slump loss can be performed by taking slump measurements every 20 minutes for at least 2 hours after batching.

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. Because of this, a contingency plan should be established during the preplacement meeting to assure uninterrupted supply of concrete.

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

When proper planning and precautions are taken in all aspects of concrete production from proportioning to curing, concrete of acceptable quality can be produced at a predetermined maximum placement temperature established for specific site conditions. Throughout planning, production, and delivery, every effort should be made to keep the temperature of the fresh concrete as low as practical. Using the relationships given in Appendix A, it is shown, for example, that the temperature of concrete is reduced by 1°F (0.5°C) if any of the following reductions are made in material temperatures:

a) 8°F (4.4°C) reduction in cement temperature
b) 5°F (2.7°C) reduction in water temperature
c) 1.5°F (0.8°C) reduction in the temperature of the aggregates

5.2.1 *Aggregate cooling*—Figure 5.2.1 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 will lower the temperature of the aggregates. 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

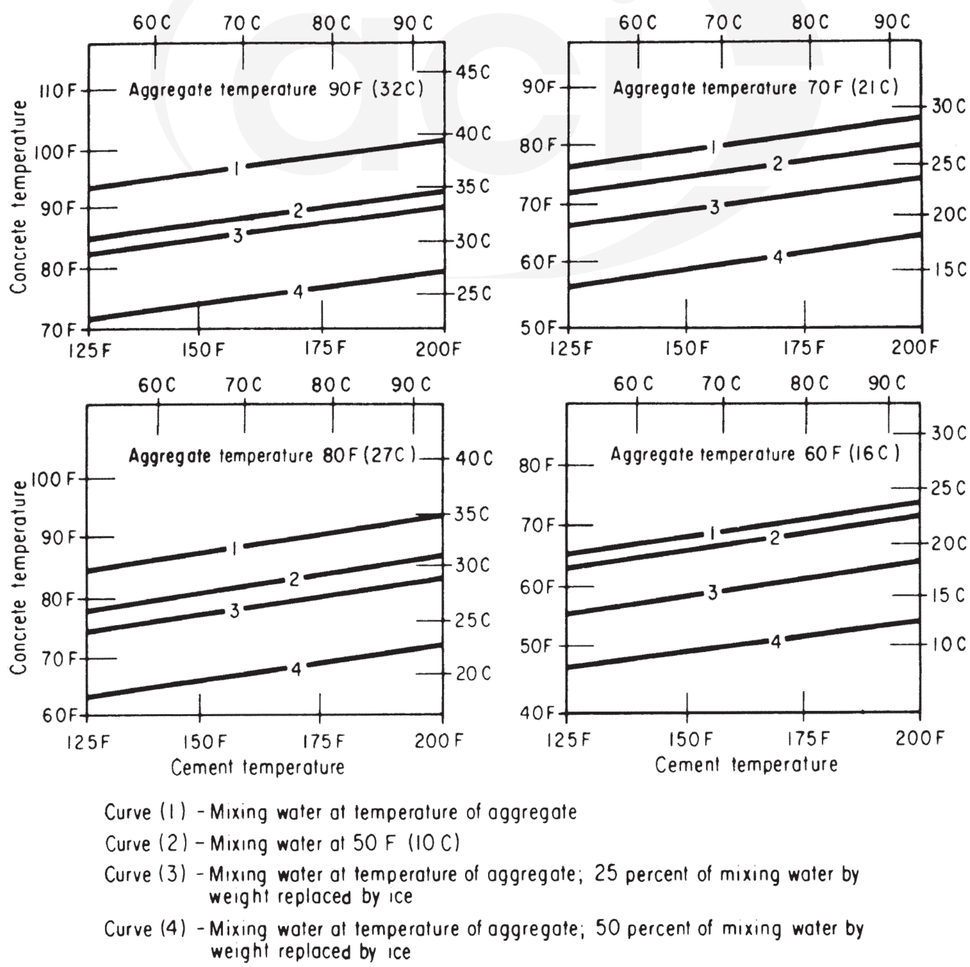

Fig. 5.2.1—Influence of temp[...]ations in Appendix A).

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 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. 5.2.1.

5.3—Batching and mixing

Batching and mixing are 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 percent 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 percent in the determination of aggregate moisture complicates moisture control, even with advanced systems. To avoid producing slump higher than specified, plant operators often batch concrete to a lower slump. Care should be taken to avoid withholding excessive water from the batch, as this could result in inadequate mixing, dry-packing, reduction in the effectiveness of chemical admixtures, or delivery at a slump below the specified minimum. Reduced workability may increase interparticle friction in transit that can lead to a slight increase in concrete placing temperature at point of delivery.

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 set-retarding or extended set-control admixtures at appropriate dosages, preferably in combination with supplementary cementitious materials, concrete can be maintained in a workable condition for extended periods, even in hot weather (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. Extended set-control admixtures offer more predictable setting times than set-retarding admixtures and may offer a better solution during hot weather conditions, especially on projects that require extended slump life. The use of set-retarding or extended set-control 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. Workability-retaining admixtures may also be used to extend slump life without extending the set time of the concrete.

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 because 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 number of truck mixer drum revolutions or time to discharge may be waived in accordance with ASTM C94/C94M for:

a) Concrete that retains its workability without the addition of water

b) Separate addition of high-range water-reducing admixtures

c) 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. If slow placement is anticipated or observed, consideration should be given to one or more of the following: reducing load size, the use of set retarding or extended set-control admixtures, or the use of cooled concrete.

5.5—Slump adjustment

Fresh concrete is subject to slump loss with time, whether it is used in moderate or hot weather. Slump changes between plant and job site should be established for given materials and mixture proportions. 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, in accordance with ASTM C94/C94M. 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 set-retarding or extended set-control 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 exceeding 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. These additions can be made at the plant, in transit, and at the job site.

CHAPTER 6—PLACING AND CURING

6.1—General

6.1.1 Properly placing concrete in hot weather requires the minimum following steps:

a) The concrete mixture should be designed to accommodate hot weather concreting

b) A pre-concrete-placement meeting should be held to discuss aspects of hot weather concreting

c) Concrete should be transported and placed where it is to remain, with minimum segregation and slump loss

d) Concrete should be placed in layers shallow enough to assure proper consolidation into the layer below, and that the elapsed time between layers should be minimized to avoid cold joints

e) Timing of finishing operations should be guided only by the readiness of the concrete

f) Curing and protection should be conducted so that at no time during placing, finishing, and curing operations will the concrete lack ample moisture and temperature control to develop its full potential strength and durability

g) Construction joints should be made on sound, clean concrete (refer to ACI 224.3R)

6.1.2 Details of placing, consolidating, and curing concrete are described in ACI 304R, 309R, and 308R, respectively. This chapter includes information on how hot weather can affect those operations, as well as the resulting concrete. Also included are recommendations on how to prevent or offset the influence of hot weather.

6.2—Preparations for placing and curing

6.2.1 *Planning hot weather placements*—At least 30 days prior to the start of hot weather concrete construction, a pre-concrete-placement meeting should be held to review the proposed concrete mixtures and to discuss the required methods and procedures to achieve the requirements of the project. A pre-concrete-placement meeting agenda should be sent to all attendees prior to the scheduled date of the meeting. The meeting discussion should include plans to minimize the exposure of concrete to adverse hot weather conditions. Whenever possible, minimize effect of drying winds by erecting wind breaks or by placing the slab on ground after the walls and roof structure are in place. A roof also reduces thermal shock from rapid temperature changes, or by cool rain on concrete heated by the sun. Under hot weather conditions, scheduling concrete placements during early morning or late-night hours may be advisable. Considerations include ease of handling and placing as well as minimizing the risk of plastic shrinkage and thermal cracking.

6.2.2 *Preparing for ambient conditions*—Personnel in charge of concrete construction during hot weather conditions should be aware of 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. 4.1.1b, to determine and prepare required protective measures. Equipment should also be available at the site to measure evaporation rate (refer to 4.2).

6.2.3 *Expediting placement*—Preparations should be made to transport, place, consolidate, and finish concrete as expeditiously as possible. Concrete placements can be affected when concrete is delivered prematurely, resulting in loss of slump and workability at the most critical time. Concrete delivery to the site should be scheduled so that concrete is placed promptly on arrival, particularly the first batch. Stable roadways at the site ensure easy access of delivery units to the unloading points, minimizing delays. Site traffic should be also coordinated for a quick turnaround. If possible, large or critical placements should be scheduled during periods of low traffic loads.

6.2.4 *Placing equipment*—Equipment for placing 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 excellent operating condition. Breakdowns or delays that stop or slow placements can seriously affect the quality and appearance of the work. Arrangements should be made for readily available backup equipment. Concrete pumping equipment 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 concrete heat gain during placement, delivery units, conveyors, pumps, and pump lines should be kept shaded when possible. In addition, pump lines should be painted white and cooled. Pump lines can also be cooled by covering or wetting with a soaker hose or other cooling methods proven effective.

6.2.5 *Consolidation equipment*—Poorly consolidated concrete can seriously impair the appearance, durability, and structural performance of reinforced concrete. Therefore, ample workers and vibration equipment should be available to properly consolidate concrete immediately as it is placed into forms. Procedures and equipment are described in ACI 309R. Standby vibrators should also be available, including at least one standby for every three vibrators in use. If the site is subject to occasional power outages, portable generators should also be available for uninterrupted vibrator operation.

6.2.6 *Preparations for protecting and curing the concrete*—Prior to concrete placement, a sufficient supply of water should be available at the project site for moistening the subgrade, as well as for fogging forms and reinforcement. For moist curing, care needs to be taken to avoid thermal shock or excessively steep thermal gradients due to the use of cold or hot curing water. 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 sites. 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 moisture-retaining (monomolecular) films, also referred to as evaporation reducers, should be available to reduce evaporation from flatwork between finishing passes. If concrete is placed during hot weather conditions and exposed to rapid temperature drops, thermal protection should be provided to protect against thermal shrinkage cracking. Finally, curing materials should be readily available at the project site to permit prompt protection of all exposed concrete surfaces from premature drying upon completion of the placement.

6.2.7 *Planning incidental work*—Hot weather concreting can accelerate the initial and final set times of concrete. Timing of final operations, including curing, saw-cutting, and slab measurements, should be expedited as quickly as possible. These operations should be planned in advance, including the timely sawing of contraction joints in flatwork to minimize cracking due to excessive tensile stress. Typically, joints that are cut using a conventional wet or dry process are made within 4 to 12 hours after the slab has been finished—4 hours in hot weather, and up 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). Slab-on-ground tolerance measurements should be taken in accordance with ASTM E1155.

6.3—Placement and finishing

6.3.1 *General*—When the concrete placing rate is not coordinated with the available work force and equipment, the quality of work will be marred by poor consolidation, cold joints, and inadequate surface finishes. Delays invite the addition of water to offset loss in slump and workability. Well-coordinated, expeditious placement and finishing reduces hot weather difficulties. Each operation in finishing should be carried out as soon as the concrete is ready; however, concrete should not be placed faster than it can be properly consolidated and finished.

6.3.2 *Placing formed concrete*—During hot weather conditions, concrete should be placed in shallow layers to ensure proper consolidation of the lower layer. 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 slabs-on-ground, the subgrade should be moist, but free of standing water and soft spots. During hot weather, it may be necessary to keep the operation confined to a small area and to proceed 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 finishing operations. Finishing of slabs on ground 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 rates. These procedures can cause a slight in-place increase in concrete temperature 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 4.1.4). Merely troweling slurry over the cracks will not be effective because these are likely to reappear if the surface is not properly protected to avoid evaporation. In large placements, additional vibration just prior to floating can sometimes close this type of cracking. Before the concrete reaches final set, plastic shrinkage 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.

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 concrete. Approved curing methods should be continued for at least 7 days. 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, including 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 bleed water 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 from a rapid temperature drop 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 at an early age 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 waterproof material over the exposed concrete, or by using other insulating methods and materials described in ACI 306R.

6.4.2 *Moist curing of flatwork*—When maintained properly, moist curing is usually the best method for maximizing strength and durability, as well as minimizing early-age drying shrinkage of concrete slabs-on-ground. Moist curing is especially beneficial for mixtures with high replacement levels of supplementary cementitious materials (SCMs). Moist curing methods include 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 rolled out flat, staying 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*—When site conditions are not favorable for moist curing, the most practical method for curing concrete is the use of a liquid membrane-forming compound. The membrane restricts the loss of moisture from the concrete, thereby allowing the development of strength, durability, and abrasion resistance of the surface. When applicable, concrete surfaces exposed to direct sunlight can use heat-reflecting, white-pigmented compounds to increase albedo (reflectivity). Compounds containing non-yellowing ultraviolet blockers may also be considered for outdoor work. Note that the solids and moisture-retention rates vary 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 C1315, limiting the moisture loss in a 72-hour period in excess of 6.6 lb/yd^3 (4.0 kg/m^3) when tested per ASTM C156. Application of a liquid membrane-forming compound should immediately follow the disappearance of surface water sheen after the final finishing pass. During application, the compound should be applied in an even, continuous film, using a spray nozzle that is positioned sufficiently close to the surface to ensure the specified application rate and prevent wind-blown dispersion. Dissipating or removable curing compounds may be applied to surfaces on which additional concrete or other bonded materials will be placed, provided the curing compound is removed such that bond is not adversely affected.

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, allowing the repaired areas to 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 liquid membrane-forming 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/C172M, C231/C231M, C232/C232M, C173/C173M, C1064/C1064M, C1611/C1611M, and C1621/C1621M, as appropriate. Tests should be performed by a 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 less than 6000 psi (40 MPa), and 68 to 78°F (20 to 26°C) for greater than or equal to 6000 psi (40 MPa). Care is also needed 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 be protected and handled carefully. They should then be stored in a moist condition at 73 ± 3.5°F (23 ± 2.0°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 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 match those of the concrete in the structure they are to represent, results of the tests can be misleading. Alternative test methods for determining in-place concrete strength are described in ASTM C900, C1074, and C918/C918M.

7.2—Inspection

7.2.1 The numerous details to be considered in concrete construction are covered in ACI MNL-2 and ACI 311.4R. Project inspection of concrete is necessary to ensure and document compliance with previously mentioned precautions and procedures. The need for such measures, such as spraying of forms and subgrade, cooling concrete, providing sunshades and windscreens, the use of evaporation retarders or fogging, and minimizing delays in placement, initial curing, and final curing procedures, should be observed and documented when the rate of evaporation is higher than the rate of bleed water coming to the surface.

7.2.2 Air temperature, concrete temperature (ASTM C1064/C1064M), general weather conditions (clear or cloudy), wind speed, relative humidity, and evaporation rate should be recorded at hourly intervals. The measurements should be taken per the instructions in Fig. 4.1.1b. In addition, the following should be recorded and identified with the work in progress so that conditions relating to any part of the concrete construction can be identified at a later date:

a) All water added to the concrete with corresponding mixing times

b) Time batched, time discharge started, and time discharge completed

c) Concrete temperature at time of delivery and after concrete is placed

d) Observations on the appearance of concrete as delivered and after placing in forms

e) Slump of concrete at point of delivery

f) Protection methods

g) Initial curing method used

h) Final curing method used

i) When a liquid membrane-forming curing compound is used, the time and rate of application and visual appearance of concrete

j) Duration and termination of curing

These observations should be included in the permanent project records.

CHAPTER 8—REFERENCES

8.1—Referenced standards and reports

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

American Concrete Institute

ACI 201.2R-16—Guide to Durable Concrete

ACI 207.1R-05(12)—Guide to Mass Concrete

ACI 207.2R-07—Report on Thermal and Volume Change Effects on Cracking of Mass Concrete

ACI 207.4R-05(12)—Cooling and Insulating Systems for Mass Concrete

ACI 211.1-91(09)—Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

ACI 211.2-98(04)—Standard Practice for Selecting Proportions for Structural Lightweight Concrete

ACI 212.3R-16—Report on Chemical Admixtures for Concrete

ACI 221R-96(01)—Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete

ACI 223R-10—Guide for the Use of Shrinkage-Compensating Concrete

ACI 224.1R-01(08)—Control of Cracking in Concrete Structures

ACI 224.3R-95(13)—Joints in Concrete Construction

ACI 225R-19—Guide to the Selection and Use of Hydraulic Cements

ACI 232.2R-18—Report on the Use of Fly Ash in Concrete

ACI 234R-06(12)—Guide for the Use of Silica Fume in Concrete

ACI 301-16—Specifications for Structural Concrete

ACI 302.1R-15—Guide for Concrete Floor and Slab Construction

ACI 304R-00(09)—Guide for Measuring, Mixing, Transporting, and Placing Concrete

ACI 305.1-14—Specification for Hot Weather Concreting

ACI 306R-16—Cold Weather Concreting

ACI 308R-16—Guide to Curing Concrete

ACI 309R-05—Guide for Consolidation of Concrete

ACI 311.4R-05—Guide for Concrete Inspection

ACI 318-19—Building Code Requirements for Structural Concrete and Commentary

ACI 544.5R-10—Report of Physical Properties and Durability of Fiber Reinforced Concrete

ACI MNL-2(19)—Manual of Concrete Inspection

ASTM International

ASTM C31/C31M-19—Standard Practice for Making and Curing Concrete Test Specimens in the Field

ASTM C138/C138M-17a—Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

ASTM C143/C143M-15a—Standard Test Method for Slump of Hydraulic-Cement Concrete

ASTM C150/C150M-19a—Standard Specification for Portland Cement

ASTM C156-17—Standard Test Method for Water Loss [from a Mortar Specimen] through Liquid Membrane-Forming Curing Compounds for Concrete

ASTM C172/C172M-17—Standard Practice for Sampling Freshly Mixed Concrete

ASTM C173/C173M-16—Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method

ASTM C192/C192M-18—Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

ASTM C231/C231M—Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C232/C232M-14(19)—Standard Test Methods for Bleeding of Concrete

ASTM C470/C470M-15—Standard Specification for Molds for Forming Concrete Test Cylinders Vertically

ASTM C494/C494M-17—Standard Specifications for Chemical Admixtures for Concrete

ASTM C595/C595M-19—Standard Specification for Blended Hydraulic Cements

ASTM C618-19—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

ASTM C666/C666M-15—Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

ASTM C900-15—Standard Test Method for Pullout Strength of Hardened Concrete

ASTM C918/C918M-13—Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength

ASTM C94/C94M-19—Standard Specification for Ready-Mixed Concrete

ASTM C989/C989M-18a—Standard Specification for Slag Cement for Use in Concrete and Mortars

ASTM C1064/C1064M-17—Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete

ASTM C1074-19—Standard Practice for Estimating Concrete Strength by the Maturity Method

ASTM C1157/C1157M—Standard Performance Specification for Hydraulic Cement

ASTM C1315-19—Standard Specification for Liquid Membrane-Forming Compounds having Special Properties for Curing and Sealing Concrete

ASTM C1579-13—Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)

ASTM C1611/C1611M-18—Standard Test Method for Slump Flow of Self-Consolidating Concrete

ASTM C1621/C1621M-17—Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring

ASTM E1115-14—Standard Test Method for Determining FF Floor Flatness and FL Floor Levelness Numbers

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APPENDIX A—ESTIMATING CONCRETE TEMPERATURE

A.1—Estimating temperature of freshly mixed concrete

Equations for estimating temperature T of freshly mixed concrete are shown in Eq. (A.1a) through (A.1c).

Without ice (in.-lb and SI units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa}}{0.22(W_a + W_c) + W_w + W_{wa}} \quad \text{(A.1a)}$$

With ice (in.-lb units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa} - 112W_i}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.1b)}$$

With ice (SI units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa} - 79.6W_i}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.1c)}$$

where T_a is temperature of aggregate; T_c is temperature of cement; T_w is temperature of batched mixing water from normal supply excluding ice; T_i is temperature of ice, °F (°C) (Note: Temperature of free and absorbed water on the aggregate is assumed to be the same temperature as the aggregate.); W_a is dry mass of aggregate; W_c is mass of cement; W_i is mass of ice; W_w is mass of batched mixing water; and W_{wa} is mass of free and absorbed moisture in aggregate at T_a, lb (kg).

A.2—Estimating temperature of concrete with ice

Equations (A.1b) and (A.2c), for estimating the temperature of concrete with ice in U.S. customary or SI units, assume that the ice is at its melting point. A more exact approach would be to use Eq. (A.2a) or (A.2b), which includes the temperature of the ice.

With ice (in.-lb units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa}}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} + \frac{T_aW_{wa} - W_i(128 - 0.5T_i)}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.2a)}$$

With ice (SI units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa}}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} + \frac{T_aW_{wa} - W_i(79.6 - 0.5T_i)}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.2b)}$$

APPENDIX B—METHODS FOR COOLING FRESH CONCRETE

The summary is limited to a description of methods suitable for most structural uses of concrete. Methods for the cooling of mass concrete are explained in ACI 207.4R.

B.1—Cooling with chilled mixing water

Concrete can be cooled to a moderate extent by using chilled mixing water; the maximum reduction in concrete temperature that can be obtained is approximately 10°F (6°C). The quantity of cooled water cannot exceed the mixing water requirement, which depends on the moisture content of aggregates and mixture proportions. The method involves a significant investment in mechanical refrigeration equipment and insulated water storage large enough for the anticipated hourly and daily production rates of cooled concrete. Available systems include one that is based on heat-pump technology, which is usable for both cooling and heating of concrete. Apart from its initial installation price, this system appears to offer cooling at the lowest price of available systems for cooling mixing water.

B.2—Liquid nitrogen cooling of mixing water

Mixing water can be chilled rapidly through injection of liquid nitrogen into an insulated holding tank. This chilled water is then dispensed into the batch. Alternatively, the mixing water may be turned into ice slush by liquid nitrogen injection into the mixing water stream as it is discharged into the mixer. The system enables cooling by as much as 20°F (11°C). The ratio of ice to water in the slush should be adjusted to produce the temperature of concrete desired. Installation of this system requires insulated mixing water storage, a nitrogen supply vessel, batch controls, and auxiliary equipment. Apart from the price of installation, there are operating expenses from liquid nitrogen usage and rental fees for the nitrogen supply vessel. The method differs from that by direct liquid nitrogen injection into mixed concrete described in B.4.

B.3—Cooling concrete with ice

Concrete can be cooled by using ice for part of the mixing water. The amount of cooling is limited by the amount of mixing water available for ice substitution. For most concrete, the maximum temperature reduction is approximately 20°F (11°C). For correct proportioning, the ice should be weighed. Cooling with block ice involves the use of a crusher/slinger unit, which can finely crush a block of ice and blow it into the mixer. A major obstacle to the use of block ice in many areas is insufficient supply. The price of using block ice is: the price of ice, including transportation; refrigerated storage; handling and crushing equipment; additional labor; and, if required, provisions for weighing the ice. An alternative to using block ice is to set up an ice plant near the concrete plant. As the ice is produced, it is weighed, crushed, and conveyed into the mixer. It can also be produced and used as flake ice. This system requires a large capital investment.