

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

$$k_C = \frac{\text{kg} \cdot \text{cal} \times \text{m}}{\text{m}^2 \times \text{hr} \times \text{C}} \quad \text{or} \quad k_F = \frac{\text{Btu} \times \text{ft}}{\text{ft}^2 \times \text{hr} \times \text{F}} \quad (1)$$

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

$$C_C = \frac{\text{kg} \cdot \text{cal}}{\text{kg} \times \text{C}} \quad \text{or} \quad C_F = \frac{\text{Btu}}{\text{lb} \times \text{F}} \quad (2)$$

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 $10 \times 10^{-6}/^{\circ}\text{C}$ ($5.5 \times 10^{-6}/^{\circ}\text{F}$), 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 Mitchell³⁸ and by Meyers³⁹ 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 hygro-thermal 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 9.0×10^{-6} to more than 21.6×10^{-6} per C (5.0 to 12.0×10^{-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 Stradling¹⁴ 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 suggested¹⁸ 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. Harada³² 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. Harada³² and Dettling³⁷ 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 12.6×10^{-6} per C (2.0 to 7.0×10^{-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 $12 \times 10^{-6}/\text{C}$ ($6.6 \times 10^{-6}/\text{F}$); rocks containing little or no quartz, such as limestone have the lowest coefficients averaging about $5 \times 10^{-6}/\text{C}$ ($2.8 \times 10^{-6}/\text{F}$); 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. Harvey⁴⁶ 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 $5.0 \times 10^{-6}/C$, respectively, or 6.3 and $2.8 \times 10^{-6}/F$).

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 Mitchell⁴⁰ the coefficient of thermal expansion α for cement mortars made with sands of different origin should be expected to vary from about 9 to $14.4 \times 10^{-6}/C$ (5 to $8 \times 10^{-6}/F$) 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 $11.3 \times 10^{-6}/C$ (2.6 to $6.3 \times 10^{-6}/F$) 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 pro-

portions, 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 Mitchell⁴⁰ the coefficient of thermal expansion α for hardened concrete is usually between 6.3 and $11.7 \times 10^{-6}/^{\circ}\text{C}$ (3.5 to $6.5 \times 10^{-6}/^{\circ}\text{F}$), provided that its variability attending moisture changes is taken into account. Work of Dettling³⁷ provided data showing values for α ranging from $5.5 \times 10^{-6}/^{\circ}\text{C}$ ($3 \times 10^{-6}/^{\circ}\text{F}$) for a water-saturated lean limestone concrete to $14 \times 10^{-6}/^{\circ}\text{C}$ ($7.8 \times 10^{-6}/^{\circ}\text{F}$) 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 $10 \times 10^{-6}/^{\circ}\text{C}$ ($5.5 \times 10^{-6}/^{\circ}\text{F}$) 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 tinguaitite is being used. This type of rock contains a hydrous mineral (i.e. natrolite) which readily dissociates losing 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, Missenard²⁹ 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 Thorne³⁰ 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 Davis⁵⁵ exposure of hardened cement paste to elevated temperatures further reduces its thermal conductivity. Results obtained by Harada⁵⁸ 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 monocystals the conductivity decreases when temperature increases. Experimental studies conducted at Canada’s Mines Branch by Mirkovich⁶⁰ 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 than 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 per-cent	10 per-cent	20 per-cent
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 Thorne³⁰ and the results are shown in Table 1-D of the Appendix. Lentz and Monfore⁶¹ 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/m³ (227 lb/ft³). 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/m³ (159 lb/ft³).^{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

gradual disintegration of cement paste takes place, resulting in further decrease in thermal conductivity.

Fig. 1-12 shows the effect of elevated temperatures on thermal conductivity of portland cement paste, mortars, and concretes during heating and after cooling, as observed by Harada.⁵⁸ He used siliceous river sand and sandstone gravel "k" value of which is high.⁵⁹ The graphs in Fig. 1-12 (a) show that the relatively low "k" value of pure cement paste at normal temperature reduced from 0.72 to 0.40 kg-cal/m hr C (0.48 to 0.27 Btu/ft hr F) upon heating to about 750 C (1382 F). Its value increased by about 60 percent when sand was added for 1:1 mortar, to 30 percent in 1:5 mortar mixes.⁵⁸ For concrete, the addition of coarse aggregate resulted in further decrease in air content and increase in thermal conductivity with the values of "k" reaching 1.5 and 1.8 kg-cal/m hr C (1.0 and 1.2 Btu/ft hr F) at about 40 C (104 F) temperature for the two concretes A (W/C = 0.6) and B (W/C = 0.7), respectively. The results indicate that conductivity decreases rapidly with the rise in temperature and assumes, at 750 C, a "k" value equal approximately to 50 percent of that of normal temperature. This holds true also for cement paste and mortar mixes. The "k" value for leaner concrete "B" was about 20 percent higher than that for richer concrete "A". However, if the cement used is below the required minimum for a good workability, poor compaction will produce concrete with increased porosity and hence lower conductivity.¹⁴

It is interesting to note in Fig. 1-12 (b) that "k" values obtained on the cooled concrete test specimens, after being exposed to elevated temperatures, are higher by approximately 10 and 20 percent, respectively, than values obtained during heating. Apparently after cooling some of the thermal movement reversed, thus partially healing the damage done to the concrete during the heat exposure.

Results obtained by Zoldners et al.^{20,21,30} show that concrete with a water cement ratio W/C = 0.62, made with heterogeneous gravel mixture, reduces in "k" value by about 16 percent upon raising heat exposure from 164 to 402 C (327 to 756 F). This is in good agreement with the above mentioned work of Harada (Fig. 1-12) showing, on similar concrete "A" within the same temperature range, a reduction of about 20 percent.

CLOSING REMARKS

It has been shown that the total thermal expansion of concrete, which determines the magnitude of the thermal stress component of the applied loading, is affected by the individual thermal expansions of the components of concrete.

As aggregate occupies most of the concrete volume, its properties are the determining factor in establishing the thermal characteristics of concrete. Exact knowledge of thermal properties of aggregate is essential in the rational design of concrete structures subjected to thermal stresses.

ACKNOWLEDGMENTS

Several staff members of Canada's Mines Branch assisted in providing specific test data and interpreting empirical results.

The author is particularly indebted to Dr. J. A. Soles for his advice in the field of mineralogy and to Dr. V. V. Mirkovich for his advice on thermal conductivity.

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TABLE 1-1—AVERAGE COEFFICIENTS OF LINEAR THERMAL EXPANSION OF MINERALS³⁷ (WITHIN NORMAL TEMPERATURE RANGES)

Type of mineral		Average coefficient of thermal expansion $\alpha \times 10^6$ per	
		C	F
<u>Silica group</u>			
Quartz, Chalcedony	—	11.5 - 12	6.4 - 6.7
Opal	—	6 - 7	3.3 - 3.9
<u>Feldspar group</u>			
Potassium Feldspars			
Orthoclase, Microcline	—	6.5 - 7.5	3.6 - 4.2
Sodium Calcium Feldspars			
Albite (sodium feldspar)	—	5 - 6	2.8 - 3.3
Oligoclase, Andesite	}	4 - 3	2.2 - 1.7
Labradorite, Bytownite			
Anorthite (calcium feldspar)	—	2.5 - 3	1.4 - 1.7
<u>Mica group</u>			
Augite - and Hornblende group	—	6.5 - 7.5	3.6 - 4.2
Olivine group	—	6 - 9	3.3 - 5.0
<u>Carbonates</u>			
Calcite	—	4.5 - 5	2.5 - 2.8
Aragonite	—	20.5	11.4

TABLE 1-2—AVERAGE COEFFICIENTS OF LINEAR THERMAL EXPANSION OF ROCKS³⁷ (WITHIN NORMAL TEMPERATURE RANGES)

Type of rock		Average coefficient of thermal expansion $\alpha \times 10^6$ per	
		C	F
Quartzite, silica shale, cherts		11.0 - 12.5	6.1 - 7.0
Sandstones		10.5 - 12.0	5.8 - 6.7
Quartz sands and pebbles		10.0 - 12.5	5.5 - 7.0
Clay and mica shales		9.5 - 11.0	5.3 - 6.1
Granites and Gneisses		6.5 - 8.5	3.6 - 4.7
Syenites, feldspathic porphyry Diorites, Andesite, Phonolite Gabbros, Diabase, Basalt		5.5 - 8.0	3.0 - 4.5
Dense, crystalline, porous limestones		3.5 - 6.0	2.0 - 3.3
Pure calcite		4.0 - 6.5	2.2 - 3.6
Marbles		4.0 - 7.0	2.2 - 3.9
Dolomites, Magnesites		7.0 - 10.0	3.9 - 5.5

Volcanic glasses and tuffs, breccias, conglomerates and grey-wackes have the same coefficients as the mineralogically corresponding rocks

TABLE 1-3—COMPOSITION, TEXTURE, STRUCTURE AND LINEAR THERMAL EXPANSION OF DIFFERENT ROCKS⁴³

Sample no.	Rock class	Mineral composition, percent ¹				Grain size ²	percent Thermal expansion, 25 to 573 C	
		Qtz	Feldspars					Ferromagnesians and miscellaneous
			K	Na	Ca			

1. IGNEOUS ROCKS								
M-194	Granite	34	31	31	—	3 Biotite	M	1.2
M-210	Qtz Monzonite	27	20	—	42	10 Biotite, Muscovite	C	1.2
M-190	Rhyolite	23	52	51	—	3 Mag	F	1.1
M-193	Anorthosite	—	1	—	97	1 Aug; 1 Mag	C	0.5
M-188	Nephel. Syen.	—	23	52	—	2 Mag; 23 Nepheline	M	1.0
M-189	Basalt	←————— 25 —————→				40 Epid; 20 Aug; 10 Cl; 5 Mag	F	0.48

2. QUARTZOSE ROCKS								
M-179	Quartz	100	—	—	—	-----	C	1.25
M-176	Sandstone	92	8	—	—	-----	F	1.3
M-200	'Taconite'	60	—	—	—	23 Grunerite; 17 Mag	M	1.0
M-199	Hbde-Qtz-Gneiss	25 (incl. Feldspar?)				70 Hbde; 5 Calcite	M	0.7

3. CARBONATE ROCKS								
		Qtz	Calcite	Dolomite	Others			
M-168	Dolostone ³	—	—	98	2 Tremolite	C	1.1	
M-187	Dolom. Limest.	—	72	27	1 Dark impurities	F	1.2	
M-185	Limestone ³	< 1	88	10	1 Diopside; 1 Graphite	C	0.55	
M-184	Limestone	<< 1	94	4	2 clay impurities	F	0.74	

Abbreviations: 1. Aug: Augite; Hbde: Hornblende; Mag: Magnetite; Cl: Chlorite

2. F: fine-grained (< 1 mm); M: medium-grained (1-5 mm); C: coarse-grained (> 5 mm)

3. Recrystallized

TABLE 1-A—EFFECT OF ELEVATED TEMPERATURES ON
EXPANSION OF SOME ROCKS

Temperature Ranges	Thermal Expansion Coefficient α , $10^{-6}/^{\circ}\text{C}$ or $^{\circ}\text{F}$			
	M-176 Sandstone	M-184 Limestone	M-193 Anorthosite	M-194 Granite
20 to 100 $^{\circ}\text{C}$ (68 to 212 $^{\circ}\text{F}$)	10.0 (5.5)	3.0 (1.7)	4.0 (2.2)	4.0 (2.2)
100 to 300 $^{\circ}\text{C}$ (212 to 572 $^{\circ}\text{F}$)	15.0 (8.5)	9.0 (5.0)	8.5 (4.7)	13.5 (7.5)
300 to 500 $^{\circ}\text{C}$ (572 to 932 $^{\circ}\text{F}$)	21.5 (12.0)	17.0 (9.5)	10.0 (5.5)	26.0 (14.5)
500 to 700 $^{\circ}\text{C}$ (932 to 1292 $^{\circ}\text{F}$)	25.0 (14.0)	33.0 (18.5)	12.5 (7.0)	47.5 (26.4)

After Canada's Mines Branch (Ref. 42, 43)

TABLE 1-B—LINEAR THERMAL EXPANSION AND THERMAL CONDUCTIVITY OF DIFFERENT ROCKS

Sample No	Rock Class	Thermal Linear Expansion to 573°C/1063°F	Coefficient of Thermal Conductivity "k"			
			at 100°C/212°F		at 573°C/1063°F	
		Per Cent	k _C *	k _F *	k _C *	k _F *
1. IGNEOUS ROCKS						
M-194	Granite	1.2	2.02	1.36	1.60	1.07
M-210	Qtz Monzonite	1.2	2.20	1.48	1.45	0.97
M-190	Rhyolite	1.1	2.50	1.68	1.60	1.07
M-188	Nepheline Syenite	1.0	1.85	1.24	1.35	0.91
M-193	Anorthosite	0.5	1.65	1.11	1.55	1.04
M-189	Basalt	0.48	—	—	—	—
2. QUARTZOSE ROCKS						
M-176	Sandstone	1.3	—	—	—	—
M-179	Quartz	1.25	5.00	3.36	2.15	1.44
M-200	'Taconite'	1.0	3.80	2.55	2.24	1.51
M-199	Hornbl.-Qtz-Gneiss	0.7	2.50	1.68	1.82	1.22
3. CARBONATE ROCKS						
M-187	Dolom. Limestone	1.2	2.00	1.34	1.15	0.77
M-168	Dolostone	1.1	3.45	2.32	1.80	1.21
M-184	Limestone	0.74	2.24	1.51	1.43	0.96
M-185	Limestone	0.55	2.00	1.34	1.40	0.94

* Coefficient k_C unit: $\frac{\text{Kg-cal.}}{\text{m. hr. deg C}}$; k_F unit: $\frac{\text{Btu}}{\text{ft. hr. deg F}}$

After Mirkovich (59)

TABLE 1-C—THERMAL CONDUCTIVITY OF LIGHTWEIGHT CONCRETE

Density		Pumice, Cinder Aggregates		Expanded, Slag Aggregates		Aerated and Foam Concretes	
Kg/cu m.	lb/cu. ft	k _C	k _F	k _C	k _F	k _C	k _F
200	12.5	0.09	0.06	—	—	0.09	0.06
300	18.7	0.10	0.07	—	—	0.10	0.07
400	25.0	0.11	0.08	—	—	0.14	0.10
500	30.2	0.13	0.09	—	—	0.19	0.13
600	37.5	0.16	0.11	—	—	0.23	0.15
800	50.0	0.23	0.16	0.22	0.15	0.34	0.23
1000	62.5	0.31	0.21	0.27	0.18	0.46	0.31
1200	75.0	0.40	0.27	0.34	0.23	0.57	0.38
1400	87.5	0.49	0.33	0.42	0.28	0.70	0.47

After Cammerer (Ref. 56, Table VI)

*Under average building conditions and 7 percent moisture

TABLE 1-D—EFFECT OF MOISTURE ON THERMAL CONDUCTIVITY OF CONCRETE

Aggregate Specimen No.	Moisture Content		Density		Therm. Conductivity	
	by weight %	by volume %	Kg. cu.m.	lb cu. ft.	k _C	k _F
Dolerite						
No. 124	8.4	18.5	2370	148	1.74	1.17
—	5.2	11.5	2290	143	1.46	0.98
—	3.5	7.9	2260	141	1.32	0.89
—	2.2	5.0	2230	139	1.25	0.84
—	0.0	0.0	2180	136	1.10	0.74
Barite						
No. 161	5.3	15.0	3080	192	1.80	1.21
—	4.8	13.7	3060	191	1.76	1.18
—	4.0	11.4	3030	189	1.68	1.13
—	0.0	0.0	2920	182	1.18	0.79
Hematite						
No. 131	8.0	22.8	3060	191	3.69	2.48
—	9.7	19.8	3030	189	3.54	2.38
—	7.0	14.4	2980	186	3.26	2.19
—	0.0	0.0	2840	177	2.26	1.52

After Campbell—Allen (Ref. 55, Table 4)

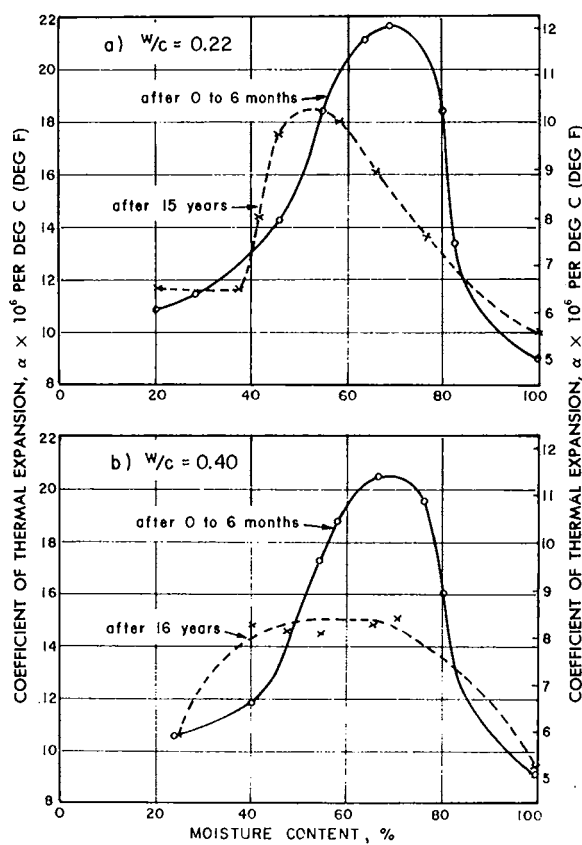


Fig. 1-1—Effect of age and moisture content on thermal expansion coefficient of hardened cement paste

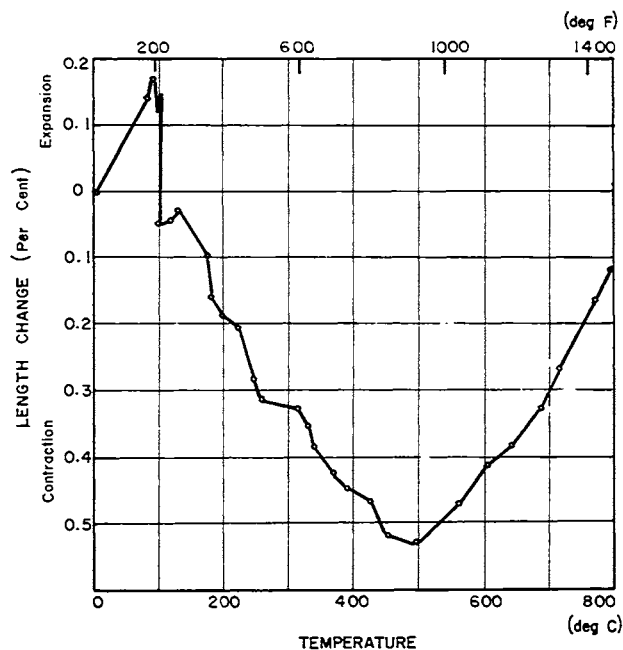


Fig. 1-2—Length change of hardened cement paste upon heating

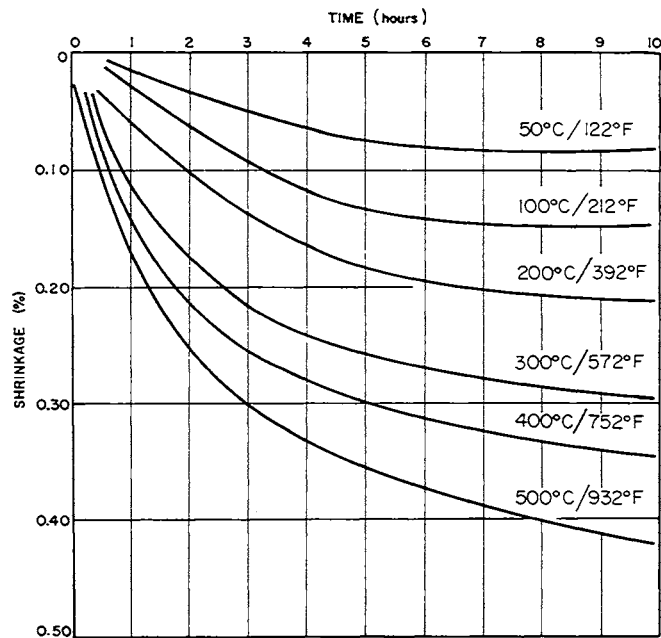


Fig. 1-3—Shrinkage of hardened cement paste at sustained elevated temperatures

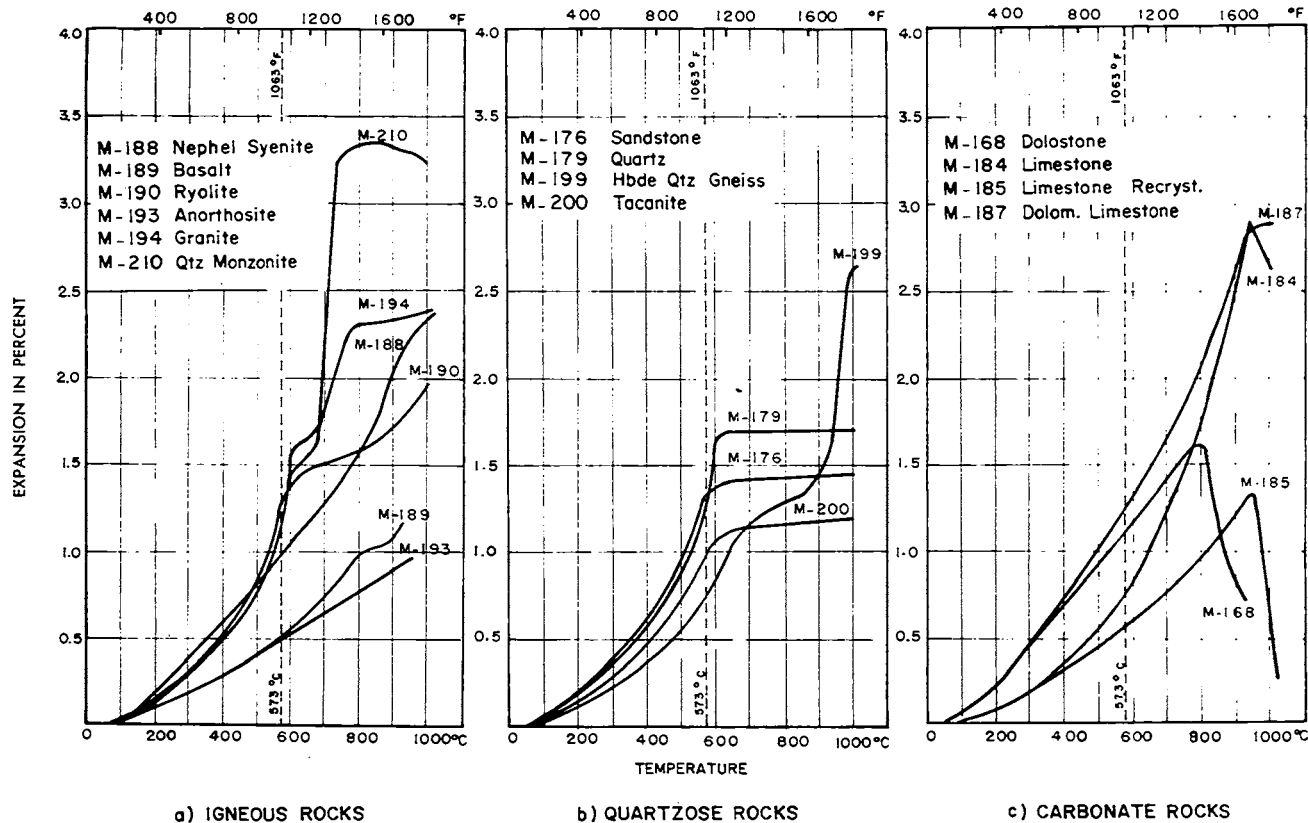


Fig. 1-4—Linear thermal expansion curves of different rocks^{42,43}

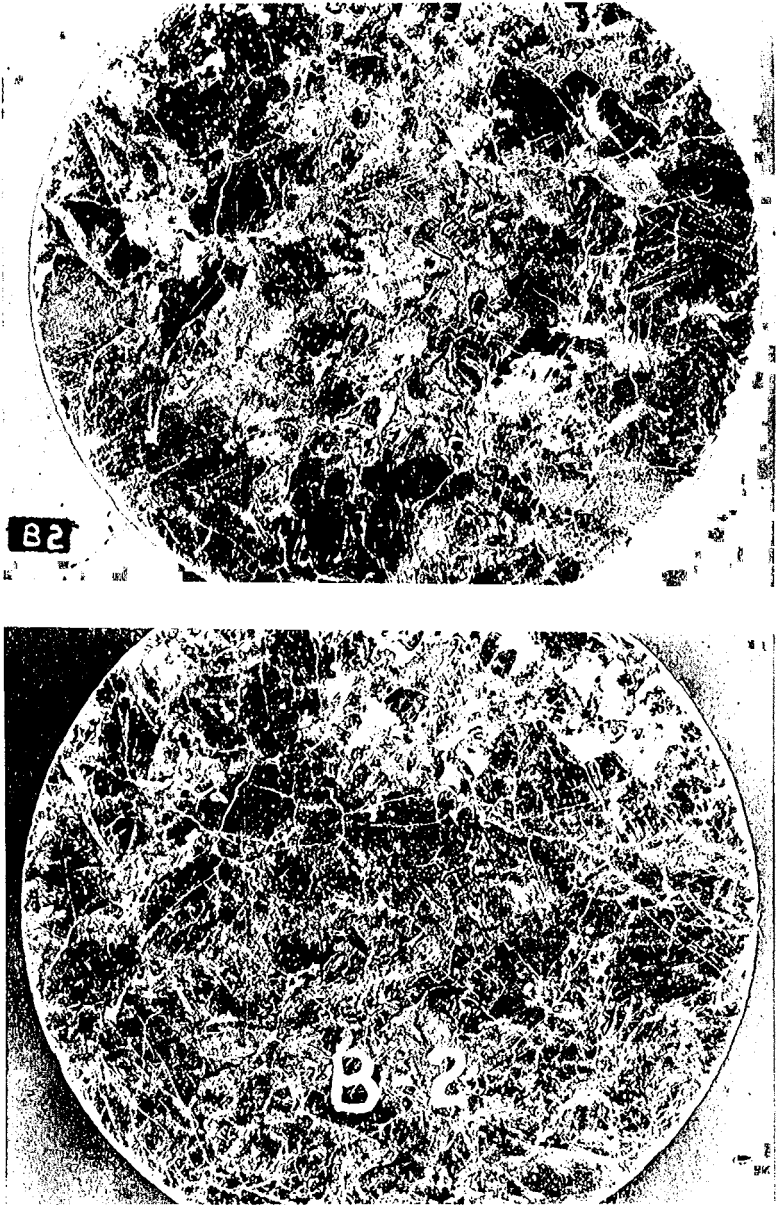


Fig. 1-5—Lake St. John anorthosite core fired at 700 C

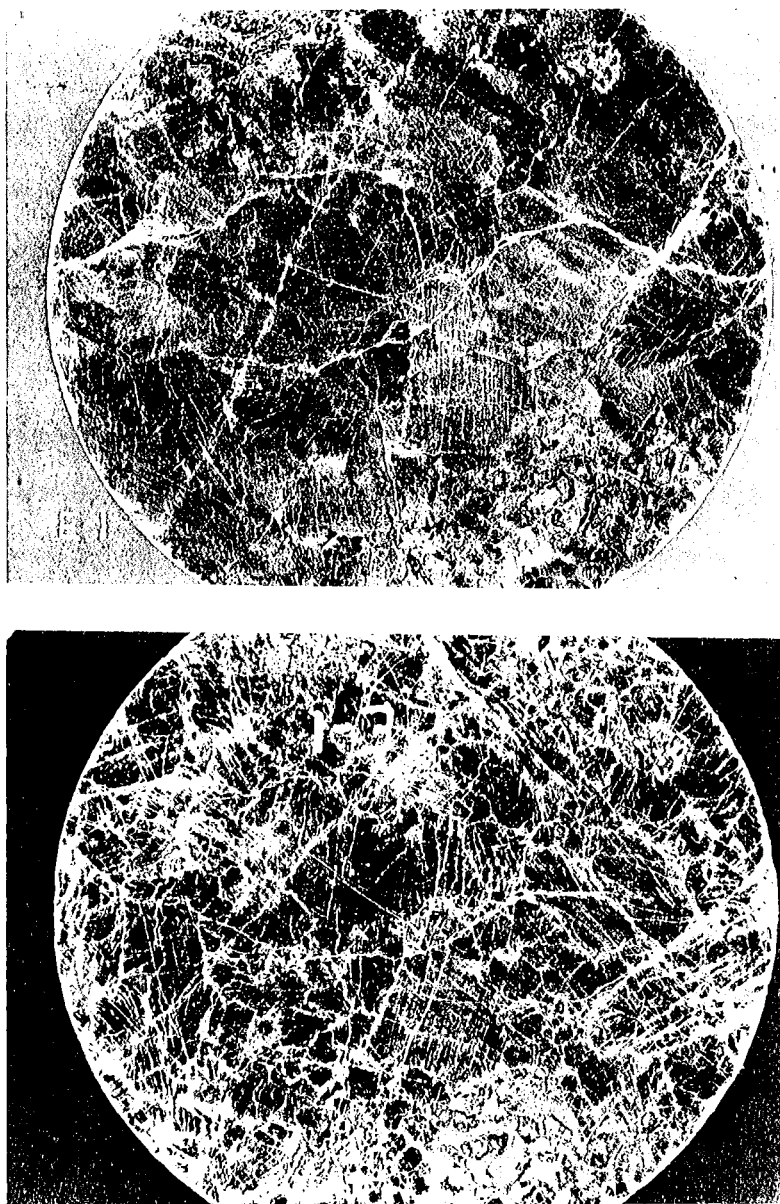


Fig. 1-6—Lake St. John anorthosite core fired at 1000 C

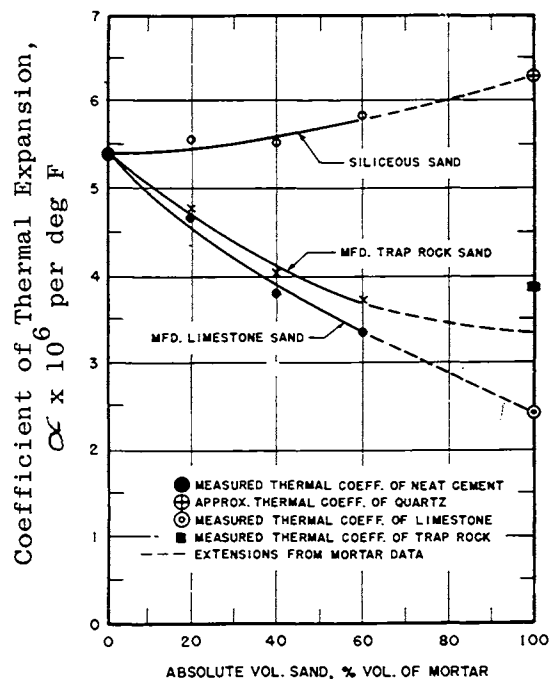


Fig. 1-7—Relationship between coefficient of thermal expansion of mortar, type of sand and mix proportions

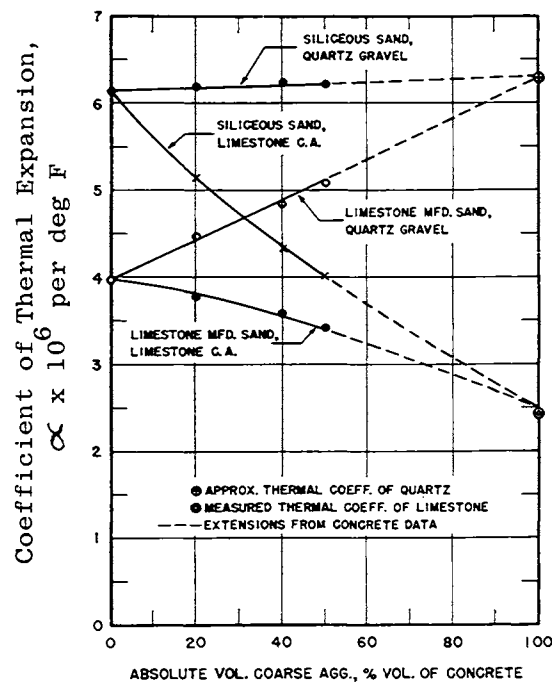


Fig. 1-8—Relationship between coefficient of thermal expansion of concrete and mix proportions for different aggregates

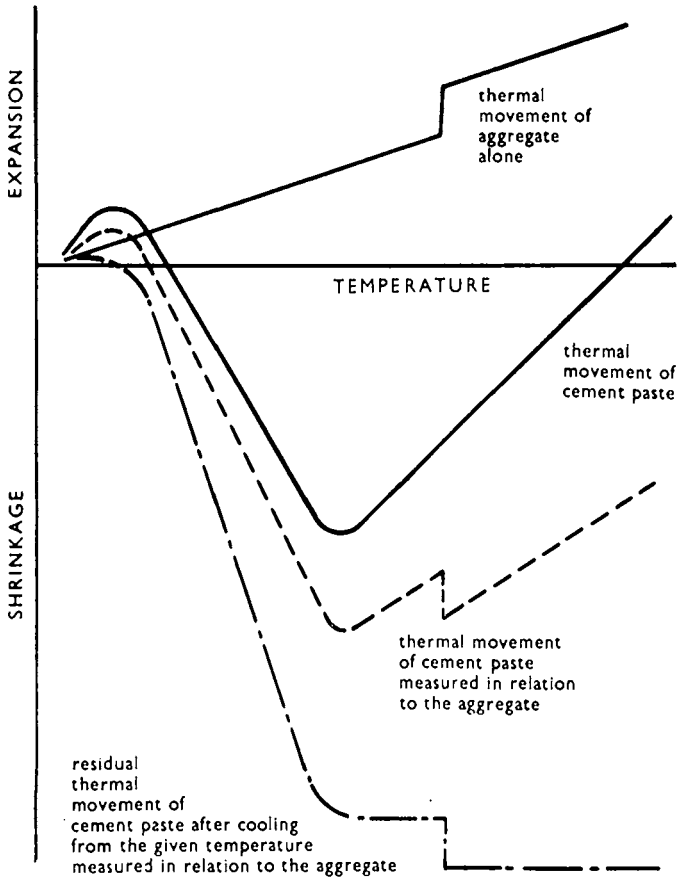
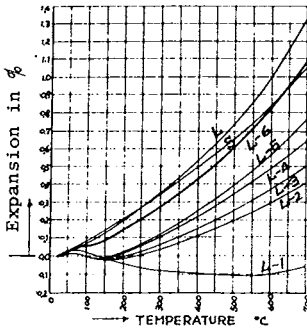
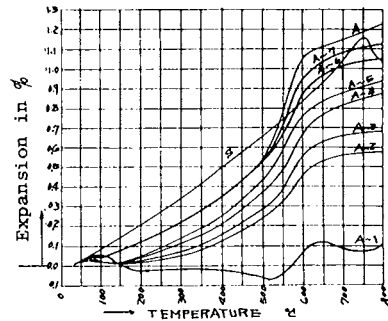


Fig. 1-9—The thermal movement of a cement paste measured relative to a typical siliceous aggregate



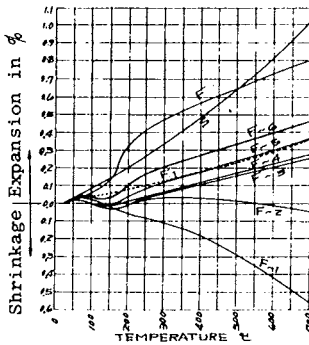
(a) LIMESTONE AGGREGATE

L: expansion of limestone
L-1 to L-5: mortars (1:1 to 1:5)
L-6: concrete (1:1.9:2:2.85)



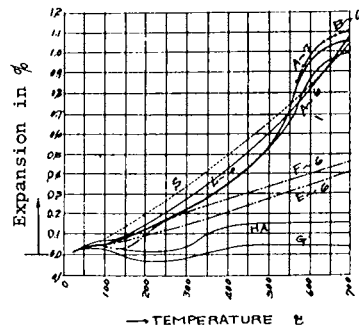
(b) SANDSTONE AGGREGATE

A: expansion of sandstone
A-1 to A-5: mortars (1:1 to 1:5)
A-6 & A-7: concrete
(1:2.0:2.5 & 1:2.3:2.9)



(c) ANDESITE AGGREGATE

F: expansion of andesite
F-1 to F-5: mortars (1:1 to 1:5)
F-6: concrete (1:2.0:3.0)



(d) CONCRETES WITH DIFFERENT TYPES OF AGGREGATES

A-6 & A-7: sandstone, as in (b)
B-6: another sandstone (1:1.8:3.6)
L-6: limestone concrete (1:1.9:2.85)
F-6: andesite concrete (1:2.0:3.0)
E-6: another andesite (1:1.7:3.4)
G: expands. of pumice concrete
HA: expands. of cinder concrete
S: expands. of reinf. steel

Fig. 1-10—Effect of elevated temperatures on length changes of mortars and concretes made with different aggregates

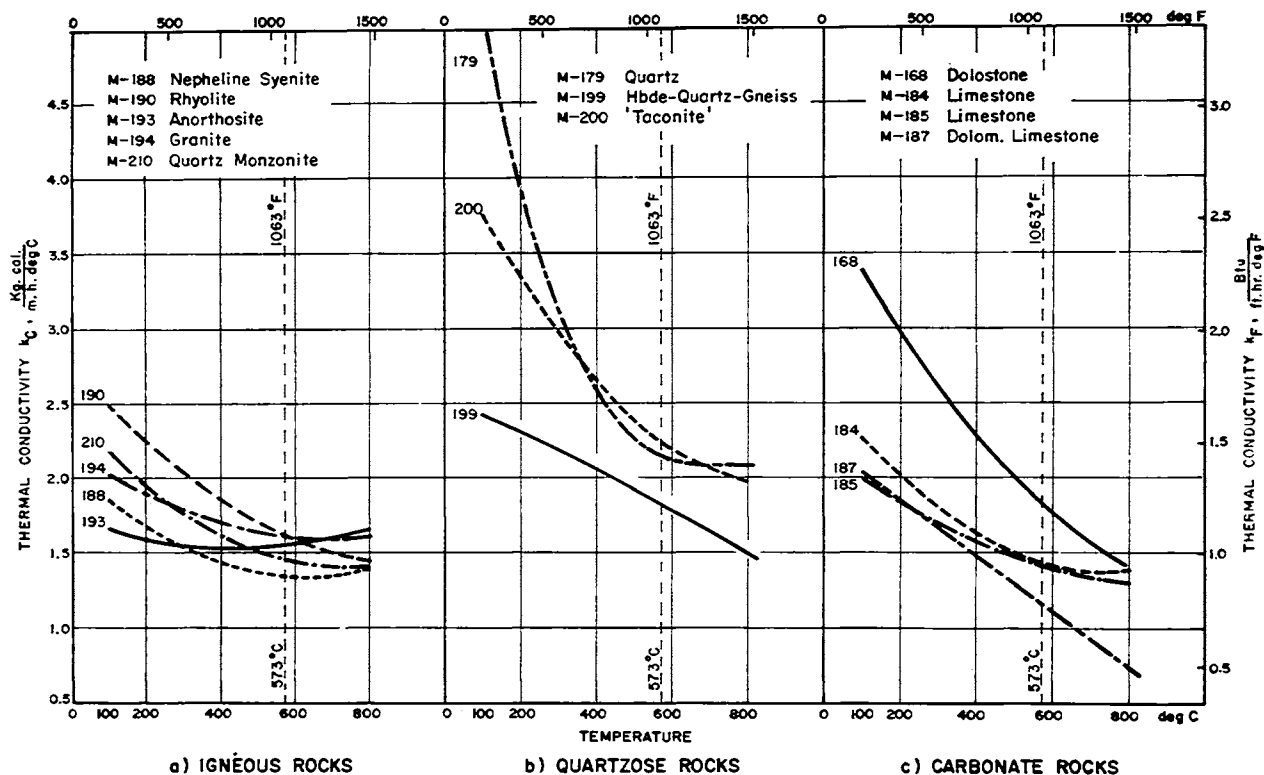


Fig. 1-11—Effect of elevated temperatures on thermal conductivity of rocks

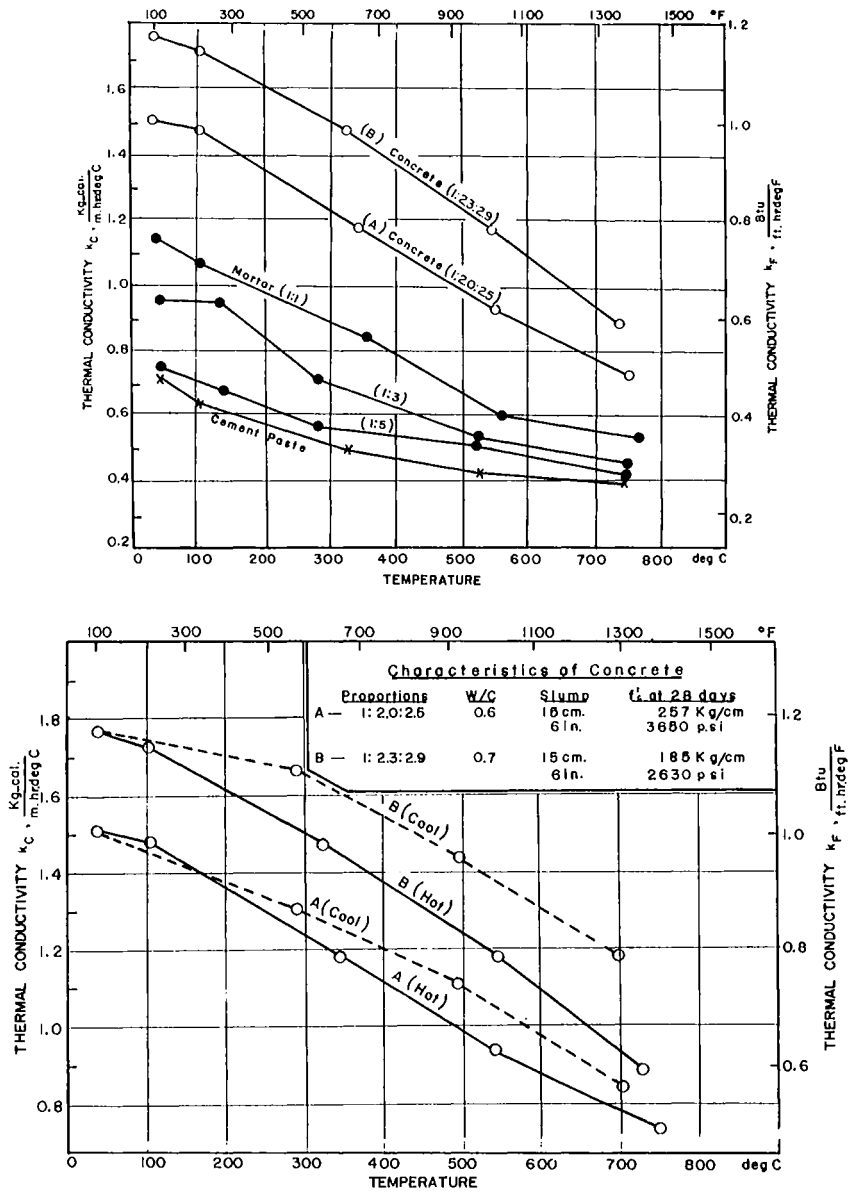


Fig. 1-12—Effect of elevated temperatures on the thermal conductivity “K”

COMPRESSIVE STRENGTH OF CONCRETE AT TEMPERATURES TO 1600F

By M. S. ABRAMS

Compressive strength tests were conducted on 3 x 6 in. (7.5 x 15 cm) cylindrical specimens heated for short duration to temperatures of 200 to 1600F (93 to 871C). Variables included aggregate type (carbonate, siliceous, and lightweight), test procedure (heated without load and tested hot, heated with load and tested hot, and tested cool after heating), and original strength of concrete (3300 to 6500 psi—230 to 455 kg/cm²). Carbonate aggregate concrete and lightweight concrete tested hot without prior loading retained about 75 percent of their original strengths (strengths prior to heating) at 1200F (649C). Above that temperature, lower strengths were obtained. Specimens heated while loaded had the highest strengths, while strengths of specimens heated, cooled, and then tested were the lowest throughout the temperature range. Original strength of concrete had little effect on the percentage of strength retained at high temperatures. The sanded lightweight concrete had strength characteristics at high temperatures similar to those of carbonate concrete. At temperatures above 800F (427C), the siliceous aggregate concrete had lower strengths than the other concretes.

Keywords: aggregates; carbonate aggregates; compressive strength; concretes; expanded shale aggregates; fire resistance; high temperature tests; lightweight aggregate concretes; lightweight aggregates; petrography; plain concrete; research; siliceous aggregates.

□ In recent years progress has been made toward the development of rational methods for calculating the behavior of concrete structures subjected to fire or to other high temperature exposure conditions. It is now possible to calculate the fire endurance of simply supported prestressed concrete beams and slabs with a reasonable degree of accuracy.¹ For simply supported members, differences in the strength of concrete in the compressive zone caused by fire are relatively minor and do not significantly affect the fire endurance. However, in the design for fire resistance of continuous beams or slabs, restrained floors or roofs, or more complex frames, data on the compressive strength of concrete at high temperatures are often needed.² At these temperatures the concrete materials may undergo transformations such as calcination of carbonate aggregates, abrupt expansion due to inversion of quartz, or dehydration of cement paste. Such transformations are likely to affect strength of concrete. This program was undertaken to develop additional desired information.

Test conditions were selected to simulate a variety of exposure environments likely to occur in a fire of several hours duration. Some tests were

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intended to simulate conditions of concrete under no initial stress (unstressed) and exposed to high temperatures. Other tests (stressed) simulated concrete in columns or compressive zones of flexural members subjected to heat. In addition, some tests (unstressed residual) were intended to yield information on strength of unstressed concrete which had been exposed to fire.

TEST PROGRAM

Specimens

Specimens were concrete cylinders 3 in. (7.5 cm) in diameter by 6 in. (15 cm) in height. They were cast in groups of 11—four for high temperature tests, six for room temperature tests, and one for monitoring humidity. The high temperature test specimens contained three thin-wire, butt-welded thermocouples along the axis, one at the middle and one 1/2 in. (1.3 cm) from each end, Fig. 2-1. Thermocouples were positioned within 1/32 in. of the desired location. Positioning was accomplished by drawing the wire taut diametrically through specially designed steel molds in which the concrete was cast. The specimen used for humidity control contained a Monfore type humidity well³ along the axis of the cylinder.

Materials

One of the variables was the type of aggregate. A carbonate, a siliceous, and an expanded shale lightweight aggregate were included. In each case the maximum size was 3/4 in. (2 cm). The carbonate aggregate was a dolomitic sand and gravel from Elgin, Illinois, while the siliceous aggregate was sand and gravel from Eau Claire, Wisconsin. Petrographic descriptions of the three aggregates are given in the Appendix.⁴ Each sand was air-dried and screened into six size fractions and recombined prior to batching in the proportions shown in Table 2-1.

A blend of four Type I cements from different sources was used.

Three different concretes, each with two strength levels, were used, and the data on the concrete mixtures are given in Table 2-2. The two light-

weight concrete mixes contained sand from Elgin, Illinois, and are referred to throughout the text as "sanded lightweight concrete."

Specimen Preparation

Each eleven-specimen group was made from a 0.7 cu ft (20 liter) batch. Concrete was consolidated in steel molds in three lifts on a table vibrator. Specimens were cured under damp burlap at 70 to 75F (21 to 24C) for 24 hours, after which the specimens were removed from the molds and stored in a fog room for 6 days. Ends of the specimens were ground plane. Test cylinders were then stored in an atmosphere of 30 to 40 percent R.H. and 70 to 75F (21 to 24C) until the relative humidity at the center of the monitor specimen reached 75 percent. A period of 3 to 6 weeks was required depending on aggregate type and concrete strength. To prevent further drying, specimens not tested immediately after reaching 75 percent R.H. were placed in air controlled at 70 to 80 percent R.H. and 70 to 75F (21 to 24C) until test. Some specimens of Mixes I, III, and V were dried at 230F (110C) to constant weight.

Test Procedures

Fig. 2-1 shows the test setup. Steel cylinders, 3 in. (7.5 cm) diameter by 6 in. (15 cm) long with machined ends were used to transmit the load from the testing machine to the specimen. To prevent excessive heat flow away from the specimen, two cement-asbestos insulating discs were placed between the steel cylinders and the testing machine. Prior to use, the discs were compressed with a load equivalent to about 1.5 times the concrete strength. This effectively prevented excessive deformation of the discs under load. Insulating rings (Fig. 2-1) of the same material were used to minimize heat loss. The arrangement effectively maintained a nearly uniform temperature throughout the specimen length.

Temperatures of the concrete were monitored throughout each test. In addition to the three internal thermocouples, a fourth one was attached to the surface of the specimen at midheight. Tests were performed at various temperatures between 70 and 1600F (21 to 871C). During heating, the temperature difference within the specimen, as measured by the thermocouples, was restricted to 150F (83C) by controlling the heat output of the electric furnace. When the surface of the concrete reached the test temperature, the specimen was allowed to equilibrate until the temperature was essentially uniform vertically and radially. For test temperatures up to 600F (316C), compression tests were not conducted until the maximum difference among the four thermocouple readings was within 20F (11C). For higher test temperatures, the difference was limited to 3 percent of the test temperature in Fahrenheit degrees. In general 3 to 4 hours were required to achieve a uniform test temperature within the specimen.

From each group of specimens, four were heated, and tests performed in one of three ways:

"Unstressed." -- Specimen was heated to the test temperature in an unloaded condition and then loaded to failure.

"Stressed." -- A compressive load was maintained on the specimen during heating. When the test temperature was reached, the load was increased until failure occurred. Prior to performing the high temperature test, the strength at room temperature, f'_c , was determined by testing the companion specimens. "Stressed" tests were performed at stress levels, f_c , of 0.25,

0.40, and 0.55 f'_c . Room temperature strength tests were made with the same equipment as that used for heated tests.

"Unstressed residual." -- The specimen was heated in an unloaded condition to test temperature and allowed to cool slowly (generally overnight) to room temperature. The specimen was then stored in air at 70 to 80 percent R.H. and 70 to 75 F (21 to 24C) for 7 days. Both the residual-strength specimens and their companion control specimens were tested in accordance with ASTM C 39.⁵

Specimens from the same group were tested at 70 F within two days of the tests of their companion heated specimens.

DISCUSSION OF TEST RESULTS

Table 2-3 gives a summary of the test program and shows the number of compression tests performed for each test condition. At least two tests were performed for each condition. In many instances, three to seven tests were conducted. All of the results for any specific test condition were used in determining the average strength for that condition. Good agreement was obtained among results for each test condition. For the 148 conditions at elevated temperatures the results, expressed in terms of the room temperature strength, differed by less than 5 percent in 74 cases, 6 to 10 percent in 30 instances, 11 to 20 percent for 34 conditions, and greater than 20 percent in 10 cases. Three or more tests were performed in nearly all instances when the difference in results exceeded 10 percent.

Other investigators have reported on differences in compressive strength test results at high temperatures. Harmathy and Berndt⁶ noted from studies on mortar and lightweight concrete that specimens assumed to be identical and subjected to the same test condition often yielded differences in results of the order enumerated above.

Results of other studies are cited in the discussion that follows. In general, direct comparisons of results of different studies are difficult to interpret because of differences in testing, materials, and specimen size.

Effect of Test Procedures

Carbonate aggregate concrete—mix I. -- Fig. 2-2 shows the effect of temperature on compressive strength of carbonate aggregate concrete, Mix I, for three conditions of test, unstressed, stressed to 0.40 f'_c , and unstressed residual. Strengths of the unstressed specimens diminished gradually from that at room temperature until at 1200 F (649C) the concrete retained about 75 percent of its original strength. At 1400 F (760C) the strength remained above 50 percent but it declined significantly at higher temperatures, probably owing to calcination of the carbonate aggregates.⁷ Strengths were higher over the entire temperature range for specimens stressed to 0.40 f'_c during heating; at 1200 F (649C) the strength was about the same as the original strength; and at 1400 F (760C) the carbonate aggregate concrete retained 80 percent of its original strength. The greatest losses in strength were recorded in the unstressed residual tests.

Siliceous aggregate concrete—mix III. -- Fig. 2-3 shows the influence of temperature on compressive strength of concrete made with siliceous aggregate for the various test procedures. In the unstressed condition the concrete retained 75 percent of its original strength at 850 F (454C), 50 percent at 1000 F (538C) and 25 percent at 1300 F (704C). The relatively high thermal

expansion of siliceous rocks and the abrupt volume change which accompanies the inversion of quartz from the α to β form at about 1060F (571C) probably account for this decrease in strength. It should be noted, however, that at 1060F (571C) there is not an abrupt change in strength.

Stressing the concrete had a beneficial effect over the entire temperature range, particularly between 800 and 1400F (427 and 760C). Malhotra⁸ has attributed the smaller strength loss under the stressed condition to a retardation of crack formation.

The unstressed residual strength of the siliceous aggregate concrete was lower than the strength at high temperatures over the entire temperature range. The residual strength declined gradually to a value of 55 percent of original at 900F (482C). At higher temperatures, the rate of strength loss was greater.

Sanded lightweight concrete—mix V. -- Fig. 2-4 shows the strength-temperature relationships for Mix V concrete specimens. Specimens stressed to 0.40 f'_c yielded higher strengths than unstressed specimens at temperatures above 700F (371C). At 1300F (704C) the sanded lightweight concrete retained more than 70 percent of its original strength and at 1500F (816C), more than 40 percent. The unstressed residual strengths were lower than the strengths at high temperatures for the sanded lightweight concrete reflecting the same pattern as the two normal weight concretes.

General comments. -- For all three concretes, specimens stressed during heating retained the highest strengths at high temperatures. Specimens heated while stressed and tested hot had strengths 5 to 25 percent higher than companion specimens that were unstressed during heating. Even so, the carbonate aggregate concrete and the sanded lightweight concrete retained over 70 percent of their original strengths at 1250F (677C) when tested by the "unstressed" procedure. The siliceous aggregate concrete retained 70 percent of its strength at 900F (482C) when tested unstressed. For all three concretes, unstressed residual strengths were lower than the "hot" strengths.

The above observations concerning the influence of test procedure generally agree with those reported by Malhotra,⁸ whose tests extended to about 1100F (593C). However, in the present study the strength reductions were smaller for all three conditions of test. Results of the unstressed sanded lightweight concrete agree closely with those reported by Harmathy and Berndt⁶ for a similar concrete tested at temperatures up to 1400F (760C). Results of unstressed tests of carbonate aggregate concrete and sanded lightweight concrete agree with those obtained by Saemann and Washa⁹ from 70 to 450F (21 to 232C) except at 200F (93C).

It appears that the testing technique used in the present study resulted in lower unstressed residual strengths than those obtained by other techniques. For example, Zoldners¹⁰ reported unstressed residual strength results of 4 x 8 in. (10 x 20 cm) cylinders made of siliceous aggregate concrete and limestone (carbonate) aggregate concrete. After a 7 day moist curing period followed by dry storage up to a year the specimens were fired. Specimens were then cooled 24 hours to room temperature, desiccated 4 hours and tested in compression. His results were higher for specimens heated throughout a range of 68 to 1472F (20 to 800C) than the unstressed residual strengths obtained in the present study. The difference in residual strengths is probably the result of the 7 day conditioning period in air at 70 to 80 percent R.H. in

the present study. This observation is supported by the work of Weigler and Fischer¹¹ who reported that the strength of portland cement mortar heated to 1022F (550C) and cooled to room temperature decreased as the storage period in air increased from 1 to 7 days. Weigler and Fischer¹¹ reported strength increases in mortar specimens when stored in water after cooling. In the current investigation, residual strength tests were not performed on concrete which was stressed during heating. Results of such tests were reported by Weigler and Fischer¹² on concretes made with barite aggregate and quartz aggregate. They observed that the specimens stressed to 0.33 or 0.50 f'_c during heating to 842F (450C) had residual strengths equal to or greater than those of companion specimens not stressed during heating.

Effect of Oven Drying

As noted previously most specimens were tested when the relative humidity reached 75 percent. However, the specimens that were tested at 200F (93C) were oven dried at 230F (110C) to constant weight prior to testing. Preliminary work showed that at 200F (93C) a specimen with 75 percent R.H. did not dry completely or uniformly during a 3 or 4 hour heating period. In fact, the reading on a humidity control specimen was 85 percent after a 4 hour heating period, indicating that the evaporable moisture was redistributed during heating and cooling. The resulting moisture gradient probably caused the periphery of the cylinder to shrink more than the center making the ends (which had been ground flat) convex. Work by Gonnerman¹³ indicated that a very small degree of convexity of the ends of specimens can result in reductions in compressive strength of 35 percent or more. Preliminary tests performed in the present study with specimens dried to 75 percent R.H. yielded results that were 20 to 30 percent lower than subsequent tests conducted on oven-dried specimens. However, at temperatures of 400F (204C) and higher no strength loss attributable to moisture gradients was observed.

Saemann and Washa⁹ reported strength losses of about 20 percent at 200F (93C) on 6 x 12 in. (15 x 30 cm) concrete cylinders. Observations of samples of concrete from the broken cylinders indicated that moisture was still present after the 24-hour preconditioning period at 200F (93C). Binner et al.¹⁴ indicated from work on high density concrete that preconditioning periods of 7 or 14 days at 200F (93C) resulted in no loss of strength when the concrete was cooled and tested. Harmathy and Berndt⁶ reported no loss in strength at 200F (93C) for lightweight concrete dried to constant weight at 221F (105C) prior to test.

Effect of Stress Intensity During Heating

Fig. 2-5 summarizes the data for all six concrete mixes on the effect of stress intensity during heating. It can be noted that in nearly every case, the stress level during heating had little effect on the compressive strength of concrete at any given test temperature. These results were independent of (a) original strength of the concrete, (b) aggregate type, and (c) the test temperature. It is of interest to note that certain results of residual strength tests reported by Weigler and Fischer¹² were invariant under a "critical load" which ranged from 0.33 to 0.50 f'_c .

Effect of Original Compressive Strength

Fig. 2-6 summarizes the data which show the effect of original compressive strength on the strength determined by the three test methods, unstressed, stressed (to 0.40 f'_c), and unstressed residual. It can be noted from the 32 comparisons that the original strength level of the concrete, within the

ranges used in this study, has little effect on the percentage of compressive strength retained at elevated temperatures or after cooling. This observation appears to be independent of test procedure, aggregate type, or exposure temperature. Malhotra⁸ and Weigler and Fischer¹¹ reported similar findings.

Effect of Aggregate Type

The data in Figs. 2-2, 2-3, and 2-4 have been replotted in Figs. 2-7, 2-8, and 2-9 to show the influence of aggregate type on compressive strength of concrete at high temperatures. In general, the three concretes exhibited similar strength loss characteristics under each test condition to about 900F (482C). Above 900F (482C) the siliceous aggregate concrete retained less strength for all three test procedures. Concretes made with either the carbonate or sanded lightweight aggregates behaved about the same over the entire temperature range.

Petrographic Examination of Heated Concretes

The high strengths retained by all three concretes at 900F (482C) and by the carbonate aggregate and sanded lightweight concretes at temperatures exceeding 1200F (649C) suggest that the physical condition of the concretes were not significantly altered by heating to those temperatures. Specimens of Mixes I, III, and V were heated without load to various temperatures up to 1500F (816C) and were allowed to cool for 24 hours. After cooling, specimens were encased in polyester resin, and sawed in half longitudinally. The sawed surface was then ground and polished. Photographs of the polished surfaces are shown in Figs. 2-10, 2-11, and 2-12.

Carbonate aggregate concretes, Fig. 2-10, heated to 800F (427C) and lower were similar to the unheated concrete. In the specimen heated to 1200F (649C), a small amount of mortar eroded around some particles of the sand during the sawing and polishing operations. The 1500F (816C) specimen, which had a lower retained strength, exhibited a higher degree of mortar erosion around the aggregate particles, indicating more extensive loss of bond between the aggregate and paste. A longitudinal crack can be seen near the surface. However, the carbonate aggregate particles appear to be unaffected.

The siliceous aggregate concrete, Fig. 2-11, which retained 70 percent of its original strength when tested unstressed at 900F (482C), shows indications of paste-aggregate bond loss at temperatures above 1000F (538C). This bond loss, as evidenced by erosion of mortar during sawing and polishing, probably accounts for the relatively low strengths at temperatures above 900F (482C).

Very little change was observed in the physical condition of the sanded lightweight concrete specimens, Fig. 2-12. The specimen heated to 1500F (816C) developed longitudinal cracks about 3/8 in. (1 cm) from the surface.

SUMMARY

1. Specimens made of the carbonate aggregate concrete or the sanded lightweight concrete (replacement of 60 percent of the fines with sand from Elgin, Illinois) retained more than 75 percent of their original strengths at temperatures up to 1200F (649C) when heated without load and tested hot. The corresponding temperature for the siliceous aggregate concrete was about 800F (427C)

2. Strengths of specimens stressed in compression during heating were generally 5 to 25 percent higher than those of companion specimens which were not stressed during heating
3. Unstressed residual strengths (specimens heated, cooled, and then tested) were somewhat lower than the strengths of companion specimens tested at high temperatures
4. Strengths of specimens stressed in compression during heating were not significantly affected by the applied stress level, which ranged from 25 to 55 percent of the original strength
5. Original strength of the concrete had little effect on the percentage of strength retained at test temperatures

These observations are based on results of compressive tests of 3 x 6-in. (7.5 x 15 cm) cylindrical specimens performed at various temperatures up to 1600F (871C). Three different concretes, each with two strength levels were used and three test procedures were followed.

ACKNOWLEDGMENT

The author is grateful to the staff of the PCA Chemical and Petrographic Research Section who conducted the petrographic examinations, and to Francis J. Hensler who performed most of the compression tests.

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TABLE 2-1—GRADING OF AGGREGATES

Sieve size	Percent retained						
	Carbonate ^a		Siliceous ^b		Expanded shale ^c		
	Sand	Gravel	Sand	Gravel	Fine	Medium	Coarse
3/4 in.	—	0	—	0	—	—	0
3/8 in.	—	50	—	50	—	1	78
No. 4	1	100	1	100	0	56	99
8	14	—	14	—	20	93	—
16	23	—	23	—	51	—	—
30	45	—	45	—	75	—	—
50	75	—	75	—	90	—	—
100	98	—	98	—	96	—	—
Fineness modulus	2.56	—	2.56	—	3.33	—	—

^aSand and gravel from Elgin, Ill.

^bSand and gravel from Eau Claire, Wis.

^cRotary-kiln produced expanded shale from Ottawa, Ill.

Note: Carbonate and siliceous aggregates were screened into individual sieve size fractions and recombined as indicated.

TABLE 2-2—DATA ON CONCRETE MIXES

Item	Mix I	Mix II	Mix III	Mix IV	Mix V	Mix VI
	Carbonate aggregate ^a concrete		Siliceous aggregate ^b concrete		Sanded lightweight ^c concrete	
Batch quantities, lb per cu yd (kg/m ³)						
Cement	398(237)	534(317)	419(249)	555(330)	444(264)	588(350)
Coarse aggregate	1825(1085)	1675(995)	1810(1080)	1680(1000)	525(312)	515(306)
Medium aggregate	—	—	—	—	305(181)	295(176)
Fine aggregate	—	—	—	—	410(244)	585(348)
Sand	1440(855)	1465(870)	1435(855)	1475(880)	870(518)	555(330)
Water	218 ^d (130)	226 ^d (134)	214 ^d (127)	221 ^d (132)	346 ^e (206)	346 ^e (206)
Average air content, percent	6.0	5.6	5.0	5.0	5.9	6.4
Average unit weight, pcf(kg/m ³)	144(2310)	144(2310)	144(2310)	146(2340)	107(1720)	107(1720)
Average compressive strength at test (unheated specimens), psi(kg/cm ²)	3900(275)	5600(395)	3900(275)	5500(385)	3900(275)	6300(445)

^a 3/4 in. (nom. 2 cm) maximum size gravel and sand from Elgin, Illinois.

^b 3/4 in. (nom. 2 cm) maximum size gravel and sand from Eau Claire, Wisconsin.

^c Rotary-kiln produced expanded shale from Ottawa, Illinois, and sand from Elgin, Illinois.

^d Based on saturated surface-dry aggregates.

^e Based on dry aggregates.

TABLE 2-3—NUMBER OF COMPRESSION TESTS PERFORMED FOR EACH CONDITION

Strength range, psi (kg/cm ²)	3410 to 4330 (240 to 305)					3310 to 4660 (230 to 330)					3420 to 4630 (240 to 325)				
Aggregate	Carbonate ^a					Siliceous ^b					Sanded lightweight ^c				
Type of test ^d	U	Stressed			R	U	Stressed			R	U	Stressed			R
Stress level during heating, f_c/f'_c	0	0.25	0.40	0.55	0	0	0.25	0.40	0.55	0	0	0.25	0.40	0.55	0
Temperature, F(C)															
70(21)	45	12	45	12	18	50	18	50	6	18	30	12	40	12	18
200(93)	2		2			2		2			2		2		
400(204)	4	4	3	2	3	4	2	5	2	2	3	2	4	2	2
600(316)	4		3			4		4			3		7		
700(371)					2					2					3
800(427)	4		3			3		5			5		6		
900(482)		2		2		2	2	5	2	2		2		2	
950(510)						4		4							
1000(538)	4		4		2	4		4		2	7		7		2
1200(649)	4		4			3		4			5		5		
1300(704)	3	2	4	2	2	2	4	2		2	2	2	2	2	2
1400(760)	2		4		2	2	3				2		2		
1500(816)	2		2			2	3				2		2		
1600(871)	2		2			2	2				2		2		2
Strength range, psi (kg/cm ²)	5310 to 6340 (375 to 445)					5380 to 5720 (380 to 400)					6000 to 6500 (420 to 455)				
70(21)	18	12	12	12	12	12	12	12	6	12	12	12	12	12	12
400(204)	3	2	2	2	2	2	4	3	2	2	2	2	2	2	2
900(482)	3	2	2		2	2	2	2	2	2	2	2	2	2	2
1000(538)				2											
1200(649)								2							
1300(704)	2	2	2	2	2	2	2	2		2	2	2	2	2	2
1400(760)					2										
1600(871)	2		2			2					2		2		2

a 3/4-in. (2-cm) maximum size gravel and sand from Elgin, Illinois.

b 3/4-in. (2-cm) maximum size gravel and sand from Eau Claire, Wisconsin.

c Rotary-kiln produced expanded shale from Ottawa, Illinois, and sand from Elgin, Illinois.

d U = Unstressed; S = Stressed; R = Unstressed Residual.

APPENDIX—PETROGRAPHIC ANALYSES OF AGGREGATES

TABLE 2-A1—PETROGRAPHY OF SAND AND GRAVEL FROM ELGIN, ILLINOIS

Component	Composition of sieve fraction, Percent on sieve of size indicated											
Sieve size	3/4 in.	1/2 in.	3/8 in.	1/4 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	No. 200
Carbonate	91.1	87.4	87.3	85.6	87.6	80.5	79.6	64.4	46.1	36.4	65.0	92.0
Chert	3.6	4.2	5.2	7.6	6.1	8.9	11.0	—	—	—	—	—
Granite	1.1	1.2	3.5	1.8	2.4	3.6	2.4	—	—	—	—	—
Basalt	2.1	3.0	1.4	2.6	2.6	3.4	2.0	1.2	—	—	—	—
Gabbro	0.3	—	—	0.2	0.5	0.2	0.7	0.3	—	—	—	—
Quartzite	1.8	3.9	1.4	1.3	0.3	3.0	4.3	—	—	—	—	—
Gneiss-schist	—	0.3	1.2	0.9	0.5	0.4	—	—	—	—	—	—
Quartz-chalcedony	—	—	—	—	—	—	—	26.5	45.1	52.5	27.2	4.0
Feldspar	—	—	—	—	—	—	—	7.6	8.8	11.1	6.1	0.5
Misc. igneous and clays	—	—	—	—	—	—	—	—	—	—	1.7	3.5

Particle shape	Percent on sieve			
	3/4 in.-1/4 in.		No. 4 - No. 200	
	Carbonates	Silicates	Carbonates	Silicates
Rounded	—	—	—	30
Subangular to subrounded	80	100	75	60
Angular	—	—	—	10
Angular to subangular	20	—	25	—

TABLE 2-A2—PETROGRAPHY OF SAND AND GRAVEL FROM
EAU CLAIRE, WISCONSIN⁴

Component	Composition of sieve fraction, Percent on sieve of size indicated											
Sieve size	3/4 in.	1/2 in.	3/8 in.	1/4 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	No. 200
Granite	37.9	32.9	25.5	31.3	27.0	27.6	12.3	7.4	1.9	4.4	0.6	—
Quartzite	21.6	29.2	34.8	24.6	24.5	20.0	12.3	12.6	10.9	3.1	2.2	—
Quartz	6.3	3.1	4.9	4.8	5.5	18.8	52.2	62.0	73.1	79.5	74.2	92.0
Chert ^a	10.8	7.0	5.2	8.1	9.8	5.9	7.7	3.5	2.0	0.8	2.8	2.0
Sandstone-quartz conglomerate	1.9	0.8	3.1	5.1	5.5	8.3	—	—	—	—	—	—
Rhyolite-dacite	13.9	6.2	2.2	5.1	7.2	4.1	0.8	2.6	1.6	0.8	0.9	—
Feldspar	—	—	—	—	—	—	1.3	5.0	6.6	5.0	10.8	4.0
Diorite	1.9	1.4	3.1	1.8	1.2	—	—	—	—	—	—	—
Graywacke ^b	1.3	9.5	5.8	5.4	4.3	6.5	2.3	1.5	0.3	—	0.6	—
Gneiss-schist	2.5	5.1	10.5	9.3	7.5	4.1	6.4	1.8	0.9	1.1	0.6	—
Basalt	1.9	4.5	4.0	3.9	6.9	3.2	2.6	2.4	0.7	—	0.3	—
Misc. igneous rocks ^c and opaque minerals	—	0.3	0.9	0.6	0.6	1.5	2.1	1.2	2.0	5.3	7.0	2.0

^a "Ironstone," made up of jasper and hematite, is included in the chert classification.

^b Includes metagraywacke.

^c The miscellaneous igneous rocks were severely altered and positive identification was impossible. The opaque minerals occurred in the No. 50 and smaller sieve sizes and were largely magnetite.

Particle shape	Percent on sieve		
	3/4 in. - 1/4 in.	No. 4 - No. 16	No. 30 - No. 200
Subrounded to rounded	30	20	10
Subrounded to subangular	40	40	40
Angular	30	40	50

TABLE 2-3A—PETROGRAPHY OF EXPANDED SHALE FROM OTTAWA, ILLINOIS

Particle shape	Particle surface texture	Microstructural character of air void system	Mineralogy
Coarse aggregate			Mineralogy was similar for all samples examined. The following constituents were present: 50-70 percent glass, Refractive Index = 1.540-1.565 10-30 percent quartz 1-10 percent feldspar 1-10 percent unidentified micro-crystalline material Less than 1 percent iron oxides
Tabular to ellipsoidal, subangular to rounded.	Dense. Few voids greater than 1000 microns diameter were exposed.	Uniform structure with few or no bedding plane separations. Most voids were nearly spherical and isolated, but if connected, showed no directional preference for such connection. Isolated voids were from 5 to 25 microns diameter; a few up to 100 microns. 50-100 micron voids showed some tendency to coalescence. Voids uniformly and closely spaced. Largest voidless area observed was 900 square microns.	
Fine aggregate			
Tabular to ellipsoidal. Progressively more angular with decreasing particle size.	Very dense, smooth. Few voids at surface were larger than 100 microns.	Voids were similar to those described for coarse aggregate. Maximum dimensions of air voids limited by particle size.	

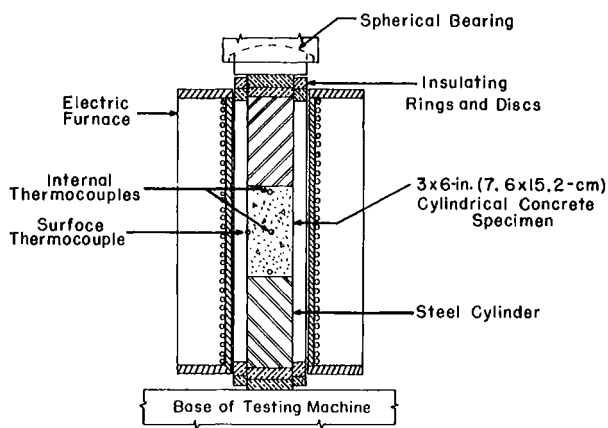


Fig. 2-1—Arrangement of test equipment

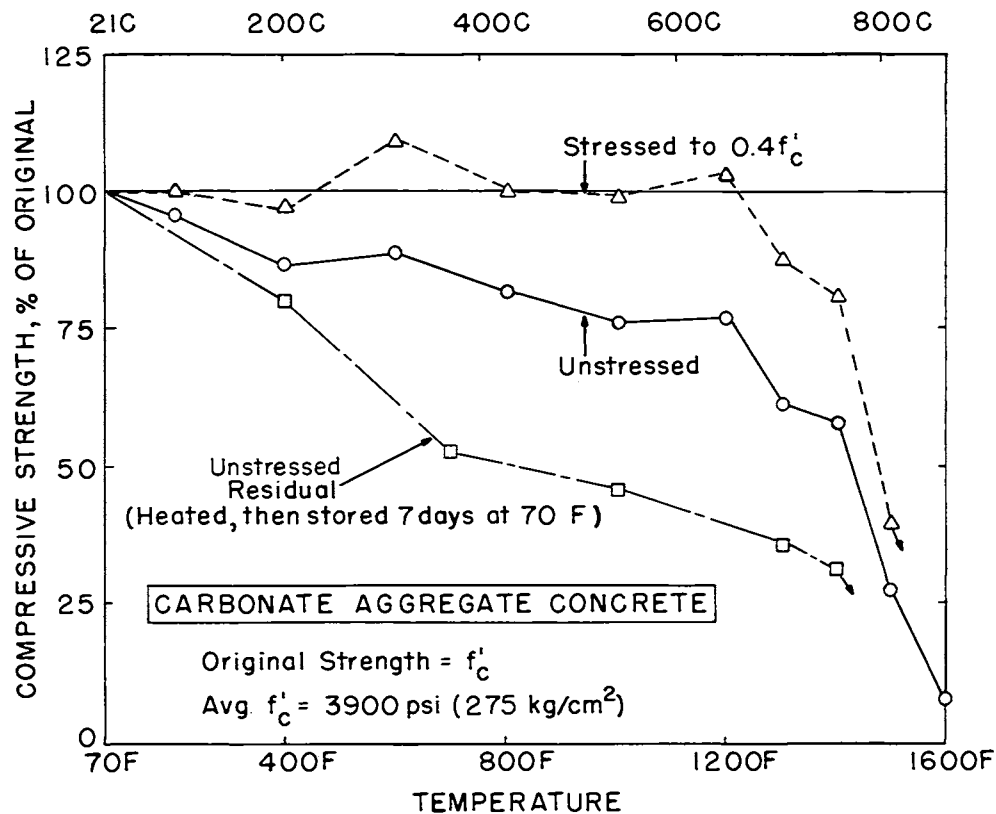


Fig. 2-2—Effect of temperature on compressive strength of carbonate aggregate concrete

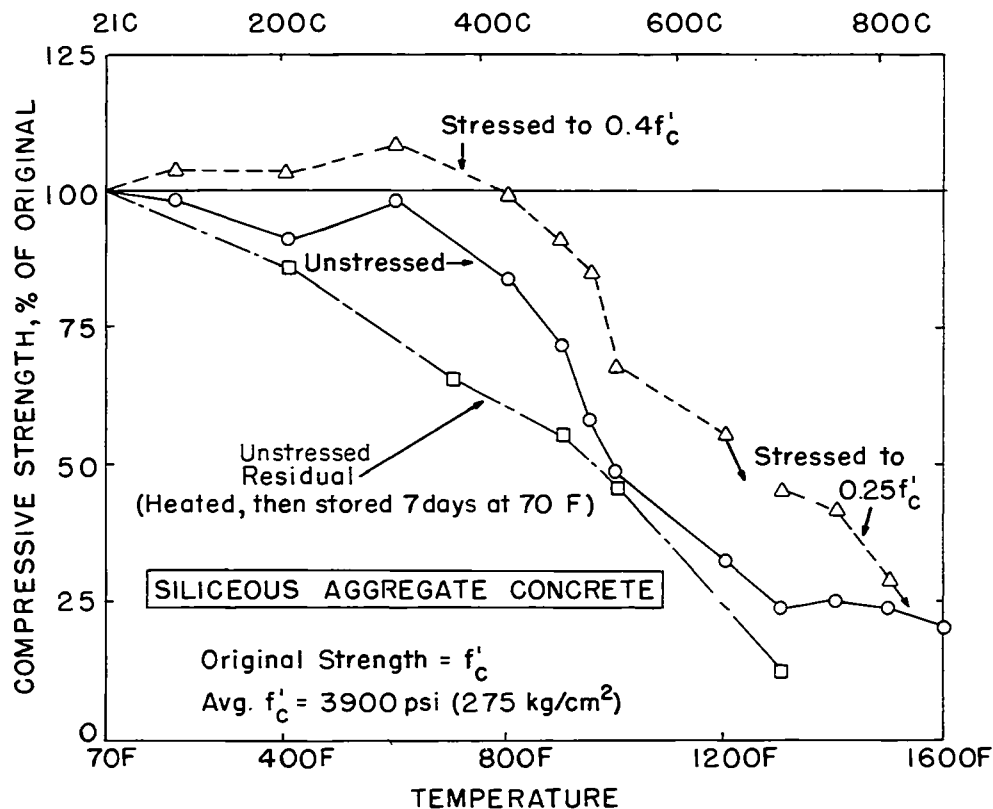


Fig. 2-3—Effect of temperature on compressive strength of siliceous aggregate concrete

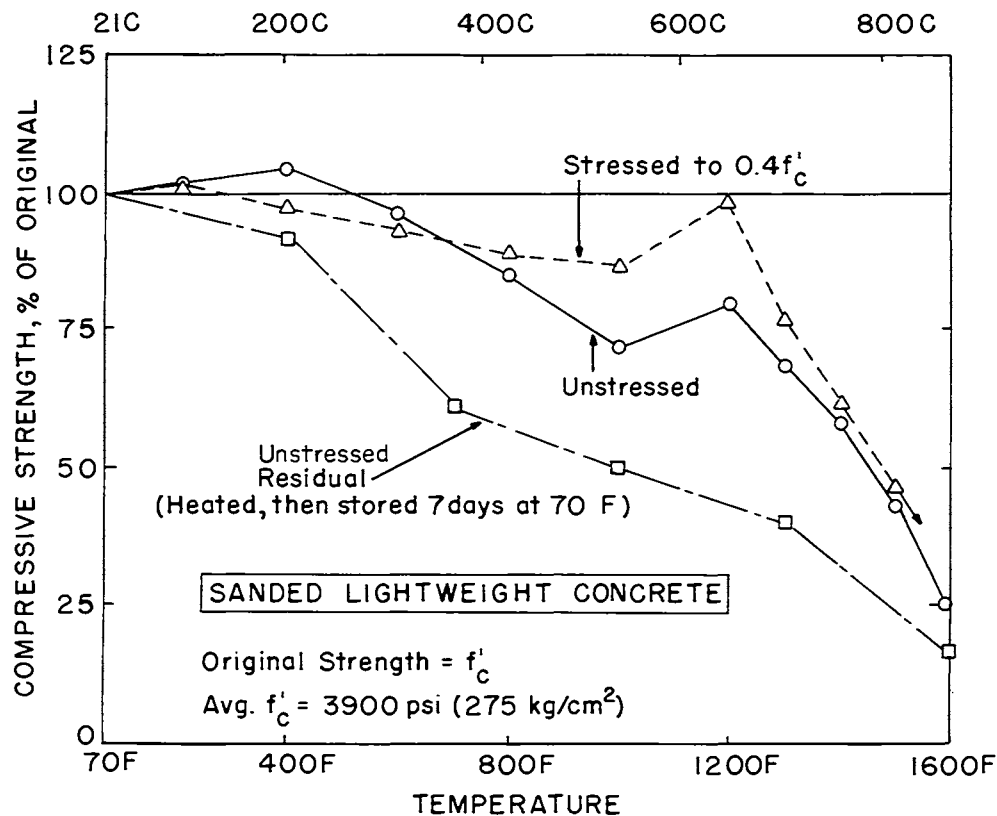


Fig. 2-4—Effect of temperature on compressive strength of sanded lightweight concrete