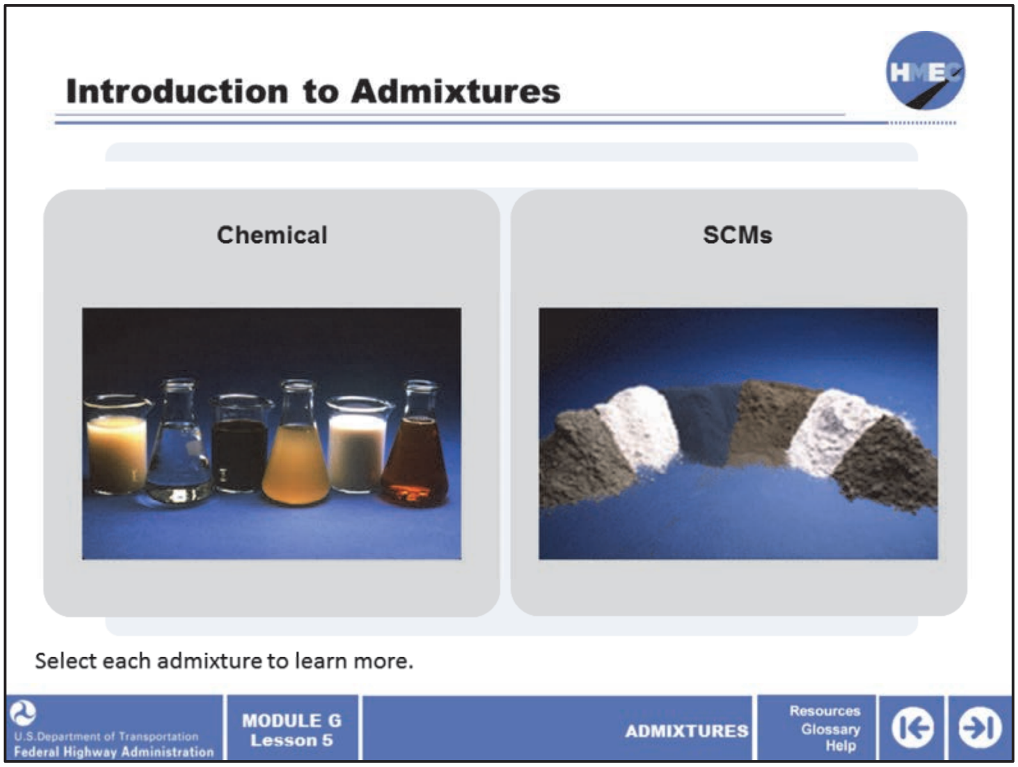
Admixtures, as defined on this slide, encompass all of the various types of admixtures. Admixtures are ingredients other than water, aggregates, hydraulic cement, and fibers that are added to the concrete batch immediately before or during mixing. This definition is applicable to both chemical and SCMs.

The term "mineral admixtures" is no longer in widespread use and this class of materials is now commonly referred to as supplemental cementitious materials, or SCMs. For the remainder of this module, we will use the term SCMs where appropriate. Note that many older references, in addition to research documents, use the term mineral admixtures.

The photo on the left shows the metering of chemical admixtures at a PCC plant. The photo on the right shows Portland cement and various SCMs.

Image description: Photo of the metering of chemical admixtures at a PCC plant.

Image description: Photo of Portland cement and various SCMs.

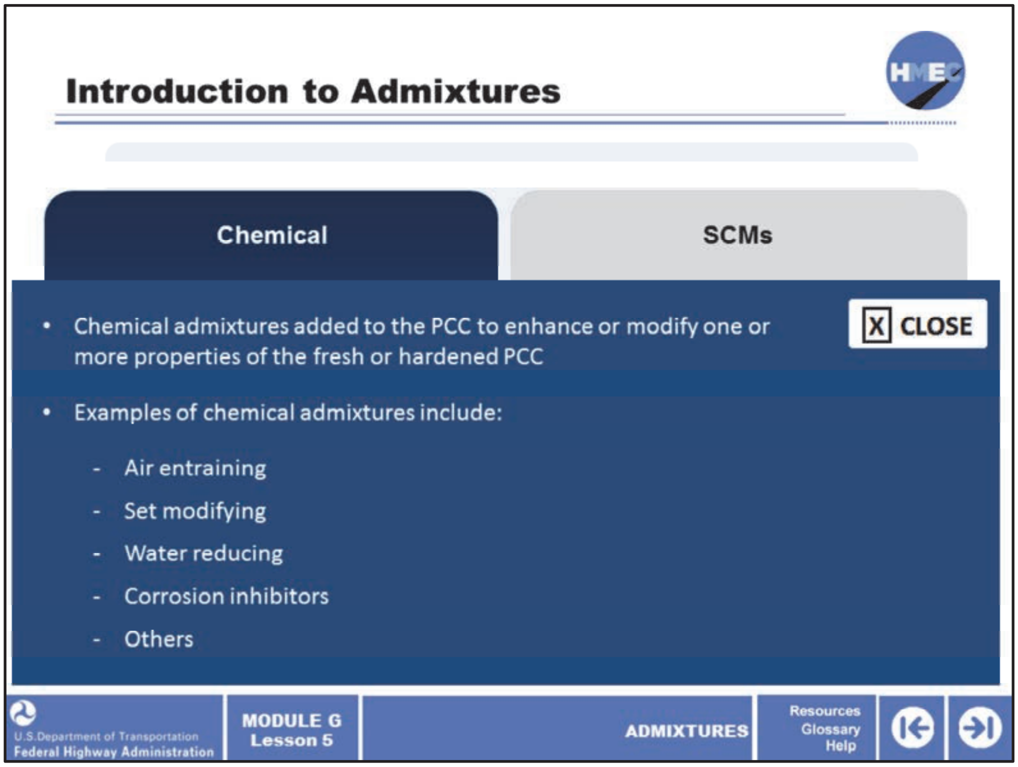


There are generally two types of admixtures: chemical and SCMs. There are, however, many different types of admixtures within these larger designations. It is safe to say that all of the PCC mixes used in highway and other transportation-related uses contain one or more admixtures. Admixtures are used to alter or enhance the PCC in terms of workability, set-time, durability, and other factors we will discuss in this lesson.

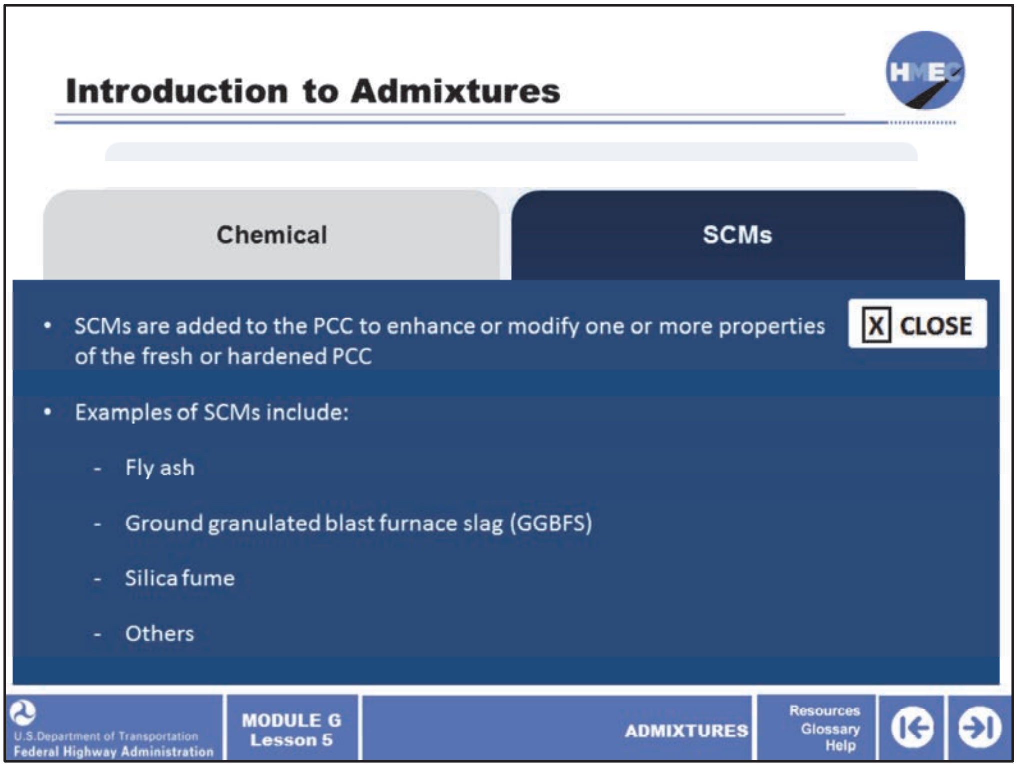
Select each admixture to learn more.

Image description: Photo of beakers filled with chemicals.

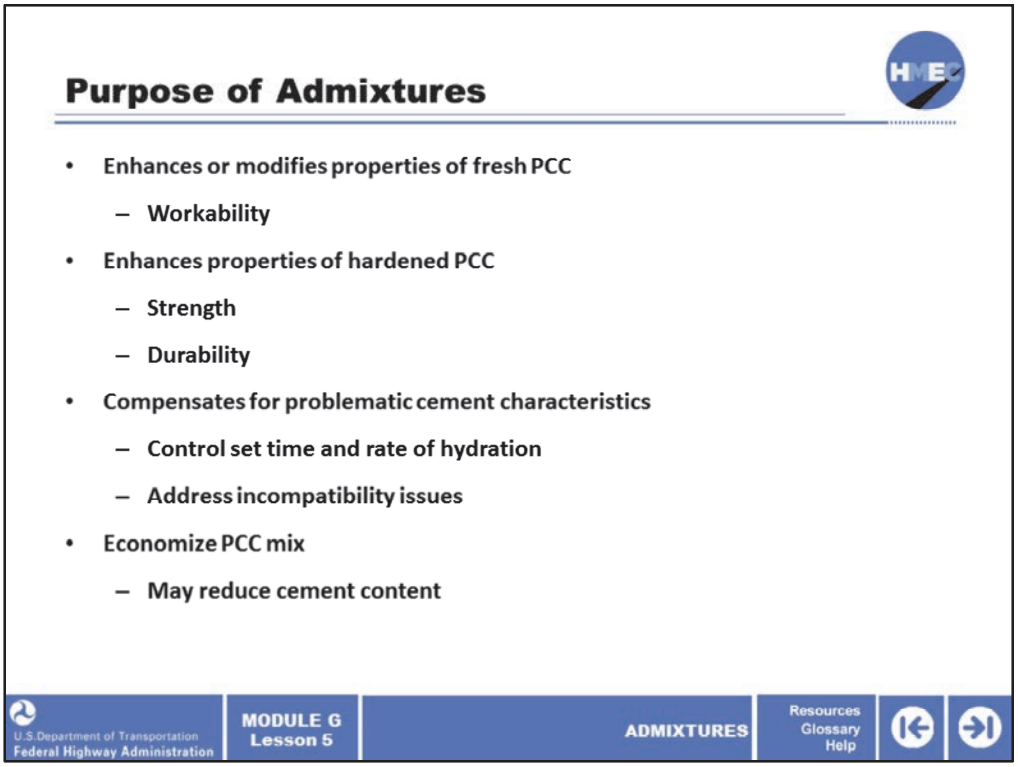
Image description: Photo of Portland cement and various SCMs.



Examples of chemical admixtures include air entraining, set modifying, water reducing, and others.



Examples of SCMs include fly ash, ground granulated blast furnace slag, silica fume, and others.



Admixtures are used for a variety of reasons, ranging from modifying the physical properties of the PCC to saving money. One of the primary uses of admixtures is to enhance the properties of fresh PCC. Equally important, admixtures are used to enhance one or more properties of hardened PCC, to compensate for potentially problematic cement characteristics and to economize the PCC mix.

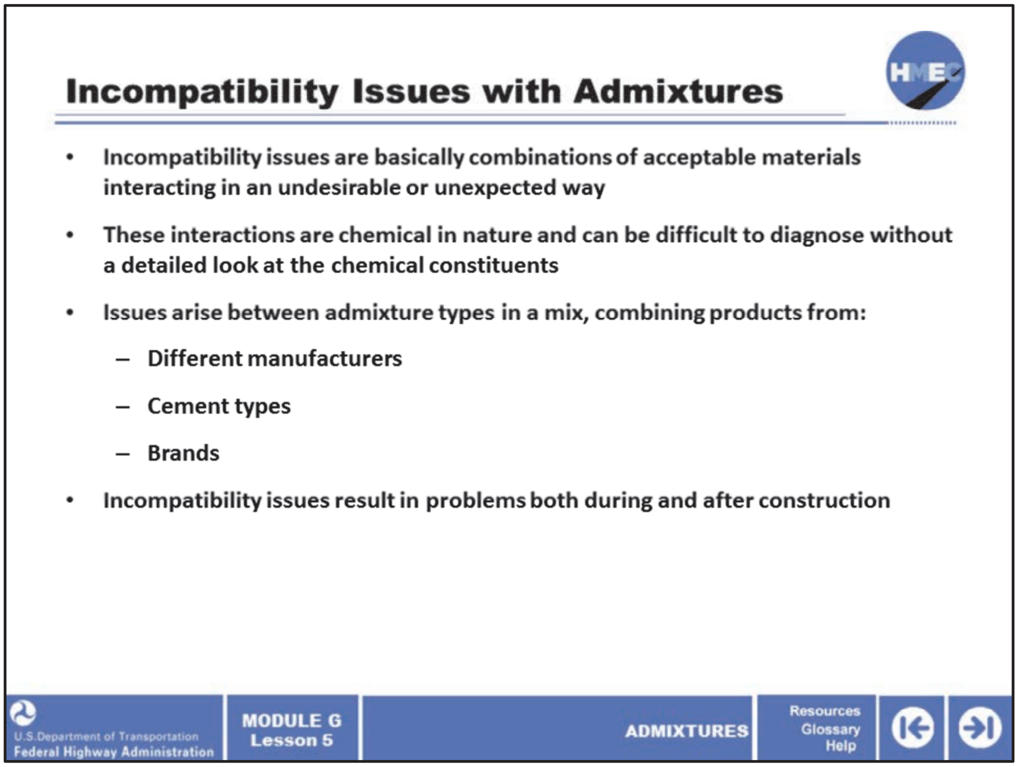
For example, chemical admixtures can be used to modify the following properties:

- Slump;
- Water requirement (water-to-cement (w/c) ratio and total water);
- Entrained air content;
- Time of initial set;
- Rate of hydration; and
- Others.

SCMs are often used for the following reasons:

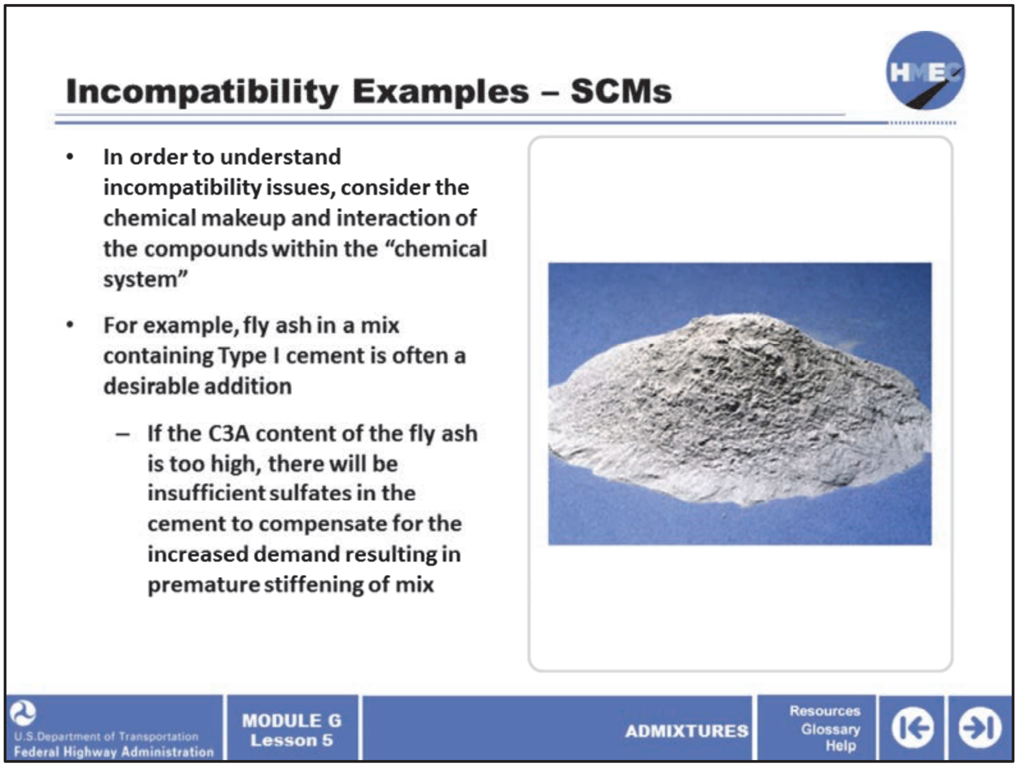
- Mitigate adverse alkali-aggregate reactions;
- Improved durability;
- Economize the mix (depending on SCM used);
- Enhanced strength; and
- Others.

Chemical and/or SCMs are used in virtually all PCC for transportation purposes. By using the correct combination of admixtures, the properties of PCC can be very tightly controlled and beneficial. Keep in mind, however, that compatibility issues do arise between various types of admixtures, and on occasion, cement.



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. Most incompatibility issues result in unusual stiffening and setting, cracking, or air void problems.



In order to understand incompatibility issues, you must consider the chemical makeup and interaction of all the compounds within the "chemical system." The use of fly ash in a mix containing Type I cement is often a desirable addition. However, if the tricalcium aluminate (C3A) 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 C3A and gypsum (sulfates)—a balance maintained during the cement manufacturing.

Image description: Photo of fly ash.

Incompatibility Examples – Chemical Admixtures

- Chemical admixtures are added separately during the batching process; failure to do so can result in a significant reduction in the efficiency of one or both of the admixtures
- The most typical scenario would be an air-entraining admixture reacting with a water reducer, the end result being an entrained air content that is very hard to control (generally on the high side)

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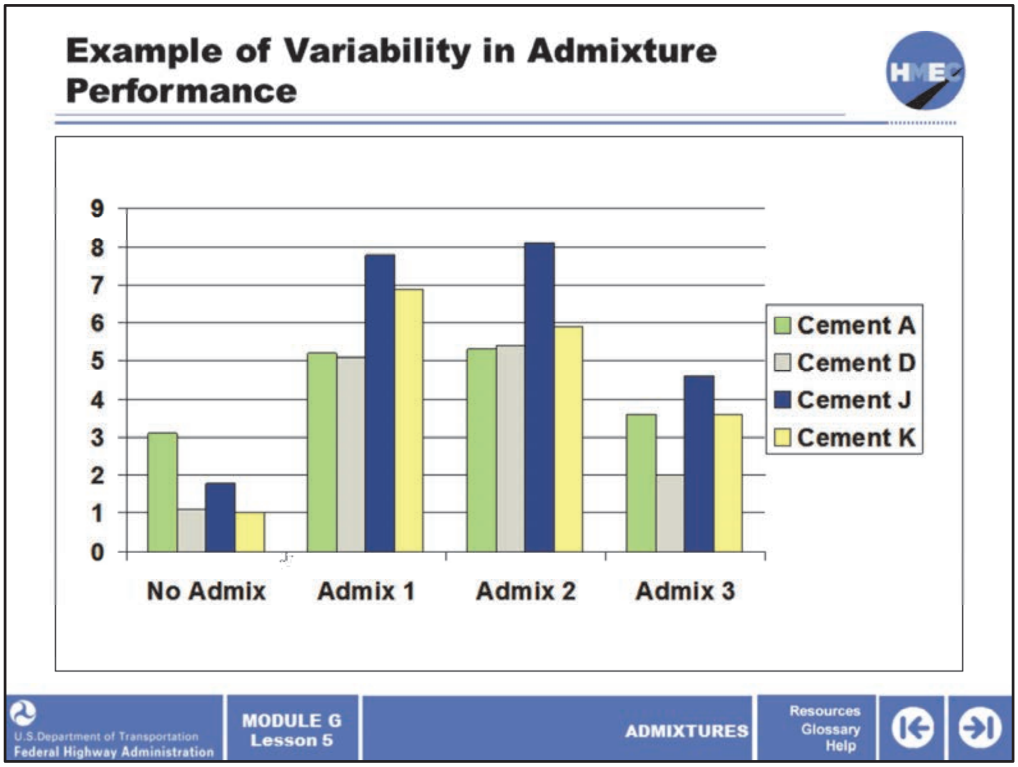
Chemical admixtures are added separately during the batching process. Failure to do so can result in a significant reduction in the efficiency of one or both of the admixtures. The most typical scenario would be an air-entraining admixture reacting with a water reducer, the end result being an entrained air content that is very hard to control (generally on the high side).

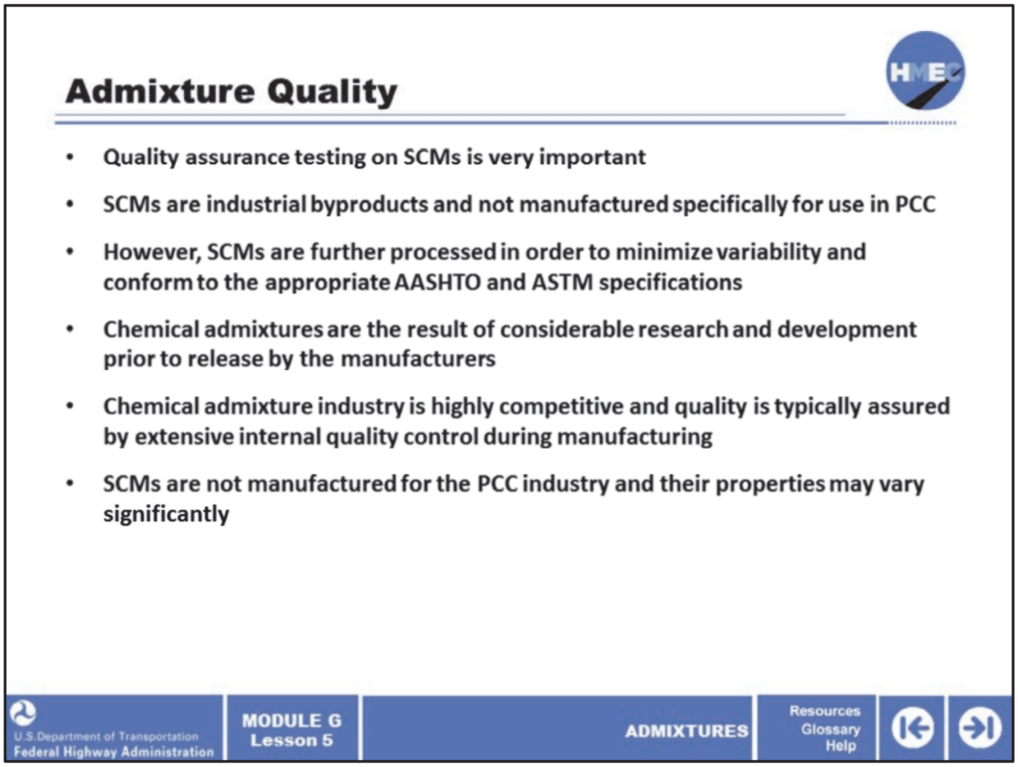
Incompatibilities are oftentimes the result of mixing various components from different sources without first performing trial batches to confirm performance.

Image description: Photo of chemical admixtures.



The graph here, 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.

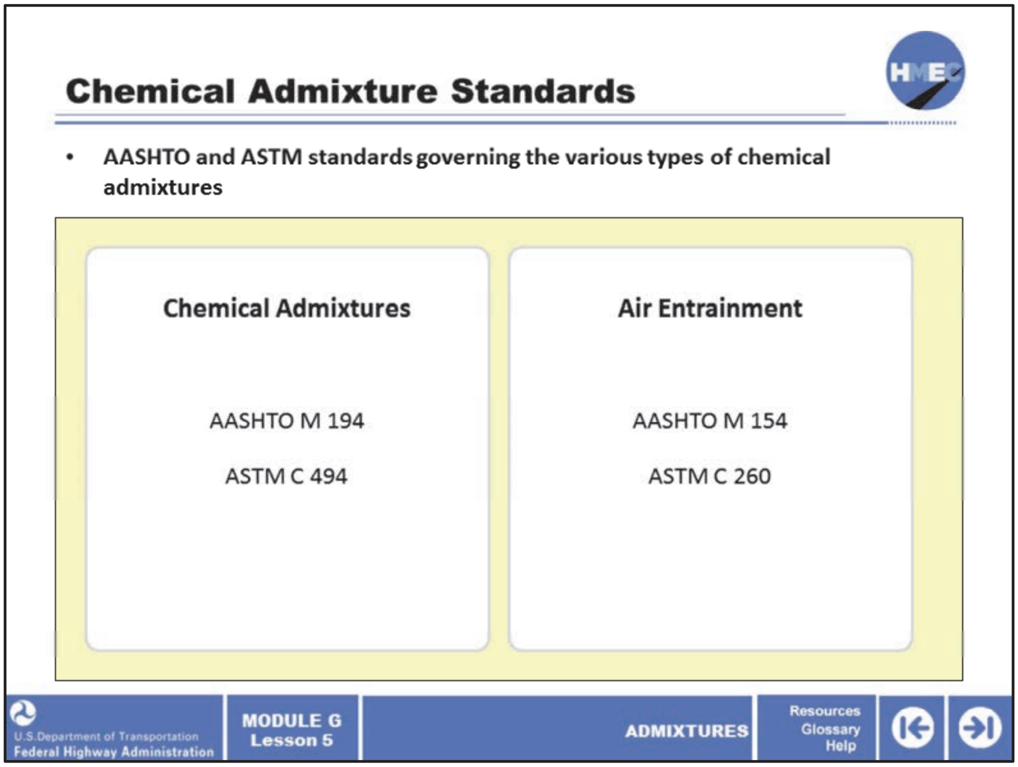
Image description: Graph showing the air content of a PCC mix using the same mix proportions.



Quality assurance testing on SCMs is very important and is very rarely an issue; however, things can happen during transport and storage that may affect admixture efficiency. SCMs for the most part are industrial byproducts and not manufactured specifically for use in PCC. However, SCMs are further processed in order to minimize variability and conform to the appropriate AASHTO and ASTM specifications.

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, SCMs are not manufactured for the PCC industry and their properties may vary significantly, even on a daily basis.



Both AASHTO and ASTM have standards governing the various types of chemical admixtures. Many agency standards are adopted from the appropriate AASHTO or ASTM standards.

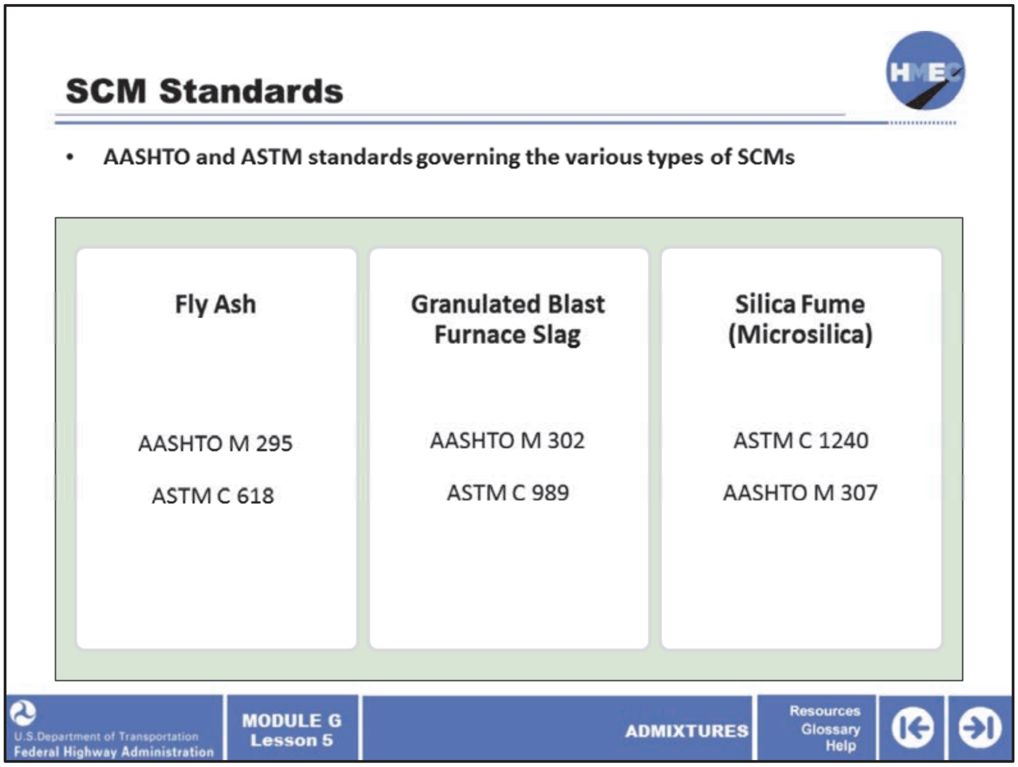
Chemical admixtures:

- AASHTO M 194; and
- ASTM C 494.

Air entrainment:

- AASHTO M 154; and
- ASTM C 260.

Chemical admixtures are well regulated in terms of performance criteria. Due to the proprietary nature of many admixtures, the detailed chemical make-up is not specified.



Both AASHTO and ASTM have standards governing the various types of SCMs. As previously mentioned, SCMs are generally an industrial byproduct that can be processed or unprocessed depending on the material. The standards are specific in terms of physical properties and limitations on compounds that can be detrimental to the performance of PCC. Here are some references for various types of SCMs.

Fly ash:

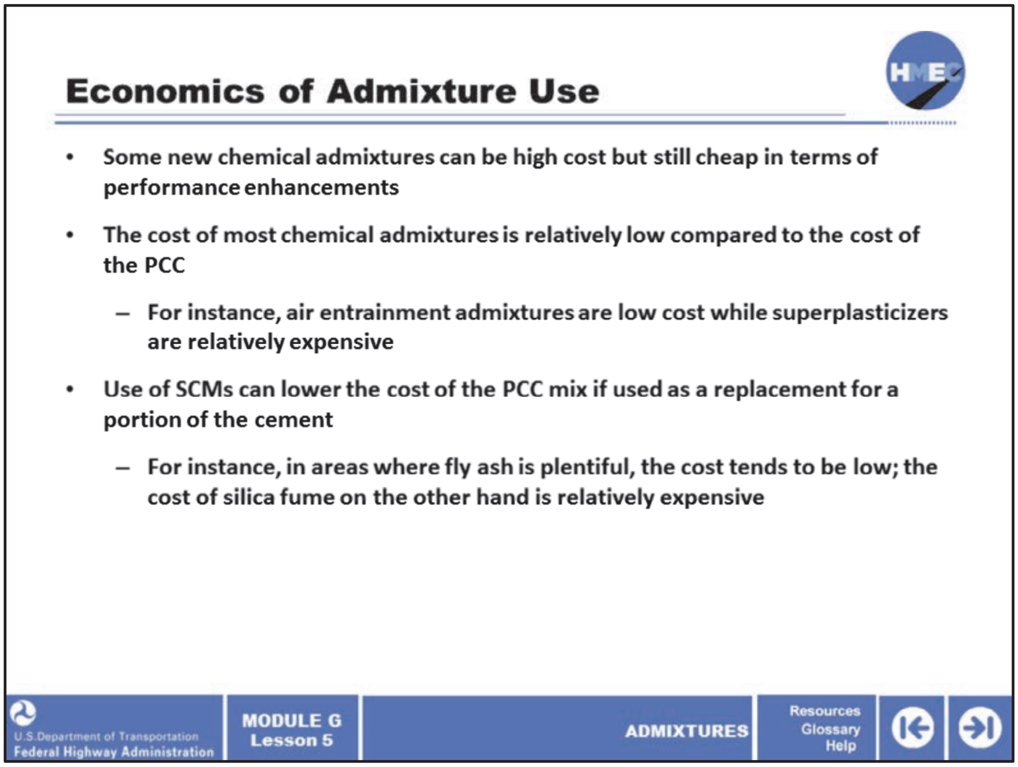
- AASHTO M 295; and
- ASTM C 618.

Granulated blast furnace slag:

- AASHTO M 302; and
- ASTM C 989.

Silica fume (microsilica):

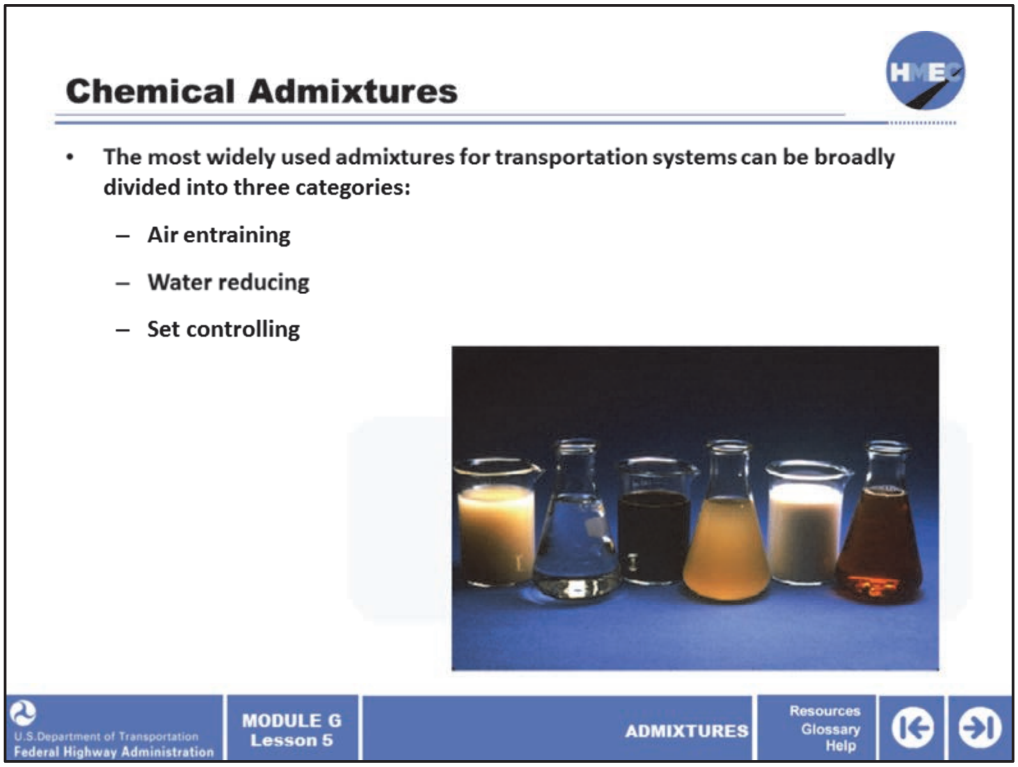
- ASTM C 1240; and
- AASHTO M 307.



The economic impact of admixtures is difficult to measure because of the perceived long-term performance enhancement that their use implies. Some of the new innovative chemical admixtures can be relatively high cost but still cheap in terms of performance enhancements.

For instance, lowering the w/c ratio while maintaining workability will result in higher strength and greater durability. Weighing the cost of a high range water reducer versus the enhanced performance is a complicated matter due to the intended use of the PCC, environmental factors, etc. The use of fly ash on the other hand is relatively easy if you weigh the cost of the fly ash against the cost savings resulting from replacing a percentage of Portland cement. In other words, the cementitious materials content is held constant but the amount of cement required is reduced.

Admixture types vary considerably in cost as well as recommended dosage rates to achieve the desired results. The cost of most chemical admixtures is incidental to the cost of the PCC. The use of SCMs can lower the cost of the PCC mix if used as a replacement for a portion of the cement.

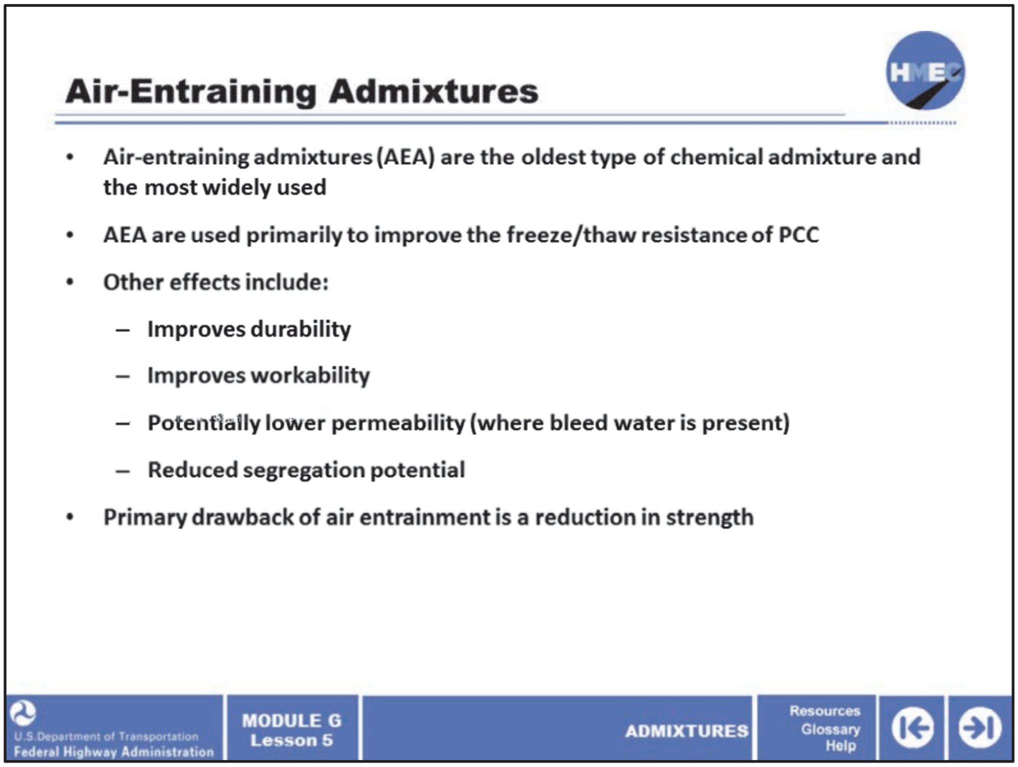


The most widely used admixtures for transportation systems can be broadly divided into three categories:

- Air entraining;
- Water reducing; and
- Set controlling.

We are going to take a detailed look at the three categories of admixtures in terms of their use, advantages, and disadvantages and briefly discuss how they work and what properties they influence.

Image description: Photo of chemical flasks and beakers.



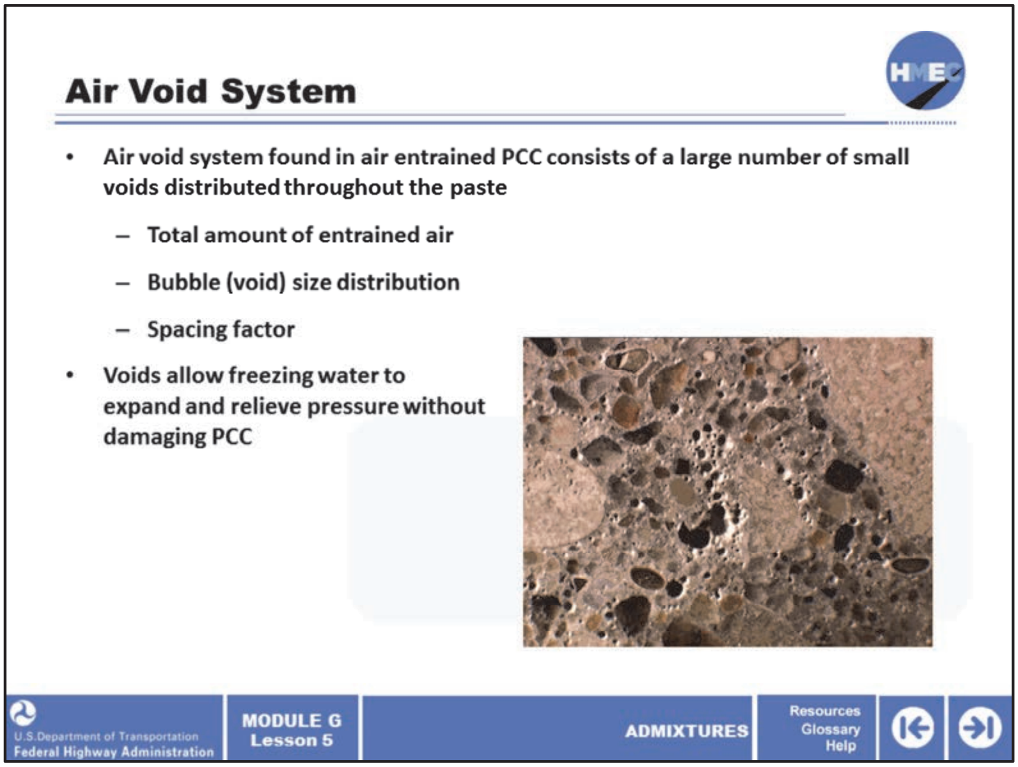
The first category we will discuss is air entraining. Air-entraining admixtures (AEA) are probably the oldest type of chemical admixtures and the most widely used. AEA are used primarily to improve the freeze/thaw resistance of PCC. In addition to improving durability, other effects include:

- Improved workability;
- Reduced water demand;
- Potentially lower permeability; and
- Reduced segregation potential.

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.

The potentially lower permeability is due to disrupting the bleed water channels and eliminating a continuous flow path for water to enter the PCC. The low w/c ratio mixes typically used for most paving and transportation structures projects do not have appreciable amounts of bleed water. However, this may be a factor when higher slump hand placements are required.

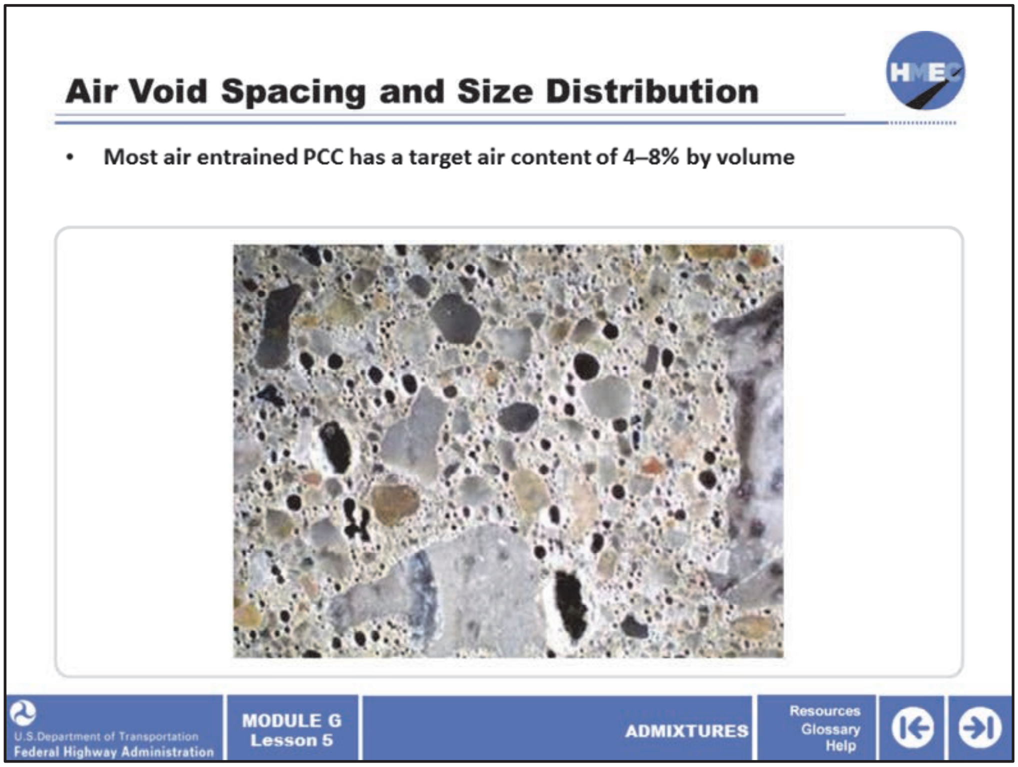
The primary drawback of air entrainment is a reduction in strength.



The air void system found in air entrained PCC consists of a large number of very small voids distributed throughout the paste. The air void system is based on the total amount of entrained air, the bubble (void) size distribution, and the spacing factor. The air-entraining admixture is used to create stable microscopic bubbles that result in voids in the hardened PCC.

These voids (if properly spaced and of the correct size) allow freezing water to expand and relieve pressure without damaging the PCC. This void system is influenced by a number of factors that will be discussed in the upcoming slides.

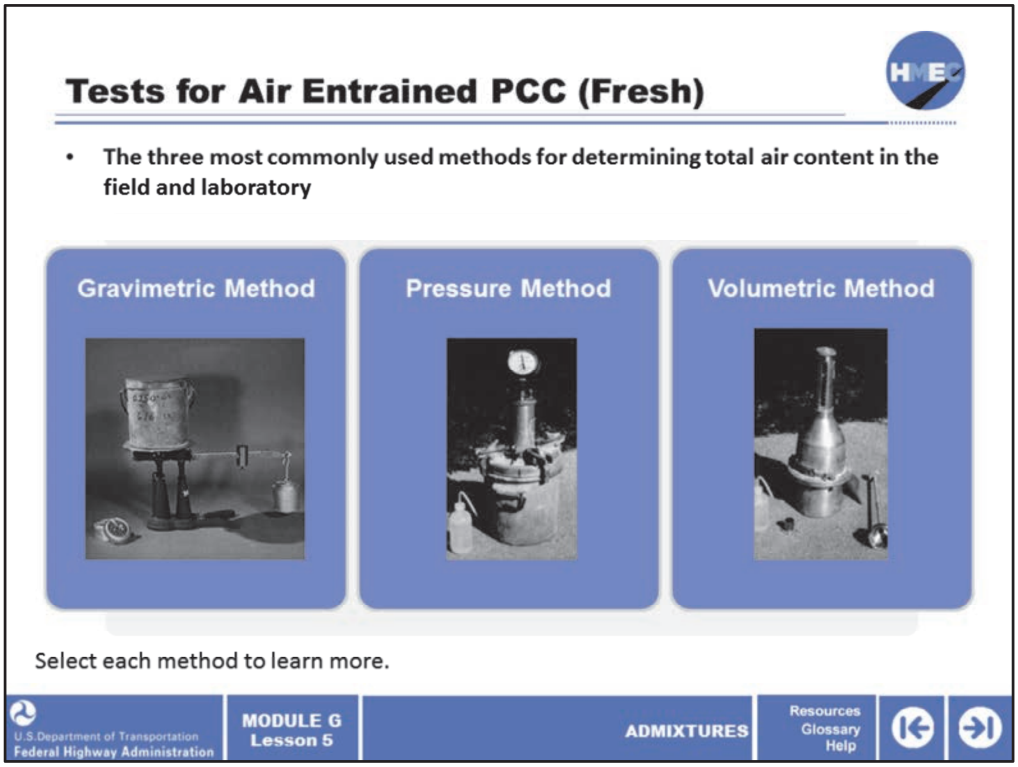
Image description: Photo of air voids.



Most air entrained PCC has a target air content of 4–8% by volume. Entrapped air voids are not a desirable characteristic due to their size and random spacing. These types of voids do not provide freeze/thaw resistance and reduce PCC strength. Entrained air consists of millions of very small voids uniformly distributed throughout the cement paste.

The goal is to is to provide ample space for water to migrate into during freezing. In addition to adequate volume, the voids must be spaced sufficiently close to allow water to move freely into the voids. The photo shown is a close-up of a hardened PCC specimen. Look closely at the tiny air bubbles distributed throughout the paste.

Image description: Photo of air voids.



There are a number of methods to determine the volume of air voids in fresh PCC. The three most commonly used methods for determining total air content in the field and laboratory are:

• Gravimetric method using a unit weight measure, which also determines unit weight and yield (AASHTO T 121, ASTM C 138);
• Pressure method using a pressure meter (AASHTO T 152, ASTM C 231); and
• Volumetric method using a rollometer (AASHTO T 196, ASTM C 173).

Tests of fresh concrete estimate total air volume only when using gravimetric, pressure, or volumetric methods.

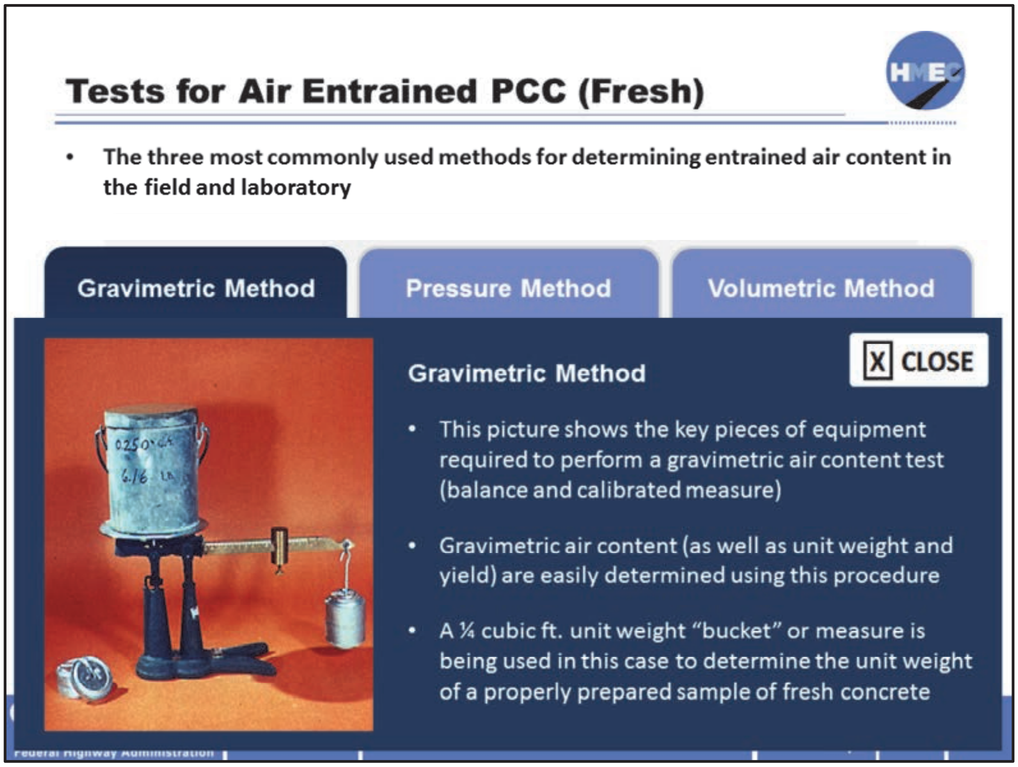
Another method is buoyancy (AASHTO T 348). The buoyancy test (also known as the air void analyzer, or AVA) can be used to estimate bubble size distribution and spacing. The AVA must be used under very tightly controlled conditions in the laboratory or field laboratory to produce reasonable results. While it does not lend itself to routine measurements at the job site, the AVA can provide a high level of detail regarding the air void system.

Select each method to learn more.

Image description: Photo of pieces of equipment required to perform a gravimetric air content test.

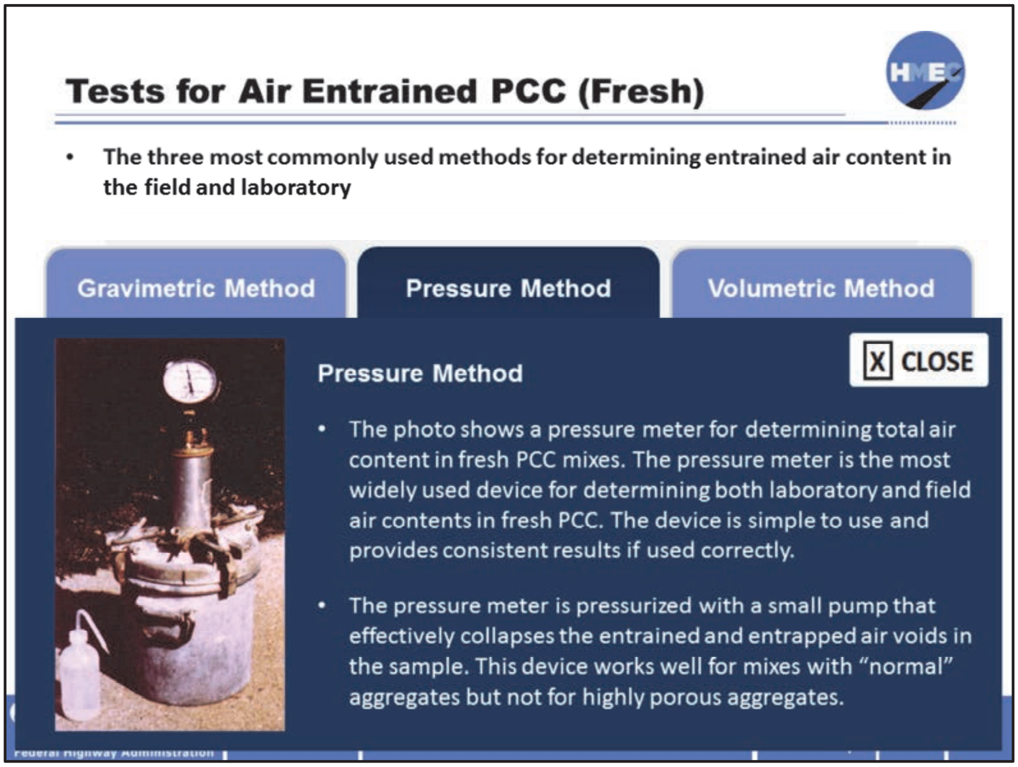
Image description: Photo of a pressure meter for determining total air content in fresh PCC mixes.

Image description: Photo of a volumetric apparatus for determining total air content in fresh PCC mixes.



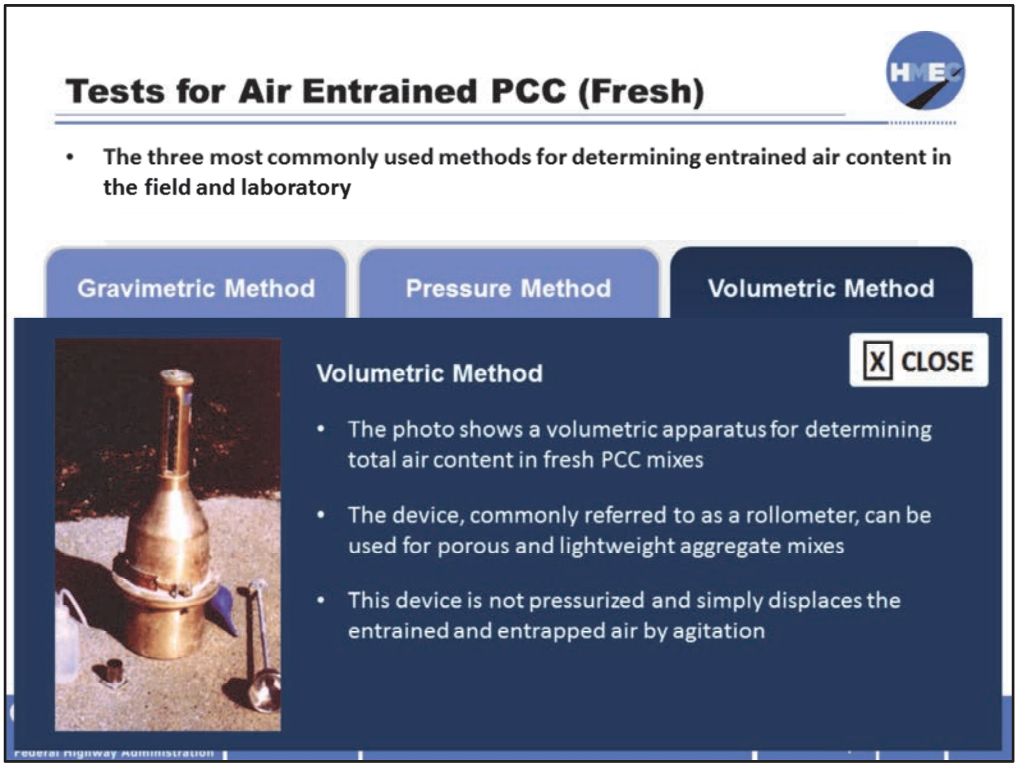
This picture shows the key pieces of equipment required to perform a gravimetric air content test (balance and calibrated measure). Gravimetric air content (as well as unit weight and yield) are easily determined using this procedure. The mix proportions and properties must be known in order to use this method for air void determination. A ¼ cubic ft. unit weight "bucket" or measure is being used in this case to determine the unit weight of a properly prepared sample of fresh concrete.

Image description: Photo of pieces of equipment required to perform a gravimetric air content test.



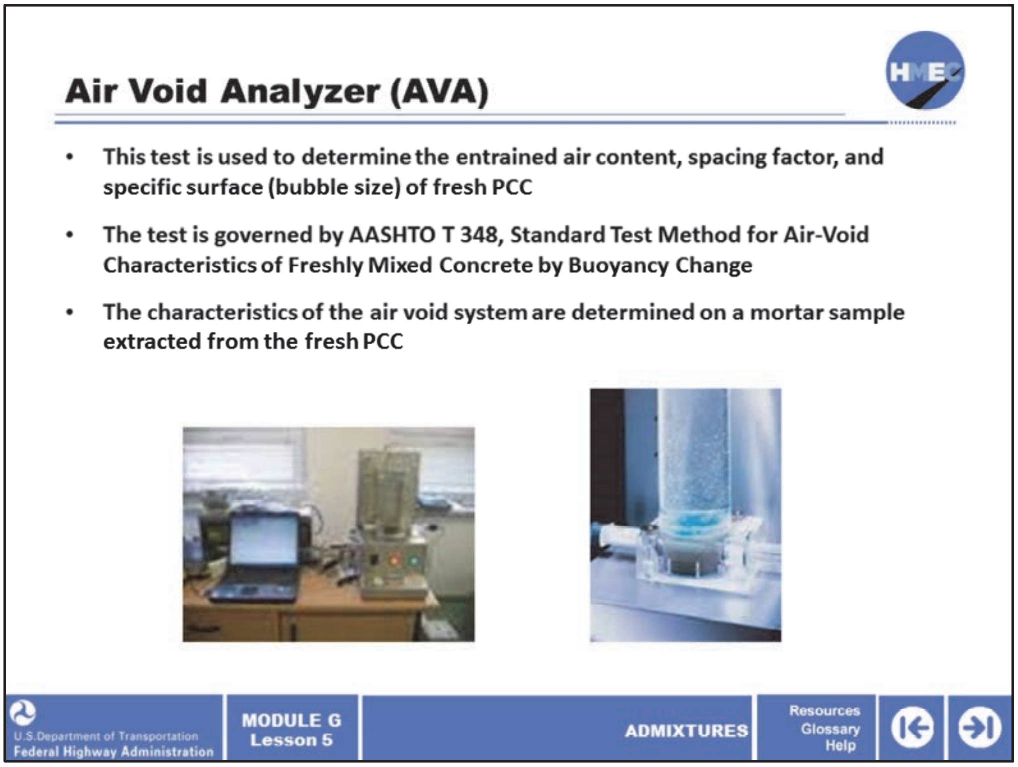
The photo shows a pressure meter for determining total air content in fresh PCC mixes. The pressure meter is the most widely used device for determining both laboratory and field air contents in fresh PCC. The device is simple to use and provides consistent results if used correctly. The pressure meter is pressurized with a small pump that effectively collapses the entrained and entrapped air voids in the sample. This device works well for mixes with "normal" aggregates but not for highly porous aggregates.

Image description: Photo of a pressure meter for determining total air content in fresh PCC mixes.



The photo shows a volumetric apparatus for determining total air content in fresh PCC mixes. The device, commonly referred to as a rollometer, can be used for porous and lightweight aggregate mixes. This device is not pressurized and simply displaces the entrained and entrapped air by agitation.

Image description: Photo of a volumetric apparatus for determining total air content in fresh PCC mixes.



The air void analyzer (AVA) is a tool for determining the entrained air content as well as the characteristics of the entrained air system in fresh PCC.

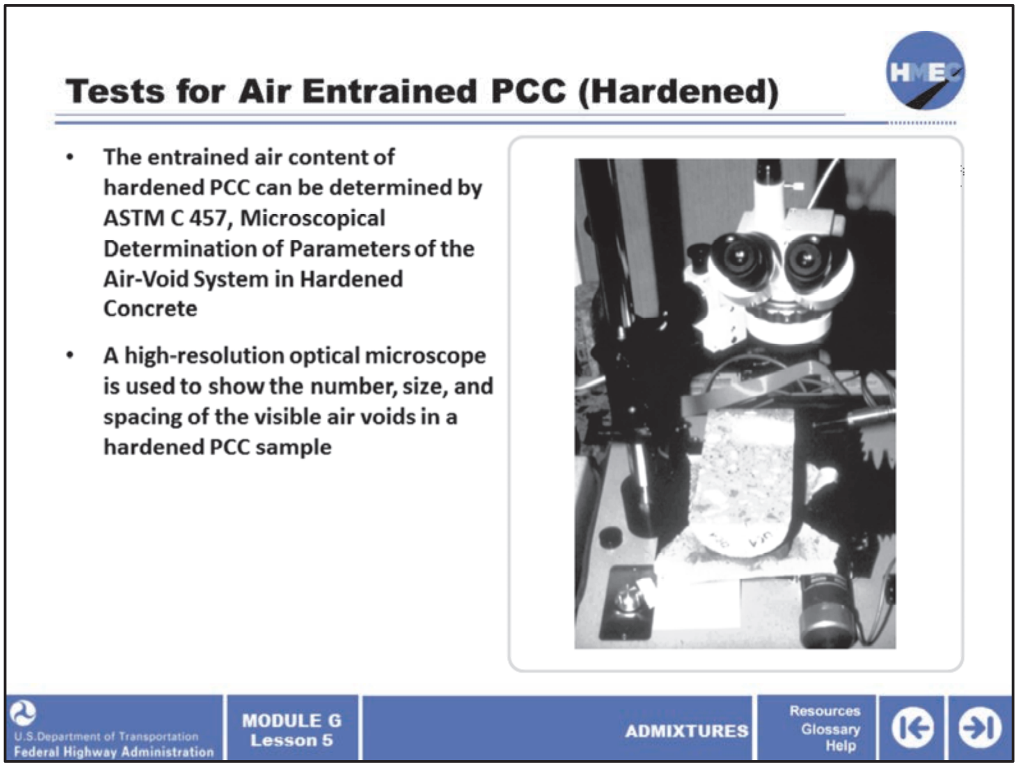
Unlike the three previous methods (gravimetric, pressure, and volumetric), the AVA gives an indication of bubble size distribution and spacing factor, both of which are critical factors for adequate freeze/thaw resistance.

Due to its sensitivity to vibration and disturbance, this method is only suited to projects where a laboratory trailer is on site or in fixed laboratory facilities.

The photo on the left shows the AVA apparatus and the photo on the right shows a close-up of the test cylinder.

Image description: Photo of the AVA apparatus.

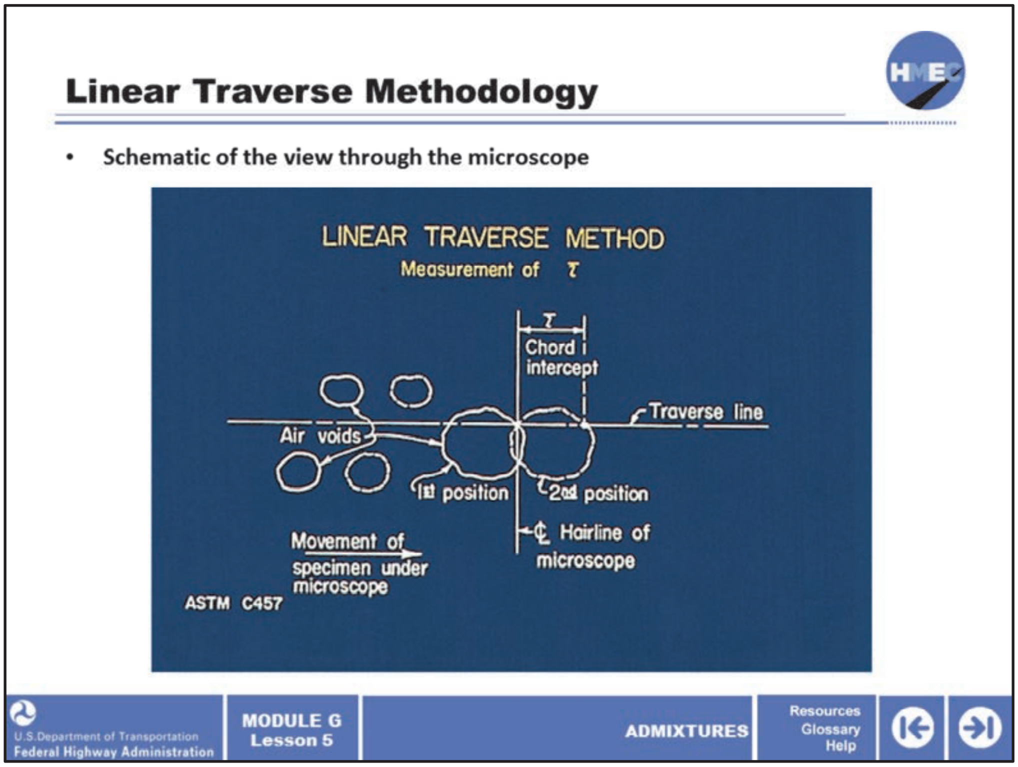
Image description: Photo of a close-up of the test cylinder.



This test method, commonly referred to as the linear traverse method, requires specialized equipment and a specifically trained technician to perform correctly. A high-resolution optical microscope is used to show the number, size, and spacing of the visible air voids in a hardened PCC sample.

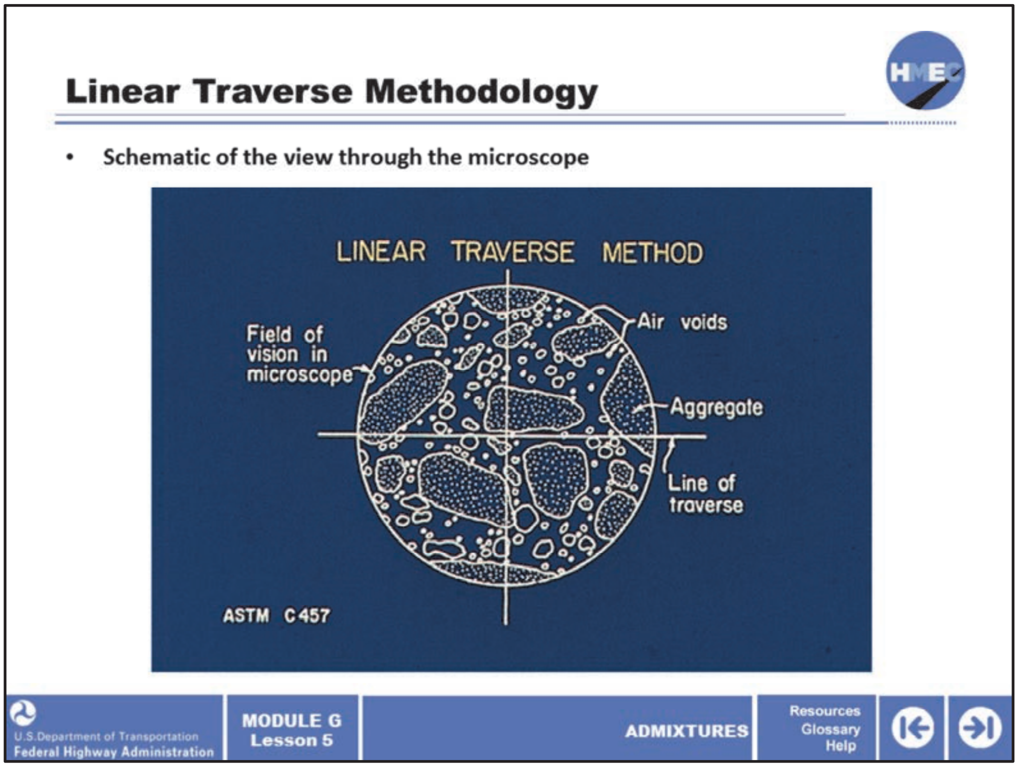
The photo shows a high-resolution optical microscope, prepared PCC core sample, and the alignment apparatus. The air void system (void size distribution and spacing) is estimated by the statistical sampling technique of ASTM C 457, based on microscopical observations of a small percentage of the voids present in a sample of PCC.

Image description: Photo of a high resolution optical microscope, prepared PCC core sample and the alignment apparatus.



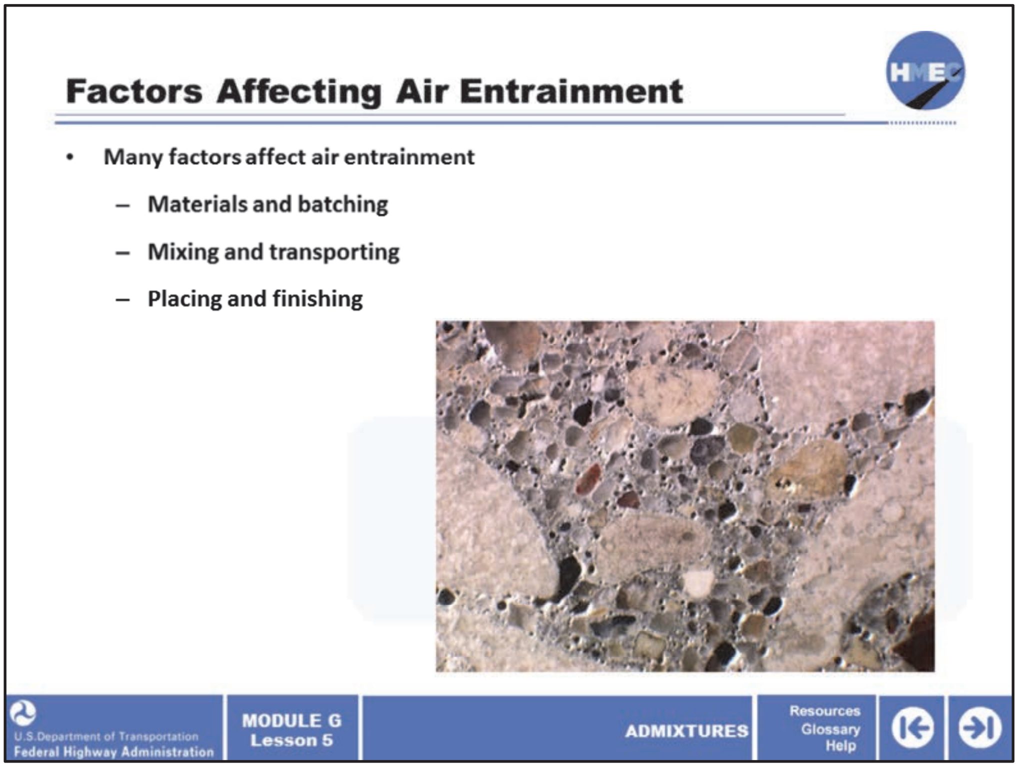
Here we see a schematic of the view through the microscope, illustrating the voids, traverse line, and direction of movement. As can be seen, the measurements must be very precise in order to produce representative results.

Image description: Schematic of the view through the microscope, illustrating the voids, traverse line, and direction of movement.



The image depicts the schematic field of view looking through the microscope. Note the line of traverse and the number, variation in size, and spacing between the air voids on the line of traverse. Statistical methods are used to estimate the air void parameters in three dimensions based on these values.

Image description: Schematic field of view looking through the microscope.

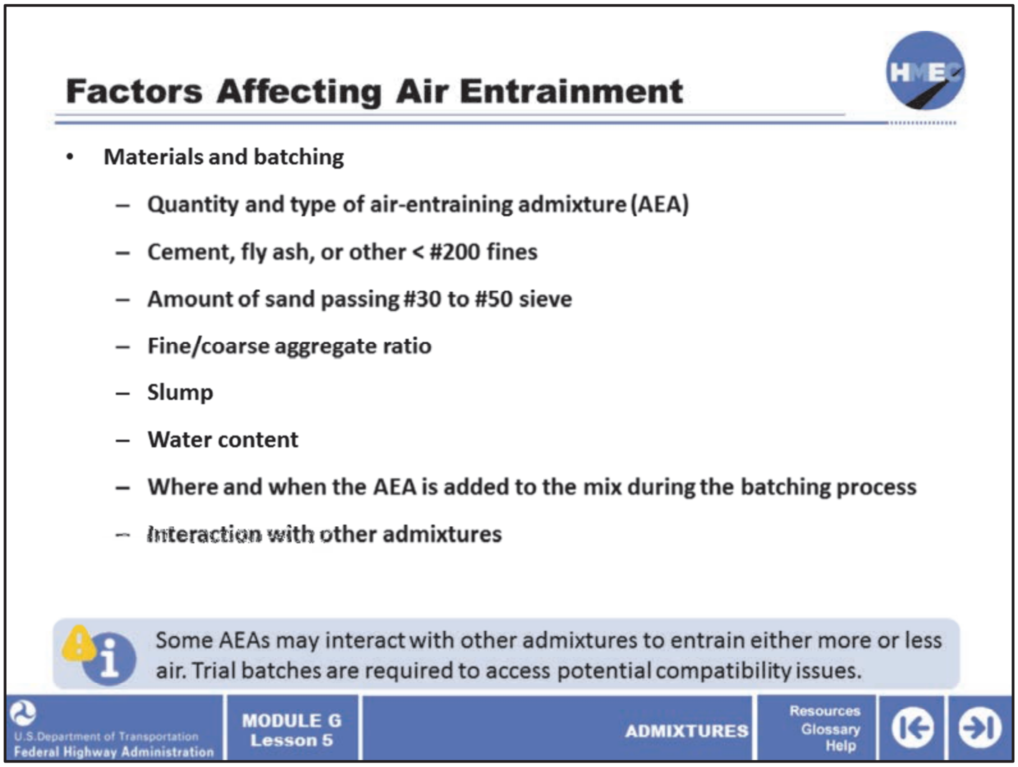


There are many factors that affect air entrainment, ranging from the basic PCC materials to final placement. To simplify the discussion, these factors have been grouped under the following categories:

• Materials and batching;
• Mixing and transporting; and
• Placing and finishing.

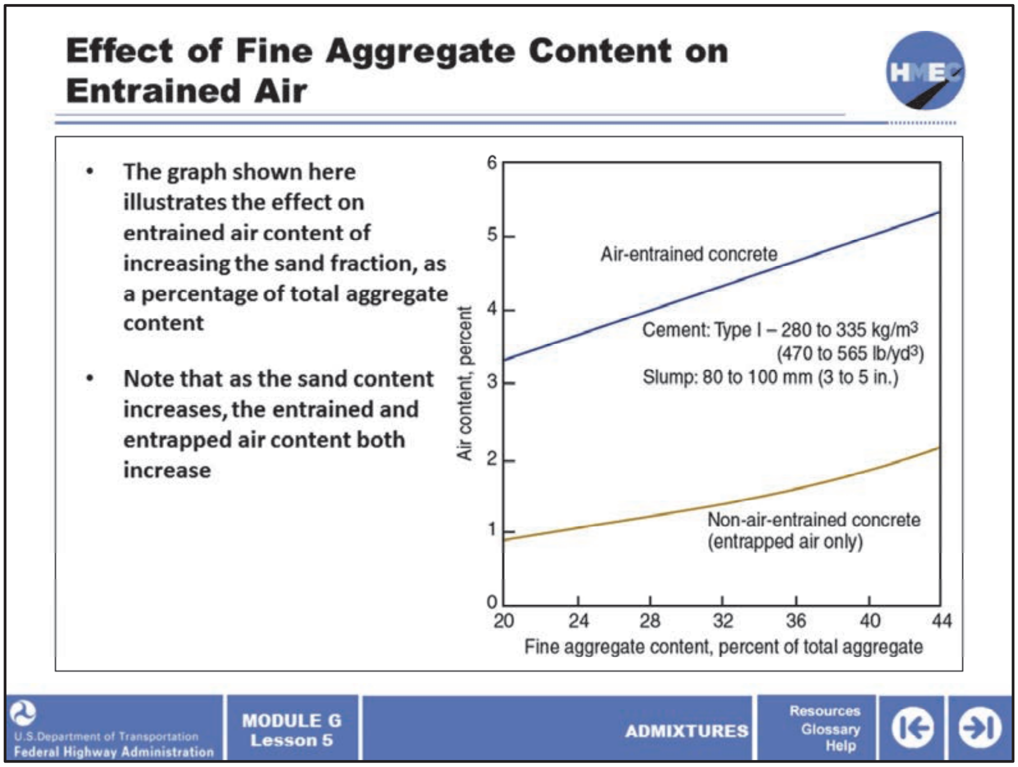
Entrained air content is one of the most difficult to control mix parameters because so many factors affect the air void system. We will look at the various factors comprising the three categories listed here in the next few slides.

Image description: Photo of air entrainment.



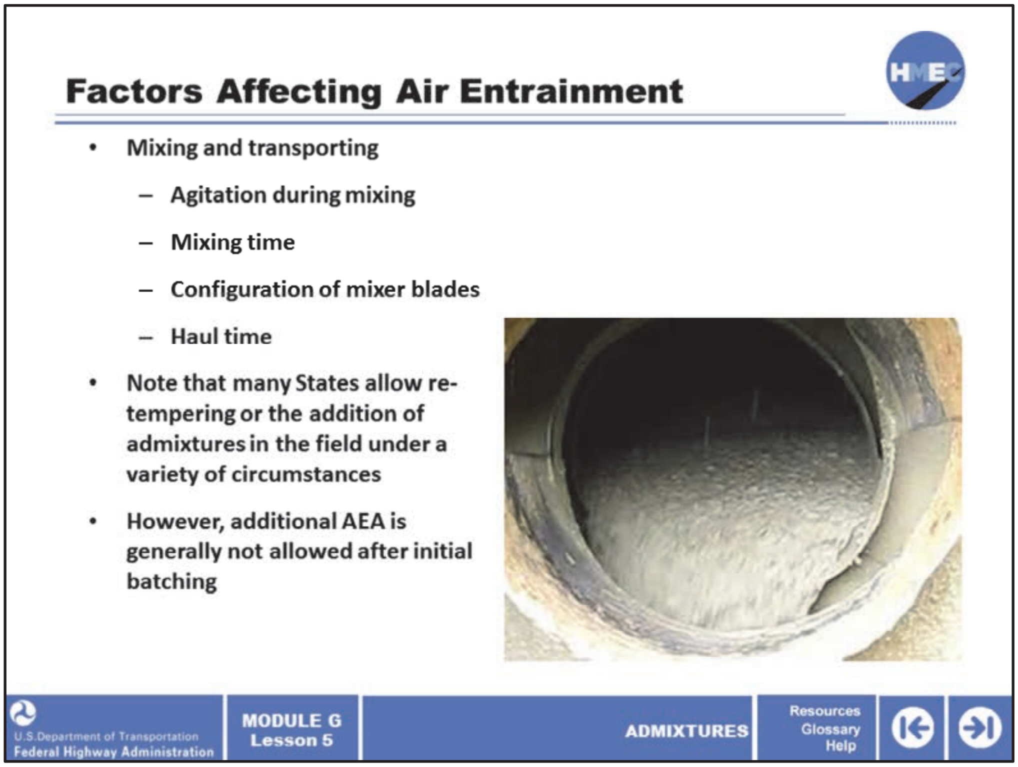
The required air content is related to the environmental exposure conditions of the PCC, the combined aggregate gradation, the cement content, the total water content, and other factors that will be discussed in the mix proportioning lesson. The entrained air content of a PCC mix is accounted for in the initial mix proportioning calculations.

Perhaps the most important factor in determining the entrained air content is the type of AEA and the dosage rate. It is common to have to adjust the dosage throughout the day as the air temperature and the temperature of the PCC components change. In order for the mixing process to entrain air, the paste has to be sufficiently fluid. This simply means that the paste content and the slump must be conducive for air bubbles to be created during mixing. For instance, a very dry, rocky mix is difficult to control in terms of air content. Note that some AEAs may interact with other admixtures to entrain either more or less air. The timing of the AEA addition and how it is integrated into the batch may also effect the entrained air content and properties. Trial batches are required to access potential compatibility issues.



The graph shown here illustrates the effect on entrained air content of increasing the sand fraction, as a percentage of total aggregate content. Note that as the sand content increases, the entrained and entrapped air content both increase. This difference is not due strictly to the increased sand content, but on changes to the other mix proportions to compensate for the varying sand/coarse aggregate ratio (changed cement and water content).

Image description: Graph illustrating the effect on entrained air content of increasing the sand fraction, as a percentage of total aggregate content.

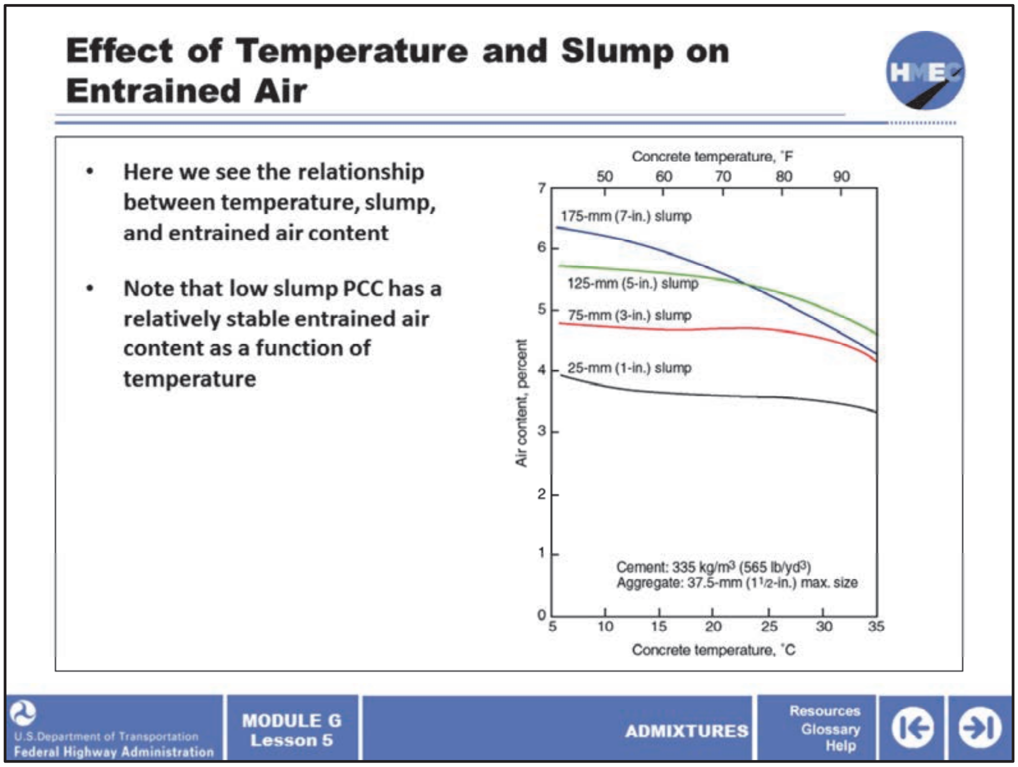


The mixing process is a crucial step in the formation and distribution of air bubbles throughout the paste. Note that the purpose of the AEA is not the creation of bubbles, but to stabilize them through all of the stages from batching and mixing until final placement. Whether the mixing takes place at a central mix plant or in a transit mix truck, the agitation and mixing time must be sufficient for formation of the air void system. The standards established for mix times or number of drum revolutions are sufficient to produce the desired air void system, assuming the mix is correctly proportioned and other interactions do not impede formation of the bubbles.

Long haul times can cause considerable variation in entrained air content. For instance, a PCC mix discharged into an end dump truck from a central mix plant has the highest air content it will see. A long or bumpy haul can reduce the air content of the mix to varying degrees based on the mix characteristics. Unless other admixtures are present, a long haul time will also result in a higher PCC temperature and lower slump. The effects of which are seen on the following slide.

The photo illustrates PCC being mixed inside of a ready mix drum.

Image description: Photo of PCC being mixed inside of a ready mix drum.



Here we see the relationship between temperature, slump, and entrained air content. Note that low slump PCC has a relatively stable entrained air content as a function of temperature. For a long haul time, this would translate into a tolerable loss of air. However, note that the beginning air content is below most agencies' lower bound of 4%. As the slump increases, the effect of temperature becomes much more pronounced. A 5-in. slump that may be required for hand-placed flatwork will experience approximately a 1% reduction in air as a result of a temperature change from 70 to 100°.

Image description: Graph showing the relationship between temperature, slump, and entrained air content.

Factors Affecting Air Entrainment

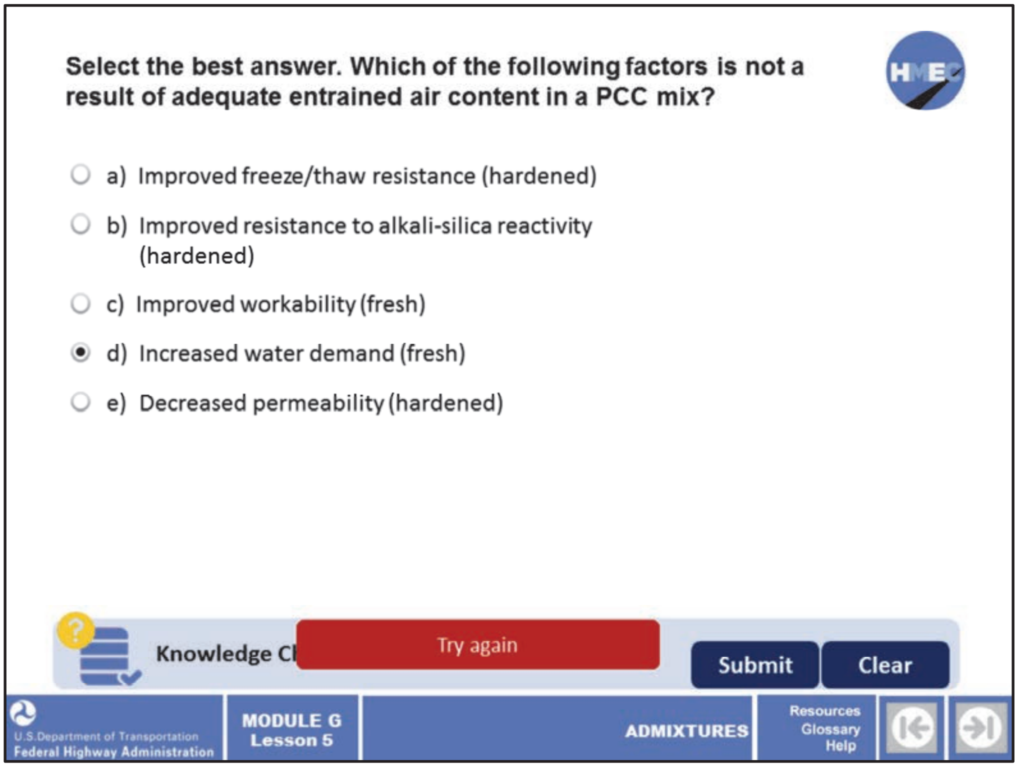
- Placing and finishing
  - Placing method
  - Consolidation
  - Finishing
  - Temperature
- Regardless of the method of placement, careful monitoring is required to ensure compliance with the specifications

Placing, whether hand placement, machine placement, or pumping tends to reduce the entrained air content by varying degrees depending on the mix characteristics. Hand placement typically uses a relatively high slump mix that can lose air relatively easy if over-vibrated during consolidation.

Machine placement mix characteristics vary somewhat depending on the type of equipment. For instance, slipform pavers generally use a 1-in. slump PCC mix that tends to maintain the target air content relatively well. However, studies have shown that even with these low slump materials, it is not uncommon to lose a percent of entrained air during placement and consolidation.

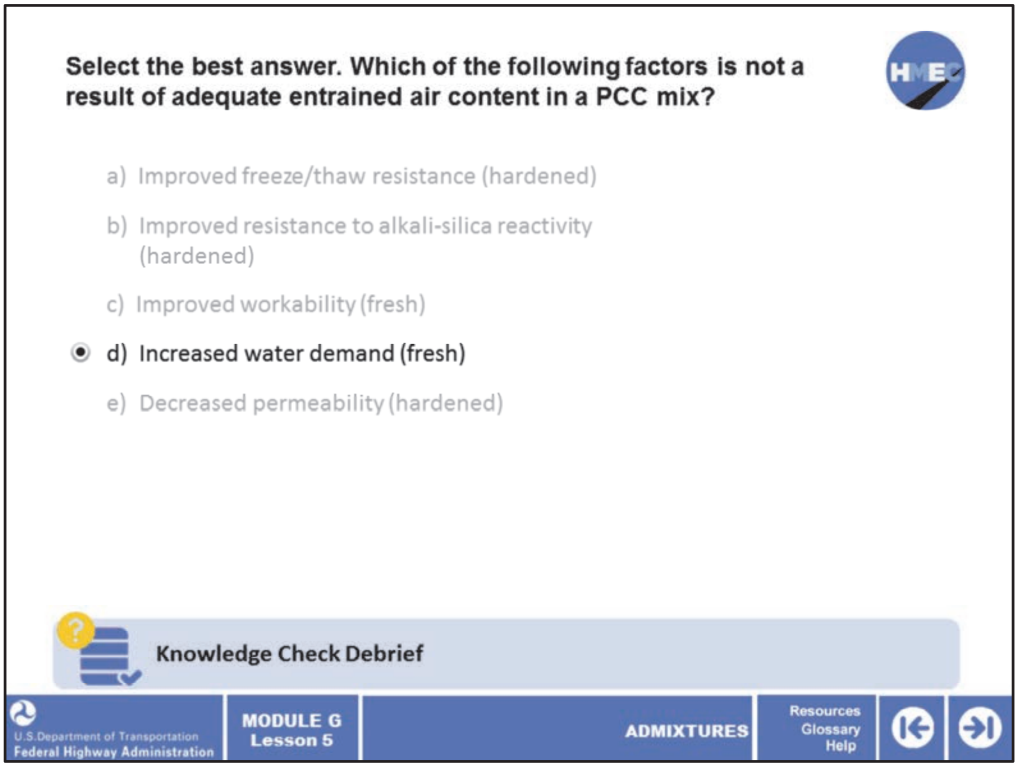
Concrete can be pumped over considerable height and distance and the possibility to lose entrained air is contingent on many factors including the type of pump, pumping distance, size of hose/pipe, discharge freefall, angle of discharge, boom angle, PCC mix design, environmental conditions, and other factors. It is very important that the entrained air content be closely monitored during placement. The effects of temperature were previously discussed but are significant enough to mention again. The entrained air content will fluctuate throughout the day for the majority of projects. This change is due primarily to temperature and must be accounted for in varying the dosage rates of the AEA.

Image description: Photo of a cement truck pouring cement and three men working.

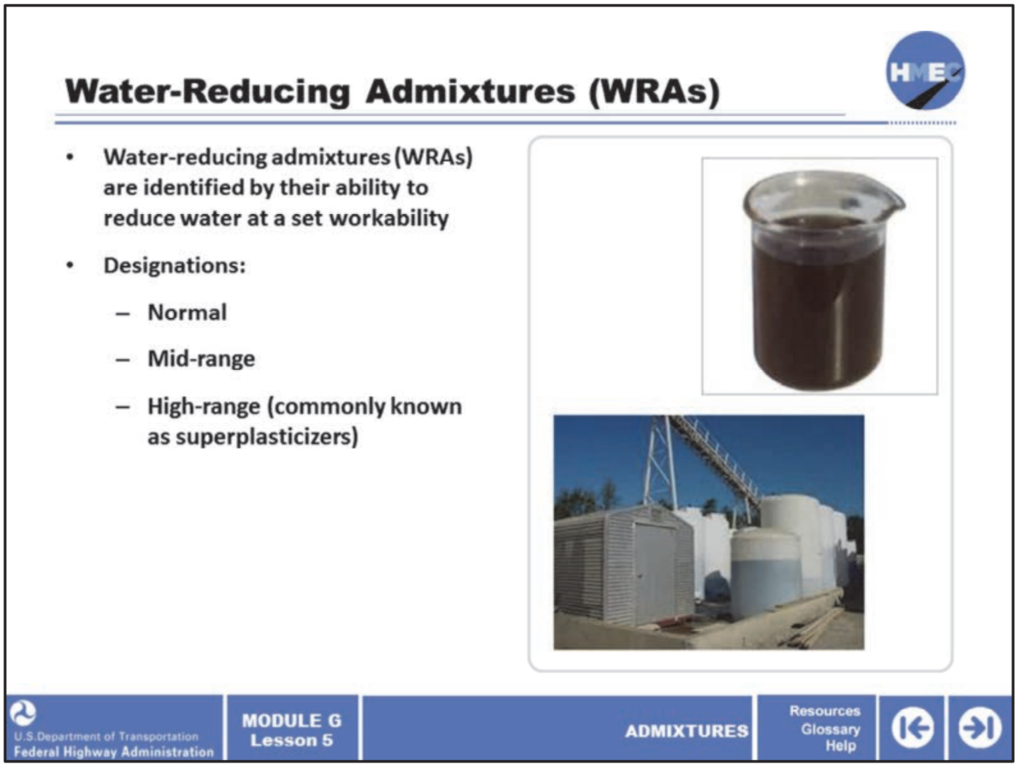


Select the best answer. Which of the following factors is not a result of adequate entrained air content in a PCC mix?

a) Improved freeze/thaw resistance (hardened);
b) Improved resistance to alkali-silica reactivity (hardened);
c) Improved workability (fresh);
d) Increased water demand (fresh); or
e) Decreased permeability (hardened).



The correct answer is d) Increased water demand (fresh).



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. They are:

• Normal;
• Mid-range; and
• High-range (commonly known as superplasticisizers).

Prior to their development, the w/c ratio of a mix was dictated by the need for a specific workability.

The upper photo shows a typical chemical admixture while the bottom photo shows on-site storage for liquid (chemical) admixtures.

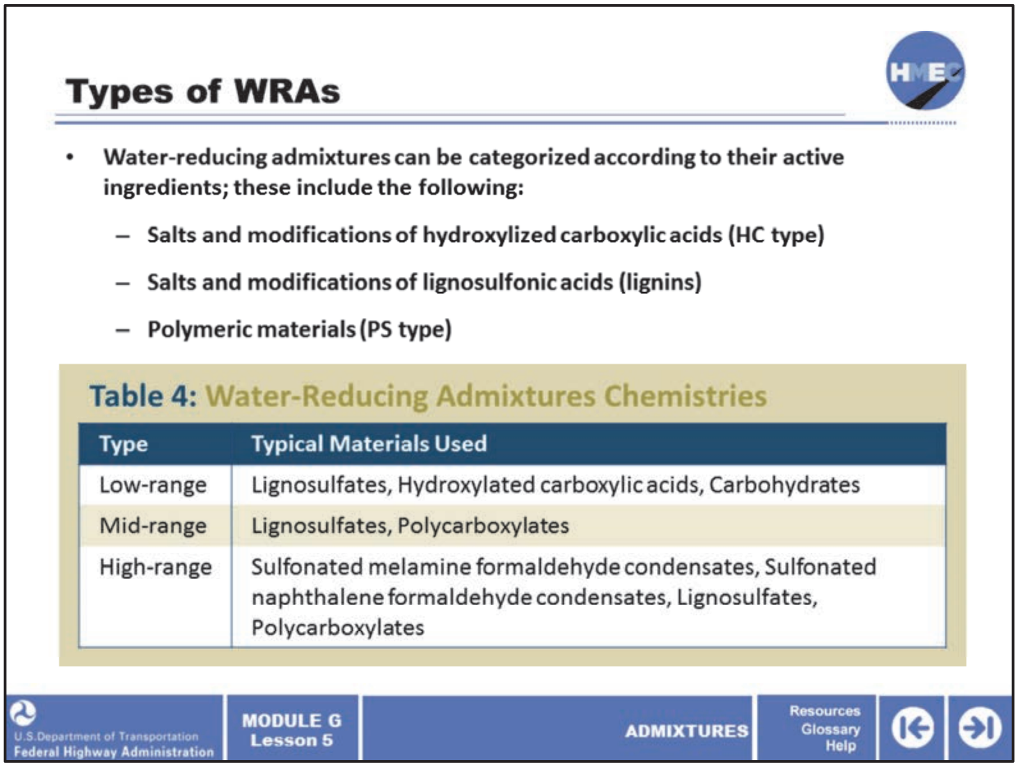
Image description: Photo of a typical chemical admixture.

Image description: Photo of on-site storage for liquid (chemical) admixtures.

How WRAs Work

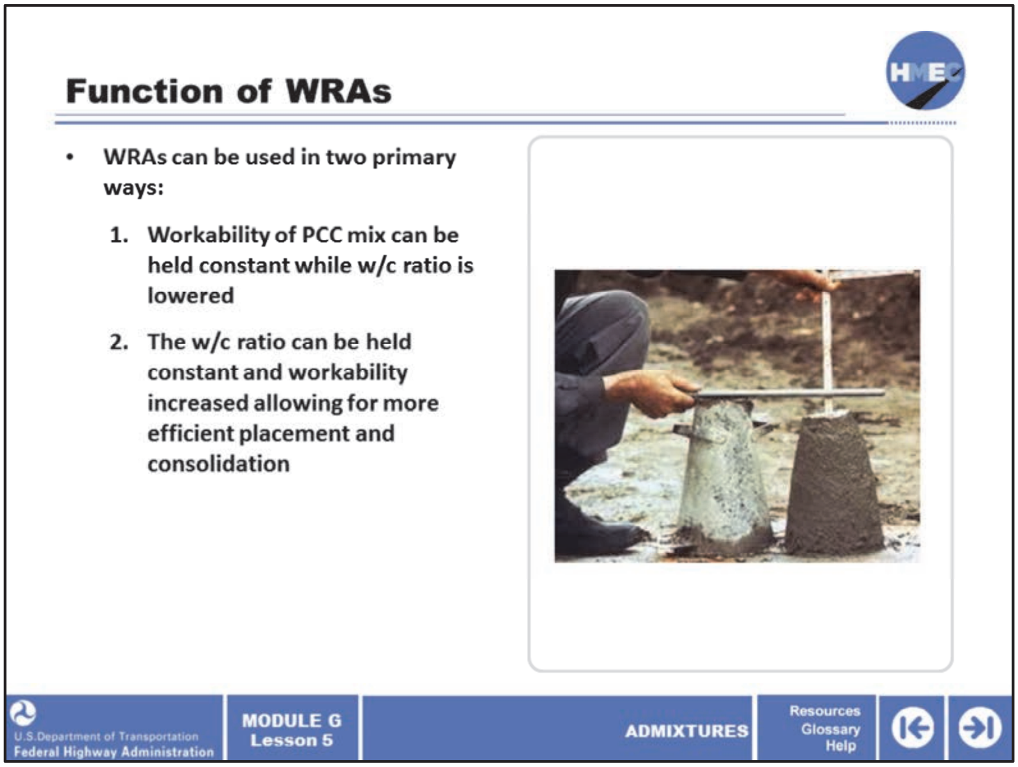
- The basic role of water reducers is to deflocculate the cement particles agglomerated together and release the water tied up in these agglomerations, producing a more fluid paste at lower water contents
- The deflocculation is accomplished by surrounding the cement grains with like charges, which causes the particles to repel one another electrostatically
- As the charges dissipate (ideally after placement and consolidation), the particles coalescence and the workability decreases

WRAs function by adhering to the cement grains and surrounding each grain with a similar charge. Since like charges repel, the effect is that the cement grains are held apart rather than flocculating together. The water that was tied up in the agglomerations of cement particles is temporarily freed thereby facilitating increased workability.



There are three basic families of WRAs as shown on this slide. The effectiveness of the WRA is dependent on the chemistry of the admixture and the dose. Each of the materials shown has specific properties but are somewhat variable based on the manufacturers formulation.

The table shows the three types of WRAs and the typical materials used. This graph is available at http://precast.org/wp-content/uploads/2010/09/admixtures_table4.gif.

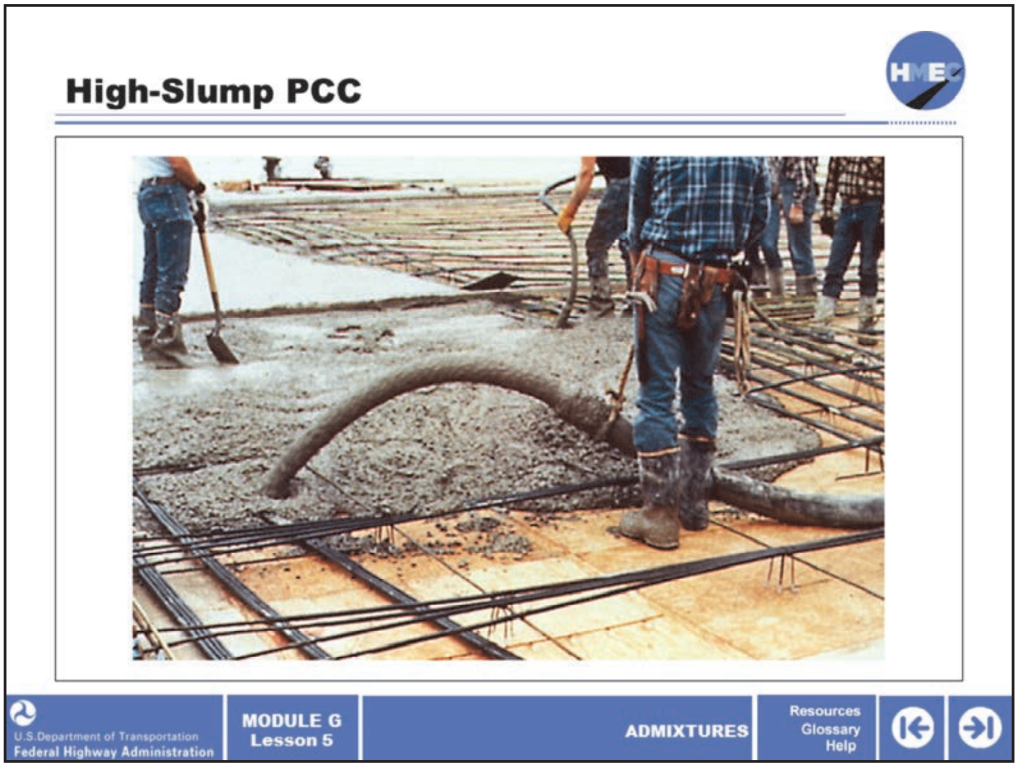


WRAs can be used in two primary ways:

1. The workability of a PCC mix can be held constant while the w/c ratio is lowered; and
2. The w/c ratio can be held constant and the workability increased allowing for more efficient placement and consolidation.

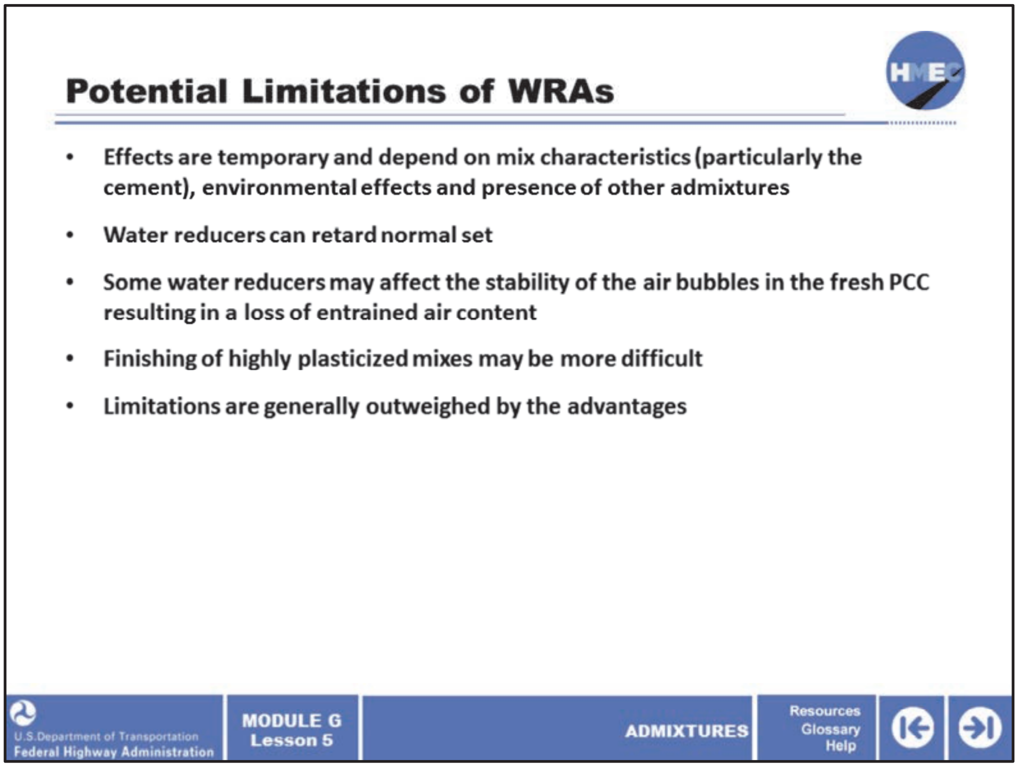
Water-reducing admixtures can be used to obtain either of the results shown on the slide or a combination of both. For instance, a flatwork project requiring hand pour placement might require a slump of 5 in. or greater. Rather than increase the w/c ratio of a “standard” 0.45 w/c ratio mix, the engineer might stipulate the use of a high-range water reducer to lower the w/c ratio to 0.38 due to harsh environmental conditions while still producing a 5-in. slump.

Image description: Photo of a man performing a field test.



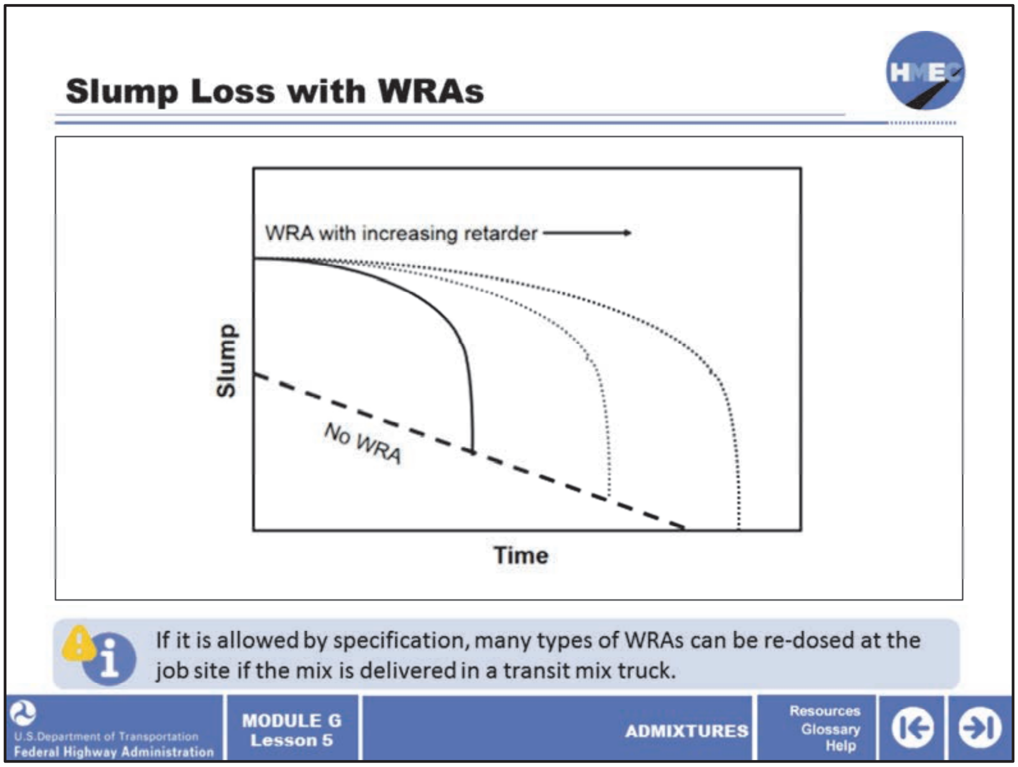
The high-slump PCC shown in this photo is common for pump delivery for flatwork and form placement. A major advantage of using a high range WRA or superplasticizer is that the segregation potential of the mix is minimized. Segregation is oftentimes a result of over-vibration so when the mix is sufficiently fluid to minimize the need for vibration, the segregation potential decreases.

Image description: Photo of high slump PCC.



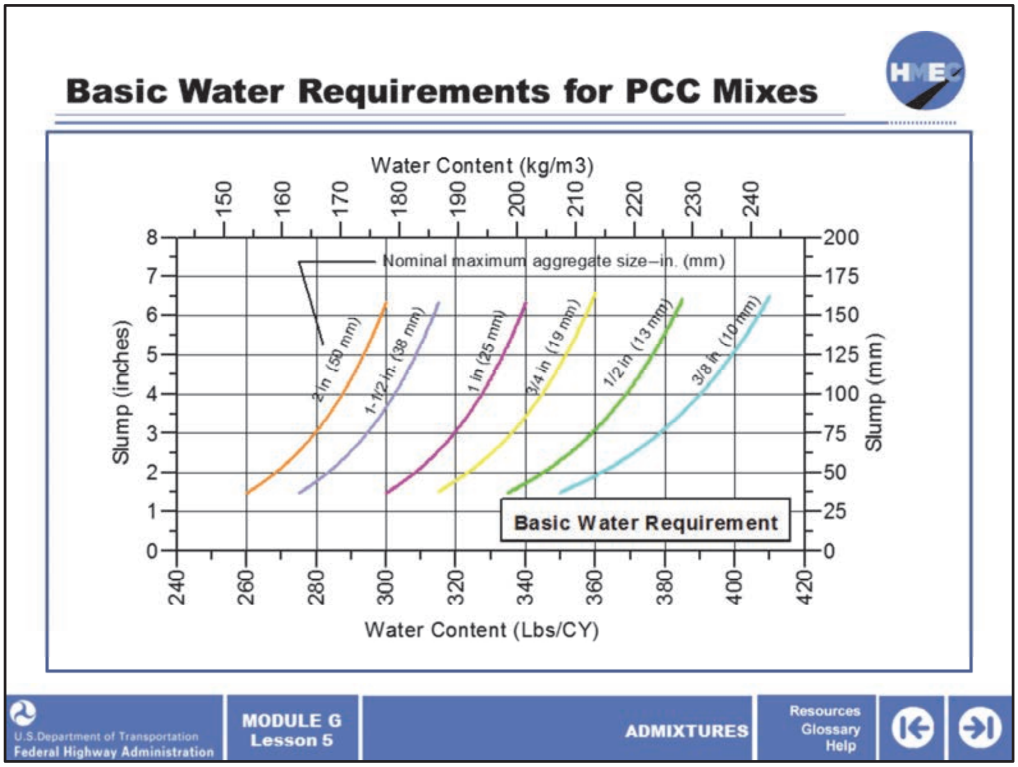
The effects of the WRA are temporary and depend on the mix characteristics (particularly the cement), environmental effects, and presence of other admixtures. Water reducers can retard normal set. Some water reducers may affect the stability of the air bubbles in the fresh PCC resulting in a loss of entrained air content.

The finishing of highly plasticized mixes may be somewhat more difficult. In order to reduce the chances for problems like the ones mentioned, we should work with the smallest WRA dosage rate that will provide the desired benefit. The limitations of using a WRA are generally outweighed by the advantages to both the fresh and hardened PCC states.



The slump loss behavior of various types of WRAs are shown in this figure. The chemistry of the overall system (cement, water, other admixtures) and temperature play a key role in this behavior. The best way to gauge slump loss with a particular mix (with other admixtures) is to perform trial batches under the most likely placement conditions. Note that if it is allowed by specification, many types of WRAs can be re-dosed at the job site if the mix is delivered in a transit mix truck.

Image description: Graph showing the slump loss behavior of various types of WRAs.



We have discussed lowering the w/c ratio of a mix by the use of a WRA. Another potential benefit of using a WRA is that the total water content required for a specific workability can be lowered. The graph shown in this slide illustrates the relationship between slump and the required water content for various nominal maximum aggregate sizes according to ACI 211.1. For instance, if we look at a 1-in. nominal maximum aggregate size requiring a 5-in. slump, approximately 335 pounds of water per cubic yard are required. If we use a WRA, we can significantly reduce this value while still maintaining the 5-in. slump.

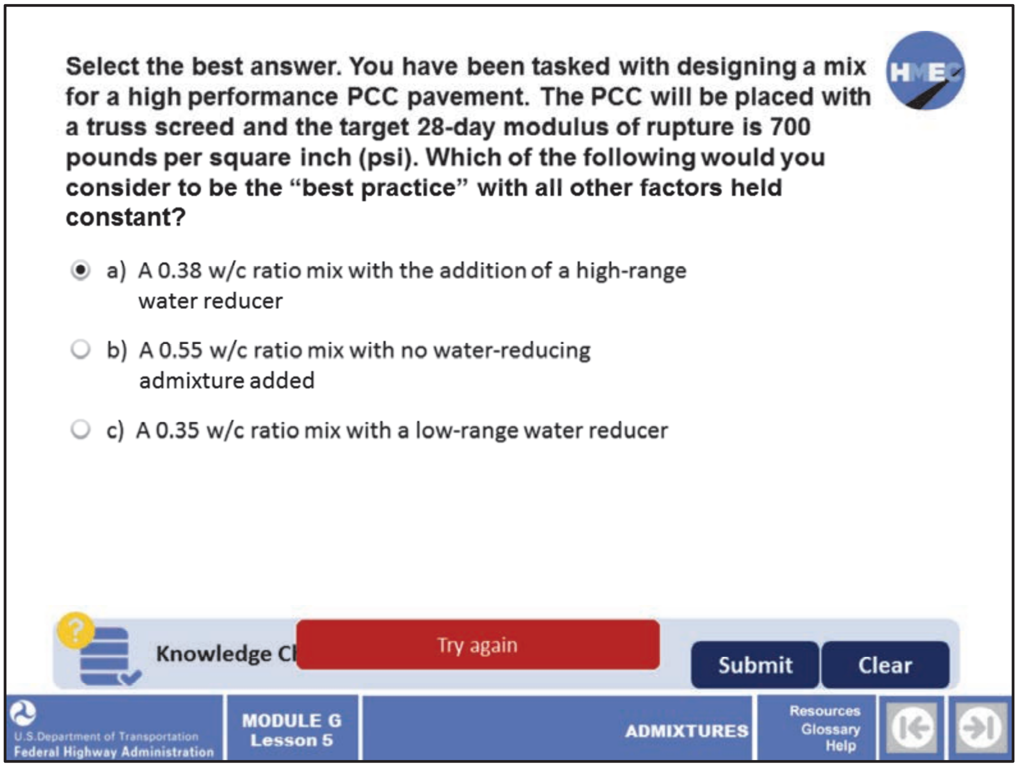
Image description: Graph illustrating the relationship between slump and the required water content for various nominal maximum aggregate sizes according to ACI 211.1.

Self-consolidating concrete (SCC) mixes are designed to ensure uniform suspension of the aggregates and solids during placement and delivery, and thereby minimize segregation. SCCs make use of high-range water reducers to enhance flowability and stability while minimizing segregation potential. The use of SCMs such as fly ash are frequently used in SCC mixes. SCC mixes are designed with a relatively high paste fraction, which can improve the cohesiveness and stability of the SCC.

If SCMs are used in the mix to reduce the amount of cement, the w/c ratio is also typically reduced and the loss in workability regained through the use of superplasticizers. The reduction in free water can reduce the concentration of viscosity-enhancing admixture (VEA) necessary to ensure proper stability during placement. SCC mixes do not require external compaction and are well suited to placement in heavily reinforced sections where uniform vibration or compaction is difficult. The photo on the left shows the flow characteristics of a typical SCC mix. The photo on the right shows a challenging placement that benefits from the use of SCC.

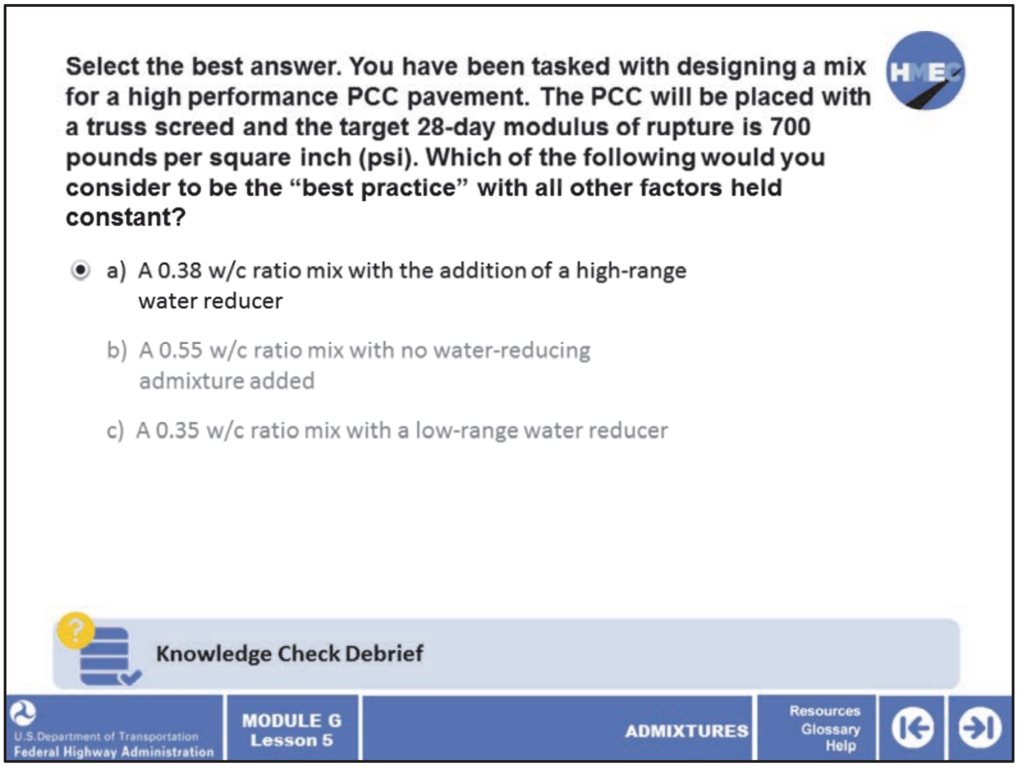
Image description: Photo of the flow characteristics of a typical SCC mix.

Image description: Photo of a challenging placement that benefits from the use of SCC.

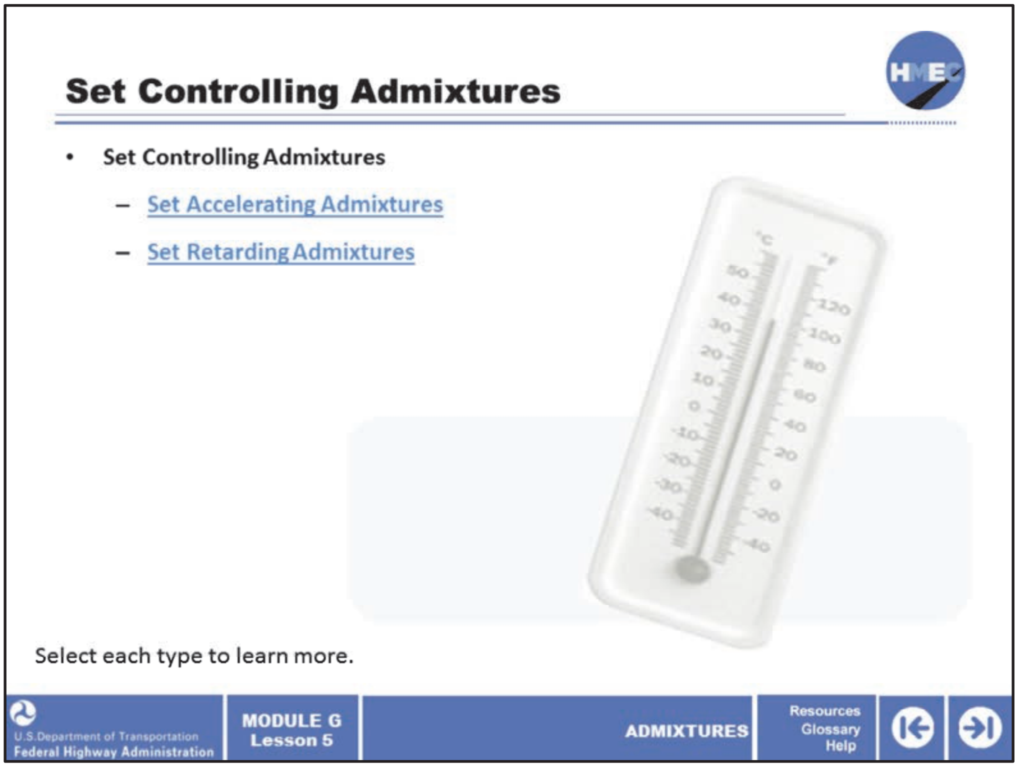


Select the best answer. You have been tasked with designing a mix for a high performance PCC pavement. The PCC will be placed with a truss screed and the target 28-day modulus of rupture is 700 pounds per square inch (psi). Which of the following would you consider to be the "best practice" with all other factors held constant?

a) A 0.38 w/c ratio mix with the addition of a high-range water reducer;
b) A 0.55 w/c ratio mix with no water-reducing admixture added; or
c) A 0.35 w/c ratio mix with a low-range water reducer.



The correct answer is a) A 0.38 w/c ratio mix with the addition of a high-range water reducer.

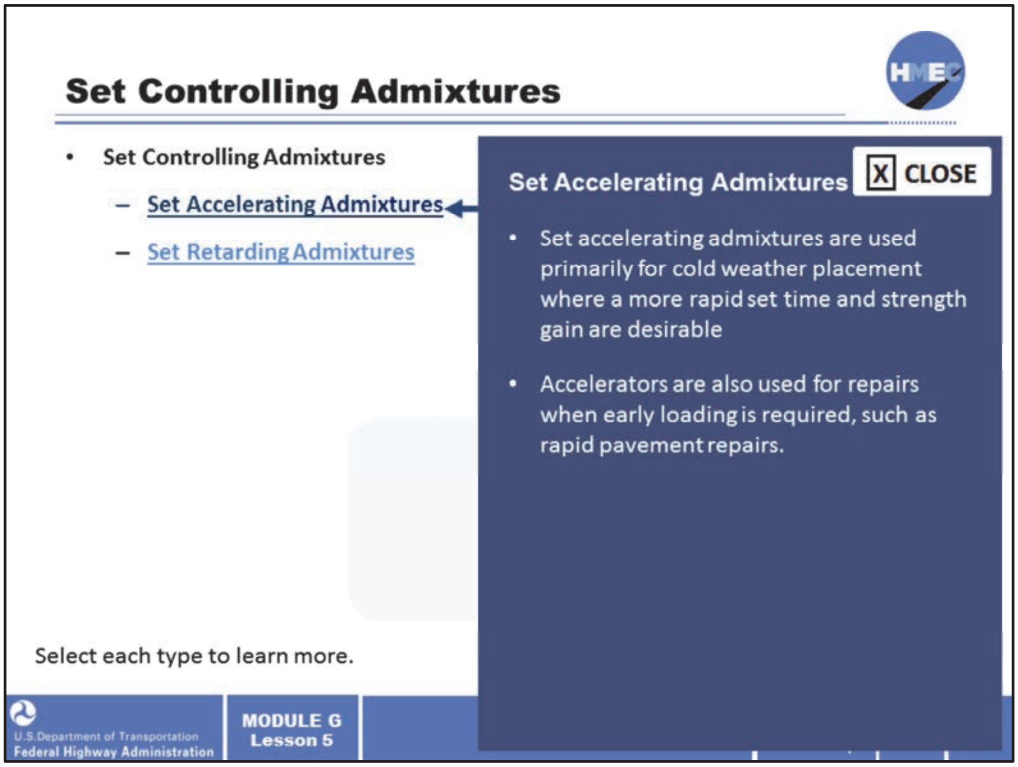


Set controlling admixtures are generally used for hot and cold weather PCC placement. They are widely used to control the set time and rate of strength gain under adverse placement conditions. They are also used for long haul distances and times. Some different types of set controlled admixtures are:

- Set accelerating admixtures; and
- Set retarding admixtures.

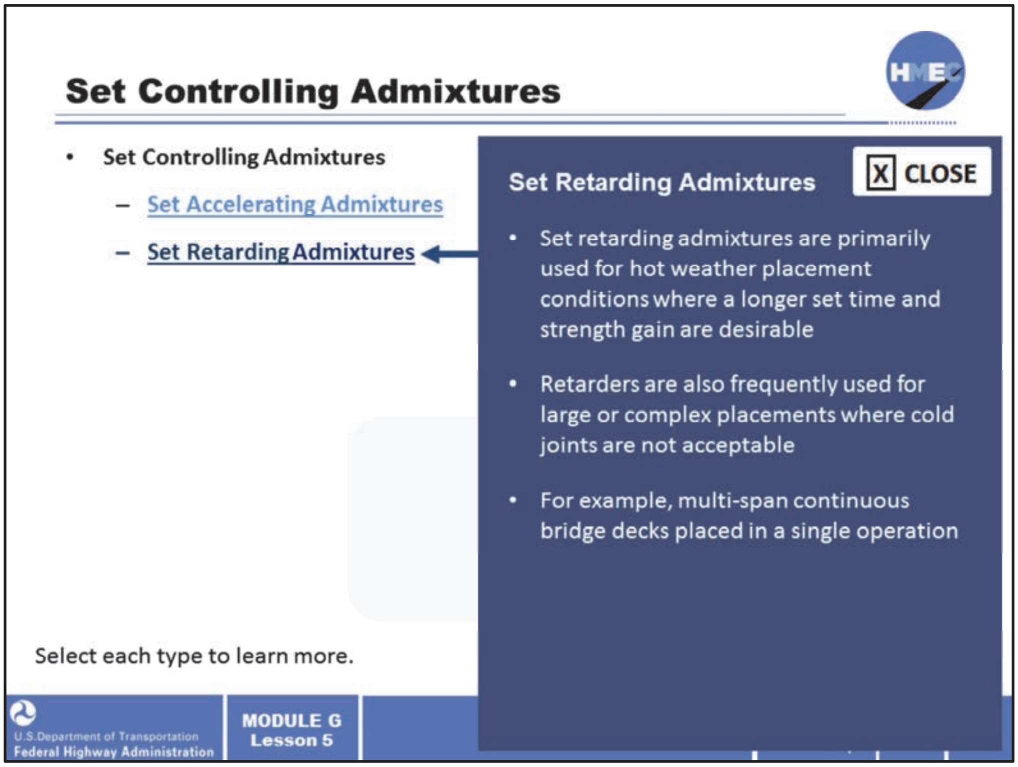
Select each type to learn more.

Image description: Image of a thermometer.



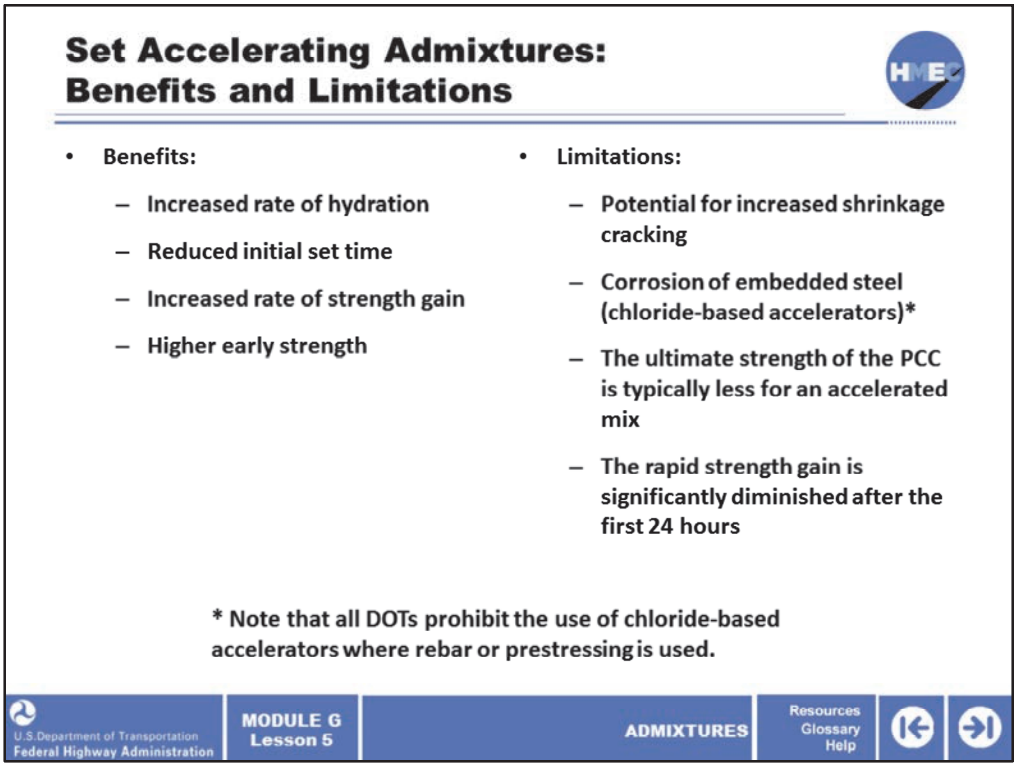
Set accelerating admixtures are used primarily for cold weather placement where a more rapid set time and strength gain are desirable.

Accelerators are also used for repairs when early loading is required, such as rapid pavement repairs.



Set retarding admixtures are primarily used for hot weather placement conditions where a longer set time and strength gain are desirable.

Retarders are also frequently used for large or complex placements where cold joints are not acceptable. For example, multi-span continuous bridge decks placed in a single operation.



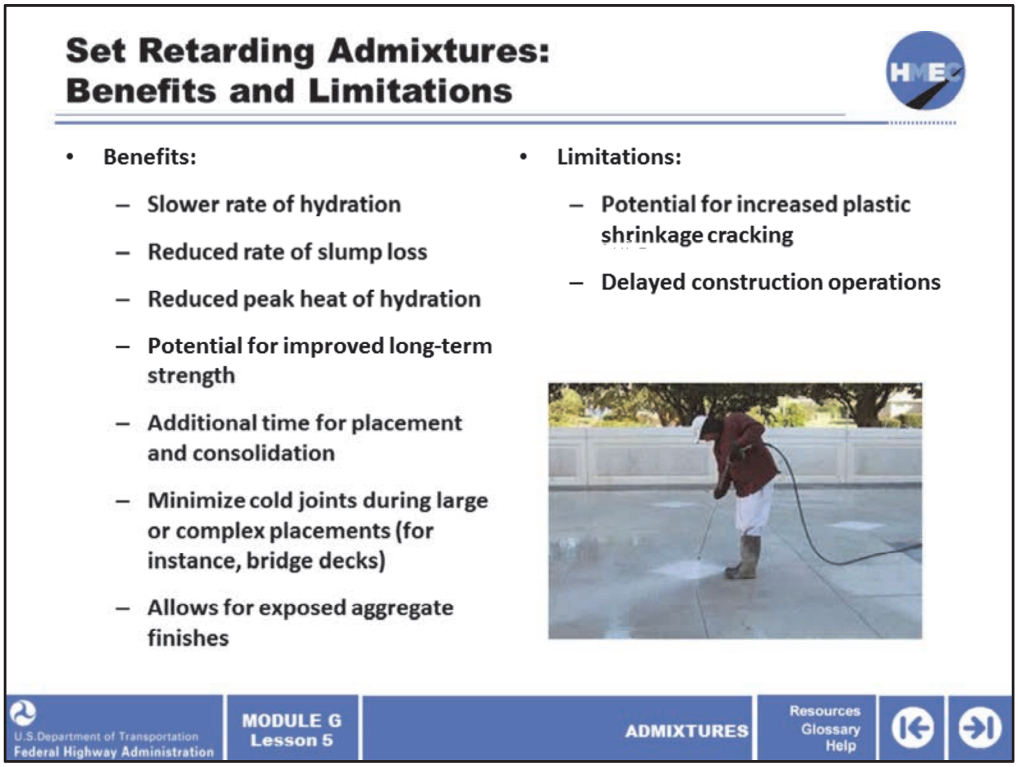
In addition to cold weather placement, accelerators are sometimes used to promote more rapid strength gain under normal temperate placement conditions. As a rule, the higher the placement temperature, the less effective accelerators are in promoting higher early strengths. Note that in many cases, accelerators 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. Set accelerating admixtures, or accelerators, have a number of benefits, including:

- Increased rate of hydration;
- Reduced initial set time;
- Increased rate of strength gain; and
- Higher early strength.

There are also several limitations worth noting, including:

- Potential for increased shrinkage cracking;
- Corrosion of embedded steel (chloride-based accelerators);
- The ultimate strength of the PCC is typically less for an accelerated mix; and
- The rapid strength gain is significantly diminished after the first 24 hours.

Note that all DOTs prohibit the use of chloride-based accelerators where rebar or prestressing is used.



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).

Set retarding admixtures, or retarders, have a number of benefits, including:

- Slower rate of hydration;
- Reduced the rate of slump loss;
- Reduced peak heat of hydration;
- Potential for improved long-term strength;
- Additional time for placement and consolidation;
- Minimize cold joints during large or complex placements; and
- Allows for exposed aggregate finishes.

There are also several potential limitations when using retarders, including:

- Potential for increased plastic shrinkage cracking; and
- Delayed construction operations.

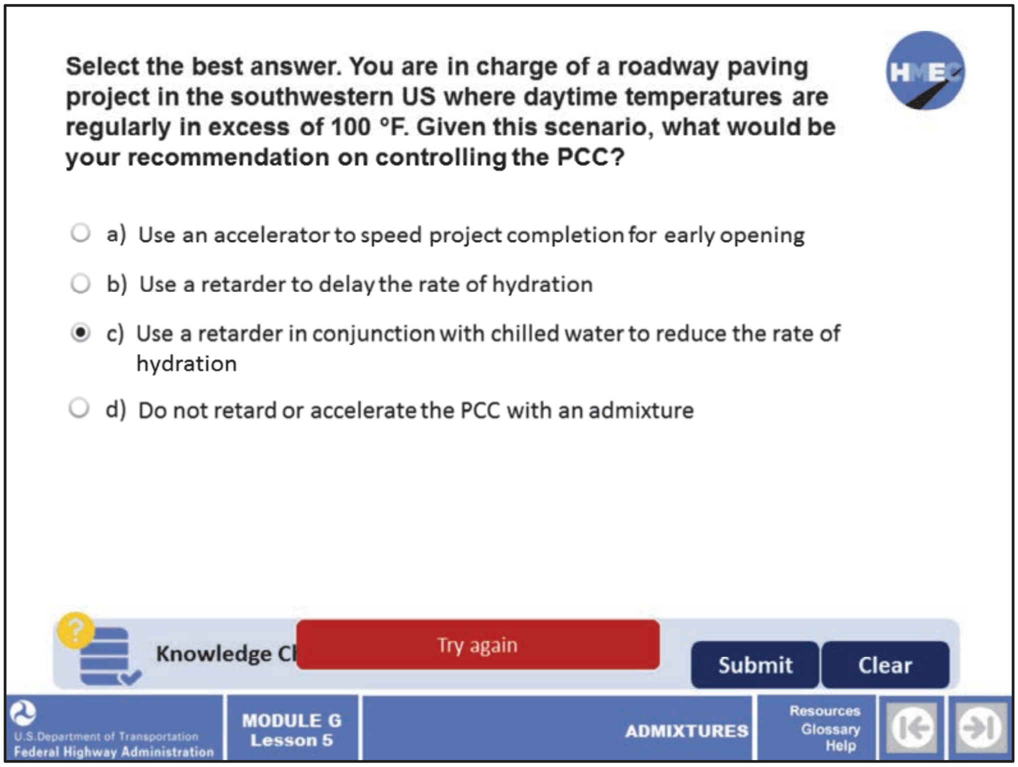
The photo shows an exposed aggregate finish that can be used for pavements to potentially reduce noise and increase skid resistance.

Image description: Photo showing an exposed aggregate finish that can be used for pavements to potentially reduce noise and increase skid resistance.

Comparison of Set Controlling Admixtures

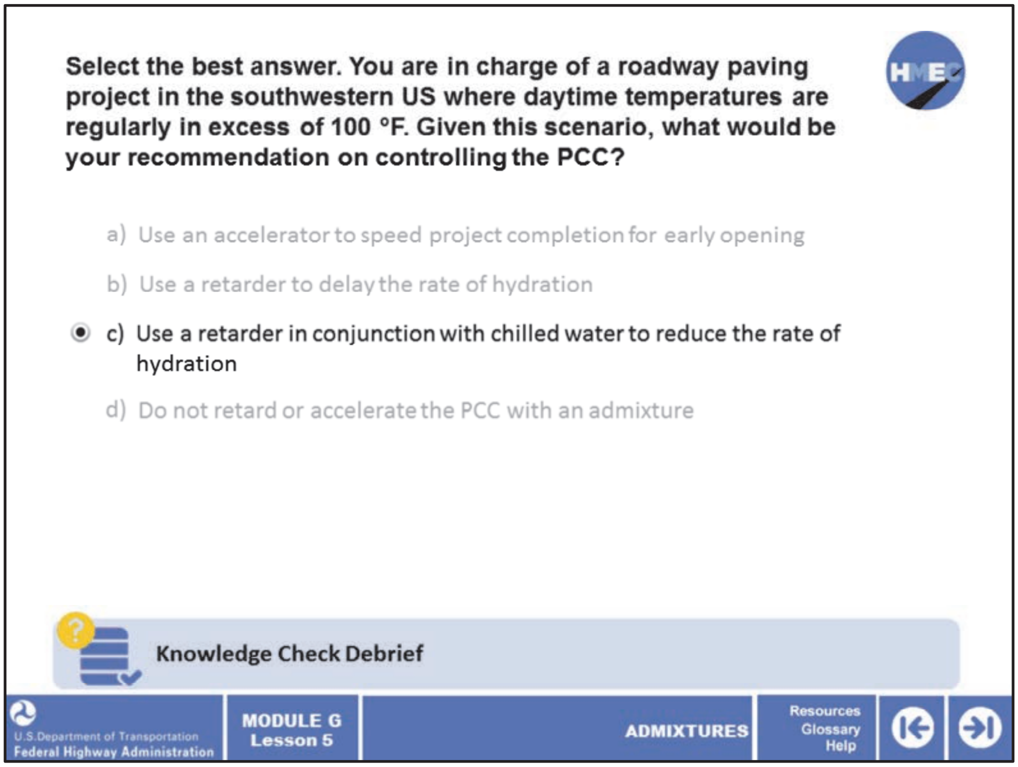
Property	Set Accelerating Admixtures	Set Retarding Admixtures
Primary use	Cold weather placement	Hot weather placement
Additional uses	Patching and rapid opening requirements	Difficult placements, long hauls
Initial set time	Decreased	Increased
Rate of strength gain	Increased	Decreased
Ultimate strength	Generally lower	Generally higher
Other considerations	Chloride-based materials are prohibited where embedded steel is present	May delay construction operations

The table shows uses for two set controlling admixtures: set accelerating admixtures and set retarding admixtures.

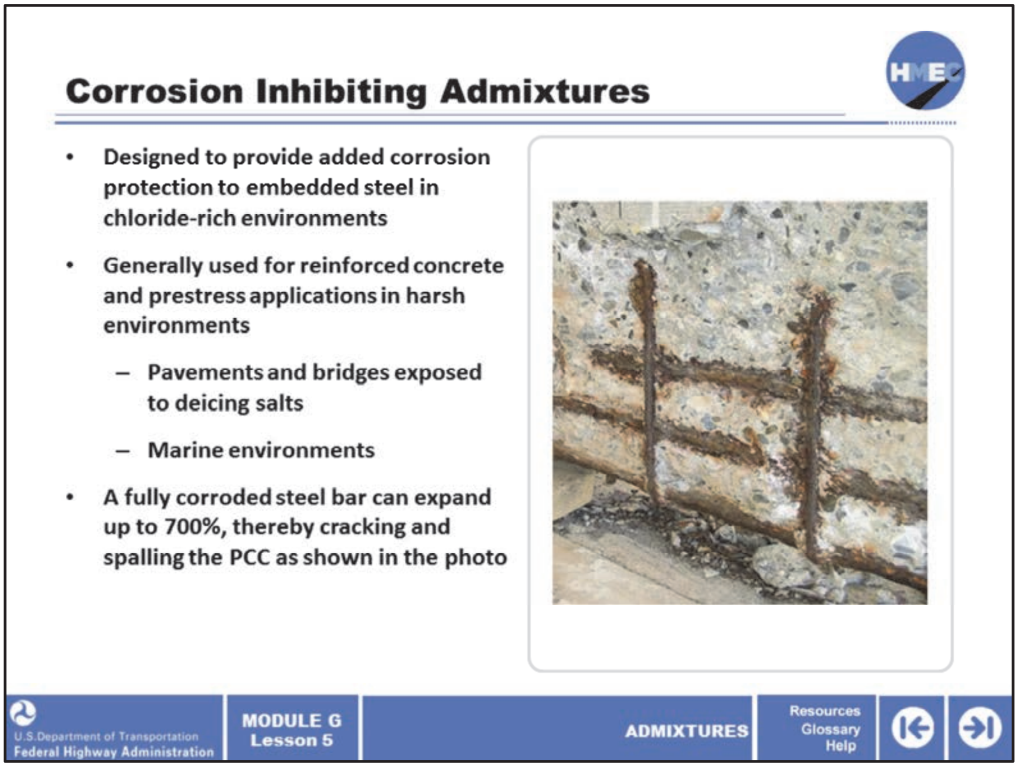


Select the best answer. You are in charge of a roadway paving project in the southwestern US where daytime temperatures are regularly in excess of 100 °F. Given this scenario, what would be your recommendation on controlling the PCC?

a) Use an accelerator to speed project completion for early opening;
b) Use a retarder to delay the rate of hydration;
c) Use a retarder in conjunction with chilled water to reduce the rate of hydration; or
d) Do not retard or accelerate the PCC with an admixture.



The correct answer is c) Use a retarder in conjunction with chilled water to reduce the rate of hydration.



Corrosion inhibiting admixtures are designed to provide added corrosion protection to embedded steel in chloride rich environments. These admixtures are generally used for reinforced concrete and prestress applications in harsh environments. Chloride-rich environments include pavements and bridges exposed to deicing salts as well as marine environments.

Corrosion inhibitors provide an additional level of corrosion resistance and are ideally used in conjunction with low permeability PCC and/or corrosion-resistant steel. However, the use of a corrosion inhibitor is always beneficial when exposure conditions warrant, and embedded steel is present regardless of the type. Corrosion in conventional reinforced PCC is very detrimental to long-term durability. As the steel oxidizes within the rigid PCC matrix, the expansion causes very high internal stresses leading to cracking and spalling. Corrosion in prestress applications is even more detrimental and can eventually result in weakening and rupture of the prestress strands.

Note that corrosion inhibitors frequently act as an accelerator. The effects of this and the other admixtures to be used in a PCC mix should be assessed with trial batches.

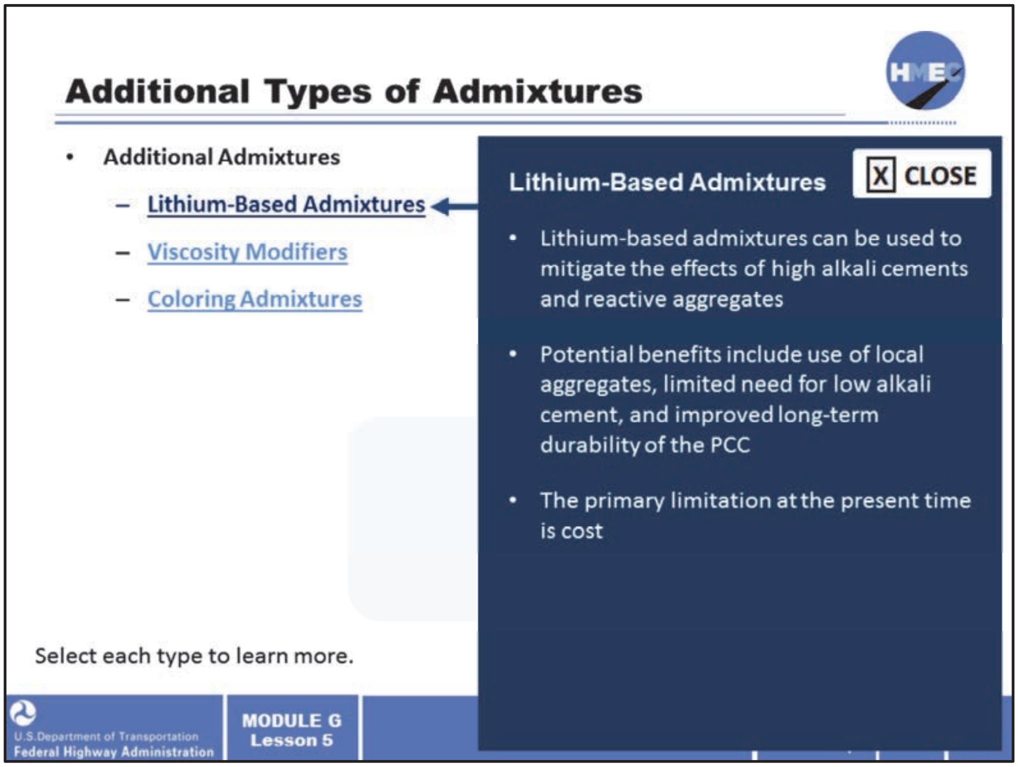
Image description: Photo of corroded steel imbedded in concrete.

There are numerous types of admixtures that are used for very specific applications. Of the numerous types currently in use, the majority fall into the categories already discussed. There are, however, a few additional types that have limited application for transportation uses. Most of these fall outside the realm of transportation-related uses. However, the following have seen limited use in pavements and structures:

- Lithium-based admixtures;
- Viscosity modifiers; and
- Coloring admixtures.

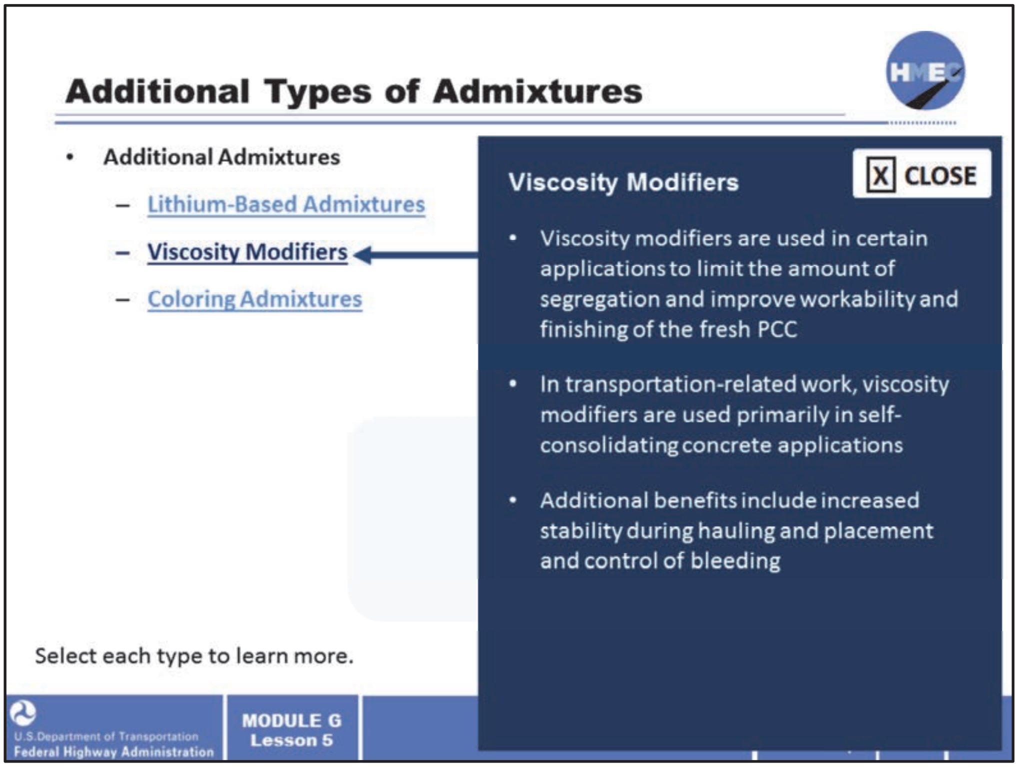
Select each type to learn more.

Image description: Photo of droplets of liquid.



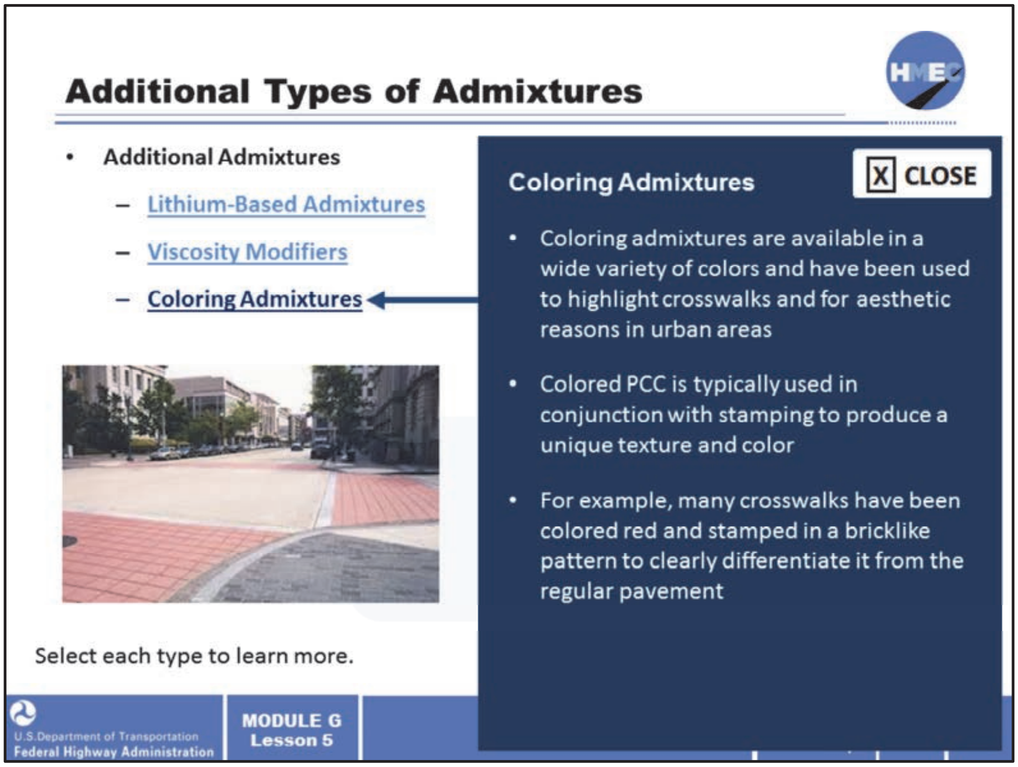
Lithium-based admixtures can be used to mitigate the effects of high alkali cements and reactive aggregates. Potential benefits include use of local aggregates, limited need for low alkali cement, and improved long-term durability of the PCC. The primary limitation at the present time is cost.

Image description:



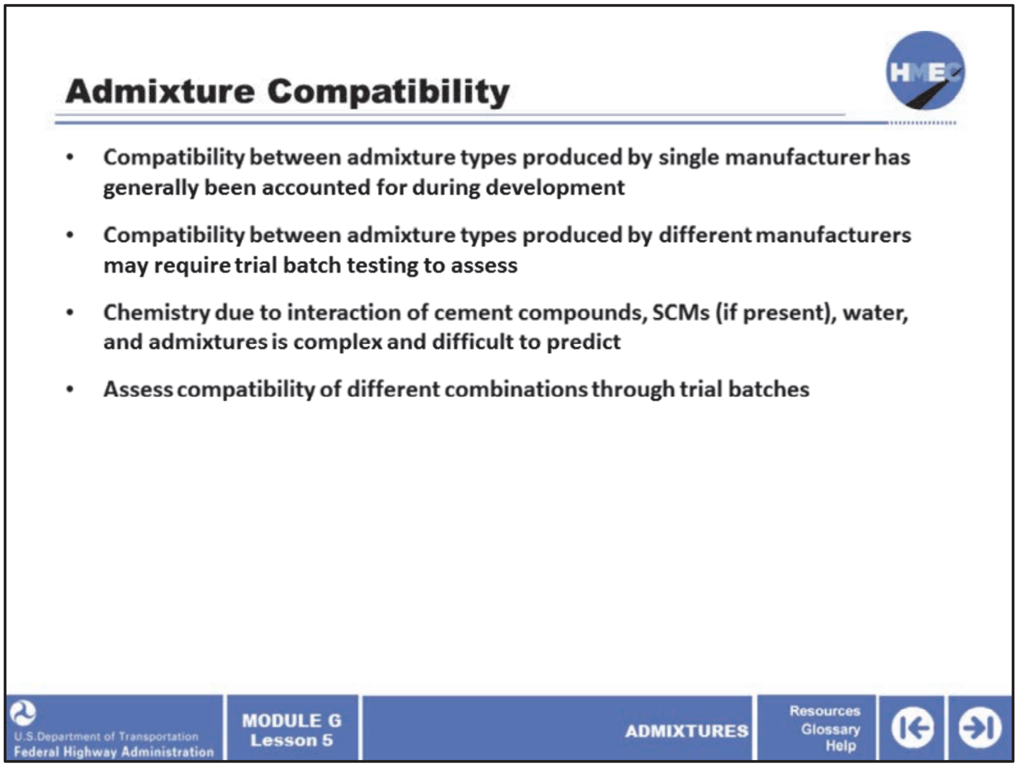
Viscosity modifiers are used in some applications to limit the amount of segregation and improve workability and finishing of the fresh PCC. In transportation-related work, viscosity modifiers are used primarily in self-consolidating concrete applications. Additional benefits include increased stability during hauling and placement and control of bleeding.

Image description:



Coloring admixtures are available in a wide variety of colors and have been used to highlight crosswalks and for aesthetic reasons in urban areas. Colored PCC is typically used in conjunction with stamping to produce a unique texture and color. For example, many crosswalks have been colored red and stamped in a bricklike pattern to clearly differentiate them from the regular pavement.

Image description: Photo of an intersection with stamped, colored crosswalks.



Compatibility between admixture types produced by a single manufacturer has generally been accounted for during development. Compatibility between admixture types produced by different manufacturers may require trial batch testing to assess. Admixture compatibility (or incompatibility) can have serious consequences to both the fresh and hardened PCC.

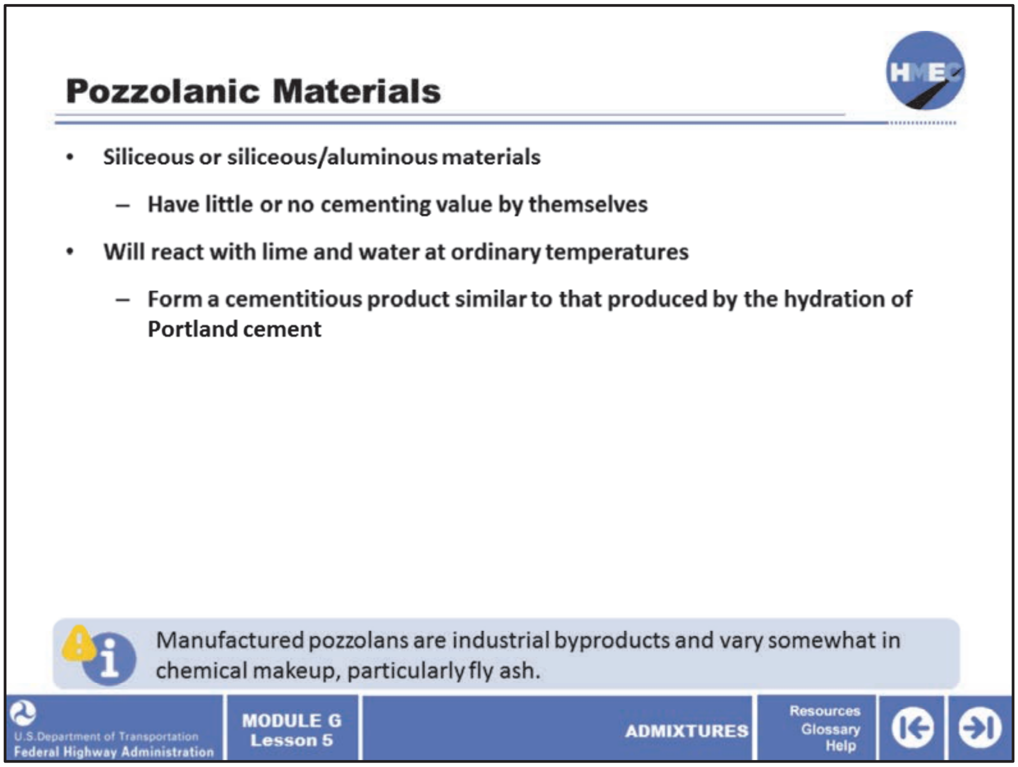
The chemistry due to the interaction of the cement compounds, SCMs (if present), water, and admixtures is very complex and difficult to predict. The only way to assess the compatibility of different combinations of admixtures is through trial batches. The trial batches must use the cement, mix water, SCMs, and admixtures that will be used on the project to be representative. The trial batches should be done as close to the temperature anticipated for the project as possible since some incompatibility issues are a function of temperature (i.e., higher temperatures drive reactions at a higher rate than cooler temperatures).

Offline Activity

- Develop a table of the admixture types used by your agency
- For each type, list where it is used and the primary purpose
- Compile a list of the quality assurance procedures employed for each admixture type
- Partial sample table

Admixture Type	Where it is Used	Primary Purpose	Quality Assurance Procedure
Air entraining	**All PCC**	**Freeze/thaw durability**	**Manufacturers data sheet, plant storage records**
Set modifying	Accelerators	Cold weather concreting, rapid repair	?

Develop a table of the admixture types used by your agency. For each type, list where it is used and the primary purpose. Compile a list of the quality assurance procedures employed for each admixture type. Here is what a partial sample table might look like.



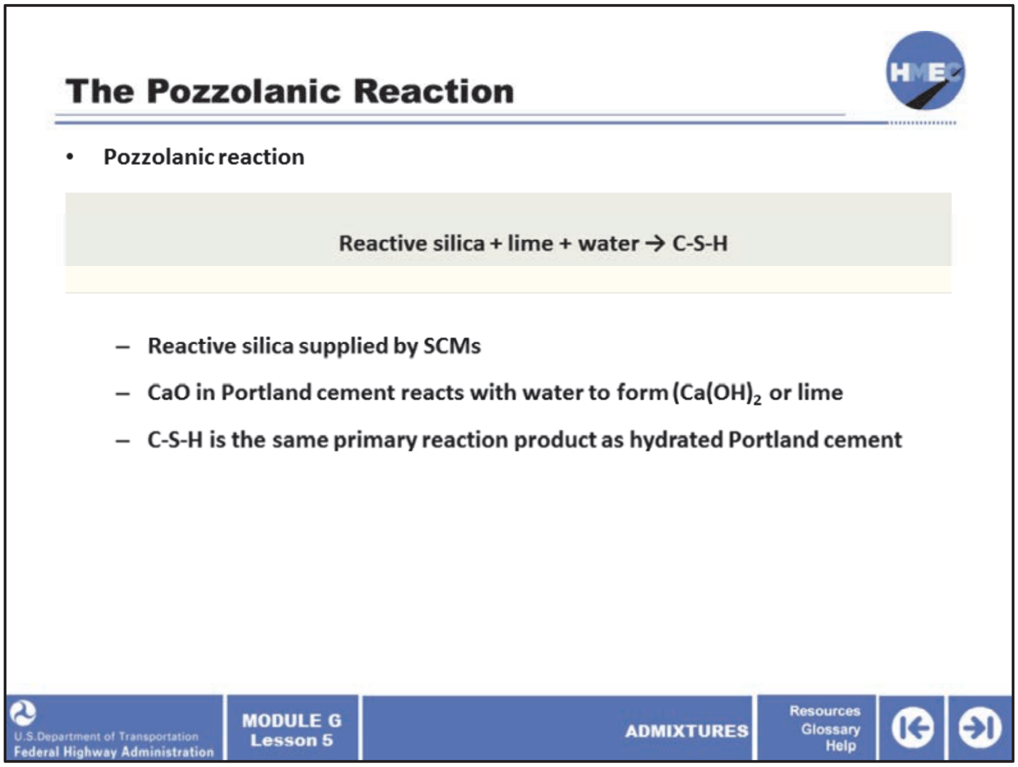
Pozzolans are siliceous or siliceous/aluminous materials which have little or no cementing value by themselves. However, pozzolans will react with lime and water at ordinary temperatures to form a cementitious product similar to that produced by the hydration of Portland cement. The SCMs we have looked at are all considered pozzolanic materials. That is, they are predominantly comprised of glassy or amorphous silica due to rapid cooling during production. Remember that the manufactured pozzolans are industrial byproducts and vary somewhat in chemical makeup, particularly fly ash.

Differences in Pozzolans

- Particle size
- Shape
- Carbon and sulfur impurities
- Reactivity
- Uniformity

Although SCMs are fundamentally the same, there are important differences, including size, shape, carbon and sulfur impurities, and reactivity. (Not all silica is converted to glass in any process. Some portion is crystalline and therefore less reactive.) The day-to-day uniformity of the product also depends on the day-to-day uniformity of the process.

Image description: Photo of Portland cement and various SCMs.



The pozzolanic reaction is a very important attribute of these four types of SCMs. They do not simply act as a finely divided filler, they actually produce cementing products. Here is an example of a pozzolanic reaction:

• Reactive silica + lime + water → C-S-H

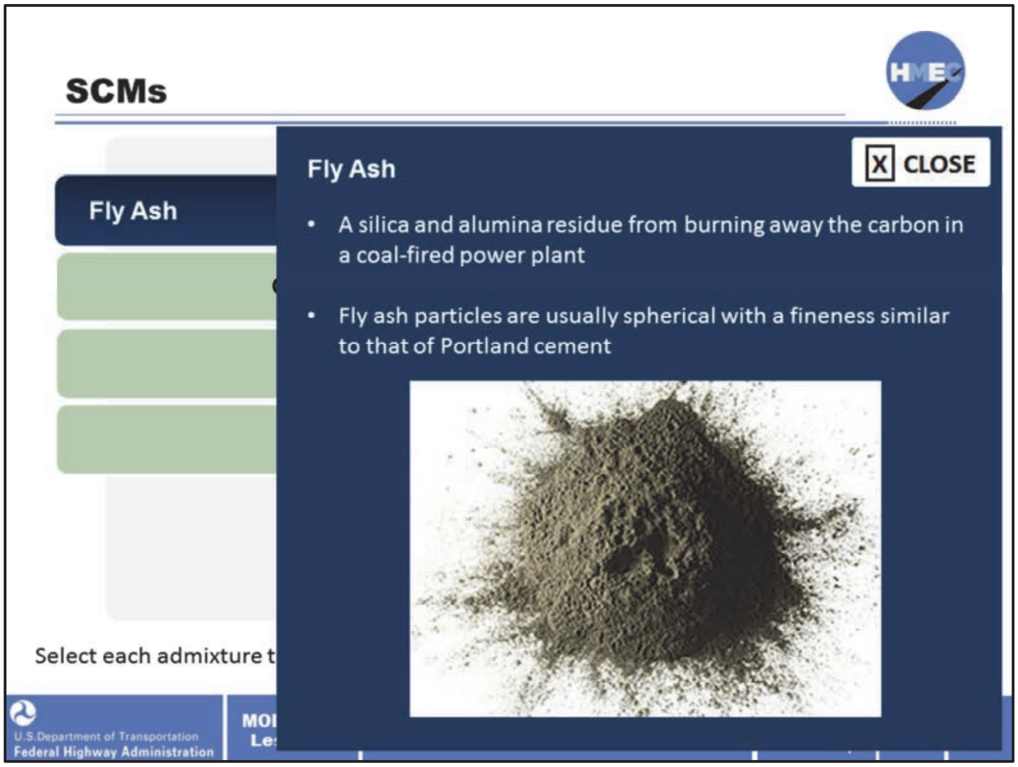
The reactive silica is supplied by the SCMs. The calcium oxide (CaO) in the Portland cement reacts with water to form calcium hydroxide ($Ca(OH)_2$ or lime. The resulting calcium-silicate-hydrate (C-S-H) is the same primary reaction product as hydrated Portland cement. The pozzolanic reaction will occur only if the silica is reactive (i.e., non-crystalline) and very finely divided with a corresponding high surface area. All of the listed SCMs meet these criteria. The pozzolanic reaction releases less heat than the hydration of an equivalent mass of Portland cement, resulting in a lower temperature gradient in the PCC.

There are four primary types of SCMs. They are:

1. Fly ash (FA);
2. Ground granulated blast furnace slag (GGBFS);
3. Silica fume (SF); and
4. Natural pozzolans.

These SCMs are known as pozzolanic admixtures or pozzolans. These materials are composed primarily of a reactive form of silicon dioxide although they may also contain appreciable amounts of other compounds.

Select each admixture to see the definition.

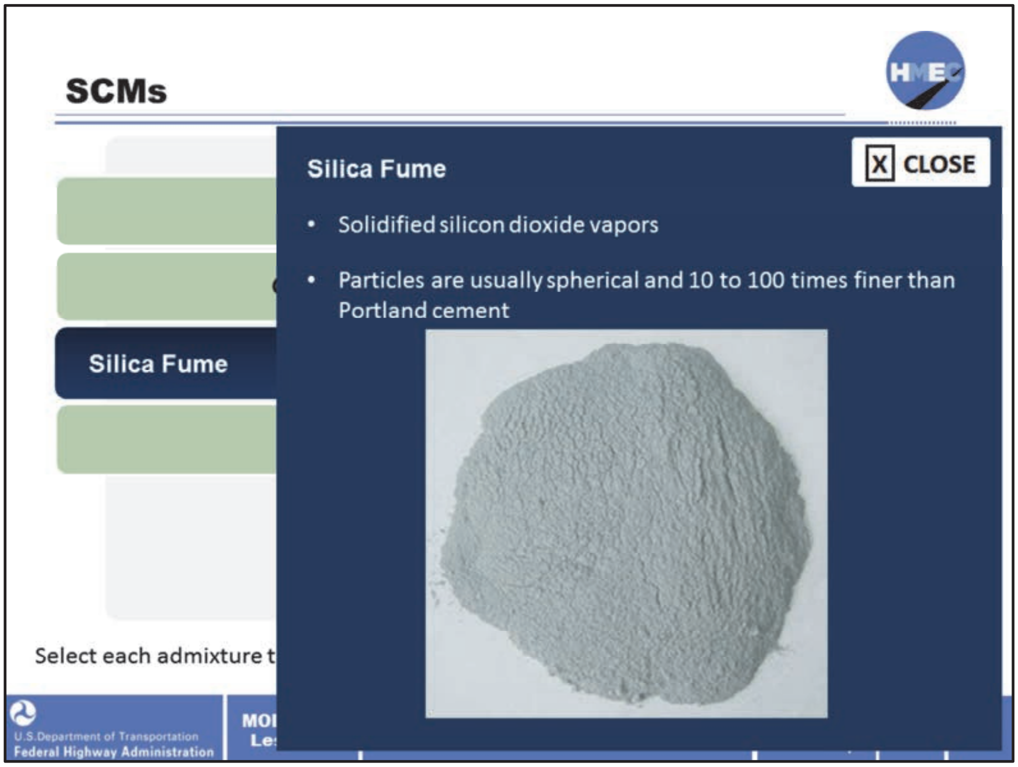


Fly ash is a silica and alumina residue from burning away the carbon in a coal-fired power plant. Fly ash particles are usually spherical with a fineness similar to that of Portland cement.

Image description: Photo of fly ash.

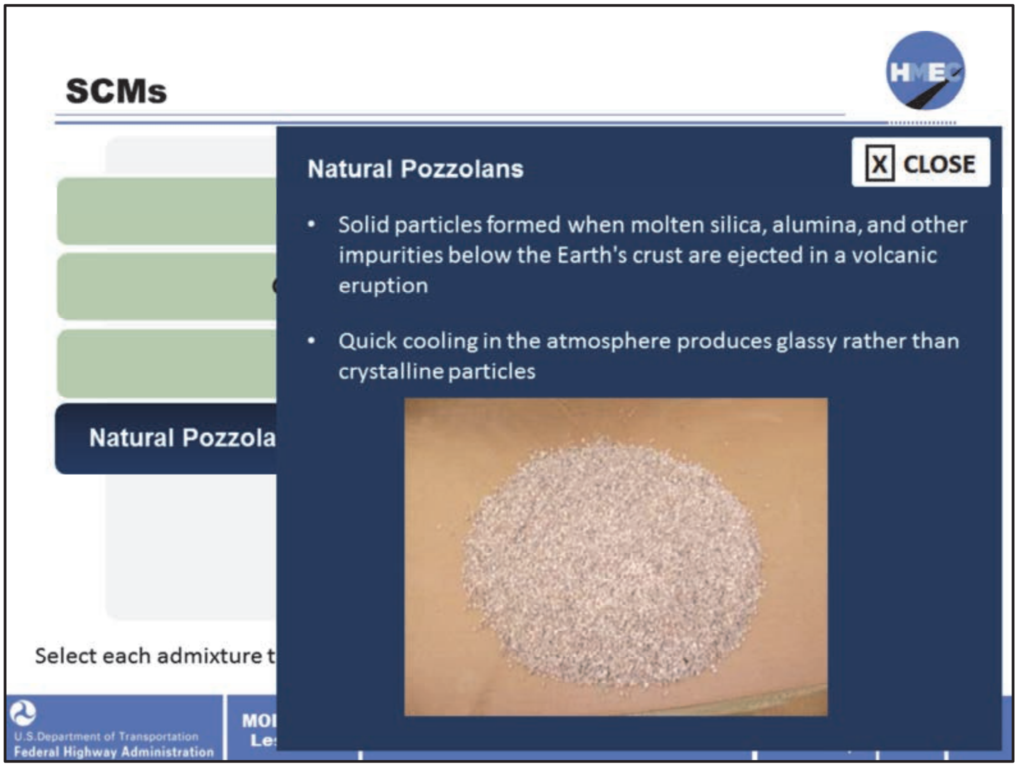
Ground granulated blast furnace slag are solid particles formed when molten silica, alumina, and other constituents are poured from the top of a blast furnace ladle into cold air or cold water.

Image description: Photo of ground granulated blast furnace slag.



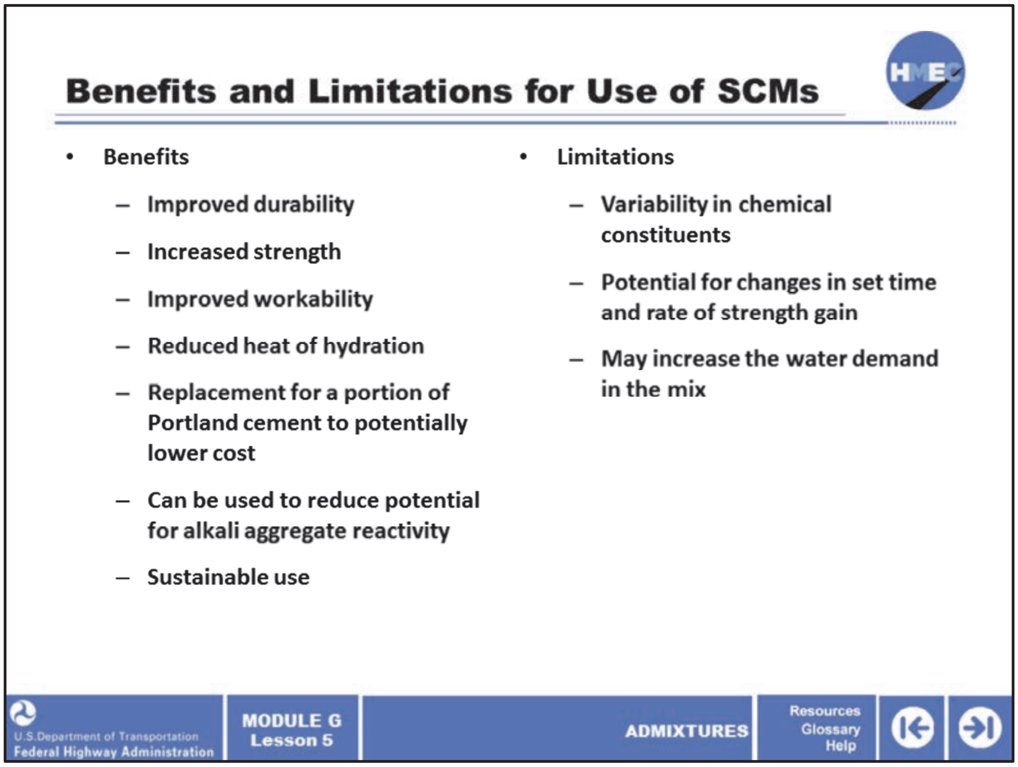
Silica fume is solidified silicon dioxide vapors. Particles are usually spherical and 10 to 100 times finer than Portland cement.

Image description: Photo of silica fume.



Natural pozzolans are solid particles formed when molten silica, alumina, and other impurities below the Earth's crust are ejected in a volcanic eruption. Quick cooling in the atmosphere produces glassy rather than crystalline particles.

Image description: Photo of natural pozzolans.



The benefits of SCMs far exceed the limitations. The vast majority of PCC mixes used for transportation-related projects contain one of more SCMs in addition to a variety of chemical admixtures. SCMs are used for a variety of reasons that benefit the PCC mix. They are:

- Improved durability due to reduced permeability and resistance to chloride intrusion.
- Increased strength;
- Improved workability (fly ash and GGBFS);
- Reduced heat of hydration (fly ash and GGBFS) for mass placements;
- Replacement for a portion of the Portland cement to lower the cost per cubic yard;
- Certain SCMs can be used to reduce the potential for alkali aggregate reactivity; and
- Sustainable use.

The limitations, particularly for fly ash, are:

- The variability in chemical constituents;
- Potential for changes in set time and rate of strength gain; and
- May increase the water demand in the mix.

Effects of SCMs on Fresh PCC

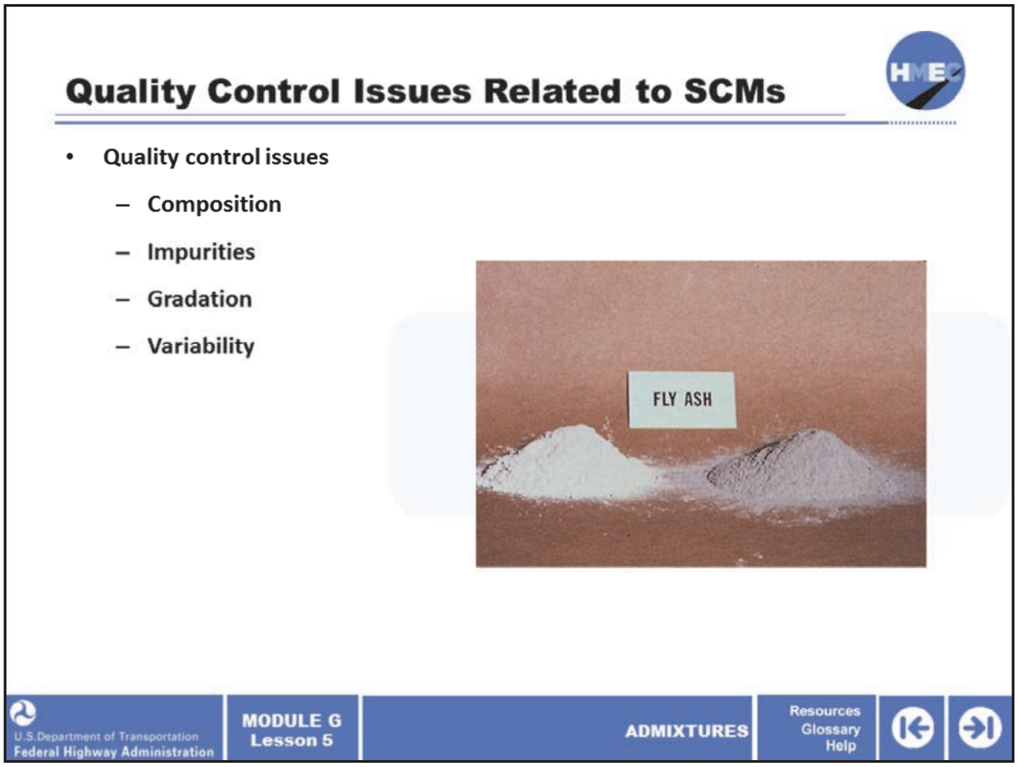
Effects of Mineral Admixtures on Freshly Mixed Concrete	
Water Content – Fly Ash and Slag:	**Reduced**
Water Content – Silica Fume:	**Increased**
Air-Entraining Admixture Dosage – Fly Ash and Silica Fume:	**Increased**
Air-Entraining Admixture Dosage – Slag:	**Varies**
Air-Content Stability:	**Varies**
Workability – Fly Ash and Slag:	**Increased**
Workability – Silica Fume:	**Decreased**
Segregation and Bleeding:	**Reduced**
Heat of Hydration (Fly Ash and Slag):	**Reduced**
Setting Time:	**Retarded**
Finishability:	**Improved**
Pumpability:	**Improved**

The degree to which each of these properties are affected is governed by the specific properties of the SCMs admixture, characteristics of the PCC mix, and environmental conditions.

Effects of SCMs on Hardened PCC

Effects of Mineral Admixtures on Hardened Concrete	
Strength Gain:	Varies
Drying Shrinkage:	No Effect
Creep:	No Effect
Permeability:	Reduced
Color:	Varies
Alkali-Silica Reactivity:	Reduced
Sulfate Attack:	Reduced
Freeze-Thaw Resistance:	No Significant Effect
Deicer Scaling:	Varies from No Significance Effect to Increased

As stated in the preceding slide, the degree to which each of these properties are affected is governed by the specific properties of the SCMs admixture, characteristics of the PCC mix, and environmental conditions.



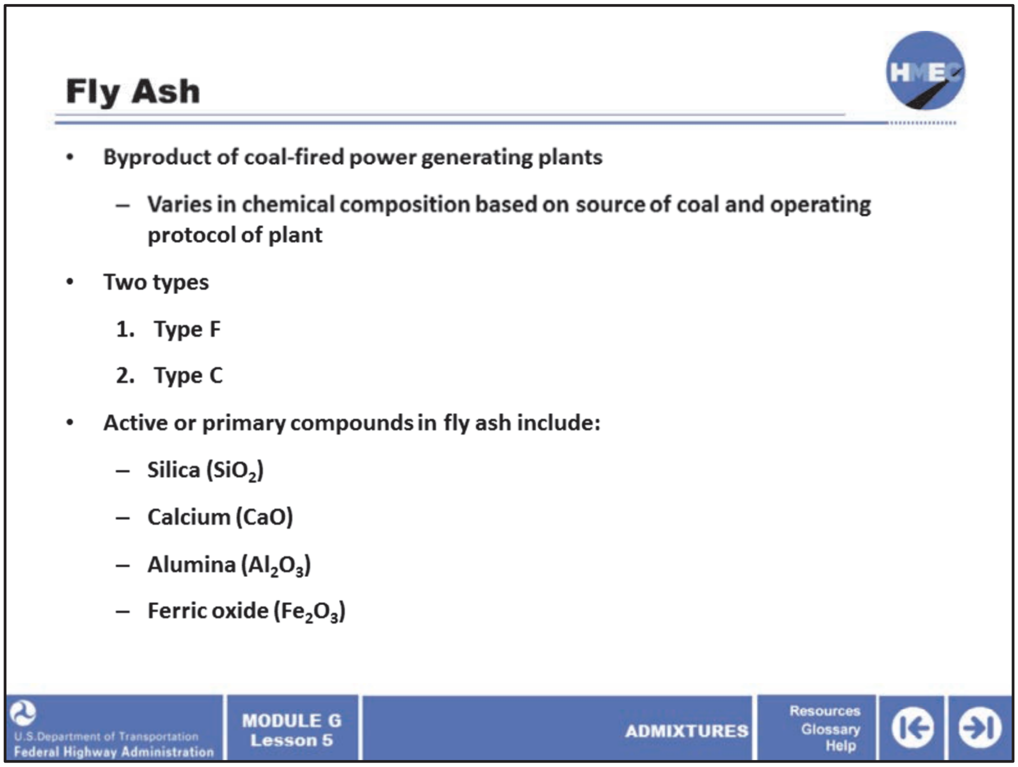
Due to the majority of SCMs being industrial byproducts (particularly fly ash), quality control issues may arise in their use. The exception being when these materials are processed specifically for use in PCC and therefore have tight controls. SCMs quality control issues generally fall into one or more of the following four categories:

1. Composition;
2. Impurities;
3. Gradation; and
4. Variability.

The photo illustrates the difference between two fly ash sources, the one on the right having a much higher carbon content. The carbon content can have effects on set time, entrained air content, and other mix related factors. Carbon reacts with the air entraining agent, essentially deactivating it and leading to a reduction in entrained air.

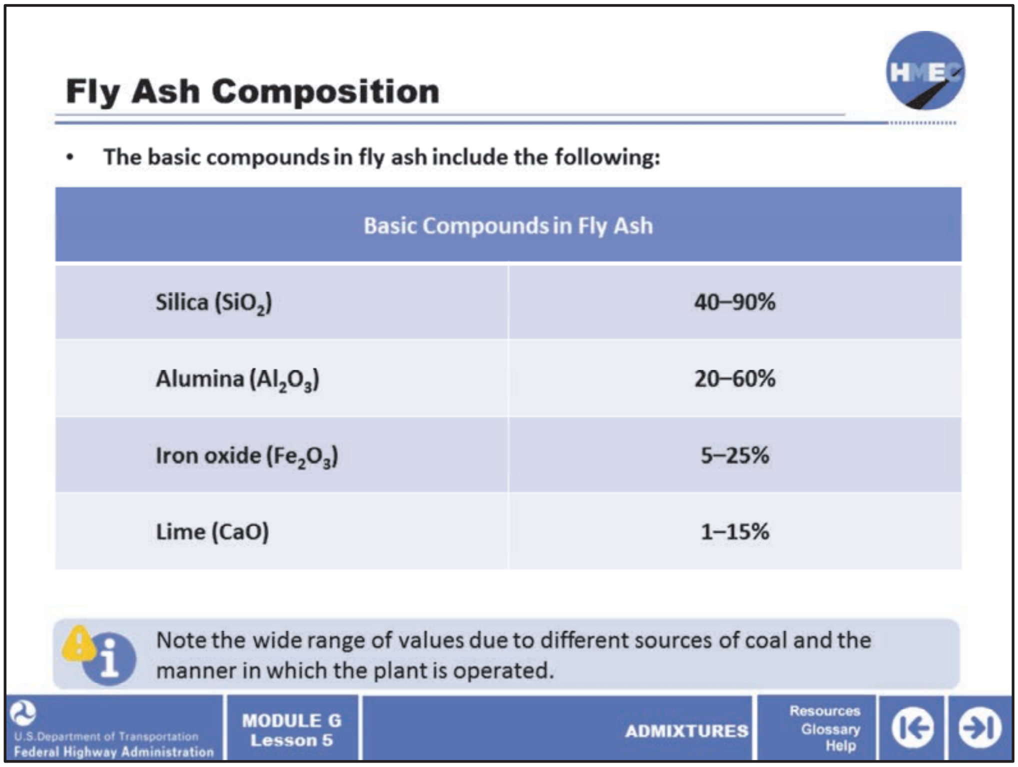
It is important to recognize when using SCMs that their effects on fresh and hardened PCC are a combination of both physical and chemical characteristics.

Image description: Photo of two piles of fly ash.



Fly ash is a byproduct of coal-fired power generating plants and varies in chemical composition based on the source of coal and the operating protocol of the plant. Fly ash is considered a waste product and the chemical composition can vary on a routine basis. There are two types of fly ash: Type F and Type C. The two types are comprised of essentially the same compounds only in different quantities. The active or primary compounds in fly ash include:

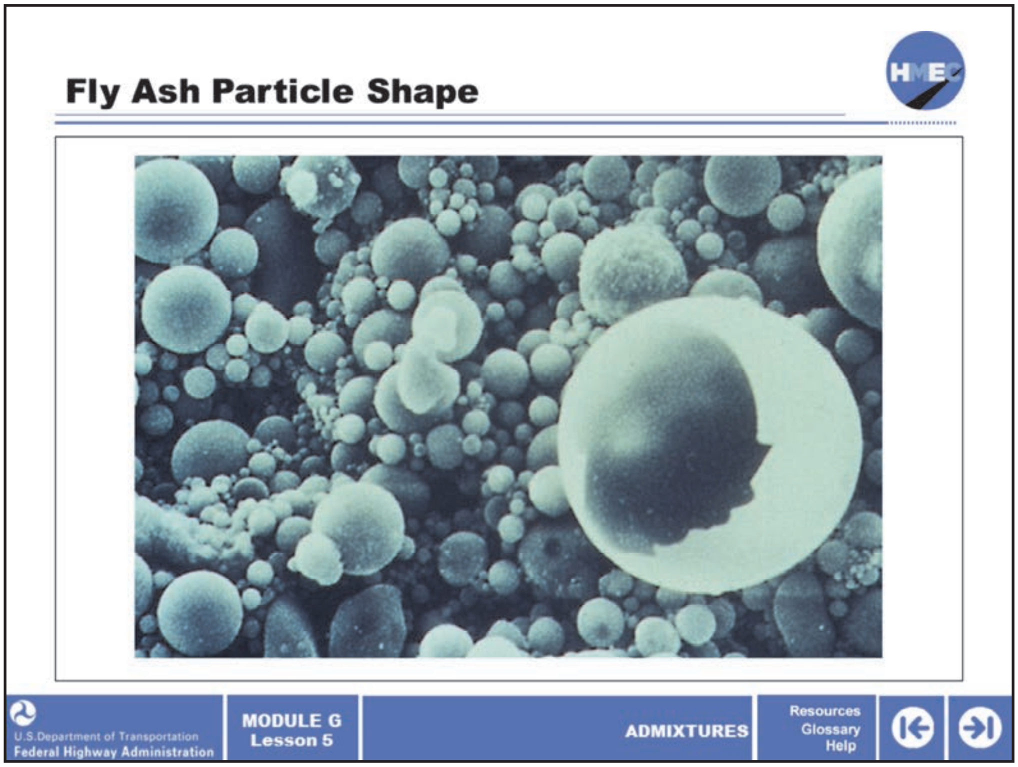
- Silica (SiO_2);
- Calcium (CaO);
- Alumina (Al_2O_3); and
- Ferric oxide (Fe_2O_3).



The basic compounds in fly ash include the following:

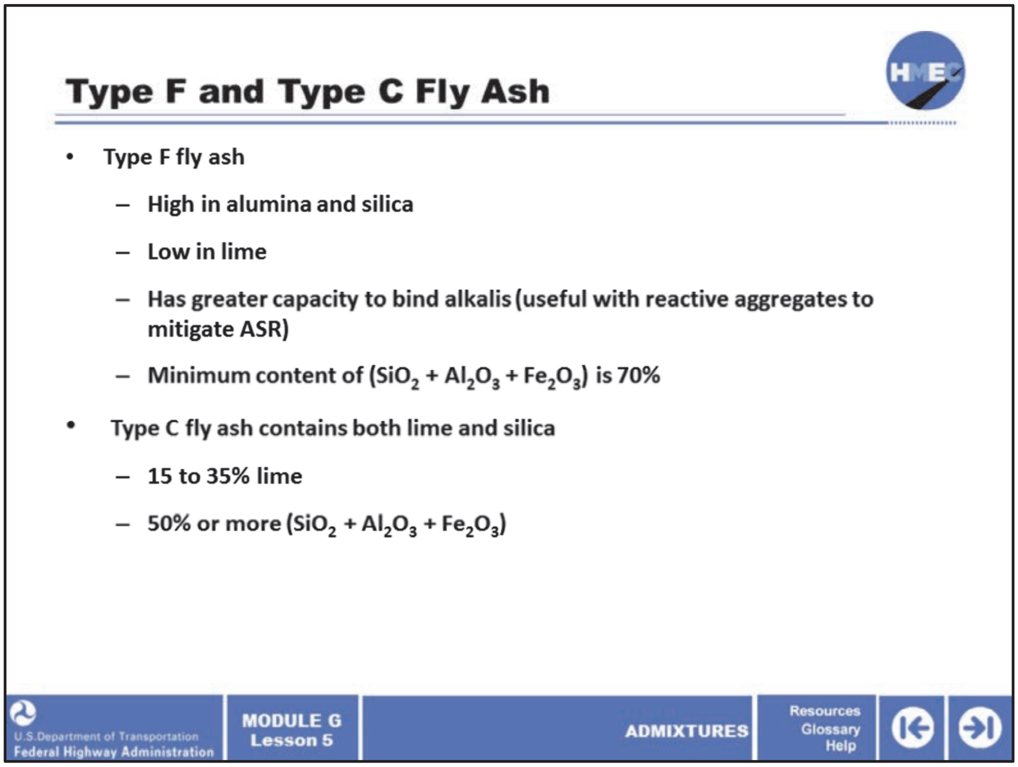
- Silica (SiO_2)=40–90%;
- Alumina (Al_2O_3)=20–60%;
- Iron oxide (Fe_2O_3)=5–25%; and
- Lime (CaO)=1–15%.

Note the wide range of values due to different sources of coal and the manner in which the plant is operated. There are many additional compounds that may be present in small quantities, the most important being carbon.

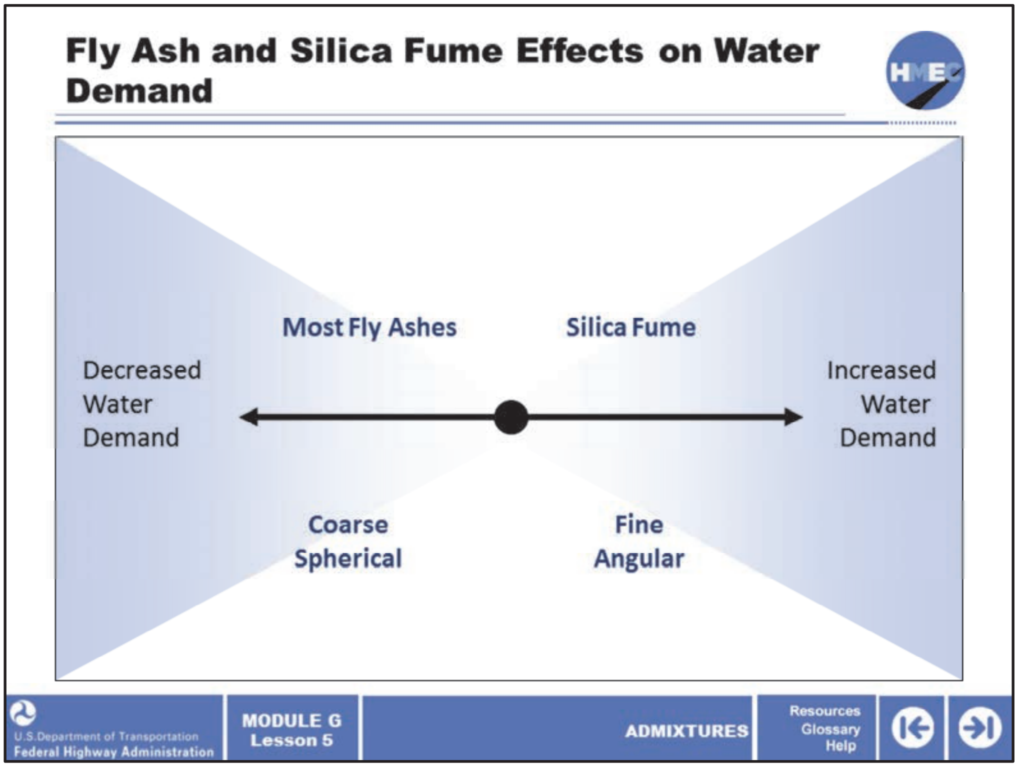


This scanning electron microscope photo shows the spherical nature of fly ash. Note the glassy and smooth surface texture that can result in a decreased water demand when a portion of the cement is replaced with fly ash. Note the wide variation in particle size. The addition of fly ash improves workability due to the lubricating action of the spherical particles.

Image description: Photo of the spherical nature of fly ash under a scanning electron microscope.

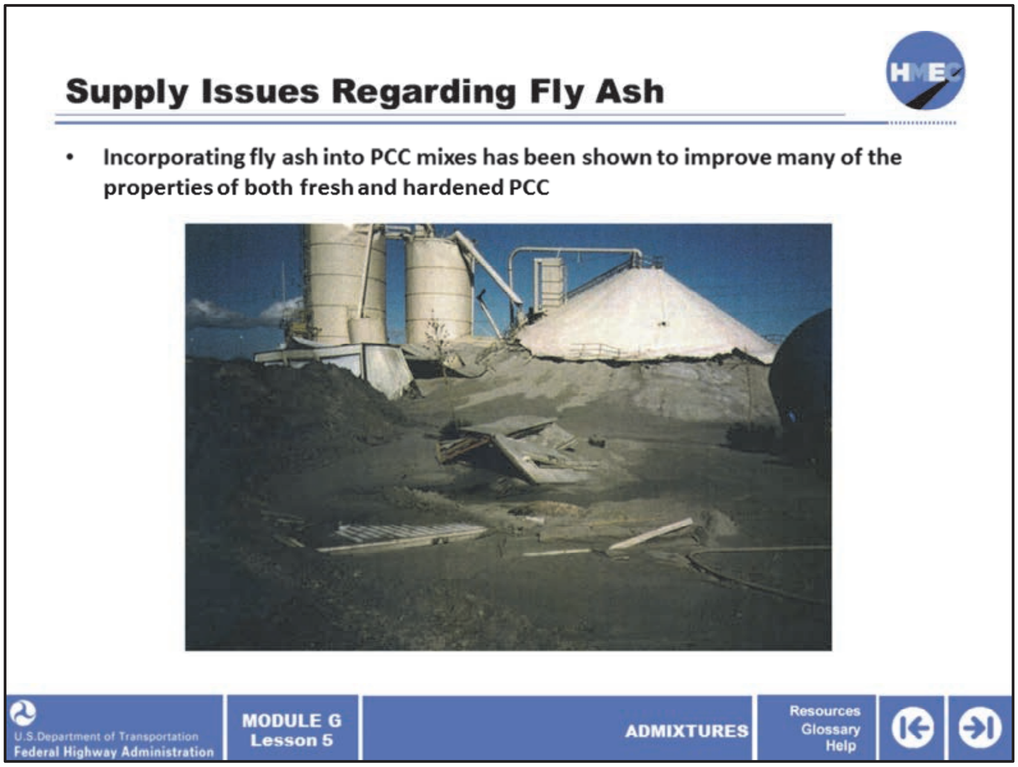


Type F fly ash is high in alumina and silica, low in lime, has a greater capacity to bind alkalis (useful with reactive aggregates to mitigate alkali-silica reaction, or ASR), and has a minimum content of ($SiO_2 + Al_2O_3 + Fe_2O_3$) of 70%. Type C fly ash contains both lime and silica with 15 to 35% lime and 50% or more ($SiO_2 + Al_2O_3 + Fe_2O_3$). Note that due to the presence of both lime and silica in Type C fly ash, these materials can form varying quantities of C-S-H independently of Portland cement. Type C fly ash behaves similarly to a Type IV Portland cement but with significantly more variability in chemistry and physical properties.



Due to the particle size of fly ash and to a much greater extent silica fume, they partially fill some of the void space between the more angular and larger cement grains. This densification improves the permeability of the hardened PCC and makes for a generally denser matrix of C-S-H. The workability and potential water-reduction benefit will depend on the fineness and shape of the particles. Fly ash generally improves workability, permitting water reduction. Silica fume hinders workability, raises water demand, and is most commonly used in conjunction with a superplasticizer, due to the small particle size and extremely high surface area.

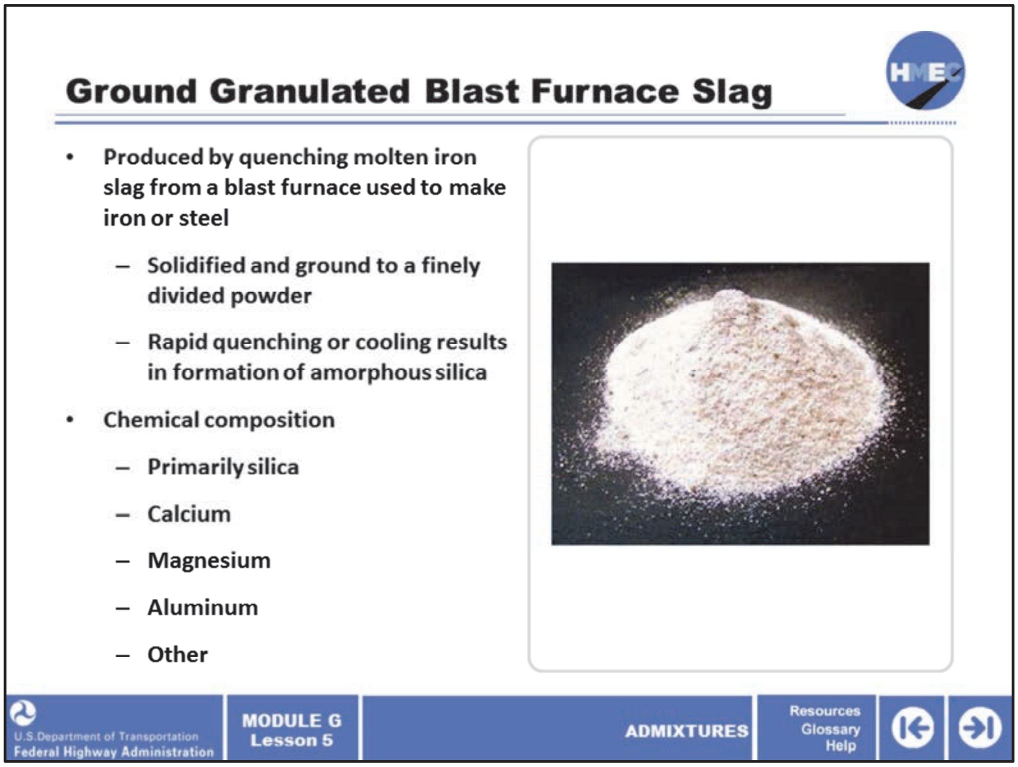
Image description: Illustration showing fly ash and silica fume effects on water demand.



Incorporating fly ash into PCC mixes has been shown to improve many of the properties of both fresh and hardened PCC. Fly ash has been readily available since most electrical power generation plants have traditionally been coal fired. While still readily available in most parts of the US, fly ash, by virtue of it being a byproduct of coal-fired power generation facilities, will likely become harder to obtain as energy policies move us away from the use of coal.

The use of an industrial byproduct was seen in the past as a “green technology.” This may change due to new EPA regulations. The effect of this, in conjunction with much more stringent EPA regulations governing coal and fly ash, may reduce the availability of fly ash and therefore increase its cost. It is likely to be many years before these issues come to pass but it is worth noting for purposes of long-term planning.

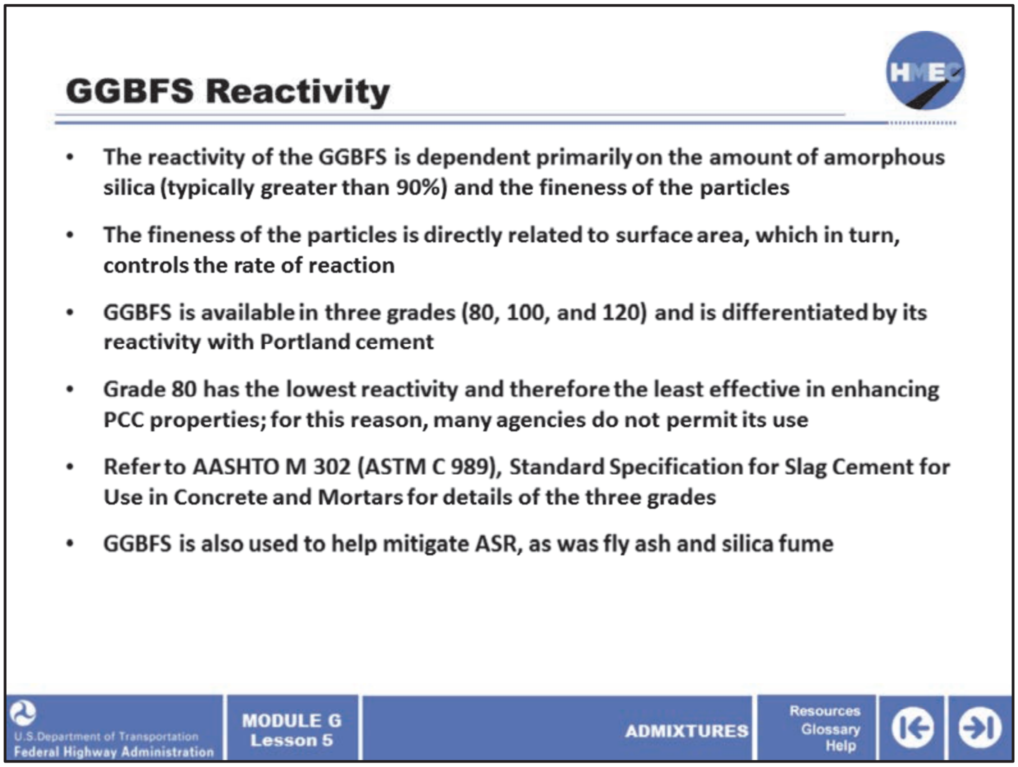
Image description: Photo of a fly ash storage facility.



The use of ground granulated blast furnace slag is growing steadily due to its relatively low cost and the beneficial properties it imparts to a PCC mix. GGBFS is another of the industrial byproducts that has found application in PCC production. GGBFS is produced by quenching molten iron slag from a blast furnace used to make iron and steel.

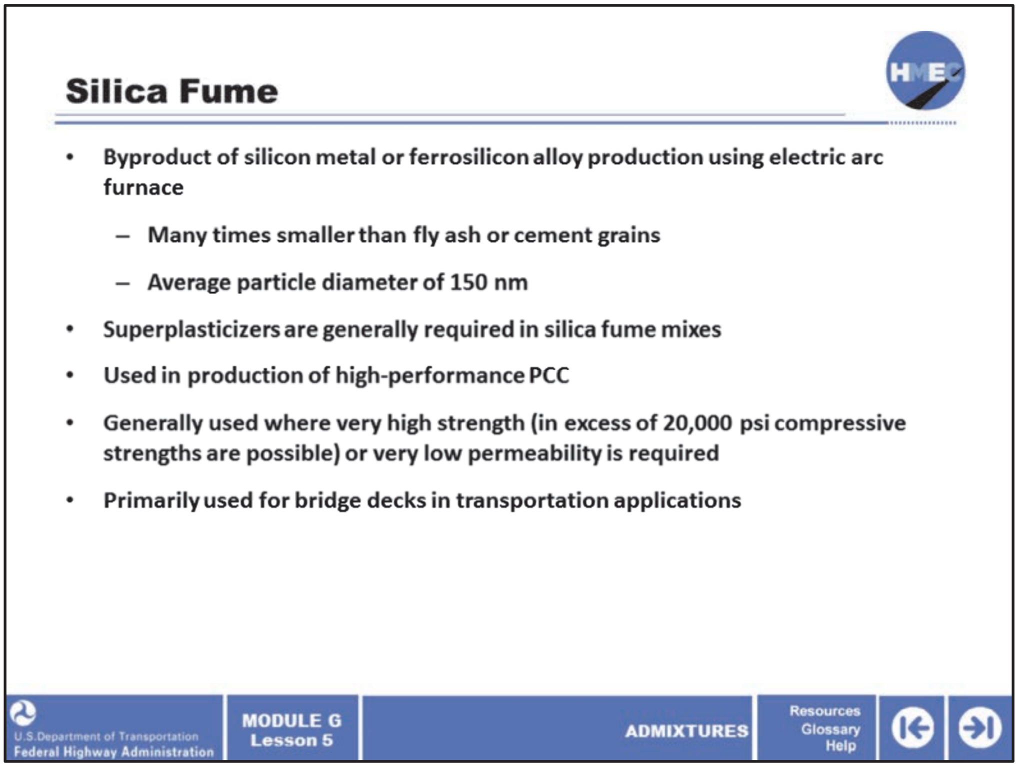
It is solidified and then ground to produce a finely divided powder that can be used as an SCM in PCC. The rapid quenching or cooling of the slag results in the formation of amorphous silica. The chemical composition of GGBFS primarily contains silica, but can also contain varying amounts of calcium, magnesium, aluminum, and other chemicals.

Image description: Photo of ground granulated blast furnace slag.



GGBFS is primarily composed of amorphous silica and reacts in the presence of Portland cement according to the pozzolanic reaction previously discussed. The rate of reactivity of the GGBFS is primarily dependent upon the amount of amorphous silica (typically greater than 90%) and the fineness of the particles. The fineness of the particles is directly related to surface area, which in turn, controls the rate of reaction.

The fineness is controlled during the grinding process. As with the other pozzolanic materials, the addition of GGBFS slows the initial set and rate of strength gain of PCC, but results in a higher ultimate strength. The permeability of PCC is reduced due to the denser C-S-H matrix, the extent of which is partially dependent on the fineness of the particles. GGBFS is also used to help mitigate ASR, as was fly ash and silica fume.

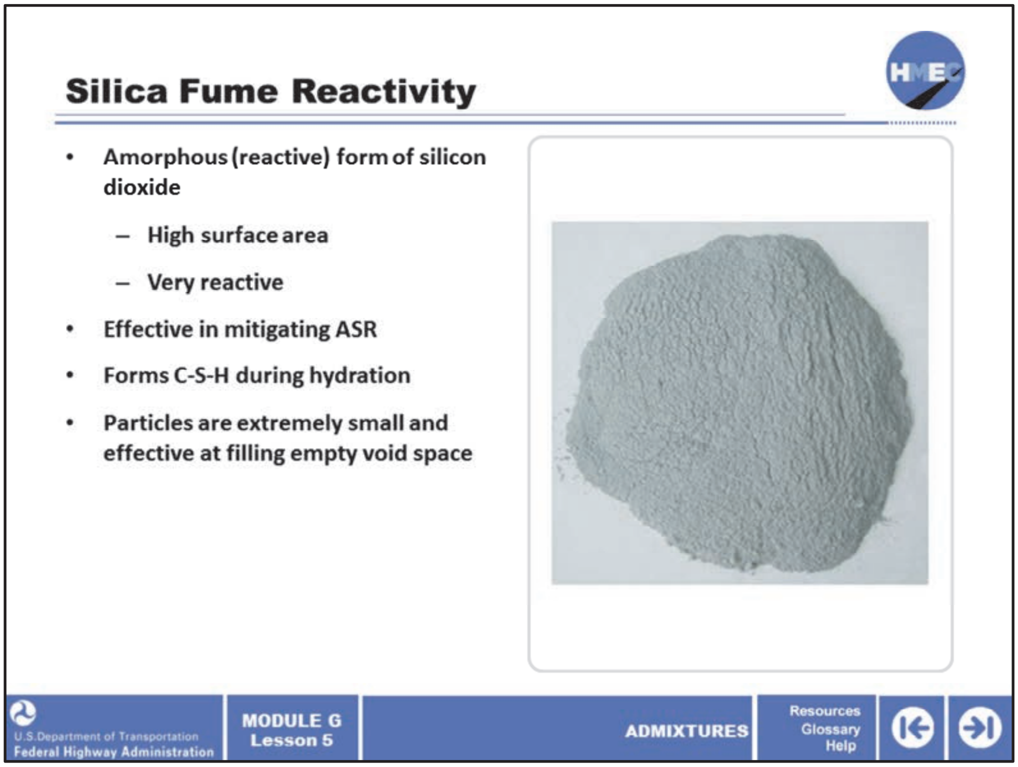


Silica fume, also known as microsilica, is a byproduct of silicon metal or ferrosilicon alloy production using an electric arc furnace. These spherical particles are many times smaller than fly ash or cement grains and have an average particle diameter of 150 nm. The particle size is such that it readily fills the void space between cement grains resulting in a very dense particle packing of reactive materials.

The end result is a very dense matrix in the fresh concrete and hardened concrete (C-S-H). It should be noted that the fineness of these particles has a corresponding extremely large surface area, which increases water demand. Superplasticizers are generally required in silica fume mixes and the possibility for early age cracking is relatively high unless adequate and timely curing is assured.

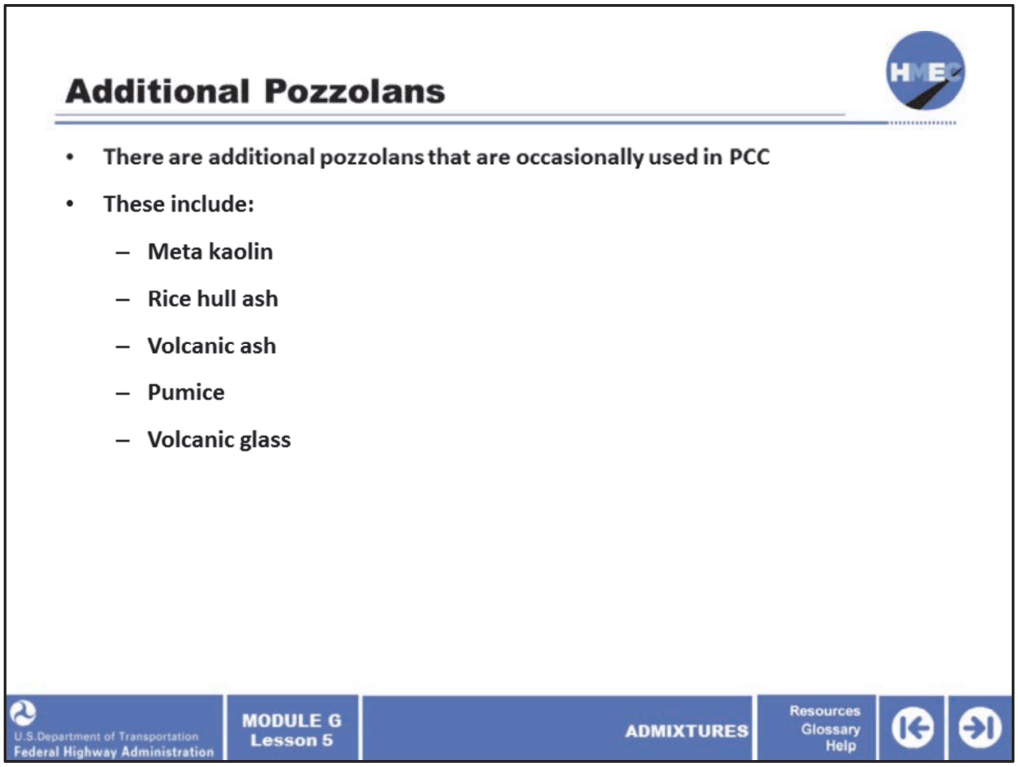
Silica fume is used in the production of high performance PCC. Silica fume is generally used where very high strength (in excess of 20,000 psi compressive strengths are possible) or very low permeability is required. In transportation systems, the primary use has been for bridge decks. Silica fume is also used in structural columns where the size of the member may be reduced by the corresponding high strength. Silica fume is not widely used in transportation systems unless ultra high performance concrete is required for a specific application (generally structural).

For example, New York uses high-performance concrete for about 70% of all transportation construction, so silica fume is used in substructures, decks, and structural precast applications.

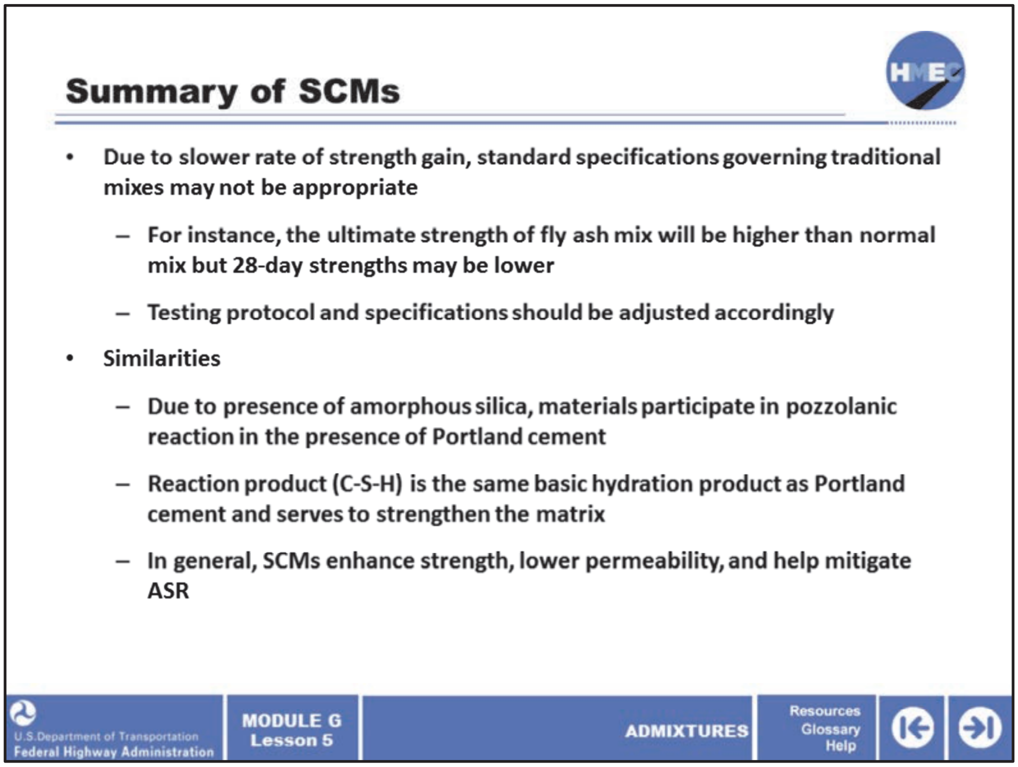


Silica fume is an amorphous (reactive) form of silicon dioxide and due to its extremely high surface area is very reactive. As with fly ash, silica fume has been shown to be effective in mitigating ASR. This material forms C-S-H during hydration, as was previously discussed in regards to the pozzolanic reaction. Silica fume particles are extremely small and are very effective at filling the empty void space between the cement grains.

Image description: Photo of silica fume.



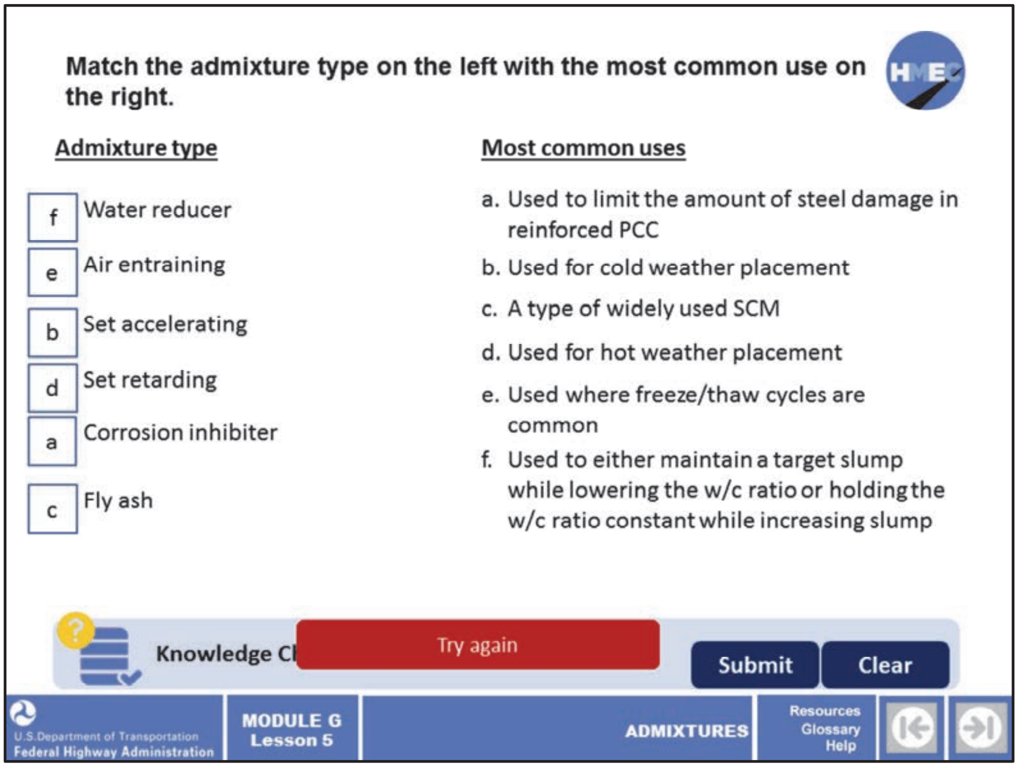
The materials listed on this slide are reactive to varying degrees but are not in widespread use, so they will not be considered in this lesson.



SCMs are very beneficial to PCC under most circumstances. It is important to note that due to the slower rate of strength gain 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. The testing protocol and specifications should be adjusted accordingly. SCMs including fly ash, silica fume, and ground granulated blast furnace slag have a number of similarities including the following:

- Due to the presence of amorphous or reactive silica, these materials participate in the pozzolanic reaction in the presence of Portland cement (or calcium hydroxide);
- The reaction product (C-S-H) is the same basic hydration product as Portland cement and serves to strengthen the matrix; and
- All of these SCMs enhance strength, lower permeability, and help mitigate ASR.

Note that some SCMs may slow the rate of strength gain and may be limited for cold weather placement.



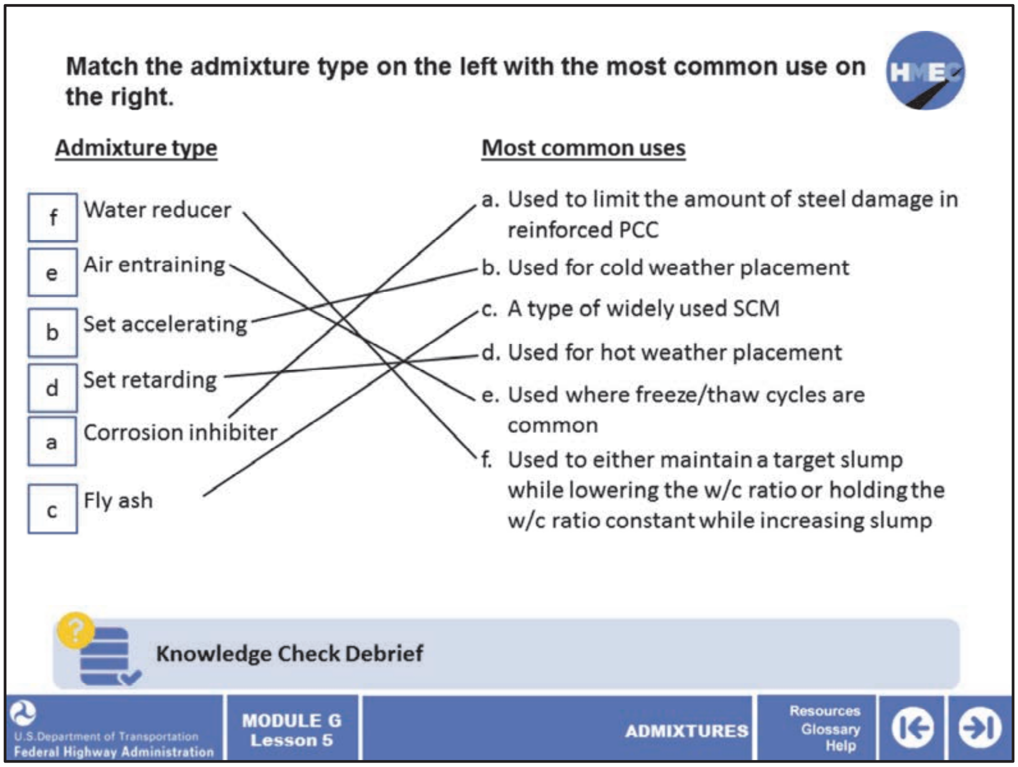
Match the admixture type on the left with the most common use on the right.

Admixture types:

- Water reducer;
- Air entraining;
- Set accelerating;
- Set retarding;
- Corrosion inhibiter; and
- Fly ash.

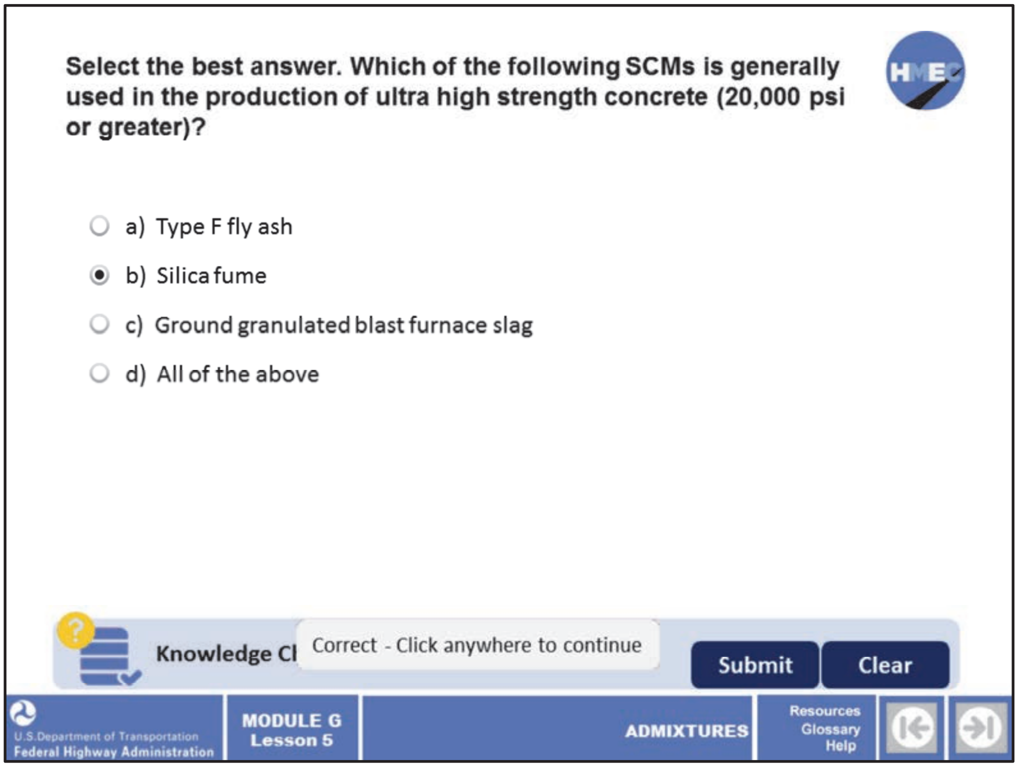
Most common uses:

a) Used to limit the amount of steel damage in reinforced PCC;
b) Used for cold weather placement;
c) A type of widely used SCM;
d) Used for hot weather placement;
e) Used where freeze/thaw cycles are common; and
f) Used to either maintain a target slump while lowering the w/c ratio or holding the w/c ratio constant while increasing slump.



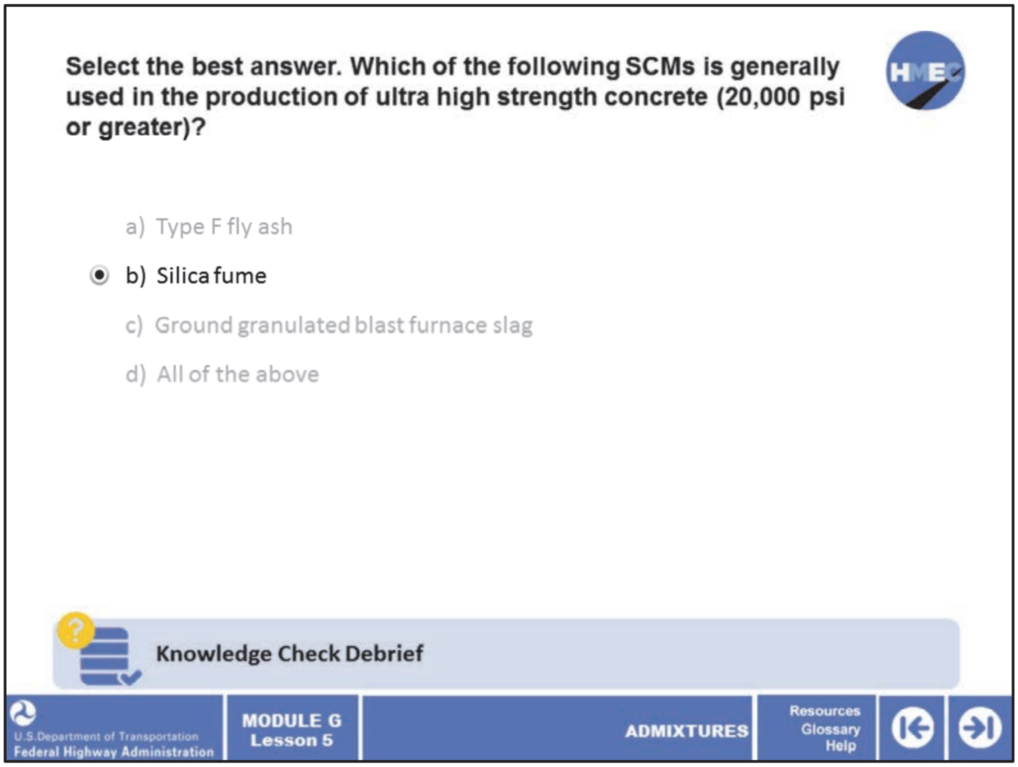
The correct answers are:

- Water reducer is f) Used to either maintain a target slump while lowering the w/c ratio or holding the w/c ratio constant while increasing slump;
- Air entraining is e) Used where freeze/thaw cycles are common;
- Set accelerating is b) Used for cold weather placement;
- Set retarding is d) Used for hot weather placement;
- Corrosion inhibiter is a) Used to limit the amount of steel damage in reinforced PCC; and
- Fly ash is c) A type of widely used SCM.

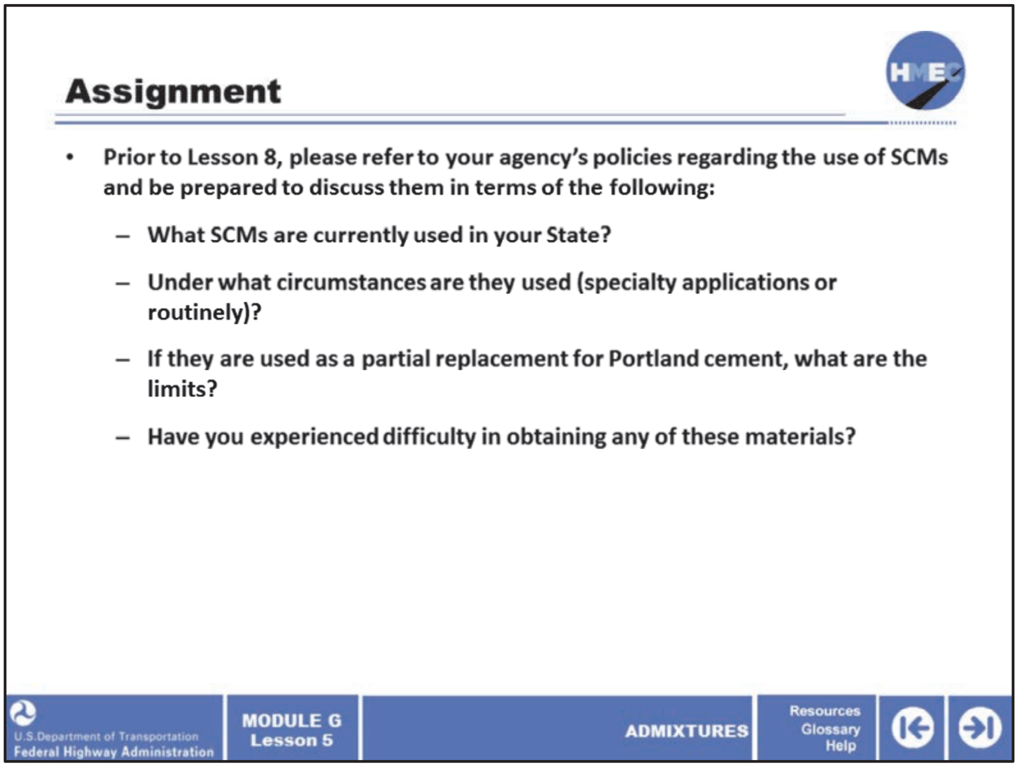


Select the best answer. Which of the following SCMs is generally used in the production of ultra high strength concrete (20,000 psi or greater)?

a) Type F fly ash;
b) Silica fume;
c) Ground granulated blast furnace slag; or
d) All of the above.

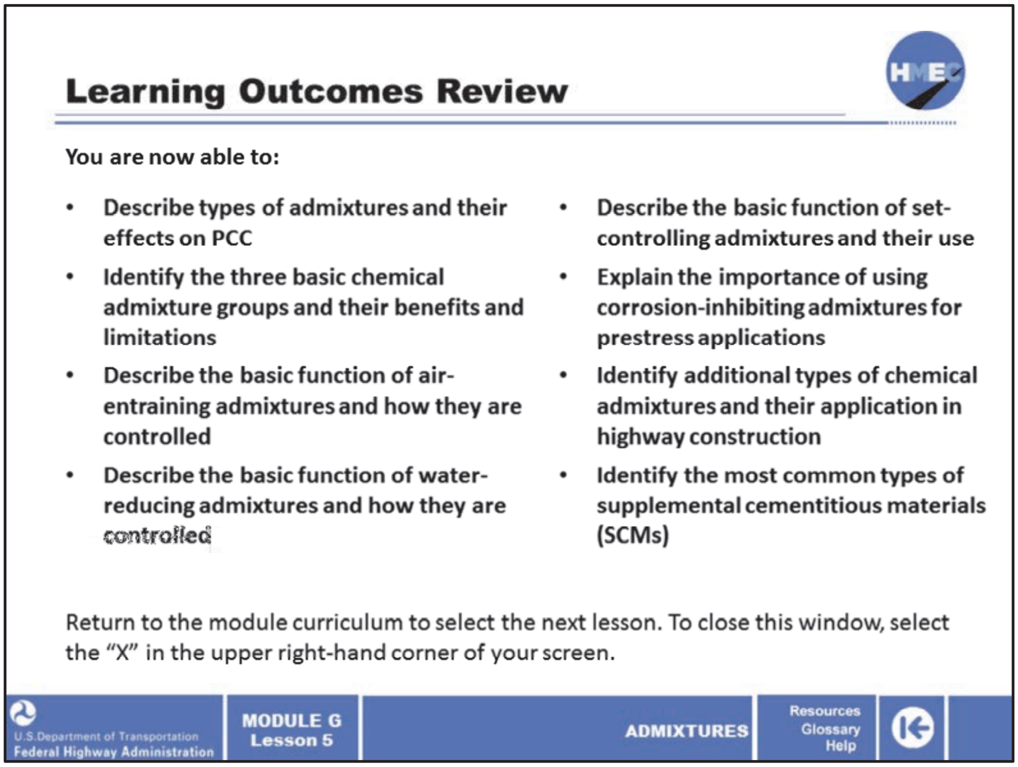


The correct answer is b) Silica fume.



Prior to Lesson 8, please refer to your agency's policies regarding the use of SCMs and be prepared to discuss them in terms of the following:

- What SCMs 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?; and
- Have you experienced difficulty in obtaining any of these materials?



You have completed Module G, Lesson 5: Admixtures.

You are now able to:

- Describe types of admixtures and their effects on PCC;
- Identify the three basic chemical admixture groups and their benefits and limitations;
- Describe the basic function of air-entraining admixtures and how they are controlled;
- Describe the basic function of water-reducing admixtures and how they are controlled;
- Describe the basic function of set-controlling admixtures and their use;
- Explain the importance of using corrosion-inhibiting admixtures for prestress applications;
- Identify additional types of chemical admixtures and their application in highway construction; and
- Identify the most common types of SCMs.

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.