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Best practices and promising technologies that can be used now to enhance concrete paving

Curing for Exterior Concrete Slabs

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PROJECT TITLE
Curing for Exterior Concrete Slabs

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Purpose

This document provides guidance to agencies on specifying and monitoring curing practices for concrete slabs.

The Need for Curing

Cement Hydration

Curing is the combination of actions taken to ensure that freshly placed concrete does not dry out and that temperatures that promote hydration are maintained.

When portland cement is mixed with water, a series of chemical reactions begins to occur that causes "fingers" of hydration products to form around the cement grains. These fingers eventually interlock, effectively starting the process of changing the mixture from a fluid to a solid. Over time, with continued hydration, the gaps between the fingers fill in, causing the system to gain strength and become less permeable. This is illustrated in Figure 1, in which hydration products (light gray) merge and overlap to form a dense, impermeable solid.

Reaction rates are initially rapid, but they slow over time. It was originally thought that reaction rates slow to effectively zero at about 28 days, hence the common use of acceptance tests conducted at that age. In reality, hydration continues for weeks and months, albeit very slowly, as long as there is water in contact with unreacted cement.

Hydration is affected by the temperature of the concrete and the availability of water. Higher temperatures increase the hydration rate, which effectively doubles with each increase in temperature of about 18°F. Conversely, lower temperatures reduce the hydration rate. Further, the hydration stops if there is insufficient water. The early drying of a concrete mixture will therefore prevent it from reaching its desired performance and the resulting system will be weaker and more porous, as seen in Figure 2.

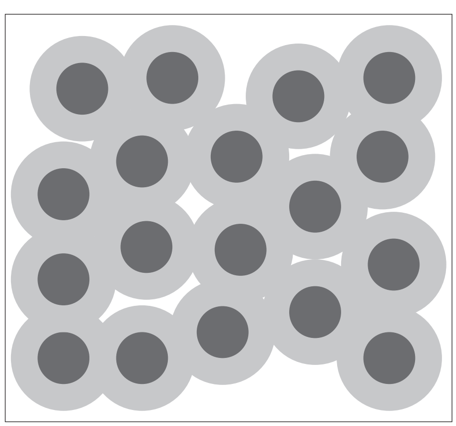

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Figure 1. Illustration of a well-hydrated system

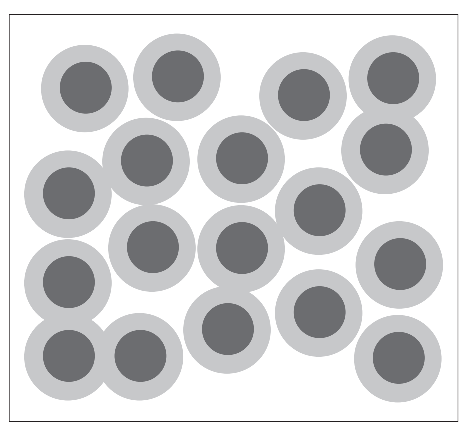

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Figure 2. Illustration of a poorly hydrated system

Replacing cement with supplementary cementitious materials, such as fly ash and slag cement, changes the rate of formation of hydration products. Hydration is initially slower in mixtures containing supplementary cementitious materials, leading to reduced performance at early ages, but the reactions continue for a longer period of time, leading to enhanced impermeability and strength beyond 28 days. This means that such mixtures require more careful attention to ensure that they do not dry out before the desired properties are achieved.

Research is needed to evaluate the curing period necessary for new cements such as portland limestone cement (PLC) and limestone calcined clay cement (LC3).

Chemical admixtures can also be added to a mixture to either accelerate or retard the hydration rate in the first few hours after mixing. Typically, portland cement-based systems that are permitted to hydrate more slowly will have a more refined microstructure and improved performance in the long term.

If curing is stopped too early, hydration slows or stops, reducing the performance of the system, as seen in Figure 3.

Curing is primarily beneficial to the surface of the concrete rather than the interior because additional water applied to the surface of a well-proportioned mixture will not penetrate far into the element once hydration has begun. For applications like pavements and bridge decks, failure mechanisms such as abrasion, cold weather damage, and cracking are normally initiated at the surface. This means that curing is essential for the overall performance of such structures.

The effects of inadequate curing on the strength of high-quality concrete are more limited because the bulk of the concrete located more than a few millimeters from the surface is unaffected by a lack of surface curing.

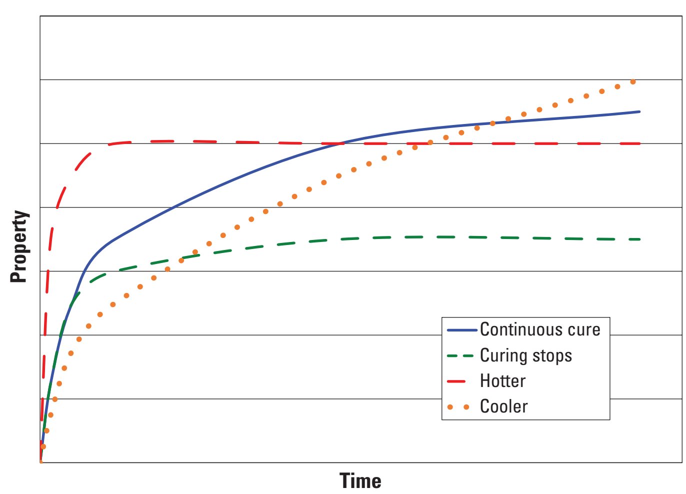

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Figure 3. Effect of inadequate curing on mixture properties at the surface of the concrete

Impacts of Curing on Hydration and Concrete Properties

Effect of Water

The factor that predominantly controls the performance of a mixture is the ratio of water to cementitious materials (w/cm) at the time of setting. Increasing the w/cm ratio may improve workability, but every other property will be compromised. Many specifications impose a maximum w/cm ratio of 0.40 to 0.45 for concrete that is exposed to freezing and thawing in order to ensure that the mixture will perform as desired. The time it takes for capillaries or voids to become discontinuous in a well-cured portland cement-based paste is estimated to be about three days in a mixture with a w/cm ratio of 0.40, seven days at a w/cm ratio of 0.45, and never at a w/cm ratio of 0.80. Therefore, it is reasonable to state that an effective curing period of about three to seven days is needed to ensure freeze-thaw resistance for currently available mixtures typically used in slabs at room temperature.

With a w/cm ratio below about 0.40, the risk increases that there will not be enough water in the mixture to hydrate all of the cement, leading to so-called self-desiccation. The curing of such mixtures cannot depend solely on sealing in the mixture water already present within the element because this water is insufficient to support complete hydration; therefore, external water will need to be added. Adding external water is a challenge, however, because such mixtures are less permeable, preventing additional external water from penetrating far beyond the surface.

It is therefore crucial that the amount of water in a mixture is carefully controlled. Sources of water include mix water, water carried with the aggregates beyond what is needed to saturate them, wash water left in the batch plant and haul trucks, and water added after initial mixing.

After setting, the requirement changes from "less water" to "more water" to ensure that the mixture, especially at the surface, is able to fully hydrate. In mixtures with a w/cm ratio above about 0.40, it is generally sufficient to seal the surfaces to prevent water loss due to evaporation. Methods to achieve this are discussed later in this MAP brief.

Another factor that impacts the performance of a mixture is the risk of early-age cracking. One of the mechanisms behind cracking is the shrinkage induced as the concrete surface dries, which is most marked if drying occurs early. Effective curing to prevent drying before and soon after setting will help reduce this risk.

Finally, once the slab is in service, the requirement flips back to "less water" because all environmental distress mechanisms involve the transport of fluids into the concrete microstructure. Reducing permeability, including through effective curing, is necessary to ensure that the concrete will be durable.

In summary, it is important to prevent moisture loss from newly placed concrete surfaces to promote hydration, reduce cracking risk, and ensure long-term durability.

Effect of Temperature

Concrete exposed to extremes of temperature is also at risk of premature distress.

As noted above, the hydration rate changes with the temperature of the mixture. Low temperatures reduce the rate of strength gain but do not significantly slow the drying rate if conditions are windy and the environmental humidity is low. Low strength and rapid drying increase the risk of early-age cracking, and therefore the prevention of moisture loss must be extended for a longer time in cold weather to achieve the required properties.

Elevated temperatures accelerate the hydration rate, which in turn further raises temperatures due to the exothermic nature of the hydration reactions. Concrete that is hot when it sets will expand, meaning that subsequent cooling, such as that occurring overnight, may lead to additional shrinkage, increasing the risk of cracking.

It is also important to ensure that temperature differentials through the thickness of a slab are minimized. Typical guidance is to keep differentials below 30°F. Differentials may be incurred if formwork is removed from warm concrete during cold weather.

Elevated temperatures during early ages may accelerate hydration but lead to a more porous microstructure in the long run, potentially increasing permeability.

Another concern is that in extreme cases, peak temperatures above 160°F can result in delayed ettringite formation at later ages, depending on the chemistry of the cementitious system. This can lead to extensive expansion and cracking.

Concrete mixtures should therefore be protected from extremes of temperatures and temperature differentials for several days after placement.

Effects of Curing on Concrete Properties

Typically, the prevention of early-age cracking is a primary concern, especially for slabs. Cracking occurs when the cumulative stresses that develop from several sources exceed the strength of the concrete. The prevention of cracking is therefore achieved by continuously controlling all of the factors that contribute to stress as much as possible on any given day.

The contributing factors include the following:

- Thermal stresses due to cooling
- Thermal stresses due to differentials through the element section
- Shrinkage stresses due to drying, leading to plastic shrinkage cracking before setting and drying shrinkage cracking later in the life of the concrete
- Structurally induced stresses such as hogging moments in elevated decks

The first three factors can be influenced by effective curing practices such as controlling the mixture temperature and moisture state. Additional factors, such as careful mixture proportioning and the placement of concrete when environmental temperatures are moderate, will also help reduce the risk of cracking.

In addition to obtaining strength sufficient to carry the self-weight of the concrete and the imposed loads, it is critically important that any concrete element has the ability to resist the aggressive environment it is exposed to, including freeze-thaw cycles, especially in the presence of deicing chemicals. All durability-related attack mechanisms involve the movement of fluids into the concrete microstructure; therefore attention is required to proportion a mixture with potentially low permeability and to provide an environment that promotes hydration long enough to achieve the intended performance, particularly at the surface.

Another key parameter affected by curing, that contributes to the continued serviceability of a slab, is the ability to resist polishing and abrasion. The most influential factor is the hardness of the fine aggregate, but the strength of the cement paste at the surface also influences performance. Since curing typically does not affect the degree of hydration more than about ½ in. below the surface, curing activities strongly influence surface hardness.

The How of Curing – Moisture

Moisture control can be separated into two phases: initial curing activities that are undertaken before the mixture sets, which reduces early moisture loss and plastic shrinkage cracking, and final curing that is conducted after bleeding ends and finishing work is completed, which promotes continued hydration.

Initial Curing

Initial curing activities preclude the direct addition of water to the surface because doing so will functionally increase the w/cm ratio at the surface and potentially mar the surface.

Traditional initial curing techniques include one or more of the following:

- Evaporation retarders
- Fog sprays
- Wind barriers

All of these approaches have their strengths and weaknesses depending on the application.

Evaporation Retarders

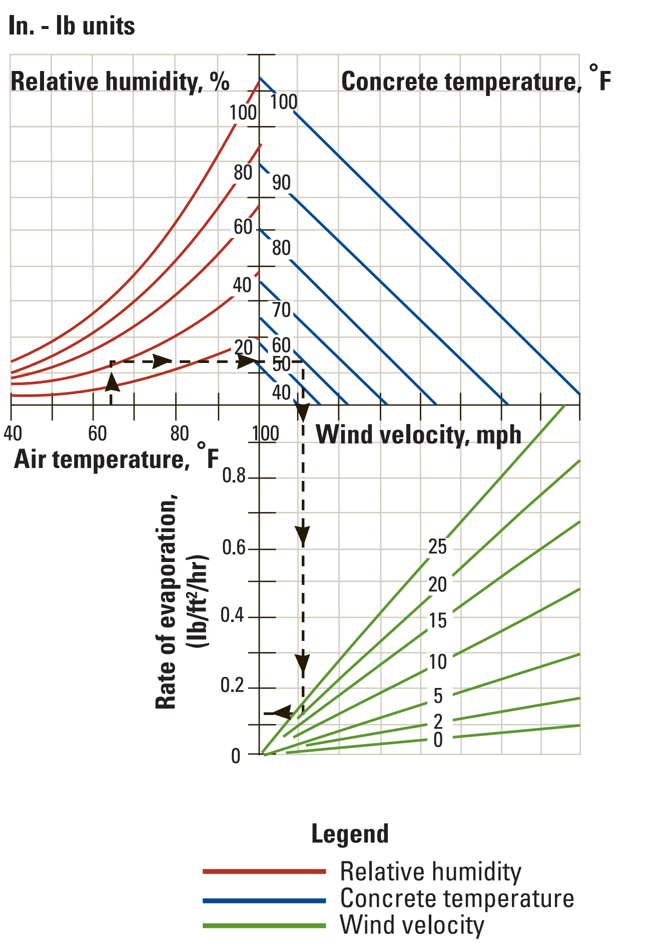
Evaporation retarders are water- and alcohol-based compounds applied to the surface after strike-off and before final finishing to slow early evaporation and associated plastic shrinkage cracking.

When environmental conditions indicate that rapid drying is likely, products specifically developed for this purpose should be applied in accordance with the manufacturer's instructions as soon as strike-off is completed. The nomograph from the American Concrete Institute (ACI) shown in Figure 4 can be used to assess the risk of rapid drying.

Evaporation reducers must be allowed to evaporate before finishing starts, and should not be used as finishing aids or worked into the surface, but rather because these practices will negatively affect the surface w/cm ratio.

Fog Sprays

The purpose of fogging is to keep the environmental humidity high at the surface of the concrete to reduce the evaporation of bleed water. The fog should consist of a fine mist that does not build up on the concrete surface. At the same time, it must be dense enough to keep the localized humidity at the concrete surface high enough to control the risk of plastic shrinkage cracking, even under ambient highly evaporative conditions.



PCA, after ACI 1999

Figure 4. ACI nomograph

ACI guidance states that coverage should be complete and uniform, achieved using atomizing nozzles that allow the fog to drift to the surface. The effectiveness of the treatment is assessed by the presence of a sheen on the surface without accumulations of water.

Fogging systems are commercially available, but there are no standards to monitor or certify their effectiveness. Instead of trying to define nozzle numbers and sizes, flow rates, and/or placements, it is more practical to address the performance that the fogging is intended to provide.

An approach to determine the acceptability of a given fogging system is to monitor the relative humidity (rH) of the air, wind speed, and temperature at the surface of the slab. This can be achieved using strategically placed sensors. An acceptance value of 0.2 $lb/ft^2/hr$ should be used as recommended by ACI (Figure 4). However, a lower acceptance value may be warranted for mixtures expected to produce less bleed water due to their supplementary cementitious materials and low w/cm ratio.

It is important that fogging is uniform over the whole area to which it is applied, which is best achieved by using several nozzles placed upwind of the surface, often in conjunction with wind barriers. Uniformity can be assessed visually or by using multiple sensors. It is also important that water does not pond on the surface because this indicates that the mist is not fine enough or that too much mist is being applied.

Fogging should be applied until the environmental conditions improve or final curing can be applied.

Wind Barriers

As indicated in the nomograph in Figure 4, wind speed has a strong impact on the risk of rapid drying. Therefore, the provision of wind barriers can be beneficial in reducing cracking. The challenge in the use of wind barriers is to provide effective barriers that protect the entire day's work without interfering with construction activities.

Final Curing

Retaining Water

For mixtures with a w/cm ratio greater than about 0.40, it is normally sufficient to simply minimize moisture loss to achieve sufficient hydration. Moisture retention can be achieved by any combination of the following:

- Keeping forms in place
- Covering the surface with a saturated layer, such as burlap
- Covering the surface with plastic sheeting
- Applying curing compound

If surface coverings are used, it is important that unprotected edges are sealed to prevent drying and to prevent wind from tunneling under the covering.

Curing compounds should be applied at the rate recommended by the manufacturer. Note that textured surfaces have far higher surface areas than smooth ones, meaning that the application rate of the curing compound must be increased for these types of surfaces. Curing compound must be applied by machines with the nozzles set at the correct height so that there is overlap between the area covered by each nozzle, as in Figure 5. Care is needed to minimize the amount of product that is carried away by the wind. Two coats, applied perpendicular to one another, are more effective than a single thick coat.

Curing compounds based on poly alpha methylstyrene (PAM) are reported to be far more effective than compounds based on other chemical compositions.

White pigmented products are recommended so that the uniformity of coverage can be observed. One acceptance metric that can be used to assess coverage is to compare the color of the coating to a piece of white paper. Work is underway to investigate a resistivity-based approach for assessing when curing compound should be applied and whether sufficient coverage has been achieved.

The moisture state at the surface should be kept high until required surface properties, such as permeability, have been achieved.

Jim Grove, ATI Inc./FHWA, used with permission

Figure 5. Curing compound being sprayed on a pavement surface

Adding Water

Providing additional water to the surface can help prevent drying of the concrete. This can be achieved by the following:

- Flooding
- Water sprays
- Coverage with continuously wetted materials
- Internal curing

Flooding and sprays can provide better protection than water retention methods, but care must be taken to prevent drying overnight or on weekends, when the system is not likely to be monitored. Additionally, these approaches are not appropriate when temperatures are approaching freezing because if the excess water freezes early in the life of the concrete, surface damage is likely. The impact of these approaches on the construction schedule must also be considered, because their use may prevent access to the concrete surface and delay the next stage of construction.

Internal curing is the practice of mixing small, porous, saturated particles into the mixture, normally through the replacement of about 20% of the fine aggregate with lightweight fine aggregate. These particles release water back into the paste when the pores start drying out, whether drying occurs through evaporation or the desiccation of mixtures with low w/cm ratios. The primary advantages of this approach are that it avoids moisture differentials through the thickness of the element and allows enhanced hydration at levels further from the surface than can be achieved using surface curing methods. In general, internal curing is of most benefit to the interior of the concrete, and hence conventional surface curing is still desirable.

The How of Curing – Temperature

Hot Weather

In hot weather, temperature-related concerns include the following:

- Accelerated drying
- Increased peak temperatures at setting time, leading to high stresses upon cooling
- Rapid hydration, leading to higher permeability in the long run

The actions that can be taken to reduce these effects include the following:

- Place the concrete at night when ambient temperatures are lower. This approach also ensures that ambient peaks do not occur at the same time as hydration peaks and that additional time passes before the next cooling cycle begins, allowing additional hydration to occur.

- Cool the mixture before placement, which again reduces hydration peaks. The mixture can be cooled by cooling the aggregate stockpiles and using chilled water. In extreme cases, the mixture can be injected with liquid nitrogen, although this approach can negatively impact the air void system.
- Cool the slab using fog sprays, as discussed above.
- Utilize control systems to control temperatures within the desired range.

Cold Weather

In cold weather (<40°F), temperature-related concerns include the following:

- Slowed hydration, which increases the risk of cracking because the drying rate is not slowed. Note that hydration only stops at about 14°F.
- The need for longer periods before form removal.

The actions that can be taken to reduce these effects include the following:

- Warm the support system and reinforcement Care must be taken to prevent the buildup of ice on the reinforcement because this will reduce its bond with the paste.
- Warm the mixture using heated water.
- Warm the slab using blankets and hot air blown under the blankets. Heated air should not contain exhaust fumes from the burners because this will accelerate carbonation of the surface, leading to dusting.
- According to traditional guidance, ensure that the concrete attains 500 psi compressive strength before it is exposed to freezing conditions.
- Leave forms in place to act as blankets.
- Remove forms or blankets during the warmest part of the day to avoid thermal shock to the surface.

When cold weather protection is removed, limit the reduction in temperature of the concrete surface to 40°F during any 24-hour period until the surface temperature of the concrete reaches that of the ambient air temperature.

If combustion-type heaters are used, ensure that they are properly vented. Position heaters and ducts so that the hot, dry air does not cause areas of the concrete surface to overheat or dry, and keep concrete surfaces moist to avoid excessive loss of moisture from the concrete when applying external heat.

Closing

Controlling the moisture and temperature state of young concrete can be very effective in reducing the risk of early-age cracking and long-term distresses.

In general, efforts should be focused on maintaining a sufficient moisture state to promote continued hydration for several days, particularly at the surface. In addition, in both severely hot and severely cold weather, actions are needed to prevent extremes of temperature and temperature differentials through the slab thickness.

References

ACI. 1999. *Hot Weather Concreting*. ACI 305R-99. American Concrete Institute, Farmington Hills, MI.