design & construction

Understanding Hot Weather Concrete

Getting the Most Out of the Summer Concrete Construction Season

By Ken Hover

After a long, cold winter the return of hot weather to North America is a welcome relief. Summer is not only the most active building season in many parts of the country, but can also be an ideal time for concrete construction, offering the advantages of faster early-age strength gain, and the ability to finish and cure the concrete sooner. However, we have to minimize the disadvantages of rapid slump loss, setting that can outpace finishing, rapid drying of concrete surfaces, the effects of differential temperatures within a concrete element, and potential reductions in later-age strength. This can be done.

The Fundamentals

Temperature and Hydration

1. The rate of hydration of portland cement varies exponentially with temperature, as shown in *Figure 1*. As is the case for many chemical and biological reactions the rate of reaction doubles whenever the temperature of the reactants increases by about 20°F, and halves whenever the temperature of the reactants decreases by about 20°F.

2. Warmer weather means casting warmer concrete. This is because the raw ingredients are warmer, the mixing, transport, and placing equipment is warmer, the forms and reinforcing steel are warmer, and the air and incident sunlight heats the concrete surface.

3. Given the impact of temperature on hydration, warmer concrete means faster rates of slump loss, setting and surface evaporation, and faster rates of early-age strength gain.

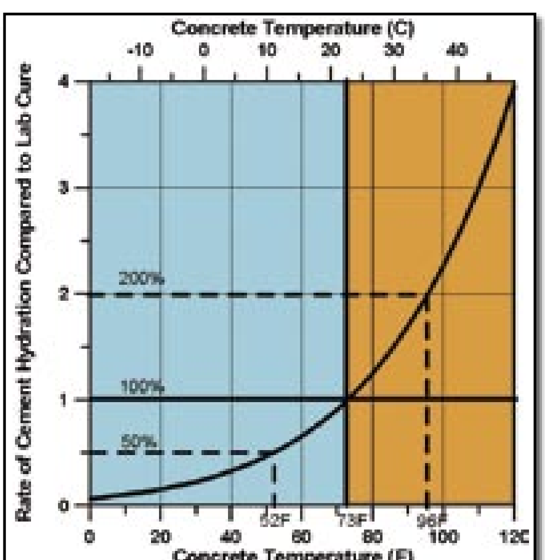

Figure 1: The rate of hydration of portland cement increases exponentially with temperature. For the particular cement represented here, hydration rate is twice as fast at a concrete temperature of 96°F when compared to hydration rate at lab curing temperature of 73°F. At concrete temperatures as mild as 52°F the concrete is hydrating only half as fast as under lab conditions.

Slump Loss and Rapid Setting

Concrete temperature not only affects early and later-age strength of the concrete, but immediately affects the rate of slump loss and the rate of setting. A 20°F increase in concrete temperature doubles the rate of slump-loss and halves the setting time. This means that even modest increases in concrete temperature can dramatically shorten the time available to transport, place, consolidate, finish, and cure the concrete. People and equipment have to be ready for hot weather concrete before the first truck arrives – a placing and finishing crew that is shorthanded because of the high summertime demand for construction labor, and a warm, fast setting concrete is a bad combination.

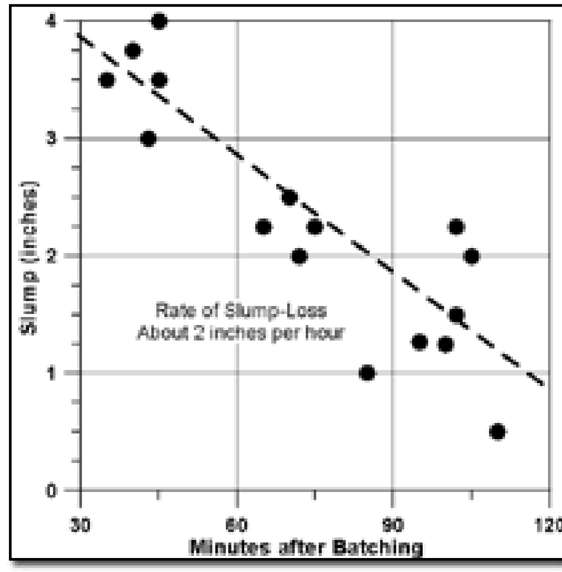

Figure 2: Slump values obtained by 6 separate testing teams over a two hour time period, on one single truckload of concrete. No single slump value is "characteristic" of this mixture. A slump loss rate of 2 inches per hour is characteristic of this mix in this particular environment.

The most common "field expedient" technique for compensating for rapid slump loss in hot weather is to add water to the truck on site. This *can be* acceptable as long as the added water is accurately metered, the total water content after water addition is in accordance with the specifications, and the concrete is mixed thoroughly after water addition. Many concrete producers include on the delivery ticket the number of gallons of water that can be added to the truck to bring the load up to the design water content. The acceptability of water addition is much more difficult to assess, however, when the concrete is being controlled by slump rather than by water content.

The advent of water reducers, air entraining admixtures, accelerators, retarders, and supplementary cementitious materials blurs any reliable relationship that may have existed between slump and water content. Second, slump is a time-dependent variable and the rate of slump loss over time depends on the mixture and on the weather (*Figure 2*). A random slump value with no reference to time after batchng is therefore of limited use for characterizing the concrete. Nevertheless, a lot of concrete is controlled on-site on the basis of slump, and water addition is permitted if the concrete is below that specified value. In hot weather, however, the chances are much greater that the slump will have decreased in transit to the point that water addition is allowed without regard to the total water content in the mix. When water is added under hot weather conditions, a frequently applied and seemingly "intuitive" justification is that this merely "replaces" water lost to evaporation in transit, when in reality the observed slump loss is not due to water loss but due to water consumption in the thermally-activated hydration process.

A second hot-weather opportunity for uncontrolled water addition presents itself when the slab concrete starts to set faster than the finishers can apply the required final texture. When premature stiffening occurs, the surface can be made "finishable" again by spraying or sprinkling water on the surface and working it in with a finishing tool. If applied soon

Figure 3: Fogging to increase the humidity of the air above the freshly-cast conrete, and thurs reduce the evaporation rate. (Photo Source—K. Hover)

enough this works because the water breaks the fragile, early hydration bonds between the cement grains, pushes the cement grains further apart and renders the surface finishable on the short term, but weaker, more porous, and less scaling- and abrasion-resistant on the long term. The acceptability of this practice depends on the trade-off between surface texture, and surface strength and long-term durability. A wise trade-off will depend on the planned use and service conditions of the slab.

Surface Drying and Curing

Drying of the concrete surface begins as soon as the rate of evaporation exceeds the rate of bleeding. Bleeding will of course stop within a short time after placing, so the real question is not whether the ambient conditions *will* dry the surface, but *how soon* the drying will begin. "How soon" is critical because restrained shrinkage induces shrinkage stress, and cracks form when the shrinkage stress equals the early-age tensile strength. Since concrete's tensile strength develops over time, the sooner the drying and shrinkage occurs, the more likely it is that the concrete will crack. These are referred to as "plastic shrinkage cracks" if the concrete is still deformable or "plastic" at the time of cracking, and as "drying shrinkage cracks" if the concrete has become a brittle solid by the time the cracks develop. The risk of plastic shrinkage cracking is therefore greater the sooner the concrete surface dries, and earlier drying is favored by a combination of an increase in the evaporative potential of the ambient air, increased surface area due to a deep surface texture such as brooming or tining, and a decrease in the rate of bleeding of the concrete.

The human body is a useful sensor of the first of these factors. For many of us a hot-dry environment is comfortable because the air has an evaporative potential that equals or exceeds perspiration rate. We stay dry and evaporative cooling keeps us comfortable, as long as we keep drinking water (human on-site water addition), and we boast that it is "a dry heat." The average perspiration rate of an adult male performing physical labor in hot weather is about 0.2 lb per ft^2 of skin surface per hour, so dry workers on a hot day means a severe evaporative potential. On the other hand, recalling Cincinnati summer days of 95°F and 95% humidity, there is nothing "dry" about that heat. Under those conditions, neither the people nor the concrete is likely to dry rapidly. It is interesting, then, that summer weather conditions that make the humans on site comfortable due to evaporative cooling are generally hostile to the concrete, and summer days that make humans miserable are fairly benign as far as concrete-drying is concerned. Further, we all know the benefits of moving air to increase summertime comfort. As air velocity increases over skin or concrete surfaces, water vapor is removed and the thickness of the still-air layer is reduced. The

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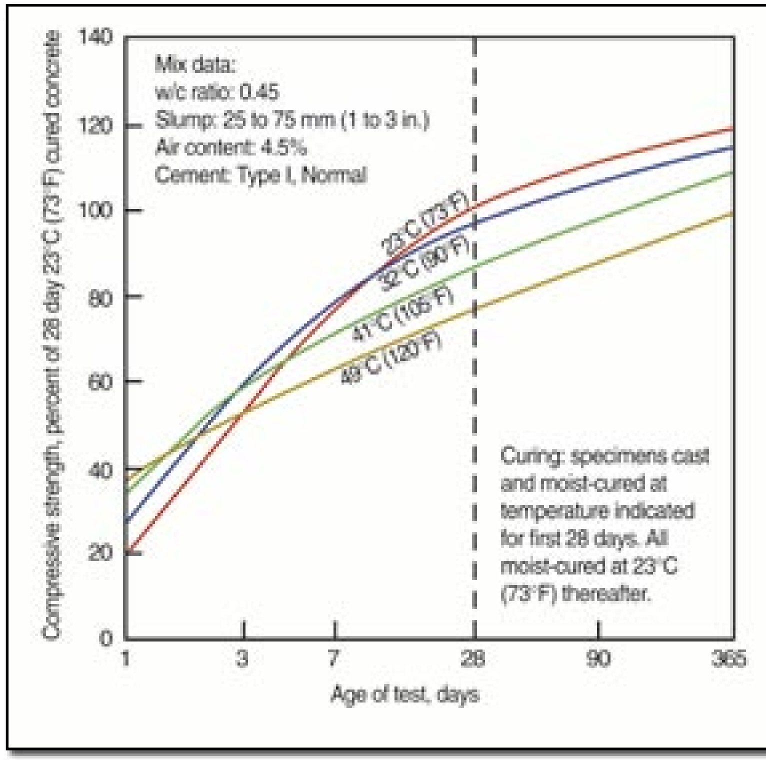

Figure 4: Higher concrete curing temperatures increase the early age strength of concrete but decrease the later age strength. At an age of 1 day higher concrete temperature leads to higher compressive strength. At an age of about 3 days the concrete strength is not significantly influenced by temperature, but after 28 days cooler temperature leads to higher compressive strength. Although the general trends remain, the quantitative impact of temperature is specific to a particular combination of materials. (Source—Portland Cement Association)

faster the wind, the sooner the temperature and humidity just above the concrete surface matches temperature and humidity of the air in general.

The time-honored suggestion is that there is risk of plastic shrinkage cracking when evaporation potential equals 0.2 lb of water per ft^2 of concrete surface per hour. Modern concrete mixtures have substantially lower bleeding rates, however, and high-performance mixes with supplementary cementitious materials, high range water reducers, and high air contents may have an essentially zero bleeding rate. The net result is that many modern mixes are at risk of plastic shrinkage cracking at evaporation rates that are markedly less than the traditional threshold. High density bridge deck overlays, for example, may be at risk of cracking when the air has an evaporation potential of 0.05 lb per ft^2 per hour or less.

One of the most effective ways to slow concrete surface drying is to reduce evaporative potential by fogging (*Figure 3*). This is done by dispersing fog drops into the air above the concrete so that evaporation of the droplets raises the local relative humidity. Those drops that gently fall to the slab surface replace bleed water, but do not damage the concrete as long as the "fog-water" is not finished-into the concrete. Another technique that has become popular is the use of an "evaporation reducer," originally developed as a chemical that forms a one-molecule thick layer ("mono-molecular film") over the surface of water stored in industrial process tanks. These products are sprayed onto the concrete surface and can work as advertised when applied to a layer of bleed water on the concrete, slowing the rate of evaporation of the bleed water. When sprayed onto a dry concrete surface, the mono-molecular film cannot form and product effectiveness is questionable.

As soon as the concrete is textured, it is time to slow the rate of evaporation by more substantial methods. Immediate curing is important because the hydrating cement (and incident sunlight) warms the concrete, increasing the temperature of the bleed water and accelerating evaporation (evaporation rate increases exponentially with the temperature of the evaporating fluid). Immediately after the last pass of the finishing tool, a membrane forming curing compound can be spray applied without the need to walk on and thus mar the freshly finished surface. These products do an effective job of dramatically reducing the rate of water loss from the concrete, but they do not prevent water loss, nor are they intended to "seal" the surface in the sense of zero water *loss*. Curing compounds cannot provide water to the hydrating cement, however, and given that portland cement has the ability to chemically and physically utilize up to 45 lb of water per

Figure 5: Infrared thermal image of concrete cylinders stored on site a few hours after casting. Surface temperature of the black plastic cylinder molds peaked at 124°F at the time of the photo. (Source—K. Hover, Concrete International December, 2004)

100 lb of cement in the multiple processes of hydration, many modern concrete mixtures benefit from a water cure. Applying wet burlap or other absorbent materials, along with associated soaker hoses and sprinklers, can damage concrete that has not yet reached final set, so the curing compound is a vital "intermediate" curing method between fogging and wet cure.

Concrete Strength

Concrete strength develops as a function of hydration, and the relationship shown in *Figure 1* shows that the *quantity* of hydration products developed per unit time increases when hot weather raises concrete temperature. Unfortunately, thermally accelerating the hydration process lowers the *quality* of those same hydration products. The net result is demonstrated in *Figure 4*, where the beneficial effect of warmer concrete is evident prior to 3 days with diminishing strength-gain between 3 and 28 days as concrete temperature increases. Evaluating the effect of hot concrete on strength therefore requires looking at both early and later age test results. Even though the later age strength may be less than obtained at a 73°F curing temperature, the final in-place result may be fully acceptable.

This important effect of temperature on concrete strength has to be considered in the context of standard testing. Standard lab-cure temperature is 73°F, and if actual in-place concrete temperature consistently exceeds 73°F, standard test cylinders are likely to underestimate in-place strength at ages up to about 3 days, and then overestimate in-place strength at later ages. A closely related testing problem relates to the on-site curing of cylinders. ASTM C 31 requires that cylinders be stored in a temperature range no cooler than 60°F and no warmer than 80°F in the first 24 hours after casting, to minimize the effects demonstrated in *Figure 4*. Despite recommendations and specifications that cylinders be kept in a temperature controlled "curing box" on site, such boxes are rare and cylinders in their black plastic molds sitting in the summer sun are a common sight. Since early heat helps early strength, up to around 3 days the "hot-cylinder" test result may be unconservatively high. At ages later than about 3 days, the "hot cylinder" will yield a strength that may be lower than the strength of the in-place concrete. The author recently monitored a project in which in-place concrete temperature was about 100°F while concrete cylinders stored on site were measured at 124°F at the same time (*Figure 5*).

In Place Temperature and Strength

Whether we measure it or not, achieving satisfactory in-place strength in the actual structure is of course the real goal. This will be a function of the concrete mixture and actual in-place temperature. Controlling in-place temperature depends on lowering the initial placing temperature, reducing the heat gain due to hydration, and controlling heat losses.

Initial Placing Temperature

Hot weather elevates the temperature of fresh concrete for several reasons. First, portland cement is often shipped hot from the cement plant during the months of peak demand. This is because the only way to meet increased product demand is to shorten the cooling period at the plant (*Figure 6*). Aggregate gets hot when stockpiled in direct sunlight, but if the air is dry with a light breeze the aggregate can be evaporatively cooled by spraying the stockpiles with water. (In a hot-wet environment, this practice merely results in hot-wet aggregates.) Initial temperature can be lowered by cooling the aggregates, or by substituting chilled water or ice for some of the batch water. Liquid nitrogen can be injected into the trucks as they arrive on site to achieve still further cooling.

Controlling placing temperature is just the beginning, however. The warmer the placing temperature, the faster the hydration, which in turn warms the concrete and further accelerates hydration and subsequent heat release. It is therefore important to not only control placing temperature, but to also reduce heat of hydration by lowering total cementitious material content or by substituting pozzolans such as Type F fly ash for a portion of the cement. Subsequent temperature rise depends not only on the heat gain due to hydration, but also on the heat lost to the environment. Relatively thin slabs with a large surface-to-volume ratio will lose heat rapidly to the ground and to the air, and thus experience far less temperature increase than a 4-foot thick footing cast with the same concrete. Member geometry also comes into play. An internal temperature difference of 30-35° F puts concrete elements at risk of

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Figure 6: Thermal infrared image of a cement storage silo at a concrete batch plant. The cement in the lighter colored zone had just been placed in the silo at 6 am on this Monday morning. The cooler material below had been received the previous Friday. The cement temperature difference was sufficient to cause a 10°F concrete temperature difference between two consecutive truckloads arriving at the job site. (Source—K.Hover, Concrete International, December, 2004)

full-depth thermal cracking due to a hot interior that is thermally expanding with a cooling exterior that is contracting. Even in summer, it can be effective to apply curing blankets to slow the rate of cooling at the exterior surfaces and thus minimize the temperature differential.

The actual in-place temperature of the concrete therefore depends only in part on the placing temperature, and largely on the size, shape, and surface area of the concrete being cast, air and ground temperature, wind, formwork and insulation, and the composition and thermal properties of the mixture ingredients. Further, the impact of temperature on the strength of the concrete will depend on the specific blend of cementitious materials and on the effect of retarders and water reducers. Such factors therefore make it tough to cite a universal limit on concrete placing temperature, if the purpose of the limit is to minimize the impact on later age strength. Default values such as 90 or 95°F can be found in documents such as ACI 301 or ACI 305, but on larger projects the engineer may want to entertain a proposal for contractor-testing to develop mixture- and application-specific limits.

Specifying Hot Weather Concrete

There are multiple sources for information and specifications for hot weather concreting. Chapter 5 of the ACI 318 Building Code includes a very brief requirement to "prevent excessive concrete temperatures or water evaporation that could impair required strength or serviceability of the member or structure." More detailed requirements are found in ACI 301, *Specifications for Structural Concrete*, although there is not a specific section on hot weather. ACI Committee 308 has published a *Guide to Curing Concrete* (ACI 308R-01) and a *Standard Specification for Curing Concrete*, (ACI 308-1.98) that covers fogging, curing compounds, and wet curing. ACI Committee 305 on Hot Weather Concreting has prepared a reference specification, and it should be open for public discussion in the very near future. Comprehensive guidance on the subject is contained in ACI 305R-99, *Hot Weather Concreting*.

Be Prepared For a Change in the Weather

Anyone who has planned a picnic or a golf outing knows how fast summer weather can change, and part of hot weather concreting is to be ready for such changes. Late afternoon thunderstorms can brew up out of nowhere, and torrential rain can ruin the most well-planned slab placement. Lightning can suddenly become the most serious problem when placing concrete in the open on a high-rise structure. A humid morning can give way to a dry, windy afternoon, and a well-coordinated nighttime placing operation can wrap up with a stiff pre-dawn breeze. In arid climates, hot days can be followed by cold nights with severe drying conditions. The contractor needs contingency plans, and needs to be ready to erect wind breaks or to cover a slab with plastic when the weather changes. For a designer-builder team that has anticipated the effects of the weather, summer can be the time to make a lot of progress!▪

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