ACI 207.4R-93
(Reapproved 1998)

Cooling and Insulating Systems for Mass Concrete

Reported by ACI Committee 207

John M. Scanlon
Chairman

Terry W. West*
Task Group Chairman

Fred A. Anderson
Howard L Boggs
Dan A. Bonikowsky
Richard A.J. Bradshaw
Edward G.W. Bush
Robert W. Cannon
James L. Cope
Luis H. Diaz
Timothy P. Dolen
James R. Graham
Michael I. Hammons
Kenneth D. Hansen
Meng K. Lee
Gary R. Mass
James E. Oliverson
Robert F. Oury
Ernest K. Schrader*
Stephen B. Tatro*

• Task group member

The need to control volume change induced primarily by temperature change in mass concrete has led to the development of cooling and insulating systems for use in mass concrete construction. This report reviews the development of these system the need for temperature control; pre-cooling post-cooling and insulating systems currently being used; and expected trens. A simplified method for computing the temperature of freshly mixed concrete cooled by various systems is also presented.

Keywords: admixtures; cement content; cement types; coarse aggregate; cooling pipes; creep; formwork (construction); heat of hydration; ice; insulation; mass concrete; modulus of elasticity; precooling; post-cooling; pozzolans; restraints; specific heat; strains; stresses; temperature rise (in concrete); tensile strain capacity; tensile strength; thermal conductivity; thermal diffusivity; thermal expansion; thermal gradient; thermal shock; thermal transmittance.

CONTENTS

ACI 207.4R-93 supersedes ACI 207.4R-80 (Revised 1986) and became effective September 1,1993.

CHAPTER l-INTRODUCTION

1.1-Scope and objective

This report presents a discussion of special construction procedures which can be used to control the temperature changes which occur in concrete structures. The principal construction practices covered are precooling of materials, post-cooling of in-place concrete by embedded pipes, and surface insulation. Other design and construction practices, including the selection of cementing materials, aggregates, chemical admixtures, cement content, and strength requirements are not within the scope of this report.

The objective of this report is to summarize experiences with cooling and insulating systems, and to offer guidance on the selection and application of these procedures in design and construction for controlling thermal cracking in all types of concrete structures.

1.2 - Historical background

The first major use of artificial cooling (post-cooling) of mass concrete was in the construction of the Bureau of Reclamation's Hoover Dam in the early 1930's. In this case the primary objective of the post-cooling was to accelerate thermal contraction of the columns of concrete composing the dam so that the contraction joints could be filled with grout to insure monolithic action of the dam. The cooling was achieved by circulating cold water through pipes embedded in the concrete. Circulation of water through the pipes was usually started several weeks or more after the concrete had been placed. Since Hoover Dam, post-cooling has been used in construction of many large dams. Generally the practices followed were essentially identical to those followed at Hoover Dam, except that circulation of cooling water was initiated simultaneously with the placement of concrete.

In the early 1940's the Tennessee Valley Authority utilized post-cooling in the construction of Fontana Dam for two purposes: (a) to control the temperature rise particularly in the vulnerable base of the dam where cracking of the concrete could be induced by the restraining effect of the foundation, and (b) to accelerate thermal contraction of the columns so that the contraction joints between columns could be filled with grout to ensure monolithic action. Post-cooling was started coincidently with the placing of each new lift of concrete on the previously placed lift and on foundation rock. The pipe spacing and lift thickness were varied to limit the maximum temperature to a pre-designed level in all seasons. In summer with naturally high (unregulated) placing temperatures, the pipe spacing and lift thickness for the critical foundation zone was 2.5 ft (0.76 m); in winter when placing temperatures were naturally low the pipe spacing and lift thickness for this zone was 5.0 ft (1.5 m). Above the critical zone, the lift thickness was increased to 5.0 ft (1.5 m) and the pipe spacing was increased to 6.25 ft (1.9 m). Cooling was also started in this latter zone coincidently with the placing of concrete in each new lift.

In the 1960's the Corps of Engineers began the practice of starting, stopping, and restarting the cooling process based on the results of embedded resistance thermometers. At Dworshak Dam and the Ice Harbor Additional Power House Units, the cooling water was stopped when the temperature of the concrete near the pipes began to drop rapidly after reaching a peak. Within 1 to 3 days, when the temperature would rise again to the previous peak temperature, cooling would be started again to produce controlled safe cooling.

First use of precooling of concrete materials to reduce the maximum temperature of mass concrete was by the Corps of Engineers during the construction of Norfork Dam (1941-1945). A part of the batch water was introduced into the mixture as crushed ice. The placing temperature of the concrete was reduced about 10 F (6 C). Precooling has become very common for mass concrete placements. It also is used for placements of relatively small dimensions such as for bridge piers and foundations where there is sufficient concern for minimizing thermal stresses. For precooling applications various combinations of crushed ice, cold batch water, liquid nitrogen, and cooled aggregate were used to achieve a placing temperature of 50 F (10 C) and in some dams to as low as 40 F (4.5 C).

Roller-compacted concrete (RCC) projects have effectively used "natural" precooling of aggregate. Large quantities of aggregate (sometimes all of the aggregate for a dam) are produced during cold winter months and placed into stockpiles. In the warm summer months the exterior of the piles warms but the interior stays cold. At Middle Fork, Monkesville, and Stagecoach Dams it was not unusual to find frost in the aggregate stockpiles during production of RCC in the summer at ambient temperatures about 75-95 F (24-35 C).

Precooling and post-cooling have been used in combination in the construction of some massive structures such as Glen Canyon Dam, completed in 1963, Dworshak

Dam, completed in 1975, and the Lower Granite Dam Powerhouse addition, completed in 1978.

Insulation has been used on lift surfaces and concrete faces which are exposed to severe winter temperatures to prevent or minimize the tendency to crack under sudden drops in ambient temperatures. This method of controlling temperature changes and the consequent cracking has been used since 1950. It has become an effective practice where needed. The first extensive use of insulation was during the construction of Table Rock Dam, built during 1955-57. Insulation of exposed surfaces, for the purpose of avoiding the development of cracking, supplements other construction control measures, such as precooling materials and post-cooling of in-place concrete.

Injection of cold nitrogen gas into the mixer has been used to precool concrete in recent years. Practical and economical considerations must be evaluated, but it is effective. As with ice, additional mixing time may be required.

1.3-Types of structures

These special construction practices have evolved to meet engineering requirements of massive concrete structures such as concrete gravity dams, arch dams, navigation locks, nuclear reactors, powerhouses, large footings, mat foundations, and bridge piers. They are also applicable to smaller structures where high levels of internally developed thermal stresses and potential cracks resulting from volume changes cannot be tolerated or would be highly objectionable (Tuthill and Adams 1972, and Schrader 1987).

l.4-Normal construction practices

In addition to controlling thermal stresses, mixing and placing concrete at temperatures as low as feasible without adversely affecting the desired early strength gain will enhance its long-term durability and strength. It will also result in improved consistency and will allow a longer placing time. The improved workability can, at times, be used to reduce the water requirement. Cooler concrete is also more responsive to vibration during consolidation. Construction operations can be conducted to achieve these nominal cooling benefits with only modest extra effort, and concurrently provide a start toward satisfying specific cooling objectives. Typical construction practices used to control temperature changes within concrete structures include:

- Cooling batch water
- Replacing a portion of the batch water with ice
- Shading aggregates in storage
- Shading aggregate conveyors
- Spraying aggregate stockpiles for evaporative cooling effect
- Immersion of coarse aggregates
- Vacuum evaporation of coarse aggregate moisture
- Nitrogen injection into the mix
- Using light-colored mixing and hauling equipment
- Placing at night
- Prompt application of curing water
- Post-cooling with embedded cooling pipes
- Controlled surface cooling
- Avoiding thermal shock at form removal
- Protecting exposed edges and comers from excessive heat loss

1.5-Instrumentation

Temperature monitoring of concrete components during handling and batching, and of the fresh concrete before and after its discharge into the forms, can be adequately accomplished with ordinary portable thermometers capable of 1 F (0.5 C) resolution. Post-cooling systems require embedded temperature-sensing devices (thermocouples or resistance thermometers) to provide information for the control of concrete cooling rates. Similar instruments will serve to evaluate the degree of protection afforded by insulation. Other instruments to measure internal volume change, stress, strain, and joint movement have been described (Carlson 1970).

CHAPTER 2-NEED FOR TEMPERATURE CONTROL

2.1-General

If cement and pozzolans did not generate heat as the concrete hardens, there would be little need for temperature control.

In the majority of instances this heat generation and accompanying temperature rise will occur rapidly enough to result in the hardening of the concrete in an expanded condition. Further, concurrent with the increase in elastic modulus (rigidity) is a continuing rise in temperature for several days or more. Even these circumstances would be of little concern if the entire mass of the placement could be:

a) limited in maximum temperature to a value close to its final cooled stable temperature;

b) maintained at the same temperature throughout its volume, including exposed surfaces; and,

c) supported without restraint (or supported on foundations expanding and contracting in the same manner as the concrete).

Obviously none of these three conditions can be achieved completely; nor simultaneously. The first and second can be realized to some extent in most construction. The third condition is the most difficult to obtain, but has been accomplished on a limited scale for extremely critical structures by preheating the previously-placed concrete to limit the differential between older concrete and the maximum temperature expected in the covering concrete. Many details of crack development and control are also discussed in ACI 207.1R, 207.2R and 224R, by Townsend (1965), Mead (1963), Tuthill and Adams (1972), Tatro and Schrader (1985), and Ditchey and Schrader (1988).

2.2 - Structural requirements

The size, type, and function of the structure, the climatological environment, and the degree of internal or external restraint imposed on it dictate the extent of the temperature control necessary. Gravity structures which depend upon structural integrity for safety and stability can usually tolerate no cracks in certain plane orientations. The number of joints should be a minimum, consistent with designers' requirements and construction practicality. The designer should establish a design strength that is consistent with requirements for structural performance, construction loads, form removal, and durability. Consideration should be given to specifying strength requirements at an age greater than 28 days. Concrete with an early (28-day) strength higher than is necessary to resist later age loading will require excessive amounts of cements, thus introducing additional heat into the concrete and aggravating the temperature control problem. Where cracks, including those resulting from thermal stress, permit the entry of water, subsequent corrosion of reinforcement, leaching, and/or freezing and thawing may result in spalling or other disruptive action.

The construction schedule, relating to rate of placement and the season of the year, should be considered by the designer. The highest peak concrete temperature will occur in concrete placed during the hot summer months; concrete placed in the late summer or early autumn will also attain a high peak temperature and will likely be exposed to abrupt air temperature drops. Winter-placed concrete will be exposed to severe low temperature conditions. These circumstances contribute to the need for temperature control consideration.

Late spring is the most suitable time for placing mass concrete because the ambient air temperature tends to increase daily, thus coinciding with the temperature rise of the concrete. The concrete thus neither absorbs much heat from the air, nor is it subjected to rapid changes in temperature at the surfaces.

2.3-Structure dimensions

Where the least dimension of a concrete unit is not large, the concrete mixture is low in heat evolution, and the heat of hydration can escape readily from the two boundary surfaces (forms not insulated), the maximum temperature rise will not be great. However, in all instances some internal temperature rise is necessary in order to create a thermal gradient for conducting the heat to the surface. Table 2.1 shows typical maximum temperatures achieved. Two factors tend to lessen the detrimental effects of heat generation: (a) the concrete begins to cool from its peak temperature while the modulus of elasticity is still low, or the creep rate is high, or both; and, (b) the total tensile force (opposed and balanced by an equal compressive force) is distributed over a significant proportion of the section, thus tending to avoid a high unit tensile stress.

A foundation slab may be considered a wall of large dimensions cast on its side, such that heat is lost principally from a single exposed surface. For this case Table 2.2 shows the typical maximum temperatures expected, which are not substantially higher than those for a vertically-cast wall. However, the maxima do occur at later ages and over large portions of the concrete mass. Since a static tension-compression force balance must exist, the compressive unit stress across the center portion is small and essentially uniform, whereas very high tensile stress exists at the exposed sides.

Proof that massive concrete structures can be produced, with modest precautions and aided by favorable climate conditions, free of cracks is illustrated by a documented construction example in Great Britain (Fitzgibbon 1973). A heavily reinforced footing, 5200 ft^2 (480 m^2) in area and 8.2 ft (2.5 m) in depth, and with a cement content of 705 lb/yd^3 (418 kg/m^3), was placed as a single unit. A maximum concrete temperature of 150 F (65 C) was attained, with side surfaces protected by 3/4 in. (19 mm) plywood forms and top surface by a plastic

Table 2.1-Temperature rise in walls

Wall thickness, ft (m)	1 (0.3)	2 (0.6)	3 (0.9)	4 (1.2)	5 (1.5)	10 (3.0)	Infinite (Infinite)
Maximum temperature rise							
deg F	1.3	3.2	5.2	7.0	8.6	13.7	17.8
(deg C)	(1.2)	(3-0)	(4.9)	(6.6)	(8.1)	(12.8)	(16.7)

Moderate heat (Type II) cement
Placing temperature equal to exposure temperature
Two sides exposed
Thermal diffusivity: 1.0 ft^2/day (0.093 m^2/day)
Temperature rise: deg F per 100 lbs cement per cu yd concrete
deg C per 100 kg cement per cu m concrete

Table 2.2-Temperature rise in slabs on ground

Slab thickness, ft (m)	3 (0.9)	5 (1.5)	10 (3.0)	15 (4.6)	20 (6.1)	25 (7.6)	Infinite (Infinite)
Maximum temperature rise							
deg F	6.0	9.3	14.0	16.0	16.8	17.3	17.8
(deg C)	(5.6)	(8.7)	(13.1)	(15.0)	(16.7)	(16.2)	(16.7)

Moderate heat (Type II) cement
Placing temperature equal to exposure temperature
Exposed top only
Thermal diffusivity: 1.0 ft^2/day (0.093 m^2/day)
Temperature rise: deg F per 100 lbs cement per cu yd concrete
deg C per kg cement per cu m concrete

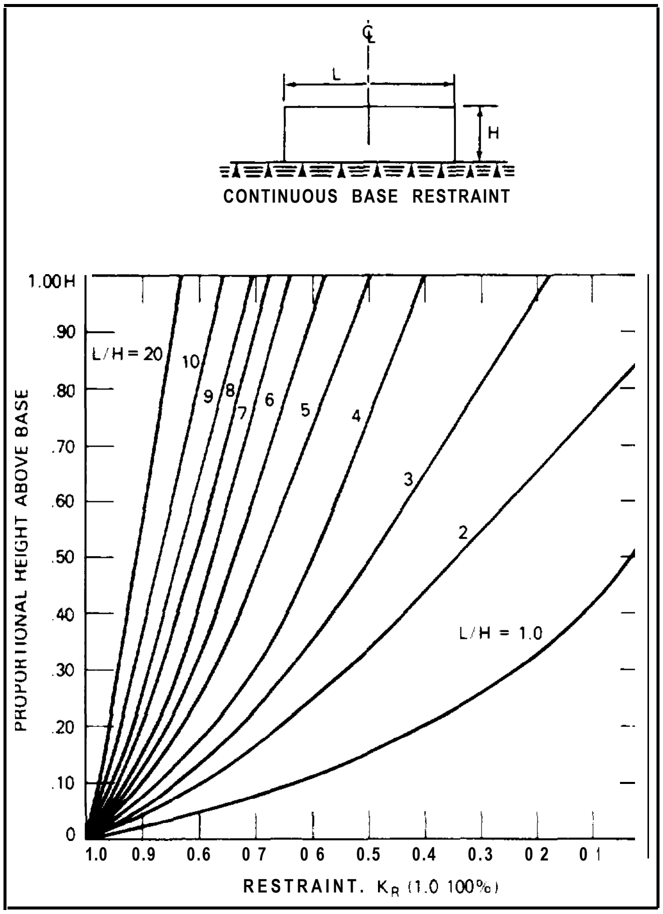


Fig. 2.1-Degree of tensile restraint at center section

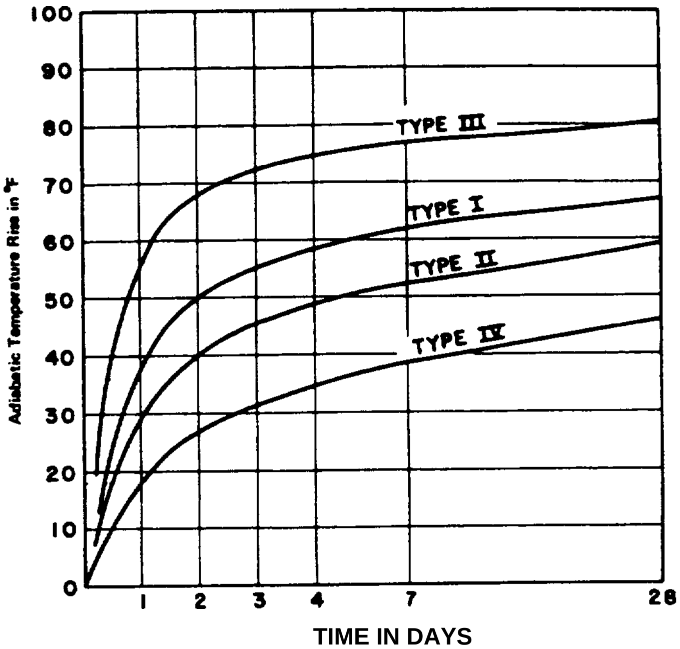
sheet under a 1 in. (25 mm) layer of sand. Plywood and sand were removed at 7-day age, exposing surfaces to the ambient January air temperature and humidity conditions.

2.4-Restraint

No tensile strain or stress would develop if the length or volume changes associated with decreasing temperature within a concrete mass or element could take place freely. When these potential contractions, either between a massive concrete structure and its rock foundation, between contiguous structural elements, or internally within a concrete member are prevented (restrained) from occurring wholly or in part, tensile strain and stress will result. Concrete placed on an unjointed rigid rock foundation will be essentially restrained at the concrete-rock interface, but the degree of restraint will decrease considerably at locations above the rock, as shown in Fig. 2.1. Yielding foundations will cause less than 100 percent restraint. Total restraint at the rock plane is mitigated because the concrete temperature rise (and subsequent decline) in the vicinity of the rock foundation is reduced as a result of the flow of heat into the foundation itself. Discussions of restraint and analytical procedures to evaluate its magnitude and effect appear in ACI 207.1R, 207.2R and 224R, Wilson (1968), and Gamer and Hammons (1991).

2.5-Heat generation

Design strength requirements, durability, and the characteristics of the available aggregates largely dictate the cement content of the mixture to be used for a particular job. Options open to the engineer seeking to limit heat generation include: (a) use of Type II, moderate heat portland cement, with specific maximum heat of hydration limit options if necessary; (b) use of blended hydraulic cements (Type IS, Type IP, or Type P) which exhibit favorable heat of hydration characteristics which may be more firmly achieved by imposing heat of hydration limit options for the portland cement clinker; and, (c) reduction of the cement content by using a pozzolanic material, either fly ash or a natural pozzolan, to provide a reduction in maximum temperatures produced without sacrificing the long-term strength development. In some instances advantage can be taken of the cement reduction benefit of a water-reducing admixture. RCC usually allows cement reduction by maintaining a low water/cement ratio while lowering the water content to a point where the mixture has no slump. RCC also may use non-pozzolanic fines to permit cement reductions. From these options, selections can be made which will serve to minimize the total heat generated. However, such lower heat-producing options may be offset by their slower strength



Cement type	Fineness ASTM C 115 cm^2/gm	Heat of hydration Calories per gm
I	1790	87
II	1890	76
III	2030	106
IV	1910	60

Fig. 2.2-Temperature rise of mass concrete containing 376 lb/yd^3 of various types of cement

gain which may require an extended design age. In some cases construction needs, such as obtaining sufficient early strength to allow for form stripping, setting of forms, and lift-joint preparation, may not permit a reduction in cement (and the corresponding early heat generation) to the extent that could otherwise be achievable. Fig. 2.2, which shows typical adiabatic temperature maxima expected in mass concrete, is adapted from ACI 207.1R.

At early ages (up to 3 days) the temperature rise of the mixture containing the pozzolan replacement results principally from hydration of the cement, with little if any heat contributed by the pozzolan. At later ages (after 7 days) the pozzolan does participate in the hydration process, and may contribute about 50 percent of the amount of heat which would have been generated by the cement it replaced. ASTM C 618 Class C fly ash generally produces more heat than Classes F or N pozzolans.

2.6-Climate

As a general rule, when no special precautions are taken, the temperature of the concrete when placed in the forms will be slightly above the ambient air temperature. The final stable temperature in the interior of a massive concrete structure will approximate the average annual air temperature at its geographical location.

Except for tropical climates, deep reservoir impoundments will maintain the concrete in the vicinity of the heel of the dam at the temperature of water at its maximum density, or about 39 F (4 C). Thus, the extreme temperature excursion experienced by interior concrete is determined from the initial placing temperature plus the adiabatic temperature rise minus the heat lost to the air and minus the final stable temperature. Mathematical procedures are available to determine the net temperatures attained in massive placements. Lifts of 5 ft may lose as much as 25 percent of the heat generated if exposed for enough time (about 5 days) prior to placing the subsequent lift, if the ambient temperature is below the internal concrete temperature. Lifts greater than 5 ft and placements with little or no difference between the air temperature and internal concrete temperature will lose little or no heat (ACI 207.1R and 207.2R).

At least of equal importance is the temperature gradient between the interior temperature and the exposed surface temperature. This can create a serious condition when the surface and near-surface temperatures decline at night, with the falling autumn and winter air temperatures, or from cold water filling the reservoir, while the interior concrete temperatures remain high. The decreasing daily air temperatures, augmented by abrupt cold periods of several days duration characteristic of changing seasons, may create tensile strains approaching, if not exceeding, the strain capacity of the concrete.

2.7-Concrete thermal characteristics

2.7.1 *Coefficient of thermal expansion*-The mineral composition of aggregates, which comprise 70-85 percent of the concrete volume, is the major factor affecting the linear coefficient of expansion of concrete. Hardened cement paste exhibits a higher coefficient than aggregate, and is particularly influenced by its moisture content. The coefficient of hardened cement paste in an air-dry condition may be twice that under either oven-dry or saturated conditions. The expansion coefficient for concrete is essentially constant over the normal temperature range, and tends to increase with increasing cement content and decrease with age. The typical range of values given in Table 2.3 represents concrete mixtures with about a 30:70 fine to coarse aggregate ratio, high degree of saturation, and a nominal cement content of 400 lb/yd^3 (237 kg/m^3).

2.7.2 *Specific heat*-The heat capacity per unit of temperature, or specific heat, of normal weight concrete varies only slightly with aggregate characteristics, temperature, and other parameters. Values from 0.20 to 0.25 Btu/lb F (cal/gm C) are representative over a wide range of conditions and materials.

2.7.3 *Thermal conductivity* - Thermal conductivity is a measure of the capability of concrete to conduct heat, and may be defined as the rate of heat flow per unit temperature gradient causing that heat movement. Mineralogical characteristics of the aggregate, and the moisture

Table 2.3-Linear thermal coefficient of expansion of concrete

Coarse aggregate	Thermal coefficient of expansion Millionths/deg F	Millions/deg C
Quartzite	7.5	13.5
Siliceous	5.2-6.5	9.4-11.7
Basalt	4.6	83
Limestone	3.0-4.8	5.4-8.6

Table 2.4-Typical thermal conductivity values for concrete

Aggregate type	Thermal conductivity Btu in./h. ft^2 F	W/m.K
Quartzite	24	3.5
Dolomite	22	3.2
Limestone	18-23	2.6-33
Granite	18-19	2.6-2.7
Rhyolite	15	2.2
Basalt	13-15	1.9-2.2

Table 2.5—Thermal diffusivity and rock type

Coarse aggregate	Diffusivity ft^2/h	m^2/h
Quartzite	0.058	0.0054
Limestone	0.051	0.0047
Dolomite	0.050	0.0046
Granite	0.043	0.0040
Rhyolite	0.035	0.0033
Basalt	0.032	0.0030

content, density, and temperature of the concrete all influence the conductivity. Within the normal concrete temperatures experienced in mass concrete construction, and for the high moisture content existing in concrete at early ages, thermal conductivity values shown in Table 2.4 are typical (ACI 207.1R).

2.7.4 *Themal diffusivity* -As discussed in ACI 207.1R, thermal diffusivity is an index of the ease or difficulty with which concrete undergoes temperature change, and numerically is the thermal conductivity divided by the product of density and specific heat. For normal weight concrete, where density and specific heat values vary within relatively narrow ranges, thermal diffusivity reflects the conductivity value. High conductivity indicates greater ease in gaining or losing heat. Table 2.5, taken from the same reference, is reproduced here for convenience. Values for concrete containing quartzite aggregate have been reported up to 0.065 ft^2/hr (0.0060 m^2/hr).

2.4-Concrete elastic properties

Prior to achieving a "set" and measurable modulus of elasticity, volume changes occur with no accompanying development of stress. At some time after placement, the concrete will begin to behave elastically. For higher cement content mixtures without retarders and placed at "warm" temperatures (in excess of about 75 F (24 C)) this may occur within a few hours. For low cement content mixtures with retarders and placed at very cold temperatures this may not occur for 1 to 2 days. Primarily for convenience, a one-&y age is frequently taken to be the earliest age at which thermally-caused stress will occur. The exact age is not critical, because the elastic modulus will initially be low and the strain-to-stress conversion result is further mitigated by high creep at early ages.

Typical instantaneous and sustained (long-term) elastic modulusvalues for four conventional mass concretes (different coarse aggregates) are given in Table 2.6. Table 2.7 shows values for some low cement content RCC mixtures. The lower modulus of elasticity values after one-year sustained loading reflect the increases in strain resulting from the time-dependent characteristic (creep) of the concrete. At intermediate dates, the unit strain increase is directly proportional to the logarithm of the duration of loading. For example, with initial loading at 90 days and basalt aggregate concrete, the initial unit strain is 0.244 millionths per psi (35.7 millionths per MPa). After one-year load duration, the unit strain value is 0.400 millionths per psi (58.8 millionths per MPa). At 100-day age, or 10 days after initial loading, the unit strain value in millionths per psi is given by the equation:

$$0.244 + (0.400 - 0.244) \log 10/\log 365$$

(in millionths per MPa: $35.7 + (58.8 - 35.7) \log 10/\log 365$)

The resulting modulus of elasticity is 3.3 x 10^6 psi (22 GPa).

Elastic properties given in Tables 2.6 and 2.7 were influenced by conditions other than aggregate type, and for major work laboratory-derived creep data based on aggregates and concrete mixtures to be used is probably warranted.

2.9-Strain capacity

Designs based on tensile strain capacity rather than tensile strength are more convenient and simpler where criteria are expressed in terms of linear or volumetric changes. Examples are temperature and drying shrinkage phenomena. The Corps of Engineers employs a modulus of rupture test as a measure of the capability of mass concrete to resist tensile strains (Hook et al. 1970) (Houghton 1976).

The tensile strain test beams are 12 x 12 x 64 in. (300 x 300 x 1600 mm), nonreinforced, tested to failure under third-point loading. Strains of the extreme fiber in tension are measured directly on the test specimen. At the 7-day initial loading age, one specimen is loaded to failure over a period of a few minutes (rapid test). Concurrently, loading of a companion test beam is started, with

Table 2.6-Typical instantaneous and sustained modulus of elasticity for conventional mass concrete

Age at time of loading (days)	Million psi (GPa)							
	Basalt		Andesite & Slate		Sandstone		Sandstone & Quartz	
	E	E	E	E	E	E	E	E'
2	1.7 (12)	0.83 (5.7)	1.4 (9.7)	054 (3.7)	2.8 (19)	1.5 (10)	1.4 (9.7)	0.63 (4.3)
7	2.3 (16)	1.1 (7.6)	2.1 (14)	1.0 (6.9)	4.2 (29)	1.9 (13)	2.2 (15)	0.94 (6.5)
28	3.5 (24)	1.8 (12)	3.5 (24)	1.8 (12)	4.5 (31)	2.6 (18)	3.6 (25)	1.8 (12)
90	4.1 (28)	2.5 (17)	4.4 (30)	2.7 (19)	5.2 (36)	3.2 (22)	4.2 (29)	2.6 (18)
365	5.0 (34)	3.1 (21)	4.7 (32)	3.5 (24)	5.7 (39)	3.6 (25)	4.6 (32)	3.1 (21)

All concrete mass mixed, wet screened to 1½in. (38 mm) maximum sizeaggregate
E = instantaneous modulus of elasticity at time of loading
E' = sustained modulus after 365 days under load
Based on ACI 207.1R

Table 2.7-Typical instantaneous and sustained modulus of elasticity for roller-compacted concrete

Age at time of loading (days)	Million psi (GPa)									
	Ignimbrite[1] (Tuff) (internal gauges)		Ignimbrite[1] (Tuff) (external gauges)		Basalt[2]		Basalt3		Basalt[4]	
	E	E	E	E	E	E	E	E	E	E
7	0.7 (5)	0.4 (3)	1.3 (9)	0.8 (6)	0.7 (5)	0.5 (3)	1.7 (11)	1.0 (6)	05 (4)	03 (2)
28	1.4 (10)	0.8 (6)	1.8 (12)	1.3 (9)	1.3 (9)	0.8 (6)	2.6 (18)	1.5 (10)	0.9 (6)	0.6 (4)
90	2.2 (15)	1.4 (10)	2.3 (16)	1.7 (12)	2.1 (14)	— —	3.2 (22)	— —	1.9 (13)	— —

(1) Cement content of 151 lbs/cy (90 kg/m³), no pozzolan.
(2) Cement content of 100 lbs/cy (59 kg/m³), no pozzolan.
(3) Cement content of 175 lbs/cy (104 kg/m³), pozzolan content of 80 lbs/cy (47 kg/m³).
(4) Cement content of 80 lbs/cy (47 kg/m³), pozzolan content of 32 lbs (19 ks/m³).
All mixes contained 3-in (76-mm) maximun size aggregate
E = instantaneous modulus of elasticity at time of loading
E = sustained modulus after 365 days under load

weekly loading additions, 25 psi/week (0.17 MPa/week), of a magnitude which will result in beam failure at about 90 days (slow test). Upon failure of the slow test beams, a third specimen is sometimes loaded to failure under the rapid test procedure to provide a measure of the change in elastic properties over the duration of the test period.

Tensile strain capacity results (Table 2.8 shows typical values) aid in establishing concrete crack control procedures. For example, assuming the first concrete in Table 2.8 has a coefficient of thermal expansion of 5.5 millionths/F (9.9 millionths/C) from Table 2.3, sufficient insulation must be used to avoid sudden surface temperature drops greater than 64/5.5 = 11.6 F (6.4 C) at early ages, and 88/5.5 = 16 F (8.9 C) at 3-month or later ages, In the event embedded pipe cooling is used, the total temperature drop should not exceed 118/5.5 = 21 F (12 C) over the initial 3-month period.

An abbreviated tensile strain capacity prediction procedure has been reported (Liu 1978), but the system is empirical, approximate, and promises no more than a moderate correlation with measured values.

2.10 - Thermal shock

The interior of most concrete structures, with a minimum dimension greater than about 2 ft (0.6 m) will be at a temperature above the ambient air temperature at the time forms are removed. At the boundary between the concrete and the forms, the concrete temperature will be below that in the interior, but above that of the air. With steel forms, the latter difference may be small, but with insulated steel or wood forms the difference may be substantial. When the forms are removed in that instance, the concrete is subjected to a sudden steepening of the thermalgradient immediately behind the concrete surface.

Table 2.8-Tensile strain capacity

Concrete components	Tensile strains (Millionths)(a)(b) Rapid test (Initial)	Slow test	Rapid test (Final)
Quartz diorite (natural) w/c = 0.66(c)	64 (89)	118 (102)	88 (78)
Quartz diorite (natural) w/(c + p) = 0.63(c)	52 (65)	88 (80)	73 (74)
Granite gneiss (crushed) w/(c + p) = 0.60	86	245	110
Limestone (crushed) Quartz sand (natural) w/(c + p) = 0.63	45 (70)	95 (89)	73 (75)
Limestone (crushed) Quartz sand (natural) w/(c + p) = 0.47	62 (66)	107 (83)	8JJ (71)

(a) At 90 percent of failure loading
(b) Strain values not in parentheses are from beams initially loaded at 7-days age. Values in parentheses are from tests started at 28-days or later
(c) w/c is water-cement ratio
w/(c + p) is water-cement plus pozzolan ratio

This sudden thermal shock can cause surface cracking.

Identical circumstances will arise with the approach of the cooler autumn months or the filling of a reservoir with cold runoff. Abrupt and substantial drops in air temperature will cause the near-surface gradient to suddenly steepen, resulting in tensile strains that are nearly 100 percent restrained. Exposed unformed concrete surfaces are also vulnerable.

These critical conditions are mostly avoided during the second and subsequent cold seasons because much of the heat has been lost from the interior concrete and the temperature gradient in the vicinity of the surface is much less severe.

CHAPTER 3 - PRECOOLING SYSTEMS

3.1-General

The possibility of cracking from thermal stresses should be considered both at the surface and within the mass. One of the strongest influences on the avoidance of thermal cracking is the control of concrete placing temperatures. Generally, the lower the temperature of the concrete when it passes from a plastic or as-placed condition to an elastic state upon hardening, the less will be the tendency toward cracking. In massive structures, each 10 F (6 C) lowering of the placing temperature below the average air temperature will result in a lowering by about 6 F (3 C) of the maximum temperature the concrete will reach.

Under most conditions of restraint, little significant stress (or strain) will be developed during and for a short time after the setting of the concrete. The compressive effects of the initial high temperature rise are reduced to near zero stress conditions due to lower modulus of elasticity and high creep rates of the early age concrete. The zero-stress condition occurs at some period in time near the peak temperature. A concrete placing temperature may be selected such that the potential tensile strain resulting from the temperature decline from the initial peak value to the final stable temperature does not exceed the strain capacity of the concrete. The procedure is described by the following relationship:

$$T_i = T_f + \frac{100 \times C}{e_t \times R} - At$$

where

T_i = placing temperature of concrete
T_f = final stable temperature of concrete
C = strain capacity (in millionths)
e_t = coefficient of thermal expansion per deg of temperature (in millionths)
R = degree of restraint (in percent)
At = initial temperature rise of concrete

The object of the precooling program is to impose a degree of control over crack-producing influences of concrete temperature changes. The designer should know the type and extent of cracking that can be tolerated in the structure. Proper design can accommodate anticipated cracking. In most circumstances it is unrealistic to expect cracking not to occur, so provisions must be implemented to deal with cracking. The benefits of temperature control and other crack control measures have been demonstrated during the construction of large concrete dams and similar massive structures.

3.2 - Heat exchange

3.2.1 *Heat capacities* - The heat capacity of concrete is defined as the quantity of heat required to raise a unit mass of concrete 1 degree in temperature. In those systems of units where the heat capacity of water is established as unity, heat capacity and specific heat are numerically the same. The specific heat of concrete is approximately 0.23 Btu/lb deg F (0.963 kJ/ kg K); values for components of the mixture range from a low of about 0.16 (0.67) for some cements and aggregates to 1.00 (4.18) for water. The temperature of the mixed concrete is influenced by each component of the mixture and the degree of influence depends upon the individual component's temperature, specific heat, and proportion of the mixture. Because aggregates comprise the greatest part of a concrete mixture, a change in the temperature of the aggregates will effect the greatest change (except where ice is used) in the temperature of the concrete. Since the amount of cement in a typically lean mass concrete mixture is relatively small its cooling may not be significant to a temperature control program.

For convenience, the concrete batch and the components of the concrete batch can be considered in terms of a water equivalent, or the weight of water having an equivalent heat capacity. An example of 1 cu yd of mass concrete and its water equivalent follows:

Ingredient	Batch weight	Specific heat capacity	Batch heat content	Water equiv-aient
	lb	Btu/lb-deg F	Btu/deg F	lb
Coarse aggregate	2817	0.18	507	507
1 percent moisture	28	1.00	28	28
Fme aggregate	890	0.18	160	160
5 percent moisture	45	1.00	45	4.5
Cement	197	0.21	41	41
Fly ash	85	0.20	17	17
Batched water	139	1.00	139	139
	4201		937	937

An example of a 1 m^3 mass concrete mixture and its water equivalent follows:

Ingredient	Batch weight	Specific heat capacity	Batch heat content	Water equiv-aient
	kg	kI/kg-deg K	kJ/deg K	kg
Coarse aggregate	1672	0.75	1254	300
1 percent moisture	17	4.18	71	17
Fine aggregate	528	0.75	396	95
5 percent moisture	26	4.18	109	26
Cement	117	0.88	103	25
Fly ash	50	0.84	42	10
Batch water	82	4.18	343	82
	2492		2318	5.55

In other words, 1 cu yd of this concrete would require the same amount of cooling to reduce (or heating to raise) its temperature 1 F as would be required by 937 lbs of water. Similarly, 1 m^3 of this concrete would require the same amount of cooling (or heating) to change its temperature 1 C as would be required by 555 kg of water.

3.2.2 *Computing the cooling requirement*-Assume that a 50 F (10 C) placing temperature will satisfy the design criteria that have been established. From the temperatures of the concrete ingredients as they would be received under the most severe conditions, a computation can be made of the refrigeration capacity that would be required to reduce the temperature of the mixture to 50 F (10 C). Using the same mass concrete mixture, the refrigeration requirement per cu yd can be computed as follows:

Ingredient	Initial temp	Degrees to 50 F	Water equivalent	Btu's to 50 F
	deg F	deg F	lb	Btu
Moist coarse agg	75	25	535	13375
Moist fine agg	73	23	205	4,715
Cement	120	70	41	2,870
Fly ash	73	23	17	391
Batched water	70	20	139	2,780
Heat of mixing (est)				1,000
			937	25,131

Refrigeration required for a 1 m^3 mixture as follows:

Ingredient	Initial temp	Degrees to 10 C	Water equivalent	kJ[(a)] to 10 c
	deg C	deg C	kg	kJ
Moist coarse agg	24	14	300	17,556
Moist fine agg	23	13	121	6,575
Cement	49	39	25	4,076
Fly ash	23	13	10	543
Batched water	21	11	82	3,770
Heat of mixing (est)				1390
			538	33,910

(a) Product of (deg to 10 C) x (water equivalent) x (4.18)

It will be observed that if this concrete is mixed under the initial temperature conditions as set forth, the mixed temperature of the concrete will be:

US

$$50\ F + \frac{25{,}131\ \text{Btu}}{937\ \text{Btu/deg}\ F} = 50\ F + 27\ F = 77\ F$$

SI units [(b)]:

$$10\ C + \frac{33{,}910\ kJ}{2{,}318\ kJ/deg\ K} = 10\ C + 15\ C = 25\ C$$

(a) U.S. **Customary Units**
(b) **Systeme Internationale Units**

To lower the temperature of the concrete to 50 F (10 C), it would be necessary to remove 25,131 Btu (33,910 kJ) from the system. The temperature of mixed concrete can be lowered by replacing all or a portion of the batch water with ice, or by precooling the components of the concrete. In this example a combination of these practices would be required.

3.2.3 *Methods of precooling concrete components* - The construction of mass concrete structures, primarily dams, has led to improved procedures for reducing the temperature of the concrete while plastic with a resultant lessening of cracking in the concrete when it is hardened.

Concrete components can be precooled in several ways. The batch water can be chilled or ice can be substituted for part of the batch water. In this event, attention should be given to addition of admixtures and adjusting mixing times. Aggregate stockpiles can be shaded. Aggregates can be processed and stockpiled during cold weather. If the piles are large, only the outside exposed portion will heat up any significant amount when warm weather occurs, preserving the colder interior for initial placements. Fine aggregates can be processed in a classifier using chilled water. Methods for cooling coarse aggregates, which provide the greatest potential for removing heat from the mixture, can range from sprinkling stockpiles with water to provide for evaporative cooling, spraying chilled water on aggregates on slow-moving transfer belts, immersing coarse aggregates in tanks of chilled water, blowing chilled air through the batching bins, to forcing evaporative chilling of coarse aggregate by vacuum. While the most common use of nitrogen is to cool the concrete in the mixer, successful mixture cooling has resulted from nitrogen cooling of aggregates and cooling at concrete transfer points. Introduction of liquid nitrogen into cement and fly ash during transfer of the materials from the tankers to the storage silos has also been effective (Forbes, Gillon, and Dunstun, 1991). Combinations of several of these practices are frequently necessary.

3.3 - Batch water

The moisture condition of the aggregates must be considered not only for batching the designed concrete mixture, but also in the heat balance calculations for control of the placing temperature. The limited amount of water normally required for a mass concrete mixture does not always provide the capacity by itself to adequately lower the temperature of the concrete even if ice is used for nearly all of the batch water.

3.3.1 *Chilled batch water*-One lb (one kg) of water absorbs one Btu (4.18 kJ) when its temperature is raised 1 F (1 C). A unit change in the temperature of the batch water has approximately five times the effect on the temperature of the concrete as a unit change in the temperature of the cement or aggregates. This is due to the higher specific heat of water with respect to the other materials. Equipment for chilling water is less complicated than ice-making equipment. Its consideration is always indicated whether solely for chilling batch water or in combination with other aspects of a comprehensive temperature control program, i.e., inundation cooling of coarse aggregates, cold classifying of fine aggregate, or post-cooling of hardened concrete with embedded cooling coils.

It is practical to produce batch water consistently at 35 F (2 C) or slightly lower. Using the mass concrete mixture discussed above, chilling the 139 lb (82 kg) of batch water from 70 F (21 C) to 35 F (2 C) will reduce the concrete temperature about 5 F (3 C).

This can be readily computed by multiplying the pounds of batch water by the number of degrees the water temperature is reduced and dividing the whole by the water equivalent of the concrete. For the illustration mix, this would be as follows:

US units:

$$\frac{139\ (lb) \times (70\ F - 35\ F)}{937\ \textit{water equivalent}\ (lb)} = 5.2\ F$$

SI units:

$$\frac{82\ (kg) \times (21\ C - 2\ C)}{555\ \textit{water equivalent}\ (kg)} = 2.8\ C$$

3.3.2 *Using ice as batch water*-One lb (kg) of ice absorbs 144 Btu's (334 kJ) when it changes from ice to water; thus, the use of ice is one of the basic and most efficient methods to lower concrete placing temperatures.

The earliest method involved the use of block ice that was crushed or chipped immediately before it was batched. Later methods utilized either ice flaking equipment, where ice is formed on and scraped from a refrigerated drum that revolves through a source of water; or equipment where ice is formed and extruded from refrigerated tubes and is clipped into small biscuit-shaped pieces as it is extruded.

It is important that all of the ice melts prior to the conclusion of mixing and that sufficient mixing time is allowed to adequately blend the last of the melted ice into the mix. Where aggregates are processed dry, this may mean adding no more than 3/4 of the batch water as ice. Where aggregates are processed wet, there will normally be enough moisture on the aggregates to permit almost all of the batch water to be added as ice with just enough water to effectively introduce any admixtures. If the entire 139 lb (82 kg) of batch water in the illustration mixture is added as ice, the effect of the melting of the ice would lower the temperature of the concrete by 21 F (12 C), computed as follows:

Us units:

$$\frac{139\ (lb) \times 144\ (Btu/lb)}{937\ \textit{water equivalent}(lb) \times (1.0\ Btu/lb\ deg\ F)} = 21.4\ F$$

SI units:

$$\frac{82\ (kg) \times 334\ (kJ/kg)}{555\ \textit{water equivalent}\ (kg) \times (4.18\ kJ/kg \cdot deg\ K)} = 11.8C$$

3.4- Aggregate cooling

Although most rock minerals have a comparatively low unit heat capacity, aggregates comprise the greatest proportion of concrete mixtures. Therefore, the temperature of the aggregates has the greatest influence on the temperature of the concrete. Under the most severe temperature conditions of construction, the objectives of a comprehensive temperature control program cannot be achieved without some cooling of the concrete aggregates.

3.4.1 *Cold weather aggregate processing*-Generally on large conventional mass concrete projects, aggregate processing occurs concurrently with concrete production and placement, Projects constructed of RCC, have required large proportions of the concrete aggregate to be processed and stockpiled prior to the commencement of placement operations. The RCC placement occurs at a much faster rate than does aggregate production. Significant aggregate temperature reductions can be realized by processing such aggregate during the colder winter season at locations where a marked winter season occurs. The use of large stockpiles and selective withdrawal of aggregates from the stockpiles can reduce the in-place temperatures of the concrete significantly. Additional thermal considerations for RCC are discussed by Tatro and Schrader (1985).

3.4.2 *Processing fine aggregate in chilled water*-Probably the most efficient way to cool fine aggregate is to use chilled water in the final classification of the fine aggregate. The effluent water from the classifier is directed to a settling tank to drop out excess fines and the water is returned to the cooler and then back to the classifier. Fine aggregate is readily cooled by this method, it gains heat quite slowly following wet classification because of the moisture it carries and the possibility for evaporation. By this method, fine aggregate can be consistently produced at temperatures between 40 F (4 C) and 45 F (7 C).

If the entire 935 lb/cu yd (554 kg/m^3) of fine aggregate (including moisture) of the illustration mixtures is reduced to 45 F (7 C) from its 73 F (23 C) temperature, the result would be a lowering of the concrete temperature by about 6 F (4 C), computed as follows:

US units:

$$\frac{205\ \textit{moist F.A water equiv (lb)} \times (73\,F - 45F)}{937\ \textit{concrete water equiv (lb)}} = 6.1F$$

SI units:

$$\frac{121\ \textit{moist FA. water equiv (kg)} \times (23C - 7C)}{555\ \textbf{concrete water equiv (kg)}} = 3.5C$$

Hollow-screw heat exchangers for contact cooling of fine aggregate have not proven as effective as has classification with chilled water.

3.4.3 *Sprinkling of coarse aggregate stockpiles*-Misting or sprinkling water onto coarse aggregate stockpiles is an inexpensive but limited means of reducing coarse aggregate temperatures. The amount of cooling that can be obtained depends upon the cooling effect of natural evaporation, which in turn, depends upon the ambient conditions of temperature, wind, and relative humidity. Adequate drainage should be provided beneath the stockpiles. Only enough water to meet evaporation rates is necessary. In very large stockpiles only the areas from which material is being withdrawn need to be sprinkled.

3.4.4 *Immersion cooling of coarse aggregate*-one of the most effective ways to cool coarse aggregate is immersion in holding tanks through which chilled water is circulated. The tanks are open at the top with a conical bottom leading to a watertight aggregate discharge gate. The water is piped into and out of the tanks for filling and circulation. The cooling cycle consists of filling the tank with chilled water, dumping the coarse aggregate into the tank, circulating the chilled water through the aggregate, draining water from the tank, and discharging the aggregate from the bottom gate. The aggregate is discharged onto a conveyor belt and fed over a vibrating screen to remove excessive moisture. With this method using 35 F (2 C) water, even the larger 6 in. (152 mm) top size cobbles for mass concrete can be cooled to about 38 F (3 C) with a circulating time of 45 min. However, the complete cycle including filling and discharging would be about 2 hr. Separate tanks, up to 125 tons (113 Mg) capacity, have been used for each size of coarse aggregate.

If the entire 2845 lb (1689 kg) of coarse aggregate (including moisture) of the illustration mixture is reduced to 38 F (3 C) from its 75 F (24 C) temperature, it would result in a lowering of the concrete temperature by about 20 F (12 C), computed as follows:

US units:

$$\frac{507\ \textit{moist C.A. water equiv (lb)} \times (75F - 38F)}{937\ \textit{concrete water equiv(lb)}} = 20.0F$$

SI units:

$$\frac{317\ \textit{moist C.A. water equiv(kg)} \times (24C - 3C)}{555\ \textit{concrete water equiv(kg)}} = 12.0C$$

3.4.5 *Chilled water spray* - Cooling the coarse aggregate while on the belt conveyor enroute to the batch bins by spraying with 40 F (4 C) water may be necessary to supplement the use of ice in the batch water. For practical reasons, the duration of the spray application is limited to a few minutes (possibly 2 to 5) while on the belt, resulting in removal of heat only from near the surfaces of the individual pieces of aggregate. Data on the exact amount of heat removed under specific conditions of belt speed, temperature, and rate of water application are not readily available. On one large mass concrete project, 150 gal. of chilled water per ton of coarse aggregate was required (in addition to other precooling techniques) to produce 45 F (7 C) concrete. Waddell (1978) gives data on cooling rates of large size aggregate.

A system for removing excess water before discharge into the batch bins is essential. Blowing chilled air through the cool and damp aggregate in the bins will further lower its temperature, but careful control is required to avoid freezing the free water.

3.5.6 *Vacuum cooling of aggregates*-Vacuum cooling of aggregates utilizes (a) the lower boiling point of water when under less than atmospheric pressure, and (b) the large heat absorptive capacity of water when it changes from liquid to vapor. Fine aggregates and all sizes of coarse aggregates can be effectively cooled by this method. The aggregates must be processed moist, or contain sufficient water to absorb the amount of heat it is desired to extract from the aggregates. Steel silos or bins, with capacities from 100 to 300 tons each (91 to 272 Mg) of aggregate exposed to a vacuum of 0.25 in. (6 mm) of mercury, will usually provide for a reduction of initial temperatures of 110 F (43 C) to a final average temperature of 50 F (10 C) over a 45-min operational cycle.

This method utilizes the free moisture on the aggregates for the evaporative cooling. The moist aggregates are fed into a pressure vessel that can be sealed at both the top inlet and the bottom outlet. Vacuum is applied from a side chamber by steam-fed diffusion pumps.

Again using the illustration mixture, if the 1 percent surface moisture carried by the coarse aggregates is evaporated, the temperature of the coarse aggregates will be lowered by about 54 F (31 C), or down to about 20 F (-8 C), computed as follows:

us units:

$$\frac{28\,(lb) \times 1040\,(Btu/lb)}{535 \text{ moist CA. water equivalent } (lb) \times 1.0\,(Btu/lb \cdot deg\ F)} = 54.4\,F$$

SI units:

$$\frac{17\,(kg) \times 2420\,(kJ/kg)}{317 \text{ moist CA. water equivalent } (kg)\ 4.18\ (kJ/kg \cdot deg\ K)} = 31.0\,C$$

In this illustration, the heat of vaporization of water at 0.25 in. (6 mm) of mercury is approximately 1040 btu/lb (2420 kJ/kg).

As a result of this cooling of the coarse aggregate, the temperature of the concrete would be lowered by about 31 F (18 C), computed as follows:

us units:

$$\frac{28\,(lb) \times 1040\,(Btu/lb)}{937 \text{ concrete water equivalent } (lb) \times 1.0\,(Btu/lb \cdot deg\ F)} = 31.1\,F$$

SI units:

$$\frac{17\,(kg) \times 2420\,(kJ/kg)}{555 \text{ concrete water equivalent } (kg) \times 4.18\ (kJ/kg \cdot deg\ K)} = 17.7\,C$$

3.4.7 *Liquid nitrogen*-An alternate method for cooling batch water and creating an ice/water mixture employs liquid nitrogen, an inert cryogenic fluid with a temperature of -320 F (-196 C) (*Concrete Construction,* May 1977, p. 257).

From a cryogenic storage tank located at the batch plant, the liquid nitrogen is injected through lances directly into the batch water storage tank to bring the water temperature down to 33 F (1 C). To promote greater cooling of the concrete, liquid nitrogen is injected into the water in a specially designed mixer just prior to the water entering the concrete mixer, whereby the liquid nitrogen causes a portion of the water to freeze. The amount of ice produced can be varied to meet different temperature requirements.

Liquid nitrogen systems have proven successful on a number of construction projects, particularly where automatic or flexible operation control is beneficial. Local availability must be considered, and cooling to temperatures below about 60 F (16 C) is currently not feasible. Liquid nitrogen has also been injected directly into mixer drums. This approach may require that the mix time be prolonged from several minutes to 10 minutes before significant cooling results.

3.5 - Cementitious materials

Cementitious materials used in concrete must be handled dry. If the temperature of the cement is brought down below the dew point of the surrounding atmosphere, moisture can condense and adversely affect the ultimate quality of the cement. As a general rule, the concrete mixture heat balance does not require cooling of the cement in order to meet the placing temperature requirements. Normally, cement is delivered at a temperature of about 130-155 F (54-68 C). The cement temperature can be increased or decreased a few degrees depending on the cement handling equipment and procedures used. However, since cement is such a relatively small portion of mass concrete mixtures, its initial temperature has little effect on the concrete temperature. Also, cooling the cement is not very practical or economical.

3.6-Heat gains during concreting operations

Considerations for temperature control should recognize the heat gains (or losses) of the concrete or the concrete ingredients during batch plant storage, during concrete mixing, and during the transportation and placement of the concrete. The placement of a large mass concrete structure can be visualized as a rapid sequence of procedures all of which are guided by several overall objectives not the least of which is to protect the concrete from any avoidable heat gain.

Ingredients can be protected against heat gain at the batch plant by means such as insulation, reflective siding, air conditioning, and circulation of chilled air through coarse aggregates. The energy required for the mixing of concrete imparts about 1000 Btu (1390 kJ) of heat per cu yd (m^3) of concrete. Where a project plant is conveniently set up to permit rapid bucket transport and placement, there will be an insignificant temperature gain between mixing and placement of the concrete. However, to account for delays and inconvenient placements, it may be judicious to include in the heat balance computation a small contingency for heat gain between mixing and placement.

3.7 - Refrigeration plant capacity

The size of the cooling plant required, expressed in tons of refrigeration, is given by

$$\frac{\text{Maximum concrete placing rate } (yd^3/h) \bullet \text{ heat to be removed (Btu/yd)}}{12{,}000 \text{ Btu/h}}$$

Because the temperatures of the aggregates will generally follow the annual cycle of ambient air temperatures, a refrigeration plant capacity requirement should be determined for specific segments of time, such as a week or a month. The refrigeration plant may be designed for the cooling of only one material, such as production of ice, or may be divided into various cooling systems for production of ice, chilled water and/or cooled air according to heat balance needs. A trial procedure for deriving the amount of ice required to satisfy a given initial temperature of 60 F (16 C) is shown in the accompanying Trial Heat Balance illustration, for the mixture proportions cited in Paragraph 3.2.1, with 79 lbs (47 kg) of ice and 60 lbs (35 kg) of chilled water.

Trial Heat Balance

Ingredient	Temperature as batched	Temperature after mixing	Water equivalent	Heat exchanged
	deg F	deg F	lb	Btu
Coarse aggregate (moist)	75	60	535	8,025
Fine aggregate (moist)	73	60	205	2,665
Cement	120	60	41	2,460
Fly ash	73	60	17	221
Heat of mixing				1,000
				14571
Batched water				
Ice	32	144[a]	79	-11,376
Ice (melted)	32	60	79	-2,212
Water (chilled)	35	60	60	-1,500
				-15,088

[a] Units of heat required to change one lb of ice at 32 F to water at same temperature.

Trial Heat Balance

Ingredient	Temperature as batched	Temperature after mixing	Water equivalent	Heat exchanged
	deg C	deg C	kg	kJ
Coarse aggregate (moist)	24	16	300	10,032
Fine aggregate (moist)	23	16	121	3,520
Cement	49	16	25	3,448
Fly ash	23	16	10	293
Heat of mixing				1,390
				18,703
Batched water				
Ice	0	334[a]	47	-15,698
Ice (melted)	0	16	47	-3,143
Water (chilled)	2	16	35	-2,048
				-20,889

[a] Units of heat required to change one kg of ice at 0 C to water at the same temperature.

3.8 - Placement area

During hot weather, precooled concrete can absorb ambient heat and solar radiation during placement, which will increase the effective placing temperature and the resulting peak temperature. This increase in temperature can be minimized or eliminated by reducing the temperature in the immediate placing area with fog spray and/or shading. Placing at night will also reduce the effects of hot weather and radiant heat.

CHAPTER 4 -POST-COOLING SYSTEMS

4.1-General

Control of concrete temperatures may be effectively accomplished by circulating a cool liquid (usually water) through thin-walled pipes embedded in the concrete. Depending on the size of the pipe, volume of fluid circulated, and the temperature of the fluid, the heat removed during the first several days following placement can reduce the peak temperature by a significant amount. The post-cooling system also accelerates the subsequent heat removal (and accompanying volume decrease) during early ages when the elastic modulus is relatively low.

The radial temperature isotherms developed around each cooling pipe create a complex, nonuniform, and changing thermal pattern. Smaller pipes with colder fluid create a more severe local condition than larger pipes with a less cold fluid. Under conditions of rapid and intense cooling, this could result in localized radial or circumferential cracks. Up to the age at which the maximum concrete temperature in the vicinity of the pipe occurs, no restriction on cooling rate is needed. After an initial peak concrete temperature has been experienced, cooling is usually continued until the first of these conditions occur:

a) The concrete cooling rate reaches the maximum that can be tolerated without cracking (see Paragraph 4.2); or

b) The temperature of the concrete decreases to about 30 F (17 C) below the initial peak value. This is an empirically-derived value (Paragraph 4.4.2) generally substantiated by slow strain capacity tests (Table 2.8).

c) The concrete has been cooled to its final stable temperature or an intermediate temperature prescribed by the designer.

The duration of this initial cooling period may be as short as several days or as long as one month. Subsequently the concrete temperature usually will increase again. If the increase is significant, one or more additional cooling periods will be necessary. Experience has shown that supplementary cooling operations can safely reduce the concrete temperatures to below a final stable value, or to a point that creates joint openings of ample width to permit grouting, if required. Cooling rates, in degrees per day, for these later periods should be lower than that permitted during the initial period because of the higher modulus of elasticity at later ages. Other methods such as evaporative cooling with a fine water spray, cool curing water, and shading may prove beneficial, but the results are variable and do not greatly affect the interior of massive placements, when the ratio of exposed surface area to volume is less than about 0.3 ft^{-1} or 1.0 m^{-1}. For example, a 3 ft (0.9 m) thick lift with only the top surface exposed for evaporative cooling would have a surface area to volume ratio of 0.33 ft- (1.1 m^{-1}).

4.2 - Embedded pipe

4.2.1 *Materials*-Aluminum or thin-wall steel tubing, 1 in. (25.4 mm) nominal outside diameter and 0.06 in. (1.5 mm) wall thickness, has been used successfully for embedded cooling coils. Plastic and PVC pipe may also be used. Couplings of the compression type used to join sections of aluminum or steel tubing should be of the same material or nonconductor sleeves and gaskets should be provided to avoid the galvanic effect of dissimilar metals. Aluminum tubing has an advantage of light weight and easy installation, but is subject to breakdown and leakage due to reaction with alkalies in the cement. When the expected active cooling period exceeds three months, aluminum should not be used. In mass concrete dam construction there have been no well-documented instances reported where the long-term effects of aluminum tubing deterioration has caused distress in the concrete; but should be avoided where absolute integrity over the life of the structure is imperative and possible leakage could be critical.

4.2.2 *Spacing*-For practical reasons, pipe coils are usually placed directly on and tied to the top of a hardened concrete lift. Thus, the vertical pipe spacing typically corresponds to the lift height. A horizontal spacing the same as the vertical spacing will result in the most uniform cooling pattern, but variations may be utilized.

Figure 5.4.2(a) through 5.4.2(c) of ACI 207.1R can be used as a guide to establish pipe spacings and amount of cooling necessary for the temperature control desired.

4.2.3 *Pipe loop layout*-Individual pipe runs may range from 600 ft to about 1200 ft in length (183 m to 366 m), with 800 ft (244 m) being a target value for design purposes. Splices within the pipe runs should be minimized as much as practical.

Pipe loops served by the same coolant distribution manifold should be approximately the same length so as to equalize the flow and cooling effect.

Tie-down wires should be embedded in the lift surfaces prior to final set. Additional tie-down wires should be placed on either side of splices to help prevent the couplings from working loose. Each pipe loop should be leak-tested before the covering concrete is placed. Each pipe run should include a visual flow indicator on the loop side of the supply or return manifold. To assure the initiation of cooling at the earliest age, to minimize damage to the emplaced pipe, and to help keep the pipe from floating in the fresh concrete, water circulation should be in progress at the time concrete placement begins in the covering lift.

4.3 - Refrigeration and pumping facilities

4.3.1 *Pumping plant*-Pumping plant requirements are determined from the number of pipe coils or loops in operation, which in turn may be established from the lift-by-lift construction schedule. The flow rate for each coil typically is from 4 to 4.5 gallons (15 to 17 liters) per minute, which for a 1 in (25 mm) diameter pipe, will result in a fluid velocity about four times the minimum necessary to insure turbulent flow conditions. Turbulent flow within the coil increases the rate of energy transfer between the fluid particles, therefore increasing the rate of heat flow by convection. Cooling water used in the system, particularly if from a river or similar untreated source, should be filtered to remove sediment so as to reduce the possibility of system stoppages at bends, constrictions, or control valves. Unless the length of the cooling run is short, flows through the coils should be reversed at least daily, automatically or manually, by valved cross-connections at the pumping plant or at the supply/return manifolds serving each bank of individual pipe coils. Insulating the exposed supply and return pipe runs will help ensure the desired water temperatures at the manifold locations. Sizing of the distribution system segments and head loss allowances should follow customary design procedures.

4.3.2 *Refrigeration plant*-The size and number of refrigeration plant components should be based on the maximum requirements (number of coils in operation at the same time and a coil inlet temperature established by the design criteria) and the need for flexibility over the expected duration of the concrete cooling operations. Chilled water as low as 37 F (3 C) has been used for post-cooling. Where lower coolant temperatures are required, a chilled mixture of 70 percent water and 30 percent antifreeze (Propylene glycol) has been effectively used at 33 F (1 C). Details of compressors, condensers, surge tanks, valves, meters, and other production and control items, for either portable or stationary plant, are mechanical engineering functions not covered in this report.

4.3.3 *Alternate water cooling practices*-Cool water from natural sources, such as wells or flowing streams, may be used as the coolant, providing the supply is adequate, the temperature is reasonably constant, and the water contains only a slight amount of suspended sediment. Manifolds, valves, gages, and loop bends are particularly vulnerable to stoppages if dirty water is used.

Water discharged back into a stream or well will be slightly warmer after circulation through the cooling pipes, and may require permits in conformance with local or national environmental codes. In favorable climates conventional cooling towers utilizing the evaporative cooling effect rather than refrigeration could be feasible.

4.4-Operational flow control

4.4.1 *Manifolds*-Supply and return headers or riser pipes should be tapped at convenient intervals with fittings for attaching manifolds to serve each bank of cooling coils. Flexible connectors with adapters and universal type hose couplings are recommended.

4.4.2 *Cooling rates*-Charts or isothermal diagrams, showing the expected final stable temperature distribution within the fully-cooled structure, provide temperature objectives for scheduling coil flow operations. During the period of early rapid heat generation and temperature rise, pipe cooling may be carried out as vigorously as the capacity of the system will permit. In general, when the concrete has reached its peak temperature, cooling should be continued for a period of about 1 to 2 weeks at a rate such that the concrete temperature drop generally does not exceed 1 F (0.6 C) per day (the maximum rate that does not exceed the early age tensile strain capacity with creep). A cooling rate of 2 F (1 C) per day can sometimes be tolerated, but only for a short period of time.

When the desired rate of temperature drop is exceeded, post-cooling operations in that bank of pipe coils should be interrupted until the temperature rises again. Cooling should be resumed when the concrete temperature exceeds the initial peak temperature and is predicted to continue to increase to unacceptable levels.

Experience has shown that most mass concretes having average elastic and thermal expansion properties can resist cracking if the temperature drop is restricted to 15 F to 30 F (8 C to 17 C) over approximately a 30-day period immediately following its initial peak.

4.4.3 *Repairs during placement*-The pipes can be damaged during concrete placement by the concrete itself, concrete buckets being dropped on it, vibrators, etc. Extra sections of pipe and couplings should be readily available in the event that a pipe is damaged during placement. The freshly placed concrete around the damaged pipe should be removed, the damaged section cut out, and a new section spliced onto the existing undamaged pipe. It is important that all of the damaged pipe be removed so that it will not restrict flow through the pipe.

4.4.4 *Temperature monitoring*-A history of concrete cooling should be maintained, using resistance thermometers or thermocouples installed at representative locations within the concrete including locations close to each pipe and midway between the pipes. Vertical standpipes embedded in the concrete and filled with water can also be used to measure the concrete temperature within selected zones. A thermometer is lowered into the standpipe to the desired elevation and held there until the reading stabilizes. Water temperatures at supply and return manifolds will also serve as a check on the amount of heat being removed from the concrete.

4.5- Surface cooling

Cooling the surfaces of a thick or massive concrete structure can be a useful crack-control practice (Carlson and Thayer, 1959). The objective of surface cooling is to create a steep, but tolerable, thermal gradient adjacent to the exposed vertical surfaces concurrently with the placing of the concrete, and to maintain the cooling a minimum of 2 weeks. The optimum period determined theoretically for a "typical" mass concrete placement is about 3 weeks. By developing an initial zero-stress condition at a low temperature, subsequent tensile strains (and stresses) due to further ambient temperature drops are reduced.

Three construction methods are: (a) circulating refrigerated water within double-walled steel forms left in place for the 3-week period, (b) discharging used cooling water from the bottom of hollow forms for the balance of the 3-week period after being raised for the next lift of concrete; and (c) a near-surface embedded pipe cooling system. The surface must not be cooled at a rate causing surface cracks that may later propagate into the mass concrete.

4.5.1 *Forms*-Where noninsulated metal forms are used, some beneficial effects can be achieved by spraying with cold water and by shading.

4.5.2 *Curing water*-Shading and water curing of formed and finished surfaces can be conducted to cool directly, with the added benefit of evaporative cooling, in some regions. On horizontal surfaces the curing should be controlled so that no water remains on the surface long enough to become warm.

CHAPTER 5 - SURFACE INSULATION

5.1-General

As mass concrete is deposited in the forms, its temperature begins to rise as a result of the hydration of the cementitious materials. With lifts of 5 ft (1.5 m) or greater and lateral form dimensions of about 8 to 10 ft (2.4 to 3 m) the temperature rise is essentially adiabatic in the central part of the mass of fresh concrete. At the exposed surfaces (formed or unformed) the heat generated is dissipated into the surrounding air at a rate dependent upon the temperature differential; therefore, the net temperature rise in the concrete adjacent to the surface (or forms) is less than in the interior. While this results in a gradually increasing temperature gradient from the surface to the interior, little or no stress (and strain) is developed because the concrete is not yet elastic. Generally lean mass concrete exhibits only a slight degree of rigidity from 4 to 8 hrs after placing depending upon the placing temperature, initial heat control, and cement characteristics. During the next 16 to 20 hrs the cement hydration rate normally increases substantially with the concrete passing from a plastic state to plastic-elastic state until at about 24 hr age the concrete begins to act in an elastic manner. During this first day the modulus of elasticity of the concrete is low and its creep is high, with the net result that the stresses (and strains) are essentially zero.

5.1.1 *Stress development*-Before initial set of concrete, the temperature gradient or thermal change causes little or no stress or strain. As the concrete begins to acquire strength and elasticity, changes in the temperature gradient result in length and volume changes which are partially restrained within the structure itself. Statically balanced tensile and compressive stresses are developed.

5.1.2 *Strength development*-The rate of strength gain is closely related to both the time and the temperature at which the hydration is taking place. Measured by compression, tensile splitting, and penetration tests, most conventional mass concrete will exhibit a slight degree of rigidity 4 and 8 hrs after placing when mean hydration temperature conditions of 90 F and 50 F (32 C and 10 C), respectively, exist. High pozzolan, low cement, highly retarded, and/or very cold mixtures may not develop any rigidity or significant hydration heat for an extended time (12 to 50 hrs). After acquiring this initial elasticity, the rate of change in strength development increases substantially over the next 16 to 20 hrs. Thus at a nominal 24-hr age, mass concrete begins to respond elastically in a generally predictable manner.

5.1.3 *Temperature gradients*-Development of steep thermal gradients near exposed surfaces during early ages while the modulus of elasticity is very low is usually not a serious condition. Low ambient temperatures during the initial 24 hrs may indeed be helpful by establishing a steep gradient at an early age before the concrete responds to stress-strain relationships. After the concrete hardens and acquires elasticity, decreasing ambient temperatures and rising internal temperatures work together to steepen the temperature gradient, and widen the stress difference between the interior and the surface. On any sectional plane the summation of internal forces must be zero. This results in a high unit tensile stress in the region of the exposed surfaces and a comparatively low unit compressive stress over the extensive interior areas. Hence a small temperature increase in the interior will cause a slight increase in compression over a large area, but will also cause a corresponding large increase in tension stress near the surface in order to maintain a zero total net force system.

As the rate of hydration slows, ambient temperature alone becomes the significant parameter, and becomes most serious at the downward sloping part of the annual temperature cycle. The effect is further intensified by short abrupt drops in ambient temperatures, which tend to be more prevalent at night and during the fall season.

5.2--Materials

The degree of protection required to avoid or reduce significantly the thermal tensile stresses at concrete surfaces can be determined theoretically and has been demonstrated in practice. A thermal resistance (R-value) of 4.0 **hr•sq ft•deg** F/Btu (0.70 sq **m•deg** K/W) has been found to be effective for moderate climates. This is provided by a 1 in. thickness of expanded synthetic material such as polystyrene or urethane, whose thermal conductivity is of the order of 0.20 and 0.30 Btu in/h sq ft deg F (0.03 to 0.04 W/m-K). The closed-cell structure of this type material is advantageous in minimizing water absorption and capillarity. Mineral wool blankets are not as effective, usually requiring additional thickness to achieve the same amount of protection. Single-ply polyethylene enclosures that remain sealed and provide a static air space between the outside environment and the concrete surface are usually less effective but more economical.

5.2.3 *Effect of sudden air temperature drop*-The calculated effects on concrete temperatures adjacent to exposed and to insulation-protected surfaces when subjected to rapid air temperature drops are compared in Tables 5.1 and 5.2. Concrete thermal properties used in the calculations were:

Density	4160 lb/yd^3 (2470 kg/m^3)
Conductivity	15.8 Btu in/hr ft^2 deg F (2.28 W/m-K)
Specific Heat	0.22 Btu/lb deg F (0.920 J/kg-K)
Diffusivity	0.039 ft^2/hr (0.0036 m^2/hr)

It was assumed that no heat was being generated within the concrete.

5.3 - Horizontal surfaces

Unformed surfaces of concrete lifts are difficult to insulate effectively because of damage from and interference with construction activities. Maximum efficiency of the insulation requires close contact with the concrete, a condition not usually attainable on rough lift surfaces. Neither ponding of water nor layers of sand have proven to be practical systems for intermediate lifts in multiple-lift construction. Mineral or glass wool blankets or batting, 2 to 4 in. (50 to 100 mm) in thickness, and a number of roll-on flexible rubber-type materials now commercially available provide considerable protection and have been widely used.

Until the next layer of concrete is placed, the need for

Table 5.1 - Effect of insulation protection of concrete exposed to a 28 F (16 C) rapid air temperature drop

Elapsed time hr	Air temp change deg F (deg C)	Concrete temperature changes, deg F (deg C), at various depths, ft (m) 0	1 (0.3)	2 (0.6)	3 (0.9)	6 (1.8)
			No insulation			
12	-14 (-8)	-9 (-5)	-2 (-1)	0	0	0
24	-21 (-12)	-16 (-9)	-5 (-3)	-1 (-1)	0	0
48	-28 (-16)	-24 (-13)	-11 (-6)	-4 (-2)	-1 (-1)	0
72	-28 (-16)	-25 (-14)	-15 (-8)	-7 (-4)	-4 (-2)	0
96	-28 (-16)	-27 (-15)	-17 (-9)	-10 (-6)	-5 (-3)	-1 (-1)
			R-factor 1.00[a]			
12	-14 (-8)	-1 (-1)	0	0	0	0
24	-21 (-12)	-3 (-2)	-1 (-1)	0	0	0
48	-28 (-16)	-9 (-5)	-3 (-2)	-1 (-1)	0	0
72	-28 (-16)	-13 (-7)	-6 (-3)	-2 (-1)	-1 (-1)	0
96	-28 (-16)	-15 (-8)	-8 (-4)	-4 (-2)	-2 (-1)	0
			R-factor 2.0[a]			
12	-14 (-8)	0	0	0	0	0
24	-21 (-12)	-1 (-1)	0	0	0	0
48	-28 (-16)	-2 (-1)	-1 (-1)	0	0	0
72	-28 (-16)	-5 (-3)	-2 (-1)	-1 (-1)	0	0
96	-28 (-16)	-7 (-4)	-3 (-2)	-2 (-1)	-1 (-1)	0
			R-factor 4.0[a]			
12	-14 (-8)	0	0	0	0	0
24	-21 (-12)	0	0	0	0	0
48	-28 (-16)	0	0	0	0	0
72	-28 (-16)	0	0	0	0	0
96	-28 (-16)	-1 (-1)	-1 (-1)	0	0	0

(a) R-value is the thermal resistance of insulation in hr•sq ftdeg F/Btu.

Table 5.2-Effect of insulation protection of concrete exposed to a 46 F (22 C) rapid air temperature drop

Elapsed time hr	Air temp change deg F (deg C)	Concrete temperature changes, dcg F (deg C), at various depths, ft (m) 0	1 (0.3)	2 (0.6)	3 (0.9)	6 (1.8)
			No insulation			
12	-26 (-14)	-17 (-9)	-4 (-2)	0	0	0
24	-39 (-22)	-30 (-17)	-9 (-5)	-2 (-1)	0	0
48	-40 (-22)	-35 (-19)	-18 (-10)	-4 (-4)	-2 (-1)	0
72	-40 (-22)	-37 (-21)	-22 (-12)	-11 (-6)	-5 (-3)	0
96	-40 (-22)	-37 (-21)	-25 (-14)	-14 (-8)	-8 (-4)	-1 (-1)
			R-factor 1.00[a]			
12	-26 (-14)	-2 (-1)	0	0	0	0
24	-39 (-22)	-6 (-3)	-1 (-1)	0	0	0
48	-40 (-22)	-15 (-8)	-5 (-3)	-1 (-1)	0	0
72	-40 (-22)	-19 (-11)	-9 (-5)	-4 (-2)	-1 (-1)	0
96	-40 (-22)	-22 (-12)	-13 (-7)	-6 (-3)	-3 (-2)	0
			R-factor 2.0[a]			
12	-26 (-14)	0	0	0	0	0
24	-39 (-22)	-1 (-1)	0	0	0	0
48	-40 (-22)	-4 (-2)	-1 (-1)	0	0	0
72	-40 (-22)	-8 (-4)	-3 (-2)	-1 (-1)	0	0
96	-40 (-22)	-11 (-6)	-5 (-3)	-2 (-1)	-1 (-1)	0
			R-factor 4.0[a]			
12	-26 (-14)	0	0	0	0	0
24	-39 (-22)	0	0	0	0	0
48	-40 (-22)	-1 (-1)	0	0	0	0
72	-40 (-22)	-2 (-1)	0	0	0	0
96	-40 (-22)	-2 (-1)	-1 (-1)	0	0	0

(a) R-value is the thermal resistance of insulation in hr•sq ftdeg F/Btu.

insulation protection of horizontal surfaces is as great as for formed surfaces, and the insulation should be applied as soon as the concrete has hardened sufficiently to permit access by workmen.

In severe climates application of insulation, by workmen in special shoes, may be required as soon as the concrete has been placed to desired elevation.

The insulation must be removed to permit lift surface clean-up, but should be replaced promptly unless the covering lift is to be placed within a few hours.

5.3.1 *Insulation rating*-Acceptable temperature gradients can be maintained during the winter season in moderate climates by the application of insulation with an R-value of 4.0 $\mathbf{hr \cdot ft^2 \cdot deg}$ F/Btu (0.70 $\mathbf{m^2 \cdot K/W}$). In severe climates insulation with a R-value of 10.0 (1.76) is recommended. Applying several layers of blankets with lower insulative value is recommended instead of one layer of high insulation material. This has the advantage of overlapping the blankets at joints to improve the uniformity of insulation, and it allows gradual removal of the insulation (for example one layer removed every 10 days). Gradual removal minimizes the problems of thermal shock to the surface when the material is removed.

The provisions of ACI 306R, which cautions against placing concrete on frozen foundations, apply equally to horizontal lift surfaces which are at or below 32 F (0 C). Prior to placing new concrete, such surfaces should be allowed to warm to 40 F (5 C) or higher so that the maximum differential temperature between the old concrete and the maximum temperature of the fresh concrete, due to heat of hydration, will not exceed 40 F (5 C). Under rigidly controlled conditions, embedded pipe may be used to circulate warm water to prevent an abrupt change in the concrete temperature gradient and to assure adequate hydration of the cement in the freshly-placed concrete. The amount of heat introduced into the concrete should be the minimum necessary to develop a temperature gradient such that strains will not exceed the strain capacity of the concrete.

5.4-Formed surfaces

Rigid synthetic cellular material in sprayed, board, or sheet form as well as blankets containing closed-cell material are practical methods of insulating. The closed-cell structure of the material results in very low absorption characteristics, and its strength and elastic properties provide adequate rigidity. Generally, foamed materials of this type are somewhat sensitive to heat at about 175 F (80 C), but temperatures of this level are not normally encountered after installation. Most synthetic materials will bum when exposed to open flame, and this is a hazard which should not be overlooked.

5.4.1 *Integral form insulation*-A minimum wood form thickness of 3 in. (75 mm) is necessary to provide the desired level of protection while the forms remain in place. Steel forms offer virtually no insulation protection, and should be supplemented with suitable insulation materials prior to placing concrete. A practical solution is to coat the exterior of reusable steel forms with a spray-on synthetic foam of the necessary thickness.

5.4.2 *Form removal*-Upon removing the forms, either wood or steel, insulation should be promptly installed against the exposed concrete surface. For unexposed formed surfaces, an alternate procedure is to install insulation on the inside of the forms, prior to concrete placement, with wire anchors which will project into the concrete when placed. The insulation then is held in place against the concrete surface when the forms are removed. This method has not been successful on exposed concrete because of surface imperfections caused by the relatively flexible insulation. In no event should the gradual surface temperature drop exceed the values recommended in ACI 306R when protection is removed.

5.5-Edges and corners

Where heat can flow concurrently in two or more directions, rapid temperature drops can occur. This results in the development of tensile strains more quickly at edges and comers than on the sides or tops of the structure. Interior concrete in the vicinity of edges and comers will also be subjected to larger tensile strains sooner than in other portions of the structure.

Increased insulation along the edges and at comers of massive concrete structures has effectively reduced the rate and magnitude of the temperature decline during the cold-weather season. Doubling the insulation thickness (reducing conductance by 1/2 over a distance of from 2 to 4 ft (0.6 to 1.2 m) from the concrete edges and comers is a reasonable provision for a structure of moderate size.

5.6 - Heat absorption from light energy penetration

During construction of Libby Dam by the Corps of Engineers, significantly higher temperatures were measured at the top surfaces of lifts protected by a urethane foam insulation exposed to direct sunlight than when shaded. This phenomena did not occur at Dworshak Dam when such surfaces were protected by layers of black sponge rubber. A limited series of experiments confirmed the conclusion that urethane foam insulation permitted light of some wavelength, probably ultraviolet, to pass through to the concrete surface, where it was converted to heat energy. The tests indicated that a barrier of some type (black polyethylene or aluminum foil) was required to block out the potential light-source energy and avoid augmenting the heat being generated within the concrete.

5.7-Geographical requirements

The period during which insulation is required for protection against thermal cracking depends on the climate and geography. In most of the United States and Canada, and especially in mountainous regions, this period extends from a more or less arbitrary date in autumn, through the winter months, to a spring date when the average ambient air temperature is rising and comparable to that of the selected autumn date. The dates in column A below reflect the seasonal decline in average air temperatures and the probability of abrupt temperature drops associated with short duration cold snaps. The column B dates recognize the beneficial effects of the seasonal air temperature trends and the lessened probability of severe and damaging temperature drops. At very high elevations and at other locations where severe climatic conditions are expected, earlier application dates may be advisable. Suggested dates for general locations in the United States are:

	A	B
	Earliest date needed	Earliest date no longer needed
Northern U.S.	15 September	31 March
Middle U.S.	1 October	15 March
Southern U.S.	15 October	1 March

Surfaces of concrete placed prior to the earliest dates needed in the preceding tabulation are to receive insulation protection no later than the date specified. Formed surfaces of concrete placed during the autumn-to-spring periods should be insulated from the time of placement, and unformed surfaces as soon as practicable following completion of placement.

CHAPTER 6 - EXPECTED TRENDS

6.1-Effects of aggregate quality

It is expected that environmental factors and lack of availability will force the increased use of marginal quality aggregates in concrete. To compensate for aggregate quality, additional cement is usually added which in turn increases the expected temperature rise. For some structures this temperature increase would have little or no effect; for others, it could significantly affect structural properties as well as costs.

6.2 - Lightweight aggregates

Lightweight aggregates have been used in structural concrete specifically for the thermal insulation benefits resulting from low thermal conductivity properties. There has been little if any use of such aggregates to modify the thermal conductivity of mass concrete. The technical and economic feasibility of using a zone of lightweight aggregate concrete adjacent to vertical surfaces, or in precast stay-in-place forms, to control temperatures and temperature gradients, could lead to significant benefits. The strength requirements of concrete for arch dams, and the density needed for gravity locks and dams, would likely preclude the use of these aggregates for entire mass concrete structures.

6.3 - Blended cements

More extensive use of portland-pozzolan and other blended cements in mass concrete for improvement of properties including temperature reduction is occurring where these materials are available and/or their importation is justified. A factor to be considered when using blended cements, in mass concrete as well as for general structural use, is the limited opportunity to vary the ratio of cement and pozzolan. Most demands for structural concrete are for faster strength development, hence greater temperature rise, whereas for mass concrete the opposite concrete properties are usually desired, and are attained by manipulating the proportions of cement and pozzolan. Along with the development of other blended cements which could reduce temperature rise and ease the requirements for temperature control in mass concrete, consideration should be given to imposing chemical and physical limits for the purpose of modifying heat generation without sacrificing long-term strength gain.

6.4-Admixtures

Chemical admixtures that permit reductions in cement content have become common in mass concrete. High-range water-reducing admixtures have not become common in typical mass concrete mixtures because of cost and the fact that they generally are less effective in low-cement content mixtures. However, they can be very effective in reducing the cement content and subsequent heat problems in structural mixtures that have sufficient volume to develop significant thermal stresses. Use of high-range water-reducing admixtures should follow the recommendations in ACI 212.2R.

6.5-Temperature control practices

Control measures to minimize thermal distress or cracking discussed in earlier chapters include precooling of the concrete components, post-cooling of the concrete by systems of embedded pipes, and insulation of forms or exposed surfaces. Improved techniques for precooling the dry components, including cement and smaller aggregate sizes, may be beneficial when a large reduction in placing temperature is necessary. More effective and rugged insulation materials may provide cost benefits.

6.6-Permanent insulation and precast stay-in-place forms

An insulation system which could be used on the faces of mass concrete to effectively reduce the thermal differential from the interior to the exterior can provide extremely beneficial temperature control. Such temperature control would reduce susceptibility to cracking caused by thermal stresses and would most certainly reduce costs for temperature control. One concept is to have a thermally adequate insulation system with sufficient structural capability so that the system can serve as the form for the placement of the concrete as well as the permanent insulator. It is considered that insulation, precasting, and waterproofing technology is sufficient to permit development of such an all-purpose insulation and forming system.

Stay-in-place precast concrete panels have been used on several RCC dams to form both upstream and downstream faces, and also to form spillway training walls. The primary purpose has been for speed and simplification of construction, but a secondary reason could be to provide permanent surface insulation. The concept should be applicable to conventional concrete as well as RCC.

6.7-Roller-compacted concrete

RCC has used very low cement contents and/or high quantities of pozzolan that result in mass concrete with a low temperature rise. At low cement contents, RCC can have low elastic modulus values and high creep rates which combine with the low temperature rise to allow large placements with minimal thermal cracking. ACI 207.5R, "Roller-compacted Mass Concrete," discusses this subject further.

CHAPTER 7 -REFERENCES

7.1 - Recommended references

The documents of the various standards-producing organizations referred to in this document are listed below.

American Concrete Institute

207.1R Mass Concrete
207.2R Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete
207.5R Roller-compacted Mass Concrete
212.2R Guide for Use of Admixtures in Concrete
305R Hot Weather Concreting
306R Cold Weather Concreting

American Society for Testing and Materials (ASTM)

C 150 Standard Specification for Portland Cement
C 494 Standard Specification for Chemical Admixtures for Concrete
C 512 Standard Test Method for Creep of Concrete in Compression
C 595 Standard Specification for Blended Hydraulic Cements
C 618 Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete

U.S. Army Corps of Engineers

CRD-C 36 Method of Test for Thermal Diffusivity of Concrete
CRD-C 38 Test Method for Temperature Rise in Concrete
CRD-C 39 Method of Test for Coefficient of Linear Thermal Expansion of Concrete
CRD-C 44 Method for Calculation of Thermal Conductivity of Concrete

Bureau of Reclamation

Concrete Manual, Eighth Edition-Revised, Denver, 1981.

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219

ASTM
1916 Race St.
Philadelphia, PA 19103

U.S. Army Corps of Engineer
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180

Bureau of Reclamation
Attn: D-7923A
P.O. Box 25007
Denver, CO 80225-0007

7.2-Cited references

Anderson, Arthur R., "Precast Concrete Panels for Cladding on Mass Concrete," *Rapid Construction of Concrete Dams*, American Society of Civil Engineers, New York, 1971, pp. 309-311.

Cannon, R. Williams, "Concrete Dam Construction Using Earth Compaction Methods," *Economical Construction of Concrete Dams*, American Society of Civil Engineers, New York, 1972, pp. 143-152.

Carlson, Roy W., and Thayer, Donald P., "Surface Cooling of Mass Concrete to Prevent Cracking," ACI JOURNAL, *Proceedings* V. 56, No. 2, Aug. 1959, pp. 107. 120.

Carlson, Roy W., "Manual for the Use of Strain Meters and Other Instruments for Embedment in Concrete Structures," Carlson Instruments, Campbell, California, 1970, 24 pp.

"Cooling Concrete Mixes with Liquid Nitrogen," *Concrete Construction*, V. 22, No. 5, May 1977, pp. 257-258.

Ditchey, E. and Schrader, E., "Monkesville Dam Temperature Studies," *International Congress on Large Dams*, Par 15, Q.62, R.21, 1988, pp. 379-396.

Fitzgibbon, Michael E., "Thermal Controls for Large Pours," *Civil Engineering and Public Works Review* (London), V. 68, No. 806, Sept. 1973, pp. 784-785.

"The Fontana Project, *Tennessee Valley Authority Technical Report* No. 12, U.S. Government Printing Office, Washington, D.C., 1950.

Forbes, B.A., Gillon, B.R., and Dunstun, T.G., "Cooling of RCC and Construction Techniques for New Victoria Dam, Australia," *Proceedings*, International Symposium on Roller-compacted Concrete Dams, Beijing, 1991, pp. 401-408.

Gamer, S., and Hammons, M., "Development and Implementation of Tune-Dependent Cracking Material Model for Concrete," *Technical Report* SL-91-7, USCAE Waterways Experiment Station, Vicksburg, MS, 1991, 44 pp.

Houghton, D.L., "Determining Tensile Strain Capacity of Mass Concrete, ACI JOURNAL, *Proceedings* V. 73, No. 12, Dec. 1976, pp. 691-700.

Houk, Ivan E., Jr.; Paxton, James A; and Houghton, Donald L., "Prediction of Thermal Stress and Strain Capacity of Concrete by Tests on Small Beams," ACI JOURNAL, *Proceeding* V. 67, No. 3, Mar. 1970, pp. 253-261.

Liu, Tony C., and McDonald, James E., "Prediction of Tensile Strain Capacity of Mass Concrete," ACI JOURNAL, *Proceedings* V. 75, No. 5, May 1978, pp. 192-197.

Mead, AR., "Temperature-Instrumentation Observations at Pine Flat and Folsom Dams," *Symposium on Mass Concrete*, SP-6, American Concrete Institute, Detroit, 1963, pp. 151-178.

Price, Walter H., "Admixtures and How They Developed," *Concrete Construction,* V. 21, No. 4, Apr. 1976, pp. 159-162.

Schrader, Ernest K, "Control Heat for Better Concrete," *Concrete Construction,* Sept. 1987, pp. 767-770.

Tatro, Stephen B., and Schrader, Ernest K., "Thermal Considerations for Roller-Compacted Concrete," ACI JOURNAL, *Proceedings* V. 82, No. 2, Mar.-Apr. 1985, pp. 119-128.

Townsend, C.L., "Control of Cracking in Mass Concrete Structures," *Engineering Monograph* No. 34, U.S. Bureau of Reclamation, Denver, 1965.

Tuthill, Lewis, and Adams, Robert F., "Cracking Controlled in Massive, Reinforced Structural Concrete by Application of Mass Concrete Practices," ACI JOURNAL, *Proceedings* V. 69, No. 8, Aug. 1972, pp. 481-491.

Waddell, Joseph J., *Concrete Construction Handbook*, 2nd Edition, McGraw-Hill Book Co., New York, 1974, Chapter 20.

Wallace, G.B., "Insulation Facilitates Winter Concrete," *Engineering Monograph* No. 22, U.S. Bureau of Reclamation, Denver, Oct. 1955.

Wilson, Edward L., "The Determination of Temperature Within Mass Concrete Structures," *Structures and Material Research Report* No. 68-17, Department of Civil Engineering, University of California, Berkeley, Dec. 1968, 33 pp.

ACI 207.4R-93 was submitted to letter ballot of the committee and processed in accordance with ACI standardization procedures.