Concrete in Practice

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CIP 1—Dusting Concrete Surfaces

WHAT is Dusting

Formation of loose powder resulting from disintegration of surface of hardened concrete is called dusting or chalking. The characteristics of such surfaces are:

a. They powder under any kind of traffic

b. They can be easily scratched with a nail or even by sweeping.

WHY Do Concrete Floors Dust

A concrete floor dusts under traffic because the wearing surface is weak. This weakness can be caused by:

a. Any finishing operation performed while bleed water is on the surface or before the concrete has finished bleeding. Working this bleed water back into the top ¼-inch [6 mm] of the slab produces a very high water-cement ratio and, therefore, a low strength surface layer.

b. Poor finishing practices such as broadcasting dry cement to speed up finishing or sprinkling water to the surface while finishing

c. Floating and/or troweling operations following the condensation of moisture from warm humid air on cold concrete. In cold weather concrete sets slowly, in particular, cold concrete in basement floors. If the humidity is relatively high, water will condense on the freshly placed concrete, which, if troweled into the surface, will cause dusting.

d. Inadequate ventilation in enclosed spaces. Carbon dioxide from open salamanders, gasoline engines or generators, power buggies or mixer engines may cause a chemical reaction known as carbonation, which greatly reduces the strength and hardness of the concrete surface.

e. Insufficient curing. This omission often results in a soft surface skin, which will easily dust under foot traffic.

f. Inadequate protection of freshly placed concrete from rain, snow or drying winds. Allowing the concrete surface to freeze will weaken the surface and result in dusting.

Dusting concrete surface

HOW to Prevent Dusting

a. Concrete with the lowest water content with an adequate slump for placing and finishing will result in a strong, durable, and wear-resistant surface. In general, use concrete with a moderate slump not exceeding 5 inches [125 mm]. Concrete with a higher slump may be used provided the mixture is designed to produce the required strength without excessive bleeding and/or segregation. Water-reducing admixtures are typically used to increase slump while maintaining a low water content in the mixture. This is particularly important in cold weather when delayed set results in prolonged bleeding.

b. *NEVER* sprinkle or trowel dry cement into the surface of plastic concrete to absorb bleed water. Remove bleed water by dragging a garden hose across the surface. Excessive bleeding of concrete can be reduced by using air-entrained concrete, by modifying mix proportions, or by accelerating the setting time.

c. *DO NOT* perform any finishing operations with water present on the surface or while the concrete continues to bleed. Initial screeding must be promptly followed by bull floating. Delaying bull floating operations can cause bleed water to be worked into surface layer. Do not use a jitterbug, as it tends to bring excess mortar to the surface. *DO NOT* add water to the surface to facilitate finishing operations.

d. Do not place concrete directly on polyethylene vapor retarders or non-absorptive subgrades as this can contribute to problems such as dusting, scaling, and cracking. Place 3 to 4 inches [75 to 100 mm] of a trimable, compactible fill, such as a crusher-run material, over vapor retarders or non-absorptive subgrade prior to concrete placement. When high evaporation rates exist, lightly dampen absorptive subgrades just prior to concrete placement, ensuring that water does not pond or collect on the subgrade surface. However, it may essential to place concrete directly on polyethylene vapor retarders for interior slabs that can receive floor coverings at any point in its service life (CIP 29). For such cases take special care to ensure that finishing operations are performed after all bleed water has dissipated from the surface.

e. Provide proper curing by using liquid membrane curing compound or by covering the surface with water, wet burlap, or other curing materials as soon as possible after finishing to retain moisture in the slab. It is important to protect concrete from the environment at early ages.

f. Placing concrete in cold weather requires concrete temperatures exceeding 50°F [10°C] as well as an accelerating admixture.

HOW to Repair Dusting

a. Sandblast, shot blast or use a high-pressure washer to remove the weak surface layer.

b. To minimize or eliminate dusting, apply a commercially available chemical floor hardener, such as sodium silicate (water glass) or metallic zinc or magnesium fluosilicate, in compliance with manufacturer's directions on thoroughly dried concrete. If dusting persists, use a coating, such as latex formulations, epoxy sealers, or cement paint.

c. In severe cases, a serviceable floor can be obtained by wet-grinding the surface to durable substrate concrete. This may be followed by properly bonded placement of a topping course. If this is not practical, installation of a floor covering, such as carpeting or vinyl tile covering, is the least expensive solution to severe dusting. This option will require some prior preparation since adhesives for floor covering materials will not bond to floors with a dusting problem and dusting can permeate through carpeting.

References

1. *Guide for Concrete Floor and Slab Construction*, ACI 302.1R. American Concrete Institute, Farmington Hills, MI.
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3. *Concrete Slab Surface Defects: Causes, Prevention, Repair*, IS177, Portland Cement Association, Skokie, IL
4. *The Effect of Various Surface Treatments, Using Zinc and Magnesium Fluosilicate Crystals on Abrasion Resistance of Concrete Surfaces*, Concrete Laboratory Report No. C-819, U.S. Bureau of Reclamation.
5. *Residential Concrete*, National Association of Home Builders, Washington, DC.
6. *Trouble Shooting Guide for Concrete Dusting*, Concrete Construction, April 1996.

Follow These Rules to Prevent Dusting

1. Use moderate slump concrete not exceeding 5 inches [125 mm].
2. Do not start finishing operations while the concrete is bleeding.
3. Do not broadcast cement or sprinkle water on concrete prior to or during finishing operations.
4. Ensure that there is adequate venting of exhaust gases from gas-fired heaters in enclosed spaces.
5. Use adequate curing measures to retain moisture in concrete for the first 3 to 7 days and protect it from the environment, especially freezing conditions.

1978, 1990, 1998, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 2 - Scaling Concrete Surfaces

WHAT is Scaling

Scaling is local flaking or peeling of a finished surface of hardened concrete as a result of exposure to cycles of freezing and thawing. Generally, it starts as localized small patches which later may merge and extend to expose large areas. Light scaling does not expose the coarse aggregate. Moderate scaling exposes the aggregate and may involve loss of up to ⅛ to ⅜ inch [3 to 10 mm] of the surface mortar. In severe scaling more surface has been lost and the aggregate is clearly exposed and stands out.

Note—Occasionally concrete peels or scales in the absence of freezing and thawing. This type of scaling is not covered in this CIP. Often this is due to the early use of a steel trowel, over-finishing or finishing while bleed water is on the surface.

WHY Do Concrete Surfaces Scale

Concrete slabs and surfaces of other members that are saturated with water and exposed to cycles of freezing and thawing are susceptible to scaling. When concrete is saturated with water and temperature approaches freezing, water expands as it forms ice and this causes stresses within concrete. As the number of cycles of freezing and thawing increases, the potential for scaling increases. Deicing chemicals exacerbate this by increasing the saturation of concrete at the surface and the number of freezing and thawing cycles. Air entrained concrete contains millions of small air bubbles that accommodate the expanding water and ice and prevent the stress buildup .

Most scaling is caused by:

a. The use of *non-air-entrained concrete* or too little entrained air, especially at the surface.
b. Using concrete that has a low strength that allows permeation to water.
c. Using the improper concrete mixture or mixture proportions for the application.
d. Application of excessive amounts of deicing chemicals, especially on newly installed concrete that tends to be saturated and of lower strength.
e. Improper finishing procedures of concrete slabs.
f. Insufficient curing resulting in a weak concrete surface.

HOW to Prevent Scaling

The potential for scaling in concrete slabs can be reduced by using good quality dense concrete with entrained air, following good practice for installing and curing, and by minimizing the use of deicing chemicals.

Scaling on Concrete Slab

For concrete that will be continuously moist, exposed to freezing temperatures and will be subject to the use of deicing chemicals, the following recommendations should be followed:

a. For exterior slabs, order concrete with specified strength of 4000 psi [28 MPa], consistent with the requirements of ACI 332, *Code for Residential Concrete*. For concrete that will not be continuously moist or where deicing chemicals will not be applied, the specified strength should be 3500 psi [24 MPa].
b. Concrete should be air-entrained. The recommended total air content for concrete containing ¾-inch [19 mm] or 1-inch 25 mm] coarse aggregate is 6 percent.
c. The quantity of supplementary cementitious materials (SCM) should not exceed one of the following: 25% fly ash, 50% slag cement or 10% silica fume, expressed as percent by weight of the cementitious materials. SCMs are beneficial to concrete, however, at higher quantities change the rate of setting, bleeding, and strength gain. These impact the process of finishing. With appropriate modifications of the finishing procedures, it is possible to use higher quantities of SCMs, but these need to be evaluated.
d. For most slab construction, place concrete at a slump in the range of 3 to 5 inches [75 to 125 mm]. Do not add excessive water at the jobsite. High slump obtained by adding water increased the potential for segregation and excessive bleeding and can result in weak mortar layer at the surface. Water reducing admixtures can provide improved workability and retain good concrete quality.
e. Placing and finishing procedures can reduce the entrained air content in concrete, making it more susceptible to scaling.
f. Do not use a jitterbug or vibrating screed with high

slump concrete as it increases segregation and result in a weak mortar layer at the surface.

g. Do not perform finishing operations with bleed water present on the surface. Bull floating must promptly follow initial screeding. Delay subsequent finishing until bleed water has risen and dissipated from the surface. This is critical when placing air-entrained concrete in dry and windy conditions where the surface may appear to be dry while concrete is continuing to bleed. The use of fog sprays or evaporation retardants are recommended in these conditions. See CIP 14 for finishing concrete.

h. Do not overwork the surface of concrete. Excessive finishing reduces entrained air in the surface layer. For most exterior surfaces a broom finish is adequate.

i. Provide proper curing by using pigmented liquid membrane curing compound or by covering the surface of newly placed slab with wet burlap and plastic sheets. Proper curing involves maintaining concrete at adequate temperature and moisture for optimum performance.

j. Protect concrete from the harsh winter environment. Apply a commercially available silane or siloxane-based breathable concrete sealer or water repellent specifically designed for use on concrete slabs. Follow the manufacturer’s recommendations. The concrete should be reasonably dry prior to the application of a sealer. Late summer with a few dry days preceding application is an ideal time .

k. Be cautious about placing exterior concrete in late fall, winter or early spring when conditions are such that it will be exposed to freezing temperatures shortly after placement while concrete is still saturated.

l. Avoid using deicing chemicals on newly placed concrete, if possible. Use clean sand for traction. When used, deicing chemicals should be applied in moderate amounts. Excessive applications increases potential for scaling. When conditions permit, hose off accumulation of salt deposited by cars on driveways and garage slabs. Deicing chemicals composed of calcium chloride and sodium chloride (rock salt) are considered acceptable for concrete. Never use ammonium sulfate or ammonium nitrate or magnesium-based salts as a deicer; these are chemically aggressive and destroy concrete surfaces. Magnesium-based salts are used for pre-snow deicing of roads and can be tracked by cars and accumulate on concrete surfaces. Poor drainage causing salt solutions to accumulate on concrete surfaces increases the severity of the exposure and may cause scaling.

HOW to Repair Scaled Surfaces

Minor scaling is a cosmetic issue and may not need to be repaired. On the other hand repairing concrete slabs with excessive and progressing scaling may not be feasible.

It is possible to repair light to moderately scaled surfaces. The repaired surface will only be as strong as the base surface to which it is bonded. The surface should be prepared to remove the unsound surface and should be free of dirt, oil or paint. The surface receiving the repair must be sound. To accomplish this, use a hammer and chisel, sandblasting, high-pressure washer, or jack hammer. The clean, rough, textured surface can be repaired with thin bonded resurfacing such as:

a. Portland cement concrete resurfacing

b. Latex modified concrete resurfacing

c. Polymer-modified cementitious-based repair mortar

Repair material will not match the color and characteristics of the original concrete.

References

1. *Guide to Durable Concrete*, ACI 201.2R, American Concrete Institute, Farmington Hills, MI.
2. *Scale-Resistant Concrete Pavements,* IS117.02P, Portland Cement Association, Skokie, IL.
3. *Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals*, National Cooperative Highway Research Program Report No. 16.
4. *Code Requirements for Residential Concrete*, ACI 332, American Concrete Institute, Farmington Hills, MI.
5. *Residential Concrete*, National Association of Home Builders, Washington, DC.
6. *Slabs on Grade*, Concrete Craftsman Series CCS-1, American Concrete Institute, Farmington Hills, MI.
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8. Concrete in Practice Series, CIP 5, 11, 14, NRMCA, Silver Spring, MD.

Follow These Rules to Prevent Scaling

1, For concrete that will be exposed to severe freezing and thawing conditions order good quality air-entrained concrete with a strength of 4000 psi [28 MPa]

2. Do not add excessive water and place concrete at a slump of 3 to 5 inches [75 to 125 mm].

3. Finish concrete after bleed water has dissipated and avoid using steel trowels when finishing.

4. Properly cure the concrete

5. Consider sealing the surface with a commercial breathable sealer.

6. Avoid the use of deicing chemicals in the first winter and subsequently use them in moderate amounts.

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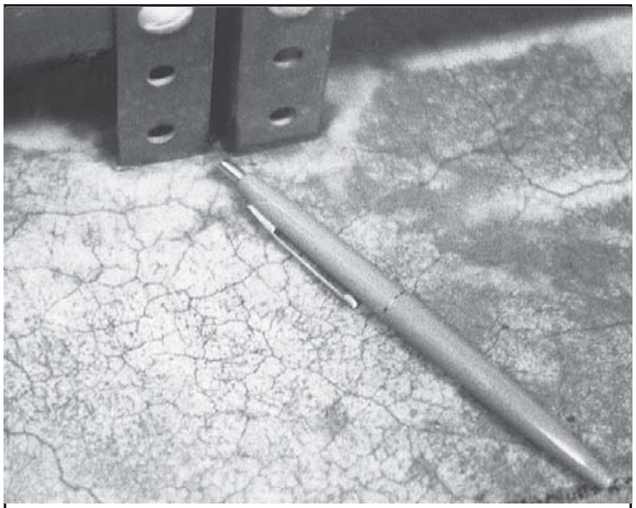
CIP 3 - Crazing Concrete Surfaces

WHAT is Crazing?

Crazing is the development of a network of fine random cracks or fissures on the surface of concrete or mortar caused by shrinkage of the surface layer. These cracks are rarely more than $^{1}/_{8}$ inch [3 mm] deep and are more noticeable on steel-troweled surfaces. The irregular hexagonal areas enclosed by the cracks are typically no more than $1^{1}/_{2}$ inch [40 mm] across and may be as small as $^{1}/_{2}$ or $^{3}/_{8}$ inch [12 or 20 mm] in unusual instances. Generally, craze cracks develop at an early age and are apparent the day after placement or at least by the end of the first week. Often they are not readily visible until the surface has been wetted and it is beginning to dry out.

Crazing cracks are sometimes referred to as shallow map or pattern cracking. They do not affect the structural integrity of concrete and rarely do they affect durability or wear resistance. However, crazed surfaces can be unsightly. They are particularly conspicuous and unsightly when concrete contains calcium chloride, a commonly used accelerating admixture.



Crazing Concrete Surface (Dampened)

WHY Do Concrete Surfaces Craze?

Hard steel-troweled slab surfaces often have craze cracks due to shrinkage of the concentrated dense paste layer at the surface. Concrete surface crazing can also occur because one or more of the rules of "good concrete practices" were not followed. The most frequent factors when crazing occurs are:

a. Poor or inadequate curing. Environmental conditions conducive to high evaporation rates, such as low humidity, extremes in ambient temperature, direct sunlight, and drying winds on a concrete surface when the concrete is just beginning to gain strength, cause rapid surface drying resulting in craze cracking. Avoid the delayed application of curing or even intermittent wet curing and drying after the concrete has been finished.

b. Too wet a mix, excessive floating, the use of a jitterbug or procedures that will depress the coarse aggregate and produce an excessive concentration of cement paste and fines at the surface.

c. Finishing operations performed while bleed water remains on the surface or the use of a steel trowel in a manner that the smooth surface of the trowel brings up excessive water and cement fines. Use of a bull float or darby with water on the surface or while the concrete continues to bleed will produce a high water-cement ratio at the surface resulting in a weak surface layer that will be susceptible to crazing, dusting, scaling and other surface defects.

d. Sprinkling cement on the surface to dry up the bleed water is a frequent cause of crazing. This concentrates fines on the surface. Spraying water on the concrete surface during finishing operations will result in a weak surface susceptible to crazing or dusting.

HOW to Prevent Crazing?

a. To prevent crazing, start curing the concrete as soon as possible. Curing retains moisture required for proper reaction of cement with water, called hydration. Keep the surface wet by either flooding with water or by covering it with damp burlap and keeping it continuously moist for a minimum of 3 days. An alternative is to spray the surface with a liquid-membrane curing compound. Avoid alternate wetting and drying of concrete surfaces at an early age. .

b. When placing, use moderate slump (3 to 5 inches [75 to 125 mm]) concrete. Higher slump (up to 6 or 7 inches [150 to 175 mm]) can be used provided the mixture is designed to produce the required strength without excessive bleeding and/or segregation. This is generally accomplished by using water-reducing admixtures.

c. *NEVER* sprinkle or trowel dry cement or a mixture of cement and fine sand on the surface of the plastic concrete to absorb bleed water. *DO NOT* sprinkle water on the slab to facilitate finishing. If necessary, remove bleed water by dragging a garden hose across the surface. *DO NOT* perform any finishing operation while bleed water is present on the surface or before the bleeding process is completed. *DO NOT* overwork or over-finish the surface.

d. When high evaporation rates are anticipated, lightly dampen the subgrade prior to concrete placement to prevent it absorbing too much water from the concrete. If a vapor retarder is required on the subgrade, cover it with 3 to 4 inches of a compactible, granular fill, such as a crusher-run material except when the slab will receive a vapor-sensitive floor covering or will be in a humidity controlled environment. See CIP 29 that discusses the location of vapor retarders.

References

1. *Guide for Concrete Floor and Slab Construction*, ACI 302.1R, American Concrete Institute, Farmington Hills, MI.
2. *Concrete Slab Surface Defects: Causes, Prevention, Repair*, IS 177T, Portland Cement Association, Skokie, IL.
3. Ward Malisch, *Avoiding Common Outdoor Flatwork Problems,* Concrete Construction, July 1990.
4. Ralph Spannenberg, *Use the Right Tool at the Right Time,* Concrete Construction, May 1996.

Follow These Rules to Prevent Crazing

1. Use moderate slump (3-5 inches) concrete with reduced bleeding characteristics.
2. Follow recommended practices and timing, based on concrete setting characteristics, for placing and finishing operations:
    a. Avoid excessive manipulation of the surface, which can depress the coarse aggregate, increase the cement paste at the surface, or increase the water-cement ratio at the surface.
    b. *DO NOT* finish concrete before the concrete has completed bleeding (look for the presence of a water sheen on the surface). *DO NOT* dust any cement onto the surface to absorb bleed water. *DO NOT* sprinkle water on the surface while finishing concrete.
3. Cure properly as soon as finishing has been completed.

1978, 1989, 1998, 2009

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What, why & how?
NRMCA

CIP 4 - Cracking Concrete Surfaces

WHAT are Some Forms of Cracks?

Concrete, like other construction materials, contracts and expands with changes in moisture and temperature, and deflects depending on load and support conditions. Cracks can occur when provisions to accommodate these movements are not made in design and construction. Some forms of common cracks are:

Fig. A: Plastic shrinkage cracks (CIP 5)
Fig. B: Cracks due to improper jointing (CIP 6)
Fig. C: Cracks due to continuous external restraint Example: Cast-in-place wall restrained along bottom edge of footing
Fig. D: Cracks due to lack of isolation joints(CIP6)
Fig. E: D-Cracks from freezing and thawing
Fig, F: Craze Cracks (See CIP 3)
Fig. G: Settlement cracks

Most random cracks that appear at an early age, although unsightly, rarely affect the structural integrity or the service life of concrete. Two exceptions are:

- D-cracks, which occur due to freeze-thaw deterioration of some types of porous aggregate in concrete. These cracks initiate at joints at the bottom of exterior slabs and typically appear at later ages.
- Cracking due to alkali aggregate reactions will lead to long term structural damage (CIP 43).

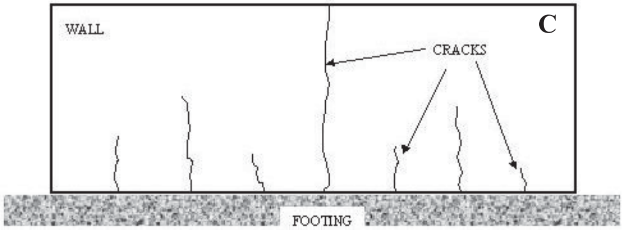
WHY Do Concrete Surfaces Crack ?

The majority of concrete cracks occur due to improper design and construction practices, such as:

a. Omission of isolation and contraction joints and improper jointing practices.
b. Improper subgrade preparation.
c. The use of high slump concrete or excessive addition of water on the job.
d. Improper finishing.
e. Rapid loss of moisture from newly placed concrete in dry conditions
f. Inadequate or no curing.


A


B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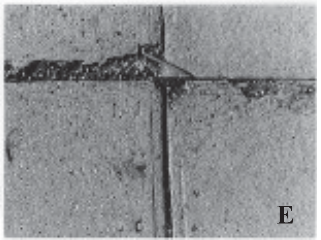
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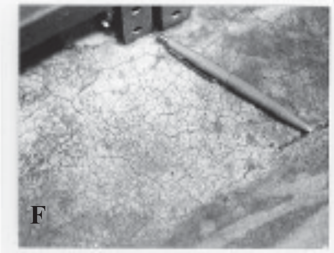
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G

HOW to Prevent or Minimize Cracking?

All concrete has a tendency to crack and it is not possible to produce completely crack-free concrete. However, cracking can be reduced and controlled if the following basic concreting practices are followed:

a. *Subgrade and Formwork*. All topsoil and soft spots should be removed. The soil beneath the slab should be compacted soil or granular fill, well compacted by rolling, vibrating or tamping. The slab, and therefore, the subgrade, should be sloped for proper drainage. In winter, remove snow and ice prior to placing concrete and do not place concrete on a frozen subgrade. Smooth, level and uniformly compacted subgrades help prevent cracking. All formwork must be constructed and braced so that it can withstand the pressure of the concrete without movement. Vapor retarders directly under a concrete slab increase bleeding and greatly increase the potential for cracking, especially with high-slump concrete. When it is required to place concrete directly on polyethylene vapor retarders (CIP 29) take special care to ensure that finishing operations are performed after all bleed water has dissipated from the surface. In dry conditions lightly dampen subgrade, formwork and reinforcement immediately prior to concrete placement.

b. *Concrete*. In general, use concrete with a moderate slump (not to exceed 5 inches [125 mm]). Higher slump can be used provided the mixture is designed to produce the required strength without excessive bleeding and/or segregation. This is generally accomplished by using water-reducing admixtures. Use air-entrained concrete for outdoor slabs exposed to freezing weather (See CIP 2). Concrete mixtures can be designed for reduced shrinkage to minimize cracking.

c. *Finishing*. Initial screeding must be promptly followed by bull floating. DO NOT perform subsequent finishing operations with water present on the surface or before the concrete has completed bleeding. Do not overwork or over-finish the surface. For better traction on exterior surfaces use a broom finish. When ambient conditions are conducive to a high evaporation rate, use means to avoid rapid drying and associated plastic shrinkage cracking by using wind breaks, fog sprays, and covering the concrete with wet burlap or polyethylene sheets between finishing operations.

d. *Curing*. Curing is an important step to ensure durable crack-resistant concrete. Start curing as soon as possible. Spray the surface with liquid membrane curing compound or cover it with damp burlap and keep it moist for at least 3 days. A second application of curing compound the next day is a good quality assurance step.

e. *Joints*. Anticipated volume changes due to temperature and/or moisture should be accommodated by contraction joints saw cut or tooled at the proper time with a depth of about ¼ to ⅓ the thickness of the slab, and with a spacing between 24 to 36 times the slab thickness. A maximum 15 feet spacing for contraction joints is often recommended. Panels between joints should be square and the length should not exceed about 1.5 times the width. Isolation joints to the full thickness of the slab should be provided whenever restriction to freedom of either vertical or horizontal movement is anticipated—such as where floors meet walls, columns, or footings. See CIP 6 for information on joints.

f. *Reinforcement*. Wire mesh and reinforcement in slabs cannot prevent cracking. When placed at the proper location, reinforcement can reduce crack width. Providing sufficient concrete cover (at least 2 inches [50 mm]) to keep salt and moisture from contacting the steel should prevent cracks in reinforced concrete caused by expansion of rust on reinforcing steel.

References

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2. *Guide for Concrete Floor and Slab Construction,* ACI 302.1R, American Concrete Institute, Farmington Hills, MI.
3. *Concrete Slab Surface Defects: Causes, Prevention, Repair*, IS177, Portland Cement Association, Skokie, IL.
4. Grant T. Halvorson, *Troubleshooting Concrete Cracking During Construction,* Concrete Construction, October 1993.
5. *Cracks in Concrete: Causes, Prevention, Repair*, A collection of articles from Concrete Construction Magazine, June 1973.

Follow These Rules to Minimize Cracking

1. Design the members to handle all anticipated loads.
2. Provide proper contraction and isolation joints.
3. In slab on grade work, prepare a stable uniformly compacted subgrade.
4. Place and finish according to recommended and established practices.
5. Protect and cure the concrete properly.

1978,1989, 1998, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 5 — Plastic Shrinkage Cracking

WHAT is Plastic Shrinkage Cracking

Plastic shrinkage cracks appear in the surface of fresh concrete soon after it is placed and while it is still plastic. These cracks appear mostly on horizontal surfaces. They are usually parallel to each other on the order of 1 to 3 feet apart, relatively shallow, and generally do not intersect the perimeter of the slab. Plastic shrinkage cracking is more likely to occur when high evaporation rates cause the concrete surface to dry out before it has set.

Plastic shrinkage cracks are unsightly but rarely impair the strength of concrete floors and pavements. These cracks, however, can permit the ingress of other aggressive chemicals that impact durability and as weak points for the initiation of later age cracking due to other reasons. The development of these cracks can be minimized if appropriate measures are taken prior to and during placing and finishing concrete.

Note: Plastic shrinkage cracks should be distinguished from other early or pre-hardening cracks caused by settlement of the concrete around reinforcing bars, formwork movement, early age thermal cracking, or differential settlement at a change from a thin to a deep section of concrete.

WHY Do Plastic Shrinkage Cracks Occur

Plastic shrinkage cracks are caused by a rapid loss of water from the surface of concrete before it has set. The critical condition exists when the rate of evaporation of surface moisture exceeds the rate at which rising bleed water can replace it. Water receding below the concrete surface forms menisci between the fine particles of cement and aggregate causing a tensile force to develop in the surface layers. If the concrete surface has started to set and has developed sufficient tensile strength to resist the tensile forces, cracks do not form. If the surface dries very rapidly, the concrete may still be plastic, and cracks do not develop at that time; but plastic shrinkage cracks will surely form as soon as the concrete starts to stiffen. Synthetic fiber reinforcement incorporated in the concrete mixture can help resist the tension when concrete is very weak.

Plastic Shrinkage Cracks

Conditions that cause high evaporation rates from the concrete surface, and thereby increase the possibility of plastic shrinkage cracking, include:

- Wind velocity in excess of 5 mph
- Low relative humidity
- High ambient and/or concrete temperatures

Small changes in any one of these factors can change the rate of evaporation of water from the concrete surface. ACI 305R provides a chart to estimate the rate of evaporation and indicates when special precautions might be required. However, the chart isn't infallible because many factors other than rate of evaporation are involved.

Concrete mixtures with an inherent reduced rate of bleeding or quantity of bleed water are susceptible to plastic shrinkage cracking even when evaporation rates are low. Factors that reduce the rate or quantity of bleeding include high cementitious materials content, high fines content, reduced water content, entrained air, high concrete temperature, and thinner sections. Concrete containing silica fume requires particular attention to avoid surface drying during placement due to its very low rate of bleeding.

Any factor which delays setting increases the possibility of plastic shrinkage cracking. Delayed setting can result from a combination of one or more of the following: cool weather, cool subgrades, high water contents, lower cement contents, retarders, some water reducers, and supplementary cementitious materials.

HOW to Minimize Plastic Shrinkage Cracking

Attempts to eliminate plastic shrinkage cracking by modifying the concrete mixture composition to affect bleeding characteristics have not been found to be consistently effective. To reduce the potential for plastic shrinkage cracking, it is important to recognize ahead of time, before placement, when weather conditions conducive to plastic shrinkage cracking will exist. Precautions can then be taken to minimize its occurrence.

a. When adverse conditions exist, erect temporary windbreaks to reduce the wind velocity over the surface of the concrete and, if possible, provide sunshades to control the surface temperature of the slab. If conditions are critical, schedule placement to begin in the later afternoon or early evening. However, in very hot conditions, early morning placement can afford better control on concrete temperatures.

b. In the very hot and dry periods, use fog sprays to discharge a fine mist upwind and into the air above the concrete. Fog sprays reduce the rate of evaporation from the concrete surface and should be continued until suitable curing materials can be applied.

c. If concrete is to be placed on a dry absorptive subgrade in hot and dry weather, dampen the subgrade but not to a point that there is freestanding water prior to placement. The formwork and reinforcement should also be dampened.

d. The use of vapor retarders under a slab on grade can increase the risk of plastic shrinkage cracking. However, it may be necessary for interior slabs that will have a floor covering at any point during its service life. See CIP 29.

e. Have proper manpower, equipment, and supplies on hand so that the concrete can be placed and finished promptly. If delays occur, cover the concrete with moisture-retaining coverings, such as wet burlap, polyethylene sheeting or building paper, between finishing operations. Some contractors find that plastic shrinkage cracks can be prevented in hot dry climates by spraying an evaporation retardant on the surface behind the screeding operation and following floating or troweling, as needed, until curing is started.

f. Start curing the concrete as soon as possible. Spray the surface with liquid membrane curing compound or cover the surface with wet burlap and keep it continuously moist for a minimum of 3 days.

g. Consider using synthetic fibers (ASTM C1116) to minimize plastic shrinkage cracking.

h. Accelerate the setting time of concrete and avoid large temperature differences between concrete and ambient air temperatures.

If plastic shrinkage cracks should appear during final finishing, the finisher may be able to close them by refinishing. However, when this occurs precautions, as discussed above, should be taken to avoid further cracking.

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6. Eugene Goeb, *Common Field Problems*, Concrete Construction, October 1985.
7. *Vapor Retarders Under Slabs on Grade*, CIP 29, NRMCA, Silver Spring, MD, www.nrmca.org

Follow These Rules to Minimize Plastic Shrinkage Cracking

1. Dampen the subgrade and forms when conditions for high evaporation rates exist.
2. Prevent excessive surface moisture evaporation by providing fog sprays and erecting windbreaks.
3. Cover concrete with wet burlap or polyethylene sheets between finishing operations.
4. Use cooler concrete in hot weather and avoid high concrete temperatures in cold weather.
5. Cure properly as soon as finishing has been completed.

1978, 1992, 1998, 2014

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NRMCA

CIP 6 — Joints in Concrete Slabs on Grade

WHAT are Joints

Concrete expands and shrinks with changes in moisture and temperature. The overall tendency is to shrink and this can cause cracking at an early age. Irregular cracks are unsightly and difficult to maintain but generally do not affect the integrity of concrete. Joints are simply pre-planned cracks. Joints in concrete slabs can be created by forming, tooling, sawing, and placement of joint formers.

Types of joints include:

a. **Contraction joints** are intended to create weakened planes in the concrete and control the location where cracks, resulting from dimensional changes, will occur.

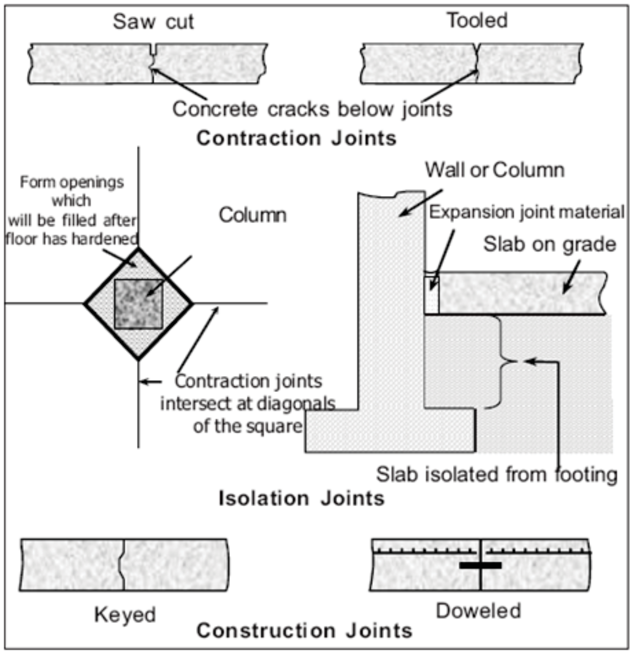
b. **Isolation or expansion joints** separate or isolate slabs from other parts of the structure, such as walls, footings, or columns; and driveways and patios from sidewalks, garage slabs, stairs, light-poles and other points of restraint. They permit independent vertical and horizontal movement between adjoining parts of the structure and help minimize cracking when such movements are restrained.

c. **Construction joints** are surfaces where two successive placements of concrete meet. They are typically placed at the end of a days work but may be required when concrete placement is stopped for a period such that the previously placed concrete has set and hardened. In slabs they may be designed to permit movement and/or to transfer load. The location of construction joints should be planned. It may be desirable to achieve bond and continue reinforcement through a construction joint for load transfer.

WHY are Joints Constructed

Cracks in concrete cannot be prevented entirely, but they can be controlled and minimized by properly designed joints. Concrete cracks because:

a. Concrete is weak in tension and, therefore, if its natural tendency to shrink is restrained, tensile stresses that exceed its tensile strength can develop, resulting in cracking.



b. At early ages, before the concrete dries out, most cracking is caused by temperature changes or by the slight contraction that takes place as the concrete sets and hardens. Later, as the concrete dries, it will shrink further and either additional cracks may form or preexisting cracks may become wider.

Joints provide relief from the tensile stresses, are easy to maintain and are less objectionable than uncontrolled or irregular cracks.

HOW to Construct Joints

Joints must be carefully designed and properly constructed if uncontrolled cracking of concrete flatwork is to be avoided. The following recommended practices should be observed:

a. The maximum joint spacing should be 24 to 36 times the thickness of the slab. For example, the joint spacing for a 4-inch [100 mm] thick slab should be about 10 feet [3 m]. It is further recommended that joint spacing be limited to a maximum of 15 feet [4.5 m].

b. All panels should be square or nearly so. The length should not exceed 1.5 times the width. Avoid L-shaped panels.

c. For contraction joints, the joint groove should have a minimum depth of ¼ the thickness of the slab, but not less than 1 inch [25 mm]. Timing of jointing operations depends on the method used:
   - Preformed plastic or hard board joint strips are inserted into the concrete surface to the required depth before finishing.
   - Tooled joints must be run early in the finishing process and rerun later to ensure groove bond has not occurred.
   - Early-entry dry-cut joints are generally run 1 to 4 hours after completion of finishing, depending on the concrete's setting characteristics. These joints are typically not as deep as those obtained by the conventional saw-cut process, but should be a minimum of 1 inch [25 mm] in depth.
   - Conventional saw-cut joints should be run within 4 to 12 hours after the concrete has been finished.

d. Raveling during saw cutting is affected by the strength of the concrete and aggregate characteristics. If the joint edges ravel during sawing, it must be delayed. However, if delayed too long, sawing can become difficult and uncontrolled cracking may occur.

e. Use premolded joint filler such as asphalt-impregnated fiber sheeting, compressible foam strips, or similar materials for isolation joints to separate slabs from building walls or footings. At least 2 inches [50 mm] of sand over the top of a footing will also prevent bond to the footing.

f. To isolate columns from slabs, form circular or square openings, which will not be filled until after the floor has hardened. Slab contraction joints should intersect at the openings for columns. If square openings are used around columns, the square should be turned at 45 degrees so the contraction joints intersect at the diagonals of the square.

g. If the slab contains wire mesh, cut out alternate wires, or preferably discontinue the mesh, across contraction joints. Note that wire mesh will not prevent cracking. Mesh tends to keep the cracks and joints from opening up.

h. Construction joints key the two edges of the slab together either to provide transfer of loads or to help prevent curling or warping of the two adjacent edges. Galvanized metal keys are sometimes used for interior slabs, however, a beveled 1 by 2 inch [25 by 50 mm] strip, nailed to bulkheads or form boards, can be used in slabs that are at least 5 inches [125 mm] thick to form a key which will resist vertical loads and movements. Keyed joints are not recommended for industrial floors. Metal dowels should be used in slabs or pavements that will carry heavy loads. Dowels must be carefully lined up and parallel or they may induce restraint and cause random cracking at the end of the dowel.

i. Joints in industrial floors subject to heavy traffic require special attention to avoid spalling of joint edges. Such joints should be filled with a material capable of supporting joint edges. Manufacturer's recommendations and performance records should be checked before use.

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2. *Guide for Concrete Floor and Slab Construction*, ACI 302.1R, American Concrete Institute, Farmington Hills, MI.
3. *Slabs on Grade*, ACI Concrete Craftsman Series CCS-1, American Concrete Institute, Farmington Hills, Ml.
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Follow These Rules for Proper Jointing

1. Plan exact location of all joints, including timing of contraction joint sawing before construction.
2. Provide isolation joints between slabs and columns, walls and footings, and at junctions of driveways with walks, curbs or other obstructions.
3. Provide contraction joints and joint filling materials as outlined in specifications.

1979, 1989, 1998. 2014

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What, why & how?
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CIP 7 - Cracks in Residential Basement Walls

WHAT Types of Cracks May Occur?

Cast-in-place concrete basements provide durable, high quality living space. Cracking of concrete is a natural occurrence and at times can be undesirable. Most common causes of cracking include:

a. Temperature and drying shrinkage cracks. Generally, newly placed concrete is at its largest volume. As concrete hardens it dries and starts to shrink. Temperature variations cause concrete to expand and contract. When these volume changes are restrained, cracking results.

b. Re-entrant corner cracking occurs diagonally from the corners of windows, doors or openings in the concrete walls. These cracks result from shrinkage.

c. Pour lines are visible demarcations between placement of two concrete loads, typically due to a delay in placing between the loads and if proper consolidation was not performed to homogenize the two portions across the separation. Pour lines are often perceived as cracks. In extreme cases they may perform as cracks if the first placement has partially hardened before the second placement. This is often referred to as a cold joint.

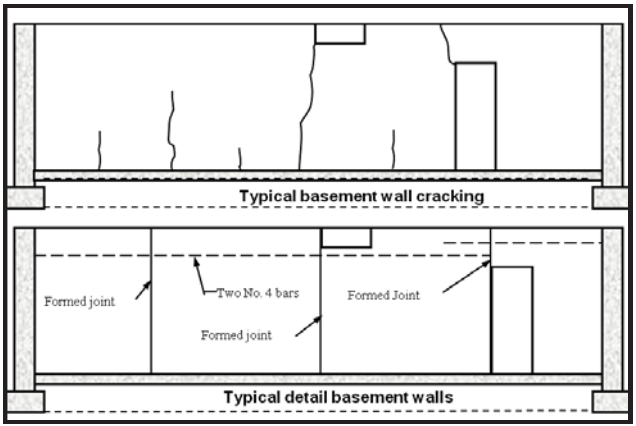
d. Vertical form lines occur between form panels and can sometimes cause weak zones due to the use of form ties that support two layers of formwork during concrete placement. Cracks may initiate at form lines.

e. Restraint cracks may form in some portions of walls where contact with footings restrains the shrinkage of the concrete wall.

f. Crazing and surface cracking may occur due to a lack of adequate curing and protection if construction is during extreme cold or hot weather.

g. Settlement cracks occur from non-uniform support of footings or occasionally from expansive soils.

h. Structural cracks may occur during backfilling if concrete strength is not adequate or the walls are not adequately supported as the design intends. This is most likely to occur when heavy equipment gets too close to the walls during the backfill process or when pressure due to backfill material exceed that anticipated in the design, for example with liquefied soils.



WHY do Basement Cracks Occur?

Some cracking is normal in concrete basement walls. Volume changes and other movements at an early age result in different types of cracks, as discussed earlier. These cracks can grow if the walls are not properly designed, due to the continued horizontal pressures applied by soils, water and temperature. Cracking can be minimized and problems prevented if the design and construction practices that follow are implemented.

Most builders or third party providers offer limited warranties for basements. A typical warranty will require repair only when cracks leak, have measurable vertical displacement, or if the crack width exceeds 1/8-in. (3 mm). The National Association of Home Builders (NAHB) requires repair or corrective action when cracks in basement walls cause leaks into the basement.

HOW to Design & Construct Quality Basements?

Cast-in-place concrete basement walls are the strongest and most effective foundation for a residence. However, climate conditions, unusual or unforeseen loads, material quality and workmanship may impact the quality of the finished basement. Proper design and construction is important. The following steps should be followed:

a. **Site conditions and excavation**. Soil type and conditions should be properly assessed for appropriate design and construction of foundations specific to the building site. The excavation should be at least to the level of the bottom of the basement slab and can be to the bottom of the footing. Soil or granular fill beneath the entire area of the basement should be well compacted by rolling, vibrating or tamping. Footings must bear on undisturbed soil or well compacted fill. Uniform soil bearing capacity should be ensured or the design should accommodate any variation.

b. **Formwork and reinforcement**. Formwork must be installed and braced to withstand the pressure of the fresh and flowing concrete. Reinforcement is used to control crack width. Wall thickness and reinforcement should be provided in accordance with International Residential Code (IRC), ACI 332, or locally adopted Code.

c. **Joints**. Some cracks in basement walls can be controlled to occur in properly located formed joints.

d. **Concrete**. Use concrete with adequate strength in accordance with the Code and project specifications. Excess water should not be added to concrete in the truck mixer. Water-reducing admixtures can be used to increase flow. Air-entrained concrete should be used for walls that may be exposed to moisture and freezing temperatures.

e. **Placement and curing**. Place concrete in a continuous operation to avoid cold joints and segregation. Adding excess water to concrete to facilitate placement will increase segregation, cause honeycombing or excessive cracking, and reduce strength. Consider placement points no greater 20 or 30 feet around the perimeter of the wall to minimize segregation. Properly designed higher slump concretes with admixtures will flow horizontally for long distances and placement points can be spread out. Curing should begin after placement. Forms should be left in place 5 to 7 days or at least until concrete attains adequate strength to support itself. Forms removed too early can result in premature drying and may cause cracking. In cold weather, forms should be insulated with blankets or other materials to retain heat. During hot dry weather, forms should be covered with wet burlap to retain moisture. Liquid membrane-forming curing compounds can be sprayed at the required coverage after forms are removed to prevent excessive drying.

f. **Waterproofing and drainage**. Waterproof membranes are best applied to the exterior of foundation walls. These are spray-applied, painted, or mechanically fastened sheet systems. Positive side waterproofing (exterior) is generally better than negative side (inside) to keep water from leaking through cracks. Drainage systems should be designed to remove excessive soil moisture along the basement wall. Provide foundation drainage by installing drain tiles or plastic pipes around the exterior of the footing and properly connect them to a removal system or drain to daylight. Surface and roof drainage should direct water away from the residence. Water should be drained to lower elevations suitable to receive storm water run off.

g. **Backfilling and final grading**. Backfilling should be done carefully to avoid damaging the walls. Brace the walls, if possible, or backfill after first floor or other structural systems are in place. Finish grade to slope ½ to 1-in. per foot (40 to 80-mm per m) for at least 8 to 10 feet (2.5 to 3 m) to drain water away from the foundation. Considering settlement, maintain this final grade to prevent water from standing along the foundation and exceeding the designed wall pressure.

h. **Crack repair**. Cracking is not necessarily a sign of poor materials or workmanship or a structural problem with the concrete wall. If repair is necessary, epoxy injection, dry-packing, or routing and sealing techniques can be used to repair and stabilize cracks. Before repairing leaking cracks, the drainage around the structure should be checked and corrected if necessary. Details of these and other repair methods are provided in Ref. 1. Seek professional advice to evaluate and repair active cracks that are widening with time.

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1979, 2000, 2014

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CIP 8—Discrepancies in Yield

WHAT is Concrete Yield

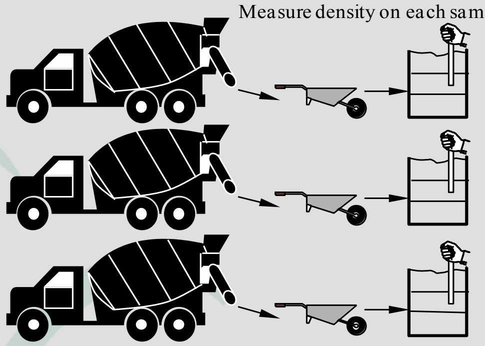
Concrete yield is defined as the volume of freshly mixed concrete produced from a known quantity of concrete materials. Ready mixed concrete is sold on the basis of the volume of fresh, unhardened concrete in cubic yards (yd^3) or cubic meters (m^3) as discharged from a truck mixer. Most materials are batched by weight so it is important to determine the volume of concrete produced from the actual batched quantities of materials. The density of the fresh concrete is used to establish this relationship.

The basis for calculating the volume or yield is described in ASTM C94, *Specification for Ready Mixed Concrete.* The volume of freshly mixed and unhardened concrete in a given batch is determined by dividing the total weight of the materials by the density (unit weight) of the concrete determined in accordance with ASTM C138. ASTM C94 requires that the yield should be determined from the average of three determinations of representative samples, each from three different delivery vehicles. It should thereby be recognized that the volume of concrete supplied is not determined from the calculated dimensions of the constructed member.

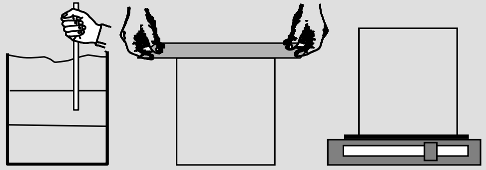
A note in ASTM C94 states: *It should be understood that the volume of hardened concrete may be, or appears to be, less than expected due to waste and spillage, over-excavation, spreading forms, some loss of entrained air, or settlement of wet mixtures, none of which are the responsibility of the producer.*

The volume of hardened concrete in place may be about 2 percent less than its volume in a freshly mixed state due to reduction in air content, settlement and bleeding, decrease in volume of the cementitious paste, and drying shrinkage due to loss of moisture.

Sample 3 truck mixers
Measure density on each sample



ASTM C138 - Test for Density (Unit Weight)
Fill density measure in 3 layers;
Rod each layer 25 times; tap sides with mallet;
Strike off with flat plate; Clean outside surfaces; and weigh



$$\text{Density, lb/ft}^3\ (\text{kg/m}^3) = \frac{\text{Wt. of concrete in measure, lb (kg)}}{\text{Volume of measure, ft}^3\ (\text{m}^3)}$$

$$\text{Average Density, lb/ft}^3\ (\text{kg/m}^3) = \frac{(D1 + D2 + D3)}{3}$$

$$\text{Batch Yield, yd}^3 = \frac{\text{Weight of Materials in Batch, lb.}}{\text{Average Density, lb/ft}^3 \times 27}$$

$$\text{Batch Yield, m}^3 = \frac{\text{Weight of Batch, kg}}{\text{Average Density, kg/m}^3}$$

WHY do Yield Problems Occur

Yield discrepancies can be real or perceived. Real discrepancies result when quantity of materials batched do not produce the intended yield. This can be evaluated by density measurements. If yield determined from density measurement indicates a discrepancy, it should be corrected by the concrete producer. Perceived discrepancies, typically under-yield, is when the concrete ordered does not fill the forms due to contingencies discussed below:

a. Miscalculation of form volume or slab thickness when the actual dimensions exceed the assumed dimensions used in estimates, even by a small amount. For example, a 1/8-inch (3-mm) difference in a 4-inch (100-mm) thick slab would mean a shortage of 3 percent or 1 yd^3 in a 32-yd^3 (1 m^3 in a 32-m^3) order.

b. Deflection or distortion of the forms resulting from pressure exerted by the concrete.

c. Placement on irregular subgrade or granular fill and settlement prior to or during placement.

d. Over the course of a large job, the small amounts of concrete returned each day or used in mud sills or incidental footings can add up to be perceived as a deficiency in yield.

An over-yield can be an indication of a problem if the excess concrete is caused by too much air, water, or aggregate, or if the forms have not been properly filled.

Differences between actual and target weights and air content in concrete, within the permitted tolerances, will result in discrepancies in yield.

HOW to Prevent Yield Discrepancies

To prevent or minimize concrete yield problems:

a. Check concrete yield by measuring concrete density in accordance with ASTM C138 early in the job. Repeat these tests if a problem arises. Ensure that the scale is accurate and placed on a level surface, that the volume density measure is accurately determined, that a flat plate is used for strike off, and that the outside of the measure is cleaned prior to weighing. Concrete yield in ft^3 (m^3) is total batch weight in pounds (kg) divided by density in lb/ft^3 (kg/m^3). The total batch weight is the sum of the weights of all materials from the batch ticket.

b. Measure formwork accurately. Order sufficient quantity of concrete to complete the job and reevaluate the amount required towards the end of the placement. Provide this estimate to the concrete producer so that the order for the last 2 or 3 loads can be adjusted to provide the required quantity of concrete. This can prevent waiting for a short load after the plant has closed or the concrete trucks have been scheduled for other jobs. Disposal of returned concrete has environmental and economic consequences to the concrete producer and the purchaser.

Example—Materials batched for 8 yd^3 / 6 m^3 load.

Material	Weight, lb	Weight, kg
Cement	3,620	1,640
Fly ash	920	420
Coarse Aggregate	14,400	6,550
Fine Aggregate	11,200	5,090
Batch Water	2,080	940
Total	32,220	14,640
Density, lb/ft^3 / kg/m^3	151.0	2,430

$$\text{Yield} = \frac{32{,}220}{151.0 \times 27} = 7.9\ \text{yd}^3$$

$$\text{Yield} = \frac{14{,}640}{2{,}430} = 6.0\ \text{m}^3$$

c. Estimate extra concrete needed for waste and increased placement dimensions over nominal dimensions. Include an allowance of 4 to 10 percent over plan dimensions for waste, over-excavation and other contingencies. Repetitive operations and slip form placement permit more accurate estimates of the amount of concrete that will be needed. Sporadic operations involving a alternating placement in slabs, footings, walls, and as incidental fill around pipes will require a bigger allowance for contingencies.

d. Construct forms with adequate bracing and shoring to minimize deflection and bulging when concrete is placed. This is important for elevated slabs.

e. For slabs on grade accurately finish and compact the subgrade to the proper elevation.

References

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5. *No Minus Tolerance on Yield*, Malisch, W. R. and Suprenant, B. A., Concrete Producer, May 1998.
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Follow These Rules to Avoid Yield Discrepancies

1. Measure forms and accurately estimate the volume of concrete needed.
2. Estimate potential waste, additional thickness, form deflection and other contingencies—order more than the original volume estimate by at least 4 to 10 percent
3. Towards the end of the placement reevaluate required volume and inform the concrete producer with adequate time to adjust subsequent loads. Avoid short loads to complete a placement.
4. To check yield, measure the density of representative samples from three separate loads—yield is the total batch weight for each load divided by the average density.

1979, 1991, 2000, 2016

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CIP 9 - Low Concrete Cylinder Strength

WHAT Constitutes Low Cylinder Strength

Strength test results of concrete cylinders are used as the basis of acceptance of ready mixed concrete when a strength requirement is specified. Cylinders are molded from a sample of fresh concrete, cured in standard conditions and tested at an age indicated in the specification, usually at 28 days. For strength test results to be reliable, procedures must be in accordance with ASTM standards. The average strength of a set of two 6×12 in. (150×300 mm) or three 4×8 in. (100×200 mm) cylinders made from the same concrete sample constitutes one test result. In some cases cylinders are tested at 7 days to get an early indication of the potential strength, but these test results are not to be used to determine the acceptability of the concrete. Cylinders used for acceptance of concrete should not be confused with field-cured cylinders. Tests of field-cured cylinders are used to evaluate whether the in-place concrete has been properly cured and protected, to estimate the early-age strength in the structure to strip forms or for post-tensioning, and to continue construction activity.

The ACI Building Code, ACI 318, and the Specification for Structural Concrete, ACI 301, recognize that when mixtures are proportioned to meet the requirements of the standards, strength test results will fail to comply with acceptance criteria about one time in 100 tests due to normal variability.

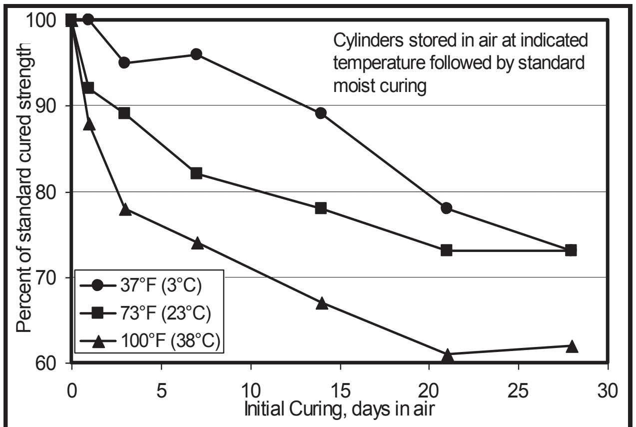
The strength acceptance criteria used are:

a. The average of three consecutive tests equals or exceeds the specified strength, and

b. No single test is lower than the specified strength by more than 500 psi (3.5 MPa) when the specified strength is less than or equal to 5000 psi (35 MPa), or

   No single test is lower than (0.9 × specified strength) when the specified strength is greater than 5000 psi (35 MPa)

An example of these strength acceptance criteria is provided in the table. If the strength test results fail either condition (a) or (b), steps must be taken to increase the strength of the concrete. If the results fail condition (b), an investigation should be made to ensure structural adequacy of that portion of the structure.



Effect of Initial Curing Temperature on Strength

WHY are Compressive Tests Low?

The major reasons for low compressive strength tests are:

1. Improper cylinder handling, curing and testing - this is typically the reason in most cases;
2. The addition of excessive water to the concrete mixture at the jobsite due to delays in placement or requests for a higher slump to facilitate placement and finishing;

Acceptance of Concrete on Compressive Strength
4000 psi Specified Strength

Test No.	Individual Cyl. No. 1	Individual Cyl. No. 2	Average (Test)	Average of 3 Consecutive
Acceptable Example				
1	4110	4260	4185	— —
2	3840	4080	3960	— —
3	4420	4450	4435	4193
4	3670	3820	3745	4047
5	4620	4570	4595	4258
Low Strength Example				
1	3620	3550	3585	— —
2	3970	4060	4015	— —
3	4080	4000	4040	3880*
4	4860	4700	4780	4278
5	3390	3110	3250†	4023

* Average of three consecutive low.
† One test more than 500 psi low.

3. High air content in the concrete (and test specimens); and
4. Errors in production and unanticipated factors during delivery

When low compressive strength test results are reported:

1. Collect all test reports and analyze the results before taking action. Labs should not provide reports of only failing tests.
2. Look at the pattern and numbers of reported strength results.
    - Considering the sequence of results—is there a violation on compliance with the strength acceptance criteria discussed above
    - The strength range of two or three cylinders prepared from the same sample should rarely exceed 8.0% or 9.5% of the strength average, respectively.
    - Do the results indicate that the cylinders are being loaded to complete failure
3. Do the test reports provide any causal reasons?
    - Review the dates and times of batching, sampling, pick up from jobsite and delivery to the lab
    - Review concrete and ambient temperatures, number of days cylinders were left in the field, procedures used for initial curing in the field, duration of transportation, and subsequent curing in the lab
    - Review the slump, air content, and density, if measured
    - Review for any reported cylinder defects.

It is important that procedures are conducted in accordance with ASTM standards. Almost all deficiencies in handling and testing cylinders will result in a lower measured strength. All violations add up to cause significant reductions in measured strength. The more significant factors are improperly finished surfaces, initial curing over 80° F (27°C); frozen cylinders; extra days in the field; damage during transportation; delay in stripping molds and curing at the lab; improper capping; and insufficient care in breaking cylinders.

The laboratory should be held responsible for deficiencies in its procedures. Field-testing technicians and laboratory personnel should be certified; construction workers untrained in concrete testing must not make and handle cylinders. ACI 318 requires laboratories to conform to ASTM C1077 for their quality system and personnel qualifications. Laboratories should be inspected by the Cement and Concrete Reference Laboratory (CCRL) laboratory inspection or an equivalent program. Field testing personnel must have a current ACI Grade I Field Testing Technician certification, or equivalent. Laboratory personnel should have the ACI Grade I and II Laboratory Testing Technician and/or the ACI Strength Testing Certification, or equivalent.

If the deficiency justifies investigation, first verify testing accuracy and then compare the structural requirements with the measured strength. If testing is deficient or if strength is greater than actually needed in that portion of the structure, there is little point in investigating the in-place strength. However, if procedures conform to the standards and the strength as specified is required for the structural capacity of the member in question, further investigation of the in-place concrete may be required. (CIP 10).

HOW to Reduce Low Strength Tests?

1. Ensure that sample of concrete at the jobsite is obtained in accordance with ASTM C172
2. Ensure that the cylinders are made and cured in accordance with the standard curing requirements in ASTM C31.
3. Ensure that cylinders are handled with care at the jobsite and during transportation.
4. Ensure the cylinders are tested in the laboratory in accordance with ASTM C39.

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1982, 1989, 2000, 2014

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CIP 10 - Strength of In-Place Concrete

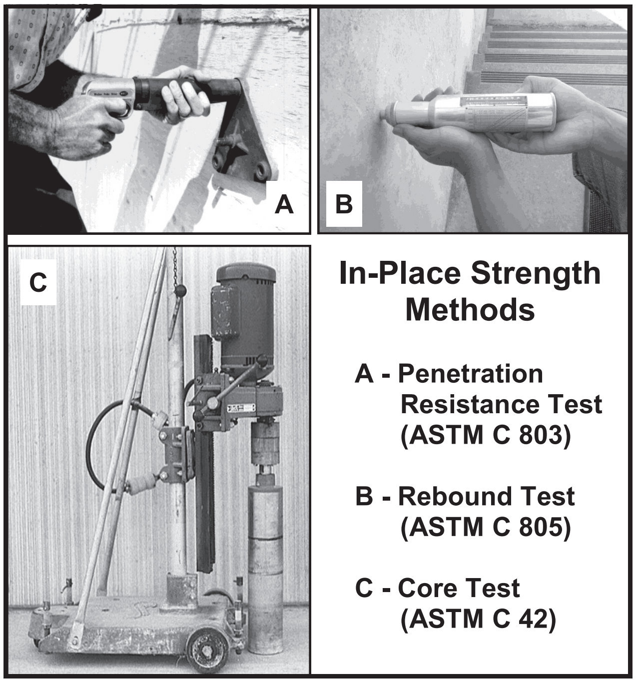
WHAT is the Strength of In-Place Concrete?

Concrete structures are designed to carry dead and live loads during construction and in service. Samples of concrete are obtained during construction and standard ASTM procedures are used to measure the potential strength of the concrete as delivered. Cylinders are molded and cured at 60 to 80°F (17 to 27°C) for one day and then moist cured in the laboratory until broken in compression, normally at an age of 7 and 28 days or at an alternative specified age.

The in-place strength of concrete will not be equivalent to that measured on standard cylinders and will generally be lower. Job practices for handling, placing, consolidation, and curing concrete in structures are relied upon to provide an adequate percentage of that potential strength, measured on cylinders, in the structure. Structural design principles recognize this and the ACI Building Code, ACI 318, has a process of assuring the structural safety during construction. In cold weather a slower rate of in-place strength gain can be expected.

Means of measuring, estimating, or comparing the strength of in-place concrete include: rebound hammer, penetration probe, pullouts, maturity, cast-in-place cylinders, tests of drilled cores, and load tests of the structural member or system.

Cores drilled from the structure is one of the methods of evaluating whether the structural capacity of a concrete member is adequate. Drilled cores generally test lower than standard-cured cylinders. The ACI Building Code (ACI 318) recognizes that concrete construction can be considered structurally adequate if the average of three cores from a region represented by non-compliant concrete strength tests is equal to or exceeds 85 percent of specified strength, f'_c with no single core less than 75 percent of f'_c. Measured core strengths are not corrected for age. TIP 11 discusses core testing for acceptance of concrete. ACI 214.4R provides detailed guidance on core testing, evaluating existing structure capacity using in-place strengths, and determining an equivalent f'_c value for evaluating the structural capacity of an existing structure. The latter process should not be used to determine the acceptability of concrete furnished to a project.



In-Place Strength Methods

A - Penetration Resistance Test (ASTM C 803)

B - Rebound Test (ASTM C 805)

C - Core Test (ASTM C 42)

WHY Measure In-Place Strength?

Tests of in-place concrete may be needed when standard cylinder strengths are low and do not comply with strength acceptance criteria outlined in ACI 318. However, do not investigate in-place without first checking to be sure that: the concrete strengths actually failed to meet the specification provisions, low strengths are not attributable to faulty testing practices, or the specified strength is really needed. (See CIP 9 and TIP 11) In many cases, the concrete can be accepted for the intended use without in-place strength testing.

There are many other situations that may require the investigation of in-place strength. These include: shore and form removal, post-tensioning, or early load application; investigation of damage due to freezing, fire, or adverse curing exposure; evaluation of older structures; and when a lower strength concrete is placed in a member by mistake. When cores or other in-place tests fail to assure structural adequacy, additional curing of the structure may provide the necessary strength. This is particularly possible with concrete containing fly ash, slag cement or some blended cements.

HOW to Investigate In-Place Strength?

If only one set of cylinders is low, often the question can be settled by comparing rebound hammer or penetration probe results on concrete in areas represented by acceptable cylinder results. Where the possibility of low strength is such that large portions need to be investigated, a well-organized study will be needed. Establish a grid and obtain systematic readings including good and questionable areas. Tabulate the hammer or probe readings. If areas appear to be low, drill cores from both low and high areas. If the cores confirm the hammer or probe results, the need for extensive core tests is greatly reduced.

Core Strength, ASTM C 42 - If core drilling is necessary observe the following:

a. Test a minimum of 3 cores for each location in the structure represented by low strength tests;
b. Obtain cores with a minimum diameter of 3.7 in. (85 mm) or at least twice the nominal maximum aggregate size. Smaller diameter cores are permitted when it is not feasible to obtain the required size;
c. The length to diameter ratio (L/D) should be around 2, but try to obtain cores with L/D of at least 1½;
d. Avoid drilling cores from the top layers of columns, slabs, walls, or footings, which will be 10 to 20 percent weaker than cores from the mid or lower portions; and
e. Store the cores in sealed watertight bags or containers and transport to the laboratory. Test the cores in accordance with ASTM C42. Saw or grind core ends within 2 days after drilling. Keep cores in a sealed conditionfor at least 5 days after last wetted. Review the requirements for conditioning cores in current versions of ACI 318 and ASTM C42.

Probe Penetration Resistance, ASTM C 803 - Probes or pins driven into concrete can be used to study relative strength of in-place concrete:

a. Different size probes or pins, or a change in driving force may be necessary for large differences in strength or concrete density;
b. Accurate measurement of the exposed length of the probe is required;
c. Probes should be spaced at least 7 in. apart and not be close to the edge of the concrete;
d. Probes not firmly embedded in the concrete should be rejected;
e. Develop a strength calibration curve for the materials and conditions under investigation; and
f. Surface conditions, moisture conditions, and aggregate characteristics can affect the results.

Rebound Hammer, ASTM C 805 - This method is also used to evaluate the relative in-place strength:

a. Wet all surfaces for several hours or overnight because drying affects rebound number;
b. Don't compare readings on concrete cast against different form materials, concrete of varying moisture content, readings from different impact directions, on members of different mass, or results using different hammers;
c. Don't grind off the surface unless it is soft, finished or textured;
d. Test structural slabs from the bottom; and
e. Do not test frozen concrete.
f. Surface conditions, moisture conditions, and aggregate characteristics can affect the results

Maturity, ASTM C1074 – If concrete maturity is used to estimate the in-place strength please refer to CIP 39

Advance Planning - When it is known in advance that in-place testing is required, such as for shore and form removal, other methods can be considered such as: cast-in-place, push-out cylinders and pullout strength measuring techniques covered by ASTM C873 and C900.

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1982, 1989, 2000, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 11 - Curing In-Place Concrete

WHAT is Curing

External curing is a step during construction that involves maintaining newly placed concrete at adequate **moisture** and **temperature** conditions so that it can develop properties, such as strength and durability, the mixture was designed to achieve. Curing begins immediately after placement and finishing and should be continued for a sufficient period of time, typically 3 to 7 days.

Hydration is the chemical reaction of cementitious materials with water that produces concrete's desired properties. The objective of curing is to prevent loss of moisture and maintain a favorable temperature to support continued hydration. Without an adequate supply of moisture, the cementitious materials in concrete cannot react to form a quality product.

Temperature is an important factor for curing. The rate of hydration, and therefore, strength development, is faster at higher temperatures. Temperature of placed concrete should be maintained above 50°F (10°C). Hydration generates heat that can be retained in cooler weather. In thicker sections curing procedures should minimize the temperature differential between the core and surface to avoid thermal cracking. Curing can also regulate the cooling rate to prevent thermal shock. See CIP 42.

When finishing, minimize the rate of moisture loss from the concrete surface to prevent plastic shrinkage cracking. See CIP 5.

Internal curing involves the use of absorptive materials, such as soaked lightweight sand and super-absorbent polymers, in the concrete mixture that release moisture with time. This is used in some applications. It does not negate the need for external curing.

WHY Cure Concrete

a. **Predictable strength gain**. Concrete in a dry environment can lose as much as 50 percent of its potential strength compared that which is moist cured. At high temperature concrete gains early strength quickly but later strengths may be reduced. At cooler temperature concrete takes longer to gain strength, delaying form removal and subsequent construction.

b. **Improved durability**. Well-cured concrete has better surface hardness to withstand surface wear and abrasion. Curing minimizes cracking and makes concrete more watertight, thereby reducing the intrusion of water and water-borne chemicals resulting in improved durability and service life.

Spray-on curing compound

Curing Blankets

c. **Better serviceability and appearance**. Lack of curing will result in a less durable surface with poor resistance to wear and abrasion. Proper curing reduces the potential for crazing, dusting, and scaling.

HOW Should Concrete be Cured

Maintaining Moisture:

Concrete should be protected from losing moisture until final finishing using fogging or evaporation retarders. Subsequent to finishing, moist curing methods can involve application of additional water or retention of water in the concrete.

Methods using application of water:

a. Continuous fogging or sprinkling is an excellent curing method. Soaker hoses can be used on vertical surfaces. Air temperatures should be above freezing and water should be readily available. Absorbent materials can be used to retain water. Alternate wetting and drying is not an acceptable curing practice.

b. Ponding is the most thorough method of water curing but is rare. A dike is created along the edge of the slab to pond water on the slab surface. It is sometimes used on smaller slabs and bridge decks. Temperatures should be above freezing for the curing duration.

c. Use of absorbent materials like burlap or cotton mats can be used to hold water on horizontal or vertical surfaces applied by a soaker hose or sprinkler. The materials should be kept wet and weighted down to keep from blowing away. Materials should not stain the concrete surface.

d. Damp earth, sand, or sawdust can be used to cure flatwork, especially floors. Materials should be clean and free of organic or iron-staining contaminants.

e. Straw or hay sprinkled with water can be used on small areas. Straw can easily blow away and, if it dries is fire hazard. The layer of straw should be 6-in. (150 mm) thick and covered with a tarp.

Methods using retention of water:

Methods reduce evaporative water loss from the surface. They can be applied earlier than water-curing methods, do not need source of water, and are easier to handle.

a. Plastic sheets - either clear, white (reflective), or black. Plastic film should conform to ASTM C171, be at least 4 mils (0.10 mm) thick. Film reinforced with fibers are more durable and less likely to tear. Clear and dark sheets absorb solar radiation and are recommended in cool weather or on shaded areas. Reflective sheets minimize heat gain when exposed to sunlight and should be used in warm weather. Plastic should be laid in direct contact with the concrete surface as soon as possible without marring the surface. Edges should overlap, be taped, and weighted down. Sheets should extend beyond the edge of slabs at least twice the slab thickness. Wrinkles will cause dark streaks or a mottled appearance due to variations of moisture and/or temperature. Plastic should not be used on concrete surfaces where appearance is important. Plastic is sometimes used over wet burlap to retain moisture.

b. Liquid membrane-forming curing compounds must conform to ASTM C309 or C1315. These are wax or resin-based materials that form a surface film and minimize evaporation. Apply to the concrete surface, at the recommended rate, immediately after disappearance of water sheen on the surface after final finishing. Delayed application after surface has dried prevents the formation of the film. While a clear liquid may be used, a white pigment provides reflective properties and coverage is visible. Two coats, applied at right angles, is desirable for even coverage. Curing materials that are wax-free are recommended for concrete surfaces that will be painted, or if a surface covering has to be bonded to the concrete. Some curing compounds are formulated to self-dissipate with time and for compatibility with surface treatments.

c. Waterproof paper - consists of two layers of kraft paper cemented together and reinforced with fiber. It is more resistant to tearing and can be reused. Paper is used like plastic sheeting and is less likely to mar the surface or cause mottling. Curing paper should conform to ASTM C171.

Evaporation retardants are used to reduce evaporation from concrete surfaces before it sets to prevent plastic shrinkage cracking. These should not be used for final curing.

Control of temperature:

In cold weather do not allow concrete to cool faster than a rate of 5°F (3°C) per hour for the first 24 hours. Concrete should be protected from freezing until it reaches a compressive strength of at least 500 psi (3.5 MPa) using insulating materials. Curing methods that retain moisture, rather than wet curing, should be used when freezing temperatures are anticipated. Guard against rapid temperature changes after removing protective measures.

In hot weather, higher initial curing temperature will result in rapid strength gain and lower ultimate strengths. Water curing and sprinkling can be used to achieve lower curing temperatures in summer. Precautions should be used to protect against cooling faster than 5°F (3°C) per hour during the first 24 hours due to temperature extremes.

Termination of Curing:

Curing should be continued as required by the specification, or for at least 3 to 7 days. Termination of curing should allow for gradual drying of concrete and to prevent large temperature differentials in the concrete member. Cover materials should be allowed to dry before removal. Controlled drying procedures should be used to control the rate of drying with wet curing methods. Use of layers of insulation can be removed sequentially to reduce the development of large thermal differential. The use of embedded temperature and relative humidity monitoring devices can be useful in critical applications.

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1982, 1989, 2000, 2017

Concrete in Practice
What, why & how?
NRMCA

CIP 12 - Hot Weather Concreting

WHAT is Hot Weather?

Hot weather, as defined by ACI 305R, is any combination of the following conditions that tends to impair the quality of freshly mixed or hardened concrete by accelerating the rate of moisture loss and rate of cement hydration, or otherwise causing detrimental results:

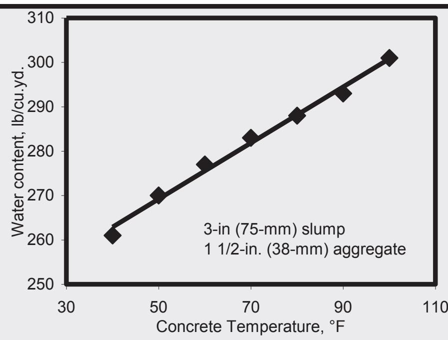
- High ambient temperature
- High concrete temperature
- Low relative humidity
- High wind speed, and
- Solar radiation

Hot weather problems are most frequently encountered in the summer, but the associated climatic factors of high winds, low relative humidity and solar radiation can occur at any time, especially in arid or tropical climates. Hot weather conditions can produce a rapid rate of evaporation of moisture from the surface of the newly placed concrete and accelerated setting time, among other problems. Generally, high relative humidity tends to reduce the effects of high temperature.

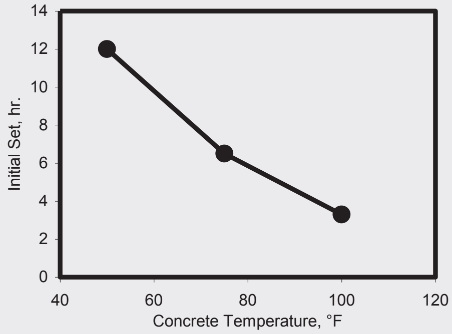
WHY Consider Hot Weather?

Hot weather should be taken into consideration when planning concrete projects because of the potential effects on fresh and newly placed concrete. High concrete temperature causes increased water demand, which, in turn, will increase the water-cementitious materials ratio and result in lower strength and reduced durability. Higher temperatures tend to accelerate the rate of slump loss and can cause loss of entrained air. Temperature also has a major effect on the setting time of concrete: At higher temperatures, concrete will set quicker and finishing operations will need to occur at a faster rate. Concrete that is cured at high temperatures at an early age will not be as strong at later ages as the same concrete cured at temperatures in the range of 70°F (20°C).

High temperatures, high wind velocity, and low relative humidity can affect fresh concrete in two important ways: the high rate of evaporation can result in plastic shrinkage before concrete sets or early-age drying shrinkage cracking. The evaporation rate removes surface water necessary for hydration unless proper curing methods are employed. Thermal cracking may result from rapid changes in temperature, such as when concrete slabs or walls are placed on a hot day followed by a cool night. High temperature also accelerates cement hydration and contributes to the potential for thermal cracking in thicker concrete sections.



Effect of temperature on water requirement of concrete (Ref. 1)



Effect of temperature on concrete setting time (Ref. 1)

HOW to Concrete in Hot Weather?

The key to successful hot weather concreting is:

1. Recognizing the factors that affect concrete; and
2. Planning to minimize their effects.

Use proven local recommendations for adjusting concrete mixture composition and proportions, such as the use of water reducing and set retarding admixtures. Extended-set control admixtures may also be used for long haul deliveries or in extremely high temperatures. Modifying concrete mixtures to reduce the heat generated by cement hydration, such as the use of an ASTM Type II moderate heat cement, blended cements with a low heat option, and the use of fly ash and slag cement can reduce potential problems with high concrete temperature. Advance planning to schedule concrete delivery to avoid interruptions and delays of placing and finishing is essential. Trucks should be able to discharge immediately and adequate personnel should be available to place and handle the concrete. When possible, avoid the hottest part of the day to place and finish concrete. Do not sprinkle water on the surface of slabs to facilitate finishing. Limits on maximum concrete temperature may be waived by the purchaser if the concrete consistency (slump) is adequate for the placement and excessive water addition is not required.

In the case of extreme temperature conditions or with thicker (mass) concrete sections, the concrete temperature can be lowered by using chilled water or ice as part of the mixing water. Chilled water can reduce concrete temperature by up to 10ºF (6ºC); ice can reduce temperature by up to 20ºF (12ºC) The ready mixed concrete producer uses other measures, such as sprinkling and shading the aggregate, to help lower the temperature of the concrete. For greater reductions in concrete temperature, liquid nitrogen can be injected into concrete mixers. This needs additional setup costs and appropriate precautions to prevent damage to blades and mixer drum.

If low humidity and high winds are predicted windbreaks, sunscreens, mist fogging, or evaporation retardants may be needed to minimize the potential plastic shrinkage cracking in slabs.

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Follow These Rules for Hot Weather Concrete

1. Make appropriate modifications to concrete mixtures to manage rate of slump loss, setting time and other characteristics. Retarders, water reducers, mid and high-range water reducers, extended set-control admixtures, moderate heat of hydration cement, pozzolanic materials, slag cement, or other proven local solutions may be used. Reduced cement content, while ensuring that concrete strength will be attained, may be appropriate. Synthetic fibers may be used to minimize plastic shrinkage cracking (CIP 24).
2. Have adequate manpower to place, finish and cure the concrete. Schedule the rate of concrete delivery that can be managed by available crew and placement equipment.
3. Limit the addition of water at the jobsite—do not exceed the quantity of mixing water established for the concrete mixture. Adding water to concrete that is more than 1½ hours old should be avoided.
4. Slabs on grade placed directly on vapor retarders (CIP 29) will need special precautions when finishing and curing to avoid cracking.
5. On dry and/or hot days, when conditions are conducive for plastic shrinkage cracking, dampen the subgrade, forms and reinforcement prior to placing concrete. Do not allow excessive water to pond.
6. Begin final finishing operations as soon as the water sheen has left the surface; start curing as soon as finishing is completed. Continue curing for at least 3 days; cover the concrete with wet burlap and plastic sheeting to prevent evaporation or use a liquid membrane curing compound, or cure slabs with water (CIP 11). Using white pigmented membrane curing compounds will help with proper coverage and reflect heat from the concrete surface.
7. Protect test cylinders at the jobsite to maintain temperature and moisture for initial curing. Field curing boxes with ice or refrigeration may be necessary to ensure maintaining the required 60 to 80°F (17 to 27°C) for initial curing of cylinders. (CIP 9 and 34)
8. Accelerators may be used in hot weather to expedite finishing operations and to avoid plastic shrinkage cracking.

1982, 1989 , 2000, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 13 - Concrete Blisters

WHAT are Blisters?

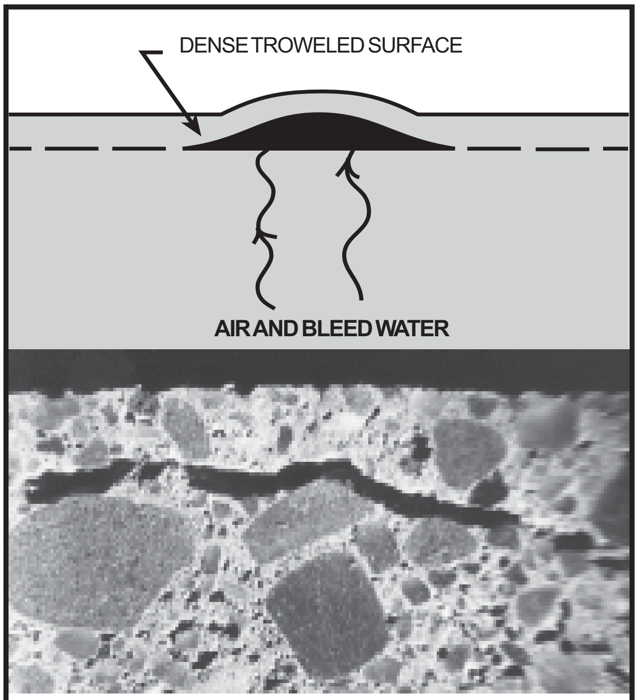
Blisters are hollow, low-profile bumps on the concrete surface, typically from the size of a dime up to 1 inch (25 mm), but occasionally even 2 or 3 inches (50 – 75 mm) in diameter. A dense troweled skin of mortar about $^{1}/_{8}$ in. (3 mm) thick covers an underlying void that moves around under the surface during troweling. Blisters may occur shortly after the completion of finishing operation. In poorly lighted areas, small blisters may be difficult to see during finishing and may not be detected until they break under traffic.

WHY do Blisters Form?

Blisters may form on the surface of fresh concrete when either bubbles of entrapped air or bleed water migrate through the concrete and become trapped under the surface, which has been sealed prematurely during the finishing operations. These defects are not easily repaired after concrete hardens.

Blisters are more likely to form if:

1. Insufficient or excessive vibration is employed. Insufficient vibration prevents the entrapped air from being released and excessive use of vibrating screeds works up a thick mortar layer on the surface.
2. An improper tool is used for floating the surface or it is used improperly. The surface should be tested to determine which tool, whether it be wood or magnesium bull float, does not seal the surface. The floating tool should be kept as flat as possible.
3. Excessive evaporation of bleed water occurs and the concrete appears ready for final finishing operations (premature finishing), when, in fact, the underlying concrete is still releasing bleed water and entrapped air. High rate of bleed water evaporation is especially a problem during periods of high ambient temperatures, high winds and/or low humidity.



Concrete Blister

4. Entrained air is used or is higher than normal. Rate of bleeding and quantity of bleed water is greatly reduced in air-entrained concrete giving the appearance that the concrete is ready to float and further finish causing premature finishing.
5. The subgrade is cooler than concrete. The top surface sets faster than the concrete in the bottom and the surface appears ready to be floated and further finished.
6. The slab is thick and it takes a longer time for the entrapped air and bleed water to rise to the surface.
7. The concrete is cohesive or sticky from higher content of cementitious materials or excessive fines in the sand. These mixtures also bleed less and at a slower rate. Concrete mixtures with lower contents of cementitious materials bleed rapidly for a

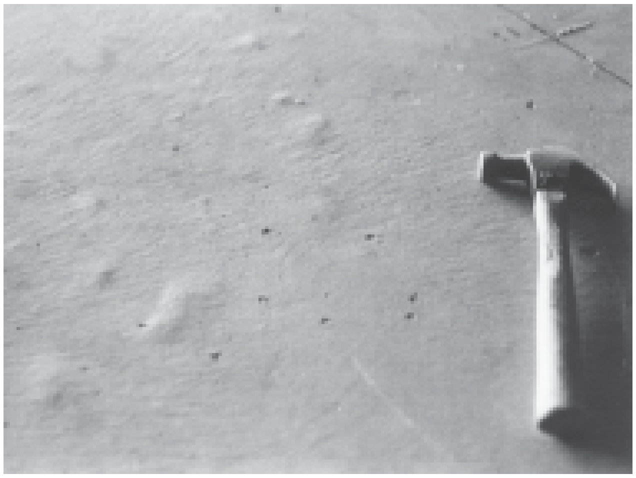
shorter period, have higher total bleeding and tend to delay finishing.

8. A dry shake is prematurely applied, particularly over air-entrained concrete.
9. The slab is placed directly on top of a vapor retarder or an impervious base, preventing bleed water from being absorbed by the subgrade.

HOW To Prevent Blisters?

The finisher should be wary of a concrete surface that appears to be ready for final finishing before it would normally be expected. Emphasis in finishing operations should be on placing, striking off and bull floating the concrete as rapidly as possible and without working up a layer of mortar on the surface. After these operations are completed, further finishing should be delayed as long as possible and the surface covered with polyethylene or otherwise protected from evaporation. If conditions for high evaporation rates exist, place a cover on a small portion of the slab to judge if the concrete is still bleeding. In initial floating, the float blades should be flat to avoid densifying the surface too early. Use of an accelerating admixture or heated concrete often prevents blisters in cool weather. It is recommended that non-air entrained concrete be used in interior slabs and that air entrained concrete not be steel troweled.

If blisters are forming, try to either flatten the trowel blades or tear the surface with a wood float and delay finishing as long as possible. Under conditions causing rapid evaporation, slow evaporation by using wind breaks, water misting of the surface, evaporation retarders, or a cover (polyethylene film or wet burlap) between finishing operations. Further recommendations are given in ACI 302.1R and ACI 305.



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Follow These Rules to Avoid Blisters

1. Do not seal surface before air or bleed water from below have had a chance to escape.
2. Avoid dry shakes on air-entrained concrete.
3. Use heated or accelerated concrete to promote even setting throughout the depth of the slab in cooler weather.
4. Do not place slabs directly on vapor retarders. If vapor retarders are essential (CIP 28) take steps to avoid premature finishing.
5. Protect surface from premature drying and evaporation.
6. Do not use a jitterbug or excessive vibration such as a vibratory screed on slumps over 5 inches (125 mm).
7. Air entrained concrete should not be steel troweled. If required by specifications, extreme caution should be exercised when timing the finishing operation.

1983, 2001, 2005

Concrete in Practice
What, why & how?
NRMCA

CIP 14 - Finishing Concrete Flatwork

WHAT is Finishing

Finishing is the operation of creating a concrete surface of a desired texture, smoothness, and durability. The finish on a concrete slab can be functional or decorative.

WHY Finish Concrete

Finishing makes the concrete slab surface functional, serviceable, and attractive. The final texture, surface hardness, and joint pattern on slabs, floors, sidewalks, patios, and driveways depend on the concrete's end use. Warehouse or industrial floors need to be flat and level and have greater wear resistance, while other interior floors covered with floor coverings do not have to be as smooth and durable. Exterior slabs must be sloped to drain water with a texture that will not be slippery when wet. Excessive finishing should be avoided. A wide range of decorative finishes are possible using special techniques not discussed here.

HOW to Place Concrete

Before finishing, concrete is placed, consolidated and leveled. These operations should be carefully planned. Skill, knowledge, and experience are required to deal with a variety of concrete mixtures, placement methods, and field conditions. Having the proper manpower and equipment available; and timing the operations properly is critical.

Complete all subgrade excavation and compaction, formwork, and placement of mesh, reinforcement, or other embedments, as required, before concrete delivery. Delays after the concrete arrives create will reduce the final quality of flatwork.

The subgrade should be compacted uniformly and properly sloped as needed for drainage. Avoid wet spots and do not place concrete on a cold subgrade.

General guidelines for placing and consolidating concrete are:

a. Selecting the correct concrete mixture for the job. Consult your concrete supplier. Do not add excess water to the load to increase slump. Concrete should be resistant to segregation, slump ordered should be appropriate to placement and finishing methods, and supply should be consistent and timely. Deposit concrete as near as possible to its final location—directly from the truck chute or use wheelbarrows, buggies, or pumps. Start at the far end placing concrete abutting previously placed concrete and work towards the near end. On slopes, use lower slump concrete and work up the slope.


Construction Crew Finishing Concrete

b. Spread the concrete using a short-handled, square-ended shovel, or a come-along. Never use a garden rake or tined tool to move concrete horizontally as it causes segregation.

c. Concrete should be well consolidated with particular attention to the edges by tamping concrete with a spade or piece of wood along form edges. For larger areas, consolidation is usually accomplished by using a vibrating screed or internal vibrator.

d. When manually striking off and leveling the concrete, use lumber or metal straightedge (called a screed). Rest the screed on edge on the top of the forms, tilt it forward and draw it across the concrete with a slight sawing motion. Maintain a head of concrete ahead of the screed to fill in any low spots. Do not use a jitterbug or vibrating screed with concrete slump that exceeds 3 inches (75 mm). Vibrating screeds should be moved rapidly to ensure consolidation but avoid working up an excessive layer of mortar on the surface. Do not overwork the surface during strike-off.

HOW to Finish Concrete

1. **LEVEL** the concrete surface using a bull float, darby, or highway straightedge soon after strike-off. This operation should be completed before bleed water appears on the surface. This operation should embed large aggregate, smooth the surface, and even out high and low spots. Keep the bull float as flat as possible to avoid sealing the surface prematurely
2. **WAIT** before starting subsequent finishing operations until the concrete has stopped *bleeding* and there is no water sheen on the surface. Any finishing operations done while the concrete is still bleeding or with water on the surface **will result** in surface defects, such as dusting, scaling, crazing, delamination and blisters. The waiting period depends on the setting and bleeding characteristics of the concrete and the ambient conditions. During the waiting period, protect against hot, dry and windy conditions that cause rapid evaporation from the concrete surface. Cover a small portion of the slab to check if it is still bleeding. Estimate set for final finishing operations when a footprint indentation on the slab is between ⅛ to ¼ inch (3 to 6 mm) deep.
3. **FLOAT** the concrete by hand or machine after bleeding has ceased. Floating embeds aggregates and levels and prepares the surface for further finishing.
4. **TROWEL** the concrete when required for its end use. Trowel finishes are more common for interior slabs For a smooth floor make successive passes with a smaller steel trowel and increased pressure. Repeated passes with a steel trowel will produce a smooth floor that will be slippery when wet. Excessive troweling may create dark *trowel burns*. Improperly tilting the trowel will cause an undesirable “chatter” texture. Exterior slabs typically require a textured finish. Trowel finishing of air-entrained concrete, like lightweight interior slabs, should be done with caution and proper timing. Rate of bleeding is slower for air entrained concrete and premature finishing will result in delamination and blisters.
5. **TEXTURE** the concrete surface as required after floating or troweling. For exterior concrete flatwork—sidewalks, patios, or driveways—texture the concrete surface after floating with a coarse or fine push-broom to give a non-slip surface. A swirl finish is used on some slabs. For interior flatwork texture the concrete surface after final troweling. Concrete can be finished with decorative treatments, such as exposed aggregate, dry shake color, integral color, and stamps or patterns. Decorative finishes need special procedures and experience.
6. **NEVER** sprinkle water or cement on concrete to facilitate finishing. This will cause dusting or scaling.
7. **EDGE** the concrete when required. Spade the concrete to break any bond with the form with a mason’s trowel. Use the edging tool to obtain durable rounded edges.
8. **JOINT** the concrete where required. Joints can be placed before concrete sets using a tool or saw cut after it has hardened. The blade of the jointing tool should be at least ¼ the depth of the slab. Use a straight piece of lumber as a guide. A shallow-bit groover should only be used for decorative grooves. Saw-cutting joints should be done as soon as the concrete is hard enough not to be torn by the blade. Early-entry saw cutting can be done before the concrete has completely hardened. See CIP 6.
9. **CURE** the concrete as soon as all finishing is completed to provide proper conditions for hydration of cementitious materials. Curing is essential to achieve the required strength and durability of the concrete surface. In severe conditions causing early drying, slab protection may be needed before finishing is complete. See CIP 11.
10. **AVOID** concrete burns to skin by following proper safety practices. Do not allow fresh concrete to come into contact with skin or eyes. Wear clothing, gloves and boots to protect against burns when working with fresh concrete. When concrete comes into contact with skin or eyes, wash off immediately with clean water.

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3. *Slabs on Grade, ACI Concrete Craftsman Series, CCS1*, American Concrete Institute, Farmington Hills, MI.
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Follow These Rules to Finish Concrete

1. Place and move concrete to its final location using procedures that avoid segregation.
2. Strike off and obtain an initial level surface without sealing the surface.
3. Wait until the bleed water disappears from the surface before starting finishing operations.
4. Use the appropriate surface texture as required for the application.
5. Avoid steel troweling air-entrained concrete or use appropriate cautions when required.
6. Cure the concrete to ensure it achieves the desired strength and durability.

1986, 1990, 2001, 2017

Concrete in Practice
What, why & how?
NRMCA

CIP 15 - Chemical Admixtures for Concrete

WHAT are Admixtures?

Admixtures are natural or manufactured chemicals added to the concrete before or during mixing. The most often used chemical admixtures are air-entraining agents, water reducers, water-reducing retarders, and accelerators.

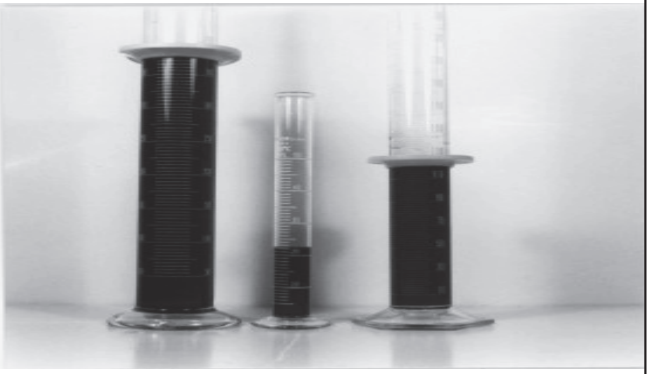
WHY Use Admixtures?

Admixtures are used to give special properties to fresh or hardened concrete. Admixtures may enhance the workability of fresh concrete and the durability strength of hardened concrete. Admixtures are used to overcome difficult construction situations, such as hot or cold weather placements, pumping requirements, early-age strength requirements, or specifications that require low water-cementitious materials ratio. Admixtures can be used to optimize the cementitious composition of concrete mixtures for performance and sustainability.

HOW to Use Admixtures?

Consult your ready mixed concrete supplier about admixture(s) appropriate for your application. Admixtures are evaluated for compatibility with cementitious materials, construction practices, job specifications and economic benefits before being used. Purchasers of ready mixed concrete should avoid requiring the use of specific brands or using products of their own accord.

Chemical Admixtures for Concrete



L to R: HRWR, Air-Entraining, Retarder
Relative quantities for one cu. yd.

Follow This Guide to Use Admixtures

1. **AIR-ENTRAINING ADMIXTURES** are liquid chemicals added when batching concrete to produce microscopic air bubbles, called entrained air, produced by the mixing action. These air bubbles improve the concrete's resistance to damage caused by exposure to cycles of freezing and thawing and deicing salt application. In fresh concrete entrained air improves workability and reduces bleeding and segregation. For exterior flatwork (parking lots, driveways, sidewalks, pool decks, patios) subject to freezing and thawing cycles, or in areas where deicer salts are used, an air content of 4% to 7% of the concrete volume is used depending on the size of coarse aggregate (see Table on next page). Air entrainment is not necessary for interior structural concrete since it is not subject to freezing and thawing. Entrained air should be avoided for concrete flatwork that will have a smooth troweled finish. In concretes with higher cementitious materials content, entrained air will reduce strength by about 5% for each 1% of air added; but in low cement content concretes, adding air has less effect and can reduce segregation and result in a modest increased strength due to the reduced water needed for required slump. Air entraining admixtures for use in concrete should meet the requirements of ASTM C260, *Specification for Air-Entraining Admixtures for Concrete*.
2. **WATER REDUCERS** are used for two different purposes: (1) to lower the water content in fresh concrete and to increase its strength; (2) to obtain higher slump without adding additional water. Water-reducers reduce the required water content of a concrete mixture for a target slump. These admixtures disperse the cement particles in concrete and make more efficient use of cement. This increases strength or allows the use of less cement to achieve a similar strength. Water-reducers are useful for pumping concrete and in hot weather, to offset the increased water demand. Some water-reducers may cause an increased rate of slump loss with time. Water-reducers should meet the requirements for Type A in ASTM C 494 *Specification for Chemical Admixtures for Concrete*.

   Mid-range water reducers are now commonly used and are used for a greater water reduction than typical water reducers. These admixtures are popular as they improve the finishability of concrete flatwork. Mid-range water reducers must at least meet the requirements for Type A in ASTM C494. There is separate classification for these products in ASTM C494.

3. **HIGH RANGE WATER REDUCERS (HRWR)** is a special class of water reducer. Often referred to as superplasticizers, HRWRs reduce the water content of a given concrete mixture between 12 and 40% to maintain the same slump. HRWRs are therefore used to increase strength and reduce permeability of concrete by reducing the water content in the mixture; greatly increase the slump to produce "flowing" concrete or self-consolidating concrete (CIP 37) by using less water. These admixtures are essential for producing high strength and high performance concretes that contain higher contents of cementitious materials and mixtures containing silica fume. Some HRWRs may cause a higher rate of slump loss with time. In some cases, HRWRs may be added at the jobsite in a controlled manner to provide the required slump for placement. HRWRs are covered by ASTM Specification C494. Types F and G, and Types 1 and 2 in ASTM C1017 *Specification for Chemical Admixtures for Use in Producing Flowing Concrete*.
4. **RETARDERS** are chemicals that delay the initial setting of concrete by an hour or more. Retarders are often used in hot weather to counter the rapid setting caused by high temperatures. For large jobs, or in hot weather, concrete with retarder allows more time for placing and finishing. Retarders are typically a component of water reducers. Retarders should meet the requirements for Type B or D in ASTM C494.
5. **ACCELERATORS** reduce the initial setting time of concrete and produces higher strength at early ages. Accelerators do not prevent concrete from freezing; rather, they speed up the setting to permit finishing concrete earlier; and increase the rate of strength gain, thereby making the concrete stronger to resist damage from freezing in cold weather. Accelerators are also used in fast track construction requiring early form removal, opening to traffic, or load application on structures. Liquid accelerators should conform to ASTM C494 Types C and E. There are two kinds of accelerating admixtures: chloride based and non-chloride based. Calcium chloride is a commonly used effective and economical accelerators, which is available in liquid or flake form. Calcium chloride must meet the requirements of ASTM D98. For non-reinforced concrete, calcium chloride can be used to a limit of 2% by the weight of the cement. Because of concerns with corrosion of reinforcing steel induced by chloride, lower limits on chlorides apply to reinforced concrete. Prestressed concrete and concrete with embedded aluminum or galvanized metal should not contain any chloride-based materials because of the increased potential for corrosion of the embedded metal. Non-chloride based accelerators are used where there is concern of corrosion of embedded metals or reinforcement in concrete.

Recommended Air Content in Concrete

Nominal max aggregate size, mm (in.)	Air Content, percent	
	Moderate Exposure	Severe Exposure
9.5 (⅜)	7.5	6
12.5 (½)	7	5.5
19.0 (¾)	6	5
25.0 (1)	6	4.5
37.5 (1½)	5.5	4.5

Moderate exposure - concrete in a cold climate will be only occasionally exposed to moisture prior to freezing and not exposed to deicing salt application.

Severe exposure - concrete in cold climate will be continuously in contact with water prior to freezing or where deicing salts are used.

Besides these standard types of admixtures, there are products available for enhancing concrete properties for a wide variety of applications. Some of these products include: corrosion inhibitors, shrinkage reducing admixtures, anti-washout admixtures, hydration stabilizing or extended set retarding admixtures, admixtures to reduce potential for alkali aggregate reactivity, pumping aids, permeability reducing admixtures, workability retaining admixtures, rheology and viscosity modifying admixtures and a variety of colors and products that enhance the aesthetics of concrete. Consult with your local ready mixed concrete producer on admixture products that add value to your project.

References

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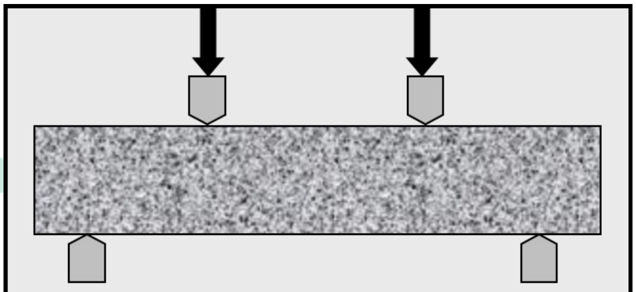
1987,1989, 2001, 2014

Concrete in Practice
What, why & how?
NRMCA

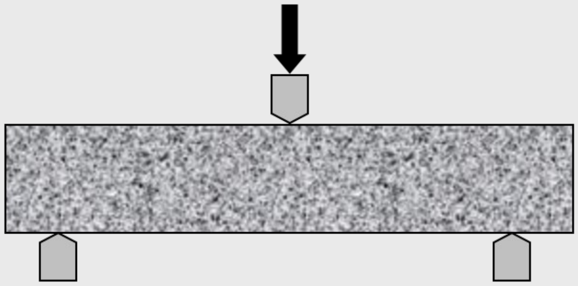
CIP 16 - Flexural Strength of Concrete

WHAT is Flexural Strength

Flexural strength is an indirect measure of the tensile strength of concrete. It is a measure of the maximum stress on the tension face of an unreinforced concrete beam or slab at the point of failure in bending. It is measured by loading 6 x 6-inch (150 x 150-mm) concrete beams with a span length at least three times the depth. Smaller beam specimens of cross-section 4 x 4-inch (100 x 100-mm) are also recognized as a standard size. The flexural strength is expressed as *Modulus of Rupture* (MR) in psi (MPa) and is determined by standard test methods ASTM C78 (third-point loading) or ASTM C293 (center-point loading). The specimen size and type of loading does impact the measured flexural strength and comparisons or requirements should be based on the same beam size and loading configuration. The MR measured by third-point loading (ASTM C78) is lower than that determined by center-point loading (ASTM C293), sometimes by as much as 15 percent. It is also observed that a lower flexural strength will be measured with larger beam specimens.



ASTM C78 - Third-Point Loading - the load is applied at two points at one-third of the span length. Maximum stress occurs over the center 1/3 portion of the beam



ASTM C293 - Center-Point Loading - the load is applied at the center of the span. The maximum stress occurs at the center of the beam under the load location.

Flexural strength is about 10 to 15 percent of compressive strength depending on the mixture proportions and type, size and volume of coarse aggregate used. For design of building members an estimate of the MR is obtained by:

$$f_r = 7.5\sqrt{f'_c}$$, where

f_r is the MR; f'_c is the specified compressive strength

When MR is critical to design, the best estimate is established from laboratory tests for specific mixtures and materials used.

WHY Measure Flexural Strength

Design of the thickness of concrete pavements are based on the flexural strength or MR. Factors include traffic loading and subgrade stiffness. Pavement designers often require validation that the proposed mixture will achieve the MR used in design. Concrete mixtures should be proportioned to achieve the MR as specified in contract documents. When acceptance in the field will be based on flexural strength tests, the concrete mixture should be appropriately designed to achieve a higher strength level that will reduce the risk of failing test results. Agencies that do not use MR for field contrl generally use compressive strength as it is more convenient and reliable to judge the quality of concrete as delivered. A pre-established relationship between compressive and flexural strength may be developed for this purpose. Flexural strength testing is not used for structural concrete.

HOW is Flexural Strength Used

Flexural strength is conservatively neglected in calculating the nominal flexural strength for design of structural members. The flexural strength, estimated from the empirical relationship, is used estimate the tensile stress that causes cracking of non-reinforced concrete and to evaluate deflections at service loads.

Most state highway agencies use compressive strength and not flexural strength tests for acceptance testing of road pavements. Flexural strength tests are useful in research and laboratory evaluation of mixtures, but the sensitivity to testing variations does not lend itself to be used as a basis for acceptance or rejection of concrete in the field. Flexural strength tests for jobsite acceptance is commonly used for airfield pavements.

Beam specimens must be prepared in accordance with ASTM C192 in the laboratory and ASTM C31 in the field. Consolidate by rodding or vibration, tap sides to release air pockets, and spade along the sides. Follow the temperature and moisture retention requirements for standard curing. *Never allow the beam surfaces to dry at any time.* Immerse in saturated limewater for at least 20 hours before testing.

Specifications and investigation of apparent low strengths should take into account the higher variability of flexural strength testing. Standard deviation for concrete flexural strength tests from subsequent loads for projects with good control range from about 40 to 80 psi (0.3 to 0.6 MPa). Standard deviation values exceeding 100 psi (0.7 MPa) may indicate problems with testing.

Where a correlation between flexural and compressive strength has been established, compressive strength of cores determined in accordance with ASTM C42 can be used. Reduced strength measured on cores should be taken into account. Sawing beams for flexural strength tests will show a greatly reduced measured flexural strength and should not be done. Splitting tensile strength of cores by ASTM C496 is sometimes used, but experience is limited.

Another procedure for in-place strength investigation uses compressive strength of cores calibrated by comparison with acceptable placements in proximity to the concrete in question:

Method to Estimate Flexural Strength Using Compressive Strength of Acceptable Lots

	Lot 1	Lot 2	Lot 3
MR, psi	730 (OK)	688 (?)	731 (OK)
Core, psi	4492	4681	4370

Estimated Flexural Strength of Lot 2 =

$$4681 \times \frac{(730 + 731)}{(4492 + 4370)} = 771 \text{ psi (OK)}$$

WHAT are Problems with Flexural Tests

Flexural tests are extremely sensitive to specimen preparation, handling, and curing procedures. Beam specimens are heavy and can be damaged during handling and transportation. Beams must be cured in a standard manner and tested while wet. *A short period of drying can produce a sharp drop in flexural strength.* Meeting all these requirements on a jobsite is extremely difficult and often result in unreliable and generally low MR test results.

NRMCA, the Portland Cement Association (PCA), and the American Concrete Pavement Association (ACPA) support the use of compressive strength testing as the preferred method of concrete acceptance. ACI Committees 325 and 330 on concrete pavement construction and design also point to the use of compressive strength tests as more convenient and reliable.

The concrete industry and inspection and testing agencies are much more familiar with traditional cylinder compressive strength tests for control and acceptance of concrete. Flexural strength can be used for design, but the compressive strength established by a correlation with laboratory trial batches or empirical relationships should be for quality assurance and acceptance of concrete.

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1989, 2000, 2016

Concrete in Practice
What, why & how?
NRMCA

CIP 17 - Flowable Fill

WHAT is Flowable Fill

Flowable fill is a self-consolidating and self-leveling low strength cementitious material with a flowable consistency that is used as an economical fill as an alternative to compacted granular fill. Flowable fill is not concrete nor is it used to replace concrete. For design purposes its characteristics should be evaluated like soil or other fill materials. Terminology used by ACI Committee 229 is *Controlled Low Strength Material (CLSM)*. Other terms used are unshrinkable fill, controlled density fill, soil-cement slurry, flowable mortar, or lean-mix backfill.

The flowability is such that it can be placed with minimal effort, flow to fill the space, and not require consolidation after it is placed. It hardens to provide required bearing capacity or filling of voids with minimal subsidence or loss of volume.

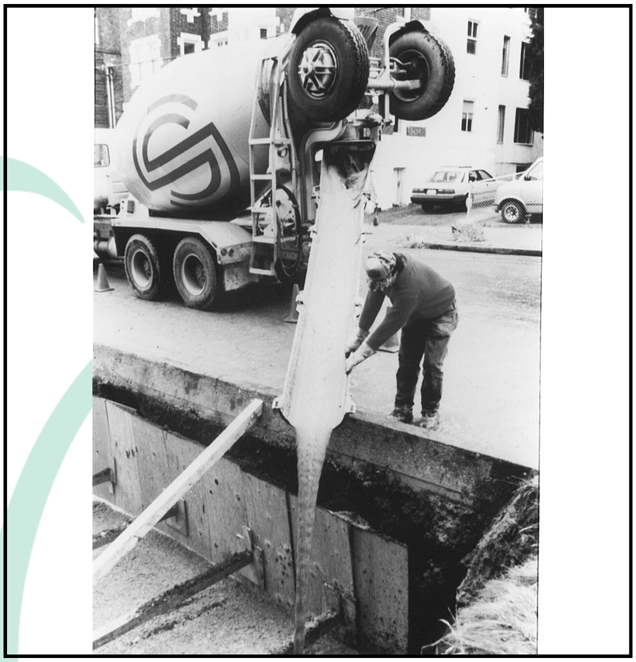
Flowable fill is defined as a material with compressive strength less than 1200 psi (8.3 MPa). Most applications, however, use mixtures with strength less than 300 psi (2.1 MPa). The ability to excavate flowable fill will depend on the equipment used for the strength and type of mixture placed.

WHY is Flowable Fill Used

Flowable fill is an economical alternative to compacted granular fill affording savings in labor, equipment, and time. Because manual compaction is not needed, trench width or the size of excavation is significantly reduced and personnel do not need to enter an excavation. It provides a solution for filling inaccessible areas, such as underground tanks, where compacted fill cannot be placed.

Uses of Flowable Fill include:

1. BACKFILL—sewer trenches, utility trenches, bridge abutments, conduit encasement, pile excavations, retaining walls, and road cuts.
2. STRUCTURAL FILL—foundation sub-base, sub-footing, floor slab base, durable pavement bases, and conduit bedding.
3. OTHER USES—abandoned mines, underground storage tanks, wells, abandoned tunnel shafts and sewers, basements and underground structures, voids under pavement, erosion control, and thermal insulation with high air content flowable fill.



   Mixtures can be developed for anti-corrosion, thermal resistance, electrical conductivity, and low permeabilility.

HOW is Flowable Fill Ordered

State the intended use and the expectation of future excavation of flowable fill when specifying or ordering the material. Flowable fill can use materials that do not comply with standards for use in concrete. Economical and recycled materials can be used. Site-excavated materials can be incorporated in flowable fill mixtures. Low-density flowable fill incorporates high air content with admixtures and pre-formed foam.

Strength—Strength will depend on bearing capacity required by design. In this regard, flowable fill is superior to compacted fill. The ultimate strength of the flowable fill should not exceed 200 psi (1.4 MPa) to be excavated with equipment like backhoes. Mixtures with coarse aggregate are more difficult to excavate. Low-density flowable fill limits strength gain and can be easily excavated. Flowable fill with a compressive strength of 50 to 100 psi (0.3 to 0.7 MPa) provides bearing capacity similar to well-compacted soil.

Hardening Time and Early Strength is important to support equipment, traffic, or construction loads and to schedule subsequent construction. ASTM C403 or ASTM D6024 may be used to estimate hardening time. A requirement for higher early-age strength may make later excavation difficult due to continued gain in strength.

In-Place density of flowable fill is in the range of 115 to 145 lb/ft^3 (1800 to 2300 kg/m^3), typically higher than that of compacted fills. Low-density fill can be used for applications that need reduced dead load, thermal insulation, or to limit higher strength.

Flowability should be such that the mixture will flow into place without additional consolidation. Flowability can be varied to suit placement requirements of the application. Hydrostatic pressure and floatation of pipes should be addressed by placing in lifts and appropriate anchorage, respectively.

Subsidence of flowable fill mixtures with high water content is on the order of 1/4 in. per ft. (20 mm per m) of depth as the solid materials settle. Low-density flowable fill with less water has minimal subsidence.

Settlement—Flowable fill will generally not settle under load after hardening.

Permeability of flowable fill can be varied to suit the application. The permeability of flowable fill is similar to or lower than compacted fill.

Durability—Flowable fill materials should not be expected to resist cycles of freezing and thawing, abrasive or erosive actions, or aggressive chemicals; If flowable fill deteriorates in place it will continue to function like a granular fill. The pH of flowable fill can protect embedded metal from corroding, depending on the cementitious materials used.

HOW is Flowable Fill Delivered and Placed

Flowable fill is delivered by ready mixed concrete trucks and placed via the chute directly into the space or cavity to be filled. The mixer drum is kept in agitating mode to maintain a homogenous mixture prior to discharge. Flowable fill can be conveyed by pump, chutes. or buckets to its final location. Mixtures with granular material can be pumped more effectively. Due to its fluid consistency it can flow long distances from the point of placement.

Flowable fill does not need to be cured like concrete but should be protected from freezing until it has hardened.

References

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TESTING FLOWABLE FILL

Quality assurance testing is typically not necessary for flowable fill mixtures. Visual checks of mixture consistency and performance have proven adequate. Test methods and acceptance criteria for concrete are not applicable. When testing is needed, the following applies:

- Obtain samples of flowable fill in accordance with ASTM D5971.
- Flow consistency is measured in accordance with ASTM D6103. A spread diameter of at least 8 in. without visible segregation indicates good flowability. Mixtures without coarse aggregate can be tested using the flow cone method, ASTM C939. An efflux time of 10 to 26 sec is generally recommended.
- Density (unit weight), yield, and air content of flowable fill are measured by ASTM D6023.
- Preparing and testing cylinders for compressive strength tests is described in ASTM D4832. Use 3 x 6 in. (75 x 150 mm) plastic cylinder molds, fill to overflowing and then tap sides lightly. Other sizes and types of molds may be used provided the length-to-diameter ratio is at least 2. Cure cylinders in the molds (covered) until time of testing (or at least 14 days). Strip carefully using a knife to cut plastic mold off. Capping with sulfur mortar can damage these low strength specimens. Neoprene caps have been used but high strength gypsum plaster seem to work best.
- Penetration resistance tests such as ASTM C403 may be useful in judging the hardening time and strength development. Penetration resistance numbers of 500 to 1500 indicate adequate hardening. A penetration value of 4000, roughly equivalent to 100 psi (0.7 MPa) compressive strength measured on cylindrical specimens, is greater than the bearing capacity of most compacted soil. In-place hardening can be evaluated using the ball drop test, ASTM D6024. A diameter of indentation of less than 3 in. (75 mm) is considered adequate for most load applications. A mixture-specific relationship between compressive strength and penetration resistance can be developed for easier assessment of hardening.

CAUTIONS

1. Flowable fill while fluid will exert fluid pressure against forms, embankment, or walls used to contain the fill.
2. Placement of flowable fill around and under tanks, pipes, or large containers can cause the these items to float or shift.
3. In-place fluid flowable fill should be covered or cordoned off for safety reasons.

1989, 2000, 2016

Concrete in Practice

What, why & how?

NRMCA

CIP 18 - Radon Resistant Buildings

WHAT is Radon?

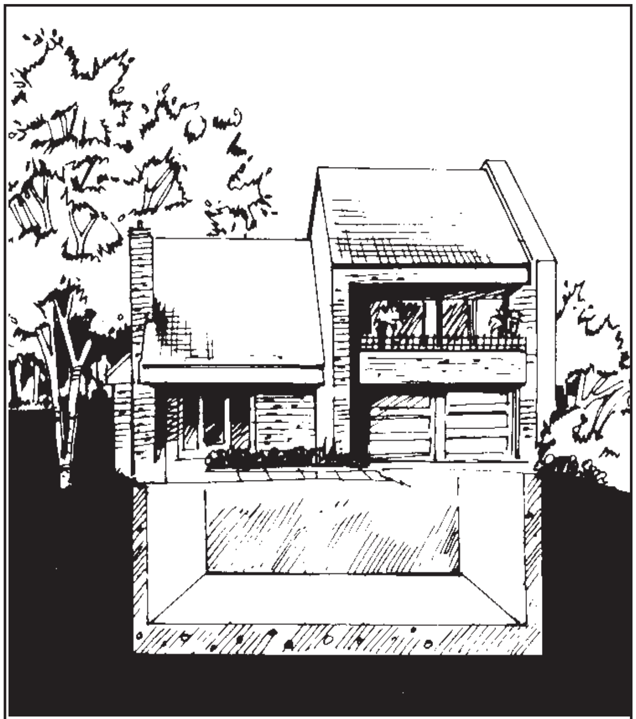
Radon is a colorless, odorless, radioactive gas which occurs naturally in soils in amounts dependent upon the geology of the location. The rate of movement of radon through the soil is dependent primarily upon soil permeability and degree of saturation, and differences in air pressure within the soil. Soil gas enters buildings through cracks or openings in the foundation, slab, or basement walls when the air pressure in the building is less than that of the soil.

Radon gas decays to other radioactive elements in the uranium series. Called "radon progeny," they exist as solid particles rather than as a gas.

WHY be Concerned About Radon Levels in Buildings?

The concern is due to an association with the development of lung cancer. Radon progeny can become attached to dust particles in the air. If inhaled, they can lodge in the lung. Energy emitted during radioactive decay while in the lung can cause tissue damage, which has been linked to lung cancer.

The level of health risk associated with radon is related to the concentration of radon in the air and the time a person is exposed to that air. The U.S. Environmental Protection Agency (EPA) has developed a risk profile for radon exposure at various concentrations, and established an action level concentration above which efforts should be made to reduce radon levels.[1] It is prudent to take measures during construction which will reduce the amount of radon entering a building.



Eliminate Entry Routes for Soil Gases by Proper Jointing, Sealing, and (When Necessary) Venting.

HOW to Construct Radon Resistant Concrete Buildings?

Solid concrete is an excellent material for use in constructing radon resistant buildings. It is an effective barrier to soil gas penetration if cracks and openings are sealed.

Solid concrete slabs and basement walls are commonly used in residential buildings. Buildings resistant to radon may be easily constructed with concrete. In concrete construction, the critical factor is to eliminate all entry routes through which gases can flow from the soil into the building.

The construction of radon resistant buildings requires adhering to accepted construction practices with attention to a few additional details. In instances where high radon levels are expected, installation of a sub-slab ventilation system incorporating an open-graded aggregate base beneath the slab may be warranted during construction. These systems provide a positive means of evacuating soil gas from beneath the slab, diverting it directly to the outside.[2,3]

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Follow these Guidelines to Reduce Radon Entry

1. Design to minimize utility openings. Sump openings should be sealed and vented outdoors.[2]
2. Minimize random cracking by using control and isolation joints in walls and floors. Planned joints can then be easily sealed.[5] If done properly, any cracks will occur at the joints and can be easily sealed.
3. Monolithic slab foundations are an effective way to minimize radon entry.[2,4,6] For slab on grade homes in warm climates, pour foundation and slab as a single monolithic unit.
4. Use materials which will minimize concrete shrinkage and cracking (larger aggregate sizes and proper water-cementitious ratio).
5. When using polyethylene film beneath the slab, place a layer of sand over the polyethylene. See CIP 5 and 7.
6. Remove grade stakes after striking off the slab. (If left, they can provide entryways through the slab.)[2]
7. Construct the joints to facilitate caulking.[5]
8. Cure the concrete adequately. See CIP 11.
9. Caulk and seal all joints and openings in the walls or floor. (If cracks occur, they should be widened, and then caulked and sealed.)[2,3]

1982, 1989 AND 2000

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CIP 19 - Curling of Concrete Slabs

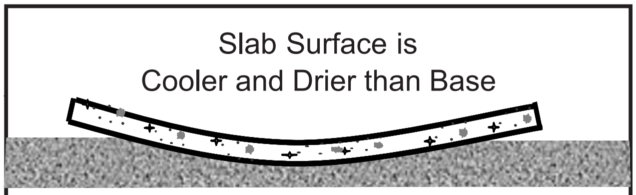
WHAT is Curling?

Curling is the distortion of a slab into a curved shape by upward or downward bending of the edges. The occurrence is primarily due to differences in moisture and/or temperature between the top and bottom surfaces of a concrete slab. The distortion can lift the edges or the middle of the slab from the base, leaving an unsupported portion. The slab section can crack when loads exceeding its capacity are applied. Slab edges might chip off or spall due to traffic when the slab section curls upwards at its edges. In most cases, curling is evident at an early age. Slabs may, however, curl over an extended period.

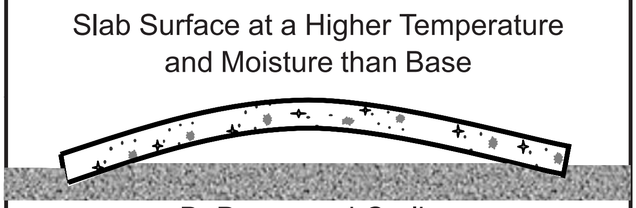
WHY do Concrete Slabs Curl?

Changes in slab dimensions that lead to curling are most often related to moisture and temperature gradients in the slab. When one surface of the slab changes size relative to the other, the slab will warp at its edges in the direction of relative shortening. This curling is most noticeable at the sides and corners. One primary characteristic of concrete that affects curling is drying shrinkage. Anything that increases drying shrinkage of concrete will tend to increase curling.

The most common occurrence of curling is when the top surface of the slab dries and shrinks with respect to the bottom. This causes an upward curling of the edges of a slab (Figure 1A). Curling of a slab soon after placement is most likely related to poor curing and rapid surface drying. In slabs, excessive bleeding due to high water content in the concrete or water sprayed on the surface; or a lack of surface moisture due to poor or inadequate curing can create increased surface drying shrinkage relative to the bottom of the slab. Bleeding is accentuated in slabs placed directly on a vapor retarder (polyethylene sheeting) or when topping mixtures are placed on concrete slabs. Shrinkage differences from top to bottom in these cases are larger than for slabs on an absorptive subgrade.



A. Upward Curling – Typical in Internal Slabs



B. Downward Curling

Curling of Concrete Slabs

Thin slabs and long joint spacing tend to increase curling. For this reason, thin unbonded toppings need to have a fairly close joint spacing.

In industrial floors, close joint spacing may be undesirable because of the increased number of joints and increased joint maintenance problems. However, this must be balanced against the probability of intermediate random cracks and increased curling at the joints.

The other factor that can cause curling is temperature differences between the top and bottom of the slab. The top part of the slab exposed to the sun will expand relative to the cooler bottom causing a downward curling of the edges (Figure 1B). Alternately, during a cold night when the top surface cools and contracts relative to the bottom surface in contact with a warmer subgrade, the curling due to this temperature differential will add to the upward curling caused by moisture differentials.

HOW to Minimize Slab Curling?

The primary factors controlling dimensional changes of concrete that lead to curling are drying shrinkage, construction practices, moist or wet subgrades, and day-night temperature cycles. The following practices will help to minimize the potential for curling:

1. Use the lowest practical water content in the concrete.
2. Use the largest practical maximum size aggregate and/or the highest practical coarse aggregate content to minimize drying shrinkage.
3. Take precautions to avoid excessive bleeding. In dry conditions place concrete on a damp, but absorptive, subgrade so that all the bleed water is not forced to the top of the slab. This may not be appropiate for interior slabs on which a moisture sensitive floor covering would be placed.
4. Avoid using polyethylene vapor retarders unless covered with at least four inches (100 mm) of a trimable, compactible granular fill (not sand). If a moisture-sensitive floor covering will be placed on interior slabs, the concrete will generally be placed directly on a vapor retarder (see CIP29) and other procedures may be necessary.
5. Avoid a higher than necessary cement content. Use of pozzolan or slag is preferable to very high cement content.
6. Cure the concrete thoroughly, including joints and edges. If membrane-curing compounds are used, apply at twice the recommended rate in two applications at right angles to each other.
7. When minimizing curling is critical, use a joint spacing not exceeding 24 times the thickness of the slab.
8. For thin toppings, clean the base slab to ensure bond and consider use of studs and wire around the edges and particularly in the slab corners.
9. Use a thicker slab, or increase the thickness of the slab at edges.
10. The use of properly designed and placed slab reinforcement may help reduce or eliminate curling. Load transfer devices that minimize vertical movement should be used across construction joints.
11. Certain types of breathable sealers or coatings on slabs can work to minimize moisture differentials and reduce curling.

When curling in a concrete slab application cannot be tolerated alternate options include the use of shrinkage reducing admixtures, shrinkage-compensating concrete, post tensioned slab construction or vacuum dewatering. These options should be decided before the construction and could increase the initial cost of the project.

Some methods of remedying slab curling include ponding the slab to reduce curl followed by sawing additional contraction joints, grinding slab joints where curling has occurred to restore serviceability and injecting a grout to fill voids under the slab to restore support and prevent break-off of uplifted edges.

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1990, 2002, 2004

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CIP 20 - Delamination of Troweled Concrete Surfaces

WHAT are Delaminations?

In most delaminated concrete slab surfaces, the top 1/8 to ¼ inch (3 to 6 mm) is densified, primarily due to premature and improper finishing, and separated from the base slab by a thin layer of air or water. The delaminations on the surface of a slab may range in size from several square inches to many square feet. The concrete slab surface may exhibit cracking and color differences because of rapid drying of the thin surface during curing. Traffic or freezing may break away the surface in large sheets. Delaminations are similar to blisters, but much larger (see CIP 13).

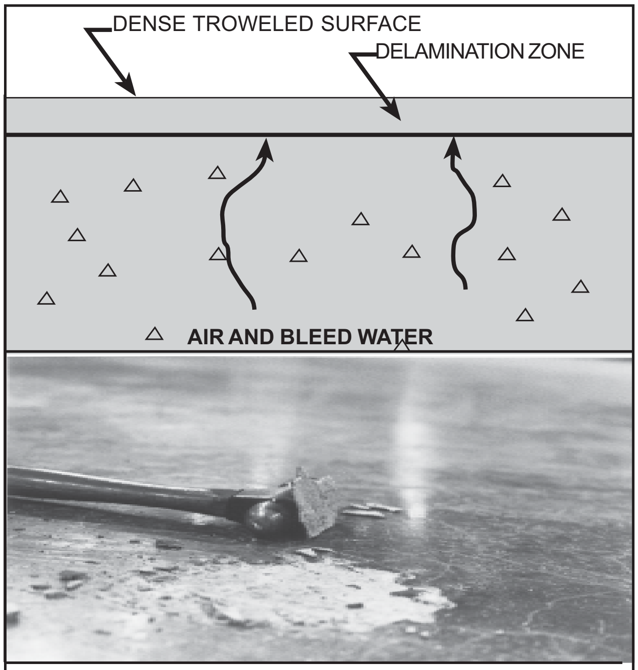
Delaminations form during final troweling. They are more frequent in early spring and late fall when concrete is placed on a cool subgrade with rising daytime temperatures, but they can occur at anytime depending on the concrete characteristics and the finishing practices used.

Corrosion of reinforcing steel near the concrete surface or poor bond between two-course placements may also cause delaminations (or spalling). The resulting delaminations are generally thicker than those caused by improper finishing.

Delaminations are difficult to detect during finishing but become evident after the concrete surface has set and dried. Delaminations can be detected by a hollow sound when tapped with a hammer or with a heavy chain drag. A procedure is described in ASTM D 4580, *Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding*. More sophisticated techniques include acoustic impact echo and ground-penetrating radar.

WHY does Delamination Occur?

Bleeding is the upward flow of mixing water in plastic concrete as a result of the settlement of the solids. Delamination occurs when the fresh concrete surface is sealed or densified by troweling while the underlying concrete is still plastic and continues to bleed and/or to release air. Delaminations form fairly late in the finishing process after floating and after the first troweling pass. They can, however, form during the floating operation if the surface is overworked and densified. The chances for delaminations are greatly increased when conditions promote rapid drying of the surface (wind, sun, or low humidity). Drying and higher temperature at the slab surface makes it appear ready to trowel while the underlying concrete is plastic and can still bleed or release air. Vapor retarders placed directly under slabs force bleed water to rise and compound the problem.



Delaminated Concrete

Factors that delay initial set of the concrete and reduce the rate of bleeding will increase the chances for delaminations. Entrained air in concrete reduces the rate of bleeding and promotes early finishing that will produce a dense impermeable surface layer. A cool subgrade delays set in the bottom relative to the top layer.

Delamination is more likely to form if:

1. The underlying concrete sets slowly because of a cool subgrade.
2. The setting of the concrete is retarded due to con-

crete temperature or mixture ingredients.

3. The concrete has entrained air or the air content is higher than desirable for the application.
4. The concrete mixture is sticky from higher cementitious material or sand-fines content.
5. Environmental conditions during placement are conducive to rapid drying causing the surface to "crust" and appear ready to finish.
6. Concrete is excessively consolidated, such as the use of a jitterbug or vibrating screed that brings too much mortar to the surface.
7. A dry shake is used, particularly with air-entrained concrete.
8. The slab is thick.
9. The slab is placed directly on a vapor retarder.

Corrosion-related delaminations are formed when the upper layer of reinforcing steel rusts thereby breaking the bond between the steel and the surrounding concrete. Corrosion of steel occurs with reduced concrete cover and when the concrete is relatively more permeable causing chlorides to penetrate to the layer of the steel (See CIP 25).

HOW to Prevent Delamination?

Accelerators or heated concrete often prevent delamination in cool weather.

Be wary of a concrete surface that appears to be ready to trowel before it would normally be expected. Emphasis in finishing should be on screeding, straight-edging, and floating the concrete as rapidly as possible—without working up an excessive layer of mortar and without sealing the surface layer. In initial floating, the float blades should be flat to avoid densifying the surface too early.

Final finishing operations to produce a smooth surface should be delayed as long as possible, and the surface covered with polyethylene or otherwise protected from evaporation.

Delamination may be difficult to detect during finishing operations. If delamination is observed, tear the surface with a wood float and delay finishing as long as possible. Any steps that can be taken to slow evaporation should help.

If a vapor retarder is required, place at least four inches (100 mm) of a trimable, compactible granular fill (not sand). Do not place concrete directly on a vapor retarder. If a moisture-sensitive floor covering will be placed on interior slabs, concrete will generally be placed directly on a vapor retarder (see CIP 29), and other procedures may be necessary.

Do not use air-entrained concrete for interior floor slabs that have a hard troweled surface and that will not be subject to freeze-thaw cycles or deicing salt application. If entrained air is necessary to protect interior slabs from freezing and thawing cycles during construction avoid using air contents over 3%.

Delaminated surfaces can be repaired by patching after the surface layer is removed and the underlaying concrete is properly cleaned. Extensive delamination may need to be repaired by grinding and overlaying a new surface. Delaminated surfaces due to steel corrosion will additionally require sandblasting to remove rust from the steel.

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Follow These Rules to Avoid Delamination

1. Do not seal surface early—before air or bleed water from below have escaped.
2. Avoid dry shakes on air-entrained concrete.
3. Use heated or accelerated concrete to promote even setting throughout slab depth.
4. Avoid placing concrete directly on vapor retarders, if the application allows.
5. Do not use air-entrained concrete for interior slabs that will receive a trowel finish.
6. Avoid placing concrete on substrate with a temperature of less than 40° F (4° C).

1992, 2002, 2004

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CIP 21 - Loss of Air Content in Pumped Concrete

WHAT is Air Loss in Pumping?

Increasingly, specifiers are requiring concrete to be tested for air content at the discharge end of concrete pumps at the point of placement in the concrete structure. In some cases it is observed that air contents are much lower than that in samples tested at discharge from the truck chute. It is normal to find a loss of about 0.5 to 1.0 percent air as concrete is conveyed through a pump. However, with long boom pumps have the boom in an orientation with a long, near vertical downward section of pipe, the air content at discharge may be less than half of that of the concrete going into the pump hopper. When the boom is upward or horizontal, or if there is a 12-ft (3.6-m) section of rubber hose placed horizontally at the discharge end, there generally is no significant loss of air. Certainly, air loss through a pump doesn't occur every time. However, it does occur often enough to be considered seriously until better solutions are developed.

WHY is Air Lost?

There are several mechanisms involved, but air loss will occur if the weight of concrete in a vertical downward section of pipe is sufficient to overcome frictional resistance to allow a slug of concrete to slide down the pipe. As the slug of concrete slides down the pipe, it develops a vacuum on the upper end that greatly expands the size of the air bubbles; and when the concrete hits an elbow in the boom or a horizontal surface, the bubbles collapse. The effect of this impact can be demonstrated by dropping concrete 15 or 20 ft (4.5 to 6 m). The loss of air can be further exacerbated due to the transition from a high pressure in the pump to a near vacuum condition in the pump line.

Most field experience suggests that air loss is greatest with high cement content, flowable concrete mixtures which slide down easier; however, air loss has also been experienced in mixtures with a moderate cement factor at about 500 lb/yd^3 (300 kg/m^3) and moderate slump. Loss of air content in pumped concrete will not reduce freeze thaw durability of concrete as long as the air void system is not compromised.

Figure 1: A vertical pump boom configuration can result in loss of entrained air in concrete

The air loss due to pumping can be determined by measuring the air content of samples discharged from the ready mixed concrete truck and at discharge from the pump. Testing concrete as discharged from the pump alongside the pump will require the most critical boom configuration that will cause the highest loss of air content. If concrete at a higher air content, to compensate for this loss, is placed at a less critical, more horizontal boom configuration, the concrete placed in the structure will be at a high air content and lower strength.

HOW to Prevent Air Loss?

To minimize the loss of air of concrete through a pump procedures should attempt to keep concrete from sliding down the line under its own weight. Ensure that there si a continuous stream of concrete within the pump and inside the pumpline. Where possible, avoid vertical or steep downward boom sections. Be cautious with high slump, and particularly with high cementitious content mixtures. Steady, moderately rapid pumping may help somewhat to minimize air loss, but will not solve most problems.

a) Try inserting a loop in the pipeline just before the rubber hose. *(Do not* do this unless pipe clamps are designed to comply with *all safety requirements).* This method helps, but won't be a perfect solution. In some cases it may cause an increase in the air content.

b) Use a slide gate at the end of the rubber hose to restrict discharge and provide resistance.

c) Use of a 6-ft. (2-m) diameter loop in the rubber hose with an extra section of rubber hose is reported to be a better solution than (a) or (b).

d) Lay 10 or 20 ft. (3 to 6 m) of hose horizontally on deck pours. This doesn't work in columns or walls and requires additional labor to manage the extra hose.

e) Reduce the rubber hose size from 5 to 4 in. (125 to 100 mm). A transition pipe of length 4 feet (1.2 m) or longer should be used to avoid blockages.

Figure 2: Loop in pump boom

PRECAUTIONS

Conduct a pre-pour conference in accordance with the agenda outlined in CIP 32 with the contractor, pump operator, and ready mixed concrete supplier present. Discuss the necessity for care in pumping air entrained concrete, and list the precautions to take when pumping air-entrained concrete. Maintain communication between all parties during the placement process.

a) Before the pour, plan alternative pump locations and decide what will be done if air loss occurs. Be prepared to test for air content frequently.

b) Sampling from the end of a pump line can be very difficult and potentially hazardous. Wear proper personal protective equipment. Never sample the initial concrete through the pump line. It is recommended that sampling be done from the concrete placed in the structure as opposed to the end of a pump line.

c) Sample the first load on the job after pumping 3 or 4 cubic yards (2 to 3 m^3). Temper it to the maximum permissible slump. Swing the boom over near the pump to get the maximum length of vertical downward pipe and drop the sample in a wheel barrow. If air is lost, take precautions and sample to measure air content at the point of placement.

d) If air loss occurs, do not try to solve the problem by increasing the air content delivered to the pump beyond the upper specification limit. High air content concrete with low strength could, or almost surely will, be placed in the structure if boom angles are reduced or somewhat lower slump concrete is pumped.

e) Research has indicated that when the loss of air content is not too high (less than about 3%), the air void system in the concrete may still be adequate for freeze-thaw resistance of concrete. This is because most of the air lost is the larger air bubbles that do not significantly affect the durability of concrete.

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1992, 2005

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CIP 22 - Grout

WHAT is Grout?

ACI defines grout as "a mixture of cementitious material and water, with or without aggregate, proportioned to produce a pourable consistency without segregation of the constituents." Grout may also contain fly ash, slag, and liquid admixtures.

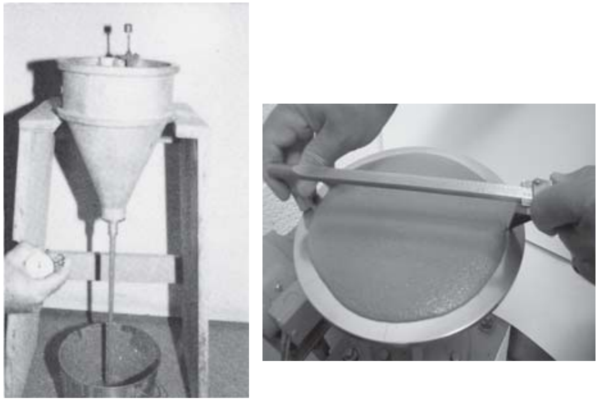
The terms grout and mortar are frequently used interchangeably but there are clear distinctions. *Grout* need not contain aggregate whereas *mortar* contains fine aggregate. *Grout* is supplied in a pourable consistency whereas *mortar* is not. *Grout* fills space whereas *mortar* bonds elements together, as in masonry construction.

Grout is often identified by its application. Some examples are: bonded prestressed tendon grout, auger cast pile grout, masonry grout, and pre-placed aggregate grout. Controlled low strength material (flowable fill) is a type of grout.

WHY is Grout Used?

Grout is used to fill space or cavities and provide continuity between building elements. In some applications, grout will act in a structural capacity, such as in reinforced masonry construction. In building construction, grout can improve fire ratings, acoustic performance, blast resistance and improve the thermal mass properties of the building elements.

In projects where small quantities of grout are required, it is proportioned and mixed on site. The ready mixed concrete producer is generally called upon when large quantities are needed.



Flow Cone **Flow Table**

HOW to Specify Grout?

For masonry grout, ASTM C 476 provides prescribed proportions by loose volumes that are convenient for small quantities of grout mixed on site. Alternatively ASTM C 476 has provisions for establishing grout proportions on the basis of specified compressive strength. The specified compressive strength must be at least 2000 psi. Grout mixtures meeting the proportion table of ASTM C 476 have high cement contents and tend to produce much higher strengths[4] than specified compressive strength requirements of ASTM C 476, ACI 530 or Model Codes. Two types of masonry grouts are defined in ASTM C 476: fine grout with aggregates smaller than 3/8 inch (9.9 mm) and coarse grout that allows aggregate sizes up to 1/2 inch (12.5 mm). Choice of grout type depensions primarily on the clear dimensions of the space being filled by the grout. Grouting of masonry construction should comply with the governing building code provisions. Information on grouts for masonry construction is available from the National Concrete Masonry Association (NCMA).

When grout is ordered from a ready mixed concrete producer, the specifications should be based on consistency and compressive strength. Converting loose volume proportions into batch weights per cubic yard is subject to errors and can lead to controversies on the job.

Specifications should address the addition of any required admixtures for grout. Conditions of delivery, such as temperature, time limits, and policies on job site addition of water, should be specified. The contractor will need to ensure that the grout consistency is sufficiently flowable. Testing frequency and methods of acceptance must be covered in specifications.

HOW to Test Grout?

The consistency of grout affects its strength and other properties. It is critical that grout consistency permit the complete filling of void space without segregation of ingredients.

Consistency of masonry grout may be measured with a slump cone (ASTM C 143), and slumps of 8-11 in. are generally required for both fine and coarse grout. Self consolidating grout is a highly fluid and stable grout mix that does not require consolidation. These grouts are tested using the slump flow test, ASTM C 1611, that measures the spread of the grout using the slump cone.

For other types of grouts without aggregate, or only fine aggregate passing a No. 8 sieve, consistency is best determined with a flow cone (ASTM C 939). For flow values exceeding 35 seconds, use the flow table in ASTM C 109, modified to use 5 drops in 3 seconds.

Masonry grout ("blockfill") for strength tests specimens should be cast in molds formed by masonry units having the same absorption characteristics and moisture content as the units used in construction (ASTM C 1019). Never use nonabsorbent cube or cylinder molds for this purpose.

Strength of other types of grout is determined using 2 in. cubes per ASTM C 942. Method C 942 allows for field preparation, recognizes fluid consistency, and also affords a means for determining compressive strength of grouts that contain expansive agents or grout fluidifiers. This is extremely important since "expansive" grouts can lose substantial compressive strengths if cubes are not confined. However, cylindrical specimens (6 x 12 in. or 4 x 8 in.), may give more reliable results for grouts containing coarse aggregate.

Special application grouts often require modification of standard test procedures. All such modifications should be noted in the specifications and discussed prior to the start of the job.

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1993, 2005

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CIP 23 - Discoloration

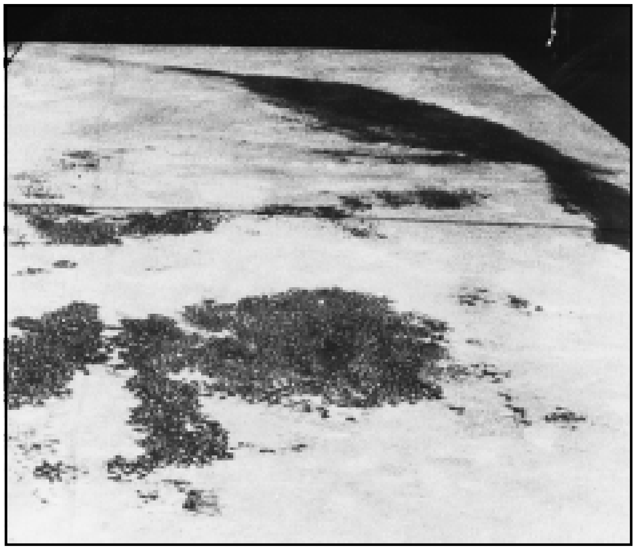
WHAT is Discoloration?

Surface discoloration is the non-uniformity of color or hue on the surface of a single concrete placement. It may take the form of dark blotches or mottled discoloration on flatwork surface, gross color changes in large areas of concrete caused by a change in the concrete mix, or light patches of discoloration caused by efflorescence. In this context, it is not intended to include stains caused by foreign material that comes in contact with the concrete surface after placement and curing, such as storm water runoff, irrigation, corrosion products, oil leaking from automobiles, etc.

WHY does Discoloration Occur?

Discoloration due to changes in cementitious materials or fine aggregate sources in subsequent batches in a placement sequence could occur, but is generally rare and insignificant. Concrete with a higher w/cm will generally be lighter in color. Inconsistent use of admixtures, insufficient mixing time, and improper timing of finishing operations can also cause discoloration. A yellowish to greenish hue may appear on concrete containing ground slag as a cementitious material. This will disappear with time, generally within a one year period. Concrete containing slag cement does, however, have a generally lighter color. The discoloration of concrete cast in forms or in slabs on grade is usually the result of a change in either the concrete composition or a concrete construction practice. In most studies, no single factor seemed to cause discoloration.

Factors found to influence discoloration are: the use of calcium chloride, variation in cement alkali content, delayed hydration of the cement paste, admixtures, hard-troweled surfaces, inadequate or inappropriate curing, concreting practices and finishing procedures that cause surface variation of the water-cementitious materials ratio, and changes in the concrete mixture proportions or constituents.



HOW to Avoid Discoloration?

1. Calcium chloride in concrete can cause concrete discoloration. Flake or pelletized calcium chloride, when not mixed uniformly, discolors more than liquid calcium chloride.
2. The type, kind, and condition of formwork can influence surface color. Forms with different rates of absorption will cause surfaces with different shades of color. A change in the type or brand of a form release agent can also change concrete color.
3. Eliminate trowel burning (hard troweling of surface after it has become too stiff to trowel properly) of the concrete. Concrete which has been hard-troweled may have dark discoloration as a result of densifying the surface, which reduces the w/cm (water to cementitious materials ratio). The

resulting low w/cm affects the hydration of the cement ferrites which contributes to a darker color. Concrete surfaces that are troweled too early will increase the water-cement ratio at the surface and lighten the color.

4. Concrete which is not properly or uniformly cured may develop discoloration. Uneven curing will affect the degree of hydration of the cement. Curing with polyethylene may also cause discoloration. When portions of the plastic sheeting are in direct contact with the concrete while other portions are not, it will cause variations in color. Using an even application of a quality spray or curing compound may be the better alternative.
5. The discoloration of a slab may be minimized or prevented by moistening absorptive subgrades, following proper curing procedures, and adding proper protection of the concrete from drying by the wind and sun.

HOW to Remove Discoloration?

Certain treatments have been found to be successful in removing or decreasing the surface discoloration of concrete flatwork. Discoloration caused by calcium chloride admixtures and some finishing and curing methods can be reduced by repeated washing with hot water and a scrub brush. The slab should be alternately flushed and brushed, and then dried overnight until the discoloration disappears.

If a discoloration persists, a dilute solution (1% concentration) of hydrochloric (muriatic) acid or dilute solutions (3% concentration) of weaker acids like acetic or phosphoric acid may be tried. Prior to using acids, dampen the surface to prevent it from penetrating into the concrete and flush with clean water within 15 minutes of application.

The use of a 20% to 30% water solution of diammonium citrate (2 lbs. in 1 gallon of water) has been found to be a very effective treatment for most discoloration. Apply the solution to a dried surface for 15 minutes. A whitish gel that forms should be diluted with water and agitated by brushing. Subsequently, the gel should be completely washed off with water. More than one treatment may be required.

Some types of discoloration, such as trowel burning, may not respond to any treatment. It may be necessary to paint or use another type of coating to eliminate the discoloration. Some types of discoloration may, however, fade with wear and age.

PRECAUTIONS?

Chemical methods to remove discoloration may significantly alter the color of concrete surfaces. Inappropriate or improper use of chemicals to remove discoloration may aggravate the situation. A trial treatment on an inconspicuous area is recommended. Acids should be thoroughly flushed from a concrete surface.

References

1. Greening, N. R. and Landgren, R., *Surfaces Discoloration of Flatwork*, Portland Cement Association RD 203, 1966.
2. Steve Kosmatka, *Discoloration of Concrete, Causes and Remedies*, Concrete Products, April 1987.
3. Neal, R. E., *Discoloration of Concrete Flatwork*, Lehigh Portland Cement Company, 1977.
4. "Removing Stains and Cleaning Concrete Surfaces," IS214.02T, PCA, 1988, www.cement.org.
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6. C.F. Ferrington, R.L. Stowe, W.G. Miller, *Removing Stains from Mortar and Concrete*, Corps of Engineers, Vicksburg, Mississsippi, Miscellaneous Paper *C-68-8.*
7. Eugene, O. Goeb, *Discolored Concrete Surfaces*, Concrete Products, Vol. 96, No. 2, February, 1993.
8. *Concrete Slab Surface Defects: Causes, Prevention, Repai*r, IS177.04T, PCA, 2001, www.cement.org.

CAUTIONS

The user of chemicals should refer to a Material Safety Data Sheet (MSDS) or manufacturer guidelines to be aware of the toxicity, flammability, and/or health hazards associated with the use of the material. The appropriate safety procedures, such as the use of chemical resistant gloves, goggles, respirators, and chemical resistant clothing may be required in the MSDS.

1993, 2007

Concrete in Practice
What, why & how?
NRMCA

CIP 24—Synthetic Fibers for Concrete

WHAT are Synthetic Fibers

Synthetic fibers engineered for use in concrete can withstand the long-term alkaline environment of concrete. These fibers are manufactured polymer-based materials such as polypropylene, nylon, or polyethylene. Synthetic fibers are added to concrete before or during the mixing operation. The use of synthetic fibers at typical addition rates of 1 to 2 lbs per cubic yard does not require any modification to concrete mixtures. At higher addition rates, workability may be reduced and water reducing admixtures may be required to retain slump.

WHY Use Synthetic Fibers

Synthetic fibers benefit the concrete in both the plastic and hardened state. Benefits include:

- reduced plastic settlement cracks
- reduced plastic shrinkage cracks
- increased toughness and impact resistance
- provides energy absorption

Macro-synthetic fibers, typically at a higher dosage rate, can be used for crack control in hardened concrete or temperature/shrinkage reinforcement in some applications. Documentation on the use of fibers for these applications should be available.

HOW do Synthetic Fibers Work in Early-Age Concrete

Early-age volume changes in concrete cause weakened planes and cracks to form due to stresses that exceed the strength of the concrete at a specific time. This is beneficial to minimize plastic shrinkage cracking. The growth of these micro shrinkage cracks is inhibited by mechanical blocking action of the synthetic fibers. The internal support system of the synthetic fibers inhibits the formation of plastic settlement cracks. The uniform distribution of fibers throughout the concrete discourages the development of large capillary channels caused by bleed water migration to the surface. These bleed water capillaries can provide locations for later age cracking.

Synthetic Fibers—Micro (top); Macro (bottom)

HOW do Synthetic Fibers Work in Hardened Concrete

Benefits seen to early-age performance of concrete continue to contribute to the performance of hardened concrete. Prevention of early age cracking in the freshly mixed stage reduces the potential for increased cracking in the hardened state. Hardened concrete attributes provided by synthetic fibers are improved toughness for energy absorption and resistance to impact forces.

The ability to resist tensile forces can be enhanced with the use of synthetic fibers to the concrete. When plain concrete develops tensile stresses that exceeds its tensile strength, due to bending or changes in temperature and shrinkage, cracking occurs. Synthetic fibers can prevent the effect of excessive tensile stresses by bridging and dispersing cracks and holds concrete tightly together. These benefits are enhanced with the use of a higher dosage than typically used for control of plastic shrinkage cracking.

Macro-synthetic fibers reduce the amount of plastic (early age) and post-hardening crack formation. Macro-synthetic fibers are thicker fibers and are used at a higher dosage rate of around 5 lbs/cubic yard. In these uses and with the higher modulus of these fibers improves toughness, resistance to cracking and crack tightness.

Synthetic fibers help concrete develop its optimum long-term integrity by the reduction of plastic and drying shrinkage crack formation, increased energy absorption and resistance to impact forces. Synthetic fibers are compatible with chemical admixtures, pozzolans, slag cement, silica fume, metakaolin, and cement chemistries.

HOW are Synthetic Fibers Used as Secondary Reinforcement

Synthetic fibers which meet certain hardened concrete criteria can be used as non-structural temperature/shrinkage or post-crack control reinforcement. These fibers should have documentation, including ASTM C1609 test results of residual flexural strength confirming their ability to hold concrete together after cracking. The uniform distribution of synthetic fibers throughout the concrete ensures the critical positioning of its use as secondary reinforcement.

Fibers used to control plastic shrinkage cracks, reducing shrinkage and temperature cracking, and in composite steel deck construction should meet the criteria of ICC Evaluation Service AC 32 (ref. 5).

References

1. ASTM C1116, *Specification Fiber Reinforced Concrete,* ASTM International, West Conshohocken, PA, www.astm.org.
2. ASTM C1609, *Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading).* ASTM International, West Conshohocken, PA, www.astm.org.
3. ACI 544.1R, *Report on Fiber Reinforced Concrete*, American Concrete Institute, Farmington Hills, MI, www.concrete.org
4. *Non-structural Cracks in Concrete*, Concrete Society Technical Report No. 22.
5. ICC Evaluation Service, Inc., AC 32, *Acceptance Criteria for Concrete with Synthetic Fibers*, December 2010.

APPLICATION GUIDELINES

Use Synthetic Fibers For:

- Reduction of concrete cracking as a result of plastic shrinkage.
- An alternate system of nonstructural shrinkage/temperature reinforcement (with documentation).
- Greater toughness and resistance to impact.
- Internal support and cohesiveness; concrete for steep inclines, shotcrete, and slip-formed placements.
- Reduction of concrete cracking as a result of plastic settlement.
- Applications where nonmetallic materials are required.

Do Not Use Synthetic Fibers For:

- Control of cracking as a result of external forces.
- Higher structural compressive or flexural strength development.
- Replacement of any moment-resisting or structural steel reinforcement.
- Decreasing the thickness of slabs on grade.
- The elimination or reduction of curling and/or creep.
- Increasing control joint spacing.
- Reduction in the size of the support columns.
- Reducing the thickness of bonded or unbonded overlay sections.

1994, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 25 — Corrosion of Steel in Concrete

WHAT is Corrosion of Steel

ASTM terminology defines corrosion as *the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.* For corrosion of steel, oxygen and moisture are required for the electrochemical reaction to occur. Corrosion results in the formation of rust that has two to four times the volume of the original steel and none of its good mechanical properties. Corrosion also produces pits or holes in the surface of reinforcing steel, reducing strength capacity as a result of the reduced cross-sectional area.

WHY is Corrosion of Steel a Concern

Structural concrete uses reinforcing steel where tensile stresses are anticipated. This provides structural capacity to members subjected to tensile and flexural loads due to traffic, winds, dead loads, and thermal cycling. However, when reinforcement corrodes, the larger volume of rust formed leads to internal stresses and subsequent delamination and spalling of the concrete cover. Reduction in the cross-sectional area of steel reduces the structural capacity of the member. If left unchecked, the integrity of the structure can be affected. Corrosion is especially detrimental to the performance of tensioned strands in prestressed concrete as failure can be catastrophic.

WHY Does Steel in Concrete Corrode

Steel embedded in concrete is in a non-corroding, passive condition because of the high alkalinity (pH>13) within concrete. However, when water-soluble chlorides are present, the passive layer protecting steel is disrupted and corrosion begins. Chlorides can be from external sources for concrete exposed to severe environments, like sea water or when deicing salts are applied; or from internal sources, primarily from materials used to make concrete.

Carbonation of concrete is another cause of steel corrosion. Atmospheric carbon dioxide reacts with lime in the concrete to form calcium carbonate. This reaction reduces the alkalinity of the concrete that protects the steel. When the pH at the level of the reinforcing steel falls below 9, corrosion begins. Chloride-induced corrosion is more common than that resulting from carbonation.


Reinforcement Corrosion in Structures

Corrosion is aggravated by factors including moisture, high temperatures, cracking, stray currents and galvanic effects.

HOW to Prevent Corrosion

Corrosion prevention strategies should ensure that reinforcing steel is embedded in good quality concrete with the minimized potential for chloride exposure and carbonation.

Design Considerations

ACI 318 *Building Code for Structural Concrete* establishes exposure classes related to corrosion of reinforcing steel:

- C0—Concrete that will be dry in service
- C1—Concrete that will be exposed to moisture in service
- C2—Concrete that will exposed to moisture and an external source of chlorides in service

For exposure class C2, ACI 318 establishes a maximum w/cm of 0.40 and minimum specified strength of 5000 psi. No w/cm limit is set for exposure classes C0 and C1 because penetration of external chlorides is not a concern. Good quality concrete, however, reduces the rate of carbonation.

Chloride limits are established for internal sources of water-soluble chlorides based on percent by weight of cement. For reinforced concrete the limits are 1.0% for C0; 0.3% for C1; and 0.15% for C2. For prestressed concrete the limit is 0.06% for all exposure classes. Water soluble chlorides are measured in accordance with ASTM C1218 on powder specimens extracted from concrete cylinders at an age between 28 and 42 days.

Adequate cover over reinforcing steel is necessary. Increasing cover reduces the rate of chloride penetration and carbonation exponentially and delays the onset of corrosion. Minimum cover requirements in ACI 318 should be increased for concrete exposed to corrosive environments. Concrete containing larger aggregates require more cover. Adequate reinforcement should be provided to keep cracks tight. ACI 224 provides guidance to minimize the formation of cracks. Allowable crack widths for concrete exposed to chlorides are about 0.006-in. Adequate drainage of water away from concrete members should be ensured.

Chloride ingress can be reduced by using membranes and sealers. Onset of corrosion can be minimized or delayed by using corrosion resistant reinforcement, such as stainless steel, galvanized steel and epoxy-coated steel.

Life-365 is available software that models the expected service life and costs of different corrosion protection strategies. It can be used to demonstrate lower life cycle cost with higher initial cost of some options.

Concrete Mixtures

Quality concrete with a low permeability slows down the penetration of chloride salts and the development of carbonation. Low permeability can be obtained with a lower w/cm ratio in the range of 0.40 to 0.50. A w/cm much less than 0.40 may result in problems with placement and increase the potential for thermal and drying shrinkage cracking. Another factor that reduces the permeability of concrete is the use of supplementary cementitious materials (SCM). Typical dosage in percent by weight of cementitious materials is 5% silica fume, 25% fly ash and 50% slag cement and combinations thereof. Low permeability of concrete mixtures can be demonstrated by indicator tests. Excessive cementitious materials increases the volume of paste and the potential for cracking. Concrete materials should not contribute chlorides to the mixture that exceed the chloride limits. Concrete exposed to freezing should be air-entrained.

Corrosion inhibiting admixtures delay the onset of corrosion. Water repellent materials may reduce the ingress of moisture and chlorides to a limited extent in low permeability concrete.

Construction Practices

Delamination, cracking and scaling accelerate corrosion of reinforcing steel. Placement and finishing should be properly scheduled with adequate crew and resources. Concrete must be adequately consolidated and cured. Curing should be performed preferably for at least 7 days. Concrete temperature should be maintained above 50°F. Early-age curing is especially important for concrete mixtures containing SCM. Numerous studies show that concrete porosity is reduced significantly with increased curing times and, correspondingly, corrosion resistance is improved.

References

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2. ACI 222R, *Corrosion of Metals in Concrete*, American Concrete Institute, Farmington Hills, MI.
3. ACI 224R, *Control of Cracking in Concrete Structures*, American Concrete Institute, Farmington Hills, MI.
4. ASTM Standards C1218, ASTM Book of Standards, Volume 04.02, American Society for Testing and Materials, West Conshohocken, PA. www.astm.org
5. Berke, N.S., *Corrosion of Reinforcing Steel*, ASTM STP 169D, 2006, pp. 164-173. www.astm.org
6. Berke, N.S., "Corrosion Inhibitors in Concrete," *Concrete International,* Vol. 13, No. 7, 1991, pp. 24-27.
7. Life-365 Software, www.life-365.org

HOW to Minimize Corrosion

1. Evaluate the anticipated exposure of concrete members and establish appropriate requirements
2. Use good quality concrete with SCM and a w/cm of about 0.40, when concrete will be exposed to chlorides.
3. Provide adequate cover to reinforcing steel.
4. Ensure that the concrete is adequately cured.
5. For critical structural members requiring long service life, consider advanced corrosion protection strategies

1995, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 26 - Jobsite Addition of Water

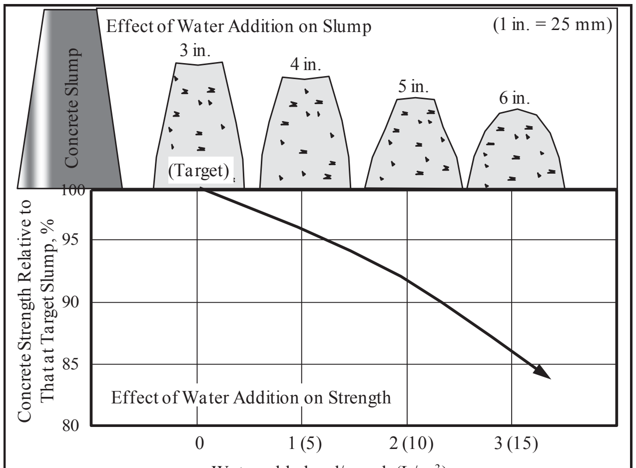
WHAT is Jobsite Addition of Water?

This is the addition of water to ready mixed concrete in a truck mixer after arrival at the location of the concrete placement. Such tempering of concrete may be done with a portion of the design mixing water which was held back during the initial mixing (referred to as *trim* water), or with water in excess of the design mixing water, at the request of the purchaser. The design mixing water is the quantity of water set by the mixture proportions for required performance of the concrete.

WHY is Water Added at the Jobsite?

Water is added to concrete at the jobsite to increase its slump. When concrete arrives at the jobsite at a slump that is lower than that allowed by design or specification and/or is of such consistency so as to adversely affect the placeability of the concrete, water can be added to the concrete to bring the slump up to an acceptable or specified level. This can be done when the truck arrives on the jobsite provided the specified slump and/or water-cementitious materials ratio (w/cm) is not exceeded. Such an addition of water is in accordance with ASTM C94, *Specification for Ready Mixed Concrete*.

The ready mixed concrete supplier establishes the proportions of materials for concrete mixtures according to industry standards to provide the intended performance. Addition of water in excess of the design mixing water will affect concrete properties, such as reducing strength (Figure 1), and increasing its susceptibility to cracking. If the purchaser requests additional water, in excess of the design mixing water, the purchaser assumes responsibility for the resulting concrete quality. The alternative of using a water reducing admixture or superplacticizer to increase concrete slump should be considered. Increasing the slump of concrete using admixtures usually will not alter concrete properties provided the mixture does not segregate. Consistent use of admixtures at the jobsite can reduce batch to batch variability. This option should be decided at a pre-pour conference as qualified personnel may need to be available at the jobsite.



Effect of water addition on slump and strength

HOW to Add Water at the Jobsite?

a. The maximum allowable slump of the concrete must be specified or determined from the specified nominal slump plus tolerance.

b. Prior to discharging concrete on the job, the actual slump of the concrete must be estimated or measured. If slump is measured, it should be on a preliminary sample obtained after discharging the first ¼ cu. yd. [0.2 m^3]. The measured slump on this sample should be used as an indicator of concrete consistency and not an acceptance test. Tests for acceptance of concrete should be on samples obtained in accordance with ASTM C172.

c. At the jobsite, water should be added before any significant quantity of concrete has been discharged from the batch so that the volume of concrete being retempered is known. Water addition can be in several increments accompanied by mixing to evaluate change in slump.

A rule of thumb that works reasonably well is—1 gallon, or roughly 10 lb., of water per cubic yard for 1 inch increase in slump [5 liters, or 5 kg, of water per cubic meter for 25 mm increase in slump].

d. All water added to concrete on the jobsite must be measured and recorded on the delivery ticket. A designated representative of the purchaser should sign or initial the delivery ticket to acknowledge the water addition and the quantity added.

e. ASTM C94 requires an additional 30 revolutions of the mixer drum at mixing speed after the addition of water. In some cases, 10 revolutions will be sufficient if the truck is able to mix at 20 revolutions per minute (rpm) or faster.
f. The amount of water added should be controlled so that the maximum slump and/or water-cementitious materials ratio, as indicated in the specification, is not exceeded. After more than a small portion of the concrete is discharged, no water addition is permitted.
g. Upon obtaining the desired slump and/or maximum water-cementitious materials ratio, no further addition of water on the jobsite is permitted.
h. A pre-placement conference should be held to establish proper procedures to be followed, to determine who is authorized to request a water addition, and to define the method to be used for documentation of water added at the jobsite.

To ensure that the design mixing water or specified w/cm is not exceeded, it is good practice for the concrete supplier to indicate on the delivery ticket the amount of *trim* water held back when concrete was batched. This sets the limit of the jobsite water addition.

When project specifications prohibit the jobsite addition of water, the concrete supplier should be notified so that the design mixing water can be added at the plant and provisions made to adjust the slump of concrete at the jobsite, if necessary, with the use of admixtures.

Some truck mixers are equipped with automated devices that monitor slump of concrete and add water to maintain a target slump. This occurs while the concrete is being transported to the jobsite. The device should be able to record the amount of water added and to terminate the addition based on set limits. ASTM C94 recognizes the use of these systems.

References

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2. NRMCA Publication 186, *Ready Mixed Concrete,* Richard D. Gaynor and Colin Lobo, NRMCA, Silver Spring, Maryland.
3. *Checklist for Pre-Construction Conference*, Joint publication of ASCC and NRMCA, NRMCA, Silver Spring, MD.
4. NRMCA Publication 188, *Truck Mixer Driver's Manual,* NRMCA, Silver Spring, MD.
5. *Adding Water to the Mix: It's Not all Bad*, Eugene O. Goeb, *Concrete Products,* January 1994.
6. *Adjusting Slump in the Field*, Bruce A. Suprenant, *Concrete Construction,* January 1994.
7. *Slump Retention of Fly Ash Concrete With and Without Chemical Admixtures*, Dan Ravina, ACI *Concrete International*, April 1995.

ASTM C94 Jobsite Water Addition

1. Establish the maximum allowable slump and water content permitted by the specification.
2. Estimate or determine the concrete slump from the first portion of concrete discharged from the truck.
3. Add an amount of water such that the maximum slump or water-cementitious materials ratio, according to the specification or designed mixture proportions, is not exceeded.
4. Measure and record the amount of water added. Water in excess of that permitted should be authorized by a designated representative of the purchaser. Purchaser should initial the ticket.
5. Mix the concrete for 30 revolutions of the mixer drum at mixing speed.
6. Do not add water if:
    a. the maximum water-cementitious materials ratio is reached,
    b. the maximum slump is obtained, or
    c. more than about ¼ cu. yd. (0.2 m^3) has been discharged from the mixer.

1995, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 27 - Cold Weather Concreting

WHAT is Cold Weather?

Cold weather is defined as a period when for more than 3 consecutive days the average daily temperature is less than 40°F [5°C] and the air temperature is not more than 50°F [10°C] for more than one-half of any 24-hr period. These conditions warrant special precautions when placing, finishing, curing and protecting concrete against the effects of cold weather. Since weather conditions can change rapidly in the winter months, good concrete practices and proper planning are critical.

WHY Consider Cold Weather?

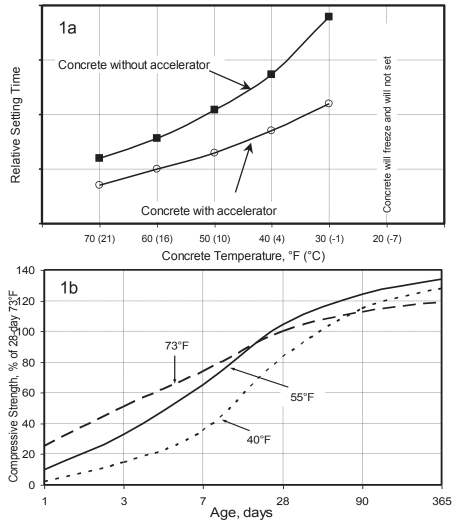
Successful cold-weather concreting requires an understanding of the various factors that affect concrete properties.

In its fresh state concrete freezes if its temperature falls below about 25°F [-4°C]. The potential strength of frozen concrete can be reduced by more than 50% and it will not be durable. Concrete should be protected from freezing until it attains a compressive strength of 500 psi [3.5 MPa] - about two days after placement.

Concrete at a low temperature has a slower setting and rate of strength gain. A rule of thumb is that a drop in concrete temperature by 20°F [10°C] will approximately double the setting time. These factors should be accounted for when scheduling construction operations, such as form removal.

Concrete that will be in contact with water and exposed to cycles of freezing and thawing should be air-entrained. Newly placed concrete is saturated with water and should be protected from cycles of freezing and thawing until it has attained a compressive strength of at least 3500 psi [24.0 MPa].

The reaction between cement and water, called hydration, generates heat. Insulating concrete retains heat and maintains favorable curing temperatures. Temperature differences between the surface and the interior of concrete should be controlled. Thermal cracking may occur when the difference exceeds about 35°F [20°C]. Insulation or protective measures should be gradually removed to avoid thermal shock.



Effect of temperature on concrete set time and strength

HOW to Place Concrete in Cold Weather?

Recommended concrete temperatures at the time of placement are shown below. The ready mixed concrete producer can control concrete temperature and furnish concrete to comply.

Section Size, minimum dimension, inch [mm]	Concrete temperature as placed
less than 12 [300]	55°F [13°C]
12 - 36 [300 - 900]	50°F [10°C]
36 - 72 [900 - 1800]	45°F [7°C]

Concrete temperature should not exceed these temperatures by more than 20°F [10°C]. Concrete at a higher temperature requires more mixing water, has a higher rate of slump loss, and is more susceptible to cracking. Concreting in cold weather provides the opportunity for better quality, as cooler initial concrete temperature will typically result in higher ultimate strength and improved durability.

In cold weather, slower setting time and rate of strength gain of concrete can delay finishing operations and form removal. Chemical admixtures and other materials can be used to offset these effects. Accelerating admixtures, conforming to ASTM C 494—Types C (accelerating) and E (water-reducing and accelerating), are commonly used.

Calcium chloride is an effective accelerating admixture, but should not exceed a dosage of 2% by weight of cement. Non-chloride, non-corrosive accelerators should be used for prestressed concrete or when corrosion of steel reinforcement or metal in contact with concrete is a concern. Accelerating admixtures do not prevent concrete from freezing and their use does not preclude the requirements appropriate curing and protection from freezing.

Rate of setting and strength gain increased by increasing portland cement content or by using a Type III cement (high early strength). The quantity of fly ash or slag cement in concrete may be reduced in cold weather for a similar effect. This may not be possible if a minimum quantity of SCM is required for durability. The selected solution should be economical and not compromise on the required concrete performance.

Concrete should be placed at the lowest practical slump. Adding water to achieve slump can delay setting time and prolong the duration of bleeding, thereby impacting finishing operations.

Adequate preparations should be made prior to concrete placement. Snow and ice should be removed and the temperature of surfaces and metallic embedments in contact with concrete should be above freezing. This might require insulating or heating subgrades and contact surfaces prior to placement.

Materials and equipment should be in place to protect concrete from freezing temperature and for adequate curing, both during and after placement. Insulated blankets and tarps, as well as straw covered with plastic sheets, are commonly used measures. Enclosures and insulated forms may be needed for additional protection depending on ambient conditions. Corners and edges are most susceptible to heat loss. Fossil-fueled heaters in enclosed spaces should be vented for safety reasons and to prevent carbonation of newly placed concrete surfaces, which causes dusting.

The concrete surface should not be allowed to dry before it sets as this can cause plastic shrinkage cracks. Subsequently, concrete should be adequately cured. Water curing is not recommended when freezing temperatures are imminent. Use membrane-forming curing compounds or impervious paper and plastic sheets for concrete slabs.

Forming materials, except for metals, maintain and evenly distribute heat and provide adequate protection in moderately cold weather. In extremely cold temperatures, insulating blankets or forms should be used, especially for thin sections. Forms should not be stripped for 1 to 7 days depending on rate of strength gain, ambient conditions, and anticipated loading on the structure. Field-cured cylinders or nondestructive methods should be used to estimate in-place concrete strength prior to stripping forms or applying loads. Removal of protective measures and formwork should not cause thermal shock to the concrete.

Concrete test specimens used for acceptance of concrete should be carefully managed. In accordance with ASTM C31, cylinders should be stored in insulated containers, which may need temperature controls, to insure that they are cured at 60°F to 80°F [16°C to 27°C] for the first 24 to 48 hours. A minimum/maximum thermometer should be placed in the curing box to maintain a temperature record of curing test specimens at the jobsite.

References

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2. *Design and Control of Concrete Mixtures*, Portland Cement Association, Skokie, IL.
3. ASTM C94 *Standard Specification for Ready Mixed Concrete*, ASTM, West Conshohocken, PA.
4. ASTM C31 *Making and Curing Concrete Test Specimens in the Field*, ASTM, West Conshohocken, PA.
5. *Cold-Weather Finishing*, Concrete Construction, November 1993

Cold Weather Concreting Guidelines

1. Use air-entrained concrete when exposure to moisture and freezing and thawing conditions are expected.
2. Keep surfaces in contact with concrete free of ice and snow and at a temperature above freezing prior to placement.
3. Place and maintain concrete at the recommended temperature.
4. Place concrete at the lowest practical slump.
5. Protect fresh concrete from freezing or drying.
6. Protect concrete from early-age freezing and thawing cycles until it has attained adequate strength.
7. Limit rapid temperature changes when protective measures are removed.

1998, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 28 - Concrete Slab Moisture

WHAT is the Problem

Concrete slab moisture can cause problems with the performance of floor-covering materials, such as vinyl tile, wood, resilient sheet flooring, carpet, and cause bond-related failures of non-breathable floor coatings. Installation guidelines of manufacturers of flooring materials and coatings require that the moisture levels of a hardened concrete slab be less than some threshold value prior to installation. In most cases newly placed concrete slabs cannot dry fast enough to comply with these moisture requirements. Fast-track construction schedules exacerbate the problem. Rapid-drying concrete mixtures are available.

WHAT are Sources of Slab Moisture

a. **Ground water**: Moisture in liquid form can rise upward from the water table by capillary action when fine-grained soil is present below the slab.

b. **Water vapor**: Regardless of the water-table depth, water in vapor form will rise and saturate the soil below the slab. Regardless of where a building is located, the relative humidity of the subgrade below a slab on ground will measure close to 100%.

c. **Fill course/blotter layer:** Granular fill material sandwiched between the vapor retarder and the slab can take on additional moisture prior to or after the slab is placed. This layer can act as a conduit for moisture through tears, punctures, or improperly sealed penetrations in the vapor retarder. A blotter layer directly under the slab is not recommended for interior slabs on ground if moisture-sensitive flooring materials are to be installed.

d. **Residual moisture in the slab:** Adequate water content is necessary in concrete mixtures for improved workability and finishability. It can take weeks to months in favorable interior ambient conditions for a concrete slab to dry to a level considered acceptable by flooring manufacturers and industry standards. Factors that affect the drying rate include the original water content in the concrete mixture, type of concrete, such as normal or lightweight, slab thickness, type of curing, and the ambient relative humidity and temperature from the time of placement to the time of installation of flooring.

e. **Moisture during construction:** Wetting of the slab after final curing from precipitation (if a roof is not installed) or construction activities will elevate moisture levels within the slab and lengthen the drying period.

Moisture-related Floor Covering Failure (PCA image)

HOW are Problems Avoided

Project personnel should be aware of the project schedule and factors related to slab moisture that impact successful floor installation. Moisture mitigation systems should be included in a bid, at least as a contingency item. Avoiding problems can be accomplished by the following means:

- Protect against ingress of water under hydrostatic pressure by ensuring that proper drainage away from the slab as part of the design.
- Use a 6 to 8 inch [150 to 200 mm] layer of coarse gravel or crushed stone as a capillary break in locations with higher water table and fine-grained soil subgrades.
- Use a vapor retarder that complies with ASTM E1745 directly beneath the slab to prevent moisture migration from the substrate. The vapor retarder should be installed in accordance with ASTM E1643. The membrane should be over-lapped, sealed at openings, and precautions should be taken to prevent damage during construction. (CIP 29).
- Use a concrete mixture with a moderately low water-cementitious material (w/cm) ratio (about 0.50). This reduces the amount of residual moisture in the slab, will require a shorter drying period, and result in a lower vapor transmission. Water reducing admixtures provide adequate workability with less water. Reduced moisture emission can be achieved by using pozzolans or slag cement in the concrete mixture.
- Rapid-drying concrete mixtures that are specifically designed for reduced moisture levels and a shortened drying period are available. Admixtures for concrete that reduce the relative humidity in concrete or moisture vapor reduction admixtures (MVRA) that

block pores within concrete are available. Conditions and validity of warranties of products and floor coverings should be assessed.

- Cure the concrete slab to retain moisture by using plastic sheeting or waterproof paper for 3 to 7 days; moist curing increases drying time. Avoid curing compounds on floors to receive coverings or coatings, unless otherwise stated by the manufacturer.
- Moisture and temperature impact drying time. Maintain slabs under actual service conditions for a sufficient period to naturally dry the concrete prior to installing flooring or coatings.
- Avoid operations that will wet the concrete floor. Use heat and dehumidifiers to accelerate drying.
- Test slab moisture condition and vapor emission prior to installing floor covering. If these test results exceeds requirements, use moisture mitigating products or systems approved by flooring or coating manufacturer.

When concrete slab moisture impacts floor covering options consider alternatives like decorative concrete, less moisture-sensitive floor coverings or adhesives, or breathable floor coatings.

HOW is Slab Moisture Measured

Qualitative and quantitative methods of measuring concrete slab moisture are described in ASTM F710. Test the moisture condition of the slab on a dry clean surface at service temperature and humidity conditions. Test at three random sample locations for areas up to 1000 ft^2 [100 m^2] and perform one additional test for each additional 1000 ft^2 [100 m^2].

Two quantitative methods establish acceptable moisture emission of a slab to receive floor covering:

Anhydrous Calcium Chloride Test (ASTM F1869): A measured amount of anhydrous calcium chloride is placed in a petri dish sealed under a plastic dome on the slab. The moisture absorbed by the salt in 60 to 72 hours is measured to calculate the moisture vapor emission rate (MVER). Maximum limits generally specified are 3 to 5 pounds of moisture per 1000 square feet per 24 hours. This test has some major shortcomings: it determines only a portion of the free moisture at a shallow depth of concrete near the surface of the slab; it is sensitive to the temperature and humidity; it provides only a *snapshot in time* of current moisture conditions and does not predict if the sub-slab conditions will cause a moisture problem later in the life of the floor. This is not considered to be an acceptable test for lightweight concrete.

Relative Humidity Probe (ASTM F2170): This procedure involves measuring the relative humidity of concrete at a specific depth from the slab surface inside a drilled or cast hole. The test hole is allowed to achieve moisture equilibrium for 72 hours after which relative humidity is measured. Typically a relative humidity of 75% to 80% is targeted for installation of floor coverings. With proper expertise, relative humidity probes can be used to determine the moisture profile from top to bottom in a slab, conditions below the slab, and can monitor the drying of a slab over time or to predict the moisture distribution after installing the floor covering.

Qualitative methods include:

Polyethylene Sheet Test (ASTM D 4263): An 18 by 18 inch [450 by 450 mm] square plastic sheet is taped tightly to the concrete and left in place for at least 16 hours. The presence of moisture under the plastic sheet is a positive indication that excess moisture is likely present in the slab. However, a negative indication is not an assurance that the slab is acceptably dry below the surface.

Concrete Surface Humidity (Hood Test) (ASTM F2420): The humidity inside a sealed dome on the slab surface is measured and is a non-evasive qualitative measure of slab surface RH level.

Mat Test: The adhesive is applied to a 24 by 24 inch [600 by 600 mm] area and a sheet vinyl flooring product is placed face down on the adhesive and sealed at the edges. A visual inspection of the condition of the adhesive is made after a 72-hour period. This test is not reliable and can produce false negative results.

Moisture meters: Electrical resistance or conductance measured between probes is proportional to moisture content and provides an approximation of relative moisture content in concrete. Other types of meters measure impedance, an alternating current measurement combining resistance and capacitance whereby the depth of signal penetration varies depending on the material and relative moisture content. Electronic meters are useful survey tools that provide comparative moisture readings across a floor .

Note: All slab-on-ground moisture tests for determining when floor covering materials can be applied are useful only when the slab has been placed in direct contact with an effective vapor retarder.

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2004, 2017

Concrete in Practice
What, why & how?
NRMCA

CIP 29 - Vapor Retarders Under Slabs on Grade

WHAT are Vapor Retarders

Vapor retarders are sheet materials that minimize the transmission of moisture or water vapor from the sub-slab support system into a concrete slab. Vapor retarders are typically specified in accordance with ASTM E1745, which requires that the permeance of the material be no greater than 0.1 US perms, when tested by ASTM E96 or ASTM F1249. Low-density polyethylene sheets that were commonly used in the past have been replaced by stronger, less permeable materials that conform to ASTM E1745. A minimum thickness of 10 mils (0.25 mm) is recommended for reduced vapor transmission and for required durability during and after installation. Membrane materials with after-conditioning permeance levels less than 0.01 perms are referred to as vapor barriers rather than retarders.

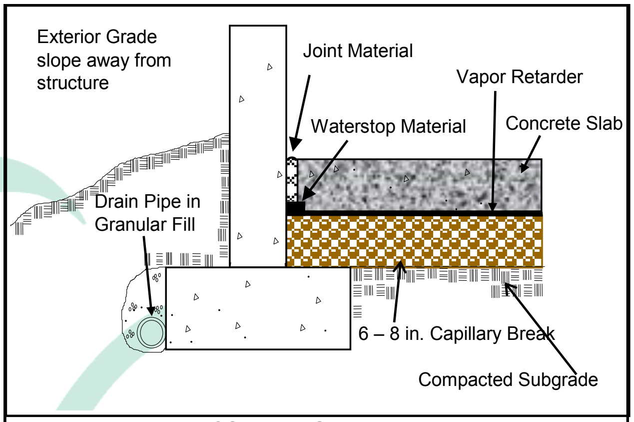
WHY are Vapor Retarders Used

Vapor retarders are frequently specified for interior concrete slabs on grade where moisture protection is desired. Protection from slab substrate moisture migration is required when floors will be covered with carpet, tile, wood, resilient, and seamless polymeric flooring, or when moisture-sensitive equipment or products will be placed on the floor. Permeation of water vapor through concrete slabs can cause failure of moisture-sensitive adhesives or coatings resulting in delamination, distortion or discoloration of flooring products, trip-and-fall hazards, and possibly fungal growth and odors. See CIP 28.

Low-permeability membranes below floor slabs on grade, in conjunction with sealed joints, also provide a barrier to radon penetration into enclosed spaces when such conditions exist.

WHAT Conditions Require Vapor

A floor is part of the building envelope and should be constructed to eliminate moisture infiltration through the slab into the occupied building space. It is common to specify the use of vapor retarders for floor slabs intended to receive floor coverings. However, floors intended for use without coatings or coverings, such as warehouses, mechanical rooms, and unfinished expansion areas, are often converted to other uses that may require the installation of moisture-sensitive flooring. Such *adaptive re-use* cannot be predicted during design and construction of a new building. Therefore, it is sensible planning to include a vapor retarder under every interior floor slab in every building. Vapor retarders are generally not necessary for exterior slabs on grade.



Typical Detail of Slab-on-Grade with Vapor Retarder

Other sources of moisture that cannot be controlled by the use of vapor retarders need to be separately addressed in contract documents to achieve the moisture emission levels required by flooring manufacturers. Exposure to moisture and re-wetting during construction will take a long time to dry out when the slab is eventually subjected to service ambient conditions with the HVAC system. The same is true for residual moisture within concrete slabs. The concrete slab should be properly cured and allowed to dry out before testing for moisture emissions. (CIP 28) Concrete mixtures with lower moisture emission can be supplied by the concrete producer. These mixtures can include supplementary cementitious materials and specialty chemical admixtures designed to control moisture emission.

HOW Should Vapor Retarders be

ACI Committee 302 recommends that concrete be placed directly on top of a vapor retarder when the concrete slab surface will receive a moisture-sensitive floor covering. A durable and good quality vapor retarder that complies with ASTM E1745 should be used and installed in accordance with ASTM E1643.

When environmental conditions cause a higher rate of evaporation, the possibility of plastic shrinkage cracking increases. Placing concrete directly on the vapor retarder can help alleviate this condition as bleed water will rise to the surface to reduce the chance of this cracking.

Placing concrete directly on the vapor retarder can also create problems. Excess bleeding that does not dissipate from the surface can delay finishing operations. Final finishing of the slab should not begin while bleed water is on the slab surface. Bleed water trapped below a finished surface causes delaminations (CIP 20) or blisters (CIP 13). Concrete may stiffen at a slower rate, which means that trowel finishing operations must be delayed; thus increasing the susceptibility to plastic shrinkage cracking. Curling (CIP 19) can occur due to differential drying and related shrinkage at different levels in the slab. Concrete producers can develop mixtures with reduced shrinkage and reduced moisture emission. With the increased occurrence of moisture related floor covering failures, minor cracking of floors placed on a vapor retarder and other problems discussed here are considered a more acceptable risk than failure of floor coverings.

The sub-grade and base should be compacted to provide uniform support to the slab. The base should be well draining and stable to support construction traffic. A clean fine-graded, preferably crushed, material with about 10 to 30 percent passing the No. 100 [150-mm] sieve and free of clay or organic material is generally recommended. Concrete sand should not be used as it is easily displaced during construction.

Jobsite moisture conditions based on the geotechnical evaluation may require a capillary break to reduce moisture migration. Install a 6 to 8 inch [150 to 200 mm] layer of coarse gravel or crushed stone as a capillary break. Note that a coarse stone capillary break will not reduce moisture vapor transmission from the slab support system. A vapor retarder is still required above a capillary break.

If coarse stone is used as the capillary break, choke off the top surface with 2-in. [50-mm] of graded, fine-grained compactable fill to prevent damage to the vapor retarder. Install the vapor retarder on top of the smooth compacted fill.

Vapor retarder sheets should be overlapped by 6 inches [150 mm] at the seams and taped and sealed around utility or column openings, the face of grade beams, footings, and the slab or foundation walls. These details are addressed in ASTM E1643.

If an interior concrete slab will not have a moisture-sensitive floor covering but will be located in a humidity controlled area it may be placed over the granular fill/blotter layer. The granular layer should be dry prior to concrete placement to function as a blotter and remove water from the fresh concrete. Moisture infiltration into the granular material should be prevented and the base and slab should be ideally constructed with a roof in place.

The granular/blotter layer should be a minimum 4 inch [100 mm] layer of compactable, easy-to-trim material. A “crusher-run” material graded from 1½ in. [37.5 mm] to dust size works well. Alternatively, use at least 3 inches [75 mm] of crushed stone sand. Do not use concrete sand. To reduce slab friction, top off the crusher-run layer with a layer of fine-graded material.

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FOLLOW THESE RULES WHEN USING VAPOR RETARDERS

1. Provide a vapor retarder directly under and in contact with all interior floor slabs.
2. Use a sheet product with a minimum thickness of 10 mils that has a permeance less than 0.1 perms when tested by ASTM E96 or F1249. Vapor retarders should comply with ASTM E1745 and be durable to retain its properties during and after construction.
3. Place the vapor retarder on a smooth base and ensure it is vapor tight to moisture sources below the slab, at its edges, and at penetrations. Installation should be in accordance with ASTM E1643.
4. Order a concrete mixture designed for low shrinkage. Concrete mixtures with reduced moisture emission can be requested.
5. Follow good concrete practices for finishing and curing to reduce potential vapor emission. If the concrete slab will receive a moisture-sensitive floor covering, cure the concrete under plastic sheeting for 3 days and do not moist cure the slab for more than 7 days.

2004, 2017

Concrete in Practice
What, why & how?
NRMCA

CIP 30 - Supplementary Cementitious Materials (SCMs)

WHAT are SCMs?

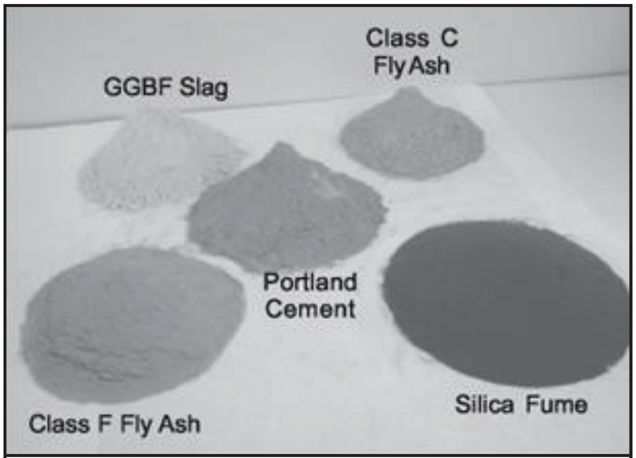
In its most basic form, concrete is a mixture of portland cement, sand, coarse aggregate and water. The principal cementitious material in concrete is portland cement. Today, most concrete mixtures contain supplementary cementitious materials that make up a portion of the cementitious component in concrete. These materials are generally byproducts from other processes or natural materials. They may or may not be further processed for use in concrete. Some of these materials are called pozzolans, which by themselves do not have any cementitious properties, but when used with portland cement, react to form cementitious compounds. Other materials, such as slag cement and ASTM C618 Class C fly ash, do exhibit cementitious properties.

For use in concrete, supplementary cementitious materials, need to meet requirements of established standards. They may be used individually or in combination in concrete. They may be added to the concrete mixture as a blended cement or as a separately batched ingredient at the ready mixed concrete plant.

Some examples of these materials are discussed below.

Fly Ash is a byproduct of coal-fired furnaces at power generation facilities and is the non-combustible particulates removed from the flue gases. Fly ash used in concrete should conform to specification ASTM C618. The amount of fly ash in concrete can vary from 15% to 65% by mass of the cementitious materials, depending on the source and composition of the fly ash and the performance requirements of the concrete. Characteristics of fly ash can vary significantly depending on the source of the coal. Class F fly ash is normally produced when burning anthracite or bituminous coal and generally has a low calcium content. Class F fly ash is pozzolanic. Class C fly ash is produced when subbituminous coal is burned and it typically has cementitious and pozzolanic properties. As defined in ASTM C618, the sum of silicon, aluminium, and iron oxides should be greater than 50% for Class C fly ashes and should be greater than 70% for Class F fly ashes.

Slag Cement is a non-metallic manufactured byproduct from a blast furnace when iron ore is reduced to pig iron. The liquid slag is rapidly cooled to form granules, which are then ground to a fineness similar to portland cement. Slag cement used as a cementitious material should conform to the specification, ASTM C989. Three grades - 80, 100, and 120 are defined in C989, with the higher grade contributing more to strength potential. Slag cement has cementitious properties but these are enhanced when it is used with portland cement. Slag is used at 20% to 70% by mass of the cementitious materials.



Types of Cementitious Materials

Silica Fume is a byproduct from the manufacture of silicon or ferro-silicon metal and is a highly reactive pozzolanic material. It is collected from the flue gases from electric arc furnaces. Silica fume is an extremely fine powder, with particles about 100 times smaller than an average cement particle. Silica fume is available as a densified powder. Silica fume for use in concrete should conform to specification ASTM C1240. It is generally used at 3 to 10% by mass of cementitious materials. Applications inclued concrete structures that need high strength or significantly reduced permeability to water and chemicals. Special procedures are warranted when handling, placing and curing silica fume concrete.

Natural Pozzolans. Various naturally occurring materials possess, or can be processed to possess pozzolanic properties. These materials are also covered under the specification, ASTM C618. Natural pozzolans are generally derived from volcanic origins. In the US, commercially available natural pozzolans include **metakaolin** and **calcined shale or clay**. These materials are manufactured by controlled calcining (firing) of naturally occurring materials. Metakaolin is produced from relatively pure kaolinite clay and it is used at 5% to 15% by mass of the cementitious materials. Calcined shale or clay is used at higher percentages by mass. Other natural pozzolans include **volcanic glass, zeolitic trass or tuffs, rice husk ash and diatomaceous earth.**

WHY are SCMs Used?

Supplementary cementitious materials can be used for improved concrete performance in its fresh and hardened state. They are primarily used to enhance the workability, durability, and strength of concrete. These materials allow the concrete producer to design and modify the concrete mixture to meet the performance requirements of the concrete application. Concrete mixtures with high portland cement contents are susceptible to cracking and increased heat generation. These effects can be controlled to a certain degree by using supplementary cementitious materials.

Supplementary cementitious materials such as fly ash, slag cement and silica fume enable the concrete industry to use hundreds of millions of tons of byproduct materials that would otherwise be landfilled as waste. Furthermore, their use reduces the consumption of portland cement per unit volume of concrete. Portland cement has high energy consumption and emissions associated with its manufacture, which is conserved or reduced when the amount used in concrete is reduced.

HOW do SCMs Affect Concrete Properties?

Fresh Concrete: In general, supplementary cementitious materials improve the **consistency** and **workability** of fresh concrete because an additional volume of fines is incorporated in the mixture. Concrete with silica fume is typically used at low water contents with high range water reducing admixtures and these mixtures tend to be cohesive and stickier than plain concrete. Fly ash and slag cement generally reduce the water demand for required concrete slump. Concrete **setting time** may be slower with some supplementary cementitious materials used at higher percentages. This can be beneficial in hot weather. The slower setting time is offset in winter by reducing the percentage of supplementary cementitious material in the concrete and be using accelerating admixtures. Because of the additional fines, the amount and rate of **bleeding** of these concretes is often reduced. This is especially significant when silica fume is used. Reduced bleeding, in conjunction with slower setting characteristics, can cause plastic shrinkage cracking and may warrant special precautions during placing and finishing. (See CIP 5)

Strength - Concrete mixtures can be proportioned to produce the required strength and rate of strength gain as required for the application. With supplementary cementitious materials other than silica fume, the rate of strength gain might be lower initially, but strength gain continues for a longer period compared to mixtures with only portland cement, frequently resulting in higher ultimate strengths. Silica fume is often used to produce concrete compressive strengths in excess of 10,000 psi [70 MPa]. Concrete containing supplementary cementitious material generally needs additional consideration for curing of both the test specimens and the structure to ensure that the potential properties are attained.

Durability - Supplementary cementitious materials can be used to reduce the heat generation associated with cement hydration and reduce the potential for thermal cracking in massive structural elements. These materials modify the microstructure of concrete and reduce its permeability thereby reducing the penetration of water and water-borne salts into concrete. Watertight concrete will reduce various forms of concrete deterioration, such as corrosion of reinforcing steel and chemical attack. Most supplementary cementitious materials can reduce internal expansion of concrete due to chemical reactions such as alkali aggregate reaction and sulfate attack. Resistance to freezing and thawing cycles requires the use of air entrained concrete. Concrete with a proper air void system and strength will perform well in these conditions.

The optimum combination of materials will vary for different performance requirements and the type of supplementary cementitious materials. The ready mixed concrete producer, with knowledge of the locally available materials, can establish the mixture proportions for the required performance. Prescriptive restrictions on mixture proportions can inhibit optimization and economy. While several enhancements to concrete properties are discussed above, these are not mutually exclusive and the mixture should be proportioned for the most critical performance requirements for the job with the available materials.

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2000, 2014

Concrete in Practice
What, why & how?
NRMCA

CIP 31 - Ordering Ready Mixed Concrete

WHAT is Ready Mixed Concrete

Concrete is a mixture of cementitious materials, water, aggregate, usually sand and gravel or crushed stone. Chemical admixtures and other products are used to enhance its fresh and hardened properties.

Ready mixed concrete is that which is manufactured and delivered to the customer in a freshly mixed and unhardened state. The customer is typically a concrete contractor. Ready mixed concrete is manufactured and delivered in accordance with ASTM C94, *Specification for Ready Mixed Concrete*.

There is no typical *recipe* for concrete mixtures. Concrete mixture materials and quantities vary depending on the required properties of fresh and hardened concrete. Concrete mixture composition is best developed by the concrete producer based on the requirements for specific applications as stated by the purchaser. Ready mixed concrete should have properties in its fresh state that will facilitate handling, placing and finishing. In its hardened state, concrete should achieve the strength and durability properties required by the designer of the structure. These would depend on the anticipated loads, environmental exposure, and service conditions.

The materials for a concrete mixture are accurately weighed and mixed, either in a mixer at the concrete plant or in a concrete truck mixer. It is typically delivered in a truck mixer, which keeps the concrete uniformly mixed until it is discharged at the placement location. Concrete remains in a fluid or unhardened condition for a sufficient period of time for it to be placed and finished. Concrete normally sets or hardens within two to eight hours after mixing and continues to gain strength for months or even years if it is properly cured during the first few days.

WHY Use Ready Mixed Concrete

Concrete is a popular, economical, and versatile building material. Concrete mixtures can be customized to provide color, texture, shape, strength and other properties required for various applications. It can be delivered at varying consistency appropriate to the placement methods. It can be proportioned to achieve a wide range of strength levels and to be durable in diverse environmental exposures and service conditions.

Concrete can serve its function for several years with minimum maintenance, provided the proper mixture relative to the application and established construction practices are used.

HOW to Order Ready Mixed Concrete

When placing an order for ready mixed concrete it is important to provide the basic information and to keep the requirements as simple as possible and relevant to the application. There may be different concrete mixtures needed for the different parts of a structure being constructed. The ready mixed concrete producer maintains several mixture formulations for a variety of applications and can help with selecting the right mixture for the project. The purchaser should provide a copy of project specifications if such applies to the project.

When ordering concrete include the following information:

Size of coarse aggregate—the nominal maximum size of aggregate should be smaller than the narrowest dimension through which concrete should flow, such as the thickness of the section, space between embedments and formwork, and spacing of the reinforcing steel, if any. For most applications, nominal maximum size of coarse aggregate is 3/4 or 1 in. (19.0 or 25.0 mm).

Slump—is a measure of consistency of concrete when it is delivered. For most applications slump required is 3 to 5 inches (75 to 100 mm). For slip-form construction maximum slump of 2 inches (50 mm) is applicable, while higher slump of 7 – 9 inches (175 – 225 mm) may be needed for basement walls, pumped concrete or when there is congested reinforcement. ASTM C94 states tolerances for slump. Adjustments are permitted at the jobsite to achieve the slump within tolerances. Water addition requested should not be excessive so as to cause segregation or reduce the quality of concrete to less than that required. Jobsite water addition can increase air content.

Air Content—Air-entrained concrete is required for concrete exposed to freezing temperatures in service. Air-entrained concrete is the default option for exterior concrete in many regions. When non air-entrained concrete is required this should be clearly stated. Target air content depends on the size of the coarse aggregate and the typical range is 4 to 6% of the concrete volume. The tolerance on air content as delivered is ±1.5%. The concrete supplier is permitted to make an adjustment for air content at the jobsite.

Quality required—The purchaser specifies the quality amd performance requirements for concrete.

The preferred method for ordering concrete is by specifying **performance** requirements that can be measured by a standard test. Concrete strength is commonly specified. Other performance characteristics, such as permeability, shrinkage or other durability requirements may be specified when appropriate to the exposure and service conditions. The concrete producer is best equipped to develop concrete mixtures, mix and supply concrete for the desired performance. The strength level is generally established by the design of the structure based on the design loads or durability requirements. Specified strength of 3500 to 5000 psi (25 to 35 MPa) is typical for most concrete applications and generally ensures durable concrete, such as resistance to wear, abrasion, and freezing and thawing cycles.

Alternatively, concrete can be ordered by **prescription** whereby the purchaser states details on the materials and quantities that make up the concrete mixture. Frequently, this approach is used when prescriptive mixture formulations have worked well in the past. This approach does not allow the producer much flexibility thereby cannot assume responsibility on the actual performance of concrete.

A mixture designation should be established for each type of mixture required on a project to ensure that concrete is placed in the correct location.

Quantity of concrete—Concrete is sold by volume, in cubic yards (cubic meters), in a freshly mixed unhardened state as discharged from the truck mixer. The basis of sale is addressed in ASTM C94. The capacity of a truck mixer is between 8 to 12 cubic yards (5 to 9 cubic meters).

Quantity of concrete ordered should be 4% to 10% more than an estimate from the plan dimensions to account for contingencies such as waste, over-excavation, spreading of forms, etc. See CIP 8. Make a good estimate of concrete required for the job before placing an order and reevaluate the quantity required to complete a placement. Avoid ordering excessive concrete or small clean-up loads less than 4 cubic yards (2.5 cubic meters).

Additional Items—A variety of value-added options are available from the ready mixed concrete producer. Chemical admixtures can modify the setting characteristics of concrete to aid in placing and finishing during hot or cold weather. Water reducing admixtures can increase slump without adding water and reducing strength. Admixtures can be used to retain workability for longer periods if needed. Synthetic fibers can reduce the potential for plastic shrinkage cracking. Color or special aggregates can enhance aesthetic characteristics. The concrete contractor is a resource for decorative options.

Scheduling delivery—Schedule the delivery of concrete to support the construction schedule. Inform the producer of the correct address, location and nature of the pour, rate of delivery based on placement methods, and estimated delivery time and pour duration. Call and place the order with the ready mixed concrete producer well in advance of the required delivery date. Concrete is a perishable product and the construction crew should be ready for concrete placement when the truck arrives. Notify the producer of any schedule changes or work stoppage immediately.

Ensure that the truck mixer has proper access to the placement location. A loaded concrete truck weighs about 80,000 lbs. (36,000 kg) and may not be able to maneuver on loose dirt and residential curbs and pathways. Consider alternative conveying and placing methods when access is limited

WHAT are the Responsibilities

The responsibilities of the various parties involved in the construction process should be addressed at a pre-construction meeting, especially on a large project. These responsibilities should be documented and distributed to all concerned for reference during the construction.

- The purchaser is responsible for communicating all information to the producer that is necessary to comply with a project specification and other project needs.
- The concrete producer is responsible for the concrete slump as specified for a period of 30 minutes after the requested time or the time the truck arrives at the site, whichever is later.
- The concrete producer is required to deliver concrete at the requested slump and air content, within tolerances, as measured at the point of discharge from the transportation unit.
- When placing procedures can potentially alter the characteristics of the fresh concrete, it is the responsibility of the purchaser to inform the producer of changes to the mixture requirements to accommodate these effects. An example is pumping concrete in place.
- When a job uses more than one type of concrete mixture, it is the purchaser's responsibility to verify the mixture delivered, based on pre-established designation, and direct it to the correct placement location.
- The purchaser should check and sign the delivery ticket and document any special occurrences on the ticket.
- The concrete producer cannot be responsible for the quality of concrete when any modification or additions are made to the mixture at the jobsite. These include addition of excessive water, admixtures, fibers or special products, or if the purchaser is not ready to accept the concrete in the placement location.
- When strength tests are used for acceptance of concrete, the samples should be obtained at the point of discharge from the transportation unit. The purchaser or his representative should ensure that facilities are available for curing test specimens at the jobsite and that standard practices are fol-lowed for subsequent curing and testing. Certified personnel should conduct the tests. Test reports should be forwarded to the producer in a timely manner so that deficiencies are rectified.

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4. *Guide for Measuring, Mixing, Transporting and Placing Concrete*, ACI 304R, American Concrete Institute, Farmington Hills, MI, www.concrete.org

CAUTION

Fresh concrete can cause severe chemical burns to skin and eyes. Keep fresh concrete off your skin. When working with concrete use rubber work-boots, gloves, protective eyeglasses, clothing and knee-boards. Do not let concrete or other cement products soak into clothing or rub against your skin. Wash your skin promptly after contact with fresh concrete with clean water. If fresh concrete gets into your eyes, flush immediately and repeatedly with water and consult a doctor immediately. Keep children away from dry cement powder and all freshly mixed concrete.

2000, 2016

Concrete in Practice
What, why & how?
NRMCA

CIP 32 - Concrete Pre-Construction Conference

WHAT is a Pre-Construction Conference?

Prior to the start of a job, especially for a major project, a concrete pre-construction conference (some times called a pre-pour meeting) should be held to define and allocate responsibilities of the entire construction team. It is imperative that all members of the team meet to establish the responsibilities of the ready mixed concrete supplier, owner, architect, structural engineer, general contractor, sub contractors, testing agencies, and inspectors. This meeting should be held well in advance of the project to ensure there is sufficient time for all parties to be absolutely clear on what their responsibilities would entail.

WHY Have a Pre-Construction Conference?

Every construction project brings together different companies, personnel and procedures, who may or may not have worked together before. Two jobs are never the same, even when working with the same companies, as personnel changes can realign the perception of individual responsibilities. Pre-construction conferences are needed to sort out the details of how a job will be executed, identify the authorized contacts for various aspects, and what should be done if some things do not go as planned. In far too many cases, projects are started without a clear understanding of assigned responsibilities resulting in extra work, lost time and major expenses. In some cases a simple pre-construction conference could have prevented some, if not all these problems from occurring. Having this meeting serves to document the chain of responsibilities, which can be referenced when needed.

HOW to Conduct Pre-Construction Conferences?

The pre-construction conference agenda should contain the following to ensure that all details are addressed prior concrete placement.

Purpose: To define and allocate individual responsibilities of the concrete construction team

Subject: Pre-construction agenda, concrete mix designs, placement, inspection and testing

Project Name and Location: Establish the project name and address.

Personnel to Attend: Contractor's project manager, owner's representative, concrete subcontractor, architect, engineer, testing lab supervisor, pumping contractor, concrete producer's quality control director, inspector and construction manager, if applicable, and anyone else with the need to know.

Minutes of the Meeting: Assign someone to take minutes. Establish a meeting distribution list.

Concrete Mix Design and Specifications: Have the mix designs been approved and what is the approval process? Are there any special concrete performance requirements or conditions? Are value-added admixtures approved for use and who can authorize them?

Ordering Concrete and Scheduling Deliveries: Ensure that concrete delivery schedules are in place. Establish the lead-time needed to place the order, especially for large placements or special concrete, and establish links of communication for last minute cancellations. Establish who has the authority to place and cancel concrete orders. Establish truck staging areas and location to wash out trucks and disposing of excess concrete.

Plant Inspections: Are plant inspections required? If so who will do the inspections and what will it entail. Will an NRMCA certification be accepted?

Job Inspections: Who is responsible for inspection and approval of forms and rebar prior to concrete placement? Who is responsible for approving adequacy of subgrade preparation for concrete slabs on grade? Who is responsible for placing and consolidation of concrete? Who will ensure that proper methods of finishing and curing are employed? What method will be used and for how long will concrete be cured? What is the minimum concrete strength required for stripping form? Will there be a formal report form for stripping forms? Will there be any in-place strength testing? Who is responsible to authorize form removal? Where will field-cured cylinders be stored and for what purpose will they be tested?

Sampling and Testing: What procedure will be followed for acceptance samples? What is the frequency for sampling and testing concrete? Will concrete be sampled as it is discharged from the truck mixer or at another location? What tests will be performed? Who will conduct the testing and who will verify that the technicians are certified? How many test cylinders will be made, how will they be cured, and at what ages will they be tested? What procedure is followed for non-conformance to specification?

Acceptance and Rejection Responsibilities for Fresh Concrete: Who has the authority to add water to the concrete on site? Who has the authority to reject concrete delivery? For what reasons can concrete be rejected? What are the tolerances for slump, air content, unit weight, and temperature? Establish re-test procedures for concrete prior to rejection.

Specimen Handling: How will cylinders be stored at the jobsite? Who is required to provide the initial curing environment for the test cylinders and how will controlled temperature and moisture be maintained? How will test cylinders be transported on weekends or non-workdays and who will arrange for access on to the site? What curing procedure is used at the testing facility? Verify that cylinders will be handled, transported and cured in accordance with ASTM C 31, or other applicable standards.

Report Distribution and Acceptance Criteria: Define the time frame for the report distribution and who will get copies of test reports. What will be on the reports and what will be the strength acceptance criteria: ACI 318, ASTM C 94 or other?

Testing of In-Place Concrete: The meeting should address what situations will require additional testing. How will the test results be evaluated, and by whom? Who incurs the expense for additional evaluations?

The items listed above are examples of some of the issues that should be discussed at a pre-construction conference. It also provides the opportunity for all involved parties to thoroughly review the specification and contract documents and if necessary make changes and improvements to them. It will also provide an understanding of responsibilities, which should be documented, for future reference.

References

1. *Ready Mixed Concrete Quality Control Checklist*, Quality Control Manual - Section 1, NRMCA, Silver Spring, MD.
2. *Concrete Pre-Construction Checklist,* Georgia Concrete & Products Association, 1st Edition.
3. *NRMCA-ASCC Checklist for the Concrete Pre-Construction Conference*, NRMCA, Silver Spring, MD.

SUGGESTED PRE-CONSTRUCTION CONFERENCE AGENDA ITEMS

- Project information and schedule
- Project participants
- Construction sequence and processes
- Base/subgrade construction and acceptance
- Site access
- Power, lighting, water
- Formwork and removal
- Placing concrete - equipment and procedures
- Vapor retarders/barriers
- Consolidation
- Finishing
- Requirements for surface finishes
- Jointing
- Curing and sealing
- Protection of concrete
- Hot and cold weather precautions
- Concrete materials and mixtures
- Specification requirements for concrete
- Jobsite adjustments
- Special materials
- Ordering and scheduling concrete delivery
- Quality control / Quality assurance
- Report distribution
- Corrective actions
- Test specimen storage, transportation and testing
- Acceptance/rejection of fresh and hardened concrete
- In-place concrete strength evaluation
- Dispute resolution and cost assignment
- Jobsite environmental management
- Jobsite safety

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Concrete in Practice
What, why & how?
NRMCA

CIP 33 - High Strength Concrete

WHAT is High Strength Concrete

It is a type of high performance concrete generally with a specified compressive strength of 8,000 psi (55 MPa) or greater. Today compressive strengths exceeding 20,000 psi (140 MPa) have been used in cast-in-place buildings. While the unit cost of high strength concrete is higher, significant cost savings are possible with optimized design of structural members for the same structural capacity.

The compressive strength is measured on 6 × 12 inch (150 × 300 mm) or 4 × 8 inch (100 × 200 mm) test cylinders generally at 56 or 90-days or some other specified age depending upon the application. Special attention and expertise is required for development, quality control, and production of high strength concrete. More attention to detail is essential for testing high strength concrete. For high strength concrete design details and empirical relationships between mechanical properties may differ from those assumed for conventional concrete. When critical to the design, these should be established from research references or developed by additional testing.

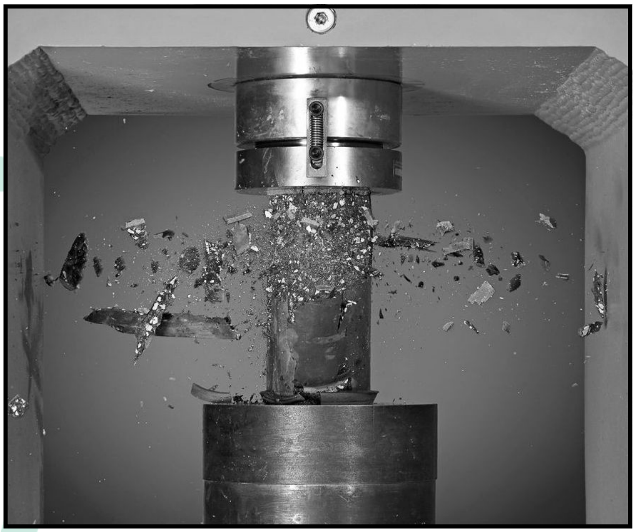
WHY Use High Strength Concrete

a. To put the concrete into service at an earlier age, for example opening the pavement to traffic or for post-tensioned members.

b. To reduce size and reinforcement in structural members, such as columns, and increase useable space, especially in high-rise buildings.

c. To build the superstructure of long-span bridges and to enhance the durability of bridge structures.

d. To achieve special properties for some applications such as abrasion resistance, modulus of elasticity, and flexural strength. Applications include dams, grandstand roofs, marine foundations, parking garages, and heavy duty industrial floors. Special properties may only be achieved with high strength concrete, which allows for more efficient structural design. High strength does not assure durable concrete. Specific requirements should address requirements for durability based on the exposure conditions.



HOW are Mixtures Developed

Developing high strength concrete mixtures involves selecting the right materials and optimizing the mixture proportions. Considerable testing and evaluation may be required to achieve the required workability and strength and other hardened concrete properties required by the designer of the structure. The limitations of concrete materials to produce high strength concrete should be recognized. Occasionally the use of some locally available materials may be precluded. It is imperative that the specification clearly state the performance requirements that can be measured by available standard test methods and clearly defined acceptance criteria. Prescriptive details that constrain the use of materials or optimizing mixture proportions should be avoided.

Some of the basic concepts that need to be understood for high strength concrete are:

1. Aggregates should be strong and durable. They need not necessarily be of high strength but need to be compatible, in terms of stiffness and strength, with the cementitious paste. Generally smaller maximum size coarse aggregate is used for higher strength concretes. Sand may have to be coarser requirements in ASTM C33 (fineness modulus greater that 3.2) because of the high fines content from the cementitious materials.

2. High strength concrete mixtures will contain a higher quantity of cementitious materials content. One or more supplementary cementitious materials, such as fly ash, slag cement, silica fume, metakaolin or natural pozzolans, will be required. The total cementitious material content will be in the range of 700 to 1000 lbs/yd^3 (400 to 600 kg/m^3). This can increases the heat of hydration and may result in higher shrinkage leading to the increased potential for cracking.
3. High strength concrete mixtures generally need to have a low water-cementitious materials ratio (w/cm) in the range of 0.23 to 0.35. These low w/cm ratios are only attainable with higher than typical dosage of high range water reducing admixtures (or superplasticizers) conforming to ASTM C494, Type F or G. A Type A water reducer may be used in combination. Other admixtures that modify the rheology of fresh concrete and retain workability for difficult placements may be necessary.
4. Air entrainment in high strength concrete will greatly reduce the strength potential, more so than in conventional concrete.

Additional lead time may be necessary for mixture development and evaluation, especially if the specification sets limits for other concrete properties such as creep, shrinkage, and modulus of elasticity. Some of these tests are specialized and can only be performed by a few testing agencies. The testing for evaluation can be more expensive than traditional tests on concrete. The engineer may choose to assume values on these properties based on published empirical relationships for the design of the structure.

Lower creep and shrinkage and high modulus of elasticity can be achieved by increasing the volume of aggregate and minimizing the paste volume in the mixture. This would typically entail using the largest size aggregate possible and medium to coarsely graded fine aggregate. Smaller maximum size aggregate are typically used to produce very high compressive strength. This increases the paste volume and make it difficult to achieve required properties like creep, shrinkage, and modulus of elasticity. Adding more cementitious material to increase strength levels is typically not appropriate or effective. Factors such as deleterious materials in aggregates, aggregate coatings, coarse aggregate fracture faces, shape and texture, and testing limitations may prevent higher strength from being achieved. Concrete mixtures developed in the laboratory are often validated by test production batches.

The production, transportation, placement and finishing of high-strength concrete can differ significantly from procedures used for conventional concrete. For projects requiring a larger volume of high strength concrete it is highly recommended that a trial pour and evaluation be conducted and included as a pay item in the contract. Pre-bid and pre-construction meetings are very important to ensure the success of projects using high strength concrete. During construction special measures should be taken to protect against plastic shrinkage and thermal cracking in thicker sections. Longer time may be needed for shoring and formwork removal.

High strength concrete test cylinders should be carefully molded, cured, and tested. Extra care and attention should be paid to handling test cylinder specimens for initial curing in the field. Some high strength concrete mixtures may set slower than conventional concrete. ASTM standards have specific procedures for testing high strength concrete. Specimen size is typically 4 x 8 in. (100 x 200 mm) cylinders. Temperature during initial curing should be maintained in the range of 68 to 78°F (20 to 26°C). Transporting cylinders from the jobsite to the laboratory may need to be delayed if the mixture takes longer to set. Unbonded caps are not permitted to test cylinders if the specified strength exceeds 12,000 psi. (85 MPa). Ends of cylindrical specimens should be capped with high strength sulfur mortar or ground to the required planeness. The testing machine should have adequate load capacity and test specimens should be tested to complete failure. Improper procedures when testing high strength concrete will have significant financial implications and will delay project schedules.

References

1. *Report on High Strength Concrete*, ACI 363R, ACI, Farmington Hills, MI, www.concrete.org.
2. *Guide to Quality Control and Assurance of High Strength Concrete*, ACI 363.2R, ACI, Farmington Hills, MI.
3. *Getting Started with High-strength Concrete*, Ron Burg, The Concrete Producer, November 1993.
4. *Effects of Testing Variables on the Measured Compressive Strength of High Strength (90 MPa) Concrete*, N.J. Carino, et al., NISTIR 5405, October 1994, NIST, Gaithesburg, MD, *www.nist.gov*.
5. *10,000 psi Concrete*, James E. Cook, ACI Concrete International, October 1989, ACI, Farmington Hills, MI.

2001, 2016

Concrete in Practice
What, why & how?
NRMCA

CIP 34 - Making Cylinders In the Field

WHAT are Concrete Test Cylinders?

Most commonly, the compressive strength of concrete is measured to ensure that concrete delivered to a project meets the requirements of the specification and for quality control. For testing the compressive strength of concrete, cylindrical test specimens of size 4 × 8-in. (100 × 200-mm) or 6 × 12-in. (150 × 300-mm) are cast and stored in the field until the concrete hardens in accordance with the requirements of ASTM C 31, *Standard Practice for Making and Curing Concrete Test Specimens in the Field*.

Technicians making cylinders in the field should be certified by the ACI Field Testing Certification Grade I, or an equivalent program. When making cylinders for acceptance of concrete, the field technician must test other properties of the fresh concrete to include temperature, slump, density (unit weight) and air content. This information should be included on the strength test report for a particular pour or pour location. A strength test result is always the average of at least two specimens tested at the same age. A set of 2 to 6 cylinders may be made from the same sample of concrete at a minimum for every 150 cubic yards (115 m^3) of concrete placed.

WHY Make Concrete Test Cylinders?

According to ASTM C31, strength results of *standard-cured* cylinders are used for:

- Acceptance testing for specified strength,
- Verifying mixture proportions for strength,
- Quality control

It is important that the specimens are made and cured following standard procedures. Any deviation from standard procedures will result in a lower measured strength and cause undue concern, cost, and delay to the project.

Field-cured cylinders are used for:

- Determining when structure can be put into service,
- Comparing with results of standard-cured specimens or in-place tests,
- Evaluating the adequacy of curing and protecting concrete in the structure, and
- Scheduling removal of forms or shoring

Because of the different purposes for strength test results, procedures for standard-curing differ from field-curing and the two should not be confused. Refer to ASTM C31 for details.

Making and Curing Cylinders in the Field

HOW to Make Concrete Test Cylinders?

Equipment needed at the job site:

- Molds for casting specimens,
- Standard tamping rod or vibrator,
- Standard rubber or rawhide mallet,
- Shovel, scoop, handheld float or trowel,
- Wheelbarrow or other sample container,
- Water tank or curing box capable of maintaining curing environment during initial curing period,
- Safety equipment to handle fresh concrete.

Sampling concrete:

It is critical that the sample of concrete obtained from the delivery vehicle is representative of the of the load. Sampling should be conducted in accordance with ASTM C172. Concrete should be sampled from the middle of the load. The first or last 10% of the discharge will not be representative and should not be used for the sample. From a truck mixer, the entire discharge stream should be diverted into a wheelbarrow. At least two portions are necessary to obtain a composite sample. The time between the first and final portion of the composite sample must not exceed 15 minutes. Minimum sample size required is 1 cu. ft. (28 L).

Prior to Casting Cylinders:

Cover the sample to protect it from evaporation, sunlight, and contamination. Move the sample to the location where the fresh concrete tests will be conducted and where the cylinders will be stored for the initial curing period. Remix the concrete in the wheelbarrow. Begin slump, density (unit weight), and air content tests within 5 minutes and start molding cylinders within 15 minutes after the sample was obtained.

Casting Test Cylinders:

- Cylinder identification labels should be placed on the outside of the mold and not on the lids or tops
- Place the cylinder molds on a level surface
- Consolidation—Use vibration for concrete slump less than 1-in. (25-mm); rodding or vibration is permitted when slump 1-in. (25-mm) or higher,
- Layers—For samples that are vibrated, fill mold in two equal layers; for rodded samples, place concrete in 3 equal layers for 6 × 12-in. cylinders and in 2 equal layers for 4 × 8-in. cylinders
- Distribute concrete inside the mold with the scoop. Rod each layer 25 times evenly distributed. For vibration, insert it long enough until large air bubbles are released. Two insertions of the vibrator are required for 6 × 12-in. and one insertion for 4 × 8-in. cylinders. Avoid over vibration. Consolidate bottom layer throughout its depth; for upper layers penetrate 1-in. (25-mm) into underlying layer.
- Tap sides of the mold 10-15 times with the mallet to close any insertion holes formed during consolidation.
- Strike off the top with a wood float or trowel to produce a flat and even surface level with the edge of mold. Cover with a plastic lid or a plastic bag.

Storing and transporting test cylinders:

- Move cylinder molds with fresh concrete very carefully by supporting the bottom
- Place the cylinders on a flat surface and in a controlled environment. Maintain temperature during initial curing in the range of 60-80ºF (16-27ºC). When concrete specified strength is greater than 6000 psi (40 MPa), the maintain temperature in the range of 68-78ºF (20-26ºC). Immersing cylinders, completely covered in water is an acceptable and preferred procedure that ensures more reliable strength results. Temperature in storage containers should be controlled using heating and cooling devices as necessary. The maximum and minimum temperature should be recorded and reported.
- Protect cylinders from direct sunlight or radiant heat and from freezing temperatures in winter.
- Cylinders must be transported back to the laboratory within 48 hours of casting. Cylinders should not be moved until at least 8 hours after final set.

When transporting cylinders, they should be protected to prevent damage, maintain temperature and prevent loss of moisture. Transportation duration from the jobsite to the laboratory should not exceed 4 hours.

Responsibilities and Reports

ACI 301 states that it is the contractor's responsibility to provide space and source of electrical power on the project site for initial curing of concrete test specimens. In some locations it is customary for the contractor to provide equipment and storage for initial curing of test cylinders. If not provided, it is incumbent on the testing agency to have such equipment available. The strength test report should include information required by ASTM C39—storage and curing of specimens before testing; location in the work represented by each strength test, date and time of sampling and batch ticket number. Distribution of test reports to all stakeholders, including concrete producers, should be done within 7 days according to ACI 301. Distribution of all strength test reports is also required by ACI 318.

CAUTION

Fresh concrete can cause severe chemical burns to skin and eyes. Keep fresh concrete off your skin. When working with concrete use rubber work-boots, gloves, protective eyeglasses and clothing. Do not let concrete or other cement-based products soak into clothing or rub against your skin. Wash your skin promptly after contact with fresh concrete with clean water. If fresh concrete gets into your eyes, flush immediately and repeatedly with water. Consult a doctor immediately. Keep children away from all freshly mixed plastic concrete.

References

1. ASTM Standards C31, C39, C172—Annual Book of ASTM Standards, Volume 04.02 , ASTM, West Conshohocken, PA, www.astm.org
2. *How Producers can Correct Improper Test-Cylinder Curing*, Ward R. Malisch, The Concrete Producer, Nov 1997, pp. 782 – 805, *www.theconcreteproducer.com*
3. NRMCA/ASCC Checklist for Concrete Pre-Construction Conference, NRMCA, Silver Spring, MD, *www.nrmca.org*
4. ACI 301 and ACI 318, American Concrete Institute, Farmington Hills, MI, *www.concrete.org*

Follow These Procedures to Make and Cure Standard-Cured Strength Test Specimens

1. Obtain a representative concrete sample
2. Place the concrete in layers in the molds and consolidate using standard equipment and procedures
3. Finish the surface smooth and cover the cylinder with a cap or plastic bag
4. For initial curing, store cylinders in the required temperature range. Protect from direct sunlight or extreme weather.
5. Transport the cylinders to the laboratory, properly protected, within 48 hours after they are made.

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Concrete in Practice
What, why & how?
NRMCA

CIP 35 - Testing Compressive Strength of Concrete

WHAT is the Compressive Strength of Concrete?

Concrete mixtures can be designed to provide a wide range of mechanical and durability properties to meet the design requirements of a structure. The compressive strength of concrete is the most common performance attribute used by the engineer when designing structures. Compressive strength is measured by breaking cylindrical concrete specimens in a compression-testing machine. Compressive strength is calculated from the failure load divided by the cross-sectional area resisting the load and reported in units of pound-force per square inch (psi) or megapascals (MPa). Concrete compressive strength can vary from 2500 psi (17 MPa) for residential concrete to 4000 psi (28 MPa) and higher in commercial structures. Some applications use higher strengths, greater than 10,000 psi (70 MPa).

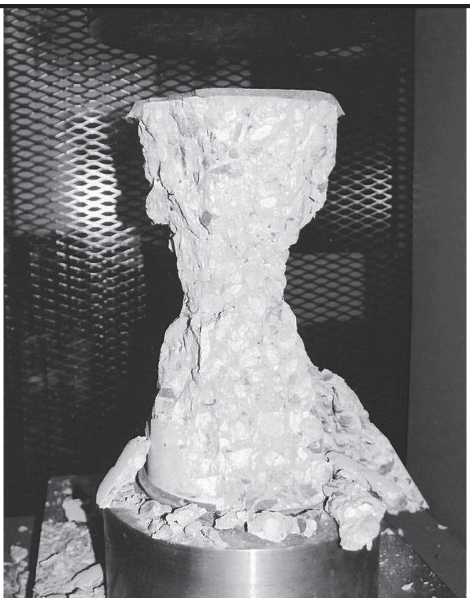
WHY is Compressive Strength Determined?

Compressive strength results are used to ensure that the concrete mixture as delivered meets the requirements of the specified strength, f'_c, in the job specification.

Strength test results from cast cylinders may be used for quality control, acceptance of concrete, for estimating the strength in a structure, or for evaluating the adequacy of curing and protection afforded to the structure. Standard-cured cylinders are tested for acceptance and quality control. Field-cured cylinders are tested for estimating the in-place concrete strength. Procedures for standard-curing and field-curing are described in ASTM C31. Cylindrical specimens are tested in accordance with ASTM C39. Standard sizes of test specimens are 4×8 in. (100×200 mm) or 6×12 in. (150×300 mm) concrete cylinders. The smaller specimens tend to be easier to make and handle in the field and the laboratory.

A strength test result is the average of at least two strength specimens made from the same concrete sample and tested at the same age. In most cases strength requirements for concrete are at an age of 28 days.

Design engineers use the specified strength f'_c to design concrete members. The specified strength is stated in project specifications. The concrete mixture is designed to produce an average strength, f'_{cr}, higher than the specified strength so that the possibility of strength tests failing the acceptance criteria is very low. Historical strength test records from a similar concrete are used to establish the target average strength of concrete mixtures. TIP 2 discusses the process of establishing the required average strength for concrete mixtures.



Fractured Test Specimen at Failure

To comply with the strength requirements of a specification both the following acceptance criteria apply:

- The average of 3 consecutive tests should equal or exceed the specified strength, f'_c
- No single strength test should fall below f'_c by more than 500 psi (3.5 MPa); or by more than 0.10 f'_c when f'_c is more than 5000 psi (35 MPa)

The same strength acceptance criteria are applicable for either cylinder size. It is important to understand that an individual test falling below f'_c does not constitute non-compliance with the strength acceptance criteria. The probability of not complying with these acceptance criteria is about 1% and that for an individual strength tests to be less than the specified strength is about 10%. This is based on the assumption that the average of strength tests are around the required average strength, f'_{cr} at the same level of variability of the assumed standard deviation

When strength test results indicate that the concrete delivered fails to comply with the acceptance criteria, it is possible that the failure may be in the testing, and not the concrete. This is especially true if the fabrication, handling, curing and testing of the cylinders are not conducted in accordance with standard procedures. See CIP 9, Low Concrete Cylinder Strength.

HOW to Test the Strength of Concrete?

- Requirements for strength testing machines are stated in ASTM C39.
- The diameter of the cylinder used should be at least 3 times the nominal maximum size of the coarse aggregate used in the concrete.
- Recording the weight of the specimens before testing provides useful information in case of disputes.
- To provide for a uniform load distribution when testing, cylinders are capped with sulfur mortar (ASTM C617) or neoprene pad caps (ASTM C1231). Sulfur caps should be applied at least two hours and preferably one day before testing. Neoprene pad caps can be used to measure concrete strengths between 1500 and 12,000 psi (10 to 80 MPa). Durometer hardness requirements for neoprene pads vary from 50 to 70 depending on the strength level tested. Pads should be replaced after 100 uses; 50 when testing strength between 7000 and 12,000 psi (50 and 80 MPa). TIP 5 discusses capping concrete specimens.
- Cylinders should not be allowed to dry prior to testing.
- The cylinder diameter should be measured in two locations at right angles to each other at mid-height of the specimen and averaged to calculate the cross-sectional area. If the two measured diameters differ by more than 2%, the cylinder should not be tested.
- The ends of the specimens should not depart from perpendicularity with the cylinder axis by more than 0.5º and the ends should be plane to within 0.002 inches (0.05 mm).
- Cylinders should be centered in the compression-testing machine and loaded to complete failure. The loading rate on a hydraulic machine should be maintained in a range of 28 to 42 psi/s (0.20 to 0.30 MPa/s) during the latter half of the loading phase. The type of break should be recorded. A common break pattern is a conical fracture as seen in the figure.
- The concrete strength is calculated by dividing the maximum load at failure by the average cross-sectional area. C39 has correction factors if the length-to-diameter ratio of the cylinder is between 1.75 and 1.00, which is rare. At least two cylinders are tested at the same age and the average strength is reported as the test result to the nearest 10 psi (0.1 MPa)
- Information to be included in the report include the specimen identification, average measured diameter, cross-sectional area, test age, maximum load applied, compressive strength, type of fracture, any defects in the cylinders or caps and, when determined, the density to the nearest 1 lb/ft^3 (10 kg/m^3). Information required by C31 should be available—location of concrete in the structure represented by test specimens; date, time and individual molding cylinders; slump, air content, temperature and density measured on the concrete sample used to make test specimens; maximum and minimum temperatures during initial curing for standard cured specimens, or details of field curing.
- Most deviations from standard procedures for making, curing and testing concrete test specimens will result in a lower measured strength.
- The coefficient of variation between companion cylinders tested at the same age should be about 2 to 3%. If the difference between companion cylinders exceeds 8% for two or 9.5% for three more than 1 time in 20, the testing procedures should be evaluated and rectified.
- Strength test results made by different labs on the same concrete sample should not differ by more than about 14% of the average.
- If one or both of a set of cylinders break at strength below f'_c, evaluate the cylinders for obvious problems and hold the tested cylinders for later examination, possibly for petrographic examination. This provides an opportunity to correct a problem. In some cases additional reserve cylinders are made and can be tested if one cylinder of a set breaks at a lower strength.
- A 3 or 7-day test may help detect potential problems with concrete quality or testing procedures at the lab but is not a basis for rejecting concrete, with a requirement for 28-day or other age strength.
- ACI 318, ACI 301 and ASTM C1077 requires that laboratory technicians involved in testing concrete must be certified.
- Reports of compressive strength tests provide valuable information to the project team for the current and future projects. The reports of all strength tests should be forwarded to the concrete producer, contractor and the owner's representative as expeditiously as possible.

References

1. ASTM C 31, C 39, C 617, C 1077, C 1231, Annual Book of ASTM Standards, Volume 04.02, ASTM, West Conshohocken, PA, www.astm.org
2. CIP 9, *Low Concrete Cylinder Strength*, Concrete in Practice Series, NRMCA, Silver Spring, MD, www.nrmca.org
3. TIP 2 and 5, *Technology in Practice Series*, NRMCA, Silver Spring, MD.
4. *In-Place Strength Evaluation - A Recommended Practice*, NRMCA Publication 133, NRMCA RES Committee, NRMCA, Silver Spring, MD
5. *NRMCA/ASCC Checklist for Concrete Pre-Construction Conference*, NRMCA, Silver Spring, MD
6. *Review of Variables That Influence Measured Concrete Compressive Strength*, David N. Richardson, NRMCA Publication 179, NRMCA, Silver Spring, MD
7. *Tips on Control Tests for Quality Concrete*, PA015, Portland Cement Association, Skokie, IL, www.cement.org
8. ACI 214R, 301 and 318, American Concrete Institute, Farmington Hills, MI, www.concrete.org

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2003, 2014

Concrete in Practice
What, why & how?
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CIP 36 - Structural Lightweight Concrete

WHAT is Structural Lightweight Concrete

Structural lightweight concrete has an equilibrium density ranging from 90 to 120 lb/ft^3 (1440 to 1840 kg/m^3) compared to normalweight concrete with a density in the range of 140 to 150 lb/ft^3 (2240 to 2400 kg/m^3). For structural applications the specified compressive strength should be greater than 2500 psi (17.0 MPa). The concrete mixture can be proportioned with combinations of normalweight and lightweight (coarse and fine) aggregates to achieve the desired equilibrium density.

Lightweight aggregates used in structural lightweight concrete are typically expanded shale, clay or slate (ESCS) materials that have been fired in a rotary kiln to develop a porous structure. Other products include expanded blast furnace slag.

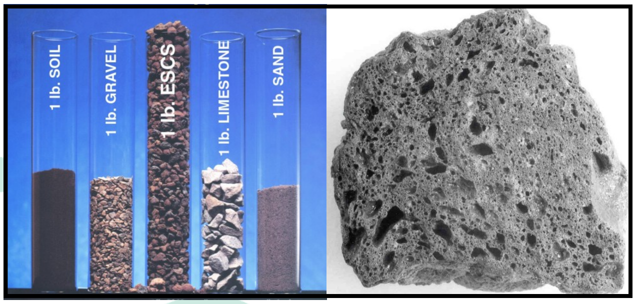
Other classes of non-structural lightweight concretes with lower density are made with other types of lightweight aggregate materials, like perlite, vermiculite, or pumice, and higher air voids in the cement paste, such as in cellular concrete. These are typically used for their insulation properties. This CIP focuses on structural lightweight concrete.

WHY Use Structural Lightweight Concrete

The primary use of structural lightweight concrete is to reduce the dead load on a structure. This allows the design to reduce the size of columns, footings and load bearing members. Structural lightweight concrete achieve similar strength, mechanical and durability properties as normalweight concrete. Structural lightweight concrete provides a more efficient strength-to-weight ratio in structural members. The marginally higher cost of the lightweight concrete is offset by reduced size of structural members, thereby reducing the volume of concrete and quantity of reinforcing steel for similar structural capacity.

In buildings, structural lightweight concrete provides a concrete structure with a higher fire rating. The higher R-values in walls provides improved insulation and can result in energy savings. The porosity of lightweight aggregate provides a source of water for internal curing of the concrete that provides continued enhancement of concrete strength and durability. This does not preclude the need for external curing.

Structural lightweight concrete has been used for bridge decks, piers and beams, slabs and wall elements in steel and concrete frame buildings, parking structures, tilt-up walls, topping slabs and composite slabs on metal deck.



HOW is Lightweight Concrete Used

Lightweight concrete is typically manufactured with combinations of normalweight and lightweight aggregates. Using all coarse and fine lightweight aggregates in a concrete mixture can decrease the concrete density to less than 90 lb/ft^3 (1440 kg/m^3).

Structural design of lightweight concrete members relies on the *equilibrium* density; the condition in which some moisture is retained within the lightweight concrete. Equilibrium density is a standardized value that represents the approximate density of the in-place concrete when it is in service. Equilibrium density is defined in ASTM C567, and can be calculated from the mixture proportions or measured as described in the standard. The calculated value is more commonly used. Project specifications should specify the equilibrium density of the lightweight concrete. Field acceptance is based on measured density of fresh concrete in accordance with ASTM C138. A correlation between fresh and equilibrium density for a specific mixture should be agreed upon prior to delivery of concrete. Equilibrium density is approximately 3 to 8 lb/ft^3 (50 to 130 kg/m^3) less than the fresh density. The tolerance for acceptance on fresh density is typically ±4 lb/ft^3 (±65 kg/m^3) from the target value.

Lightweight aggregates should comply with ASTM Specification C330. Due to the cellular nature of lightweight aggregate particles, absorption is in the range of 6% to 30% by weight of dry aggregate. Lightweight aggregates are maintained in a wet condition prior to use to achieve a high degree of saturation. This will prevent absorption by dry aggregate and result in loss of slump. Some concrete producers may not have the capability of prewetting lightweight aggregates in cold weather if temperature controlled storage is not available. Some lightweight aggregate suppliers furnish vacuum saturated aggregate.

The porous nature of the aggregate makes it difficult to separate the absorbed and free moisture for lightweight aggregate so as to estimate the mixing water content in a concrete mixture. Hence, the w/cm ratio of structural lightweight concrete cannot be precisely determined. While a maximum w/cm requirement for durability applies for conventional concrete, ACI 318 and ACI 301 waives this requirement and retains the minimum specified strength for lightweight concrete. Concrete producers may still proportion lightweight concrete mixtures using relationships between w/cm and strength or durability.

Lightweight concrete is typically air-entrained to achieve lower density. Air content of structural lightweight concrete must be closely controlled to ensure that the required density is being achieved. Testing for air content must be according to the volumetric method, ASTM C173. Underwriter Laboratory (UL) fire rating for most of the D9xx series requires air content to be in the range of 4 to 7%.

Finishing lightweight concrete requires proper attention to detail. Excessive amounts of water or excessive slump will cause the lightweight aggregate to segregate from the mortar. Bullfloating will generally provide an adequate finish. If an interior floor is to receive a hard troweled finish, use precautions to minimize the formation of blisters or delaminations. See CIPs 13 and 20. Requiring non-air entrained concrete because of finish requirements can result in non-compliance with specified density and impacts the fire rating of an assembly or the dead load assumptions used in design.

Moisture emission from concrete slabs and drying time to acceptable moisture levels for installation of floor coverings is sometimes an issue. With similar slab thickness, lightweight concrete has a higher total moisture content than does normalweight concrete. When comparing equivalent fire-rated floor assemblies studies have shown that drying time for lightweight concrete can be similar to that of normalweight concrete or can take longer by about two to three weeks. Admixtures and supplementary cementitious materials have been used to shorten the drying period of concrete slabs when necessary.

A modification factor (λ) is used in design of lightweight concrete members to reflect the lower tensile-to-compressive strength ratio compared to normalweight concrete. The factor varies between 0.75 and 1 depending lightweight aggregate content or equilibrium density. In some cases the designer may request tests of splitting tension and compressive strength to determine a mixture-specific λ-factor. Splitting tensile strength testing is not used as a basis for field acceptance of lightweight concrete.

Ensure that the requirements of the designer relative to fire resistance or insulation properties of lightweight concrete building elements are in conformance with applicable industry standards. For a successful project, information is available from the supplier of lightweight aggregate and the ready mixed concrete producer. With proper planning, structural lightweight concrete can provide an economical solution to many engineering applications.

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Guidelines For Pumping

Lightweight concrete placements frequently employ pumps and this can be done successfully when a few precautions are considered prior to the actual placement.

1. Aggregate should be adequately pre-soaked as pressure during pumping will drive water into the aggregate pores and cause slump loss that may result in plugging of the pump line and difficulties in placement and finishing.
2. Pump lines should be as large as possible, preferably 5-inch (125-mm) diameter, with a minimum number of elbows, reducers or rubber hose sections.
3. The lowest practical pressure should be used.
4. Pump location should be such that vertical free-fall of the concrete is minimized.
5. Adjustments to mixture characteristics, such as slump, aggregate content and air content may be necessary to ensure adequate pumpability for the job conditions.
6. Decide on where concrete samples for acceptance tests will be taken and what implications this would have on the concrete mixture proportions and properties as delivered to the jobsite.

2003, 2016

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CIP 37 - Self Consolidating Concrete (SCC)

WHAT is Self Consolidating Concrete?

Self consolidating concrete (SCC), also known as self compacting concrete, is a highly flowable, non-segregating concrete that can spread into place, fill the formwork and encapsulate the reinforcement without any mechanical consolidation. The flowability of SCC is measured in terms of spread when using a modified version of the slump test (ASTM C 143). The spread (slump flow) of SCC typically ranges from 18 to 32 inches (455 to 810 mm) depending on the requirements for the project. The viscosity, as visually observed by the rate at which concrete spreads, is an important characteristic of plastic SCC and can be controlled when designing the mix to suit the type of application being constructed.

WHY is SCC Used?

Some of the advantages of using SCC are:

1. Can be placed at a faster rate with no mechanical vibration and less screeding, resulting in savings in placement costs.
2. Improved and more uniform architectural surface finish with little to no remedial surface work.
3. Ease of filling restricted sections and hard-to-reach areas. Opportunities to create structural and architectural shapes and surface finishes not achievable with conventional concrete.
4. Improved consolidation around reinforcement and bond with reinforcement
5. Improved pumpability.
6. Improved uniformity of in-place concrete by eliminating variable operator-related effort of consolidation.
7. Labor savings.
8. Shorter construction periods and resulting cost savings.
9. Quicker concrete truck turn-around times enabling the producer to service the project more efficiently.
10. Reduction or elimination of vibrator noise potentially increasing construction hours in urban areas.
11. Minimizes movement of ready mixed trucks and pumps during placement.
12. Increased jobsite safety by eliminating the need for consolidation.

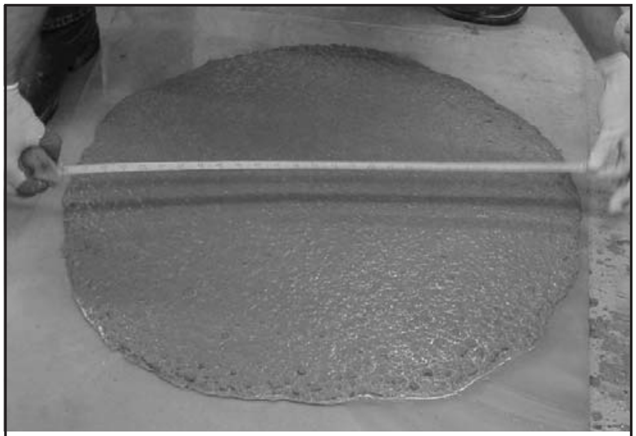

Figure 1: SCC with a slump flow of 29-inches (725-mm) tested by the slump flow test

HOW is SCC Achieved?

Two important properties specific to SCC in its plastic state are its *flowability* and *stability*. The high flowability of SCC is generally attained by using high-range-water-reducing (HRWR) admixtures and not by adding extra mixing water. The stability or resistance to segregation of the plastic concrete mixture is attained by increasing the total quantity of fines in the concrete and/or by using admixtures that modify the viscosity of the mixture. Increased fines contents can be achieved by increasing the content of cementititious materials or by incorporating mineral fines. Admixtures that affect the viscosity of the mixture are especially helpful when grading of available aggregate sources cannot be optimized for cohesive mixtures or with large source variations. A well distributed aggregate grading helps achieve SCC at reduced cementitious materials content and/or reduced admixture dosage. While SCC mixtures have been successfully produced with 1½ inch (38 mm) aggregate, it is easier to design and control with smaller size aggregate. Control of aggregate moisture content is also critical to producing a good mixture. SCC mixtures typically have a higher paste volume, less coarse aggregate and higher sand-coarse aggregate ratio than typical concrete mixtures.

Retention of flowability of SCC at the point of discharge at the jobsite is an important issue. Hot weather, long haul distances and delays on the jobsite can result in the reduction of flowability whereby the benefits of using SCC are reduced. Job site water addition to SCC may not always yield the expected increase in flowability and could cause stability problems.

Full capacity mixer truck loads may not be feasible with SCCs of very high flowability due to potential spillage. In such situations it is prudent to transport SCC at a lower flowability and adjust the mixture with HRWR admixtures at the job site. Care should be taken to maintain the stability of the mixture and minimize blocking during pumping and placement of SCC through restricted spaces. Formwork may have to be designed to withstand fluid concrete pressure and conservatively should be designed for full head pressure. SCC may have to be placed in lifts in taller elements. Once the concrete is in place it should not display segregation or bleeding/settlement.

SCC mixtures can be designed to provide the required hardened concrete properties for an application, similar to regular concrete. If the SCC mixture is designed to have a higher paste content or fines compared to conventional concrete, an increase in shrinkage may occur.

HOW to Test SCC?

Several test procedures have been successfully employed to measure the plastic properties of SCC. The slump flow test (see Figure 1), using the traditional slump cone, is the most common field test and is in the process of being standardized by ASTM. The slump cone is completely filled without consolidation, the cone lifted and the spread of the concrete is measured. The spread can range from 18 to 32 inches (455 to 810 mm). The resistance to segregation is observed through a visual stability index (VSI). The VSI is established based on whether bleed water is observed at the leading edge of the spreading concrete or if aggregates pile at the center. VSI values range from 0 for “highly stable” to 3 for unacceptable stability.

During the slump flow test the viscosity of the SCC mixture can be estimated by measuring the time taken for the concrete to reach a spread diameter of 20 inches (500 mm) from the moment the slump cone is lifted up. This is called the T_{20} (T_{50}) measurement and typically varies between 2 and 10 seconds for SCC. A higher T_{20} (T_{50}) value indicates a more viscous mix which is more appropriate for concrete in applications with congested reinforcement or in deep sections. A lower T_{20} (T_{50}) value may be appropriate for concrete that has to travel long horizontal distances without much obstruction.

The U-Box and L-Box tests are used for product development or prequalification and involve filling concrete on one side of the box and then opening a gate to allow the concrete to flow through the opening containing rebar. The J-ring test is a variation to the slump flow, where a simulated rebar cage is placed around the slump cone and the ability of the SCC mix to spread past the cage without segregation is evaluated. The U-box, L-box and J-ring tests measure the *passing ability* of concrete in congested reinforcement. Another test being standardized is a column test which measures the coarse aggregate content of concrete at different heights in a placed columnar specimen as an indication of stability or resistance to segregation.

HOW to Order or Specify SCC?

When ordering and/or specifying SCC, consideration must be given to the end use of the concrete. Ready mixed concrete producers will generally have developed mixture proportions based on performance and applications. The required spread (slump flow) is based on the type of construction, selected placement method, complexity of the formwork shape and the configuration of the reinforcement. ACI Committee 237 is completing a guidance document that will provide guidelines to select the appropriate slump flow for various conditions. The lowest slump flow required for the job conditions must be specified. This will ensure SCC can be attained easily with required stability and at the lowest possible cost. The hardened concrete properties should be specified by the design professional based on structural and service requirements of the structure. For the most part, hardened concrete properties of SCC are similar to conventional concrete mixtures. Based on the requirements of each project, SCC concrete designs can be submitted by the producer only after specification provisions regarding the performance of the concrete in its plastic and hardened state are clearly defined.

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2004

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CIP 38 - Pervious Concrete

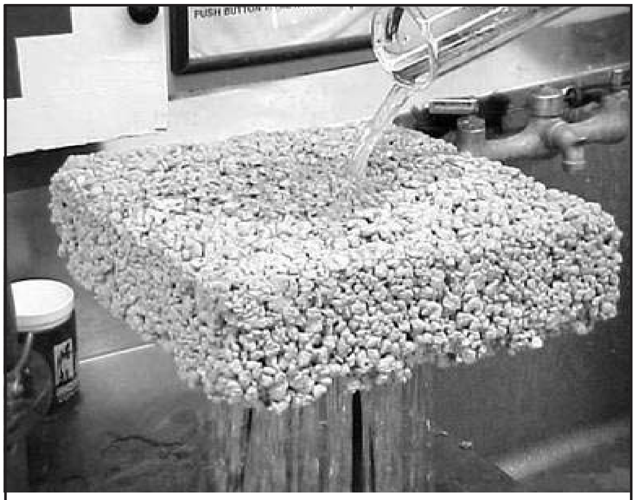
WHAT is Pervious Concrete?

Pervious concrete is a special type of concrete with a high porosity used for concrete flatwork applications that allows water from precipitation and other sources to pass through it, thereby reducing the runoff from a site and recharging ground water levels. The high porosity is attained by a highly interconnected void content. Typically pervious concrete has little to no fine aggregate and has just enough cementitious paste to coat the coarse aggregate particles while preserving the interconnectivity of the voids. Pervious concrete is traditionally used in parking areas, areas with light traffic, pedestrian walkways, and greenhouses. It is an important application for sustainable construction.

WHY Use Pervious Concrete?

The proper utilization of pervious concrete is a recognized Best Management Practice by the U.S. Environmental Protection Agency (EPA) for providing first-flush pollution control and storm water management. As regulations further limit storm water runoff, it is becoming more expensive for property owners to develop real estate, due to the size and expense of the necessary drainage systems. Pervious concrete reduces the runoff from paved areas, which reduces the need for separate storm water retention ponds and allows the use of smaller capacity storm sewers. This allows property owners to develop a larger area of available property at a lower cost. Pervious concrete also naturally filters storm water and can reduce pollutant loads entering into streams, ponds and rivers. Pervious concrete functions like a storm water retention basin and allows the storm water to infiltrate the soil over a large area, thus facilitating recharge of precious groundwater supplies locally. All of these benefits lead to more effective land use.

Pervious concrete can also reduce the impact of development on trees. A pervious concrete pavement allows the transfer of both water and air to root systems allowing trees to flourish even in highly developed areas.



Pervious Concrete permits storm water to percolate

HOW to Install Pervious Concrete Pavement?

An experienced installer is vital to the success of pervious concrete pavements. As with any concrete pavement, proper subgrade preparation is important. The subgrade should be properly compacted to provide a uniform and stable surface. When pervious pavement is placed directly on sandy or gravelly soils it is recommended to compact the subgrade to 92 to 96% of the maximum density (ASTM D 1557). With silty or clayey soils, the level of compaction will depend on the specifics of the pavement design and a layer of open graded stone may have to be placed over the soil. Engineering fabrics are often used to separate fine grained soils from the stone layer. Care must be taken not to over-compact soil with swelling potential. Moisten the subgrade prior to concrete placement, and wheel ruts from the construction traffic should be raked and re-compacted. Moistening the subgrade prevents pervious concrete from setting and drying too quickly.

Typically pervious concrete has a water to cementitious materials (w/cm) ratio of 0.35 to 0.45 with a void content of 15 to 25%. The mixture is composed of cementitious materials, coarse aggregate and water with little to no fine aggregates. Addition of a small amount of fine aggregate will generally reduce the void content and increase the strength, which may be desirable in certain situations. This material is sensitive to changes in water content, so field adjustment of the fresh mixture is usually necessary. The correct quantity of water in the concrete is critical. Too much water will cause segregation, and too little water will lead to balling in the mixer and very slow mixer unloading. Too low a water content can also hinder adequate curing of the concrete and lead to a premature raveling surface failure. A properly proportioned mixture gives the mixture a wet-metallic appearance or sheen.

A pervious concrete pavement may be placed with either fixed forms or slip-form paver. The most common approach to placing pervious concrete is in forms on grade that have a riser strip on the top of each form such that the strike off device is actually 3/8-1/2 in. (9 to 12 mm) above final pavement elevation. Strike off may be by vibratory or manual screeds, though vibratory screens are preferable. After striking off the concrete, the riser strips are removed and the concrete compacted by a manually operated roller that bridges the forms. Rolling consolidates the fresh concrete to provide strong bond between the paste and aggregate, and creates a smoother riding surface. Excessive pressure when rolling should be avoided as it may cause the voids to collapse. Rolling should be performed immediately after strike off.

Jointing pervious concrete pavement follows the same rules as for concrete slabs on grade, with a few exceptions. With significantly less water in the fresh concrete, shrinkage of the hardened material is reduced significantly, thus, joint spacings may be wider. The rules of jointing geometry, however, remain the same (See CIP 6). Joints in pervious concrete are tooled with a rolling jointing tool. This allows joints to be cut in a short time, and allows curing to continue uninterrupted.

Proper curing is essential to the structural integrity of a pervious concrete pavement. Curing ensures sufficient hydration of the cement paste to provide the necessary strength in the pavement section to prevent raveling. Curing should begin within 20 minutes of concrete placement and continue through 7 days. Plastic sheeting is typically used to cure pervious concrete pavements.

HOW to Test and Inspect Pervious Concrete Pavement?

Pervious concrete can be designed to attain a compressive strength ranging from 400 psi to 4000 psi (2.8 to 28 MPa) though strengths of 600 psi to 1500 psi (2.8 to 10 MPa) are more common. Pervious concrete, however, is not specified or accepted based on strength. More important to the success of a pervious pavement is the void content. Acceptance is typically based on the density (unit weight) of the in-place pavement. An acceptable tolerance is plus or minus 5 lb/cu.ft. (80 kg/m^3) of the design density. This should be verified through field testing. The fresh density (unit weight) of pervious concrete is measured using the jigging method described in ASTM C 29. Slump and air content tests are not applicable to pervious concrete. If the pervious concrete pavement is an element of the storm water management plan, the designer should ensure that it is functioning properly through visual observation of its drainage characteristics prior to opening of the facility. Questions have been raised about the freeze thaw durability of pervious concrete. Even though most of the experience with pervious concrete has been in warmer climates recently there have been several pervious concrete projects in colder climates. Pervious concrete in freeze thaw environment must not become fully saturated. Saturation of installed pervious concrete pavement can be prevented by placing the pervious concrete on a thick layer of 8 to 24 inches (200 to 600 mm) of open graded stone base. Limited laboratory testing has shown that entrained air may improve the freeze thaw durability even when the pervious concrete is in a fully saturated condition. However, the entrained air content cannot be verified by any standard ASTM test procedure.

EPA recommends that pervious concrete pavement be cleaned regularly to prevent clogging. Cleaning can be accomplished through vacuum sweeping or high pressure washing. Even though pervious concrete and the underlying soil provide excellent filtration capabilities, all the contaminants may not be removed. In critical situations to preserve the quality of ground water, storm water testing is recommended.

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2004

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CIP 39 - Maturity Methods to Estimate Concrete Strength

WHAT is Concrete Maturity?

The maturity concept uses the principle that concrete strength (and other properties) is directly related to both age and its temperature history. Maturity methods provide a relatively simple approach for reliably estimating the in-place early-age compressive (and flexural) strength of concrete (14 days or less) during construction. The maturity concept assumes that samples of a concrete mixture of the same maturity will have similar strengths, regardless of the combination of time and temperature yielding the maturity. The measured *maturity index* of in-place concrete, a function of temperature history and age, is used to estimate its strength development based on a pre-determined calibration of the time-temperature-strength relationship developed from laboratory tests for that mixture.

WHY use Maturity Methods?

Maturity methods are used as a more reliable indicator of the in-place strength of concrete during construction in lieu of testing field-cured cylinders. The traditional approach of measuring the strength of field-cured cylinders, cured in the same conditions as the structure, are used to schedule construction activities such as removal of forms or reshoring, backfilling walls, schedule prestressing and post-tensioning operations, determining the time for opening the pavements or bridges to traffic, sawing joints, and to determine when protection measures can be terminated in cold weather.

Maturity methods use the fundamental concept that concrete properties develop with time as the cement hydrates and releases heat. The rate of strength development at early ages is related to the rate of hydration of cement. Heat generated from the hydration reaction will be recorded as a temperature rise in the concrete. The main advantage of the maturity method is that it uses the actual temperature profile of the concrete in the structure to estimate its in-place strength. The traditional approach of using field-cured cylinders does not replicate the same temperature profile of the in-place concrete and likely does not estimate its in-place strength as accurately. With maturity methods strength information is provided in real-time since maturity measurements are made on-site at any time. As a result, construction workflow is optimized, and construction activity timing can be based on more accurate in-place strength information.

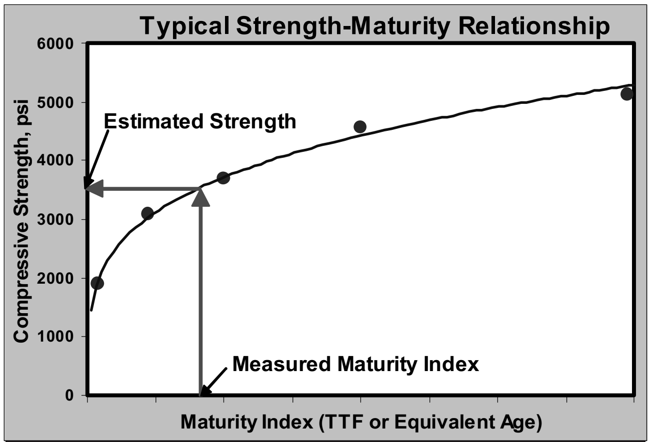

Figure 1: Strength-Maturity Relationship from lab tests used to estimate in-place strength from measured maturity index.

HOW are Maturity Methods Used?

The procedure for estimating concrete strength using maturity concepts is described in ASTM C 1074, *Standard Practice for Estimating Concrete Strength by the Maturity Method*. The temperature-time-strength relationship of a concrete mixture is developed in laboratory tests. This establishes one of two maturity functions (explained below) for that mixture. During construction a maturity index is determined from measured temperature and age. The maturity index is used to estimate the in-place strength from the pre-established maturity-strength relationship. This is illustrated in Figure 1.

The maturity concept is governed by the underlying assumption that concrete samples of a given mixture will have the same strength when they have the same maturity index. For example, concrete cured at a temperature of 50°F (10°C) for 7 days may have the same maturity index as concrete cured at 80°F (27°C) for 3 days and therefore would have similar strengths.

ASTM C 1074 provides two types of maturity functions:

The Nurse-Saul function assumes that the rate of strength development is a linear function of temperature. The maturity index is expressed as a *temperature-time factor* (TTF) from the product of temperature and time in °C-hours or °C-days. The method requires a value for a *datum temperature* below which it is assumed that no cement hydration occurs. ASTM C 1074 provides a procedure to determine this value for the specific concrete mixture or suggests assuming a value of 0°C. The accuracy of the Nurse-Saul prediction breaks down when there are wide ranges of curing temperatures, but its accuracy is considered adequate for most applications.

The **Arrhenius function** assumes that the rate of strength development follows an exponential relationship with temperature. The maturity index is expressed in terms of an *equivalent age* at a reference temperature. Actual age is typically normalized to an equivalent age at 20°C or 23°C. A value of the *activation energy* is needed for this maturity function. ASTM C 1074 provides a procedure to determine the activation energy or alternatively suggests that a value of 40,000 to 45,000 J/mol is a reasonable assumption for concrete with a Type I cement. Using the established maturity function, the actual age and measured temperature is converted to an equivalent age to predict the concrete strength.

The Arrhenius function is considered to be more scientifically accurate. However, the Nurse-Saul function is more commonly used by the various state highway agencies in the United States mainly due to its simplicity.

The maturity method involves the following steps:

- Determine a strength-maturity relationship for the concrete mixture to be used in the structure using materials and mixture proportions proposed for the project. Monitor the temperature history of the test specimens using temperature probes embedded in one or more of the cylinders. Measure the compressive strength of standard-cured test cylinders at various ages. These data are used to establish the maturity function (Nurse-Saul or Arrhenius).
- Measure the temperature history of the concrete in the structure by embedding sensors at locations in the structure that are critical in terms of exposure conditions and structural requirements.
- Calculate the maturity index from the recorded temperature and age.
- Estimate the in-place strength of the field concrete from the calculated maturity index and the predetermined strength-maturity relationship (Figure 1).

Some of the limitations of maturity methods that can lead to erroneous estimation of in-place strength are:

a. Concrete used in the structure is not representative of that used for the labortory calibration tests - due to changes in materials, batching accuracy, air content, etc.
b. High early age temperatures will result in incorrect prediction of long-term strength;
c. Concrete should be properly placed, consolidated and cured - conditions should permit continued cement hydration;
d. Use of datum temperature or activation energy values that are not representative of the concrete mixture.

Points (a) and (b) above are inherent limitations of maturity methods. ASTM C 1074 suggests that supplementary tests be conducted prior to performing safety-critical operations such as formwork removal or post-tensioning. While these additional tests are not always required, it is a good idea to periodically verify that the established maturity-strength relationship for the specific concrete is still valid. Suggested methods include:

(1) In-place non-destructive tests ASTM C 803 (penetration resistance), ASTM C 873 (cast-in-place cylinders), or ASTM C 900 (pullout strength).
(2) Test method C 918 that projects later age strength from early age tests.
(3) Using accelerated curing of test specimens to estimate later age strength according to ASTM C 684.
(4) Early-age tests of field molded cylinders instrumented with maturity instruments.

Strength-maturity relationships, datum temperature and activation energy are concrete mixture specific. Therefore any significant modifications to the mixture design or material source should be accompanied by a re-calibration of these values.

Several maturity devices are commercially available that continuously measure concrete temperature, calculate maturity and display the maturity index digitally at any time. An unlimited number of locations can be monitored simultaneously. It is important to select a system that is rugged, provides uninterruptible and unalterable data, supports the maturity function being used for the project, and allows adjustment of the appropriate maturity constants.

It is important to realize that maturity is not intended to replace standard cured cylinder testing. Maturity used in conjunction with other non destructive testing can replace field cured cylinder testing and facilitate decision making for construction operations. It can be a good tool for quality control while reducing the amount of strength tests performed. Because of maturity testing, projects are proceeding more quickly, safely, and economically as a result of having the right information at the right place and at the right time.

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2006

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CIP 40 - Aggregate Popouts

WHAT is Popout?

A “popout” is a small, generally cone-shaped cavity in a horizontal concrete surface left after a near-surface aggregate particle has expanded and fractured. Generally, part of the fractured aggregate particle will be found at the bottom of the cavity with the other part of the aggregate still adhering to the point of the popout cone. The cavity can range from ¼ in. (6 mm) to few inches in diameter.

WHY do Concrete Popouts Occur?

The aggregate particle expands and fractures as a result of a physical action or a chemical reaction:

Physical

The origin of a physical popout usually is a near-surface aggregate particle having a high absorption and relatively low relative density (specific gravity). As that particle absorbs moisture; or if freezing occurs under moist conditions, its swelling creates internal pressures sufficient to rupture the particle and the overlying concrete surface. The top portion of the fractured aggregate particle separates from the concrete surface taking a portion of the surface mortar with it. In some cases the aggregate forces water into the surrounding mortar as it freezes thus causing the surface mortar to pop off, exposing an intact aggregate particle. Clay balls, coal, wood or other contaminants can uptake water and swell even without freezing, but the resulting pressure rarely is great enough to cause popouts. Also, there are reported cases of grain (soybeans, corn) contamination of aggregate shipments that have resulted in surface popouts. Such occurrences are not within the scope of this document.

Popouts as a result of physical action are typically only a problem with exterior flatwork in climates subject to freezing and thawing under moist conditions and resulting expansion. Even aggregates which meet the requirements of ASTM C 33 Class 5S, for architectural concrete in severe exposure, allow several types of particles which may cause popouts when exposed to freezing and thawing in the saturated condition. The most common type of particles resulting in popouts are low density chert in natural aggregate deposits.

Aggregate Popout

Courtesy PCA

Crushed aggregates are less likely to contain lightweight, absorptive particles which are more susceptible to popouts.

Chemical

The cause of a popout due to a chemical reaction is often related to alkali-silica reaction (ASR). Alkalis from cement or other source cause an environment of high pH (high concentrations of OH ions) causing the breakdown of silica and formation of an ASR gel, which absorbs water and expands, removing a small portion of the surface mortar with it. These are called ASR Popouts. They are typically small and are often accompanied by a small spot that is discolored and/or appears to be damp. The aggregate particle does not often fracture and split as is the case of popouts from physical action. However, the ASR phenomenon can result in micro-fractures within the aggregate particles. Some alkali-silica reaction popouts can occur within a few days after the concrete is placed.

HOW to Avoid Concrete Popouts?

Most popouts are aesthetic defects that do not impact the structural performance of the concrete members. A large number of popouts however make it easier for water and other harmful chemicals to enter the concrete, which can ultimately lead to other forms of deterioration such as corrosion of steel reinforcement. The following steps can be taken to avoid concrete popouts.

Physical Popouts

1. Avoid using aggregates which contain particles which may cause popouts, or that have a history of popouts. However, in some parts of the United States, the available natural gravels contain some particles that are likely to result in surface popouts. Due to the unavailability of economical alternate aggregates, the occurrence of popouts on sidewalks and pavements is an accepted , albeit undesirable, likelihood in those locations.
2. If popouts are unacceptable, an alternate source of aggregates must be located. If appropriate, two-course construction can be used, whereby the popout susceptible aggregate is used for the lower course and the pop-out free aggregat that is likely to be more expensive is used for the surface course.
3. Aggregates can be beneficiated to remove lightweight materials, but the added cost of beneficiation can be prohibitive for most uses.
4. Reduce the water to cementitious materials ratio of the concrete, as this will reduce the likelihood of saturation and will increase the resistance to swelling forces. Provide proper curing for exterior flatwork, as this results in improved strength of the cementitious materials, especially on the surface. This will reduce permeability thereby lowering the amount of water migrating to coarse aggregate particles. These steps can reduce the frequency, but will not necessarily, eliminate popouts.
5. Reduce the maximum aggregate size, as smaller aggregates will develop lower stresses due to freezing, and fewer popouts will occur. Those that do will be smaller and less objectionable.

Chemical Popouts

1. Use a low-alkali cement or a non-reactive aggregate. This is often not a practical option in many regions
2. Flush the surfaces with water after the concrete has hardened and before applying the final curing. This will remove the alkalis that may have accumulated at the surface as a result of evaporation of bleed water.
3. Permit the use of Class F fly ash or slag cement as a partial cement substitute to reduce the permeability of the paste and mitigate deleterious reactions due to ASR.

HOW to Repair Concrete Popouts?

Prior to undertaking a repair program, it is advisable to confirm the cause of the popouts by obtaining core samples containing one or more typical popouts and having them studied by a qualified petrographer.

Popouts can be repaired by chipping out the remaining portion of the aggregate particle in the surface cavity, cleaning the resulting void, and by filling the void with a proprietary repair material such as a dry pack mortar, epoxy mortar, or other appropriate material following procedures recommended by the manufacturer. It will be difficult to match the color of the existing concrete. If the popouts in a surface are too numerous to patch individually, a thin bonded concrete overlay may be used to restore a uniform surface appearance. Specific recommendations for such overlays are beyond the scope of this publication.

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2007

Concrete in Practice
What, why & how?
NRMCA

CIP 41 - Acceptance Testing of Concrete

WHAT is Acceptance of Concrete?

Acceptance testing is the process of testing representative samples of concrete furnished to a project. Acceptance testing includes tests on plastic concrete for slump, air content, density (unit weight), temperature, and tests on hardened concrete for strength and other durability properties as required in Contract documents or project specifications.

Acceptance testing on hardened concrete is conducted in accordance with standardized procedures to determine whether the concrete as delivered has the potential of developing the desired properties intended by the design professional. These test results are not intended to imply the actual properties of concrete in the structure. There are several variables during construction that will impact in-place concrete properties that are beyond the control of the concrete supplier.

WHY Conduct Acceptance Testing?

Acceptance testing is conducted to quantitatively verify that concrete conforms to the requirements of the purchaser. The requirements of the purchaser, relative to the tests and acceptance criteria, are generally stated in writing in project specifications or are invoked by reference to industry standards, such as ACI 301, ACI 318 and ASTM C 94.

Contractors are legally bound to facilitate or to conduct acceptance testing by local jurisdictions which adopt model codes such as such as the International Building Code. These model codes in turn refer to the ACI 318 Building Code.

It is important for those involved in testing to realize that the results of acceptance testing have significant implications on the project schedule, cost to project participants, and may impact the safety of the structure and its inhabitants.

HOW Should Acceptance Testing Be Conducted?

Acceptance testing must be conducted by certified technicians who have demonstrated a written and practical knowledge of performing tests in accordance with the pertinent standards. Certification programs are offered by the American Concrete Institute (ACI) and other organizations for test conducted in the field and laboratory. Laboratories performing acceptance tests should conform to the requirements of ASTM C 1077. Laboratories should be proficient in testing concrete, should have been through quality system audit by an independent evaluation organization and participate in reference sample testing programs to evaluate their testing proficiency and correct processes if necessary. Laboratory inspections and reference sample programs of the Cement and Concrete Reference Laboratory (CCRL), or equivalent, are established standards.


Typical Equipment for Acceptance Tests

All acceptance testing of concrete must be conducted in accordance with established standards referenced in Contract documents. Any deviation from standard procedures is adequate reason for invalidating test results so obtained.

It is important that the process of conducting acceptance testing and the responsibilities of all involved parties for proper sampling, specimen storage, handling, transportation to the laboratory, jobsite sample disposition and subsequent laboratory testing are clearly defined prior to the start of a project. In medium to large projects a pre-construction conference is strongly recommended to establish processes, contingencies and responsibilities (CIP 32).

Sampling: Samples of concrete from concrete delivery vehicles for acceptance tests should be obtained in accordance with ASTM C 172. The sample should be obtained at the end of the truck chute. Two or more portions of concrete as discharged from the middle portion of the load are composited to obtain a sample that is representative of the load. When the specification requires additional tests to be conducted at the point of placement in the structure after concrete has been moved through some conveying means (such as a pump, bucket or conveyor) sampling procedures should be conducted such that the means of conveyance is not temporarily shut off or relocated to ease sampling as this can temporarily change the properties measured. ASTM C 94 permits a preliminary sample to be obtained after 0.25 yd^3 (0.20 m^3) has been discharged to measure slump and air content and make appropriate adjustments to the load at the jobsite. The preliminary sample should not be used to make specimens for acceptance tests of hardened concrete.

Slump and Air Content: When the slump and air content measured on the preliminary sample are lower than specified jobsite adjustments with water or admixtures followed by adequate mixing are permitted. If slump and air contents are higher then a retest is made immediately and if the retest fails then the concrete is considered to have failed the requirements of the specification.

Slump of concrete is measured in accordance with ASTM C 143. The tolerance on slump varies by slump level as ordered or specified. The slump tolerances of ASTM C 94 are summarized in the table below. There is no established tolerance for the slump flow of self consolidating concrete, that is measured in accordance with ASTM C 1611.

Specified Slump	Tolerance
Specified as a Maximum Slump	
<3 in. (75 mm)	+0 to -1½ in. (40 mm)
>3 in. (75 mm)	+0 to -2½ in. (65 mm)
Specified as Nominal Slump	
<2 in. (50 mm)	±½ in. (15 mm)
2 - 4 in. (50 - 100 mm)	±1 in. (25 mm)
>4 in. (50 mm)	±1½ in. (40 mm)

The air content of concrete is measured in accordance with the pressure method, ASTM C 231 or by the volumetric method, ASTM C 173 for lightweight concrete or for aggregates with high absorptions. For air-entrained concrete, the tolerance on air content as ordered or specified is ±1.5%.

Density and Yield: When samples are obtained for strength tests ASTM C 94 requires measuring the density (unit weight) of the concrete in accordance with ASTM C 138. This can be done by determining the weight of the air meter container after the sample has been prepared. The minimum container size based on the nominal maximum size of the aggregate in the concrete mixture should be followed. Density measurements can also be correlated with air content measurements and can be an indicator of the water content in the mixture. When determining yield, ASTM C 94 requires that the density should be determined on separate samples from three different loads of concrete and compliance with volume of concrete ordered be done on that basis (CIP 8).

Temperature: The temperature of concrete is measured in accordance with ASTM C 1064. Temperature is measured to determine conformance to temperature limits in a specification and is a required test when strength test specimens are prepared. It is permitted to measure the temperature of concrete in place when it is not measured in conjunction with strength tests.

Hardened Concrete Tests: ASTM C 31 describes the procedures for preparing cylinders and beams for compressive and flexural strength tests, respectively. It describes the procedures for storing specimens at the jobsite and transporting specimens to the laboratory. ASTM C 31 requires the test specimens to be maintained in a moist condition in a temperature range of 60 to 80°F (16 – 27°C) in the field. For high strength concrete with a specified strength greater than 5000 psi (35 MPa), the storage temperature limits are tighter at 68 to 78°F (20 – 26°C). A record of the temperature conditions during field storage of the specimens should be maintained. A curing box with max/min temperature recording device is generally required to verify conformance to these requirements. The same procedures should be adhered to for test specimens prepared for other tests. Test specimens should not be stored at the jobsite for longer than 48 hours. Specimens should be protected with adequate cushioning when transported to the laboratory. Transportation time should not exceed 4 hours. Specimens delivered to the laboratory should be stripped of molds, logged and placed in moist curing as defined in ASTM C 31 as soon as possible and no later than about 6 hours. More details can be found in CIPs 9 and 34.

While most specifications delegate the contractor with the responsibility for providing adequate facilities for storage of specimens at the jobsite, it is also incumbent on the testing technicians and the individual certifying test results to ensure that standard procedures are followed. Concrete is very sensitive to temperature and moisture at early ages and any deviation from standard procedures is a basis for rejecting results of these acceptance tests as it increases the likelihood of failing test results of acceptable concrete. This has implications to the project cost and schedule. A significant number of low strength results can be attributed to cylinders being subjected to non standardized initial curing at the job site (CIP 9).

Test reports with data on all tests conducted, as well as other reporting requirements addressed in the standards, should be distributed to the owner or his representative, contractor and concrete producer in a timely manner. This is very important to the ongoing project quality and serves as documentation for the ability of the concrete producer to furnish quality concrete for future projects.

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2007

Concrete in Practice
What, why & how?
NRMCA

CIP 42- Thermal Cracking of Concrete

WHAT is Thermal Cracking?

Thermal cracking occurs due to excessive temperature differences within a concrete structure or its surroundings. The temperature difference causes the cooler portion to contract more than the warmer portion, which restrains the contraction. Thermal cracks appear when the restraint results in tensile stresses that exceed the in-place concrete tensile strength. Cracking due to temperature can occur in concrete members that are not considered mass concrete.

WHY Does Thermal Cracking Occur?

Hydration of cementitious materials generates heat for several days after placement in all concrete members. This heat dissipates quickly in thin sections and causes no problems. In thicker sections, the internal temperature rises and drops slowly, while the surface cools rapidly to ambient temperature. Surface contraction due to cooling is restrained by the hotter interior concrete that doesn't contract as rapidly as the surface. This restraint creates tensile stresses that can crack the surface concrete as a result of this uncontrolled temperature difference across the cross section. In most cases thermal cracking occurs at early ages. In rarer instances thermal cracking can occur when concrete surfaces are exposed to extreme temperature rapidly.

Concrete members will expand and contract when exposed to hot and cold ambient temperatures, respectively. Cracking will occur if this bulk volume change resulting from temperature variations is restrained. This is sometimes called temperature cracking and is a later age and longer term issue.

Mass concrete

The main factor that defines a mass concrete member is its minimum dimension. ACI 301 suggests that a concrete member with a minimum dimension of 4 feet (1.3 m) should be considered as mass concrete. Some specifications use a volume-to-surface ratio. Other factors where precautions for mass concrete should be taken even for thinner sections are with higher heat generating concrete mixtures - higher cementitious materials content or faster hydrating mixtures.

The main concern with mass concrete is a high thermal surface gradient and resulting restraint as discussed above. These conditions can result during the initial stages due to heat of hydration and during the later stages due to ambient temperature changes. Another factor is a temperature differential between a mass concrete member and adjoining elements. As the mass member cools from its peak temperature, the contraction is restrained by the element it is attached to, resulting in cracking. Examples are thick walls or dams restrained by the foundation.

Thermal cracks in a thick slab Courtesy CTLGroup

Other Structures

Temperature cracking can occur in structures that are not mass structures. The upper surface of pavements and slabs are exposed to wide ranges of temperature while the bottom surface is relatively protected. A significant temperature differential between the surface and the protected surface can result in cracking. Concrete has a thermal coefficient of expansion in the range of 3 to 8 millionths/°F (5.5 to 14.5 millionths/°C). A concrete pavement cast at 95ºF (35ºC) during the summer in Arizona may reach a maximum temperature of 160ºF (70ºC) and a minimum temperature in winter of 20ºF (-7ºC), resulting in an annual temperature cycle of 140ºF (75ºC). Expansion joints and spacing between joints have to be designed to withstand such temperature induced expansion and contraction to prevent cracking.

HOW To Recognize Thermal Cracking?

Thermal cracks caused by excessive temperature differentials in mass concrete appear as random pattern cracking on the surface of the member. Checkerboard or patchwork cracking due to thermal effects will usually appear within a few days after stripping the formwork. Temperature-related cracks in pavements and slabs look very similar to drying shrinkage cracks. They usually occur perpendicular to the longest axis of the concrete. They may become apparent any time after the concrete is placed, but usually occur within the first year or summer-winter cycle.

HOW To Minimize Thermal Cracking?

The key to reducing thermal or temperature-related cracking is to recognize when it might occur and to take steps to minimize it. A thermal control plan that is tailored to the specific requirements of the project specification is recommended. See Ref. 2 for guidance.

Typical specifications for mass concrete include a maximum temperature and a maximum temperature differential. The maximum temperature addresses the time it takes for the concrete member to reach a stable temperature and will govern the period needed for protective measures. Excessively high internal concrete temperatures also have durability implications. A temperature differential limit attempts to minimize excessive cracking due to differential volume change. A limit of 35ºF (20ºC) is often used. However, concrete can crack at lower or higher temperature differentials. Temperature differential is measured using electronic sensors embedded in the interior and surface of the concrete.

The peak temperature of a concrete mixture can be estimated assuming perfectly insulated conditions. See Ref. 1 and 2. Thermal modeling can also be used to predict temperature and potential for cracking based on thermal controls planned. Two models are HIPERPAV (www.hiperpav.com) for pavements and ConcreteWorks (www.texasconcreteworks.com) for pavements and other mass concrete members. Consultants can also assist with these analyses.

A large part of the responsibility to minimize thermal cracking lies with the designer and contractor. Steps include establishing the concrete mixture, specification limits for temperature of concrete as delivered and in the structure, insulating the structure and termination of protective measures, and in critical conditions, post-cooling of structural members.

Some steps to minimize thermal cracking are:

- Concrete mixture - Reduce heat of hydration by optimizing the cementitious materials using supplementary cementitious materials like fly ash or slag; or using a portland cement that generates a lower heat of hydration. Avoid specifying an excessively low w/cm. Retarding chemical admixtures may delay but not reduce peak concrete temperatures. A cooler initial concrete temperature will reduce the peak temperature in the structure but needs to be balanced with practical feasibility and project costs.
- Mass concrete - Ensure that thermal control measures are agreed upon in a pre-construction meeting. Some things to consider include placement method and details, establishing temperature requirements for concrete as delivered and temperature monitoring of in-place concrete, curing methods and duration that do not increase temperature differentials, use of insulation - including when and how the insulation will be removed, and use of cooling pipes if necessary. Placing concrete in lifts along with timing of successive lifts can minimize the overall peak temperature and time of thermal control but this needs to be balanced against construction joint preparation and the design requirements. Water curing will cool concrete surfaces and water retention curing methods may be more appropriate. Wood forms provide insulation while metal forms do not. Covering forms with insulating blankets may be necessary. The removal of insulation or formwork should be scheduled based on monitored in-place temperature and thermal shock to the surface should be avoided. Reinforcing steel protruding from a massive beam can act as a heat sink to draw heat out of the interior of the beam. When needed, cooling pipes, typically plastic, can be embedded in the concrete about 3 feet (1m) apart to reduce peak internal temperatures.
- Pavements and slabs – Reduce heat gain from solar radiation by misting slabs and pavements or providing shade for the work. Placing concrete in the early morning may result in a more critical situation if the peak temperature from hydration coincides with peak ambient temperature. Wind breaks may increase heat gain if they inhibit evaporative cooling of the concrete. Curing blankets can reduce heat loss from slabs and pavements during cold weather conditions.

The key to reducing thermal cracking is good communication between the designer, contractor, and concrete producer.

HOW To Repair Thermal Cracking?

Repairs to concrete structures must be undertaken with the advice and consent of the designer. Inappropriate repair techniques can result in greater damage later. Pavements and slabs can be repaired using acceptable and compatible repair materials or by cutting out the cracked areas and replacing them with infill strips. Repair of mass concrete members will depend on the crack width and the service conditions of the structure. Fine hairline cracks are aesthetically unpleasing and may not require any repair. However, these cracks may prove to be a future durability problem depending on the service conditions. Wider cracks may need to be sealed by epoxy injection followed by a seal coating. Recommendations for crack repair are provided in ACI 224.1R and by the International Concrete Repair Institute (www.icri.org).

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2009

Concrete in Practice

What, why & how?

NRMCA

CIP 43 — Alkali Aggregate Reactions (AAR)

WHAT is Alkali Aggregate Reactivity?

AAR results in deleterious expansive cracking of concrete occurring at later ages after construction. While mostly inert, some concrete aggregates, can react in the highly alkaline environment in concrete resulting in internal expansion that causes deleterious cracking. Alkalis include sodium and potassium that are minor constituents in portland cement but can be from other concrete ingredients or from external sources. Expansion due to AAR is a slow process and results in visible deterioration 10 to 15 years after the concrete structure has been built. In rare cases deterioration at earlier ages may be observed.

Two forms of alkali aggregate reactions are recognized:

Alkali carbonate reactions (ACR) occur with dolomitic limestone aggregate of a specific mineralogy and microstructure. Sources of these aggregates is relatively rare. ACR is typically a more aggressive reaction and occurs earlier in the life of the structure.

Alkali silica reactions (ASR) occur with certain forms of silica (SiO_2) minerals in aggregates that react in a high alkaline (pH) medium in concrete creating an expansive gel. The gel expands by absorbing moisture that causes the expansion of concrete and subsequent damage. Three conditions are required for deleterious ASR to occur:

1. reactive forms of silica in aggregate,
2. high alkali pore solution (pH) in concrete, and
3. presence of moisture.

WHY is AAR a Concern?

Deterioration to concrete structures due to AAR does not generally result in catastrophic failures. Where dimensional stability is important, such as in dams, the expansions can impact the functioning of the structure. In most cases, synergy with other deterioration processes like cycles of freezing and thawing and corrosion of reinforcement exacerbates the rate of deterioration of concrete structures. ASR in concrete pavements and transportation infrastructure can result in spalling of cracked sections. Moisture, additional alkalis from deicing salts, and traffic loading accelerate the process.

HOW is the Potential for AAR Determined?

Aggregates with a distinct mineralogy of dolomite crystals embedded in a clay matrix cause ACR. A qualified petrographer can identify this. Quarries in North America where these aggregates occur are known and their use in hydraulic cement concrete is avoided. Test methods for determining potential for ACR include a rock cylinder expansion test, ASTM C586 and an expansion test of concrete prisms, ASTM C1105.

ASR Cracking and Expansion in Sidewalk

Cases of ASR have been noted in most areas in North America. Existing signs of ASR in concrete structures in a region is the most definitive way of establishing that the problem exists. A petrographic evaluation of an aggregate source, ASTM C295, can identify potentially reactive silica minerals in aggregates but will not definitively establish whether an ASR problem will occur when the aggregate is used in concrete.

The more reliable test method that has been correlated to actual deterioration in field structures or field-exposed test specimens is an expansion test using concrete prisms, ASTM C1293. This test requires a one-year period and may not be conducive to project schedules if not conducted ahead of time. Aggregates are considered to be potentially reactive when the expansion exceeds 0.04% at 12 months.

A more common test is an accelerated mortar bar expansion test, ASTM C1260. This test provides a result in about 2 weeks. Aggregates are considered potentially reactive when the expansion exceeds 0.20% (ASTM C33). Many agencies, however, use an expansion criterion of 0.10% at 14 days. ASTM C1260 is an aggressive test and aggregates that do not cause deleterious ASR reactions in the field are often characterized as reactive by the test. It is recommended that ASTM C1260 results should be supplemented with other information in determining the potential reactivity of an aggregate source.

Other test methods, like the quick chemical test, ASTM C289 and a longer term mortar bar expansion test, ASTM C227 are not considered to be reliable.

The Appendix of ASTM C33, *Specification for Concrete Aggregates*, provides guidance on AAR test methods, criteria and mitigation methods.

HOW is AAR Avoided?

There are no recommended methods of preventing deleterious expansion when the available aggregate source has been verified to be ACR reactive. The only recourse is to use an alternative source of aggregate.

For deleterious ASR expansion to occur the three factors discussed before are required: alkalis, reactive silica and exposure to moisture. Concrete that remains dry inside buildings and not in contact with soil will typically not need preventive measures. In other situations various strategies can be used to avoid damage due to ASR.

One option is to avoid the use of aggregate sources that are determined to be reactive. This may not be feasible because alternative non-reactive aggregates may not be economically available or data may not exist as to their potential performance.

Another option is the use of a low alkali cement, typically characterized as one with Na_2O_{eq}, less than 0.60%. Low alkali cement, however, is not available in many regions. Alternatively, limiting the total alkali content in concrete is often considered a better option. Only the alkali from portland cement is considered. The total alkali content in concrete is determined by multiplying the cement content by the alkali content. Concrete alkali content is typically limited to a 5.0 lb/yd^3 (3.0 kg/m^3) or lower for more critical structures, like in concrete dams. With this option — low alkali cement or low concrete alkali content — it should be recognized that alkali concentrations can build up in concrete during service conditions from exposure to external sources like deicing chemicals and sea water, or from migration of alkalis within concrete due to drying.

The more accepted option to mitigate deleterious ASR is to incorporate a supplementary cementitious materials (SCM) in concrete. SCM include fly ash, natural pozzolan, slag cement, or silica fume. SCMs bind alkalis in the hydration products and prevents the deleterious expansion from occurring. One exception is fly ashes that have calcium oxide contents greater than 20%, typically characterized as Class C fly ash. Class C fly ashes typically need higher dosage levels to mitigate the reaction.

The quantity of SCM required will depend on the reactivity of the aggregate, the alkali loading in the concrete, the type of SCM and the exposure of the concrete to external sources of alkalis. In many regions historically established SCM contents required to mitigate ASR are used and work well. Alternatively, the effectiveness of an SCM can be evaluated by testing. The SCM contents evaluated should cover a range typical of those proposed for construction. The more common test methods are ASTM C441, ASTM C1293, and ASTM C1567. These test methods accelerate the reaction either by using highly reactive artificial aggregates, elevating the alkali loading in the test mixture, exposure to highly alkaline solutions, use of elevated temperature, or some combination thereof. The concrete prism test, ASTM C1293 is performed for a 2-year period at which point the expansion should be less than 0.04%. This tends to be too long for typical project submittals. More commonly SCMs are evaluated using ASTM C1567 with a 14-day expansion criterion of 0.10%. Research supports that these methods provide a conservative estimate of the quantity of SCM needed to mitigate ASR in concrete. Regardless of the process used to establish the minimum SCM content required, the impact on other project requirements for concrete must be considered. These include, but are not limited to setting time, bleeding characteristics, workability, and early and later age strength development.

Chemical admixtures, primarily lithium nitrate, have been shown to be effective to mitigate deleterious ASR. Manufacturer recommendations should be sought to establish effective dosage levels for specific concrete mixtures. The Corps of Engineers method CRD-C 662 is referenced to evaluate the effectiveness of the lithium admixture dosage. In some cases, combinations of these options such as the use of SCM and lithium admixtures have proven successful.

Because test methods accelerate the reaction, none evaluate potential for deleterious ASR of the actual composition of concrete mixtures proposed for projects. No test evaluates the effectiveness of the alkali content of portland cement. Test methods evaluate single aggregate sources. When the fine and coarse aggregates are determined to be reactive, the dosage of SCM that mitigates the more reactive aggregate should be used.

AASHTO PP65 provides a step by step method for evaluating aggregates and a prescriptive and performance-based methodology to minimize the potential for damage in field concrete. The methodology requires consideration of the risk level for the occurrence of ASR in structure to establish preventative measures.

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2014

Concrete in Practice
What, why & how?
NRMCA

CIP 44 - Durability Requirements for Concrete

WHAT are Durability Concerns

Concrete is a versatile construction material that can be used in a wide range of service and environmental conditions. Conditions that can impact the service life of concrete structures should be identified during design and addressed in project specifications. To address durability of concrete, ACI 318, *Building Code Requirements for Structural Concrete*, has specific requirements for concrete for defined environmental exposure conditions. These provisions are covered in Chapter 19 of ACI 318-14. The following Exposure Categories are covered:

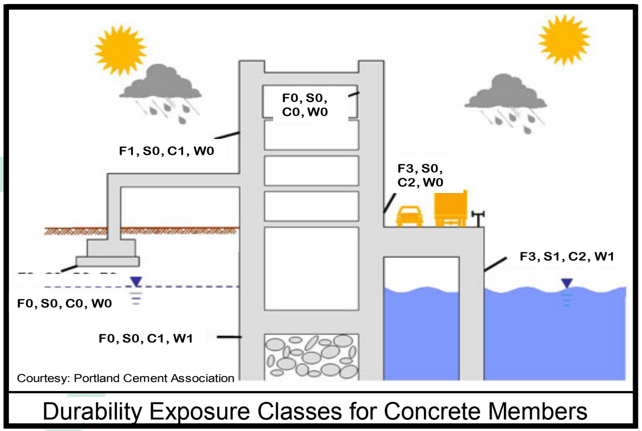
F	Concrete exposed to cycles of freezing and thawing
S	Concrete exposed to water soluble sulfates
C	Conditions requiring corrosion protection of reinforcement
W	Concrete members in contact with water

Similar exposure categories are addressed in ACI 332, *Residential Code Requirements for Structural Concrete*. The durability requirements of ACI 318 are covered in specification format in ACI 301, *Specifications for Structural Concrete*

Additional durability considerations, such as cracking due to drying shrinkage or thermal gradients, abrasion, and alkali aggregate reactions, may need to be considered by the engineer designing the structure.

WHY should Durability be Addressed

Buildings must comply with the locally adopted Building Code; generally these refer to ACI 318 for structural concrete. Transportation structures must comply with the requirements of state highway agencies. Appropriate durability requirements in specifications minimizes the potential for deterioration of concrete to assure public safety and provide adequate service life of concrete structures. If owners want to further extend service life, design and specifications should exceed the minimum stated in building codes. When the defined exposure conditions do not exist, the requirements related to these conditions should not be specified as this can increase cost with no real benefit.



Courtesy: Portland Cement Association

Durability Exposure Classes for Concrete Members

HOW Should Durability be Addressed

Concrete that has a low permeability to water and dissolved chemicals will generally be durable in most exposure conditions. Permeability of concrete is impacted by water-to-cementitious materials ratio (w/cm), and type and proportions of cementitious materials used in the mixture. The w/cm is the ratio of the weight of mixing water to the weight of all cementitious materials. For durability, ACI 318 requires specifying a max w/cm and min specified strength, f'_c. Since w/cm cannot be verified when concrete is delivered, strength tests are used as the basis of acceptance. The Code cautions that specified strength, f'_c, should be reasonably consistent with the w/cm required for durability.

Supplementary cementitious materials (SCMs), like fly ash and slag cement, reduce the permeability relative to mixtures that contain only portland cement. SCMs also make concrete more resistant to chemical factors that impact concrete durability, like sulfate attack and alkali aggregate reaction.

ACI 318 defines Exposure Classes (EC) within each Exposure Category based on the severity of exposure. Increasing severity is represented by higher numerical value in the EC designation. The numeral “0” is used when the condition does not apply. The **designer** is required to assign the durability EC for each member type in a structure. This sets the basis and lends clarity to the requirements for concrete. It can avoid problems while accepting bids and during construction.

Freezing and thawing exposure (Category F). Four ECs are defined:

- **F0** for no exposure;
- **F1** for a lower level of saturation when exposed to freezing;
- **F2** for higher level of saturation; and
- **F3** same as F2 and the potential for application of deicing chemicals.

Examples of member types for each EC are provided in the commentary of ACI 318. Requirements for concrete for these ECs include max w/cm, min f'_c, and air content. Air content can be reduced by 1% for f'_c greater than 5000 psi. For plain concrete (non-reinforced) assigned to EC F3, the max w/cm and min f'_c are the same as for EC F2. Limits on quantity of SCMs are applicable to concrete assigned to EC F3. The intent for these limits is to minimize the potential for surface scaling as this will reduce cover and can initiate corrosion of reinforcement. Limits on SCMs should not be specified if EC F3 does not apply.

Sulfate exposure (Category S).

ECs are defined based on concentration of water-soluble sulfates (SO_4^{2-}) in soil (% by mass) or water (ppm) in contact with the member.

S0	<0.10%	<150 ppm;
S1	0.10—0.20%	150—1500 ppm & seawater
S2	0.20—2.00%	<1500—10,000 ppm;
S3	>2.00%	>10,000 ppm;

Sulfate resistance is improved with lower concrete permeability and a sulfate resistant cementitious system. For each EC, the Code states a max w/cm and min f'_c and the type of cementitious material. Sulfate resisting cements include Type II and Type V portland cements (ASTM C150) and moderate sulfate (MS) and high sulfate (HS) resistant blended cements (ASTM C595 and C1157). For EC S3, additional quantity of SCMs that improve sulfate resistance is required. The sulfate resistance of a cementitious system can be determined by service history or by test—ASTM C1012.

Corrosion protection of reinforcement (Category C). Three ECs are defined :

- **C0** for members dry in service;
- **C1** for moist in service; and
- **C2** for moist and exposed to an external source of chlorides.

Reinforcement embedded in concrete is protected from corrosion because of the high pH. Corrosion initiates when chlorides exceed a threshold concentration or the cover concrete carbonates. For ECs C0 and C1 there is no max w/cm. For EC C2, the Code requires a max w/cm and min f'_c. For reinforced concrete, the Code has max limits on water-soluble chloride ion concentration, expressed as percent by weight of cement, for each EC. Chloride limit for all prestressed concrete is 0.06%. Chloride limits will generally preclude the use of chloride-based admixtures in reinforced and prestressed concrete. Corrosion inhibiting admixtures are effective for improving corrosion resistance of reinforcement.

Concrete in contact with water (Category W).

Two exposure classes are defined:

- **W0** for dry in service or in contact with water where low permeability is not required; and
- **W1** for concrete in contact with water requiring low permeability.

For EC W1 a max w/cm and min f'_c apply.

There may be other durability issues that the engineer of record needs to address and specify for concrete. More details on durability and methods to minimize deterioration are available in other references.

Min Specified Strength f'_c and Max w/cm for ACI 318 Durability Exposure Classes

Exposure Class	Max w/cm	Min f'_c, psi
F0, S0, W0, C0, C1	None	2500
F1	0.55	3500
S1, W1	0.50	4000
S2, S3, F2, F3 (plain)	0.45	4500
C2, F3 (reinforced)	0.40	5000

References

1. ASTM Standards, *Annual Book of Standards*, Vols. 04.01 and 04.02, ASTM International, West Conshohocken, PA, www.astm.org
2. *Building Code Requirements for Structural Concrete*, ACI 318 *and Commentary* 318R, ACI, Farmington Hills, MI, www.concrete.org.
3. *Specifications for Structural Concrete*, ACI 301, ACI, Farmington Hills, MI, www.concrete.org.
4. *Residential Code Requirements for Structural Concrete and Commentary*, ACI 332, ACI, Farmington Hills, MI, www.concrete.org.
5. *Guide to Durable Concrete*, ACI 201.2R, ACI, Farmington Hills, MI, www.concrete.org.
6. *Design and Control of Concrete Mixtures,* EB001, 16th ed. Ch. 14, PCA, www.cement.org
7. *Guide to Improving Specifications for Ready Mixed Concrete*, Pub 2PE004, NRMCA, www.nrmca.org.

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