the Construction Specifier

Solutions for the Construction Industry July 2008

Photo courtesy Lafarge

Concrete Failures

… and how SCMs can help prevent them

by Greg Daderko

When properly produced, placed, finished, and cured, concrete provides years of service with minimal maintenance. The type, quality, and quantity of its three basic components—cement, water, and aggregate—can greatly enhance its workability, setting times, finishing traits, durability, and strength gain characteristics. To achieve optimal performance, it is critical to use quality ingredients in accordance with various industry standards and to carefully design the concrete mix specifically for the intended use.

Concrete may have a reputation for lasting 'forever,' but there are chemical and physical reactions leading to deterioration over time. One major cause of failure is corrosion of embedded steel reinforcement; it is often seen in pavement structures (*e.g.* elevated expressways) subject to de-icing salt or marine exposure.

As steel corrodes, it produces a corrosion by-product (*i.e.* rust) that can expand to many times its original volume. The resulting expansive pressure causes the concrete to crack and spall, permitting chlorides, moisture, and other corrosive contaminants to penetrate at even a faster rate. Uncontrolled, the problem can eventually cause complete separation (delamination) and failed structural components.

Besides corrosion, several other potential deterioration mechanisms can have an impact on a structure's life expectancy. Two of the most significant are alkali-silica reaction (ASR) and sulfate attack.

ASR results from the interaction of alkalies in portland cement (and potential other sources of alkalies) with certain aggregates, leading to abnormal internal expansion. The phenomenon is relatively complex and different theories have been proposed. American Concrete Institute (ACI) 201.2R, *Guide to Durable Concrete,* contends:

> If the amount of alkali available is relatively high with respect to the reactive aggregate surface, interior alkali-silica gel with unlimited expansive potential will form, imbibe water, and exert potentially destructive force.

Sulfates of sodium, potassium, and magnesium (present in rain, groundwater, and seawater) can attack concrete. Referring once again to ACI 201.2R:

> The two recognized chemical consequences of sulfate attack on concrete components are the formation of ettringite and gypsum. The formation of ettringite can result in an increase in solid volume, leading to expansion and cracking. The formation of gypsum can lead to softening and loss of concrete strength.

The demand for higher-performance building solutions continues to grow as long-term durability becomes increasingly important for those who build, occupy, and use structures of all kinds. Innovative design and construction practices have resulted in high-performance concrete (HPC) projects designed to last for 100 years even under the harshest environments.

To make concrete stronger, more workable, and more resistant to chemical and environmental attack, HPC mixtures generally incorporate supplementary cementitious materials (SCMs), such as:

- slag cement (a by-product of iron manufacturing);
- fly ash (a coal combustion by-product from power plants); and
- silica fume (a by-product of manufacturing silicon metals and ferro-silicon alloys).

These SCMs can be used in concrete mixes either as a separate component or combined in blended cement. Ternary mixes involving a combination of supplementary cementitious materials with portland cement frequently offer the best performance, because the materials tend to work synergistically.

Depending on the type of SCM(s) used, initial costs can be higher or lower than concrete mixes without supplementary materials. That said, if the structure's life is extended appreciably due to the use of SCMs, their initial cost should be less relevant.

How SCMs improve performance

When water is added to portland cement, it forms calcium silicate hydrate (CSH)—the 'glue' holding concrete together. When SCMs are added, they are typically finer than portland cement and, through physical particle packing, form a denser matrix. Then, as the hydration process continues, SCMs provide extra 'glue' within the concrete paste. With the formation of additional CSH, the concrete is less permeable and typically stronger. Understanding these improvements and other performance enhancements is vital.

Reduced permeability

SCMs can significantly extend the life of concrete by reducing the material's permeability for ingress of aggressive agents. When used properly, silica fume has a very profound effect on permeability, exhibiting as much as a five-fold reduction in permeability when using only eight percent silica fume.

The Rapid Chloride Permeability Test, as described in ASTM International C 1202 (American Association of State Highway and Transportation Officials [AASHTO] T 277), *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration,* is a reliable indicator of permeability. It determines the electrical conductance of concrete, providing a rapid (*i.e.* about 20 hours of preparation after specified curing time) indication of resistance to the penetration of chloride ions. One should always test with actual project materials before committing to a performance standard. Figure 1 shows typical data.

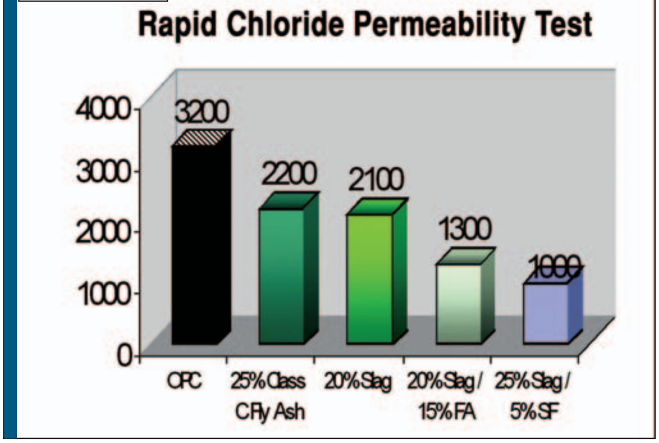
Improved workability

SCMs generally enhance concrete's workability. The spherical shape of fly ash particles and the glassy nature of slag particles reduce the amount of water necessary to achieve equivalent workability. They can also improve the concrete's pumpability.

Effect on set time

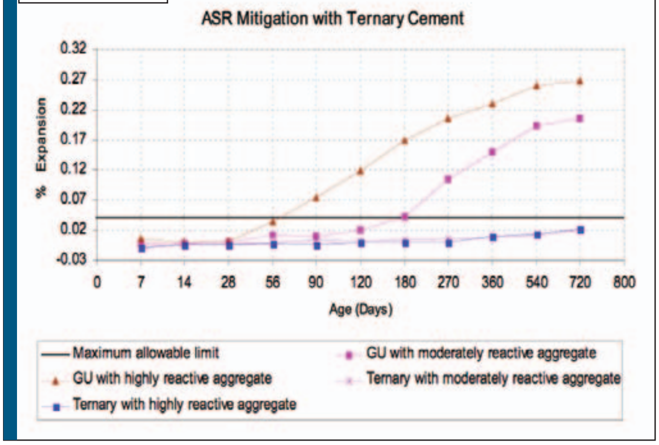
Slag cement and fly ash tend to extend the set time of concrete, providing extra time for placement, consolidation, and

Figure 1



This graph shows the typical rankings seen in ASTM C 1202: more than 4000 is high, 2000–4000 is moderate, 1000–2000 is low, 10–1000 is very low, and less than 10 is negligible.

Figure 2



The above graph provides an example of synergistic effects in combating alkali-silica reaction (ASR) when using multiple supplementary cementitious materials.

Images courtesy Portland Cement Association

finishing in warmer temperatures. This can be beneficial since most construction activity occurs during the warm summer months. In cooler seasons, the use of heated water and aggregates or the addition of an accelerating concrete admixture may be necessary to adjust setting time. Silica fume, on the other hand, typically has little effect on concrete setting times.

Controlled bleeding

Bleed water on the concrete surface can negatively impact finishing and durability. Usually, slag cements ground finer than the portland cement in the mixture reduce bleeding, while coarser slag generally increases it. Fly ash typically reduces bleeding, and silica fume—due to its very fine particles—virtually eliminates it.

Enhanced strength

SCMs typically lower early (one-day) strengths; however, depending on the proportions and materials used, they can significantly improve long-term strength (28 days and beyond). Both compressive and flexural strengths can markedly increase at 28 days and beyond with the addition of SCMs.

Resistance to sulfate attack

As pointed out by ACI 201.2R, protection against sulfate attack can be obtained by using materials unsusceptible to deterioration when exposed to sulfate ions, in addition to producing concrete that retards the ingress and movement of water. Concrete containing SCMs generally offers superior resistance to sulfate attack as they lower permeability, thereby restricting the ingress and movement of sulfate-bearing ions. In a number of cases, they reduce the compounds that can react with sulfates.

Typically slag, silica fume, and Class F fly ashes are very effective in improving sulfate resistance. The effectiveness of Class C fly ashes depends on the ash chemistry and the replacement level.[1] Actual project materials should be assessed prior to use to confirm performance.

Mitigation of alkali-silica reaction

When used in the correct proportions, SCMs can effectively prevent excessive expansion due to ASR in three ways:

1. SCMs can reduce the available alkali loading in the concrete, as they generally contain fewer alkalies than portland cement. (However, this needs to be assessed for each application.)
2. The reaction of fly ash and slag with portland cement consumes alkalies, making them unavailable for the reaction with the aggregate.
3. Lower permeability afforded by SCMs reduces the ingress and movement of water.

The choice and amount of SCMs can be a complex decision dependent on the specific nature of the supplementary material, the reactivity of the aggregate, and the alkali loading of the concrete. Various test methods are available to assess the options, and actual project materials should be used to confirm performance.

In ternary mixtures with multiple SCMs, a synergistic effect is possible. An example can be seen in Figure 2 (page 28), where a mixture with 20 percent slag and five percent silica fume provides adequate protection from ASR expansion.

Figure 3

Plastic shrinkage cracking can vary from spacings of a few inches to more than 3 m (10 ft) apart.

Figure 4

Dusting results from the formation of laitance—a weak, thin layer of water, cement, and fine particles.

Slab surface defects

The most commonly encountered types of slab surface defects are discussed briefly in the following paragraphs. All can be significantly reduced, if not eliminated, with the right mix of quality materials, good design, and proper workmanship.

Plastic shrinkage cracking

On days when wind, low humidity, and high temperature occur, surface moisture can evaporate more rapidly than it can be replaced by rising bleed water. This causes the surface to shrink more than the interior concrete. Stresses develop that exceed the material's tensile strength, resulting in surface cracks in fresh concrete soon after it is placed and while it is still plastic (Figure 3). These plastic-shrinkage cracks are of varying lengths, spaced from a few inches up to 3 m (10 ft) apart.

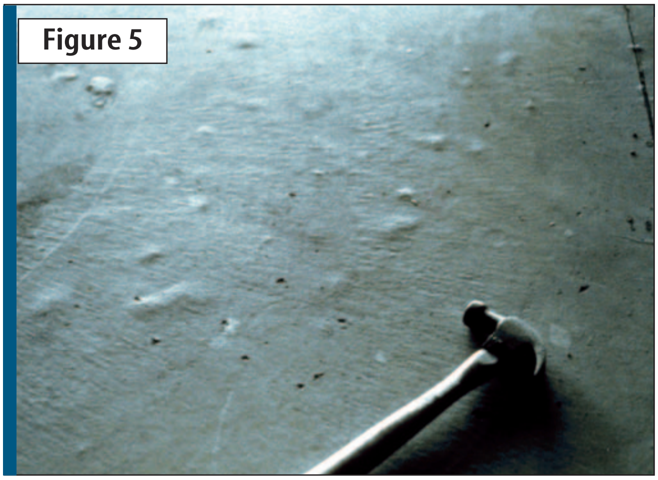
Plastic shrinkage cracking can be minimized if proper measures are taken prior to and during placing and finishing. Mixtures with an inherent reduced rate of bleeding or quantity of bleed water are more susceptible to plastic shrinkage cracking, even when evaporation rates are low. Concrete containing silica fume requires particular attention to avoid surface drying during placement. When conditions are conducive to a high evaporation rate, fogging the air above the concrete, employing wind breaks, using an approved evaporation retardant product, and covering the concrete with burlap or polyethylene sheets between finishing operations lessen the risk of plastic-shrinkage cracking.

Dusting/laitance

Dusting, which is the development of a fine, powdery material that easily rubs off the surface of hardened concrete, is the result of laitance—a thin, weak layer composed of water, cement, and fine particles (Figure 4). Finishing the concrete surface while bleed water is present can cause serious dusting. Floating and troweling before bleeding completion may trap water under the surface. Dusting may also be caused by:

- exposure to water during finishing;
- spreading dry cement over the surface in order to accelerate finishing;
- low cement content;
- too wet a mix;
- lack of proper curing;
- carbonation;
- surface freezing; and
- dirty aggregate.

Figure 5



A number of factors during concrete finishing can cause blistering. Finishing when the concrete is still bleeding is one cause of this slab surface defect.

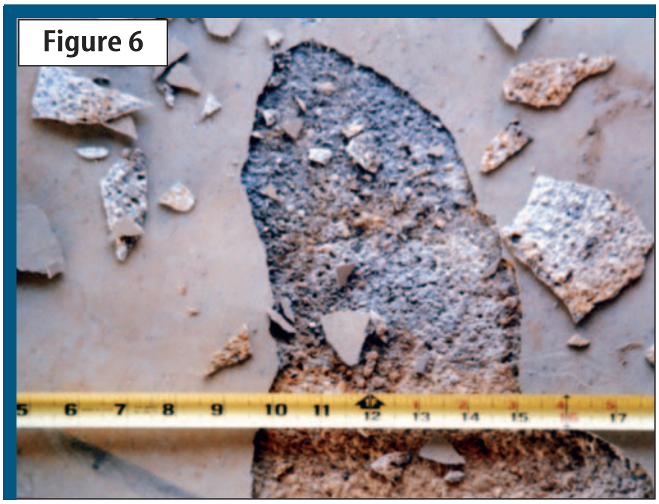


Figure 6

Unsightly delaminations, like the one in the photo above, can be minimized through avoiding the use of concrete with excessive slump, air content, or fines.

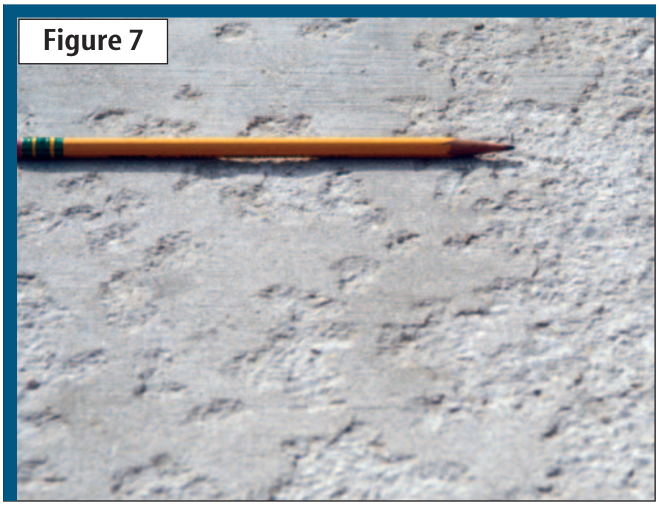


Figure 7

When the hydraulic pressure of water's freeze–thaw in the concrete exceeds the material's tensile strength, scaling can result in the absence of entrained air voids.

The use of a properly proportioned, moderate-slump, air-entrained concrete with an adequate cementitious content and properly graded fine aggregate minimizes bleeding and dusting problems. Water-reducing admixtures are typically employed to increase slump while maintaining a low water content.

One should neither start finishing while the concrete is bleeding nor sprinkle water/cement on the surface before or during finishing. Unless properly vented to outside the heated enclosure, carbon dioxide-producing heaters should also be avoided:

- while placing and finishing concrete; and
- over the first 24 to 36 hours of the curing period.

Blisters

Blisters result from entrapped air and/or bleed water beneath the surface of the concrete during finishing operations (Figure 5). The primary causes of blistering are:

- sticky or tacky concrete that becomes more easily sealed when floating or finishing;
- insufficient vibration that does not adequately release entrapped air;
- overuse of vibration that leaves excessive fines on the surface, inviting crusting and early finishing; and
- finishing when the concrete is still bleeding.

Sticky or tacky concrete can be fixed by reducing the amount of sand in the mix. The slightly harsher mix should release most of the entrapped air through normal vibration. Overworking of the concrete should be avoided. When surface crusting occurs, different finishing techniques may be needed, such as the use of wood floats to keep the surface open and flat troweling to avoid enfolding air into the surface under the blade action. Evaporation over the slab can be reduced by using a fog spray or cover.

Delamination

Delaminations are separations in a slab that are caused by accumulated water or air trapped just below the surface (Figure 6). This typically occurs when a finish is applied before the bleed water can reach the surface, but it can also happen when the ambient conditions of temperature, wind, and humidity result in a high evaporation rate of the bleed water. This causes premature drying and stiffening of the near-surface layer, trapping additional bleed water and air below the surface.

To avoid delaminations, concrete with a high slump, excessively high air content, or excess fines should be avoided. Further, concrete needs to be placed when ambient conditions are not conducive to rapid evaporation of bleed water, and the slab must not be prematurely finished. An air content over three percent is not recommended for interior slabs.

Scaling

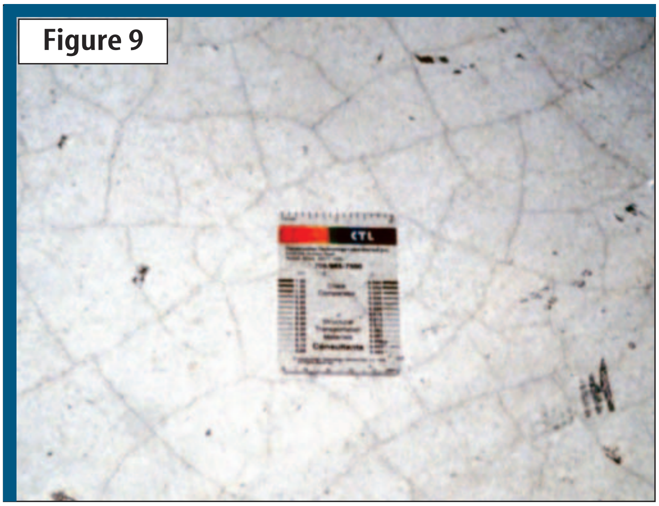
Scaling is the flaking or peeling off of surface mortar, usually caused by hydraulic pressure from water freezing and thawing within the concrete (Figure 7). When the pressure exceeds the material's tensile strength, scaling can result if entrained-air voids are not present to act as internal pressure relief valves. De-icer solutions in water-soaked concrete during freezing can aggravate the condition.

The extent of scaling depends on the de-icer's amount and application frequency. Sodium chloride and weak solutions of calcium chloride do not chemically attack the concrete,

Figure 8

Popouts are fragments that break out of the concrete's surface, leaving behind cone-shaped parts.

Figure 9



Crazing (or 'alligatoring') is barely visible until the concrete is drying after the surface has been wet.

but de-icers with ammonium sulfate or ammonium nitrate can cause deterioration and should not be used.

Provided the concrete has been properly proportioned, produced, placed, finished, and cured, it should have excellent resistance to surface scaling due to freezing and thawing and the application of de-icer chemicals. Properly air-entrained concrete of moderate slump (up to 125 mm [5 in.]) and adequate quality should be used. For concrete exposed to de-icing chemicals, ACI 318/318R, *Building Code Requirements for Structural Concrete and Commentary,* allows up to:

- 25 percent for fly ash;
- 50 percent for slag; and
- 10 percent for silica fume.

Higher doses of SCMs can be used if adequate durability is demonstrated and approved by the project engineer. However, stringent enforcement of proper placing, finishing, and curing procedures is critical to ensure a satisfactory product.

Popouts

Popouts generally appear as conical fragments that break out of the concrete surface (Figure 8). The resulting cone-shaped pits usually vary in size from 5 to 50 mm (0.25 to 2 in.) in diameter. Popouts can be caused by a porous aggregate particle near the surface that absorbs so much water it cannot accommodate the expansion and hydraulic pressure occurring during the freezing process. The result is aggregate expansion and possible concrete deterioration. Popouts may also occur to relieve pressure created by ASR.

To minimize or eliminate popouts, air-entrained concrete with low water content and slump should be used, as well as a durable aggregate. Blended cement, low-alkali products, or Class F fly ash can be beneficial where popouts are caused by ASR.

Crazing

Crazing, a network pattern of fine cracks that do not penetrate much below the surface, is caused by minor surface shrinkage (Figure 9). Often called 'alligatoring,' it is barely visible except when the concrete is drying after the surface has been wet. Predominantly caused by improper finishing and curing practices, crazing encompasses small areas less than 50 mm in dimension. Additionally, low humidity, high air temperature, or drying wind can cause rapid surface drying, encouraging these fine cracks.

Any finishing operation performed on the surface of a slab while bleed water is present can cause crazing, as can spreading dry cement on a wet surface to take up excess water. If possible, such wet spots should be avoided through adjustments in aggregate gradation, mix proportions, and consistency. When wet spots occur, finishing operations should be delayed until the water either evaporates or is removed. On hot days, wet-curing methods should be employed to control drying rate and lower the surface temperature.

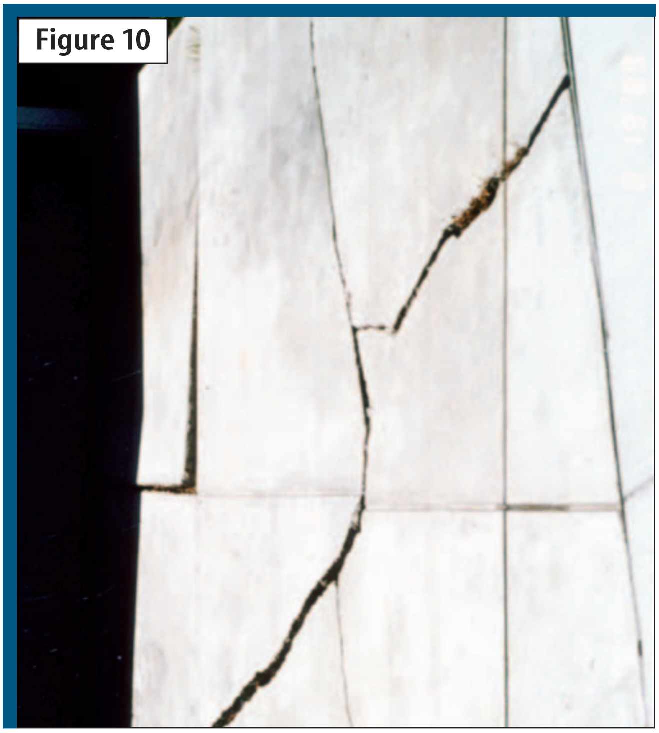
Settlement cracking

Settlement cracking typically develops when the sub-base material is inadequately placed and compacted (Figure 10). Slabs on grade cannot 'bridge' a structurally deficient sub-base. Cracking occurs when the concrete's tensile capacity is exceeded.

Discoloration

Concrete discoloration can appear as gross color changes over large areas, spotted or mottled blotches on the surface, or early light patches of efflorescence (Figure 11). The appearance of discoloration very soon after placing the

Figure 10



Settlement cracking occurs because slabs on grade cannot bridge a structurally deficient sub-base.

Figure 11

Concrete discoloration can occur due to numerous factors that must be considered to ensure the final aesthetic is the desired one.

concrete may be caused by:

- calcium chloride admixtures;
- cement alkalies;
- hard-troweled surfaces;
- inadequate or inappropriate curing;
- a wet substrate;
- variation of the water/cement ratio (w/c) at the surface; and
- changes in the concrete mix.

Substituting one cement for another may change the color of the concrete, and mixes incorporating SCMs could differ in hue from those without. The sand's color also has an effect on the final product appearance, and high-strength concrete with a low water/cement ratio is darker than low-strength concrete with a high w/c.

The surface should not be hard-troweled after it becomes too stiff, since the dense, low-w/c concrete in this area is almost always darker than the adjacent concrete. Waterproof paper and plastic sheets used to moist-cure concrete have been known to give a mottled appearance to flat surfaces.

Significant and sometimes permanent discoloration problems can be minimized by:

- avoiding use of calcium chloride admixtures;
- using consistent concrete ingredients uniformly proportioned from batch to batch; and
- employing proper and timely placing, finishing, and curing practices.

Photo courtesy Lafarge

Also pictured on the cover, the Washington, D.C. Convention Center exemplifies the importance of properly produced, placed, finished, and cured concrete. Supplementary cementitious materials can avoid concrete failures, providing long-term performance with minimal maintenance.

Figure 12

The slump test assesses workability. Slump is measured as the difference in height between the top of the cone and the displaced center of the concrete to the nearest 5 mm (0.25 in.).

Specifying for performance

Various organizations offer recommendations on how to specify mixtures containing SCMs. As with all concrete mixtures, trial batches should be prepared to verify properties. Often, the best approach for specifiers is to move from materials-based specifications to a performance-based one, which is strongly supported by the National Ready Mixed Concrete Association (NRMCA) in their 'Prescription to Performance' initiative.[2]

By focusing on concrete properties such as consistency, strength, aesthetics, and durability, performance-based specifications encourage innovation, along with cost-effective construction and quality control. For example, a producer may be able to use cement in different proportions or employ SCMs to deliver high strength while improving workability and reducing overall costs. Industry associations and manufacturers can assist in creating performance-based specifications that offer greater flexibility for materials selection while ensuring performance objectives are achieved.

A well-written performance-based specification includes the test methods used to verify the requirements. (See "ASTM and AASHTO," page 36.) Field tests include temperature, slump, unit weight, air content, and making strength specimens; laboratory testing is normally required for strength determination.

Slump test

Workability can be measured by the slump test per ASTM C 143, *Standard Test Method for Slump of Hydraulic-cement Concrete* (Figure 12, page 35). Slump is measured on a sample from a fresh batch of concrete. The cone is placed with the wide end down onto a level, non-absorptive surface. It is then filled in three layers of equal volume, with each layer being tamped with a steel rod for consolidation.

When the cone is carefully lifted off, the enclosed material 'slumps' a certain amount due to gravity. A relatively dry sample slumps very little, having a value of 25 to 50 mm (1 to 2 in.). A relatively wet sample, on the other hand, may slump as much as 150 to 175 mm (6 to 7 in.).

Figure 13

This photo illustrates the compressive strength testing of a 150-mm (6-in.) diameter cylindrical concrete specimen.

Compressive strength test

Most mixes require a minimum level of strength for structural design purposes. Test cylinders of fresh concrete are prepared onsite in accordance with ASTM C 31, *Standard Practice for Making and Curing Concrete Test Specimens in the Field*, and tested in accordance with ASTM C 39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* (Figure 13). Using an instrumented hydraulic ram, the test provides a precise measure of the force needed to break the concrete cylinders at various ages.

Engineers usually specify the required compressive strength of concrete at 28 days. In some cases, cylinders are tested at three or seven days to get an early indication of the potential strength, but these results are not normally used for concrete acceptance. A 25 percent strength gain between seven and 28 days is often observed with 100 percent ordinary portland cement mixtures, and up to 40 percent strength gain can be realized with the inclusion of SCMs. If project schedules permit, it might be appropriate to specify strength requirements for later ages, such as 56 or 90 days. This allows the use of higher volumes of SCMs.

Investigation guidelines

Concrete that is properly produced, placed, finished, and cured should provide many years of service with minimal maintenance. Even this industry workhorse, however, can be adversely affected by various environmental factors and deteriorate over time.

Most problems can be attributed to the quality of the material, design issues, and/or the placing and finishing techniques. When defects arise, understanding their cause can help prevent them in the future. A variety of activities are involved in this effort, including:

- identifying the perceived problem;
- collecting data and reviewing project information;
- taking advantage of industry resources;
- conducting extra testing and analyses;
- determining the need for additional assistance; and/or
- drawing appropriate conclusions.

Manufacturers can provide technical assistance to help develop or modify specifications, and most offer detailed test results, quality control records, and additional support. For further guidance on specifying supplementary cementitious materials, see "Further Concrete Reading."

Notes

[1] Fly ash is classified as either Class F or Class C per ASTM C 618, *Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.* Class F is normally produced from burning anthracite or bituminous coal, whereas Class C normally comes from lignite or sub-bituminous coal.

[2] For more on performance-specifying concrete, see J. Braselton and B. Blair's "Performance-based Specifications for Concrete," in July 2004 issue of *The Construction Specifier.*

ASTM and AASHTO

Relevant standards from ASTM International and the American Association of State Highway and Transportation Officials (AASHTO) include:

- ASTM C 989 (AASHTO M 302), *Standard Specification for Ground Granulated Blast-furnace Slag for Use in Concrete and Mortars;*
- ASTM C 618 (AASHTO M 295), *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete;*
- ASTM C 1240 (AASHTO M 307), *Standard Specification for Silica Fume Used in Cementitious Mixtures;*
- ASTM C 150 (AASHTO M 85), *Standard Specification for Portland Cement;*
- ASTM C 595 (AASHTO M 240), *Standard Specification for Blended Hydraulic Cements;* and
- ASTM C 1157, *Standard Performance Specification for Hydraulic Cement.*

ASTM tests include:

- temperature—ASTM C 1064, *Standard Test Method for Temperature of Freshly Mixed Hydraulic-cement Concrete;*
- slump—ASTM C 143, *Standard Test Method for Slump of Hydraulic-cement Concrete;*
- unit weight—ASTM C 138, *Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete;*
- air content—ASTM C 231, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method;*
- strength specimens—ASTM C 31, *Standard Practice for Making and Curing Concrete Test Specimens in the Field;* and
- compressive strength—ASTM C 39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.*

Further Concrete Reading

To gain a better understanding of the issues discussed in this article, the following organizations can be invaluable resources:

- American Concrete Institute (www.concrete.org);
- American Coal Ash Association (www.acaa-usa.org);
- Portland Cement Association (www.portcement.org);
- Slag Cement Association (www.slagcement.org); and
- Silica Fume Association (www.silicafume.org).

Other resources that should be required reading include:

- *Manual of Concrete Practice* (American Concrete Institute [ACI], 2008);
- S.H. Kosmatka et al's "Design and Control of Concrete Mixtures" (Portland Cement Association [PCA], 2002);
- J. Lafave et al's "Using Mineral and Chemical Durability-enhancing Admixtures in Structural Concrete," *Concrete International* (vol. 24, no. 8, August 2002);
- "Concrete Slab Defects: Causes, Prevention, Repair" (PCA IS177, 2001); and
- K. Obla et al's "Specifying Concrete for Durability: Performance-based Criteria Offer Best Solutions" (National Ready Mixed Concrete Association [NRMCA]).

Additional Information

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MasterFormat No.
03 05 00–Common Work Results for Concrete

UniFormat No.
A1030–Slab on Grade
B2010–Exterior Walls

Key Words
Division 03
Concrete failures
Supplementary cementitious materials
Performance specifications

Abstract

In this article, the author reviews important issues affecting concrete failures and guidelines on how to prevent them. It covers corrosion-related failures, alkali-silica reactions, strength issues, and cosmetics and finishing defects. The article also discusses how supplementary cementitious materials (SCMs) can improve the performance of concrete mixes, the benefits of writing performance-based specifications, and guidelines for investigating problems.