Chapter 8
Concrete Construction

8-1. Forms

a. Types of materials. The contract specifications specify the types of finish required for the various formed surfaces and the types of materials permitted for each class of finish. If more than one type of material is permitted with each class of finish specified, the Contractor should always be permitted to employ his choice of materials.

b. Quality verification. After concrete forms have been set to line and grade and prior to permitting any concrete to be placed therein, the forms should be carefully inspected for compliance with all specification requirements, including sheathing materials, alignment of form surfaces, mortar tightness, and apparent strength.

c. Form coating. Most of the form coatings commercially available are satisfactory for wood forms. Quite frequently, form coatings which are satisfactory for wood forms do not perform satisfactorily on steel forms. If the form coating being used on the work is unsatisfactory, its use should be immediately discontinued and the Contractor should be required to obtain a suitable form coating.

8-2. Placing

a. General. The practices followed in the placement of concrete should have the principal objectives of concrete that is bonded to the foundation or to the previous lift, uniform in quality, free from any objectionable segregation, and thoroughly consolidated. These objectives are best accomplished by adequately cleaning and preparing the top surface of the foundation or the previously completed lift, delivering the freshly mixed concrete to its approximate final position in the structure with a minimum of segregation, and consolidating the concrete by means of sufficient vibration to consolidate it completely. In addition to these very general practices, the more detailed practices outlined below should be followed.

b. Bedding mortar on rock foundations. All rock foundations should be covered with a layer of mortar just prior to concrete placement. The mortar should be composed of the same fine aggregate and cementitious material used in the exposed concrete mixture. The sand/cementitious material and w/c of the mortar should also be the same as that used in the exterior concrete mixture proportions. Addition of an air-entraining admixture is not required. The thickness of the mortar layer should be approximately 1/4 in. The delivery and spreading of the mortar should be scheduled so that all mortar is covered by the concrete before the initial set of the mortar.

c. Mass concrete. The general nature of mass concrete, having a stiff and dry consistency and containing 75- and 150-mm (3- and 6-in.) maximum size aggregates, is such that the concrete must be deposited in the final position in the structure in which it is to remain when compacted. The quantity of interior mass concrete that can be properly compacted in one operation is recognized to be about 4 yd^3. The project specifications will usually limit the amount to be deposited in one pile for compaction to 4 yd^3 in uncongested areas and to smaller quantities in congested areas. Depositing 8 yd^3 in two contiguous piles from a two-compartment (4-yd^3 each) bucket is recognized to be in compliance with this requirement. Whenever the top of a lift is not horizontal, the placement must proceed up the slope. The thickness of the exterior concrete in a mass concrete structure is governed by the size of the bucket or the delivery equipment used in placing the concrete. Since the project specifications will limit the amount of concrete that may be deposited in one pile to 4 yd^3, the exterior concrete will usually average about 5 to 6 ft thick. The placing procedure to be followed includes practices designed to keep the thickness of the exterior mixture to a practical minimum. Usually, a 7-1/2-ft lift of mass concrete is placed in five layers, and a 5-ft lift of mass concrete is placed in three layers as shown in Figures 3-1 and 3-2 of this manual. For example, in dam construction, if both interior and exterior mass concrete are used, the placement should begin with the first layer of interior mass concrete at the upstream end of the placement, leaving a space of the minimum practical, or specified, width between the interior mass concrete and the form for the placement of the exterior mixture concrete. The exterior mass concrete layer should be placed after the corresponding interior concrete layer has been placed, so as to keep the thickness of the exterior concrete to a practical minimum, or that specified. The intersection of the interior and exterior concretes should be carefully consolidated and "knit" together during vibration. The placement should then proceed toward the downstream face with the bottom layer preceding the second layer by an approximate distance equivalent to 4 yd^3 of concrete compacted. Each successive layer above should follow the layer below by approximately the same distance, thus providing a stepped placing procedure. The placement should follow a regular sequence for the successive layers by maintaining the stepped relationship of the layers until the lift is completed. Dumping of concrete on slopes and chasing it downhill with vibrators is not to be permitted under any circumstances. The transporting of concrete by vibration is not permitted.

d. Structural concrete. Proper care must be taken to avoid segregation when placing concrete into structural units such as walls, columns, slabs, beams, etc. The concrete is to be deposited in approximately its final position in the structure where it is to remain and should not be moved within the forms with vibrators. As a general rule, when the concrete bucket cannot be lowered to within 5 ft of the position where the concrete is to be placed, elephant trunks with a rigid drop chute bottom section are to be used. All belt conveyors must have elephant trunks at their discharge ends. The thickness of the layers should not exceed 20 in. The vibrators should be handled carefully so that thorough consolidation is achieved without damaging the forms or displacing embedded items. The vibrator should not be operated while being held against the form which results in sandy streaks or markings in the finished surface.

e. Tunnel linings.

(1) Inverts. The concrete for tunnel inverts may be delivered to the placement site by any practical means. It should be brought to grade in layers not to exceed approximately 1-1/2 ft and thoroughly consolidated with vibrators.

(2) Sidewalls and crown. Use of a positive displacement pump is the normal method of placing the concrete in tunnel linings. In the tunnel sidewalls, the concrete should be placed in successive layers of approximately 1-1/2 ft deep and thoroughly consolidated by vibration. In the crown of the tunnel where vibration is impossible, a length of the special pipeline used in the concrete pumping operation is kept buried in the fresh concrete. This is necessary to achieve consolidation of the concrete and to force the concrete into the overbreaks in the rock. Placement of the concrete in the crown must begin at the end of the form that is opposite the concrete pump, and the embedded pipeline will be backed out as the crown is filled. Short sections of vertical riser pipes have been used satisfactorily, in lieu of the buried pipeline, to place concrete in the tunnel crown. Pumping concrete is discussed in paragraph 10-6 of this manual and in ACI 304.2R.

f. Consolidation. Concrete that is placed in the dry with conventional methods should be consolidated by means of mechanical vibration equipment. The performance of the vibrators used by the Contractor should be periodically checked for compliance with the performance characteristics required by the contract specifications. Vibrators should never be used to transport the fresh concrete within the forms. The duration of vibration at a single point in the fresh concrete being consolidated should be approximately 10 to 15 sec or until the entrapped air is released, which is indicated when large air bubbles stop coming to the top of the mixture near the insertion point of the vibrator. It is essential that the points of vibration be fairly closely spaced to obtain thorough and complete consolidation of fresh concrete. Proper care must be exercised to thoroughly vibrate the concrete in all forms, including flowing concrete, to minimize rock pockets, honeycomb, and other defects. It is almost impossible to over vibrate a properly proportioned concrete mixture. Emphasis should be placed on having closely spaced applications of appropriate duration rather than prolonged vibration at widely spaced distances. The latter method will result in inadequate consolidation in some parts of the concrete, which will result in an overall general reduction in the quality of the hardened concrete. In general, the use of internal vibrators for consolidation of freshly mixed concrete has been satisfactory. A thorough discussion of consolidation is given in ACI 309R.

g. Protection of waterstops. There are many cases of leakage through a joint because of faulty installation of the waterstop. To eliminate such failures, particular care must be exercised to ensure that waterstops are properly protected and installed. Adequate provisions must be made to support and protect all waterstops against damage during the progress of the work. Extraordinary care must be employed in the placement and consolidation of the concrete adjacent to the waterstops to ensure that the waterstops are not damaged and that they are in the correct position and properly embedded in the concrete.

8-3. Finishing

a. Formed surfaces. The finishing of concrete structures consists of dressing up the formed surfaces by patching the form bolt holes and removing any defective concrete and replacing it with sound durable concrete. This latter operation can be largely avoided by paying particular and vigilant attention to the details of the concrete placement operations, especially the consolidation, so that defective concrete will not occur. When such conditions do occur on exposed surfaces, the defective concrete must be chipped back to sound concrete and replaced by dry packing or a conventional concrete placement. In the removal of the defective concrete, care should be taken to prevent damaging the adjacent concrete while creating a dovetail or key into the hardened concrete to firmly anchor the new repair concrete. All defective concrete on the surface of a structure that is permanently exposed to view should be repaired. Additional guidance on repair materials and methods may be found in EM 1110-2-2002, "Evaluation and Repair of Concrete Structures." Honeycomb and rock pockets on bulkhead faces usually do not need to be repaired unless they are of considerable extent or depth. Extra care must be taken to assure that the color and texture of the repair concrete closely matches that of the surrounding concrete. The guide specifications are clear and detailed in their requirements for all formed surfaces. The key to quality is the strict enforcement of the specification requirements. Class A finish is the best finish with the most strict requirements, while Class D is the least restrictive. Class AHV is a special finish for spillways, tunnels, or other water passages where the velocity of the water is expected to be 40 ft/s or higher. The materials and workmanship for forming of Class AHV are the same as the Class A finish requirements in Guide Specification CW-03101, "Formwork for Concrete," except that steel forms may be used. The allowance for offsets for Class AHV is more restrictive.

b. Unformed surfaces. The finishing of unformed surfaces is a very critical operation and requires the use of judgment, experience, and skill to produce a finished surface of the specified quality and durability. Crazing, scaling, and other defects are usually directly attributable to the use of concrete which is too wet (too high a slump), improper finishing procedures, or a combination of both. Overworking the surface is probably the most common cause of defective surface finishes. The fresh concrete should be thoroughly consolidated. The surface of the consolidated concrete should be slightly above grade. Screeding, or strikeoff, should be done immediately after consolidation. The screeding operation, when accomplished by hand methods, is to be accomplished with a sawing motion of the screed in the transverse direction to the line of travel of the screed. This will accomplish the dual purpose of screeding and compacting the surface at the same time. Any excess concrete that is left above grade should be carried ahead of the screed. In a properly proportioned air-entrained concrete, a characteristic roll of fresh concrete will form in front of the screed. In air-entrained concrete which has been properly consolidated, a slight rebound of the fresh concrete will occur behind the screed. Screeding should be limited to two passes of the screed. After the second pass of the screed, the rebound will be diminished to a negligible amount. Floating or darbying should be completed immediately after screeding and should be limited to that necessary to fill in low spots. The use of a jitterbug or tamper to embed the coarse aggregate particles should not be allowed. Floating and troweling should not be permitted on any part of the surface where any bleed water has collected. This bleed water must either be allowed to evaporate or be removed in a satisfactory manner. Dry cement, or a mixture of cement and fine sand, should never be applied directly to a surface to be finished for the removal of bleed water or for any other purpose. Adding water to the surface by use of a large brush, or other means, should also be prohibited. The use of power rotary troweling machines needs to be carefully controlled to prevent overfinishing and the resultant crazing.

(1) Ogee crest. One of the most difficult finishing jobs on unformed surfaces is the ogee crest of a spillway. The following procedure is the most satisfactory one developed to date. The spillway piers and the high-strength erosion-resistant concrete in the spillway surface are placed monolithically with the spillway except for the top lift, which includes the ogee crest. Adjustable vertical rigid supports, conforming to the ogee shape are installed in the placement, raising the depth of the screed above the finished grade and bridging the placement surface. Concrete is placed and consolidated in the usual manner and then screeded and finished using the pipe as an elevation guide. When these operations are properly executed, a durable surface is produced.

(2) Spillway aprons. No general rules can be given for finishing of spillway aprons or stilling basin slabs. Since the shapes required to meet the hydraulic requirements differ for different projects, it is usually necessary to develop special methods for each situation. The finishing is frequently done by hand, although properly designed heavy-duty mechanical screeding equipment is acceptable. The method described above for ogee crests is suitable, with appropriate modifications, to the finishing of stilling basins, the curved transition surfaces at the toe of a dam, or for flip bucket spillways.

(3) Trapezoidal channel lining. The methods to be used on bottom slabs are the same as for any flat or nearly flat slab. The concrete should be placed and consolidated in the usual manner and left slightly above grade. The slab should then be struck off to grade by screeding and given a float finish. Finishing the sideslope paving in small channels will usually be accomplished by hand methods. Placing of the concrete will proceed upslope. The concrete should be of medium to dry consistency. The use of a mechanical screeding machine is considered advisable. Hand-manipulated screeds which are moved by mechanical means can also be used. Screeding should always proceed upslope. After screeding, the surface should be given a float finish.

(4) Surfaces exposed to high-velocity flow of water. Surfaces to be exposed to waterflow velocities greater than 40 ft/s should be finished carefully (AHV finish) since any discontinuity especially a positive offset in downstream direction in the surface can be the cause of cavitation. Cavitation has the potential of seriously eroding concrete

surfaces so the finishing of areas subject to cavitation damage should be carefully inspected.

(5) Floors.

(a) Monolithic. Where monolithic floors are specified, the completion of the floors should be delayed, if possible, until all other construction work from which damage to the floor might occur is completed. If this is impracticable, the floor should be adequately protected from damage.

(b) Bonded topping. In areas where structural slabs must be completed for the work to be accomplished, bonded or "two-course" floors are usually selected so that the final finish can be delayed until all other work is virtually complete. This eliminates the necessity for special protection; however, the rough slab should be protected against spillage of liquids or other materials which might later interfere with bonding of the floor topping. The surface of the base slab should be prepared for the topping in the same manner as the surface of any horizontal construction joint.

c. Tolerance requirements for surface finish.

(1) General. Control of surface tolerance may be critical in some types of structures such as warehouse guideway surfaces and surfaces subject to high-velocity flow (over 40 ft/s). There are two approaches in controlling the floor surface tolerance; using straightedge (or curved templates for curved surfaces) or measuring the F numbers in accordance with ASTM E 1155 (CRD-C 641). Both approaches are used in Corps of Engineers (CE) specifications depending upon the type of structures.

(2) Control surface tolerance by straightedge. This is the traditional method for measuring surface tolerance. The tolerance is defined as the maximum gap between a fixed length straightedge and the concrete surface at any point. The device is simple, portable, and easy to use. There will be no calculation or data collection. This procedure can be used on any surface; horizontal, vertical, overhead, even curved surface (by using a curved template). However, there are some limitations on this approach. The measurements are arbitrary, subjective, and generally nonrepeatable. There is no mention of the number of measurements to be made and therefore it totally depends on the operator. The difficulty in enforcing the requirement using this method often results in controversies between owners and contractors. This procedure is specified for mass-concrete structures and minor concrete structures and may be specified as an option in cast-in-place concrete structures in CE civil works projects. For mass-concrete structures, the requirement of surface tolerance falls into two extremes. The surface tolerances for most mass-concrete structures, such as surfaces of a dam or floors of a lock chamber or gallery, are less critical where tight control is not necessary. Although a 10-ft straightedge has been commonly used in the industry, a 5-ft straightedge is specified for mass concrete due to the difficulty in handling the 10-ft straightedge on surfaces other than floors. On the other extreme, the surface subject to high-velocity water flow requires extreme tight control in surface tolerance to reduce the possibility of cavitation and erosion. A special surface class (Class AHV) has been created for this purpose. The straightedge or curved template is specified in this case since most of the surfaces involved are either vertical, overhead, or curved where the F-number system cannot be used. For minor concrete structures where a small quantity of concrete is used, the control of surface tolerance is less critical. The use of the F-number system in these structures is not necessary.

(3) Control floor tolerance by F-number system. In 1987 ASTM issued a standard test procedure, ASTM E 1155, for measuring floor surface profiles and for estimating the characteristic flatness and levelness of a floor. This procedure measures elevations at regular intervals along straight lines on the surface. The differences in elevations between adjacent points and between all points 10 ft apart are then calculated. The results of these calculations are analyzed statistically to obtain floor flatness number (F_F) and floor levelness number (F_L). Floor flatness is defined as the degree to which a surface approximates a plane while levelness is defined as the degree to which a surface parallels horizontal. These two numbers represent the average quality of floor finish in a predefined area and are reliable and repeatable. It should be noted that there is no direct correlation between straightedge tolerances and F-numbers. However, based on the effort required to finish a floor to the corresponding tolerance, Table 8-1 provides a rough correlation between the two systems. The F-number system may be specified as an option for all cast-in-place concrete floors for consistency with industry standards and practices. Currently, the construction technology can achieve F_F 25 at little or no additional cost. Therefore, for normal slab or floor construction, F_F should be at least 25. F_L should be used for slab on grade only, since the levelness of an elevated floor is beyond the control of the Contractor due to camber and deflection of supporting system. In some cases, it may be necessary to specify localized F_F/F_L in addition to the overall F_F/F_L to assure a uniform floor quality. Details and concept of the F-number system are available in ACI 302.1R, ACI 117R commentary, and ASTM E 1155.

Table 8-1
Floor Quality as Determined by F-Number System and Straightedge

	F-Number	Gap Under an Unleveled 5-ft Straightedge, in.	Gap Under an Unleveled 10-ft Straightedge, in.
Bull floated	F_F 12	3/8	1/2
Straightedged	F_F 20	1/4	5/16
Flat	F_F 32	1/8	3/16
Very flat	F_F 50	1/16	1/8

8-4. Curing

a. General. Early hydration proceeds at an acceptable rate only if the concrete is maintained at a high humidity. Thus, positive curing procedures are essential, especially for thin sections. Even in massive sections, the quality of the surface concrete is dependent upon adequate curing. The Contractor should present his plans for curing for approval well before concreting begins. During construction, these operations must be continually checked. Form curing, where no additional moisture is added, is not an acceptable method of curing. Where forms are left in place during curing, the forms should be kept wet at all times.

b. Moist curing. Proposed methods of keeping concrete surfaces continually moist by spray-pipe or fog systems, soaker hoses, ponding, or covering with damp earth, saturated sand, or burlap maintained in a damp condition in contact with the concrete are satisfactory. Plastic, aluminum, galvanized, or alloy pipe should be required to avoid rust stains on the concrete surfaces. Hand sprinkling is not satisfactory and should not be permitted except as an emergency measure. Water that will stain the concrete should not be approved unless it is not practical to furnish a nonstaining water. The Contractor should be required to clean surfaces permanently exposed to view if he uses water that stains.

c. Membrane curing. Areas cured by pigmented membrane-forming coring compounds are relatively easy to inspect and should be specified wherever possible. Uneven distribution of the compound is readily revealed by a nonuniform appearance. In those areas in which a nonpigmented compound is required such as surfaces to be exposed to view, a government quality verifier should be on hand during all spraying operations and should check closely the uniformity of the application. In a hot, dry environment, the energy from the direct sunlight may raise the surface temperature significantly which will promote formation of shrinkage cracks on the surface. Therefore, when using nonpigmented curing compound, it is required that shading should be provided for 3 days whenever the maximum ambient temperature during that period is expected to be higher than 90 °F. Compressed air lines must have traps to prevent moisture or oil from contaminating the compound. Ordinary garden hand-spray outfits are not satisfactory and should not be permitted. Application by brushing or rolling should not be permitted. Pigmented compounds should be thoroughly mixed in the receiving containers by the insertion of a compressed air pipe into and near the bottom of the container prior to withdrawing the material for use. Continuity of the membrane coating must be maintained for the duration of the full specified curing period. The membrane should be protected by suitable means if traffic thereon is unavoidable. Any damage to the membrane during the curing period should be immediately repaired at the original specified rate of coverage. Additional information may be found in ACI 308.

d. Sheet curing. Sheet curing is an acceptable curing method, although it is not often used except for curing slabs. Some of the materials used are easily torn by equipment or by wind, and constant inspection and maintenance is required. It is important that very secure tiedowns or heavy objects be used with this system to maintain a sealed environment for curing the concrete. Polyethylene film is easily torn and tends to leave a pattern on the surface where the film wrinkles. Maintenance of the film during the curing period is a constant problem due to wind and construction activity. Inspection requires constant scrutiny. It is not allowed except for smaller jobs.

8-5. Cold-Weather Concreting

a. General. Cold weather is defined by ACI 306R as a period of three or more consecutive days when the average daily ambient temperature is less than 40 °F, and the ambient temperature is not greater than 50 °F for more than one-half of any 24-hr period. The average daily air temperature is the average of the highest and the lowest temperatures occurring during the period from midnight to midnight. The objectives of cold-weather concreting practices are to:

- Prevent damage to concrete due to freezing at early ages.

- Assure that the concrete develops the required strength for safe removal of forms, shores, and reshores and for safe loading of the structure during and after construction.

- Maintain curing conditions which foster normal strength development without using excessive heat and without causing critical saturation of the concrete at the end of the protection period.

- Limit rapid temperature changes, particularly before the concrete has developed sufficient strength to withstand induced thermal stresses.

- Provide protection consistent with the intended serviceability of the structure.

Proper cold-weather concreting practices and procedures are based on the principles that:

- Concrete that is protected from freezing until it has attained a compressive strength of at least 500 psi will not be damaged by a single freezing cycle.

- Where a specified concrete strength must be attained in a few days or weeks, protection at temperatures above 50 °F is required.

- Little or no external supply of moisture is required when concrete is properly protected and sealed during cold weather except within heated protective enclosures.

b. Planning. Proper planning by the contractor to protect fresh concrete from freezing and to maintain temperatures above the required minimum values should be made well before the freezing temperatures are expected to occur. Equipment and materials required to protect concrete from freezing should be at the job site before cold weather is likely to occur, not after the concrete is placed and its temperature begins to approach the freezing point. All surfaces that will be in contact with newly placed concrete should be at temperatures that cannot cause early freezing or seriously prolong setting time of the concrete. Ordinarily, the temperatures of these contact surfaces, including subgrade materials, need not be higher than a few degrees above freezing.

c. Protection system. ACI 306R provides guidance on minimum concrete placing temperatures and on the maintenance duration of these temperatures. The actual temperature at the concrete surface determines the effectiveness of protection, regardless of the ambient temperature. Therefore, monitoring concrete temperatures at several locations along the concrete surface, particularly at corners and edges, is important. As noted in paragraph 4-2d of this manual, concrete should not be exposed to cycles of freezing and thawing while in a critically saturated condition until it has attained a compressive strength of approximately 3,500 psi. The specific protection system required to maintain concrete temperatures above freezing depends on such factors as the ambient weather conditions, the geometry of the structure, and the mixture proportions. In some cases, covering the concrete with insulating materials to conserve the heat of hydration may be all the protection that is necessary. Insulation must be kept in close contact with the concrete or the form surface to be effective. Some commonly used insulating materials include polystyrene foam sheets, urethane foam, foamed vinyl blankets, mineral wool, or cellulose fibers, straw, and commercial blanket or batt insulation. In more extreme cases, i.e. ambient temperatures less than -5 °F, it may be necessary to build enclosures and use heating units to maintain the desired temperatures. Heat can be supplied to enclosures by live steam, forced hot air, or combination heaters of various types. Although steam provides an excellent curing environment, it may offer less than ideal working conditions and can cause icing problems around the perimeter of the enclosure. Heaters and ducts should be positioned not to cause areas of overheating or drying of the concrete surface. Combustion heaters should be vented for safety to prevent reaction of carbon dioxide in the exhaust gases with the exposed surfaces of newly placed concrete.

d. Curing. Concrete exposed to cold weather is not likely to dry at an undesirable rate unless the protection which is selected for use increases the likelihood of rapid drying. Measures should be taken to prevent drying when concrete is warmer than 60 °F and exposed to air at 50 °F or higher. Either steam or a liquid membrane-forming curing compound should be used to retard moisture loss from the concrete. Water curing should not be used since it increases the likelihood of concrete freezing in a critically saturated condition when protection is removed.

e. Accelerating early strength. Accelerating admixtures, Type III portland cement, or additional cement can be used to shorten the times needed to achieve setting and required strength if proper precautions are taken. Reduction in time of setting and acceleration of strength gain may permit shorter protection periods, faster reuse of forms, earlier removal of shores, or less labor in finishing of flatwork. The acceleration of strength development of mass concrete should not be allowed since doing so will tend to increase internal temperature rise of the concrete. A more thorough discussion of all topics related to cold weather concreting is given in ACI 306R.

8-6. Hot-Weather Concreting

a. General. ACI 305R defines hot weather as any combination of the following conditions that tend to impair the quality of freshly mixed or hardened concrete by accelerating the rate of moisture loss and rate of cement hydration, or otherwise resulting in detrimental results:

- High ambient temperature.
- Low relative humidity.
- Wind velocity.

Hot weather may lead to concrete mixing, placing, and curing problems which adversely affect its properties and serviceability. Most of these problems relate to the increased rate of cement hydration at higher temperature and the increased evaporation rate of moisture from the freshly mixed concrete. Detrimental effects of hot weather on freshly mixed concrete may include increases in: water demand, rate of slump loss, rate of setting, tendency for plastic shrinkage, and difficulty in controlling air content. Hardened concrete may potentially experience decreased 28-day and later age strengths, increased tendency for drying shrinkage, and differential thermal cracking, decreased durability resulting from cracking, increased permeability, and greater variability of surface appearance. In addition, proper temperature control of mass concrete may be more difficult to achieve during hot weather.

b. Planning. Damage to concrete caused by hot weather can never be fully alleviated, and so good judgment is necessary to select the most appropriate compromise of quality, economy, and practicability. The type of construction, characteristics of the concrete materials, and the hot-weather concreting experience of the Contractor all affect the procedures used to minimize potential problems. Lack of hot-weather concreting experience by the Contractor's personnel usually causes the most difficulties in achieving concrete of the required quality. Early preventative measures should be applied with the emphasis on materials evaluation, advanced planning, and coordination of all phases of the work. Detailed procedures for mixing, placing, protecting, curing, temperature monitoring, and testing of concrete during hot weather should be submitted by the Contractor prior to the beginning of hot-weather concreting. The potential for thermal cracking, either from overall volume changes or from internal restraint, should be anticipated. Items that should be considered to control cracking include limits on concrete temperature, cement content, heat of hydration of cement, form-stripping time, selection and dosage rate or quantity of chemical admixtures and pozzolans, joint spacing, and use of increased amounts of reinforcing steel.

c. Alleviating measures. Practices and measures which will help to reduce or avoid the potential problems of hot-weather concreting include:

- Using concrete materials and proportions with satisfactory records in field use under hot weather conditions.
- Using cooled concrete. For general types of construction in hot weather, it is not practical to recommend a maximum limiting ambient or concrete temperature because circumstances vary widely. Therefore, ACI 305R recommends that, if possible, a practical maximum concrete temperature of between approximately 75 and 100 °F be determined. This should be done by testing laboratory trial batches of concrete which are produced at the selected limiting temperature or at expected job site high temperature. For projects using CW 03305, "Mass Concrete," the maximum placing temperature for concrete in the massive features should be determined by a thermal study. For all other concrete, the maximum placing temperature should be as shown in Table 8-2, which relates maximum concrete temperature to relative humidity.
- Using a concrete consistency that permits rapid placement and effective consolidation.
- Transporting, placing, consolidating, and finishing the concrete with the least delay.
- Scheduling placing operations during times of the day or night when weather conditions are favorable.

Table 8-2
Maximum Placing Temperature

Average Annual Relative Humidity, %	Maximum Concrete Temperature, °F, at Placement
>60	90
40-60	85
<40	80

NOTE: If the period that the concrete placements may occur can be anticipated, then the Weather Service Office in the project area should be asked to supply an average monthly relative humidity for that period.

• Protecting concrete against moisture loss at all times during placing, finishing, and during its curing period.

d. Placing temperature. The problems of placing concrete in hot weather involve, among other things, slump loss during mixing and transporting and surface crazing after placement. To reduce these problems, limits are placed on the concrete placing temperature in the guide specifications. The temperatures that are selected for inclusion in each paragraph are dependent on the normal relative humidity in the project area. The required maximum placing temperature may be lower if required by thermal studies and included in the appropriate DM.

e. Plastic-shrinkage cracks. Plastic-shrinkage cracking is often associated with hot-weather concreting, particularly in arid climates. It occurs primarily in flatwork, but beams and footings are also susceptible if the evaporation rate exceeds the rate of bleeding. Plastic-shrinkage cracking is easily identified since it begins to appear before the concrete completely hardens. The cracks appear in a random pattern on the surface and are wide at the surface, tapering to nothing at a shallow depth. The cracks may be up to 1/4 in. (6 mm) wide at the surface and seldom more than 4 to 6 in. (100 to 150 mm) deep. High concrete temperatures, high ambient temperatures, high wind velocity, and low relative humidity, alone or in combination, cause rapid evaporation of water from the concrete surface and significantly increase the probability of plastic-shrinkage cracking. ACI 305R provides a graphical means for making evaporation rate estimates based on all the major factors that contribute to plastic-shrinkage cracking. A close approximation of evaporation rate can also be made in the field by evaporating water from a shallow pan of known surface area. Initial and subsequent weighings made to the nearest 0.1 g every 15 to 20 min allow the evaporation rate to be calculated in a reasonably short period of time prior to concrete placement. When the evaporation rate approaches 0.2 lb/ft^2/hr, precautions should be taken by the Contractor to reduce moisture loss, or plastic-shrinkage cracking may occur.

f. Effect on strength and durability. Concrete material properties and the concrete mixture proportions have a significant effect on both fresh and hardened properties of concrete placed during hot weather. High mixing water temperatures cause higher concrete temperatures which, in turn, increase the amount of water needed to achieve a given slump. If additional water is added so that the w/c is increased, the strength and durability of the concrete may be detrimentally affected. A 1-in. slump decrease may typically be expected for every 20 °F increase in concrete temperature. The increase in water content necessary to maintain concrete slump in hot weather will range between 2 and 4 percent depending on the concrete temperature. This increase may be significantly less if WRA or HRWRA is used. The use of a slower setting Type II portland cement may help improve the handling characteristics of concrete in hot weather; however, concrete made with slower setting cements may be more likely to exhibit plastic-shrinkage cracking. Because the cement makes up only 5 to 15 percent of the mass of a concrete mixture, its temperature has a relatively minor effect on concrete temperature. An 8 °F increase in cement temperature is typically required to increase concrete temperature 1 °F. If the cement has a false set tendency, slump loss may be aggravated in hot weather. Retarding WRA and HRWRA have all been beneficial in offsetting some of the undesirable effects of hot weather on concrete. Admixtures without a performance history with the concrete materials selected for the work should first be evaluated in laboratory trial batches at the expected high temperature, using procedures described in ACI 305R. Some HRWRA's may not demonstrate their potential benefits when used in small laboratory batches. Further testing may then be required in full-size batches. Since concrete contains a relatively large mass of coarse aggregate, changes in its temperature have a considerable effect on concrete temperatures. For example, a 1.5 to 2 °F coarse aggregate temperature reduction will lower the concrete temperature about 1 °F. Therefore, cooling coarse aggregate is a very effective means of lowering concrete temperature.

g. Cooling. If limiting temperatures govern the delivery of the concrete, the availability of cooled concrete should be ascertained well in advance of the need. Cooling of the concrete will require installation of special equipment and assurance of an ample supply of cooling materials such as ice or liquid nitrogen for the anticipated concrete volume and placement rate. Maintaining a continuous flow of cooled concrete to the placement is important to avoid the possible development of cold joints. Arrangements should be made for the ready availability of backup placing equipment and vibrators in the event of mechanical breakdowns. Arrangements should be made for ample water supply at the site for wetting subgrades, fogging forms, and for moist curing, if applicable. The fog nozzles used should produce a fog blanket and should not be confused with common garden-hose nozzles. Materials and means should be on hand for erecting temporary windbreaks and shades as needed to protect the concrete against drying winds and direct sunlight. The materials and means for the curing methods selected should be readily available at the site to permit prompt protection of all exposed concrete surfaces from drying upon completion of the placement.

h. Curing. Proper moist curing of concrete placed in hot weather is the best curing method for assuring strength development and minimizing drying shrinkage. It can be provided by ponding, covering with prewetted burlap or cotton mats, covering with clean sand kept continuously moist, or continuous sprinkling. The use of a liquid membrane-forming curing compound may be more economical and practical than moist curing in many instances. Properly applied pigmented membrane-forming curing compounds provide good protection from direct sunlight. On flatwork, application should be started immediately after disappearance of the surface water sheen after the final finishing operation. Forms should be covered and kept continuously moist during the early curing period. They should be loosened, as soon as practical without damaging the concrete, and provisions made for curing water to run down inside them. A thorough discussion of curing and other topics related to hot-weather concreting is given in ACI 305R.