the hotter part of the day, or the hotter months of the year, to a full treatment of refrigerating the various parts of the concrete mix to obtain a predetermined, maximum concrete-placing temperature. Between these extremes, evaporative cooling of aggregate stockpiles has been used with some degree of success, but is restricted to areas where the relative humidity is low. Replacement of a portion of the mix water with ice has been of definite benefit. Insulating and/or painting the surfaces of the batch plant, waterlines, etc., with reflective paint has proved beneficial.

From these partial treatments have developed complete precooling treatments which include reducing the temperature of the mix water to approximately 32 deg F; replacing a portion of the mix water with ice; reducing the temperature of the coarse aggregates to 35 to 40 deg F, either by inundating the aggregates in cold-water tanks or by wetting the aggregates with cold-water sprays and then subjecting the wetted aggregates to cold-air jets; and of cooling the sand, either by cold-air blasts as the sand is transported over the conveyor belts or by passing the sand through hollow tubes inundated in refrigerated water. Treatments which reduce the temperature of the cement have not been too successful. The most that can generally be hoped is that it will lose a sizeable portion of its excess heat during shipment to the site or in storage at the site prior to use.

Use of these treatments has resulted in concrete placing temperatures of not over 50 deg F in a number of instances. Concrete placing temperatures consistently lower than 50 deg F have been obtained, but were achieved principally by placing during the colder months of the year. For planning purposes, the temperature of the concrete at the mix plant should be 3 to 4 deg lower than the desired temperature when placed in the forms. This will compensate for the heat developed and absorbed by the concrete during mixing and transporting.

Minimizing temperature rise

The second method for controlling the temperature drop in concrete is to minimize the temperature rise in the concrete immediately after placement. Measures used to minimize the temperature rise may be employed alone or in conjunction with precooling measures, depending upon the degree of temperature control desired. A number of different measures may be used, the more common of which are: (a) the use of embedded pipe coils for artificially cooling the concrete; (b) reducing the cement content; (c) specifying a cement which has a low heat-producing characteristic; (d) use of pozzolan; (e) use of retarding agent; (f) water curing, and (g) utilizing construction lifts to fit the site conditions.

rising again. This part of the temperature history is primarily dependent upon the thickness of section and the exposure temperatures occurring at the time. Any continued heat of hydration at this age would be of secondary importance. Subsequent to the initial cooling period and the no-cooling period, intermediate and final cooling periods are employed to obtain desired temperature distributions or desired temperatures prior to contraction joint grouting. The intermediate cooling periods are actually a part of final cooling. They are used as a separate cooling operation, however, to reduce the vertical temperature gradients which occur between concrete which has already undergone final cooling and concrete which has not been cooled.

METHODS OF TEMPERATURE CONTROL

When mass concrete construction is not located in an area where the ideal condition can be attained, measures for the prevention of temperature cracking are generally those which minimize the temperature drop. This is accomplished by lowering the placing temperature of the concrete, by minimizing the temperature rise after placement, or a combination of the two methods.

Ideal condition

Basically, the ideal temperature condition would be to simply eliminate any temperature drop. Most methods for the prevention of temperature cracking in mass concrete are directed toward approaching as close to this ideal condition as practicable. The degree of success, however, is related to site conditions, economics, and design stresses in the structure. This could be achieved by placing concrete at such a low temperature that, when combined with the rise due to hydration of the cement, would result in the temperature of the concrete rising to its stable state temperature. Such a condition would be possible where the stable state temperature would be high, as in southern Asia or eastern Africa where mean annual air temperatures are as high as 88 deg F, but present a rather impractical means in the northern part of the United States where mean annual air temperatures are in the mid 30's. In the southern part of the United States, the ideal condition could be approached by appropriate temperature control methods since the mean annual air temperatures in some of these areas are in the low 70's.

Precooling measures

Reduction in the placing temperature which would otherwise be obtained at a site has varied from restricting concrete placement during

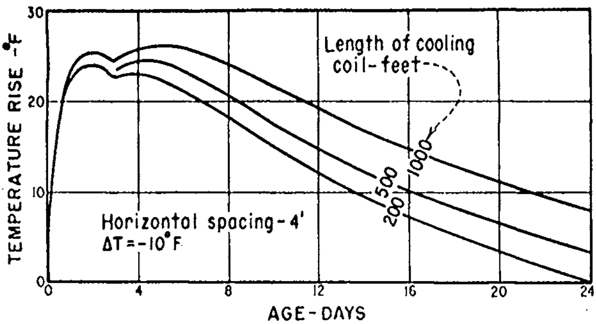


Figure 7-4 Artificial cooling of concrete—effect of coil length

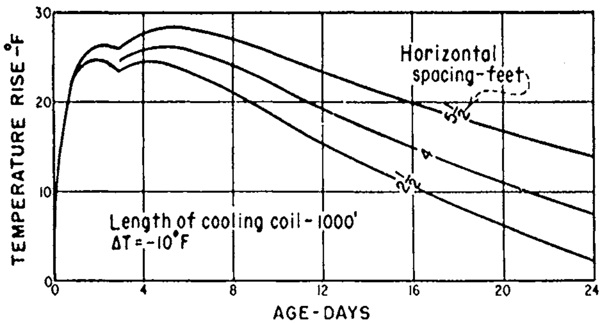


Figure 7-5 Artificial cooling of concrete—effect of horizontal spacing

varying from 2½ feet on the rock foundation to 6 feet on tops of 7½-foot lifts have been used. The temperature of the cooling water has varied from a brine at about 30 deg F to river water as high as 75 deg F. Varying the size of the embedded pipe and varying the rate of flow through the pipe will affect the cooling results but are uneconomical means as compared to the other variables. For practical purposes, 1-in. outside-diameter pipe carrying about 4 gallons per minute is used.

Cement content

Structures within the general terminology of mass concrete structures have the advantage over the ordinary size concrete structures in that they require lesser amounts of cement. Since the heat generated within the concrete is directly proportional to the amount of cement, the mix selected should be that mix which will provide the required strength and durability with the lowest cement content. Whereas the *cement* content in the earlier mass concrete structures was from four to six sacks of cement per cubic yard, present-day structures have contained

Artificial cooling

Artificially cooling the concrete by circulating cold water through embedded cooling coils placed in a grid-like pattern on the top of each construction lift will materially control the peak temperature of the concrete. These embedded coils will not prevent a temperature rise in the concrete because of the high rate of heat development in the concrete during the first few days after placement and the relatively low conductivity of the concrete. The design of the artificial cooling system requires a study of each structure, its environment, and the maximum and minimum temperatures which are acceptable from the standpoint of crack control. Varying the length of each embedded coil, the spacing of the pipe both horizontally and vertically, and the temperature of the water circulated through the coil are effective means of varying the cooling operation to obtain the desired results. Figures 7-3, 7-4, and 7-5 show how three of these variables affect the concrete temperatures. These studies were made using four sacks of Type II cement per cubic yard, a diffusivity of 0.050 ft^2/hr, a flow of 4 gallons per minute through 1-inch outside-diameter pipe, 5-foot placement lifts, and assumed a 3-day exposure of each lift. Figures 7-4 and 7-5 were derived using the adiabatic temperature rise shown in Figure 7-3. In general, cooling coil lengths of 800 to 1200 feet are satisfactory. Spacing

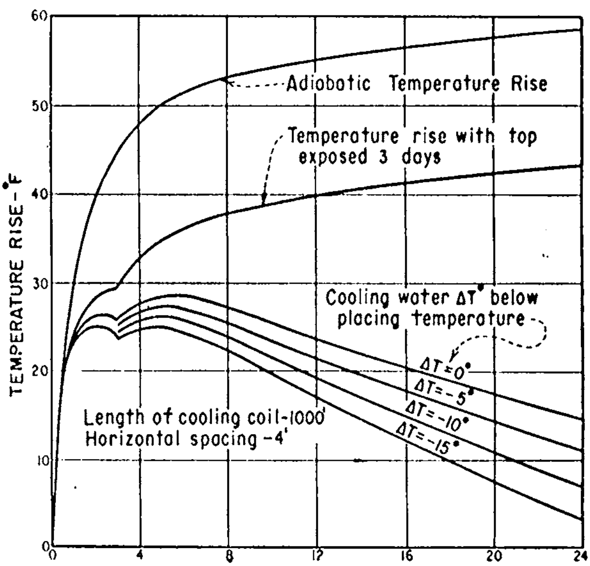


Figure 7-3 Artificial cooling of concrete—effect of cooling water temperature

as low as two sacks of cement plus other cementing materials. In thin arch structures, durability of the concrete also has to be considered, and the required strength plus desired durability may require three to four sacks of cement.

Type of cement

The heat-producing characteristics of cement play an important role in the amount of temperature rise in concrete. Although cements are classified by type as Type I, Type II, etc., the heat generation within each type may vary widely. Federal Specification SS-C-192 for portland cement does not state within what limits the heat of hydration shall be for each type of cement. This specification places maximum percentages on the C_3A compound of the cement and, for Types II and V cement, on the C_3A plus C_3S content. It further permits the purchaser to specifically request maximum heat of hydration requirements of 70 to 80 calories per gram at ages 7 and 28 days, respectively, for Type II cement; and 60 to 70 calories per gram at ages 7 and 28 days, respectively, for Type IV cement. Knowing the chemical composition of several cements, the cement with the lowest heat generation can be selected since the C_3A and C_3S compounds in the cement primarily determine the amount of heat of hydration in the cement. A number of Type I (standard) cements from the California area actually meet or exceed any invoked Federal specification heat of hydration requirements for Type II cement. Before paying any premium for a Type II cement, Type I cements in the area of supply should be investigated to see if they are close to or equal to Type II cements in C_3A and C_3S composition. For temperature control studies, laboratory tests should be made to determine the actual heat of hydration developed by the particular cement to be used.

Pozzolans

Pozzolans are used in concrete for several reasons, one of which is to obtain a lower total heat of hydration from the cementing materials within the mix. The more common pozzolans used in concrete include calcined clays, diatomaceous earth, volcanic tuffs and pumicites, and fly ash. Pozzolans develop heat of hydration in the same general manner as cement, but at a much lower rate. As with cements, the heat-developing characteristics of pozzolans vary widely and should be determined by laboratory tests. For planning purposes, it can be estimated that the heat of hydration of pozzolan will contribute about 50 percent of what would have been developed by an equal amount of cement. Figure 7-6 shows how some pozzolans vary in heat-generating characteristics, not only as to total amount but at different rates at

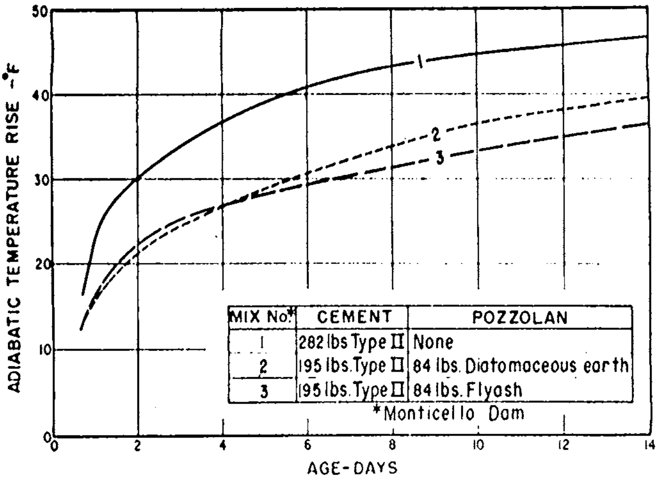
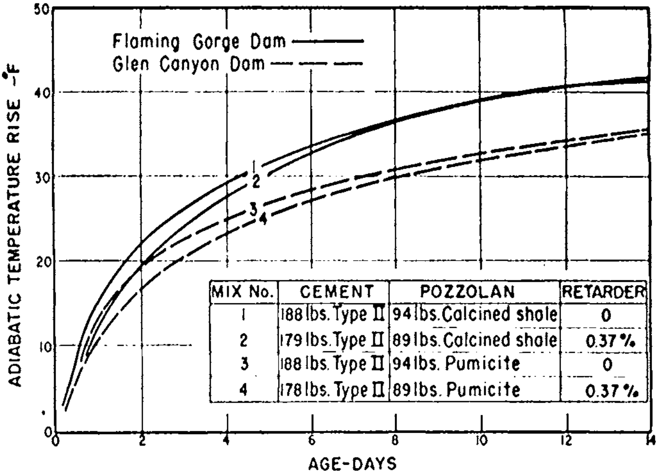


Figure 7-6 Temperature effects of pozzolans in concrete

different ages. These data were obtained on mixes prepared in the laboratory for Monticello Dam. For example, this particular diatomaceous earth used as a pozzolan generated a smaller amount of heat during the period 1 day to 4 days than fly ash. After age 4 days, however, the fly ash generated heat at a lower rate. The 2 sacks of cement to 1 sack of pozzolan shown on Figure 7-6 are commonly used in mass concrete mixes.

Retarding agents

Retarding agents added to the concrete mix will provide a temperature benefit when used in conjunction with pipe cooling. If pipe cooling is not used, little if any temperature benefit is achieved because the overall heat development of the mix will be about the same whether the retarder is used or not. The retarding agents reduce the early rate of heat generation of the cement so that the total heat generated during the first 2 to 3 days will be 2 deg, perhaps up to 3 deg, lower than a similar mix without retarder. Since it takes about 2 days after the start of artificial cooling for the temperature gradient between the concrete and the individual cooling pipe to be fully developed, peak temperatures can be reduced about 2 deg because the embedded cooling pipes will remove the heat of hydration as fast as it is developed after this time. The actual benefit varies with the type and amount of retarder used. Figure 7-7 shows the effect of retarders on the adiabatic temperature rise of Flaming Gorge and Glen Canyon Dam mixes. Most retarders used for this purpose are adipic acid of various salts of lignosulfonic



MIX No.	CEMENT	POZZOLAN	RETARDER
1	188 lbs. Type II	94 lbs. Calcined shale	0
2	179 lbs. Type II	89 lbs. Calcined shale	0.37 %
3	188 lbs. Type II	94 lbs. Pumicite	0
4	178 lbs. Type II	89 lbs. Pumicite	0.37 %

Figure 7-7 Temperature effects of retarders in concrete

acid. The percentage of retarder by weight of cement is generally about 0.37 percent. Percentages larger than this will give added temperature benefit but can create construction problems such as delay in form removal, strength of form ties required, etc.

Water curing

Water curing on the top and sides of each construction lift will aid in reducing the temperature rise in concrete, particularly if the exposure conditions at the site are high and curing water temperatures are relatively low. Two effects are obtained by water curing, both of which accrue to the lower surface temperature. The first is to reduce the absorbing of heat from outside the lift during the early age when exposure temperatures are higher than the interior temperatures. The second effect is to increase the loss of heat from the interior to the surfaces when the concrete temperatures are higher than the exposure temperatures. Figure 7-8 shows the results of Glen Canyon Dam studies on the effect of lowering the surface temperature by water curing. In this particular study, concrete was to be placed in 7½-foot lifts at 50 deg F, and daily exposure temperatures resulting from water curing were assumed to vary from 80 to 90 deg F in one instance and from 70 to 80 deg F in the other. To obtain the most temperature benefit, the surfaces should be kept constantly and not periodically wetted. Proper application of water to the surfaces will cause the surface temperature to approximate the curing water temperature instead of the prevailing air temperatures. In areas of low humidity, the evaporative

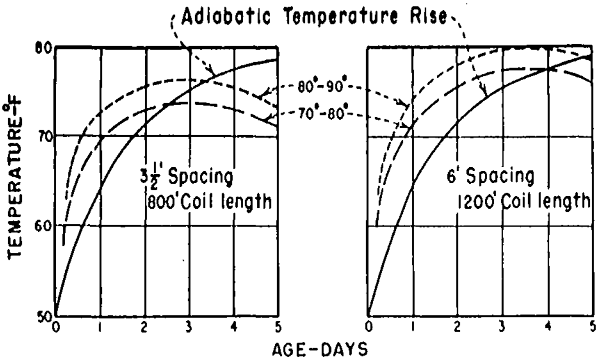


Figure 7-8 Influence of exposure temperatures

cooling effect may result in even lower surface temperatures than the curing water temperature.

Construction lifts

Shallow placement lifts will normally permit a greater percentage of the total heat generated in a placement lift to be lost to the surface. Such a temperature benefit exists only if the exposure temperatures are lower than the concrete temperature. For this condition, the longer the delay between lifts the greater the heat loss. Where precooling is used, the opposite effect is often the case, and the exposed lift surface will absorb heat from the surrounding air. In this case, exposures should be held to a minimum. Unless the site conditions are such that a sizeable benefit is obtained, shallow placement lifts are seldom used except over construction joints which have experienced prolonged exposure periods, or over foundation irregularities where they are beneficial in preventing settlement cracks.

RATE OF TEMPERATURE DROP

In addition to precooling measures and measures employed to minimize the temperature rise after placement, other means are available to lessen the temperature stresses and the resultant tendency to crack in mass concrete. One of these is to control the rate of temperature drop. Another is the time when this temperature drop occurs. Temperature stresses developed in mass concrete are related to these factors. Figures 7-9, 7-10, and 7-11 show the development of stresses for a 1 deg F temperature drop per day for a period of 40 days, starting at various ages. The stress values shown are the maximum uniaxial stresses assuming 50 percent foundation restraint, and need to be further modified to take into consideration the foundation modulus, E_f as described earlier.

In thick sections with no artificial cooling, the temperature drop will normally be slow enough as to be no problem. In thin sections with artificial cooling, however, the temperature drop may have to be controlled. This can be accomplished by reducing the amount of cooling

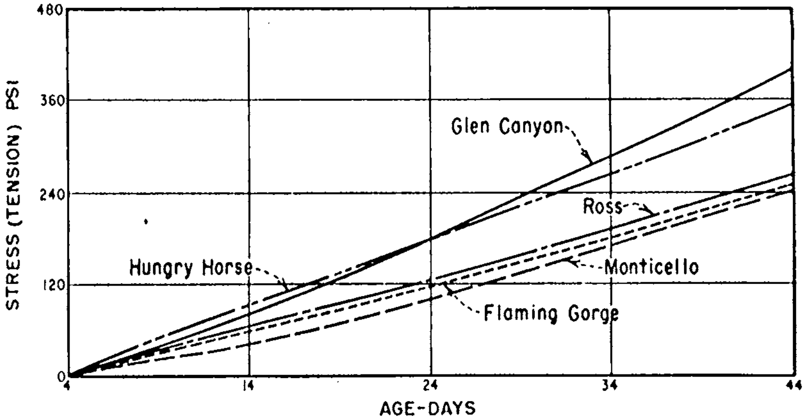


Figure 7-9 Temperature stresses for a one-degree daily temperature drop—4-day age of loading

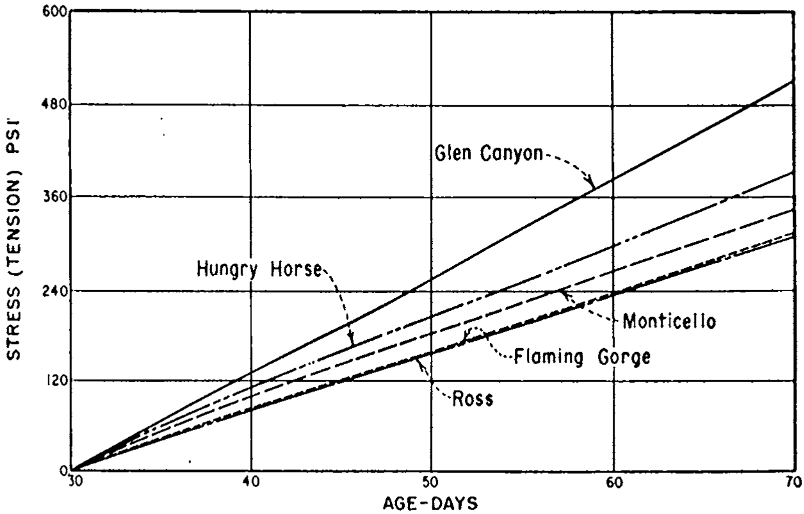


Figure 7-10 Temperature stresses for a one-degree daily temperature drop—30-day age of loading

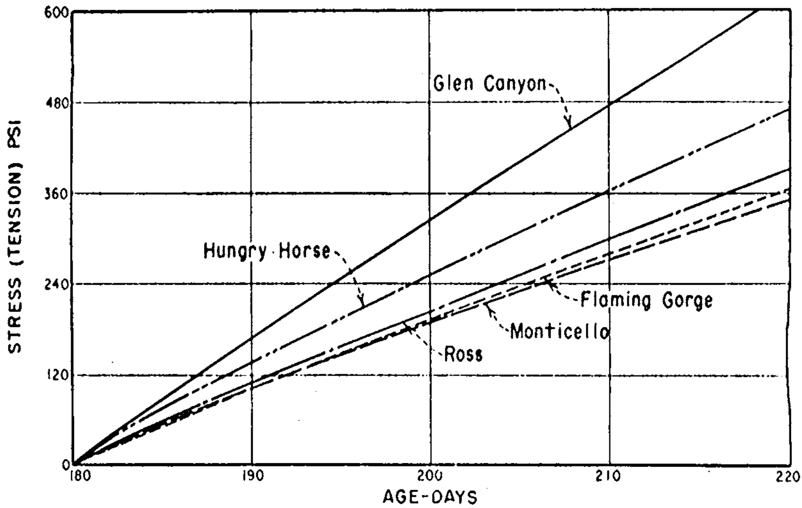


Figure 7-11 Temperature stresses for a one-degree daily temperature drop —180-day age of loading

water circulated or by controlling the cooling water temperature. The operation of the cooling systems and the layout of the header systems to supply the individual cooling coils should be such that each coil can be operated independently of all other coils. No-cooling periods should also be utilized where necessary. In thin sections where no artificial cooling is employed, the temperature drop during periods of cold weather should be controlled by the use of insulating forms or insulation placed on the exposed surfaces. Such measures not only reduce the rate of change, but also reduce the temperature gradients near the surface with a definite reduction in cracking tendency.

SURFACE TREATMENTS

Because most cracks start at an exposed surface, temperature cracks in mass concrete can be minimized if conditions are established which will reduce or eliminate tensile stresses at these surfaces. Such conditions may be approached by causing the surface of the concrete to set u.; .. a relatively cool temperature as compared to the internal temperature. Later, as the internal temperatures drop, the surface is put into compression which will effectively reduce temperature cracks. This will be especially effective on the larger massive sections. Causing the surfaces to set at a relatively cool temperature is of small benefit in thin structures where very little, if any, load transfer effect is obtained.

Surface cooling can be accomplished by closely spaced embedded