THERMAL PROPERTIES OF CONCRETE UNDER SUSTAINED ELEVATED TEMPERATURES

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Thermal properties of concrete are defined and thermal expansion and thermal conductivity of cement paste, aggregate, mortar and concrete are discussed in detail.

Both thermal expansion and conductivity values of concrete vary with the temperature and are affected by the properties of the components of concrete. As aggregate occupies most of the volume of concrete, it mainly determines the thermal characteristics of concrete. On the other hand, hygrothermal movement of cement paste upon heating has a critical influence on the strength of concrete.

The paper is concluded with 61 pertinent references from the United States, England, Canada, Germany, France, Japan, Australia and the Soviet Union.

Keywords: age; aggregates; carbonate aggregates; cement pastes; concretes; high temperature; igneous rocks; lightweight concretes; moisture content; mortars material; quartzites; shrinkage; thermal conductivity; thermal expansion; thermal properties.

☐ There are many ways of exposing concrete structural members to elevated temperatures. One of the most common types of exposure is by accidental fire in a building. Normally such fires are of short duration but of a high intensity, with the temperature reaching up to 1000C (1832F). In the case of a building fire the cardinal problem is public safety. Building codes specify the fire protection requirements for specific structural members in terms of fire-resistance ratings based upon tests made in accordance with standard methods.[1,2,3] Different structural assemblies have been fire tested and given hourly endurance ratings in a fire retardant classification.[4]

Another type of heat exposure may be found in some industrial installations where concrete is used in places exposed to sustained elevated temperatures ranging from 100 to 1000C (212 to 1832F).

Much information has been collected over the years on fire endurance of concrete assemblies.[5] On the other hand, only limited data are available on the effect of sustained elevated temperatures on the thermal properties of concrete. Only recently, has much attention been given to fundamental research in this field. Besides published work on this subject in the United States,[6-13] notable contributions have come from research organizations in England,[14-19] Canada,[20-23] West Germany,[24-28] France,[29] Australia,[30-31] Japan,[32] Denmark,[33] and particularly from the Soviet Union.[34-36]

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This paper reviews the current literature available on thermal properties of concrete under sustained elevated temperatures.

THERMAL PROPERTIES OF CONCRETE

The principal thermal properties of concrete are thermal expansion, thermal conductivity, specific heat, and diffusivity.

The coefficient of thermal expansion α represents the change of concrete volume or, as usually measured on test specimens, the change in length with change in temperature. It is expressed in terms of percent or millionths per C or millionths per F.

The coefficient of thermal conductivity k represents the uniform flow of heat through a unit of thickness over a unit area of concrete subjected to a unit temperature difference between the two faces. It is expressed as

$$k_C = \frac{kg - cal \times m}{m^2 \times hr \times C} \quad \text{or} \quad k_F = \frac{Btu \times ft}{ft^2 \times hr \times F} \; . \tag{1}$$

Specific heat is the amount of heat required to raise the temperature of a unit mass of concrete by one degree, and is identified by symbol C. It is expressed as

$$C_C = \frac{kg - cal}{kg \times C} \quad \text{or} \quad C_F = \frac{Btu}{lb \times F} \; . \tag{2}$$

Diffusivity is an index of the facility with which concrete will undergo temperature change, and it is identified by the diffusion constant a. It is expressed in m^2/hr or ft^2/hr and may be determined from the formula: $a = \frac{k}{C\rho}$, where k = thermal conductivity; C = specific heat; and ρ = density of concrete in kg/m^3 or lb/ft^3.

In addition to the above thermal properties there is also the property of adiabatic temperature rise in concrete due to heat of hydration of the cement. This property and its proper control is of vital consideration in the design of massive concrete structures.

This paper will confine itself to the detailed discussion of thermal expansion and thermal conductivity of hardened concrete exposed to sustained elevated temperatures.

TYPES OF EXPOSURE TO ELEVATED TEMPERATURES

Generally speaking, we are presently concerned with long exposures of concrete to elevated temperatures. Such exposures are imposed on foundations for blast-furnaces and coke batteries, furnace walls, doors and dampers, industrial chimneys and flues, floors on which metal parts are heat-treated, floors below boilers and kilns, aprons of jet-engine test-stands and nuclear-reactor pressure vessels. Concrete in these installations is subjected normally to a considerable thermal gradient ranging from a maximum temperature on the exposed face to temperatures at normal levels on the outside.

In exposure to sustained elevated temperatures we are dealing with the steady-state condition. In this type of exposure, the rate of heat flow remains constant. In the design of heat-exposed concrete structural members consideration must be given to the magnitude of the thermal gradient in order to prevent the stresses in concrete from exceeding their specified maximum ratings. The principal factor involved in such stress analysis is differential thermal expansion in concrete structural members. Another important factor in the design of heat-resistant concrete is its thermal conductivity. This is important for both insulation and heat transfer purposes.

THERMAL EXPANSION

Thermal expansion is a physical phenomenon common to all materials. This is, however, complicated in concrete by differential expansion of its components to produce high internal stresses.

Thermal expansion has an important effect on all types of concrete structures, such as buildings, bridges, pavements, dams and shields of nuclear reactors. The consideration of expansion and application of a proper thermal expansion coefficient for concrete in structural design will help to avoid damage of buildings from stresses created by the thermal volume changes of concrete. These changes depend mainly on the volume changes of its two principal components, the cement paste and the aggregate.

Cement Paste

Recent investigations indicate that changes of length (or volume) are complex processes. The actual expansion resulting from heating seems to be a combined effect of true thermal expansion based on kinetic molecular movements, and the super-imposed apparent thermal expansion. The latter is caused by a hygrothermal volume change associated with the movement of internal moisture from capillaries to gel pores, under capillary forces produced by temperature changes, without change in the water content of the body in question.[37] If the values for the true thermal expansion are essentially constant, averaging about 10×10^{-6}/C (5.5×10^{-6}/F), the magnitude for the apparent thermal expansion will depend on the moisture content and capillary structure of hardened cement paste as well as on the quantity and expansion properties of cement gel.

Research work by Mitchell[38] and by Meyers[39] shows that moisture content may cause the coefficient of expansion of neat cement paste to vary by as much as 100 percent, with minimum values obtained in both oven-dry and saturated conditions, and a maximum value at an intermediate, 'critical' moisture content, which at ages up to 6 months is about 65 to 70 percent, and after several years is 45 to 50 percent of saturation. The apparent or hygrothermal expansion may equal, or even exceed, the true thermal expansion. Values of the thermal coefficient, which represent the total expansion of neat cement paste, may vary from less than 9.0 x 10^{-6} to more than 21.6 x 10^{-6} per C (5.0 to 12.0 x 10^{-6} per F), depending upon the differences in cement fineness, composition, water/cement ratio (w/c) and moisture content. It is a function of age, becoming smaller in time with aging of cement gels (Fig. 1-1).

In an early work by Lea and Stradling[14] the length changes of hardened portland cement paste have been determined (Fig. 1-2). Up to a temperature of 100 C (212 F) cement paste expands; when water is given off, and if the temperature is sustained sufficiently long, a contraction results which more than equals the previous expansion. This contraction continues as the temperature rises, and with rising temperature the different hydrates, present in the cement paste, break down and give off water. The connection between shrinkage and weight loss due to removal of moisture was discussed by Philleo.[7] Crowley suggested[18] that the thermal movement of cement paste may be considered to be the sum of a reversible and an irreversible component. His work indicated that the residual shrinkage strains obtained after cooling will be greater than any that occur during heating. Harada[32] shows that with increased rate of heating the initial expansion of the paste increases and reverses into shrinkage at somewhat higher temperature. He also shows that at about 700 C (1292 F) the shrinkage changes again into expansion. Harada[32] and Dettling[37] have shown that thermal expansion and contraction of cement paste is not a function of the temperature difference alone, but depends to a considerable extent on the duration of the exposure. Shrinkage of hardened cement paste at sustained temperatures is shown in Fig. 1-3.

Aggregate

The mineral composition and structure of aggregates is the major factor in determining the coefficient of thermal expansion of concrete. The hardened cement paste component of concrete has a coefficient which is generally higher than that of the aggregate, but as the aggregate occupies about 70 to 80 percent of the total volume of hardened concrete, the coefficient of thermal expansion of concrete is nearly directly proportional to that of its aggregate.

The coefficient of thermal expansion α of various rocks which may be used as aggregate in concrete under normal temperature conditions* varies from less than 3.6 to more than 12.6 x 10^{-6} per C (2.0 to 7.0 x 10^{-6}/F).[38,40,41] Rock consisting of one mineral as a rule has the average expansion coefficient of the individual mineral crystals. Table 1-1 presents average values

*Normal temperature in this report means range from 10 to 65 C (50 to 150 F).

of coefficients of thermal expansion for different minerals and Table 1-2 shows values of α per different rocks, as given in the literature.[37]

Data obtained by numerous scientists across the world indicate that the main factor influencing the thermal expansion of rock, and, therefore, of concrete, is the proportion of quartz present. Rocks with a high quartz content, such as quartzite and sandstone, have the highest coefficients, averaging about 12 x 10^{-6}/C (6.6 x 10^{-6}/F); rocks containing little or no quartz, such as limestone have the lowest coefficients averaging about 5 x 10^{-6}/C (2.8 x 10^{-6}/F); and rocks with medium quartz content, such as igneous rocks (granite, rhyolite, basalt, etc.), have intermediate values.

A wide scatter in the thermal expansion values is noted in anisotropic rocks. To find the cause one must study the more important petrographic and physical properties of the rock. Because anisotropic minerals expand differently in different directions, the orientation of crystals in a rock will result in anisotropic thermal expansion. A mineral in the amorphous state can have a considerably lower thermal expansion than in the crystalline and, as a rule, this will lead to a reduction of the coefficient of thermal expansion of a composite rock.

Air-dry rocks may have a 10 percent higher thermal expansion than water-saturated rocks.[37] The coefficient of thermal expansion has a non-linear relation to temperature; as a rule it increases with increasing temperature. Thus a coefficient of thermal expansion can be reliably given only for a limited temperature range.

In an experimental study recently conducted at Canada's Mines Branch,[42,43] the thermal expansion of different rock types was examined at elevated temperatures of up to 1000 C (1832 F). Results indicate that the rate of thermal elongation of rocks increases several times over normal when exposed to temperatures of about 500 C (932 F) or higher. The rocks for this study were selected to represent certain petrographic groups having distinctive types of structure and compositions, so that the influence of these features on the thermal properties of the rock could be determined. Accurate mineralogical compositions were obtained by counting grains, and both megascopic and microscopic structures were studied. Table 1-3 gives average values of the total percent linear thermal expansion determined from 25 to 573 C (77 to 1063 F) for the selected rocks; rock composition was the controlling factor in tabulating the results. The igneous rocks are listed roughly according to decreasing quartz content and increasing Ca-Mg-Fe minerals content. The miscellaneous quartzose rocks are also listed according to decreasing quartz content and increasing Ca-Mg-Fe content. Carbonate rocks are tabled according to decreasing dolomite content.

The study showed that thermal expansion of a rock is greatly influenced by structural variation, but the dominant factor appeared to be mineralogical composition. Elongation measurements were made on several companion specimens of the same rock when compositional differences were observed, and the values were averaged to plot the expansion curves shown in Fig. 1-4 for temperatures ranging from 25 to 1000 C (77 to 1832 F). The Fig. 1-4 shows that the normal characteristics of the rocks change with exposure to higher temperature, reflecting changes in physical properties of the minerals. An abrupt levelling of an expansion curve around 600 C (1112 F) invariably indicates the presence of quartz; carbonate rocks often shrink after 900 C (1652 F) or earlier, if dolomite is present; and a high expansion rate after 650 C (1202 F) may indicate a high biotite content. The typical behavior of the quartz-rich rocks is attributed by many researchers to the inversion of quartz. Heating of quartz up to 500 C (932 F) causes a volume expansion of about 2.8 percent, but a more significant change occurs near 573 C (1063 F), when inversion of α-quartz to β-quartz results in a sudden volume expansion of about 2.4 percent, causing shattering of the rock structure. This is followed by a period of no additional expansion up to about 900 C (1652 F); when dissociation of gases and irregular volume changes take place.[24,25,44,45]

For composite rocks the coefficient of thermal expansion may be computed from the proportions of the principal minerals and their average expansion (Table 1-1).

The increasing values for the coefficients of thermal expansion for some rocks were determined within different ranges of elevated temperatures. These values, derived from the corresponding expansion graphs shown in Fig. 1-4, are given in Table 1-A in the Appendix.

Of all the rocks tested the best thermal stability was shown by anorthosite (M-193). This has been confirmed also by work of others,[45] which showed that anorthositic rocks are relatively stable up to 1000 C (1832 F). Photo enlargements of polished anorthosite rock surface before and after exposure to 700 and 1000 C (1292 and 1832 F) are shown in Fig. 1-5 and 1-6. Although basalt rock (M-189) has shown similar low expansion up to 600 C (1112 F), it increased at higher temperatures. At an exposure to heat over 900 C (1652 F) basalt rock, due to developing gases, expands rapidly.[24]

It may be noted that the finely crystalline rocks are generally more durable from the thermal standpoint than coarse ones. Thermal expansion and deformations of coarsely crystalline rocks are mostly irreversible after cooling. Harvey[46] shows that within temperature range from 30 to 80 C (86 to 176 F) the coefficient of thermal expansion for a coarse-grained limestone is about twice than that for fine-grained specimens (11.3 and 5.0 x 10^{-6}/C, respectively, or 6.3 and 2.8 x 10^{-6}/F).

Mortar and Concrete

The linear expansion of hardened cement mortar changes in proportion to the cement content in the mixture. Generally, richer mixes expand more because expansion of cement paste is greater than that of aggregate. If, however, aggregate with a high coefficient of expansion is used (i.e. silica sand), elongation will increase in proportion to aggregate content. Relationship between coefficient of thermal expansion α of mortar, and quantity and type of sand is shown in Fig. 1-7.[53] The maximum expansion of mortar is reached at about 80 to 90 C (176 to 194 F) after which it normally starts to shrink.

According to Mitchell[40] the coefficient of thermal expansion α for cement mortars made with sands of different origin should be expected to vary from about 9 to 14.4 x 10^{-6}/C (5 to 8 x 10^{-6}/F) at normal temperatures. Harada,[32] for the 1:1 mortars made with seven different sands arrived at somewhat lower coefficient values such as 4.7 and 11.3 x 10^{-6}/C (2.6 to 6.3 x 10^{-6}/F) for andesite and quartz sands, respectively. The results obtained by others are between these two extreme values.[47,48,49]

Actual experimental measurement is unavoidable for accurate determination of thermal expansion of concrete. The latter is affected by the mix proportions, moisture content, age of concrete and coefficients of thermal expansion α of individual concrete components. At room temperature, it increases with increasing cement content and decreases with increasing age of the concrete. Air-dried concrete has a larger coefficient of thermal expansion than the extremely dry, or water-saturated concrete. This increase in α value is due to movement of water in the pore system; such movement is absent from both the oven-dried and the saturated specimens.[50] For a given moisture content and concrete mix, the coefficient of thermal expansion of the aggregate is the most significant parameter. Expansion coefficient α for concrete made with different aggregates can be computed from the solid volume fraction and the expansion coefficient for each component.[37,50] Work of Stanton Walker et al.[51,54] supports the suggestion that the thermal coefficient of concrete is approximately the weighted average of the coefficients of its ingredients. Fig. 1-8 shows the relationship between the coefficient of thermal expansion of concrete, type of aggregate and variable coarse aggregate proportions by absolute volume (cement/sand ratio was kept constant 1:2.85). Investigations indicate that the coefficient of expansion is essentially constant over the normal temperature range. According to Mitchell[40] the coefficient of thermal expansion α for hardened concrete is usually between 6.3 and 11.7 x 10^{-6}/C (3.5 to 6.5 x 10^{-6}/F), provided that its variability attending moisture changes is taken into account. Work of Dettling[37] provided data showing values for α ranging from 5.5 x 10^{-6}/C (3 x 10^{-6}/F) for a water-saturated lean limestone concrete to 14 x 10^{-6}/C (7.8 x 10^{-6}/F) for an air-dry concrete made with a high cement content and quartzose aggregate. Thus the maximum value of α is more than 2.5 times its minimum value. When a precise value is not required, a value of 10 x 10^{-6}/C (5.5 x 10^{-6}/F) for α is frequently used.

Exposure to Elevated Temperatures

When cement mortar or concrete is exposed to elevated temperatures the observed volume change is a result of complex processes consisting of thermal expansion of aggregate and hygrothermal volume change of cement paste. As was shown before, after initial expansion of cement paste its volume change is reversed to contraction or shrinkage, rate of which depends on the rate and duration of heating. However, shrinkage of cement paste is overshadowed in mortar and concrete by the aggregate expansion and the resultant curve is a sum of the length changes of cement paste and aggregate at the temperature of exposure. If idealized data are taken for the thermal movements of a cement paste and a siliceous aggregate, the general manner in which the strain difference due to incompatibility varies with temperature can be found.[52] This is shown in Fig. 1-9, from which it can be seen that at first these differential strains will induce a small compressive stress in the cement paste but that with increasing temperature this is reduced and changes to a much larger tensile stress. The residual strains obtained after cooling are also shown in this Fig. 1-9. In rich 1:1 mortar the summary curve normally shows slight contraction, whereas in leaner mixes the result will be expansion. In concrete, where the proportion of aggregate to cement is greater, the resultant curve will approach asymptotically that of the rock itself. This is well indicated by the mortar and concrete expansion curves in Fig. 1-10 presenting some of the results obtained by Harada.[53] Fig. 1-10 (a) shows that expansion curve of limestone concrete (L-6) approaches asymptotically to that of the limestone rock itself (L), and is very close to the expansion curve of reinforcement steel (S). Fig. 1-10 (b) indicates clearly that the magnitude of the expansion of sandstone concretes

(A-6 & A-7) in temperatures up to 500 C (932 F) coincides with that of the sandstone rock itself (A). Fig. 1-10 (c) shows that andesite (F) has a low coefficient of expansion; therefore 1:1 mortar mix shows large contraction and 1:2 mix only minor length changes. Fig. 1-10 (d) shows that of all aggregates investigated by Harada the two lightweight rocks pumice (G) and cinder (HA) are the most stable aggregates for heat exposure. Concretes made with two different andesite rocks (E-6 & F-6) produce thermal expansion about half of that of sandstone (A-6 & A-7) and limestone (L-6) concrete.

Zoldners et al.[20,21] have shown the effect of different aggregates on residual volume change of concrete exposed to elevated temperatures up to 800 C (1472 F). The results indicate that concrete made with thermally stable aggregates such as expanded slag or shale after heating showed residual contraction instead of expansion. On the other hand, concrete may deteriorate at temperatures as low as 300 C (572 F) if thermally unstable aggregate such as phonolite or tinguaite is being used. This type of rock contains a hydrous mineral (i.e. natrolite) which readily dissociates loosing its water of constitution. It is accompanied by extensive cracking of concrete and loss of aggregate-mortar bond. When, after cooling, concrete is exposed to air, water is absorbed and concrete disintegrates further as rehydration of calcined minerals takes place.[21]

THERMAL CONDUCTIVITY

Thermal conductivity of concrete is a property which is of prime importance in the design of heat-exposed concrete installations. The conductivity of concrete is determined by the conductivities of its constituents. Of all the factors likely to influence the conduction of heat in concrete, Missenard[29] lists four major variables as follows: (1) conductivity of the cement, (2) conductivity of the aggregate, (3) mix proportion, (4) compactness of the placed concrete. Campbell-Allen and Thorne[30] point out another important factor, the moisture content of concrete.

Generally speaking, thermal conductivity of concrete is essentially a function of that of the cement paste and the aggregate.

Cement Paste

The thermal conductivity factor "k" of hardened, saturated paste of different types of portland cements may vary within the range of normal temperature from 0.8 to 1.1 kg-cal/m hr C (0.5 to 0.7 Btu/ft hr F).[6,29] Cement pastes with higher water-cement ratios have lower thermal conductivities. Although drying reduces the amount of water, a low-conductivity ingredient, it further lowers conductivity because this loss increases air void content of still lower conductivity.[38,61] As shown by Davis[55] exposure of hardened cement paste to elevated temperatures further reduces its thermal conductivity. Results obtained by Harada[58] show that factor "k" at a temperature of 750 C (1382 F) is about half of that at normal temperatures. This may be explained by microcracking of cement paste caused by shrinkage and increasing porosity upon exposure to elevated temperatures.

Aggregate

The different rock types which may be used as aggregate in concrete have a thermal conductivity factor "k" ranging under normal temperature conditions from less than 1.0 to more than 4.5 kg-cal/m hr C (0.7 to 3.0 Btu/ft hr F).[29] Quartzite, sandstone and other quartzose rocks show the highest conductivity. Igneous rocks such as granites, gneisses, rhyolites, as well as carbonate rocks, such as limestone and dolomites, have an intermediate "k" values ranging from 2.0 to 2.5 kg-cal/m hr C (1.3 to 1.7 Btu/ft hr F). Basalt, anorthosite, dolerite and barite are among the rock types having a low conductivity with "k" value ranging from 1.0 to 1.7 kg-cal/m hr C (0.7 to 1.1 Btu/ft hr F).[30,40]

It must be noted that rocks with crystalline structure show higher heat conductivity than the amorphous and vitreous rocks of the same composition. Therefore, the conductivity of a rock depends much more on the degree of its crystallization than on its composition.[29] Lightweight aggregates due to their porosity have much lower "k" value. Rocks in moist condition show appreciably higher conductivity than in dry state.

Changes in "k" value of a rock caused by heating depends essentially upon the structure of the rock. With the exception of amorphous rocks and monocrystals the conductivity decreases when temperature increases. Experimental studies conducted at Canada's Mines Branch by Mirkovich[60] produced values of thermal conductivity for different rocks exposed to elevated temperatures ranging from 100 to 800 C (212 to 1472 F). Rocks investigated in this study were the same as used for thermal elongation study.[42] Thermal conductivity "k" values of these rocks at 100 and 573 C (220 and 1063 F) together with corresponding thermal expansion are given in Table 1-B in the Appendix. Thermal conductivity "k" values obtained for igneous, quartzose and carbonate rocks plotted against temperature are shown in Fig. 1-11. In general, conductivity decreases with temperature increase. Though the "k" value has a wide spread for various rocks at low temperatures, the differences decrease with increasing temperature. Thermal conductivity of some rocks decreased to about half when temperature was increased from 100 to 573 C. This large decrease in thermal conductivity seems to correspond significantly with a large thermal expansion of these rocks (i.e. quartz, sandstone, granite, dolostone). On the other hand, rocks which have shown low expansion characteristics also showed little change in "k" value (i.e. anorthosite, basalt, limestone). Apparently a relationship exists between thermal expansion and thermal conductivity of rocks. Both these properties depend upon the composition and structure of the material. Internal stresses created by thermal expansion may cause microcracking of crystals and loosening of grains. The rupturing of intercrystalline bonds, which causes increased porosity of a rock, would normally result in lower thermal conductivity.

Mortar and Concrete

Thermal properties of concrete made with different types of aggregates were investigated by the U.S. Bureau of Reclamation.[6] The results of that study show that the thermal conductivity of normal, saturated concrete with similar mix design but different aggregates varied from 1.8 to 3 kg-cal/m hr C (1.2 to 2.0 Btu/ft hr F) at temperature ranging from 10 to 65 C (50 to 150 F). The range will be wider if concretes of different mix design are used. Mix proportions of cement, aggregate and free water influence the conductivity of concrete. If the water content of concrete mixture is kept constant the effect of richness of the mix will depend on the type of aggregate: in the case of lightweight aggregates, where "k" factor is generally less then that of cement paste, the richer the mix the higher the conductivity; while in the case of conventional aggregate, where "k" factor is greater than that of the paste, the richer the mix the lower the conductivity.[30] Wet concrete mixes with a high water-cement ratio upon hardening will produce porous concrete with a low conductivity, especially when dry. However, an increase of water content in the mix proportion from four to eight percent of the concrete weight will decrease thermal conductivity only by about 10 percent.[6] When concrete is moist, pores are filled with water, and conductivity increases appreciably.[55,56] In general, the porosity of concrete tends to reduce the density and at the same time also conductivity. This is particularly true in cellular and lightweight aggregate concrete in which low thermal conductivity is an essential factor for their insulation values, which changes with the moisture content of concrete.

Coefficient of thermal conductivity "k" values for lightweight concretes made with porous aggregates, or aerated and foamed concretes, with a moisture content as at the average building conditions, are given for various densities in Table 1-C of the Appendix. Effect of moisture content on thermal conductivity of different types of concrete is shown in Table 1-4.

TABLE 1-4—EFFECT OF MOISTURE ON THERMAL CONDUCTIVITY OF CONCRETE (REF. 57, TABLE XIX)

Type of concrete	Density or unit weight		Coefficient of thermal conductivity k for totally dry state		Increase of coefficient of thermal conductivity k in percent for each 1 percent moisture in concrete (percent by vol.)		
	kg/cu m	lb/cu ft	k_C	k_F	5 percent	10 percent	20 percent
Conventional concrete	2245	140.2	1.10	0.73	13.4	9.6	—
Lightweight aggr. concr.	1590	99.4	0.36	0.24	10.0	8.4	—
Pumice concrete	1150	71.9	0.20	0.13	14.0	11.2	8.5

k_C (Kg-cal/m hr C); k_F (Btu/ft hr F)

Effect of moisture content on coefficient of thermal conductivity values of normal and high-density concretes made with three types of rock was investigated by Campbell-Allen and Thorne[30] and the results are shown in Table 1-D of the Appendix. Lentz and Monfore[61] have shown that conductivity of moist limestone and sandstone concretes at 75 F increased by about five and eight percent, respectively, for each percent increase in moisture of the oven-dry weight.

High density of concrete does not necessarily indicate high conductivity. For instance, concrete made with barite aggregate has a "k" value of 1.2 kg-cal/m hr C (0.8 Btu/ft hr F) with a density of 3636 kg/m^3 (227 lb/ft^3). On the other hand Bull Run Dam concrete made with largely igneous gravel had a "k" value of 1.24 kg-cal/m hr C (0.83 Btu/ft hr F) at a density of 2547 kg/m^3 (159 lb/ft^3).[6,40]

Exposure to Elevated Temperatures

Only limited data are available on the effect of elevated temperatures on thermal conductivity of concrete and mortars. Since moisture content decreases with exposure time and temperature, the conductivity of cement paste, mortars and concrete decreases with increasing temperature. At temperatures above 400 C (752 F), at which complete dehydration occurs, a