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ACI 305R-10

Guide to Hot Weather Concreting

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Environmental factors, such as high ambient temperature, low humidity, high wind, or both low humidity and high wind, affect concrete properties and the construction operations of mixing, transporting, and placing of the concrete materials. This guide provides measures that can be taken to minimize the undesirable effects of these environmental factors and reduce the potential for serious problems.

This guide defines hot weather, discusses potential problems, and presents practices intended to minimize them. These practices include selecting materials and proportions, precooling ingredients, and batching. Other topics discussed include length of haul, consideration of concrete temperature as placed, facilities for handling concrete at the site, and, during the early curing period, placing and curing techniques, and appropriate testing and inspection procedures in hot weather conditions.

The materials, processes, quality control measures, and inspections described in this document should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI certifications or equivalent.

Keywords: air entrainment; cooling; curing; evaporation; high temperature; hot weather construction; plastic shrinkage; production methods; retempering; slump tests; water content.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Hot weather can create problems in mixing, placing, and curing hydraulic-cement concrete that adversely affect the properties and serviceability of the concrete. Most of these problems relate to the increased rate of cement hydration at higher temperature and increased evaporation rate of moisture from the freshly mixed concrete. The rate of cement hydration depends on ambient and concrete temperature, cement composition and fineness, amount and type of supplementary cementitious materials, and admixtures used.

A maximum as-placed concrete temperature is often specified in an effort to control rate of setting, strength, durability, plastic shrinkage cracking, thermal cracking, and drying shrinkage. The placement of concrete in hot weather, however, is too complex to be dealt with by setting a maximum as-placed or as-delivered concrete temperature. Concrete durability is defined as the ability of concrete to resist weathering action, chemical attack, abrasion, or any other process of deterioration (ACI 201.2R). Generally, if concrete strengths are satisfactory and curing practices are sufficient to avoid undesirable drying of surfaces, the durability of hot weather concrete will not differ greatly from similar concrete placed at normal temperatures.

Where an acceptable record of field tests is not available, concrete proportions can be determined by trial batches (ACI 301 and 211.1). Trial batches should be made at temperatures anticipated in the work and mixed following one of the procedures described in Section 4.10, Proportioning. The concrete supplier is generally responsible for determining concrete proportions to produce the required quality of concrete unless specified otherwise.

If the initial 24-hour curing is at 100°F (38°C), the 28-day compressive strength of the test specimens may be 10 to 15% lower than if cured at the required ASTM C31/C31M curing temperature (Gaynor et al. 1985). If the cylinders are allowed to dry at early ages, strengths will be reduced even further (Cebeci 1987). Therefore, proper curing of the test specimens during hot weather is critical, and steps should be taken to ensure that the specified procedures are followed.

The effects of high air temperature and low relative humidity are more pronounced with increases in wind speed. The potential problems of hot weather concreting can occur at any time of the year, but generally occur during the summer season. Drying conditions can occur even at lower ambient temperatures, with slower set times, lower relative humidity, and wind, all of which are conducive to higher evaporation. Precautionary measures required on a windy, sunny day will be stricter than those required on a calm, humid day, even if air temperatures are identical.

1.2—Scope

This guide identifies problems associated with hot weather concreting and describes practices that alleviate these potential adverse effects. These practices include suggested preparations and procedures for use in general types of hot weather construction, such as pavements, bridges, and buildings. Temperature, volume changes, and cracking problems associated with mass concrete are treated more thoroughly in ACI 207.1R, 207.2R, and 224R.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

E = evaporation rate, lb/ft^2/h (kg/m^2/h)
e_a = water vapor pressure in mmhg (psi) in the air surrounding the concrete obtained by multiplying the saturation vapor pressure at the temperature of the air surrounding the concrete by the relative humidity of the air. Air temperature and relative humidity are measured approximately 1.2 to 1.8 m (4 to 6 ft) above the concrete surface on the windward side and shielded from the sun's rays
e_o = saturation water vapor pressure in mmhg (psi) in the air immediately over the concrete surface, at the concrete temperature. Obtain e_o from Table 4.2(a) or (b)
e_s = saturation vapor pressure, kPa (psi)
r = (relative humidity percent)/100
T = temperature, °C (°F)
T_a = air temperature, °F (°C)

the delivery time and hot weather environment expected at the project. Trial batches used to select proportions are normally prepared in accordance with ASTM C192/C192M. The method requires concrete materials to be at room temperature (in the range of 68 to 86°F [20 to 30°C]). Trial batches, however, should also be performed at the expected maximum placing temperature using a mixing and agitating period longer than that required in ASTM C192/C192M to help define the performance to be expected.

When determining mixture proportions using laboratory trial batches, estimate the slump loss during the period between first mixing of the concrete and its placement in the form by use of Procedures A and B, adopted from ACI 223, Section 4.5.2. The procedures from ACI 223 produce a rate of slump loss similar to that expected for a 30- to 40-minute delivery time.

4.10.1.1 *Procedure A*

1. Prepare the batch using ASTM C192/C192M procedures, but add 10% additional water over that normally required;
2. Mix initially in accordance with ASTM C192/C192M (3 minutes of mixing followed by a 3-minute rest and a 2-minute remixing);
3. Determine the slump and record as initial slump;
4. Continue mixing for 15 minutes;
5. Determine the slump and record as estimated placement slump. Experience has shown this slump correlates with that expected for 30- to 40-minute delivery time. If this slump does not meet the specification limits, either discard and repeat the procedure with an appropriate water adjustment, or add water to give the required slump and then test the concrete; and
6. Determine other properties of fresh concrete (temperature, air content, unit weight), and mold strength test specimens.

4.10.1.2 *Procedure B*

1. Prepare the batch using ASTM C192/C192M procedures for the specified slump;
2. Mix in accordance with ASTM C192/C192M (3 minutes of mixing followed by a 3-minute rest and a 2-minute remixing) and confirm the slump;
3. Stop the mixer and cover the batch with wet burlap;
4. After 20 minutes, remix for 2 minutes, adding water to produce the specified slump. The total water (initial water plus the remixing water) can be expected to equal that required at the batch plant to give the required job site slump; and
5. Determine other properties of fresh concrete (temperature, air content, and unit weight) and mold-strength test specimens.

4.10.1.3 *Alternative to Procedures A or B*—As an alternative to Procedures A or B, the use of full-size production batches may be considered for verification of mixture proportions, provided the expected high temperature levels of the concrete can be attained. This may be the preferred method when admixtures selected for extended slump retention are used. It requires careful recording of batch quantities at the plant and of water added for slump adjustment before sampling. Sampling procedures of ASTM C172 should be strictly observed.

CHAPTER 5—PRODUCTION AND DELIVERY

5.1—General

Production facilities and procedures should be capable of providing the required quality and quantity of concrete under hot weather conditions at production rates required by the project. Satisfactory control of production and delivery operations should be assured. Concrete plant and delivery units should be inspected and in good operating condition. Intermittent stoppage of deliveries due to equipment breakdown can be much more serious under hot weather conditions than in moderate weather. In hot weather concreting operations, concrete placements can be scheduled at times other than during daylight hours, such as during the coolest part of the morning. Night-time production requires additional planning and lighting.

5.2—Temperature control of concrete

Concrete can be produced in hot weather without maximum limits on placing temperature, and perform satisfactorily when proper precautions are observed in proportioning, production, delivery, placing, consolidating, finishing, and curing. As part of these precautions, an effort should be made to keep the temperature of the fresh concrete as low as practical. Using the relationships given in Appendix A, it can be shown, for example, that the temperature of concrete can typically be reduced by 1°F (0.5°C) if any of the following reductions are made in material temperatures:

- 8°F (4°C) reduction in cement temperature;
- 4°F (2°C) reduction in water temperature; or
- 2°F (1°C) reduction in the temperature of the aggregates.

5.2.1 *Aggregate cooling*—Figure 5.1 shows the influence of the temperature of concrete ingredients on concrete temperature. As the greatest portion of concrete is aggregate, reduction of aggregate temperature brings about the greatest reduction in concrete temperature. Therefore, all practical means should be employed to keep the aggregates as cool as possible. Shaded storage of fine and coarse aggregates, and sprinkling or fog spraying of coarse aggregate stockpiles under arid conditions will help. Sprinkling coarse aggregates with cool water reduces aggregate temperature by evaporation and direct cooling (Lee 1987). Passing water through a properly sized evaporative cooling tower will chill the water to the wet bulb temperature. This procedure has greater effects in areas that have low relative humidity. Wetting of aggregates can cause variations in surface moisture. Moisture tests or the use of moisture probes are necessary to ensure that the correct batch adjustments are made. Above-ground storage tanks for mixing water should be provided with shade and thermal insulation. Silos and bins absorb less heat if coated with heat-reflective paints.

5.2.2 *Mixer drum color*—Painting mixer surfaces white to minimize solar heat gain also helps. Based on a 1-hour delivery time on a hot, sunny day, concrete in a clean, white mixer drum, should be 2 to 3°F (1 to 1.5°C) cooler than in a black or red mixer drum, and 0.5°F (0.3°C) cooler than in a cream-colored drum. When an empty mixer drum stands in the sun for an extended period before concrete is batched, the heat stored in the white mixer drum will raise concrete

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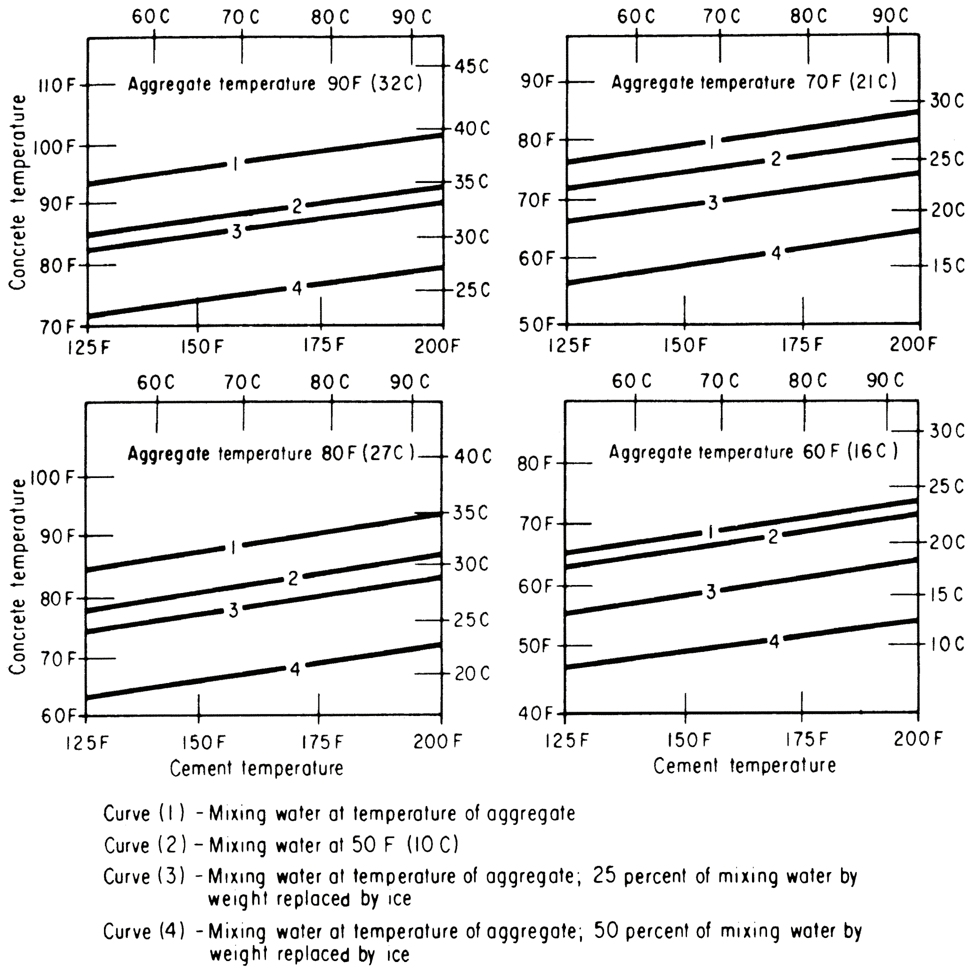

Fig. 5.1—Influence of temperature of concrete ingredients on concrete temperature (calculated from equations in Appendix A).

temperatures 0.5 to 1°F (0.3 to 0.5°C) less than a yellow or red mixer drum. Spraying the exterior of the mixer drum with water before batching or during delivery has been suggested as a means of minimizing concrete temperature, but it provides only a marginal benefit.

5.2.3 *Project plan*—Setting up the means for cooling sizeable amounts of concrete production requires planning well in advance of placement and installation of specialized equipment. This can include chilling of batch water by water chillers or heat pump technology as well as other methods, such as substituting crushed or flaked ice for part of the mixing water, or cooling by liquid nitrogen. Delivery of the required quantity of cooling materials should be ensured for each placement.

Details for estimating concrete temperatures are provided in Appendix A. Various cooling methods are described in Appendix B. The general influence of the temperature of concrete ingredients on concrete temperature is calculated from the equations in Appendix A, and shown in Fig. 5.1.

5.3—Batching and mixing

Batching and mixing is described in ACI 304R. Procedures under hot weather conditions are not different from good practices under normal weather conditions. Producing concrete with specified properties, such as slump, is essential because an interruption in the concrete placement due to rejection can cause the formation of cold joints or serious finishing problems. Testing of concrete is discussed in Chapter 7.

For truck-mixed concrete, an initial mixing of approximately 70 revolutions at the batch plant before transporting allows for an accurate verification of the condition of the concrete, primarily its slump and air content. Generally, centrally mixed concrete can be inspected visually as it is being discharged into the transportation unit.

5.3.1 *Slump control*—Slump can easily change due to minor changes in materials and concrete characteristics. For example, an undetected change of only 1.0% moisture content of the fine and coarse aggregates could change slump by 1 to 2 in. (25 to 50 mm) (ACI 211.1). An error range of approximately 0.5% in the determination of aggregate moisture complicates moisture control, even with advanced systems. Plant operators often batch concrete in a drier condition than desired to avoid producing a slump higher than desired or specified. Care should be taken to avoid withholding excessive water from the batch, as this could result in inadequate mixing, dry-packing that reduces the effectiveness of chemical admixtures, or delivery at a slump below the specified minimum.

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5.3.2 *Hydration control*—Hot weather conditions and extended hauling time can indicate a need to split the batching process by batching the cement at the job site, or layering the materials in the mixer drum at the plant to keep some of the cement dry and then mixing the concrete after arrival at the job site. This, however, can decrease concrete uniformity between loads. These methods can, on occasion, offer the best solution under existing conditions. A better-controlled concrete can usually be provided when all materials are batched at the concrete production facility.

By using some effective retarding admixtures at appropriate dosages, preferably in combination with cementitious material of slow-setting characteristics, concrete can be maintained in a placeable condition for extended periods, even in hot weather (Section 4.8). Field experience indicates that concrete set retardation can be extended further by separately batching the retarding admixture with a small portion of mixing water (1 to 2 gal/yd^3 [5 to 10 L/m^3]), after the concrete has been mixed for several minutes. These admixtures, together with the cementitious materials and other ingredients proposed for the project, should be evaluated in the field for desired properties. Should the slump be lower than required, the use of mid-range or high-range water-reducing admixtures is recommended to increase the concrete slump.

5.3.3 *Mixer control*—Under hot weather conditions, mixer revolutions at mixing speed should be held to a minimum to avoid unnecessary heat gain of the concrete (ACI 207.4R). For efficient mixing, mixers should be free of buildup of hardened concrete and excessive wear of mixer blades. As soon as the concrete has been mixed to a homogeneous condition, all further drum rotation should be at the lowest agitating speed of the unit (generally one revolution per minute). The drum should not be stopped for extended periods of time. There is the potential for false setting problems to cause the concrete to stiffen rapidly or set in the drum, or to flatten the mixer rollers.

Specifications that govern the total number of revolutions of the drum usually set a limit of 300 revolutions for truck mixers. This limit should be waived for:

- Concrete that retains its workability without the addition of water;
- Separate addition of high-range water-reducing admixtures; or
- Direct addition of liquid injected nitrogen into the mixer as a means of lowering the concrete temperature.

5.4—Delivery

While the concrete is in the mixer, cement hydration, temperature rise, slump loss, aggregate grinding, and change of air content all occur with the passage of time; thus, the period between start of mixing to placement of the concrete should be minimized. Coordination of mixer truck dispatching with the rate of concrete placement helps to avoid delays in arrival or waiting periods until discharge. On major concrete placements, provisions should be made for good communication between the job site and concrete production facility, and they should be scheduled during periods of lower urban traffic. When placement is slow, consideration should be given to reducing load size, using set-retarding admixture, or using cooled concrete.

5.5—Slump adjustment

Fresh concrete is subject to slump loss with time, whether it is used in moderate or hot weather. With given materials and mixture proportions, the slump change characteristics between plant and job site should be established. If, on arrival at the job site, the slump is less than the specified maximum, additional water can be added if the maximum allowable water content is not exceeded. When water is added to increase slump, the drum or blades should be turned an additional 30 revolutions or more, if necessary, at mixing speed. For expeditious placement and effective consolidation, structural concrete should have a minimum slump of 4 in. (100 mm). Slump increases should be allowed when chemical admixtures are used, provided that the admixture-treated concrete has the same or lower *w/cm* and does not exhibit segregation potential.

5.6—Properties of concrete mixtures

The proposed mixtures should be suitable for expected job conditions. This is particularly important when there are no limits on ambient placing temperatures, as is the case in most construction in warmer regions. Use of cements or cementitious materials that perform well under hot weather conditions, in combination with water-reducing and retarding admixtures, can provide concrete with the required properties (Mittelacher 1985). When using high-range water-reducing and retarding admixtures, products should be selected that provide extended slump retention in hot weather (Collepardi et al. 1979; Guennewig 1988). In dry and windy conditions, the setting rate of concrete used in flatwork should be adjusted to minimize plastic shrinkage cracking or crusting of the surface, whereas the lower layer remains in a plastic condition. The type of adjustment depends on local climatic conditions, timing of placements, and concrete temperatures. A change in quantity or type of admixture or cementitious materials can often provide the desired setting time.

5.7—Retempering

Laboratory research, as well as field experience, shows that strength reduction and other detrimental effects are proportional to the amount of retempering water added. Therefore, water additions in excess of the proportioned maximum water content or *w/cm* to compensate for loss of workability should be prohibited. Adding chemical admixtures, particularly high-range water-reducing admixtures, can be very effective to maintain workability.

CHAPTER 6—PLACING AND CURING

6.1—General

6.1.1 The requirements for good results in hot weather concrete placing and curing are no different than in other weather. They are:

- Concrete should be handled and transported with a minimum of segregation and slump loss;
- Concrete should be placed where it is to remain;

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- Concrete should be placed in layers shallow enough to assure vibration well into the layer below and that the elapsed time between layers should be minimized to avoid cold joints;
- Construction joints should be made on sound, clean concrete (refer to ACI 224.3R);
- Finishing operations and timing should be guided only by the readiness of the concrete for them, and nothing else; and
- Curing should be conducted so that at no time during the prescribed period will the concrete lack ample moisture and temperature control to permit full development of its potential strength and durability.

6.1.2 Details of placing, consolidation, and curing procedures are described in ACI 304R, 308R, and 309R. This chapter points out hot weather factors that can affect these operations and the resulting concrete and recommends what should be done to prevent or offset their influence.

6.2—Preparations for placing and curing

6.2.1 *Planning hot weather placements*—Before the start of the project, plans should be made to minimize the exposure of the concrete to adverse conditions. Whenever possible, slab placement should be scheduled after the roof structure and walls are in place to minimize drying winds and direct sunlight. A roof also reduces thermal shock from rapid temperature drops caused by wide day and night temperature differences or cool rain on concrete heated by the sun earlier in the day.

Under hot weather conditions, scheduling concrete placements at other-than-normal hours may be advisable. Pertinent considerations include ease of handling and placing, and minimizing the risk of plastic shrinkage and thermal cracking.

6.2.2 *Preparing for ambient conditions*—Personnel in charge of concrete construction should be aware of the damaging combinations of high air temperature, direct sunlight, drying winds, and high concrete temperature. Local weather reports should be monitored, and routine recordings of site conditions should be made, including air temperature, sun exposure, relative humidity, and prevailing winds. These data, together with projected or actual concrete temperatures, enable supervisory personnel, using Fig. 4.2, to determine and prepare the required protective measures. Equipment should also be available at the site to measure the evaporation rate (refer to Section 4.2.2).

6.2.3 *Expediting placement*—Preparations should be made to transport, place, consolidate, and finish the concrete at the fastest possible rate. Concrete delivery to the job should be scheduled so that it is placed promptly on arrival, particularly the first batch. Many concrete placements get off to a bad start because the concrete was ordered before the job was ready, and slump control was lost at this most critical time. Traffic arrangements at the site should ensure easy access of delivery units to the unloading points over stable roadways. Site traffic should be coordinated for a quick turnaround of concrete mixer trucks. If possible, large or critical placements should be scheduled during periods of low urban traffic loads.

6.2.4 *Placing equipment*—Equipment for placing the concrete should be of suitable design and have ample capacity to perform efficiently. All equipment should have adequate power for the work and be in first-class operating condition. Breakdowns or delays that stop or slow the placement can seriously affect the quality and appearance of the work. Arrangements should be made for readily available backup equipment. Concrete pumps, where used, should be capable of pumping the specified class of concrete through the length of line and elevation at required rates per hour. Where placement is by crane and buckets, wide-mouth buckets with steep-angled walls should be used to permit rapid and complete discharge of bucket contents. Adequate means of communication between bucket handlers and placing crew should be provided to ensure that concrete is charged into buckets only when the placing crew is ready to use the concrete without delay. Concrete should not be allowed to rest exposed to the sun and high temperature before it is placed into the form. To minimize the heat gain of the concrete during placement, delivery units, conveyors, pumps, and pump lines should be kept in the shade where possible. In addition, pump lines should be painted white. Lines can also be cooled by being covered with damp burlap or kept wet with a soaker hose.

6.2.5 *Consolidation equipment*—There should be ample vibration equipment and workers to consolidate the concrete immediately as it is received in the form. Procedures and equipment are described in ACI 309R. Provisions should be made for an ample number of standby vibrators—at least one standby for each three vibrators in use. Where a site is subject to occasional power outages, portable generators should be available for uninterrupted vibrator operation. Apart from the unsightliness of poorly consolidated concrete, insufficient compaction in the form can seriously impair the durability and structural performance of reinforced concrete.

6.2.6 *Preparations for protecting and curing the concrete*—Ample water should be available at the project site for moistening the subgrade, as well as for fogging forms and reinforcement before concrete placement. For moist curing, use water with a temperature no more than 20°F (11°C) cooler than the concrete temperature to avoid thermal shock where applicable. Fog nozzles should produce a fog blanket. They should not be confused with common garden-hose nozzles, which generate an excessive washing spray. Pressure washers with a suitable nozzle attachment can be a practical means for fogging on smaller jobs. Materials and means should be on hand for erecting temporary windbreaks and shades as needed to protect against drying winds and direct sunlight. Plastic sheeting or sprayable compounds for applying temporary moisture-retaining films should be available to reduce evaporation from flatwork between finishing passes. Where concrete placed under hot weather conditions is exposed to rapid temperature drops, thermal protection should be provided to protect the concrete against thermal shrinkage cracking. Finally, curing materials should be readily available at the project site to permit prompt protection of all exposed surfaces from premature drying upon completion of the placement.

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6.2.7 *Preparing incidental work*—Due to faster setting and hardening of the concrete in hot weather, timing of various final operations, such as saw cutting joints and applying surface retarders, becomes more critical; therefore, these operations should be planned in advance. Plans should be made for the timely sawing of contraction joints in flatwork to minimize cracking due to excessive tensile stress. Typically, joints that are cut using the conventional wet or dry process are made within 4 to 12 hours after the slab has been finished; 4 hours in hot weather, to 12 hours in cold weather. For early entry dry-cut saws, the waiting period will typically vary from 1 hour in hot weather to 4 hours in cold weather (ACI 302.1R).

6.3—Placement and finishing

6.3.1 *General*—Expeditious placement and finishing materially reduces hot weather difficulties. Delays increase slump loss and invite the addition of water offsets to offset those losses. Each operation in finishing should be carried out promptly when the concrete is ready. The concrete should not be placed faster than it can be properly consolidated and finished. When the placing rate is not coordinated with the available work force and equipment, the quality of the work will be marred by cold joints, poor consolidation, and uneven surface finishes.

6.3.2 *Placing formed concrete*—In hot weather, it is usually necessary to place concrete in shallower layers than those placed in moderate weather to ensure coverage of the lower layer while it will still respond readily to vibration. The interval between monolithic wall and deck placements becomes very short in hot weather. This interval can be extended by the judicious use of set-retarding admixtures.

6.3.3 *Placement of flatwork*—When concrete is deposited for flatwork on the ground, the subgrade should be moist, but free of standing water and soft spots. When placing concrete slabs of any kind in hot weather, it may be necessary to keep the operation confined to a small area and to proceed on a front with a minimum amount of exposed surface to which concrete is added. A fog nozzle should be used to cool the air, to cool any forms and steel immediately ahead, and to lessen rapid evaporation from the concrete surface before and after each finishing operation. Excessive fog application (which would wash the fresh concrete surface or cause surplus water to cling to reinforcement or stand on the concrete surface during floating and troweling) should be avoided. Other means of reducing moisture loss include spreading and removing impervious sheeting or applying sprayable moisture-retaining (monomolecular) films one or more times as needed between the various finishing operations. Finishing of flatwork should begin after the surface sheen of the (monomolecular) film has disappeared. These products should not be used as finishing aids or worked into the surface, as concrete durability can be reduced. The product manufacturer should be contacted for information on proper application and dosage. These procedures can cause a slight increase in concrete temperature in place due to reduced evaporative cooling. Generally, the benefit from reduced moisture evaporation is more important than the increase of in-place concrete temperature (Berhane 1984).

6.3.4 *Plastic shrinkage cracks*—Without protection against moisture loss, plastic shrinkage cracks can occur (refer to Section 4.1.4). In relatively massive placements, revibration before floating can sometimes close this type of cracking. Before the concrete reaches final set, the cracks can frequently be closed by striking the surface on each side of the crack with a float. The affected area is then retroweled to a level finish.

It serves no lasting purpose to merely trowel a slurry over the cracks, because these are likely to reappear when not firmly closed and immediately covered to avoid evaporation.

6.4—Curing and protection

6.4.1 *General*—Immediately following completion of finishing operations, efforts should be made to protect the concrete from low humidity, drying winds, and extreme ambient temperature differential. Whenever possible, the concrete and surrounding formwork should be kept in a uniform moisture and temperature condition to allow the concrete to develop its maximum potential strength and durability. High initial curing temperatures can negatively affect ultimate strength and durability to a greater degree than high placement temperatures of fresh concrete (Bloem 1954; Barnes et al. 1977; Gaynor et al. 1985). Procedures for keeping exposed surfaces from drying should begin promptly and continue without interruption. Failure to do so can result in excessive drying shrinkage and related cracking, which can impair the surface durability of the concrete. An approved curing method should be continued for at least 7 days. If more than one curing method is used during this period, any changes in method should be done after a minimum of 3 days. In addition, concrete surfaces should not be allowed to become surface-dry at any point during the transition. A variety of curing methods are described in ACI 308R. ACI 308R addresses in detail the concept of initial curing during the plastic stage of the concrete. Initial curing techniques, such as fog spray, can be used to ensure timely replacement of bleedwater and avoidance of plastic shrinkage cracking. Concrete should also be protected against thermal shrinkage cracking due to rapid temperature drops, particularly during the first 24 hours. Thermal shrinkage cracking is associated with a cooling rate of more than 5°F (3°C) per hour, or more than 50°F (28°C) in a 24-hour period for concrete with a least dimension less than 12 in. (300 mm). Concrete exposed to rapid cooling develops lower tensile strain capacity, and is more susceptible to other types of shrinkage cracking than concrete that cools at a slower rate (ACI 207.4R). Hot weather patterns increase the potential for thermal cracking due to vast day and night temperature differences. Additionally, seasonal weather patterns often include passing cold fronts that produce rain, which can induce thermal shock to exposed concrete sections. Under these conditions, concrete should be protected by placing an approved waterproof material over the exposed concrete, or by using other insulating methods and materials described in ACI 306R.

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6.4.2 *Moist curing of flatwork*—Moist curing is usually the best method for maximizing strength and durability and minimizing early-age drying shrinkage of concrete flatwork. Examples of moist curing methods are ponding, covering exposed concrete surfaces with clean sand kept continuously wet, fog-spraying, or continuous sprinkling. These methods require a sufficient water supply and disposal of any runoff. Where sprinkling is used, care should be taken that surface erosion does not occur. A common and practical method of moist curing is to cover the concrete with impervious sheeting or fabric mats kept continuously wet with a soaker hose or similar means. Other suitable coverings are described in ACI 308R. Curing materials should be kept in contact with the concrete surface at all times. Alternating cycles of wetting and drying should be avoided, as it will result in pattern cracking. The temperature of water used for initial curing should be as close as possible to that of the concrete to avoid thermal shock.

6.4.3 *Membrane curing of flatwork*—Where job conditions are not favorable for moist curing, the most practical method of curing is liquid membrane-forming compounds. The membrane restricts the loss of moisture from the concrete, thereby allowing the development of strength, durability, and abrasion resistance of the surface. Concrete surfaces exposed to direct sunlight should use heat-reflecting, white-pigmented compounds where applicable. Note that the moisture-retention rate varies considerably between products. For use in hot weather conditions, a material should be selected that ensures equal or greater moisture retention than required by ASTM C309, and limits the moisture loss in a 72-hour period in excess of 9 lb/yd^3 (0.55 kg/m^3) when tested per ASTM C156. Some agencies have a more restrictive moisture loss limit of 6.4 lb/yd^3 (0.39 kg/m^3) in a 72-hour period. Application of an approved moisture-retentive material should immediately follow the disappearance of surface water sheen after the final finishing pass. When a spray application is required or approved, the spray nozzle(s) should be positioned sufficiently close to the surface to ensure the correct application rate and prevent wind-blown dispersion. Manual spray application should be performed in two passes, with the second pass perpendicular to the first pass. Most curing compounds should not be used on any surface against which additional concrete or other materials are to be bonded. The curing compound material will not reduce bond strength if removal of the curing compound is assured before subsequent bonded construction.

6.4.4 *Concrete in formwork*—Forms should be covered and kept continuously moist during the early curing period. Formwork should be loosened or removed at the earliest practical age without damage to the concrete, and provisions should be made for an approved curing method to begin. Following formwork removal, tie holes and significant defects can be filled and repairs made by exposing the smallest practical section of concrete at one time to perform the work. All repairs should be completed within the first few days following form stripping so to the repaired areas cure with the surrounding concrete. At the end of the curing period, the covering should be left in place without wetting for several days (4 days is suggested) so that the concrete surface will dry slowly and be less prone to surface shrinkage cracking. Surface cracking due to drying can be minimized by applying a curing compound to exposed surfaces at the end of the moist-curing period.

CHAPTER 7—TESTING AND INSPECTION

7.1—Testing

Tests on the fresh concrete sample should be conducted and specimens prepared in accordance with ASTM C31/C31M, C138/C138M, C143/C143M, C172, ASTM C231/C231M, C232/C232M, C173/C173M, C1064/C1064M, C1611/C1611M, and C1621/C1621M, as appropriate. Tests should be performed by an certified ACI Concrete Field Testing Technician – Grade I. ASTM C31/C31M requires that the concrete samples be protected from exposure to sun, wind, rapid evaporation, and contamination. Failure to do so will not provide valid test results. High temperature, low relative humidity, and drying winds affect the rate of evaporation of the concrete sample surface when not protected properly as recommended by ASTM C31/C31M.

It is desirable in hot weather to conduct tests, such as slump, air content, ambient and concrete temperature, relative humidity, and density (unit weight), more frequently than in normal conditions.

7.1.1 *Curing test specimens*—Particular attention should be given to the protection and curing of strength test specimens used as a basis for acceptance of concrete. Due to their small size, test specimens are quickly influenced by changes in ambient temperatures. Extra care is needed in hot weather to maintain strength test specimens at a temperature of 60 to 80°F (16 to 27°C) for < 6000 psi (40 MPa), and 68 to 78°F (20 to 26°C) for ≥ 6000 psi (40 MPa), and to prevent moisture loss during the initial curing period, in accordance with ASTM C31/C31M, with the exception of C1611/C1611M and C1621/C1621M for self-consolidated concrete. The specimens should be provided with an impervious cover and placed in a temperature-controlled cylinder box or building immediately after molding. When stored outside, exposure to the sun should be avoided. Curing in a no-moisture-loss environment within the prescribed temperature range is also required.

Molds should not be manufactured of a material that expands when in contact with moisture or when immersed in water, and should meet the requirements of ASTM C470/C470M. Merely covering the top of the molded test cylinder with a lid or plate is usually not sufficient in hot weather to prevent loss of moisture and to maintain the required initial curing temperature. During the transfer to the testing facility, the specimens should be kept moist and also be protected and handled carefully. They should then be stored in a moist condition at 73 ± 2°F (23 ± 1.8°C) until the moment of testing as per ASTM C31/C31M.

7.1.2 *Additional test specimens*—Specimens, in addition to those required for acceptance, can be made and cured at the job site to assist in determining when formwork can be removed, when shoring can be removed, and when the structure can be placed in service. Unless the temperature and moisture conditions of concrete specimens used for these purposes

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