1 INTRODUCTION

Under normal conditions, most concrete structures are subjected to a range of temperature no more severe than that imposed by ambient environmental conditions. However, there are important cases where these structures may be exposed to much higher temperatures (e.g., jet aircraft engine blasts, building fires, chemical and metallurgical industrial applications in which the concrete is in close proximity to furnaces, and some nuclear power-related postulated accident conditions). Of primary interest in the present study is the behavior of reinforced concrete elements in designs of new-generation reactor concepts in which the concrete may be exposed to long-term steady-state temperatures in excess of the present *American Society of Mechanical Engineers Pressure Vessel and Piping Code (ASME Code)* limit of 65°C (Ref. 1). Secondary interests include performance of concrete associated with radioactive waste storage and disposal facilities and postulated design-basis accident conditions involving unscheduled thermal excursions. Under such applications the effect of elevated temperature on certain mechanical and physical properties may determine whether the concrete will maintain its structural integrity.

Concrete's thermal properties are more complex than for most materials because not only is the concrete a composite material whose constituents have different properties, but its properties also depend on moisture and porosity. Exposure of concrete to elevated temperature affects its mechanical and physical properties. Elements could distort and displace, and, under certain conditions, the concrete surfaces could spall due to the buildup of steam pressure. Because thermally induced dimensional changes, loss of structural integrity, and release of moisture and gases resulting from the migration of free water could adversely affect plant operations and safety, a complete understanding of the behavior of concrete under long-term elevated-temperature exposure as well as both during and after a thermal excursion resulting from a postulated design-basis accident condition is essential for reliable design evaluations and assessments. Because the properties of concrete change with respect to time and the environment to which it is exposed, an assessment of the effects of concrete aging is also important in performing safety evaluations. Presented in the following sections of this report is a review of the effects of elevated temperature on concrete materials, concrete materials for elevated-temperature service, code and design considerations for reinforced concrete structures exposed to elevated temperature, and the performance of selected structural members subjected to elevated temperature.

2 EFFECTS OF ELEVATED TEMPERATURE ON ORDINARY PORTLAND CEMENT CONCRETE MATERIALS

Portland cements are manufactured by mixing finely divided calcareous materials (i.e., lime containing) and argillaceous materials (i.e., clay). The four compounds that make up more than 90% of the dry weight of the cement are tricalcium silicate ($3CaO \bullet SiO_2$), dicalcium silicate ($2CaO \bullet SiO_2$), tricalcium aluminate ($3CaO \bullet A1_20_3$), and tetracalcium aluminoferrite ($4CaO \bullet A1_20_3 \bullet Fe_20_3$). When water is added to Portland cement, an exothermic reaction occurs, and new compounds are formed (i.e., hydrated cement paste): tobermorite gel [$(Ca_5Si_60_{16}(OH)_2 \bullet 4H_20)$], calcium hydroxide, calcium aluminoferrite hydrate, tetracalcium aluminate hydrate, and calcium monosulfoaliminate. Mature cement paste is normally composed of 70–80% layered calcium-silicate-hydrate (C-S-H) gel, 20% $Ca(OH)_2$, and other chemical compounds.[2] The C-S-H gel structure is made up of three types of groups that contribute to bonds across surfaces or in the interlayer of partly crystallized tobermorite material: calcium ions, siloxanes, and water molecules. Bonding of the water within the layers (gel water) with other groups via hydrogen bonds determines the strength, stiffness, and creep properties of the cement paste. Tobermorite gel is the primary contributor to the cement paste structural properties. Under elevated-temperature exposure, the Portland cement paste experiences physical and chemical changes that contribute to development of shrinkage, transient creep, and changes in strength. Key material features of hydrated Portland cement paste affecting the properties of concrete at elevated temperature are its moisture state (i.e., sealed or unsealed), chemical structure (i.e., loss of chemically bound water from the C-S-H in the unsealed condition, CaO/SiO_2 ratio of the hydrate in the sealed condition, and amount of $Ca(OH)_2$ crystals in sealed or unsealed conditions), and physical structure (i.e., total pore volume including cracks, average pore size, and amorphous/crystalline structure of solid).[3]

Concrete is a heterogeneous multiphase material with relatively inert aggregates that is held together by the hydrated Portland cement paste. When concretes are exposed to high temperatures, changes in mechanical properties and durability occur. Nonlinearities in material properties, variation of mechanical and physical properties with temperature, tensile cracking, and creep effects affect the buildup of thermal forces, the load-carrying capacity, and the deformation capability (i.e., ductility) of the structural members. The property variations result largely because of changes in the moisture condition of the concrete constituents and the progressive deterioration of the cement paste-aggregate bond, which is especially critical where thermal expansion values for the cement paste and aggregate differ significantly. The bond region is affected by the surface roughness of the aggregate and its chemical/physical interactions.[3] Chemical interaction relates to the chemical reactions between the aggregate and cement paste that can be either beneficial or detrimental. Physical interaction relates to dimensional compatibility between aggregate materials and cement paste. Behavior of concrete at high temperature depends on exposure conditions (i.e., temperature-moisture-load-time regime). Curing influences the degree of hydration, while the temperature and load history prior to exposure to elevated temperature could have a significant effect on the behavior of the Portland cement paste and therefore the concrete. Concrete at elevated temperature is sensitive to the temperature level, heating rate, thermal cycling, and temperature duration (as long as chemical and physical transformations occur). Table 1 presents a summary of environmental factors that affect heated concrete and provides an indication of their relative influence.[3]

Research has been conducted on the thermal behavior of concrete in connection with the development of prestressed concrete pressure vessels for nuclear power plants (i.e., 20°C to 200°C) and to study the behavior of reinforced concrete members under fire conditions (i.e., 20°C to 1000°C) (Ref. 4). Interpretation of these results can be difficult however because (1) test materials and curing conditions

Table 1 Influence of Environmental Factors on Heated Concrete

Factor	Influence	Comment
Temperature Level	***	• Chemical-physical structure (see Chapter 2) & most properties (see Chapters 6-14).
	**	• The properties of some concrete (e.g. compressive strength and modulus of elastcicity) when heated under 20-30% load can vary less with temperature - up to about 500^{o}C - than if heated without load (see Chapters 6 & 14).
Heating Rate	**	• *< 2^{o}C/min:* Second order influence.
	***	• *> about 5^{o}C/min:* Becomes significant ⇒ explosive spalling.
Cooling Rate	*	• *< 2^{o}C/minute:* Negligible influence.
	**	• *> 2^{o}C/minute:* Cracking could occur.
	***	• *Quenching*: Very significant influence.
Thermal Cycling	**	• *Unsealed Concrete:* Significant influence mainly during first cycle to given temperature.
	**	• *Sealed concrete*: Influence in so far as it allows longer duration at temperature for hydrothermal transformations to develop.
Duration at Temperature	**	• *Unsealed concrete*: Only significant at early stages while transformations decay.
	***	• *Sealed concrete*: Duration at temperature above 100^{o}C ⇒ Continuing hydrothermal transformations.
Load-Temp. Sequence	***	• Very important - not usually appreciated
Load Level	***	• < 30%: Linear influence on Transient Creep (Chapter 9) at least in range up to 30% cold strength.
	***	• >50%: Failure could occur during heating at high load levels.
Moisture Level	**	• *Unsealed*: Small influence on thermal strain and transient creep particularly above 100^{o}C.
	***	• *Sealed*: Very significant influence on the structure of cement paste and properties of concrete above 100^{o}C.

*** First order influence. ** Second order influence. * First order influence.

Source: G. A. Khoury, "Performance of Heated Concrete—Mechanical Properties," Contract NUC/56/3604A with Nuclear Installations Inspectorate, Imperial College, London, United Kingdom, August 1996.

were different, (2) descriptions of materials are incomplete, (3) different test procedures were utilized (e.g., heating rates and exposure times), (4) test conditions are not comparable (e.g., tested at temperature or permitted to cool to room temperature prior to testing, and loaded or unloaded while heating), and (5) shape and size of the test articles were different (e.g., cube and cylindrical). Contained in the following sections of this chapter is a summary of literature that has been identified addressing the general behavior and pertinent mechanical and physical properties of concrete materials under elevated-temperature conditions.

2.1 General Behavior

2.1.1 Concrete Materials

If concrete made with Portland cement or blast furnace slag cement is subjected to heat, a number of transformations and reactions occur, even if there is only a moderate increase in temperature.[5,6] As aggregate materials normally occupy 65 to 75% of the concrete volume, the behavior of concrete at elevated temperature is strongly influenced by the aggregate type. Commonly used aggregate materials are thermally stable up to 300°C–350°C. Aggregate characteristics of importance to behavior of concrete at elevated temperature include physical properties (e.g., thermal conductivity and thermal expansion), chemical properties (e.g., chemical stability at temperature), and thermal stability/integrity. Aggregate materials may undergo crystal transformations leading to significant increases in volume [e.g., crystalline transformation of α-quartz (trigonal) to β-quartz (hexagonal) between 500 and 650°C with an accompanying increase in volume of ~5.7%]. Some siliceous or calcareous aggregates with some water of constitution exhibit moderate dehydration with increasing temperature that is accompanied by shrinkage (i.e., opal at 373°C exhibits shrinkage of ~13% by volume).[7] Most nonsiliceous aggregates are stable up to about 600°C. At higher temperatures, calcareous aggregates (calcite – $CaCO_3$), magnesite ($MgCO_3$), and dolomite ($MgCO_3/CaCO_3$) dissociate into an oxide and CO_2 ($CaO + CO_2$). Calcium carbonate dissociates completely at 1 atm pressure at 898°C with partial dissociation occurring at temperatures as low as 700°C (Ref. 8). Above 1200°C and up to 1300°C some aggregates, such as igneous rocks (e.g., basalt), show degassing and expansion. Refractory aggregates can be utilized to produce significant improvements in the heat resistance of Portland cement concretes. It has been noted that the thermal stability of aggregates increases in order of gravel, limestone, basalt, and lightweight.[9]

Apart from the crystalline transformations occurring mainly in the aggregate materials during heating, a number of degradation reactions occur, primarily in the cement paste, that result in a progressive breakdown in the structure of the concrete. An increase in temperature produces significant changes in the chemical composition and microstructure of the hardened Portland cement paste. At low temperatures these reactions mainly take the form of dehydration and water expulsion reactions. Changes in the chemical composition and microstructure of the hardened Portland cement paste occur gradually and continuously over a temperature range from room temperature to 1000°C. At room temperature, between 30 and 60% of the volume of saturated cement paste and between 2 and 10% of the volume of saturated structural concrete are occupied by evaporable water. As the temperature to which the cement paste is subjected increases, evaporable water is driven off until at a temperature of about 105°C all evaporable water will be lost, given a sufficient exposure period. At temperatures above 105°C, the strongly absorbed and chemically combined water (i.e., water of hydration) are gradually lost from the cement paste hydrates, with the dehydration essentially complete at 850°C. Dehydration of the calcium hydroxide is essentially zero up to about 400°C, increases most rapidly around 535°C, and becomes complete at about 600°C (Ref. 10). Figures 1 and 2 indicate the influence of temperature on the ultimate compressive strength and modulus of elasticity of a Portland cement paste (Type I Portland cement; water/cement = 0.33) (Ref. 11).

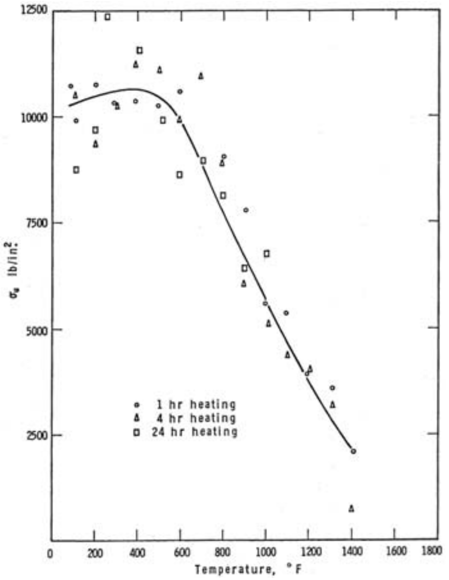

Figure 1 **Ultimate strength in compression of hydrated Portland cement (w/c = 0.33) at elevated temperature**

Source: T. Z. Harmathy and J. E. Berndt, “Hydrated Portland Cement and Lightweight Concrete at Elevated Temperatures,” *J. American Concrete Institute* **63**, 93–112 (1966).

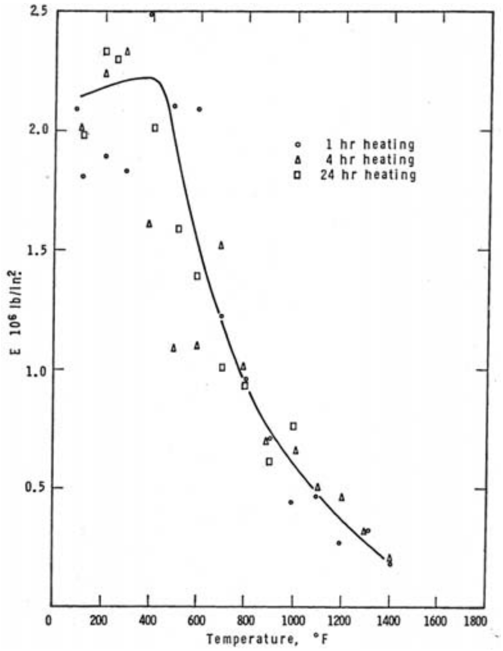

Figure 2 **Modulus of elasticity in compression of hydrated Portland cement (w/c = 0.33) at elevated temperature**

Source: T. Z. Harmathy and J. E. Berndt, “Hydrated Portland Cement and Lightweight Concrete at Elevated Temperatures,” *J. American Concrete Institute* **63**, 93–112 (1966).

A good summary of the degradation reactions that occur in Portland cement concrete is provided in Ref. 4. Upon first heating, substantial water evaporation occurs from the larger pores close to the concrete surface. Then, from 100°C onward, the evaporation proceeds at a faster rate with water being expelled from concrete near the surface as a result of above-atmospheric vapor pressure (i.e., steam flow). At 120°C the expulsion of water physically bound in the smaller pores, or chemically combined, initiates and continues up to about 500°C where the process is essentially complete. From 30°C to 300°C, in conjunction with evaporation, dehydration of the hardened cement paste occurs (first stage) with the maximum rate of dehydration occurring at about 180°C [Tobermorite gel is stable up to a temperature of 150°C (Ref. 12)]. In the temperature range from 450°C to 550°C there is decomposition of the portlandite [i.e., $Ca(OH)_2 \rightarrow CaO + H_2O$) (Ref. 12)]. At 570°C the $\alpha \rightarrow \beta$ inversion of quartz takes place with the transformation being endothermic and reversible. A further process of decomposition of the hardened cement paste takes place between 600°C and 700°C with the decomposition of the calcium-silicate-hydrate phases and formation of β-C_2S. Between 600°C and 900°C the limestone begins to undergo decarbonation (i.e., $CaCO_3 \rightarrow CaO + CO_2$). The rate of decomposition and the temperature at which it occurs are not only dependent on temperature and pressure, but also by the content of SiO_2 present in the limestone. Above 1200°C and up to 1300°C, some components of the concrete begin to melt. Above 1300°C to 1400°C concrete exists in the form of a melt. Apparently liquifaction of the concrete commences with melting of the hardened cement paste followed by melting of the aggregates.[13–15] The melting points of aggregates vary greatly. At 1060°C basalt is at the lower limit of all types of rock, with quartzite not melting below 1700°C (Ref. 5).

2.1.2 Steel Reinforcing Materials

Bonded reinforcement (i.e., deformed bars) is provided to control the extent and width of cracks at operating temperatures, resist tensile stresses and computed compressive stresses for elastic design, and provide structural reinforcement where required by limit condition design procedures. Bonded reinforcement in nuclear power plant structures is often used in conjunction with prestressed steel. The prestressed steel provides the structural rigidity and the major part of the strength while the bonded reinforcement distributes cracks, increases ultimate strength and reinforces those areas not adequately strengthened by the prestressed steel, and provides additional safety for unexpected conditions of loading.

Structural elements fabricated from reinforced concrete, because of their typical size, have a high thermal inertia that results in relatively slow rates of temperature increase through the cross section. As a result, the steel reinforcement temperatures are kept sufficiently low to avoid significant softening. In addition, due to the monolithic nature of construction, the existence of alternate load paths, and compartmentation of fires (i.e., conventional civil engineering construction), reinforced concrete structures generally perform well under elevated-temperature conditions that could result from a fire. However, under certain scenarios (e.g., rapid heat buildup), spalling of the concrete could occur to expose the steel reinforcement to the effects of elevated temperature. Such conditions at a nuclear power plant would occur only in the unlikely event of an accident. For completeness, limited information is provided below on effects of elevated temperature on steel reinforcing bars.

During heating of steels, crystalline transformations occur depending on the temperature (e.g., perlite at 721°C and Curie point at 768°C). Information on the density, mean specific heat, thermal conductivity, thermal diffusivity, and coefficient of thermal expansion of different steels is presented in Figs. 3–7, respectively.[5] Strength characteristics and mechanical properties of steels depend on several factors: amount and type of alloying constituents, heat treatment during manufacture, and retreatment in cold state (e.g., cold drawing). Figures 8–10 present stress-strain relationships, Young's modulus/elongation, and yield/ultimate tensile strength data as a function of temperature for 3500 kgf/cm^2 specified minimum

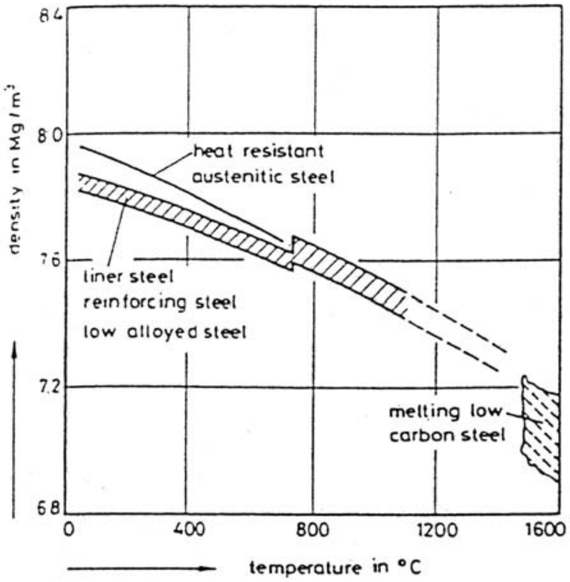

Figure 3 Density of different steels

Source: U. Schneider, C. Diererichs, and C. Ehm, “Effect of Temperature on Steel and Concrete for PCRV’s,” *Nuclear Engineering and Design* **67**, 245–258 (1981).

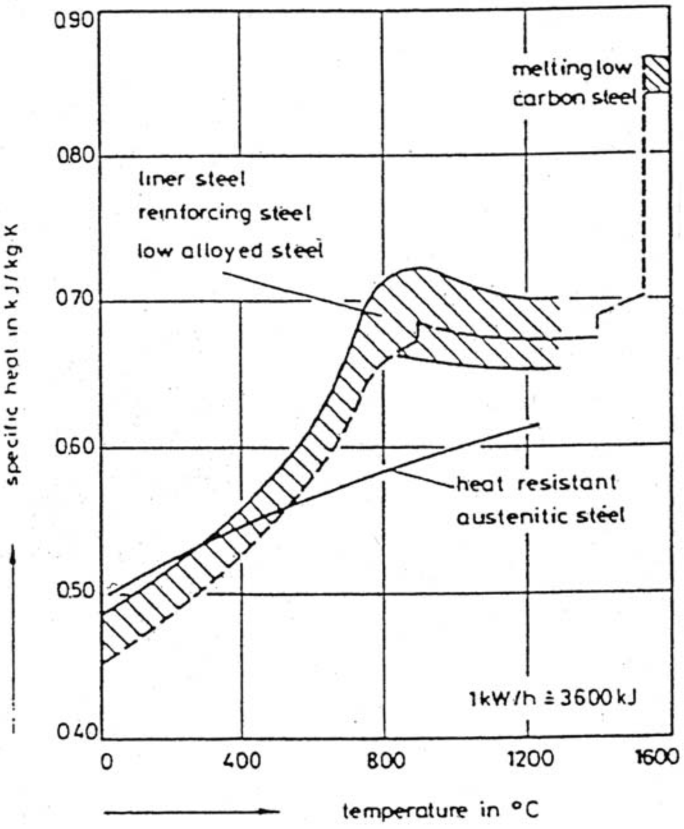

Figure 4 Mean specific heat of different steels

Source: U. Schneider, C. Diererichs, and C. Ehm, “Effect of Temperature on Steel and Concrete for PCRV’s,” *Nuclear Engineering and Design* **67**, 245–258 (1981).

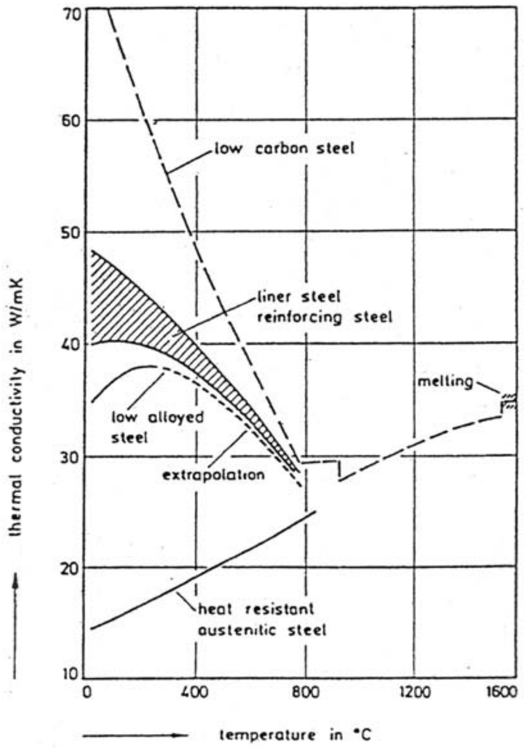

Figure 5 Thermal conductivity of different steels

Source: U. Schneider, C. Diererichs, and C. Ehm, "Effect of Temperature on Steel and Concrete for PCRV's," *Nuclear Engineering and Design* **67**, 245–258 (1981).

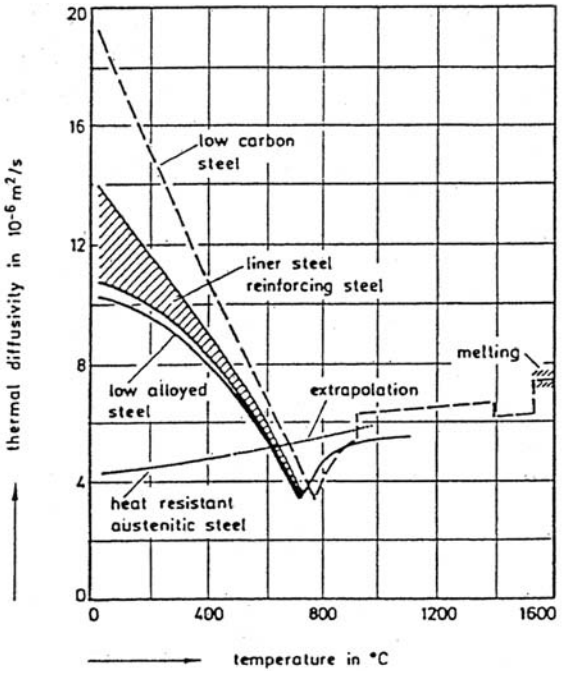

Figure 6 Thermal diffusivity of different steels

Source: U. Schneider, C. Diererichs, and C. Ehm, "Effect of Temperature on Steel and Concrete for PCRV's," *Nuclear Engineering and Design* **67**, 245–258 (1981).

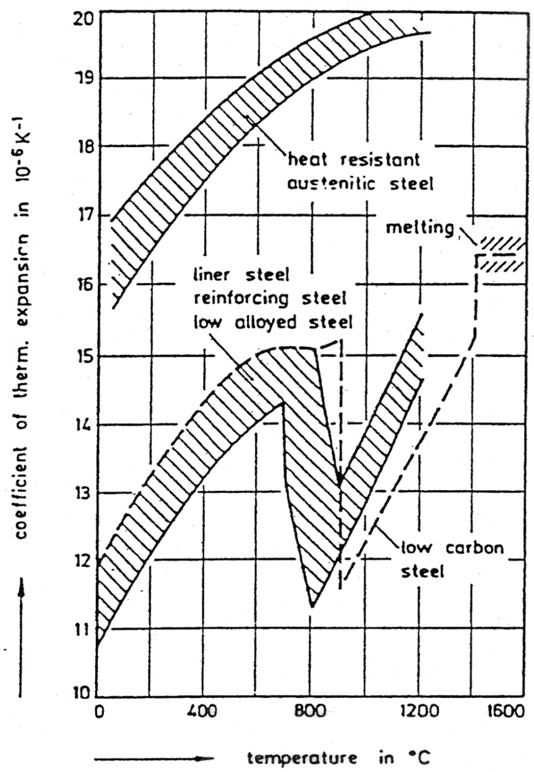

Figure 7 **Coefficient of expansion of different steels.** *Source*: U. Schneider, C. Diererichs, and C. Ehm, "Effect of Temperature on Steel and Concrete for PCRV's," *Nuclear Engineering and Design* **67**, 245–258 (1981).

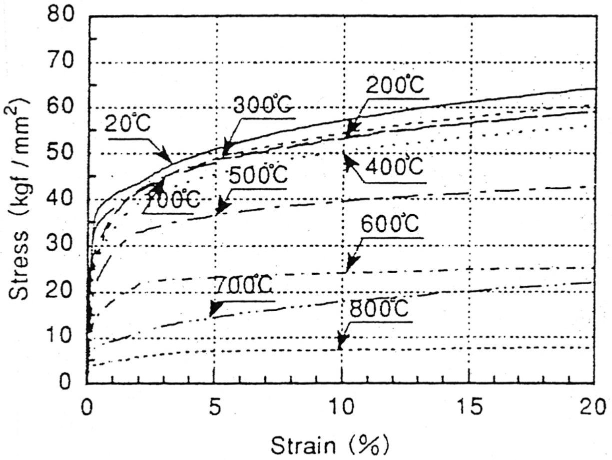

Figure 8 **Stress-strain relationships of reinforcing bars at elevated temperature.** *Source*: M. Takeuchi et al., "Material Properties of Concrete and Steel Bars at Elevated Temperatures," *12th International Conference on Structural Mechanics in Reactor Technology*, Paper H04/4, pp. 133–138, Elsevier Science Publishers, North-Holland, The Netherlands, 1993.

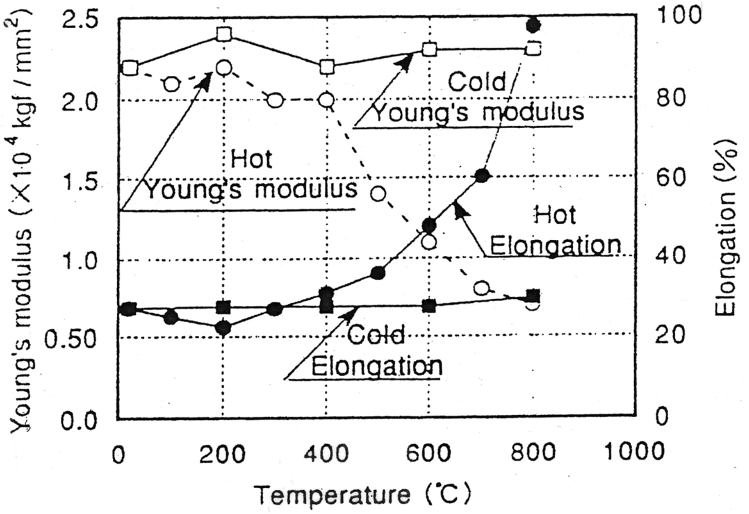

Figure 9 **Influence of temperature on Young's modulus and elongation of reinforcing bars.** *Source*: M. Takeuchi et al., "Material Properties of Concrete and Steel Bars at Elevated Temperatures," *12th International Conference on Structural Mechanics in Reactor Technology*, Paper H04/4, pp. 133–138, Elsevier Science Publishers, North-Holland, The Netherlands, 1993.

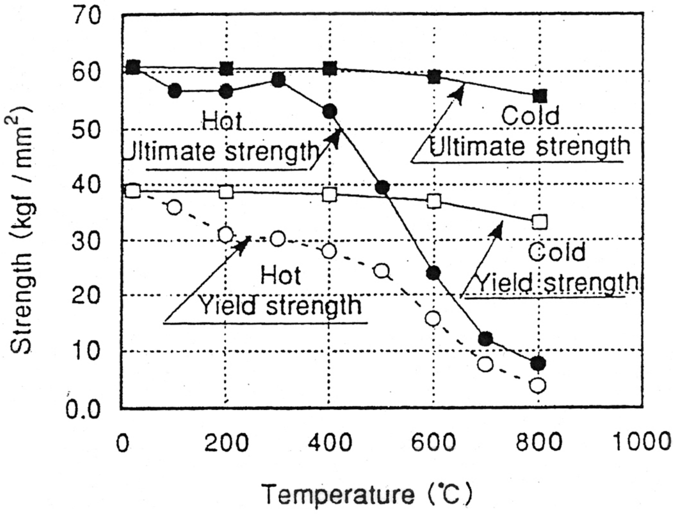

Figure 10 **Yield strength and ultimate tensile strength of reinforcing bars at elevated temperature.** *Source*: M. Takeuchi et al., "Material Properties of Concrete and Steel Bars at Elevated Temperatures," *12th International Conference on Structural Mechanics in Reactor Technology*, Paper H04/4, pp. 133–138, Elsevier Science Publishers, North-Holland, The Netherlands, 1993.

yield strength 51-mm-diameter steel bars.[16] Information on the effect of elevated-temperature exposure on tensile strength of prestressing steels is available.[5]

2.2 Mechanical and Physical Properties

Material properties are closely related to the specific test method employed. The properties of concrete at elevated temperature can be defined from a number of viewpoints (e.g., ranging from transient such as representing fire conditions to steady-state such as a structure operating at elevated temperature). To interpret results, knowledge of the test condition(s) employed is required. Three main test parameters are involved in the development of data: heating, application of load, and control of strain.[17] These parameters can be fixed at constant values or be varied during testing to provide transient conditions. Six regimes have been identified for determining properties of concrete.[4,17]

1. Stress-strain relationships (stress-rate controlled): data provide stress-strain relationships that can be used to establish tensile strength, modulus of elasticity, and ultimate strain at collapse.
2. Stress-strain relationships (strain-rate controlled): data also provide stress-strain relationships to establish properties noted above as well as mechanical dissipation energy.
3. Creep: steady-state creep tests in which the specimens are heated to a specified temperature and then loaded to provide a relationship between strain and time at different temperatures.
4. Relaxation: specimen heated to a specified temperature, loaded, strain held constant, load monitored as function of time.
5. Total deformation: data provide a relationship between total strain and time and enable failure temperature values and transient creep values for different stress levels to be established.
6. Total forces: data provide a relationship between stress and time for different initial stress or strain levels and can be expressed as a relationship between restraint forces and temperature developed as a consequence of heating.

Each of these methods or regimes determines a specific feature of material behavior. Regimes 1 through 4 are related to steady-state tests and regimes 5 and 6 transient tests. For the current study, the steady-state regimes are of most interest because the transient regimes are primarily related to fire. For example, unstressed tests can simulate conditions of concrete under no initial stress and exposed to high temperature, stressed tests simulate concrete in columns or compressive zones of flexural members subjected to heat, and unstressed residual yields information on strength of unstressed concrete that has been exposed to a thermal excursion. More detailed descriptions of these regimes are available.[4,17]

2.2.1 Mechanical Properties

It has been established that the mechanical properties of concrete can be adversely affected by elevated-temperature exposure.[18–22] Quantitative interpretation of available data is difficult, however, because (1) samples were either tested hot or cold, (2) moisture migration was either free or restricted, (3) concrete was either loaded or unloaded while heated, (4) mix constituents and proportions varied, (5) test specimen size and shape were not consistent, (6) specimens were tested at different degrees of hydration, and (7) heat-soak duration varied from test to test. To provide a consistent basis for evaluation of data, it is recommended that several factors be taken into account:[23] (1) concrete strength class; (2) test specimen size; (3) thermal compatibility of aggregate and cement paste matrix; (4) cement and concrete composition; (5) level of temperature; (6) degree of hydration; (7) moisture content; (8) moisture gradients, rate of drying or wetting; (9) temperature gradient, rate of heating or cooling; (10) duration of temperature exposure; (11) loading during temperature exposure; (12) temperature-activated transformations in microstructure and chemical composition of cement; (13) state of specimens tested—hot or cold; (14) strength testing procedure; and (15) reference strength selected—wet, moist, or dry.

A review of methods used by various investigators for elevated-temperature testing of concrete indicates that, generally, the tests can be categorized according to cold or hot testing. In cold testing, specimens are gradually heated to a specified temperature, permitted to thermally stabilize at that temperature for a prescribed period of time, permitted to slowly cool to ambient, and then tested to determine residual mechanical properties. In hot testing, specimens are gradually heated to a specified temperature, permitted to thermally stabilize at the temperature for a prescribed period of time, and then tested at temperature to determine mechanical properties. During testing, specimens are maintained in either an open environment where water vapor can escape (unsealed) or a closed environment where the moisture is contained (sealed). The closed environment represents conditions for mass concrete where moisture does not have ready access to the atmosphere, and the open environment represents conditions where the element is either vented or has free atmospheric communication. During heating and cooling, the specimens may be either loaded or unloaded. Mechanical properties in which the specimens have been permitted to return to room temperature prior to testing are referred to as residual properties.

The performance of concrete can be measured by the change of its stiffness, strength, or some other property that would affect its main function in service. Because concrete has a relatively low tensile strength, it is normally relied upon to take compressive forces, with tensile forces taken by steel reinforcement. As a consequence, much of the research conducted on concrete at elevated temperature has concentrated on compressive strength as the fundamental property in examining its deterioration. However, it has been noted that the compressive strength may not be as good an indicator of deterioration at elevated temperature as tensile or flexural strength under short-term loading.[24]

Stress and Strain Characteristics

Evaluation of structures for small strain conditions involves elastic analysis procedures for which knowledge of the concrete modulus of elasticity and strength is sufficient. When large strains are involved, such as could occur when a structure is subjected to elevated temperature, elastic-plastic analysis procedures are required that involve use of the load-deformation or stress-strain relations developed for concrete at the temperature level of interest. A number of relationships have been proposed by various authors to describe concrete's stress-strain behavior.[25,26] These expressions generally provide good agreement with the ascending portion of the stress-strain curve but differ significantly beyond the point of maximum stress. Reference 27 notes that the stress-strain relationships at elevated temperature may be derived from the room-temperature relationships if the variation of maximum stress and corresponding strain with temperature are known.

The majority of stress-strain data reported in the literature are for concrete heated to test conditions without load or loaded under stress-controlled conditions. Stress-strain diagrams for sealed and unsealed limestone aggregate concretes tested at temperature are presented in Figs. 11 and 12, respectively.[28] These results indicate that the unsealed specimens are stiffer than the sealed specimens, but strains at ultimate load were reduced. Figure 13 presents the influence of test temperature on the stress-strain relationship of a quartz aggregate concrete in a stress-rate controlled test.[29] These data show a significant increase in ultimate strain and a loss of stiffness with increasing temperature. Figure 14 shows specimens made from quartz aggregate concrete that are tested at temperature are stiffer and stronger than identical companion specimens heated to the same temperatures and then permitted to cool to room temperature before testing (i.e., up to 450°C the stress-strain curves of specimens tested at temperature do not change appreciably).[30] It was also concluded from this study that the type of cement and the duration of thermal

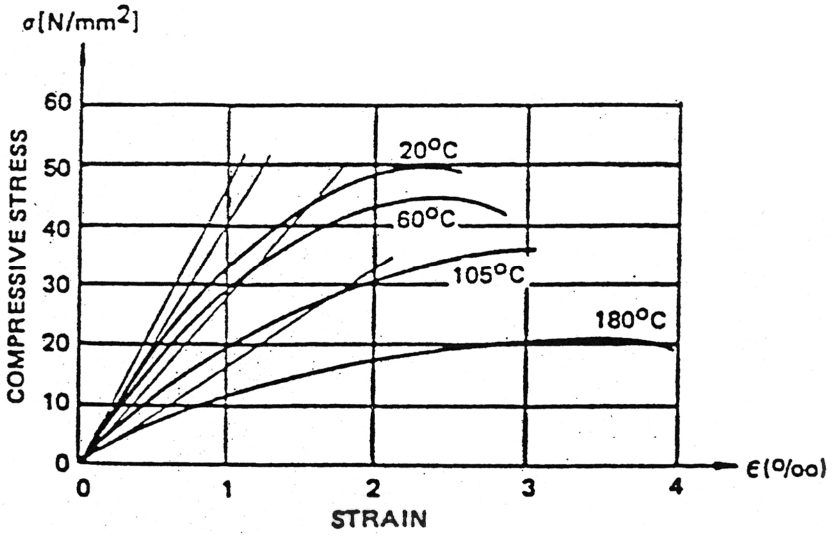

Figure 11 Stress-strain diagrams of sealed limestone concrete specimens. *Source*: R. Kottas, J. Seeberger, and H. K. Hilsdorf, “Strength Characteristics of Concrete in the Temperature Range of 20° to 200°C,” Paper HO1/4 in *5th International Conference on Structural Mechanics in Reactor Technology*, p. 8, Elsevier Science Publishers, North-Holland, The Netherlands, August 1979.

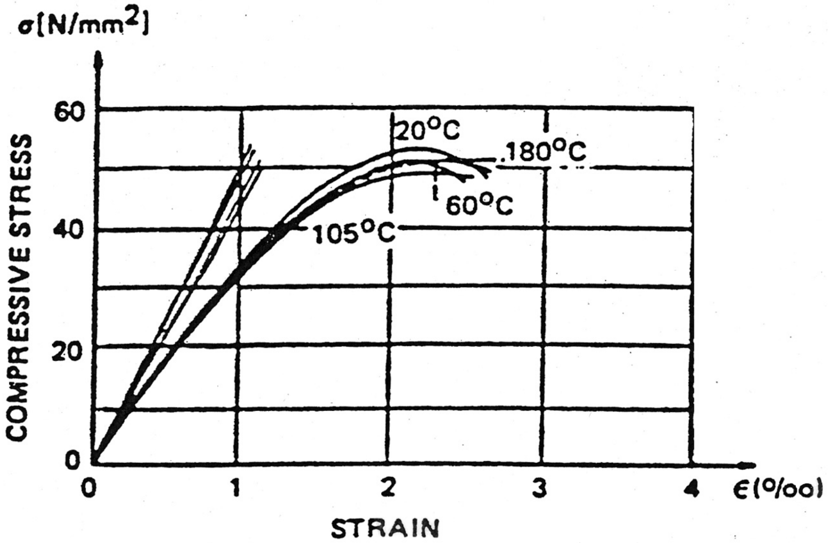

Figure 12 Stress-strain diagrams of unsealed limestone concrete specimens. *Source*: R. Kottas, J. Seeberger, and H. K. Hilsdorf, “Strength Characteristics of Concrete in the Temperature Range of 20° to 200°C,” Paper HOI/4 in *5th International Conference on Structural Mechanics in Reactor Technology*, p. 8, Elsevier Science Publishers, North-Holland, The Netherlands, August 1979.

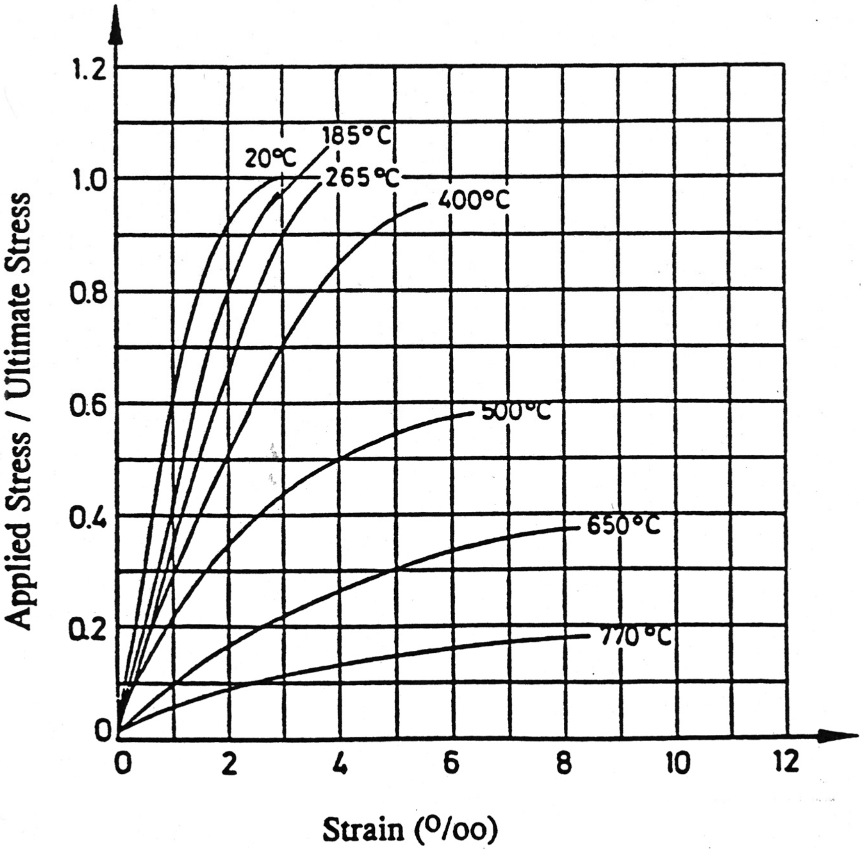

Figure 13 Influence of temperature on the stress-strain relation of unsealed quartz aggregate concrete. *Source*: Y. Anderberg and S. Thelanderson, "Stress and Deformation Characteristics of Concrete at High Temperatures, 2-Experimental Investigation and Material Behaviour Model," Bulletin 54, Lund Institute of Technology, Lund, Sweden, 1976.

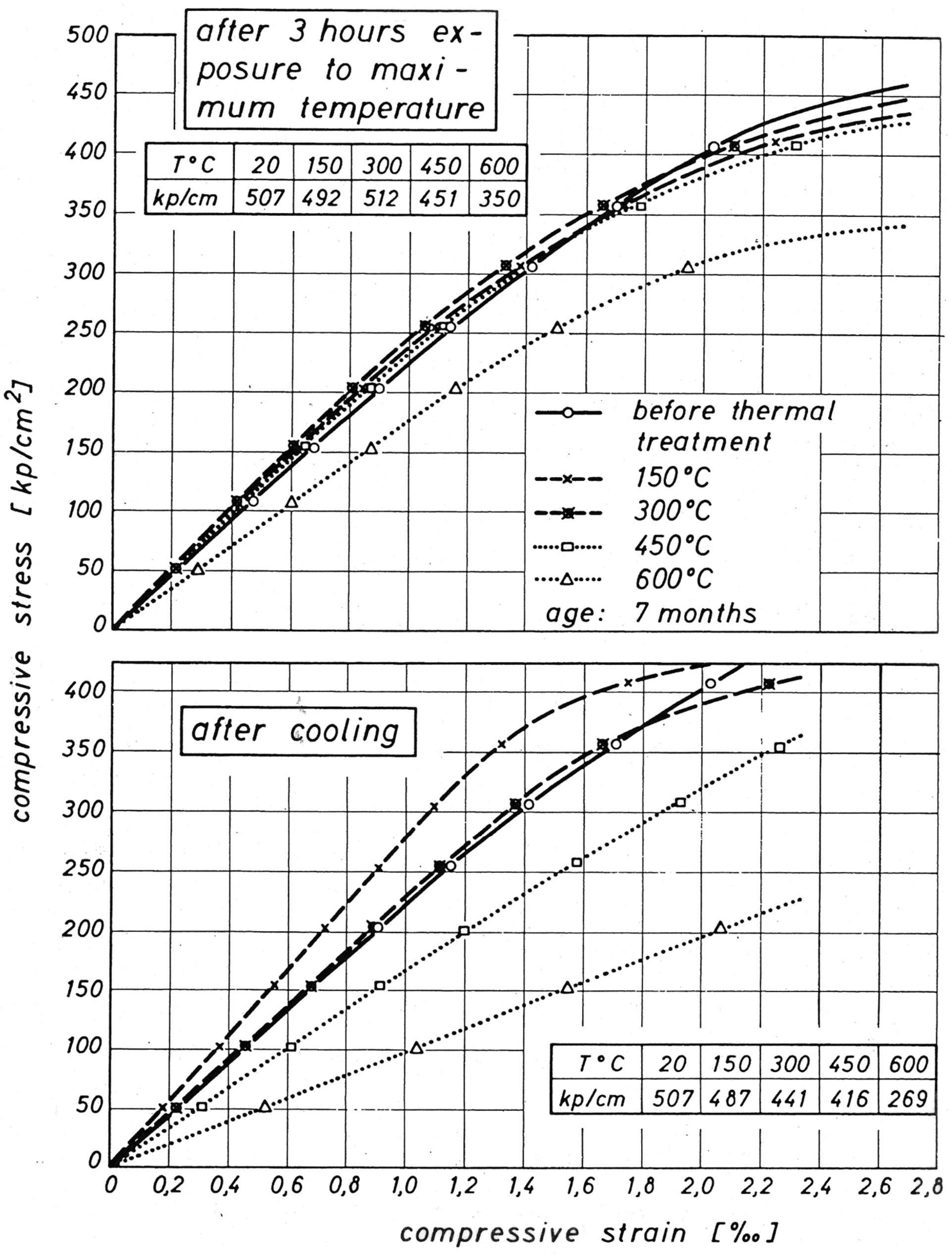

Figure 14 Effect of elevated temperature on stress-strain behavior of a quartz concrete. *Source*: H. Weigler and R. Fischer, “Influence of High Temperatures on Strength and Deformations of Concrete,” Paper Sp 34-26 in Special Publication SP-34, Vol. I–III, American Concrete Institute, Farmington Hills, Michigan, 1972.

treatment had a minor affect on the slope of the stress-strain curve. Many nuclear power plant structures, such as prestressed concrete pressure vessels, will be under a compressive load prior to heating. The beneficial effect of applied preload load (0, 10, or 30% the reference strength) during exposure to temperatures of either 250°C or 450°C on strength and stiffness is demonstrated by results presented in Fig. 15.[4]

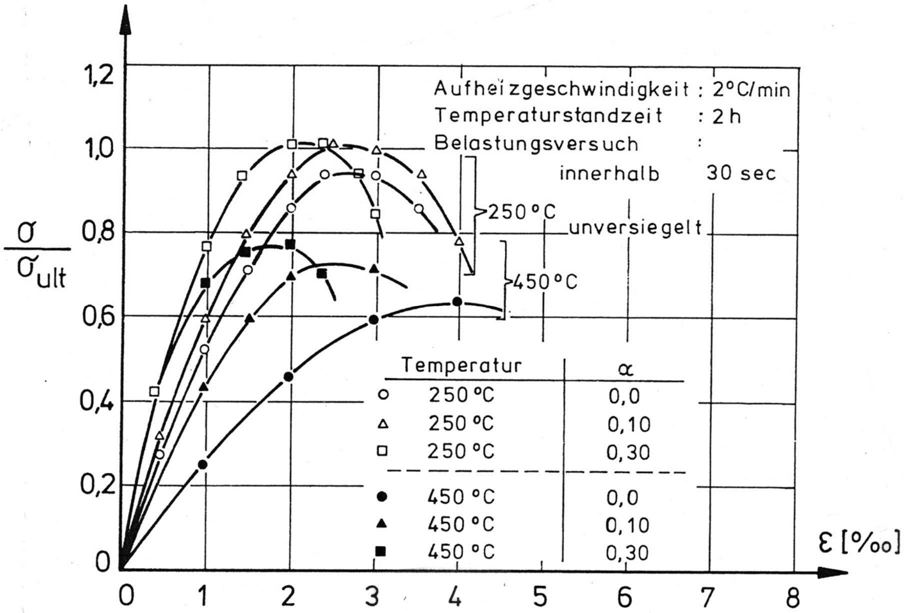

Figure 15 Stress-strain relationship of normal concrete with specimens loaded during the heating period. *Source*: U. Schneider, "Behaviour of Concrete at High Temperature," HEFT 337, Deutscher Ausschuss fur Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

Relative to temperature effects on concrete's stress-strain curve, several general observations can be made. Under steady-state conditions, the original concrete strength, water-cement ratio, heating rate, and type of cement have minor influence on the stress-strain behavior. Aggregate-cement ratio and aggregate type are the main factors affecting the shape of the stress-strain curve. Concretes made with hard aggregates (e.g., siliceous or basalt) generally have a steeper decrease of the initial slope at high temperature (e.g., >550°C) than softer aggregates (e.g., lightweight). Curing conditions influence the stress-strain behavior only at relatively low temperatures (<300°C) (Ref. 17).

Poisson's Ratio

Poisson's ratio is needed for conducting structural analyses of flat slabs, arch dams, tunnels, tanks, and other statically indeterminate members. At normal ambient conditions, Poisson's ratio for concrete can vary from 0.11 to 0.32, but is generally in the range from 0.15 to 0.20. Available data do not indicate a consistent trend for variation of Poisson's ratio with age, strength, or other concrete properties. However, some test results indicate that the ratio increases with age of concrete up to about 2 years and is lower for higher strength concretes.[31,32]

Data on the effect of elevated temperature on Poisson's ratio are somewhat limited and tend to be inconsistent. Some data indicate that the Poisson's ratio decreases with increasing temperature,[33] whereas elsewhere it has been reported that it ranged from 0.11 to 0.25 at 20°C to 400°C, while above 400°C it increased.[34] Additional data for higher strength concrete indicated that when the stress did not exceed

50% of peak value, the Poisson's ratio decreased with an increase in temperature.[35] Figure 16 presents Poisson's ratio results for a hard sandstone aggregate concrete after various heating periods (i.e., 1, 7, 28, and 91 d) at 175°C for specimens that were either sealed or unsealed during heating.[36] Poisson's ratio ranged from 0.14 to 0.22 with the trend for it to increase with increasing moisture content of the concrete.

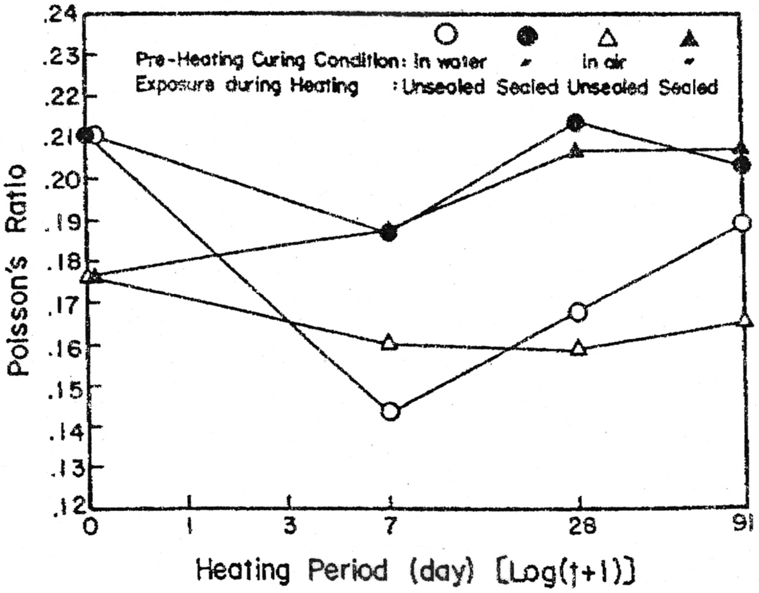

Figure 16 **Poisson's ratio results.** *Source*: K. Hirano et al., "Physical Properties of Concrete Subjected to High Temperature for MONJU," Paper P2-25, Power Reactor and Nuclear Fuel Development Corporation, Tokyo, Japan.

Modulus of Elasticity

Concrete's modulus of elasticity—a measure of its stiffness or resistance to deformation—is used extensively in the analysis of reinforced concrete structures to determine the stresses developed in simple elements and the stresses, moments, and deflections in more complicated structures. Because concrete's stress-strain curve is nonlinear, the modulus of elasticity is determined either by the initial tangent modulus, secant modulus, or tangent modulus method. Principal variables affecting the modulus include (1) richness of the mix (richer the mix, the greater the modulus increase with age); (2) water/cement ratio (higher values reduce modulus); (3) age (modulus increases rapidly during first few months and shows continual increase up to ~3 years); (4) kind and gradation of aggregate (stiffer aggregates produce higher modulus concretes, and the modulus increases with aggregate fineness modulus as long as the mix is workable); and (5) moisture content at time of test (wet specimens produce higher modulus values than dry specimens). Temperature can significantly affect the modulus values.

Figure 17 summarizes results from several researchers on the temperature dependence of the concrete modulus of elasticity (normalized to reference room temperature modulus.[25] Results for normal strength concrete (NSC) and high-strength concrete (HSC) from researchers in China is presented in Fig. 18.[37] Results show that the elastic modulus for the NSC decreased monotonically with increasing temperature. From the NSC and HSC elastic modulus results obtained at temperature or after thermal exposure (residual), Ref. 37 notes that the elastic modulus after high-temperature exposure (residual) was lower than that obtained at temperature and was influenced by type aggregate, the elastic modulus decreased much more for concrete cured in water than for concrete cured in air, and the deterioration in elastic modulus was more related to the maximum temperature during heating than to the heating-cooling cycle.

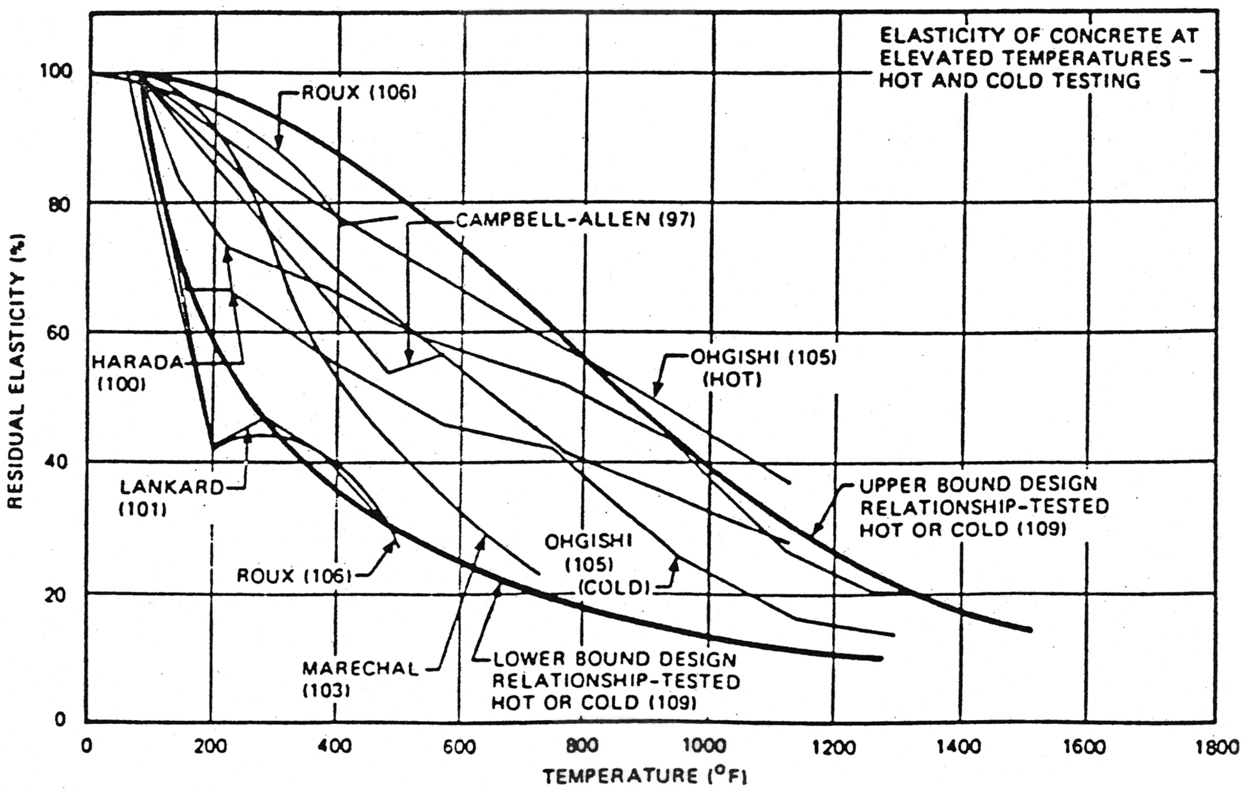

Figure 17 Effect of temperature on the modulus of elasticity of concrete: hot and cold test results. *Source*: G. N. Freskakis, "Behavior of Reinforced Concrete at Elevated Temperature," Paper 3-4, *Source: ASCE Conf. on Civ. Eng. and Nuclear Power* **1**, Paper 3-5, pp. 3-5-1 to 3-5-21, Knoxville, Tennessee, Sept. 15–17, 1980.

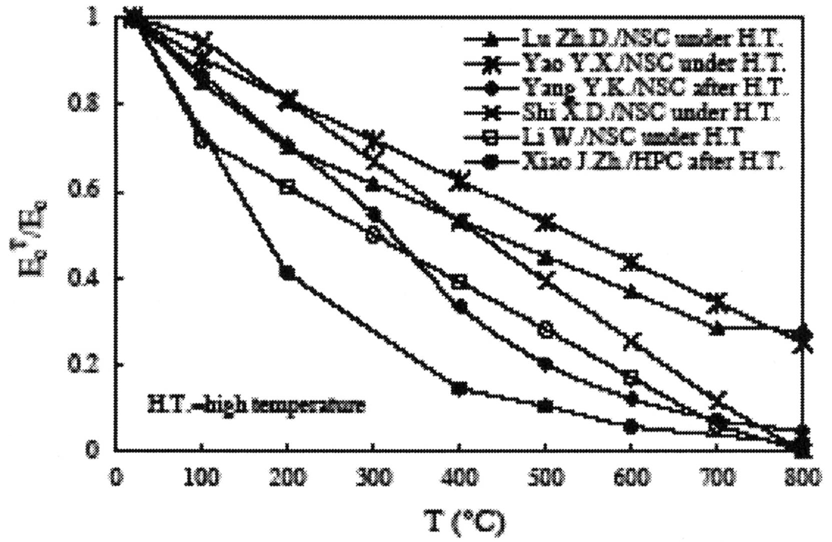

Figure 18 Temperature dependence of the concrete modulus of elasticity (normalized). *Source*: J. Xiao and G. König, "Study of Concrete at High Temperature in China—An Overview," *Fire Safety Journal* **39**, 89–103 (2004).

The strong influence of aggregate type on modulus is presented in Fig. 19.[5] Other conclusions from this study were that a sustained stress during heating affects the modulus significantly and the type of cement had little affect. The influence of water/cement ratio on static and dynamic modulus is illustrated in Fig. 20.[4] Results presented in Fig. 21 for a 31-MPa and a 63-MPa limestone concrete tested at temperature indicate that, when normalized with respect to the room temperature modulus of elasticity, the strength of the concrete does not have a significant effect on the modulus-temperature response.[38]

Results in the literature indicate that the primary factors affecting the modulus of elasticity at high temperature are the type of aggregate (limestone concrete has less loss than quartz concrete) and the presence of sustained stress during heating (sustained stress results in lower decreases in modulus with increasing temperature). Duration of temperature exposure, sealing, type of cement, water/cement ratio and original concrete strength have little effect on modulus results. The age at test apparently also does not affect the residual modulus as noted for a flint/beach gravel concrete for which results were obtained to 150°C at concrete ages of 3 months and 1 year.[39]

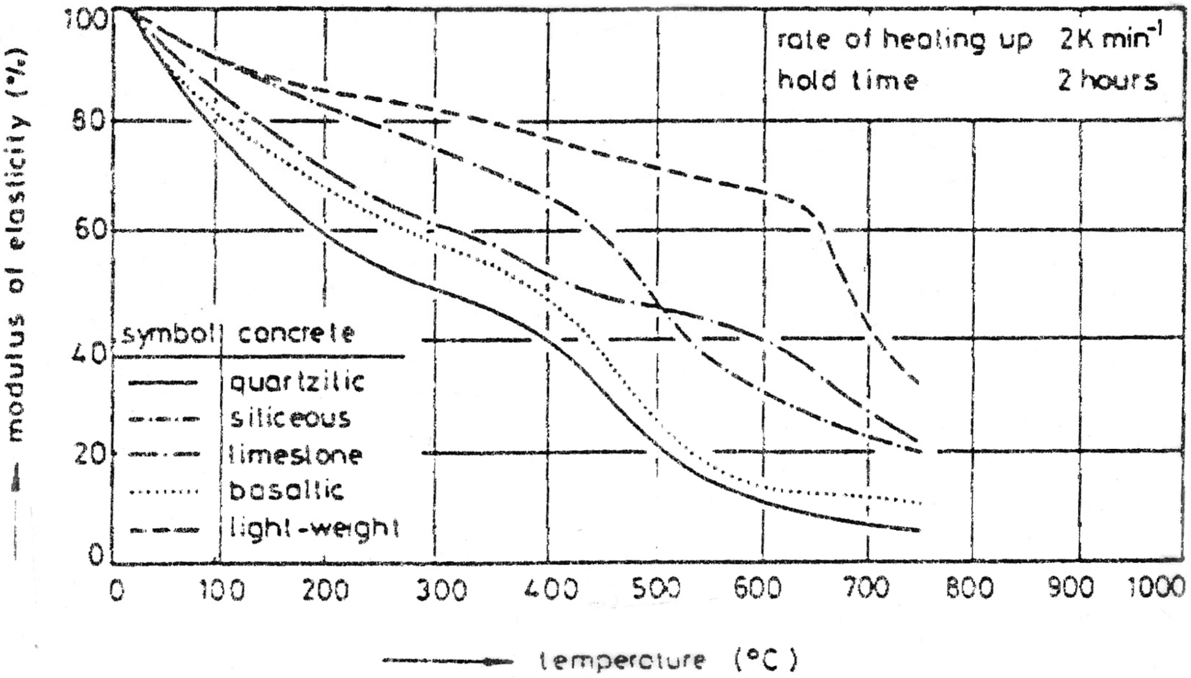

Figure 19 Modulus of elasticity of different concretes at elevated temperature. *Source*: U. Schneider, C. Diererichs, and C. Ehm, "Effect of Temperature on Steel and Concrete for PCRV's," *Nuclear Engineering and Design* **67**, 245–258 (1981).

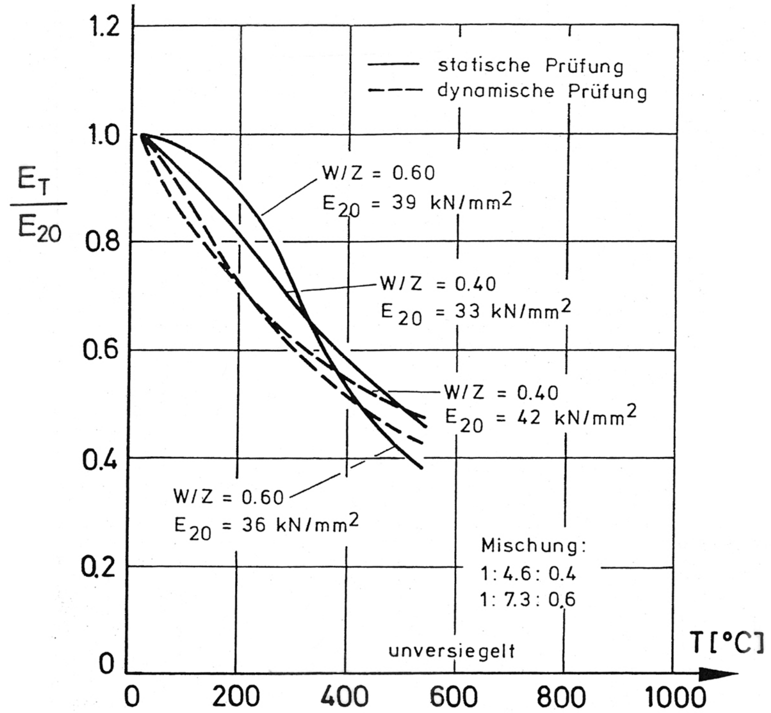

Figure 20 **Influence of water/cement ratio on modulus of elasticity of concrete at elevated temperature.** *Source*: U. Schneider, “Behaviour of Concrete at High Temperature,” HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

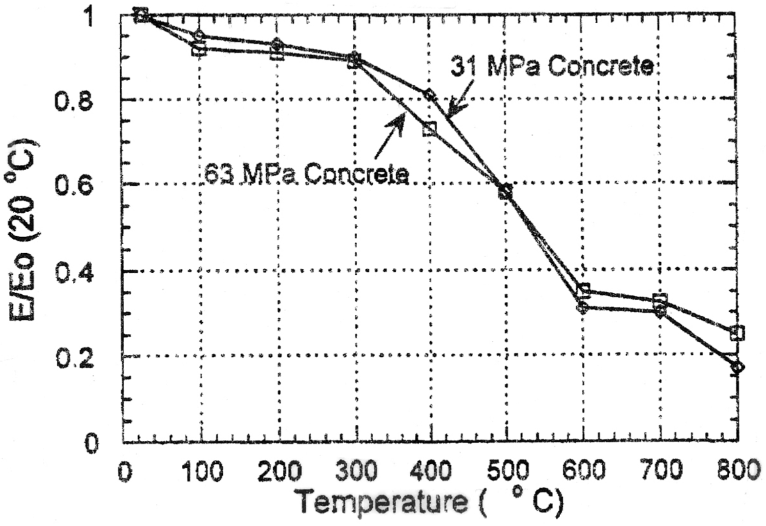

Figure 21 **Normalized modulus of elasticity versus temperature relationships NSC and HSC.** *Source*: C. Castillo and A. J. Durani, “Effect of Transient High Temperature on High-Strength Concrete,” *J. American Concrete Institute*, **87**(1) (1990).

Compressive Strength

The compressive strength influences the load-carrying capacity of a structure. Compressive strength of concrete is generally considered to be its most valuable property.

Thermal gradients affect the concrete strength as well as its stiffness. Figures 22 and 23 present normalized compressive strength results for unstressed specimens tested cold (residual) and at temperature (hot), respectively, that are based on results from several investigators.[25,33,40–51] Additional information is presented in Fig. 24 on the effect of elevated-temperature exposure on the compressive strength of unsealed nuclear power plant PCPV-type concretes (limestone, basalt, or gravel aggregate materials) tested either hot (H) or cold (C) (Ref. 3). These figures indicate the influence of the concrete and the test condition on the residual compressive strength after thermal exposure. The general trend for a strength loss with increasing temperature reflects the influence of the cement paste and the increasing role of the aggregate materials at higher temperatures. Factors have been identified that may contribute to the general trend for loss of compressive strength with increasing temperature:[3] aggregate damage; weakening of the cement paste-aggregate bond; and weakening of the cement paste due to an increase in porosity on dehydration, partial breakdown of the C-S-H, chemical transformation on hydrothermal reactions, and development of cracking. A number of material and environmental-related factors affect the response of concrete materials to elevated-temperature conditions. As many of the aggregate materials are thermally stable up to temperatures of 300°C to 350°C, which includes the temperature range considered for most applications, the compressive strength of concrete at elevated temperature is dependent in large measure on the interaction between the cement paste and aggregate.

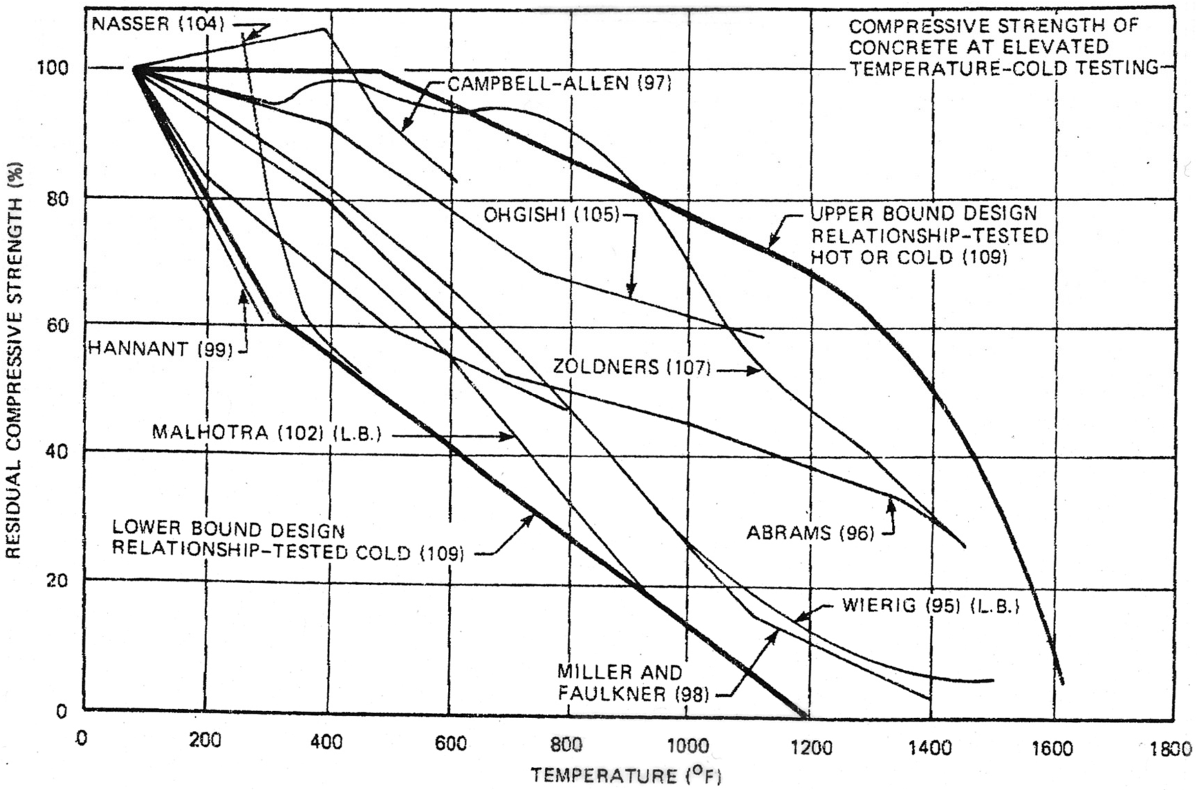

Figure 22 Effect of temperature exposure on compressive strength of concrete: tested cold. *Source*: G. N. Freskakis et al., "Strength Properties of Concrete at Elevated Temperature," *Civil Engineering Nuclear Power*, Vol. 1, ASCE National Convention, American Society of Civil Engineers, Boston, Massachusetts, April 1979.

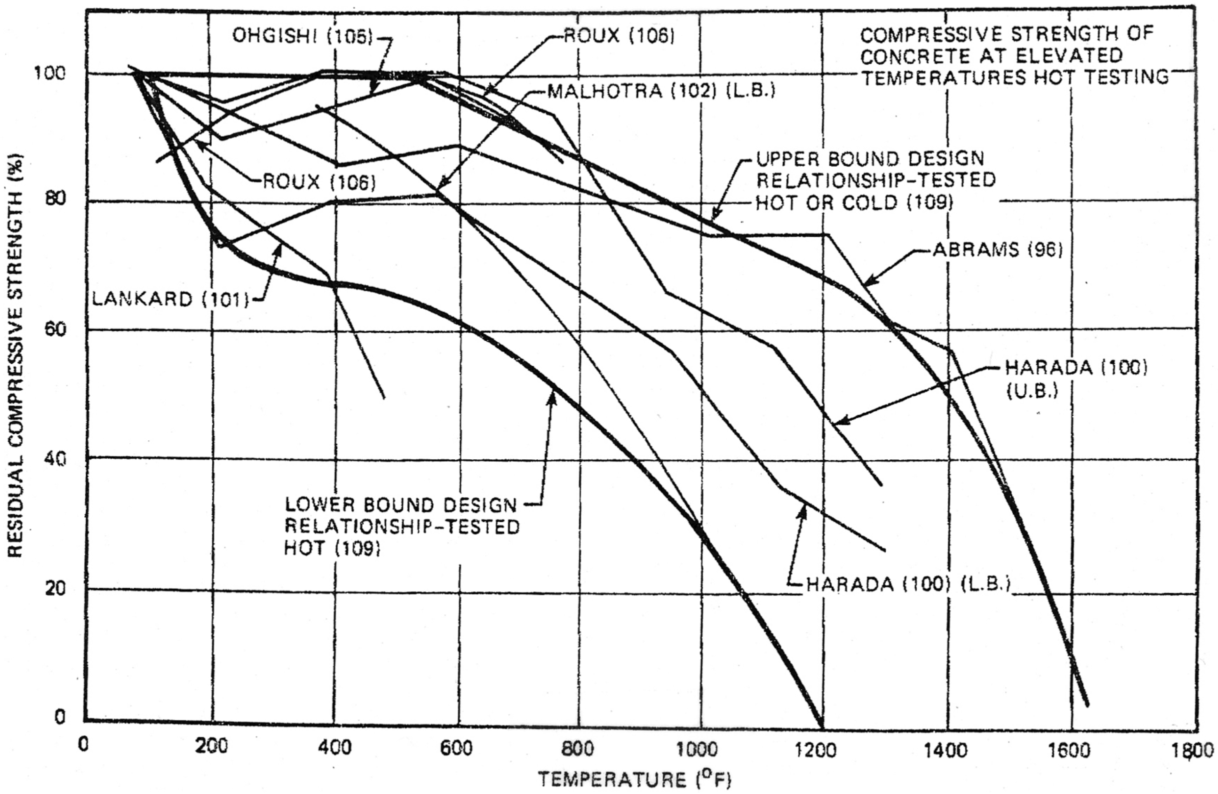

Figure 23 Effect of temperature exposure on compressive strength of concrete: tested hot. *Source*: G. N. Freskakis et al., "Strength Properties of Concrete at Elevated Temperature," *Civil Engineering Nuclear Power*, Vol. 1, ASCE National Convention, American Society of Civil Engineers, Boston, Massachusetts, April 1979.

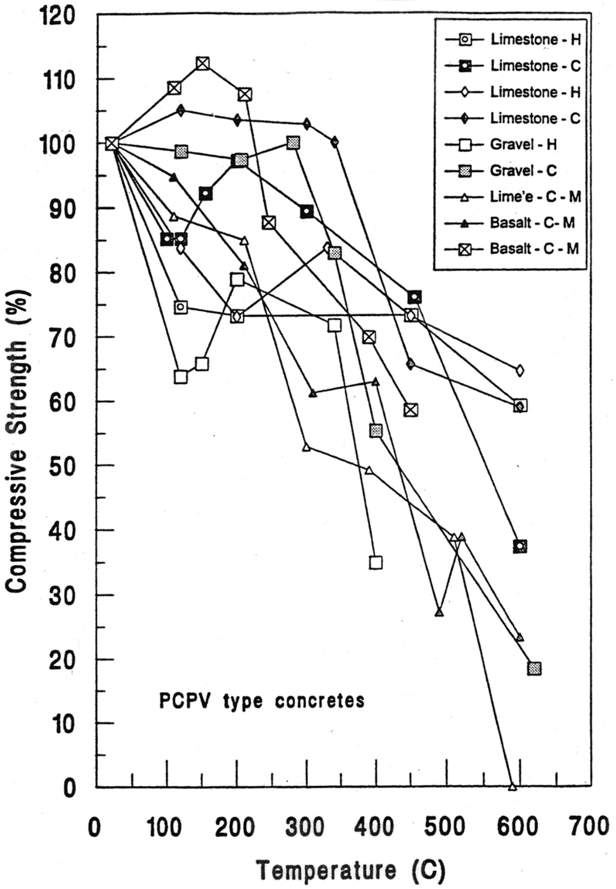

Figure 24 Effect of temperature on uniaxial compressive strength of PCPV unsealed concretes (H = hot, C = cold). *Source*: G. A. Khoury, "Performance of Heated Concrete—Mechanical Properties," Contract NUC/56/3604A with Nuclear Installations Inspectorate, Imperial College, London, United Kingdom, August 1996.

Figure 25, which presents results for unsealed mortars fabricated from ordinary Portland cement, blast furnace slag cement, and truss cement, indicates little difference in strength-temperature characteristics, except the ordinary Portland cement mortar exhibited a sharper decrease in strength at temperatures greater than 500°C (Ref. 4). Another study utilizing a number of cement types (e.g., ordinary Portland cement, fly ash, and blast furnace slag cement) also noted that up to 600°C there was little effect of the cement type.[52] Results presented in Fig. 26 indicate that partial replacement of ordinary Portland cement with pulverized fly ash improves the residual strength and may even produce an increase in strength at higher temperatures.[3,53,*] Water/cement ratio does not appear to have a significant influence on the residual compressive strength of unsealed cement paste as noted by similar trends for three different w/c ratios shown in Fig. 27.[3] These results indicate a peak strength at about 150°C where the residual

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[*] A similar effect was achieved through partial replacement of the ordinary Portland cement with ground granulated blast furnace slag. Partial replacement with silica fume was not beneficial and in some cases produced detrimental residual strength results for unsealed specimens.

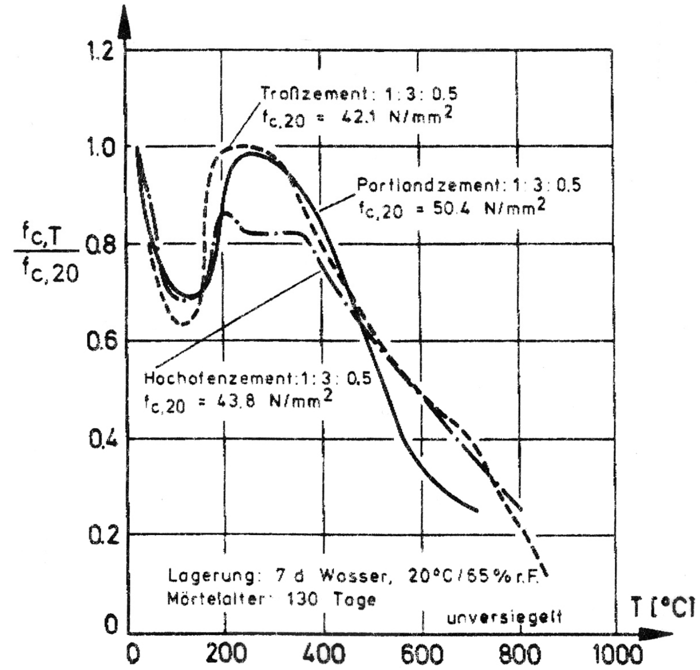


Figure 25 Influence of type of cement on strength loss of mortars. *Source*: U. Schneider, "Behaviour of Concrete at High Temperature," HEFT 337, Deutscher Ausschuss fiir Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

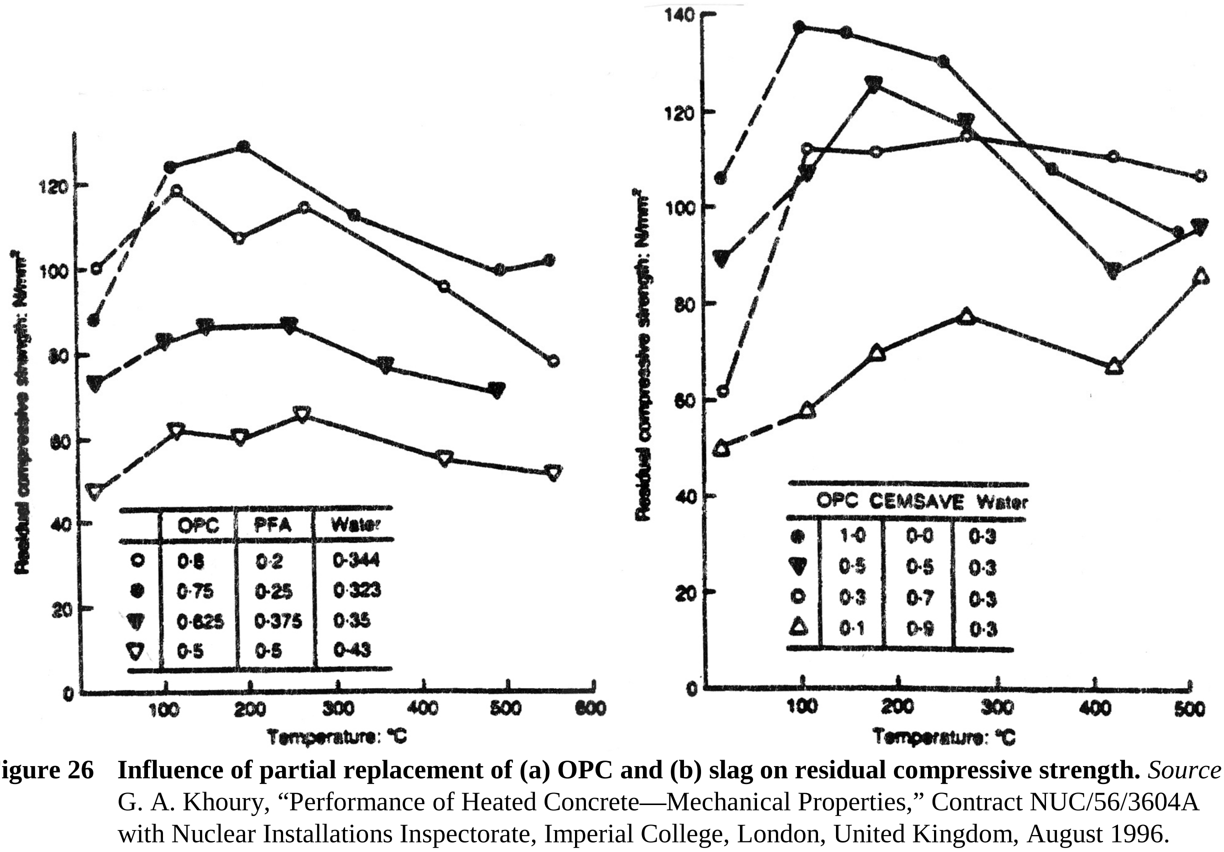


Figure 26 Influence of partial replacement of (a) OPC and (b) slag on residual compressive strength. *Source*: G. A. Khoury, "Performance of Heated Concrete—Mechanical Properties," Contract NUC/56/3604A with Nuclear Installations Inspectorate, Imperial College, London, United Kingdom, August 1996.

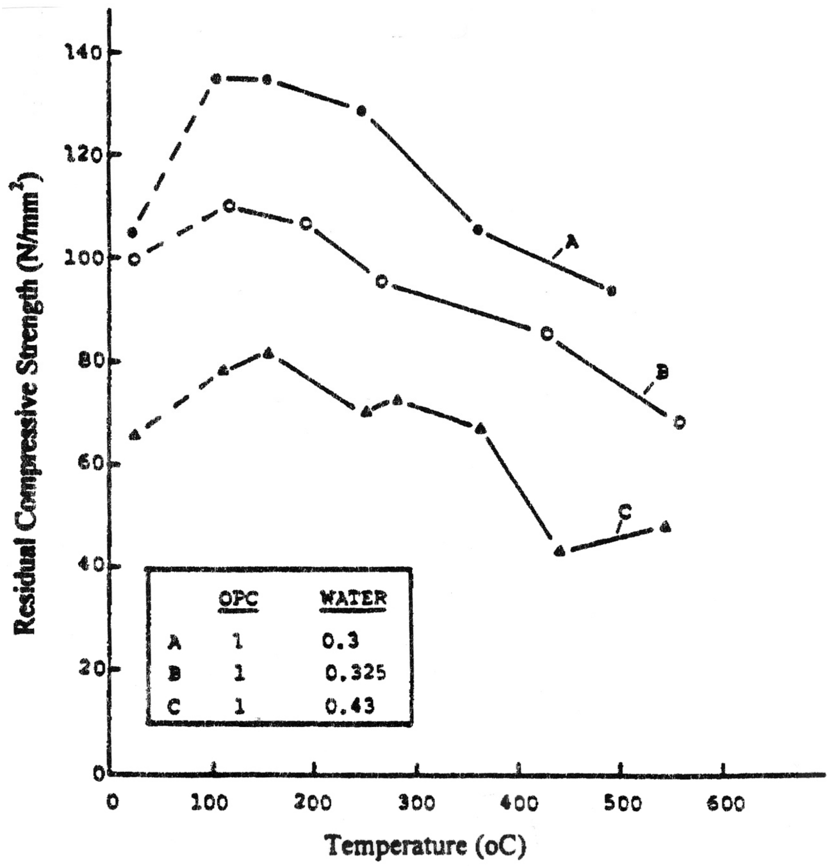


Figure 27 Effect of water/cement ratio on residual compressive strength of OPC. *Source*: G. A. Khoury, “Performance of Heated Concrete—Mechanical Properties,” Contract NUC/56/3604A with Nuclear Installations Inspectorate, Imperial College, London, United Kingdom, August 1996.

strengths were 10 to 30% higher than the reference room temperature strength. Although the strength declined at temperatures higher than 300°C to 350°C, at temperatures of 300°C to 350°C it was still higher than the reference strength. Research presented elsewhere involving several aggregate types indicates that the effects of water/cement (w/c) ratio had little influence on the residual compressive strength up to 600°C (Ref. 52). For normal strength Portland cement concretes, the concrete strength has a secondary effect on strength-temperature characteristics. Residual compressive strength results are presented in Fig. 28 for concretes having compressive strengths ranging from 19.6 to 74 MPa (Ref. 54). This study concluded that a HSC has a higher rate of reduction in residual compressive strength (and modulus) than a NSC. Results of unstressed tests for ordinary Portland cement concretes having reference compressive strengths either of 21, 42, or 60 MPa are presented in Fig. 29.[55] Results obtained for each of the concretes was similar in that the compressive strength decreased at 100°C, recovered to the room temperature strength at 200°C, and then decreased monotonically with increasing temperature beyond 200°C. The effect of curing conditions (e.g., in water unsealed, sealed, in-air unsealed) prior to elevated-temperature exposure is presented in Fig. 30.[36] After at least 91 d cure, the specimens, either in a sealed or unsealed condition, were subjected to 175°C for up to 91 d. Unstressed and residual compressive strengths were determined periodically over the exposure period. Although differences in compressive strengths occurred at smaller exposure ages, after 91 d exposure to 175°C, similar results were provided under all test conditions.

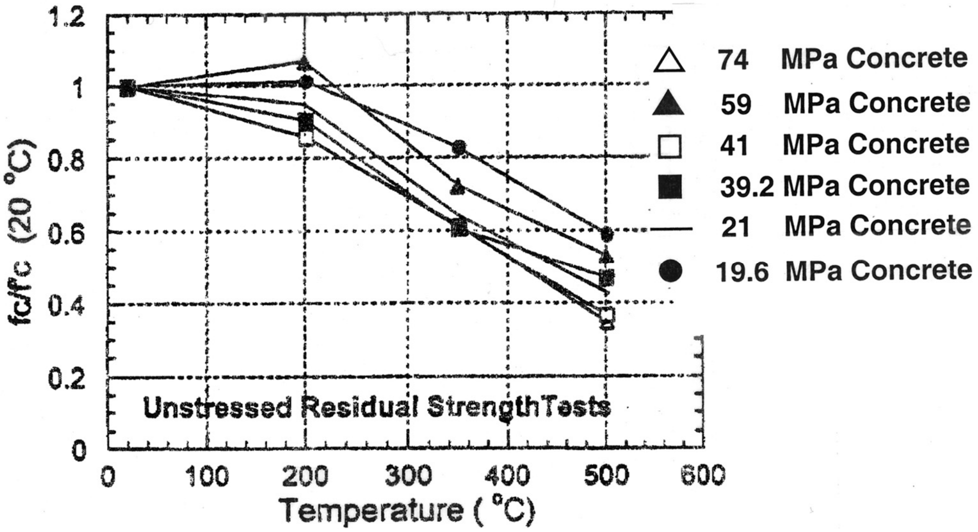


Figure 28 Residual normalized strength vs temperature. *Source*: T. Morita et al., "Residual Mechanical Properties of High Strength Concrete Members Exposed to High Temperature—Part 1. Test on Material Properties," *Summaries of Technical Papers of Annual Meeting,* Architectural Institute of Japan, Naiigata, August 1992.

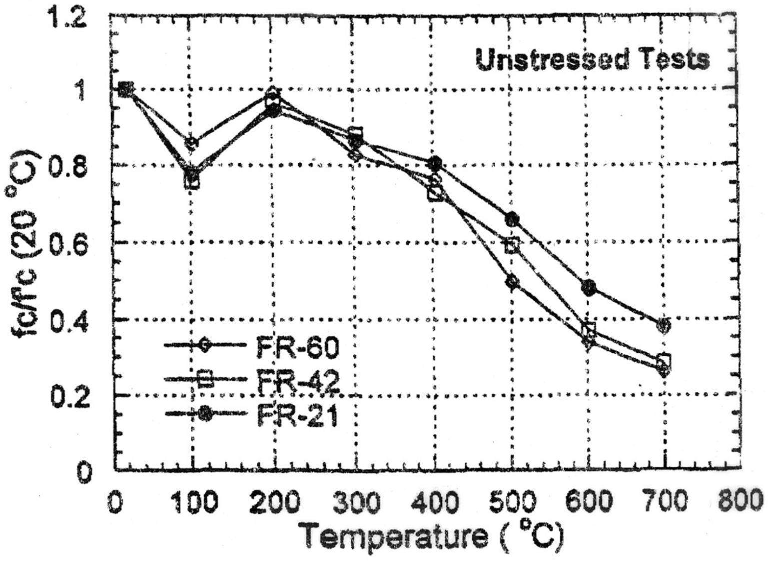


Figure 29 Elastic modulus vs temperature. *Source*: T. Furumura, T. Abe, and Y. Shinohara, "Mechanical Properties of High Strength Concrete at High Temperatures," *Proc. of 4th Weimar Workshop on High Performance Concrete: Material Properties and Design,* held at Hochschule für Architektur und Bauwesen (HAB), Weimar, Germany pp. 237–254, 4–5 October 1995.

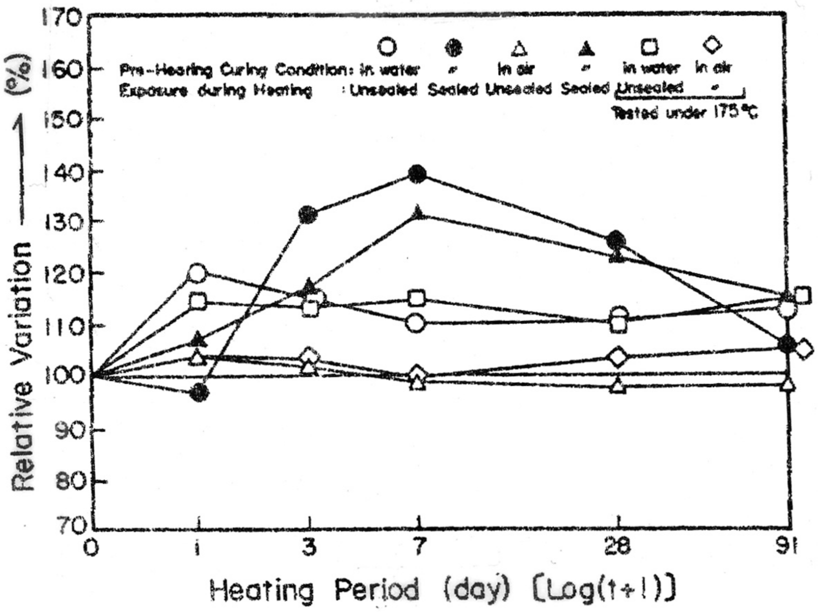


Figure 30 Effect of curing conditions prior to elevated-temperature exposure on relative compressive strength. *Source*: K. Hirano et al., "Physical Properties of Concrete Subjected to High Temperature for MONJU," Paper P2-25, Power Reactor and Nuclear Fuel Development Corporation, Tokyo, Japan.

The age at which the concrete is subjected to elevated-temperature exposure has little effect on the strength-temperature response as long as the concrete has adequate curing (e.g., 90 d). A comparison of residual unstressed compressive strength results for a nuclear power plant concrete (Temelin NPP) at ages of 28-d and 90-d for temperatures to 280°C is presented in Fig. 31.[56] Residual compressive strength results for sealed and unsealed specimens cast from a NPP siliceous aggregate concrete at curing ages of 3 months and 1 year are presented in Fig. 32.[39] These results indicate that some improvement in residual compressive stress due to more extended curing occurs, but it was not significant.

As long as the rate of heating does not produce significant thermal gradients, the rate of heating has a secondary effect on the concrete strength-temperature response, particularly at high temperatures. The effect of rate of heating on residual strength of crushed basalt concrete is presented in Fig. 33.[57] These results indicate that the rates of heating had an insignificant effect on residual strength for temperatures of 600°C and 800°C. However, the heating rate had an effect on the residual compressive strength at lower temperatures. Exposure times at temperature beyond 1 h had an effect on the residual compressive strength, but this effect diminished as the level of exposure temperature increases, with the majority of strength loss occurring in the first 2 h of temperature exposure (Fig. 34). The effect of duration of temperature exposure (exposure periods to 42 d) on the relative strength change of sealed and unsealed gravel and limestone concretes at exposure temperatures to 180°C is shown in Fig. 35.[28] For all temperatures investigated, and for sealed and unsealed conditions, the river gravel concrete generally exhibited a slight strength increase. The compressive strength of the limestone concrete was relatively constant with increasing exposure period for the unsealed condition, but exhibited a decline in compressive strength with increasing temperature level for the sealed condition. The explanation for this

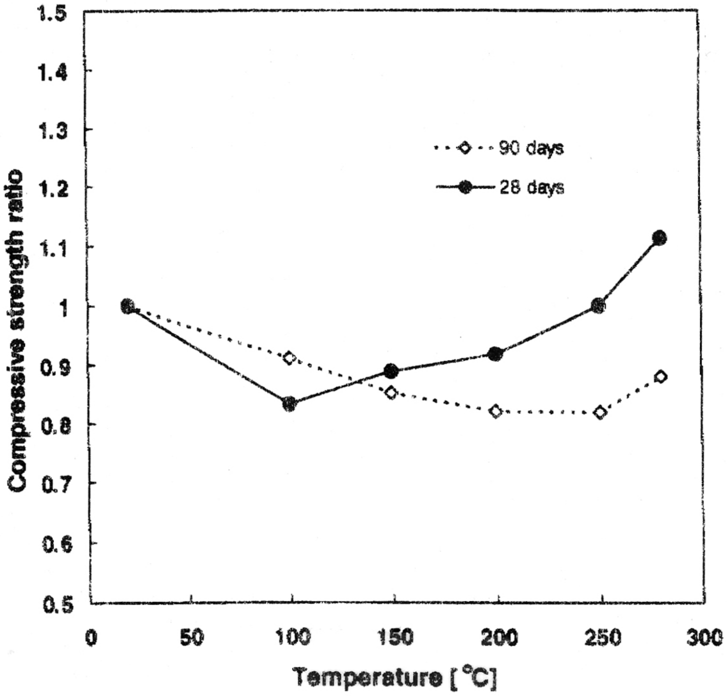


Figure 31 Effect of temperature on compressive strength ratio of concrete. *Source*: F. Vodak et al., "The Effect of Temperature on Strength—Porosity Relationship for Concrete," *Construction and Building Materials* **18**, 529–534 (2004).

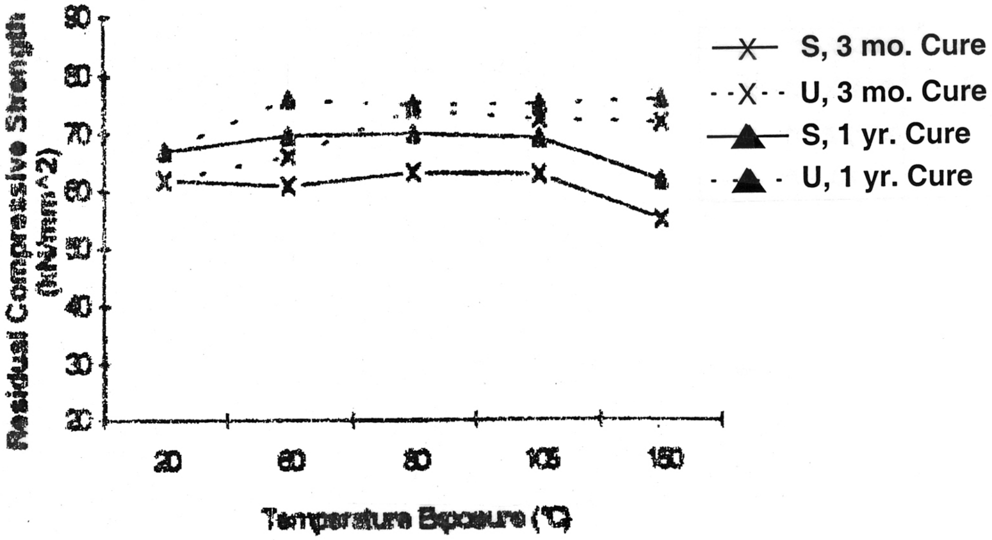


Figure 32 Effect of curing age and exposure condition on residual compressive strength (S = sealed, U = unsealed). *Source*: J. Guo and P. Waldron, "Deterioration of PCPV Concrete," *Nuclear Engineering and Design* **198**, 211–226 (2000).

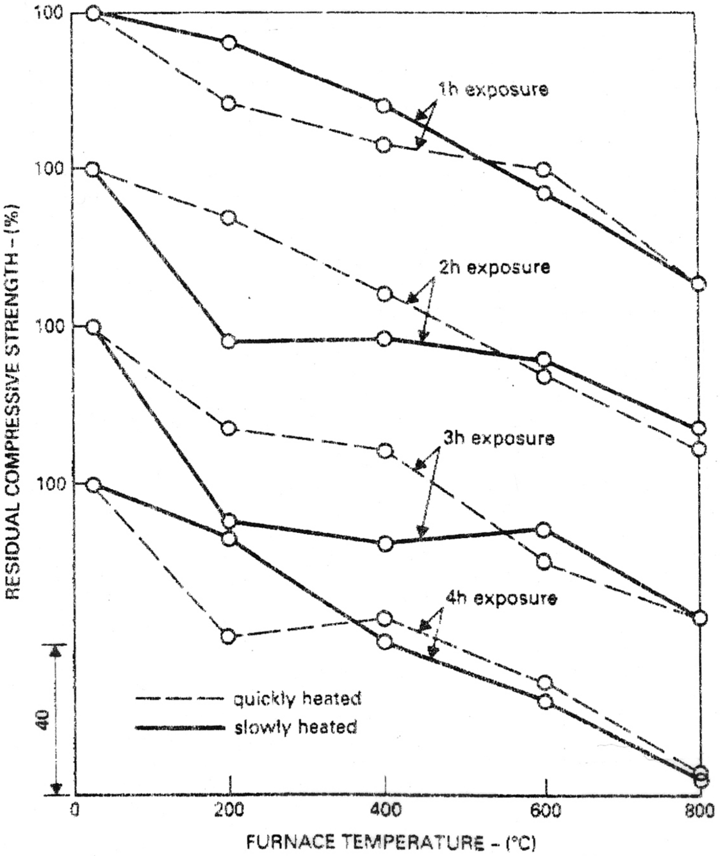


Figure 33 **Effect of rate of heating on residual strength of slowly cooled concrete.** *Source*: G. T. C. Mohamedbhai, "Effect of Exposure Time and Rates of Heating and Cooling on Residual Strength of Heated Concrete," *Magazine of Concrete Research* **38**(136), 151–158 (September 1986).

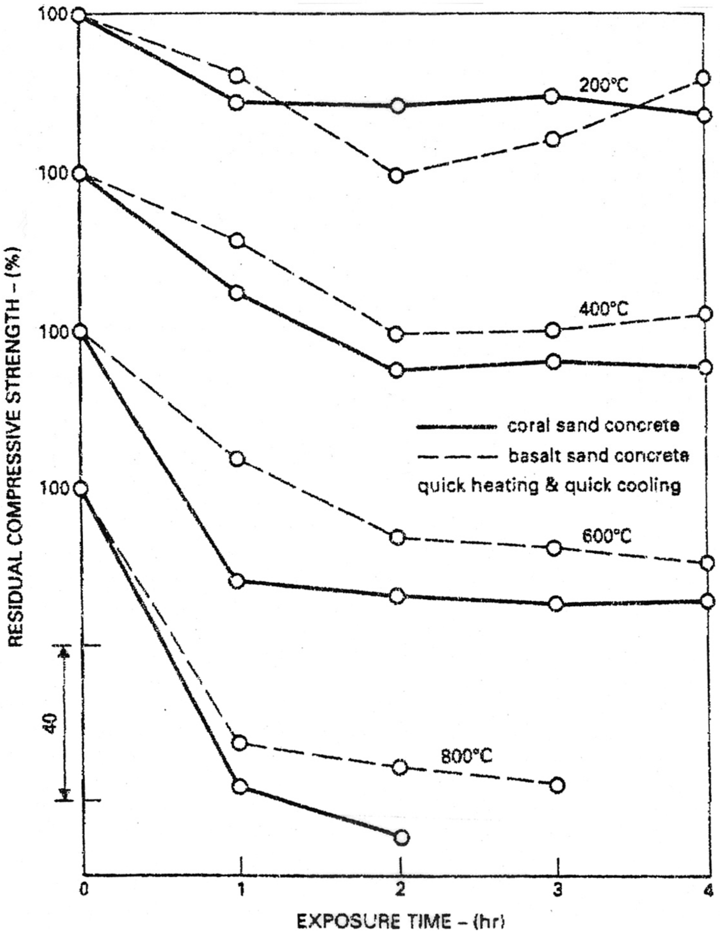
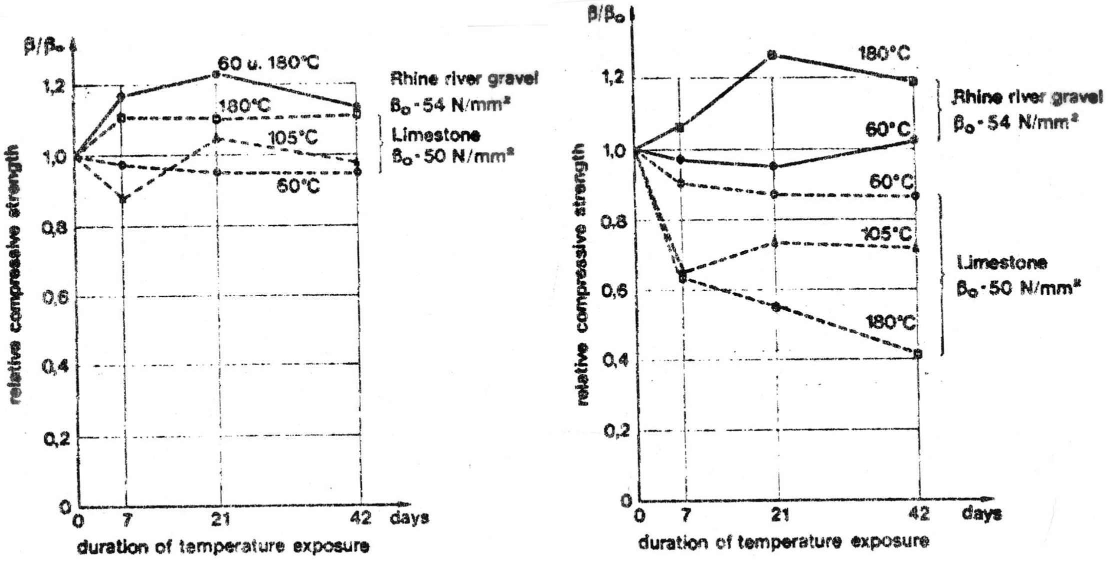


Figure 34 **Effect of exposure time on residual strength of coral sand and basalt sand concretes.** *Source*: G. T. C. Mohamedbhai, "Effect of Exposure Time and Rates of Heating and Cooling on Residual Strength of Heated Concrete," *Magazine of Concrete Research* **38**(136), 151–158 (September 1986).



Unsealed Sealed

Figure 35 **Relative strength development of concrete exposed to elevated temperature.** *Source*: R. Kottas, J. Seeberger, and H. K. Hilsdorf, "Strength Characteristics of Concrete in the Temperature Range of 20° to 200°C," Paper HO1/4 in *5th International Conference on Structural Mechanics in Reactor Technology*, p. 8, Elsevier Science Publishers, North-Holland, The Netherlands, August 1979.

behavior was that the strength loss of the limestone concrete was caused by changes in the microstructure of the hydrated cement paste when exposed to hydrothermal conditions. In the river gravel concrete the strength loss was counteracted by a reaction between the silicates of the fine aggregate particles and the $Ca(OH)_2$ of the hydrated cement paste.

The aggregate type is one of the main factors influencing the compressive strength of concrete at elevated temperature. Figure 36 presents a comparison of stressed, unstressed residual, and unstressed compressive strength results for carbonate and siliceous aggregate concretes at temperatures to 871°C (Ref. 40). Results of this study indicate the influence of the aggregate type, show the beneficial effect of stressing the specimens (within limits) while heated, and indicate that unstressed results obtained at temperature exceed those obtained under unstressed residual conditions (i.e., hot strength results were generally greater than residual strength results). The influence of aggregate type on results is further illustrated in Fig. 37 where the compressive strength of limestone and other concretes is presented.[4,*] It was noted in this reference that for the temperature range shown in the figure, quartz and basalt aggregate are less sensitive to temperature effects than the limestone aggregate concrete.

Results in the literature indicate that the original concrete strength (NSC), type of cement, aggregate size, heating rate, and water/cement ratio have little affect on the relative strength vs temperature characteristics; exposure times at temperatures beyond 1 h had an effect on residual compressive strength, but this effect diminished as the level of exposure temperature increased, with the majority of strength loss occurring in the first 2 h. Age of concrete is important in so far as concretes with relatively

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[*] See also Fig. 72.

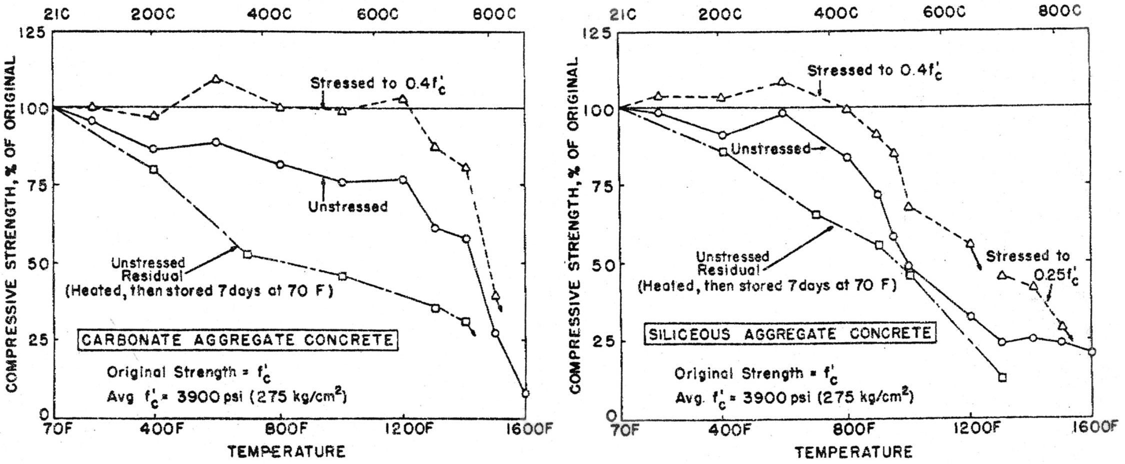


Figure 36 Effect of exposure time on residual strength of carbonate and siliceous aggregate concretes. *Source*: M. S. Abrams, "Compressive Strength of Concrete at Temperatures to 1600°F," SP-25 *Temperature and Concrete,* American Concrete Institute, pp. 33–58, 1971**.**

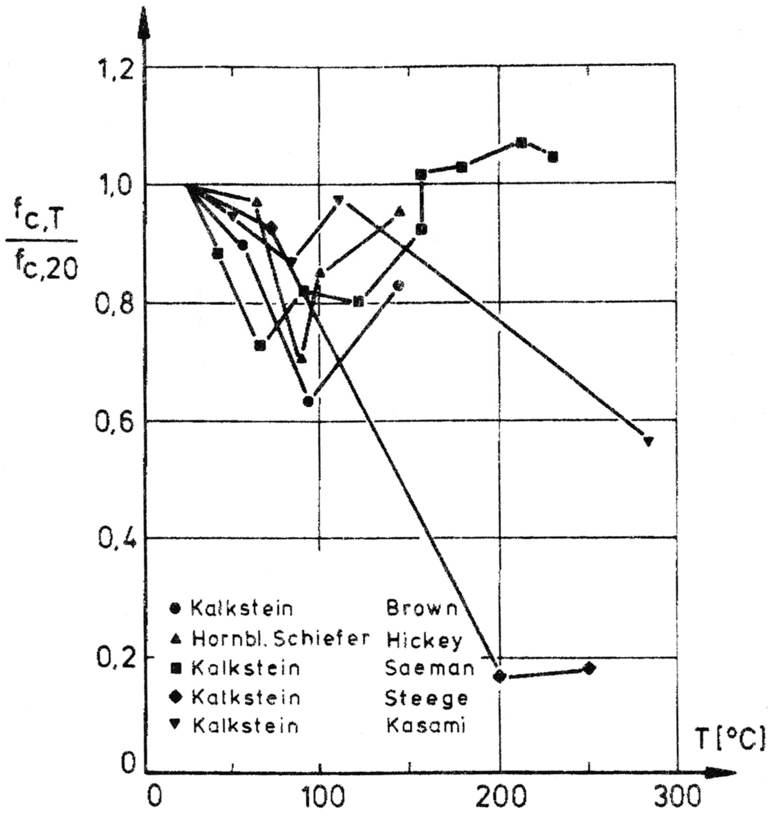


Figure 37 Compressive strength of concretes with limestone and other aggregate types. *Source*: U. Schneider, "Behaviour of Concrete at High Temperature," HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

incomplete hydration of cement may indicate a strength increase for temperature up to 400°C due to accelerated hydration; maximum test temperature influences the strength recovery in that after exposures to above about 600°C there is no strength recovery; aggregate/cement ratio has a significant affect on strength of concrete exposed to high temperature with the reduction being proportionally smaller for lean mixtures than for rich mixtures. Type of aggregate appears to be one of the main factors influencing concrete strength at high temperature with siliceous aggregate concrete having lower strength (by percentage) at high temperature than calcareous and lightweight concrete; and stressed specimens resulted in higher compressive strength at high temperature than unstressed specimens.

Thermal Cycling

Thermal cycling, even at relatively low temperatures (65°C), can have some deleterious effects on concrete's mechanical properties (i.e., cyclic heating generally gives lower strengths than a single heating).[45] The effect of temperature cycling on a limestone aggregate concrete is presented in Fig. 38[58] and in Fig. 39[59] for a sealed limestone concrete. Results indicate that the compressive, tensile, and bond strengths, and the modulus of elasticity are reduced, and that Poisson's ratio is increased.[58,59] As shown in Fig. 39, the sealed limestone concrete exhibited a 50% loss of strength after 14 cycles at 150°C. At higher temperatures (200°C to 300°C), the first thermal cycle causes the largest percentage of damage, with the extent of damage markedly dependent on aggregate type and is associated with loss of bond between the aggregate and cement paste matrix.[58]

Tensile Strength

The tensile strength of concrete is important because it determines the ability of concrete to resist cracking. At room temperature, concrete's tensile strength generally varies from 7 to 11% its compressive strength. Direct measurement of concrete's tensile strength is seldom made because of difficulties in gripping the specimen to apply loads. An indication of concrete's tensile strength can be obtained by the splitting-tension and flexure tests. The splitting-tension test is an indirect test for tensile strength of concrete in that a horizontal concrete cylinder is loaded in compression through bearing strips placed along two axial lines that are diametrically opposite on the specimen.[60] Flexural strength of concrete is expressed in terms of modulus of rupture that is determined from beam specimens loaded in four-point bending until failure occurs. Because the modulus of rupture is calculated based on linear-elastic conditions, it is a fictitious value, but convenient for comparison purposes. For normal strength concretes tested at room temperature, the modulus of rupture is 60 to 100% higher than the direct tensile strength and 100 to 133% the splitting-tension strength.[31] Most tests to determine elevated-temperature effects on concrete tensile strength used splitting-tension tests with the residual tensile strength determined.

Unstressed residual tests of a normal-strength (38.1-MPa) and high-strength (61.1-MPa) calcareous aggregate concrete were conducted to evaluate the effect of elevated temperature on the direct-tensile and splitting-tensile strengths.[61] The experimental results, Fig. 40, show that the residual tensile strengths for both NSC and HSC decreased similarly and almost linearly with increasing temperature. Also, tensile strengths measured by the splitting-tension test were consistently higher than those obtained by the direct-tension test. Results presented in Ref. 52, in which residual tensile-strength ratio results were determined

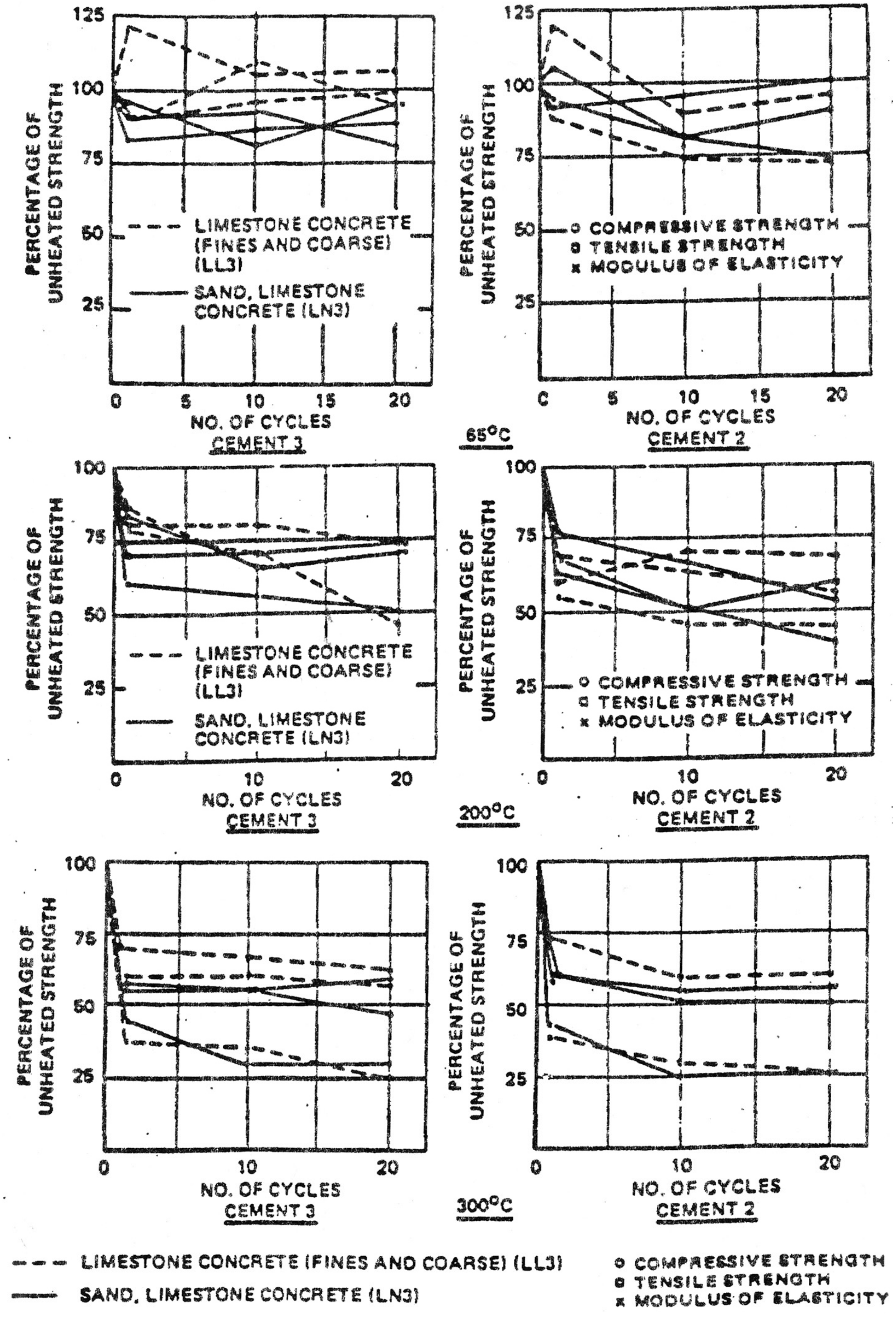


Figure 38 Effect of temperature cycles on limestone concretes. *Source*: D. Campbell-Allen and P. M. Desai, "The Influence of Aggregate on the Behavior of Concrete at Elevated Temperature," *Nucl. Eng. and Design* **6**(1), 65–77 (August 1967).

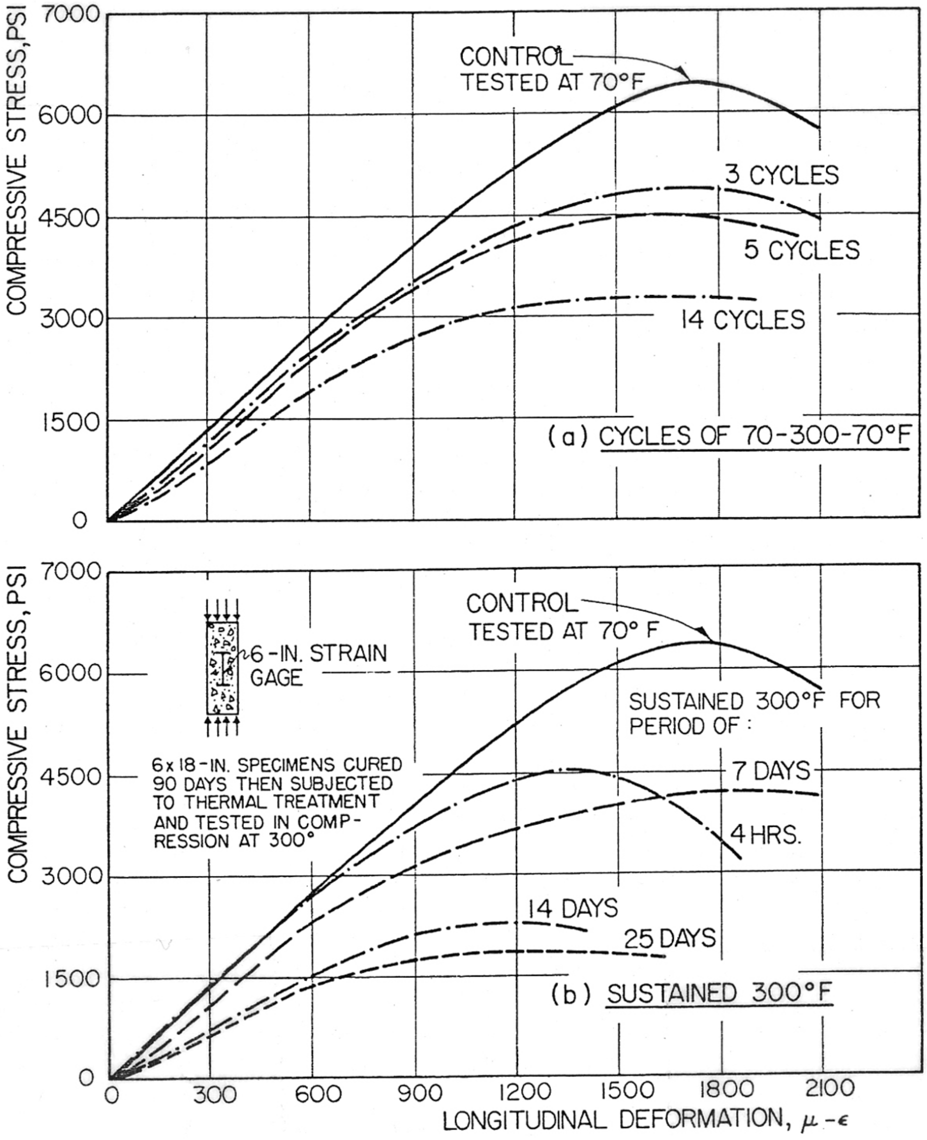


Figure 39 **Influence of thermal cycling on σ-e response of sealed concrete tested at 300°F (149°C).** *Source*: V. V. Bertero and M. Polivka, “Influence of Thermal Exposures on Mechanical Characteristics of Concrete,” Paper SP 34-28 in Special Publication 34, Vol. I-III, American Concrete Institute, Farmington Hills, Michigan, 1972.

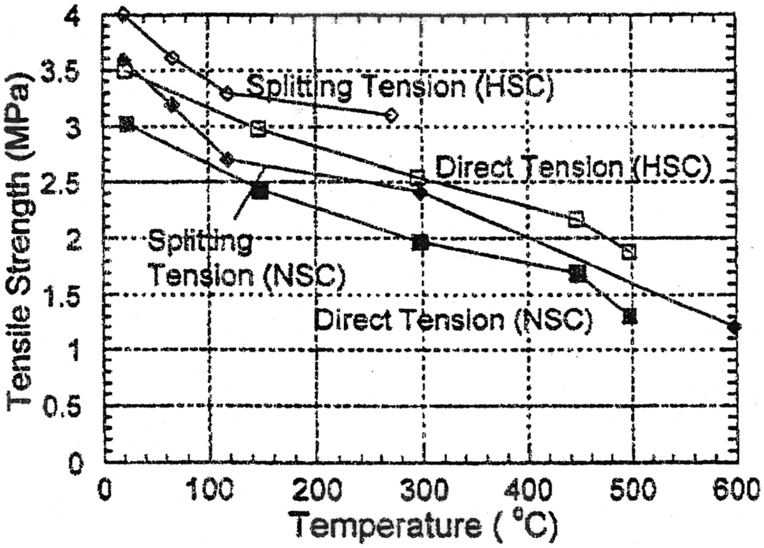


Figure 40 Residual tensile strengths of HSC and NSC. *Source*: A. N. Noumowe et al., "Thermal Stresses and Water Vapor Pressure of High Performance Concrete at High Temperature," *Proc. 4th International Symposium on Utilization of High-Strength/High-Performance Concrete, Paris, 1996.*

at temperatures of 300°C and 600°C for unsealed specimens, indicate that the residual ratios decrease with the rise of heating temperature, except for alumina cements there was little difference in results up to 600°C for several cement types investigated, and there was no significant variation in residual ratio results resulting from different water/cement ratios utilized (i.e., 0.45, 0.55, and 0.65). The influence of exposure condition on the splitting-tensile strength has been investigated.[39] Residual splitting-tensile strength results for sealed and unsealed specimens cast from a NPP siliceous aggregate concrete at curing ages of 3 months and 1 year are presented in Fig. 41.[39] Unlike the residual compressive strength results obtained in the investigation, the tensile strength of sealed concrete specimens that had experienced temperature exposure is higher than that for unsealed specimens (except at 150°C). Comparing compression and tensile results, the splitting-tensile strength appears to be more sensitive to the effect of moisture content as well as to microcracking caused by the temperature exposure. A comparison of the effect of elevated-temperature exposure on residual compressive, tensile (splitting-tension), and bend strengths (notched beams) for a siliceous gravel concrete exposed to temperatures up to 600°C is presented in Fig. 42.[62] Results in the figure indicate that the residual tensile strength, either splitting-tensile or notched beam, is affected more significantly as the temperature increases than the compressive strength.

Modulus of rupture results presented in Ref. 63 show that an increase in temperature beyond room temperature caused the modulus of rupture to decrease to minimum values between 38°C and 65°C. The modulus of rupture was reduced to 50% and 10% compared to room temperature values, for rich and lean mixtures. A further increase in temperature produced a slight increase in the modulus of rupture compared with room temperature values with rich mixes showing a large increase in modulus of rupture with increase in temperature to 121°C with the values being 20% higher than the room temperature results. Changes in flexural strength of Portland cement containing gravel or limestone aggregate heated to

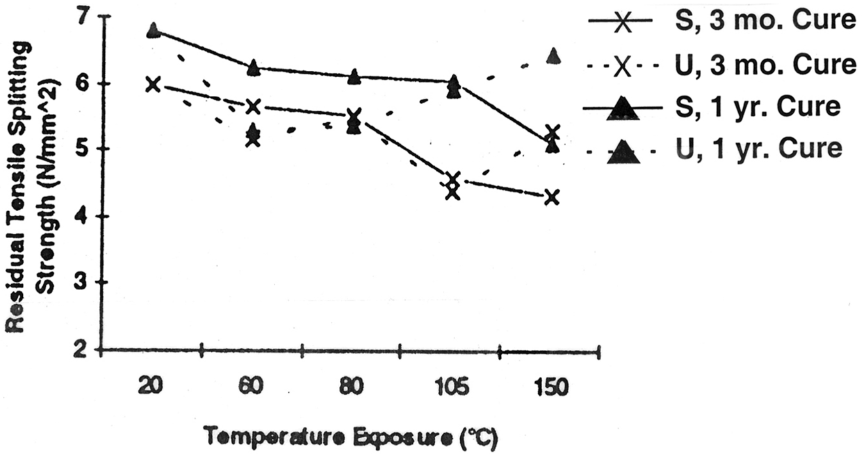


Figure 41 Effect of curing age and exposure condition on residual splitting-tensile strength (Solid line = sealed, dashed line = unsealed). *Source*: J. Guo and P. Waldron, "Deterioration of PCPV Concrete," *Nuclear Engineering and Design* **198**, 211–226 (2000).

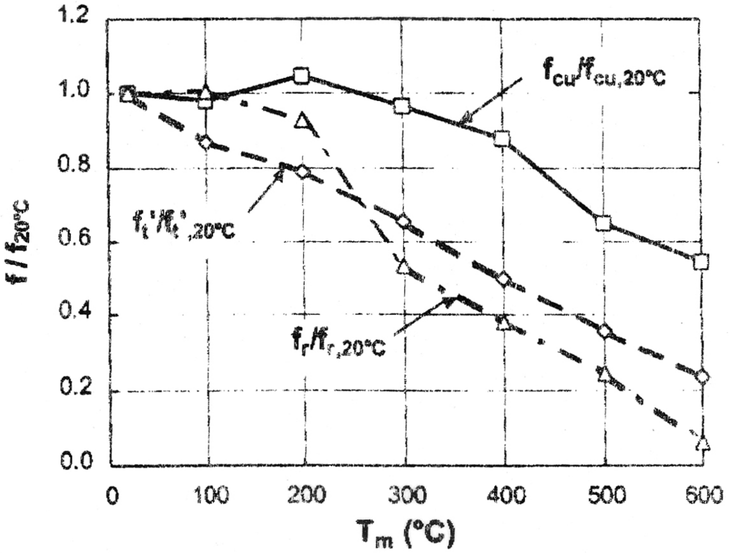


Figure 42 Comparison of the effect of elevated-temperature exposure on residual compressive, tensile (splitting-tension), and bend strengths (notched beams) of siliceous aggregate concrete. *Source*: B. Zhang et al., "Relationship Between Brittleness and Moisture Loss of Concrete Exposed to High Temperatures," *Cement and Concrete Research* **32**, 363–371 (2002).

temperatures up to 260°C were studied.[45] The results showed that the unsealed gravel and limestone concretes heat treated at 79°C exhibited a slight increase in flexural strength, whereas concrete heat treated at 121°C and 260°C exhibited a loss of flexural strength. The gravel concrete showed a lesser degree of flexural strength loss than the limestone concrete at elevated temperature. Flexural strength results have been presented for concrete in which the cement was partially replaced by fly ash (i.e., 10, 20, or 30%) and the specimens subjected to elevated-temperature exposures of 100, 200, or 250°C for 1-, 2-, or 3-h durations.[64] Figure 43 presents the variation of maximum flexural strength with temperature for the control and three mixes with different partial placements of cement with fly ash exposed to elevated temperature for 60 min. Figure 44 shows the variation of residual flexural strength with percentage fly ash for three different exposure temperatures and times. Conclusions of this study were that the fly ash consistently showed the same pattern of flexural behavior (i.e., trend) with temperature as that exhibited by concrete without fly ash for thermal exposures up to 250°C; the exposure time had an effect on the residual flexural strength of concrete, but the majority of strength loss occurred within the first hour of exposure.

Conclusions from the limited tensile test data available in the literature are that the aggregate type and mixture proportions have a significant effect on the tensile strength vs temperature relationship; the decrease in tensile strength of calcareous aggregate concrete is twice as high as that of siliceous aggregate concrete at 500°C; concretes with lower cement content have lower reduction in tensile strength than those with higher cement content; the rate of heating has minimal effect on tensile strength at high temperature; and the residual tensile strength is somewhat lower than the tensile strength measured at elevated temperature.

Shrinkage and Creep

Shrinkage of concrete is important because of its effect on movement of the structure and its tendency to induce cracking. Shrinkage occurs as a result of two effects: (1) drying or (2) autogeneous volume change. Drying shrinkage results from the loss of absorbed water and is generally the more predominant of the two effects. Autogeneous shrinkage is more prevalent in mass concrete structures where the total moisture content remains relatively constant; it results from continued cement hydration reducing the free-water content (products of hydration occupy less volume than the sum of the separate volumes of the components). Several factors affect concrete drying shrinkage: (1) cement and water contents (shrinkage

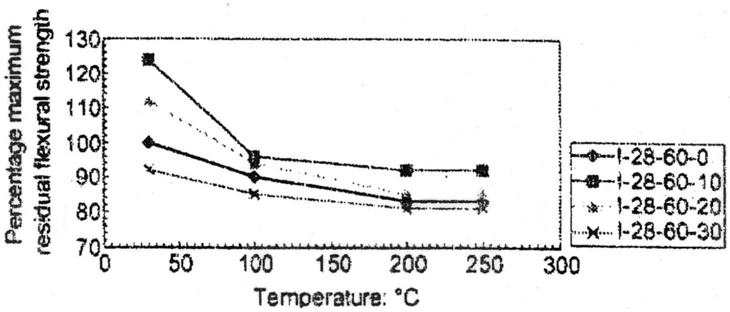


Figure 43 Variation of flexural strength with temperature. *Source*: M. P. Raju, M. Shobha, and K. Rambabu, "Flexural Strength of Fly Ash Concrete Under Elevated Temperatures," *Magazine of Concrete Research* **56**(2), 83–88 (March 2004).

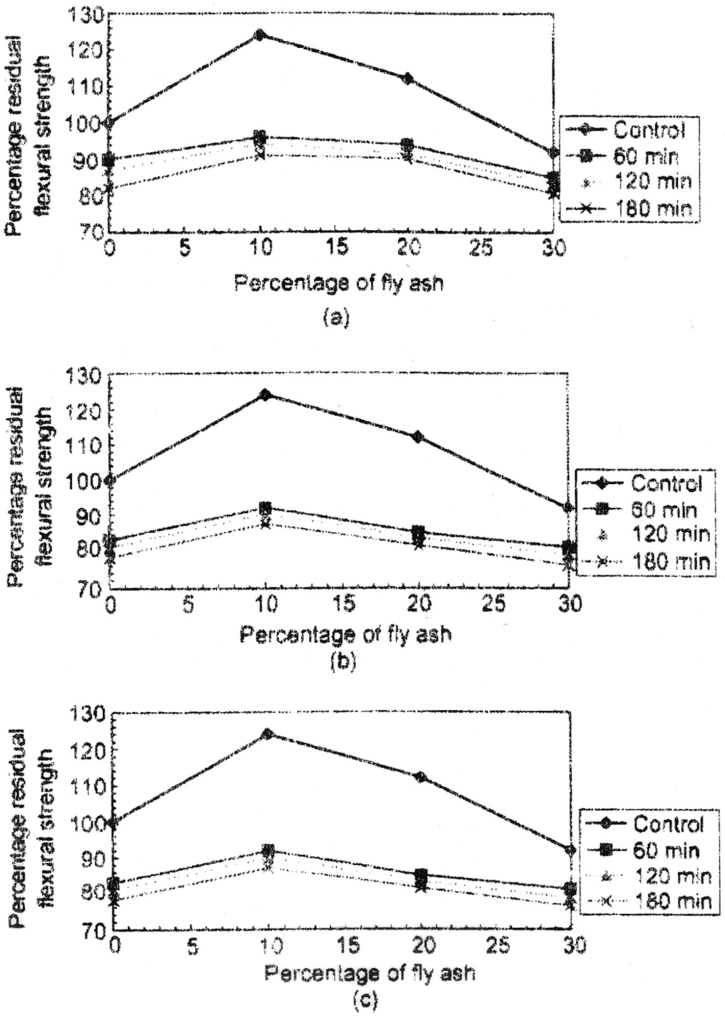


Figure 44 Variation of percentage residual flexural strength for (a) 100°C, (b) 200°C, and (c) 250°C. *Source*: M. P. Raju, M. Shobha, and K. Rambabu, "Flexural Strength of Fly Ash Concrete Under Elevated Temperatures," *Magazine of Concrete Research* **56**(2), 83–88 (March 2004).

varies directly with water-cement ratio);[65] (2) composition and fineness of cement; (3) type and gradation of aggregate (shrinkage inversely proportional to size and amount of coarse aggregate-sandstone, slate, basalt and trap rock produce concretes having greater shrinkage than quartz, limestone, dolomite, granite and feldspar aggregate concretes); (4) admixtures (those that reduce water requirement reduce shrinkage); (5) moisture and temperature conditions; and (6) amount and distribution of reinforcement. The effects of several variables influencing autogeneous shrinkage are summarized in Fig. 45.[66] In mass structures where the concrete is maintained below 100°C, shrinkage will not be a significant factor over the 30- to 40-year design life of a structure such as a PCPV.[67] The rate and magnitude of drying shrinkage generally increase with temperature.

Creep can be defined as the increase in strain in a structural member with time due to sustained stress. Because creep affects strains, deflections, and stress redistribution, it is important with respect to

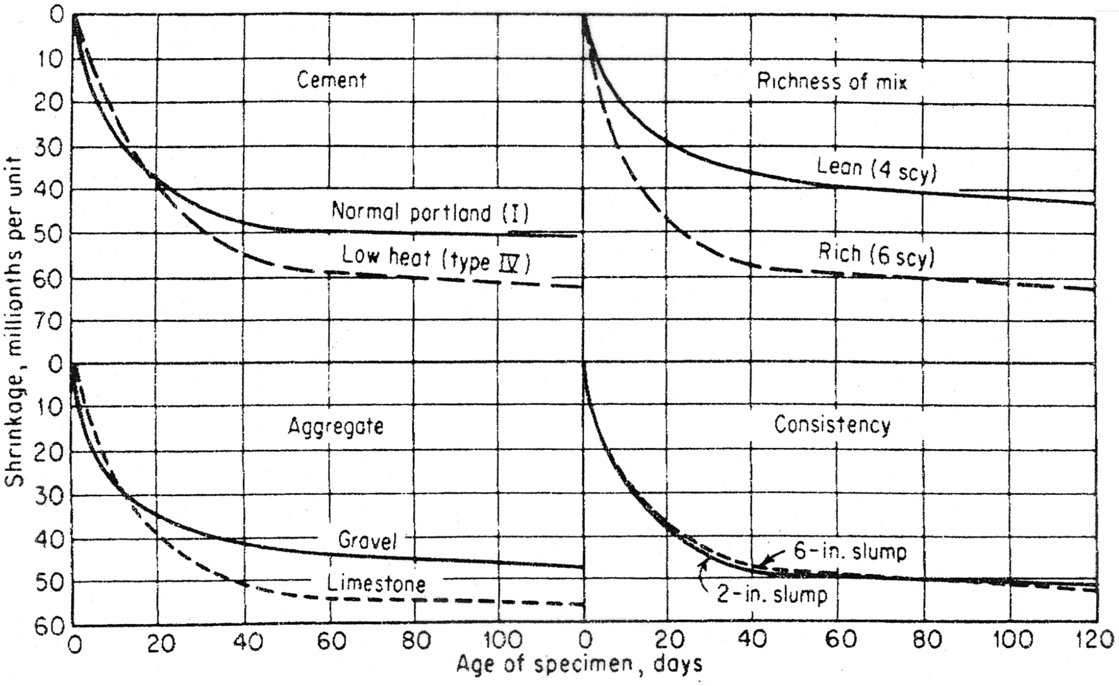


Figure 45 Effect of several factors on autogenous shrinkage of concrete. *Source*: G. E. Troxell, H. E. Davis, and J. W. Kelly, "Composition and Properties of Concrete," 2nd Ed., McGraw-Hill, New York, 1968.

structural analysis. Creep may also be viewed from another standpoint: if a loaded specimen is restrained from movement (constant net strain), creep will manifest itself as a progressive decrease in stress with time (stress relaxation). Although creep is generally considered only for specimens loaded in compression, creep of concrete in tension also occurs and is on the same order of magnitude as creep in compression.[68] Also, upon release of the sustained load, an initial elastic recovery of strain occurs followed by creep recovery that can continue for several days. The magnitude of creep recovery is greater for concrete specimens that were loaded later in their cure cycle, and it is inversely proportional to the period of sustained stress.

Several theories for the creep mechanism have been proposed: viscous flow of the cement-water paste, closure of internal voids, crystalline flow of aggregate, and seepage into internal voids of colloidal (adsorbed) water formed by cement hydration.[31] Some investigators[69] divide creep into two types: (1) basic creep under conditions of hygrometric equilibrium caused by molecular diffusion of the gel and absorbed water, causing a partially viscous (irrecoverable) and partially delayed elastic (partially recoverable) behavior; and (2) drying creep caused by a mechanism similar to that involved in free shrinkage due to desiccation. Basic creep has been defined as the load-induced, time-dependent deformation of a specimen which is loaded after achieving thermal, hygral, chemical, and dimensional stability at first heating to a given temperature.[70] Creep of specimens that are loaded after achieving stability at temperature higher than the temperature at loading can be termed basic creep. Drying creep is a function of the moisture loss from the concrete and is related to drying shrinkage. In sealed concrete, drying creep is absent and it is usually the practice to describe the creep during first heating simply as transitional thermal creep. Reference 3 provides a very complete description of the strains that develop for loaded and unloaded concrete during first heat-up, at constant temperature, during cooling, and residual strains. Also included in this reference is a method for isolating individual strain components and performing an assessment of their magnitude.

Several physical and environmental parameters affect creep deformations of normal-weight concrete. Physical parameters inherent to the particular concrete mix include: (1) cement type (degree of hydration); (2) cement paste proportions and content (creep proportional to volume fraction of cement paste in mix); (3) aggregate properties and volume fraction [(a) aggregate restrains creep, (b) mineral character effects are presented in Fig. 46, and (c) creep tends to be inversely proportional to maximum aggregate size for uniformly graded mixes[31,71]]; (4) strength and stage of hydration [(a) creep decreases with degree of cement hydration of a mix, and (b) generally the amount of creep is inversely proportional to the concrete strength]; (5) moisture conditions of storing [creep is generally inversely proportional to the relative humidity of the medium surrounding the concrete (Fig. 47)[32]], and (6) size of mass (the larger the mass, the lower the creep). Mechanical parameters include: (1) state of stress: [under uniaxial compressive stress for stress/strength ratio < 0.4, creep is proportional to applied stress; (b) at high stress-strength levels (>0.85), creep can lead to failure; (c) creep under multiaxial compression is less than under uniaxial compression of the same magnitude in the given direction (Fig. 48); (d) creep occurs under hydrostatic compression[72–74]]; (2) age at loading [specific creep decreases for increased loading age]; and (3) temperature [(a) creep follows the same general pattern as creep at room temperature—being an exponential function of time under load and a relatively linear function of stress up to a stress-strength

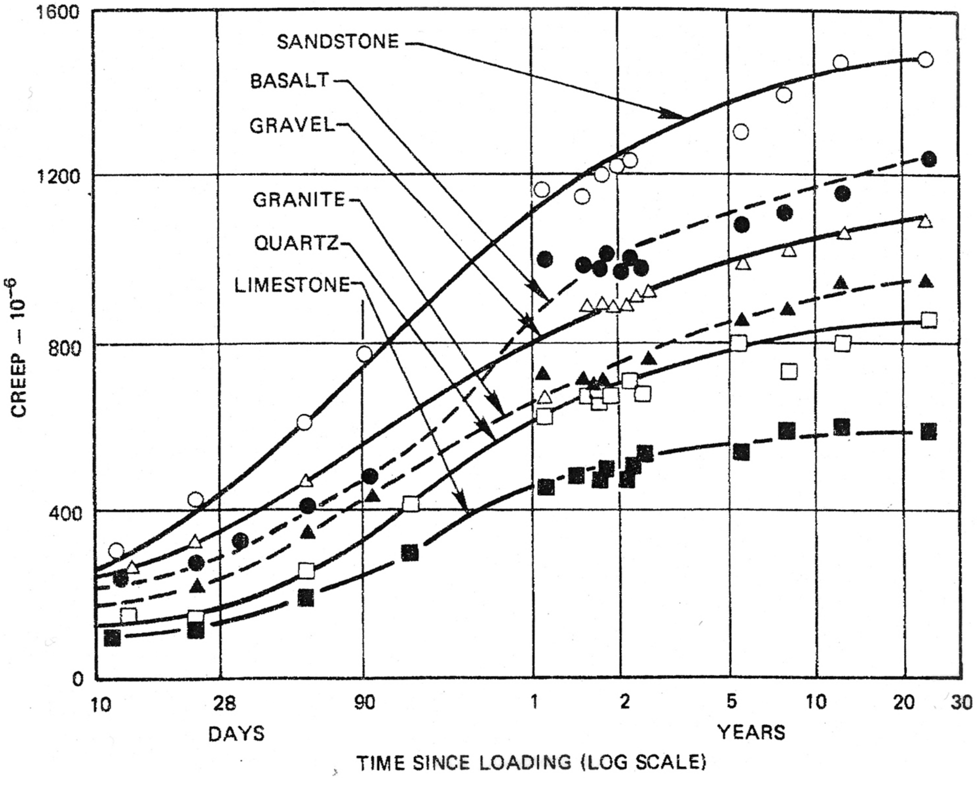


Figure 46 Creep of concrete with different aggregates (aggregate/cement ratio = 5.67, w/c = 0.59, stress = 56 kg/cm^2). *Source*: G. E. Troxell et al., *Composition and Properties of Concrete,* 2nd Ed., McGraw-Hill, New York, 1968.

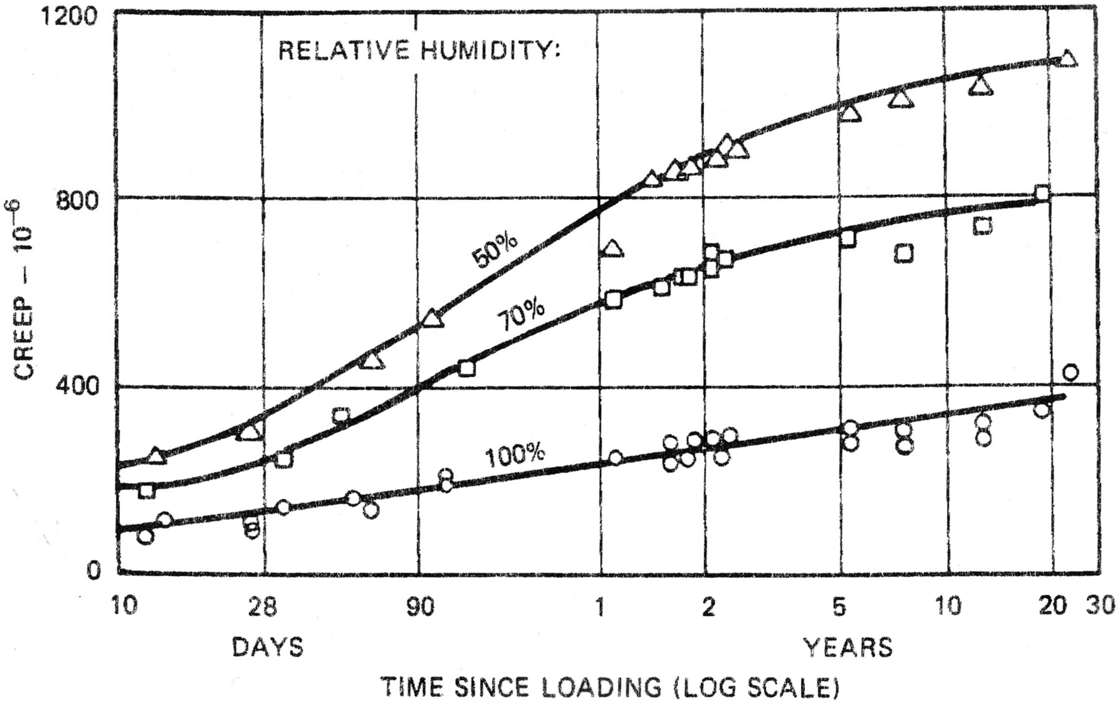


Figure 47 Creep of concrete stored at different relative humidities. *Source:* A. M. Neville, *Properties of Concrete*, Pitman, London, United Kingdom, 1970.

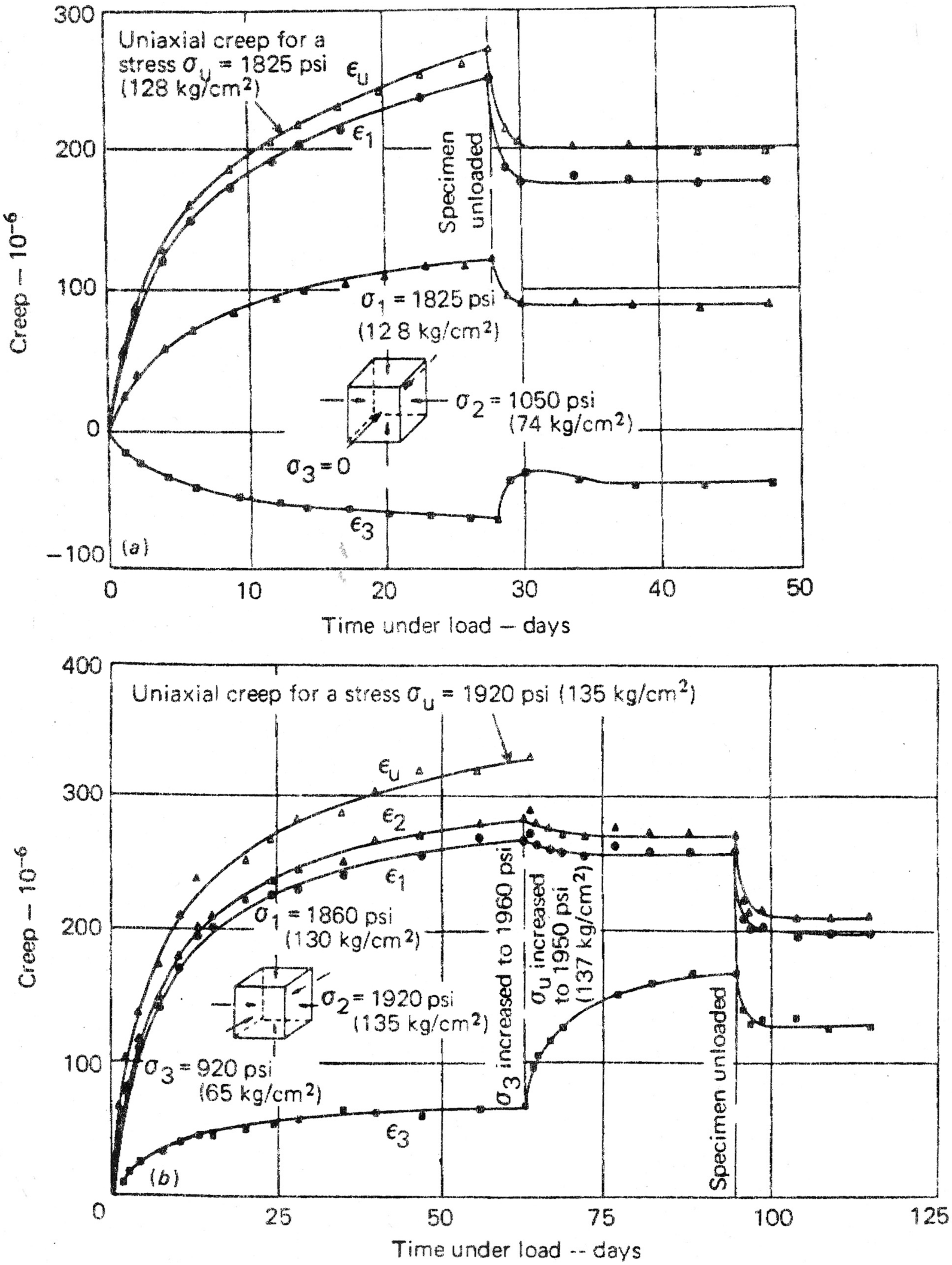


Figure 48 **Typical creep-time curves under multiaxial compression: (a) biaxial, and (b) triaxial.** *Source*: A. M. Neville, *Creep of Concrete: Plain, Reinforced and Prestressed*, North-Holland Publishing Company, Amsterdam, The Netherlands, 1970.

ratio of ~0.4; (b) sealed specimens exhibit less creep than unsealed; (c) creep definitely increases with temperature up to at least 50°C and probably increases with temperature up to 150°C (Fig. 49); and (d) the degree of creep recovery appears to be more dependent on stress level than temperature].[47,75]

As noted in Ref. 76, the effects of temperature on the creep of hardened cement paste can be broadly classified as thermal and structural. The thermal effect of temperature is that which is due to the temperature at loading, being seated in the molecular agitation caused by temperature. The structural effect will depend on the maximum exposure temperature, on the assumption that cooling down to the loading temperature does not reverse any structural changes caused by heating or cause structural changes of its own. The above assumption regarding the cooling will be true only if differential thermal strains within the specimen are minimized by a slow rate of cooling and if hydration is not allowed to take place. It was shown that (1) the thermal effect of temperature on creep can be modeled by an Arrhenius-type rate theory, (2) the structural effect of temperature on creep can be classified as that due to loss in strength and that due to stabilization process, and (3) in the range 300°C to 635°C, the above two processes are opposed to each other (i.e., strength is reduced causing an increase in creep potential, while stabilization, reflected by percentage weight loss, is increased causing a decrease in creep potential).

Like all solid materials, creep of concrete increases with temperature. Below 100°C, concrete creep at moderate stress levels originates in the cement paste, probably because of the mutual approach of adjacent laminar particles of cement gel, which is facilitated by the presence of water in gaps between the particles.[6] Temperature effect on creep, presented in Fig. 50,[33] is caused by acceleration of the diffusion of the solid components and water along gaps between the particles. At moderate temperature levels (T < 105°C), hydration (aging) accelerates, but at T > 100°C the reverse of this effect takes place (dehydration accelerates creep). Above 100°C, drying of the concrete is very rapid with an associated

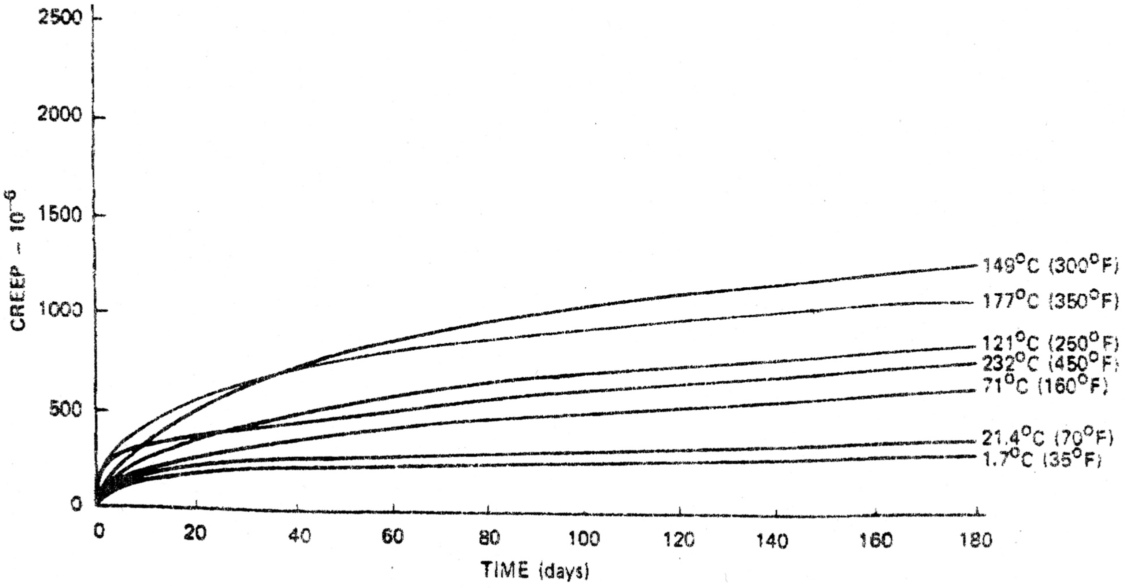


Figure 49 Creep of sealed concrete at various temperatures. *Source*: K. W. Nasser and R. P. Lohtia, "Mass Concrete Properties at High Temperatures," *J. Am. Concr. Inst.* **68**(3), 180–81 (March 1971).

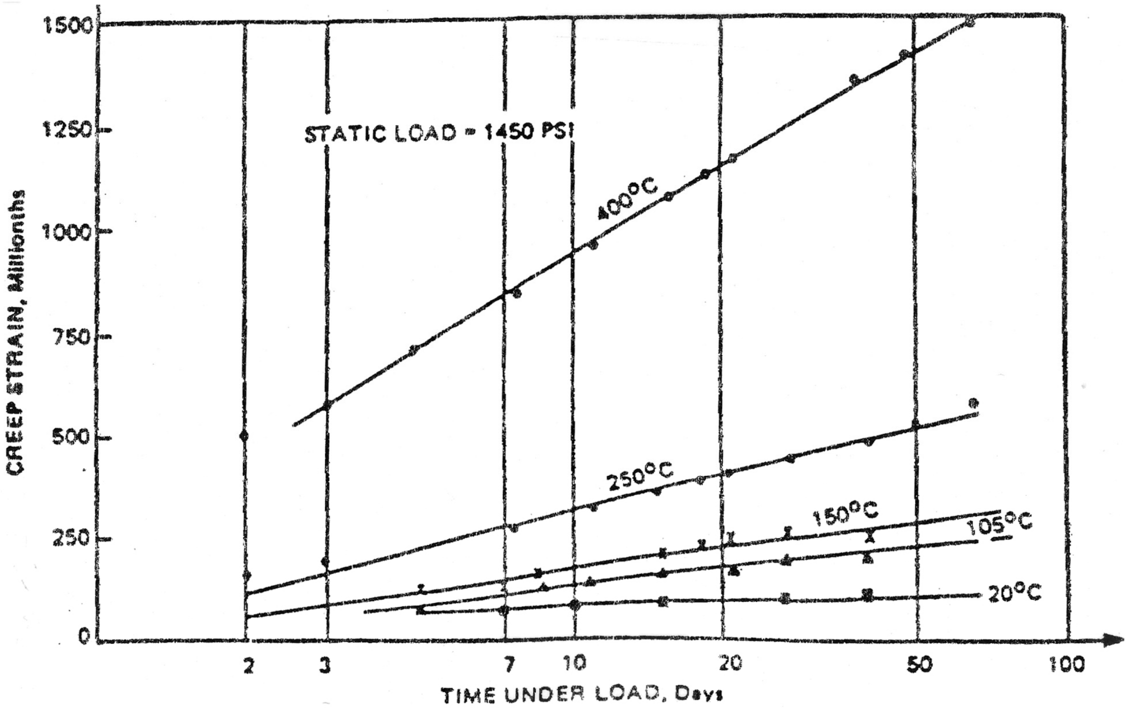


Figure 50 Creep of Portland cement/porphyry concrete at various temperatures. *Source*: A. C. Marechal, “Variations in the Modulus of Elasticity and Poisson's Ratio with Temperature,” Paper SP 34-27 in Special Publication SP-34, Vol. I-III, American Concrete Institute, Farmington Hills, Michigan, 1972**.**

increase in the creep rate until a stable moisture condition is reached.[33] In addition to the moisture content and drying effects, the size and shape of the structural member are also important in that they affect the time and rate of moisture loss [i.e., large section members such as walls or a base mat in a nuclear power plant require extended periods of time (days or years) for the moisture to diffuse out of the structure]. Results presented in Ref. 77 indicate that when the magnitudes of creep strains in unsealed concrete are compared with the magnitudes of sealed ones (mass concrete), the creep of sealed concrete is greater with it being 0.7 to 5 times greater than the corresponding values for unsealed concrete above a temperature of 93°C.

Creep data under elevated-temperature conditions using sealed specimens to represent mass concrete are limited because of the difficulty in sealing the specimens to prevent moisture loss. Several steady-state creep tests have been conducted in support of development of prestressed concrete reactor vessels for high-temperature gas-cooled reactor applications. Test temperatures were generally limited to the ASME Code limit of 65°C, although some data are available at higher temperatures (see Fig. 49).

Reference 78 summarizes a 5-year investigation on creep and other properties of concrete for prestressed concrete reactor vessels (PCRVs). The creep tests were made on sealed concrete specimens to simulate the mass concrete. The test parameters included temperatures of 23, 43, and 71°C, nominal stress levels of 30, 45, and 60% of the reference compressive strength, and ages at loading of 28, 90, and 270 d. Additional tests were conducted to determine autogeneous length change and drying shrinkage of the concrete, the effect of testing temperature (23, 43, and 71°C) on compressive strength, and the influence of up to five thermal cycles (23°F to 71°F to 23°F) on compressive strength, splitting-tensile strength, modulus of elasticity, and Poisson's ratio. All creep specimens were cast in the vertical position with sealing of the specimen against loss of moisture accomplished by means of steel end plates and a wrapping of 1.59-mm-thick butyl rubber around the specimen. All specimens were stored at 23°F prior to testing. In Fig. 51 the total strains obtained for Mix No. 1 are plotted for the 13 test conditions investigated. Making a direct comparison of strain data obtained at different levels of stress requires that values of total strain per unit of applied constant stress be computed. The effect of temperature on total strains of concrete per unit of applied stress was for the strains to increase with an increase in temperature. Concrete tested at higher stress levels achieved higher total strains and thus exhibited the highest strains per unit of applied constant stress. Age at loading had a more significant effect on strains of concretes tested at 23°C than for concretes tested at 43°C or 71°C. For the seven groups of specimens for which creep recovery at 23°C or 71°C was obtained, about 39% of the 90-d creep recovery occurred during the first day and 65% within 10 d after unloading, independent of the previous applied stress level. At 71°C creep recovery of only one group of specimens was observed. This group experienced 31% and 52% of the 90-d creep recovery at 1 and 10 d, respectively, after unloading. In general, the drying shrinkage strains leveled off between 400 and 600 microstrains at all test conditions, with the higher drying shrinkage strains occurring at the higher temperatures where humidities were lowest. Modulus of elasticity of the creep specimens was determined during loading, subsequent unloading, and when testing the creep specimens to failure on completion of the creep phase of the program. The modulus of elasticity of the concretes ranged from 40.7 to 44.8 GPa, with an average Poisson's ratio of 0.22. The splitting-tensile strength was about 9% the compressive strength at all ages of testing. The compressive strength of

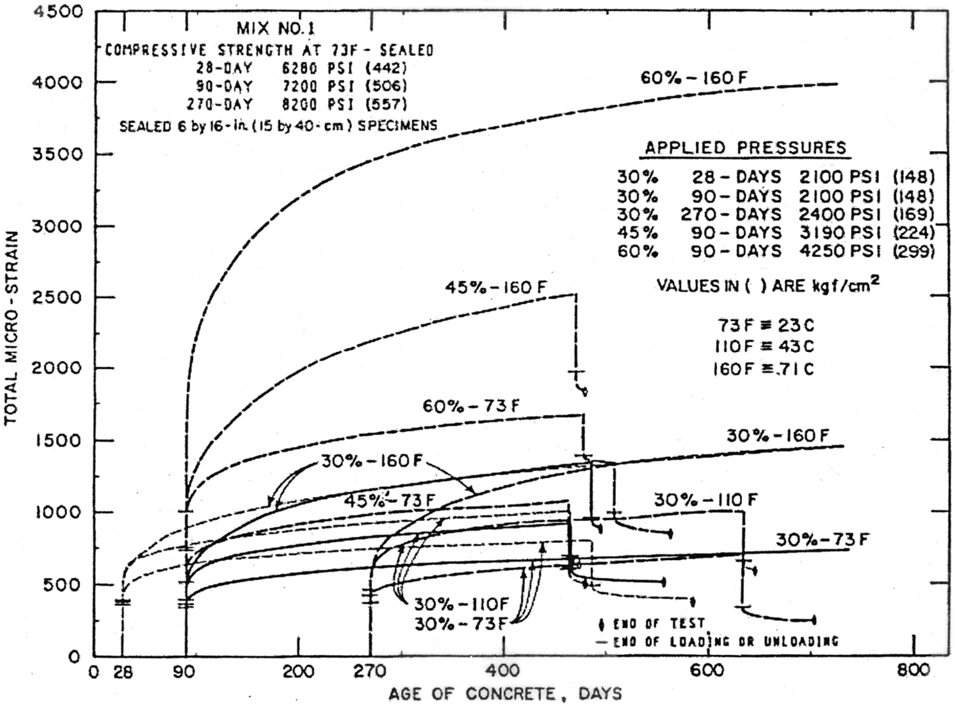


Figure 51 **Total strains for a number of test parameters.** *Source*: J. Komendant et al., "Effects of Temperature, Stress Level, and Age at Loading on Creep of Sealed Concrete," Paper SP 55-3 in *Douglas McHenry International Symposium on Concrete and Concrete Structures*, American Concrete Institute, Farmington Hills, Michigan, 1978.

specimens tested at 43°C was reduced 3 to 11% relative to specimens tested at 23°C. At 71°C, the reductions were about 11, 18, and 21% for concretes tested at 28, 90, and 270 d, respectively. Adiabatic curing resulted in a 12% increase in the 28-d compressive strength and an 8% increase in the 60-d strength in comparison to the strength of specimens cured continuously at 23°C. Thermal cycling results indicate that the compressive strength was reduced about 5% after two thermal cycles and about 2% after completion of five thermal cycles. The modulus of elasticity was reduced about 5% after the first cycle and remained stabilized at this reduced level for the subsequent four cycles. Poisson's ratio was not affected. The thermal cycles also had no significant effect on the splitting-tensile strength of the tested concretes. Long-term exposure to 71°C had a smaller impact on strength loss than short-term exposure to elevated temperature. Additional results for creep of concretes at temperatures to 65°C are available.[79]

The influence of load level and temperature on creep of NSC and high-temperature creep of NSC containing quartz aggregate is presented in Figs. 52[80] and 53,[4] respectively. Results show increased creep with increasing steady-state load and increasing temperature of exposure.

Conclusions from results presented in the literature specific to creep at elevated temperature are that the different types of concretes produced with dense aggregate materials do not have a significant effect on the steady-state creep; however, low-modulus aggregates exhibit increased creep; creep rates at higher temperatures are significantly higher than under ambient conditions; creep increases with increasing load level; sealing as it affects moisture transport is important, particularly for temperatures < 100°C; and curing of specimens at elevated temperature leads to lower creep at elevated temperature compared to specimens cured at room temperature.

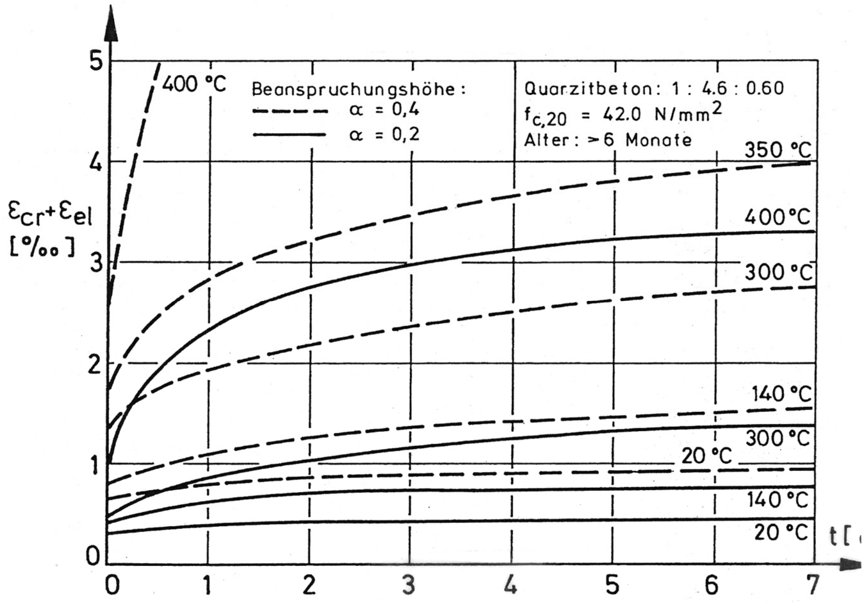


Figure 52 Influence of load level and temperature on the creep of normal concrete. *Source*: H. Gross, "On High Temperature Creep of Concrete," Paper H6/5 in *Proc. 2nd International Conference on Structural Mechanics in Reactor Technology*, Elsevier Science Publishers, North-Holland, The Netherlands, 1973.

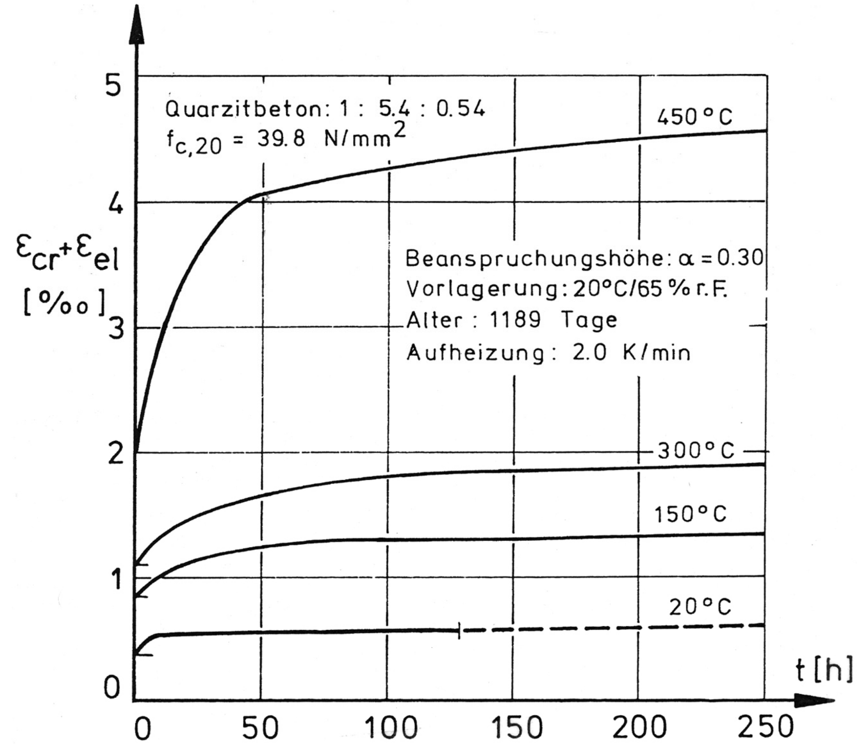


Figure 53 High-temperature creep of ordinary concrete with quartz aggregate.
Source: U. Schneider, "Behaviour of Concrete at High Temperature," HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

Concrete–Steel Reinforcement Bond Strength

Bond arises primarily from friction and adhesion between concrete and steel and may be affected by the relative magnitude of concrete shrinkage. It is a function of (1) the concrete properties (cement type, admixtures, water-cement ratio), (2) the mechanical properties of the steel (size and spacing of lugs), and (3) rebar position within the concrete member (bond is greater for vertical bars than for horizontal bars). Permissible bond stresses are generally specified as percentages of concrete's compressive strength. Although considerable research has been conducted investigating the bond between concrete and steel at room temperature, results indicating the effect of elevated-temperature exposure are somewhat limited.

In testing specimens fabricated from river gravel concretes containing embedded plain, round steel bars,[81] it was found that the residual bond stress after subjecting the specimens to 300°C for 90 d and then cooling to room temperature was only about 50% the reference value before heating. Figure 54 indicates the importance of reinforcement type.[82] This figure shows that ribbed bars experienced a loss of bond strength only above 400°C, but the smooth bars lost strength after only a small temperature increase. A comparison of the effects of elevated temperature on ribbed and plain round bars for different concrete strengths is presented in Fig. 55.[83] The effect of bar diameter on bond strength after elevated temperature for ribbed and plain round bars is presented in Fig. 56.[84] Bond-stress-slip results as a function of temperature are presented in Fig. 57 for cold deformed steel and prestressing steel reinforcement.[85] Figure 58 presents a comparison of bond strengths of cold-deformed steel, heavily rusted plain round bars, plain round bars, and shaped prestressing strand.[85] The effect of elevated-temperature exposure time

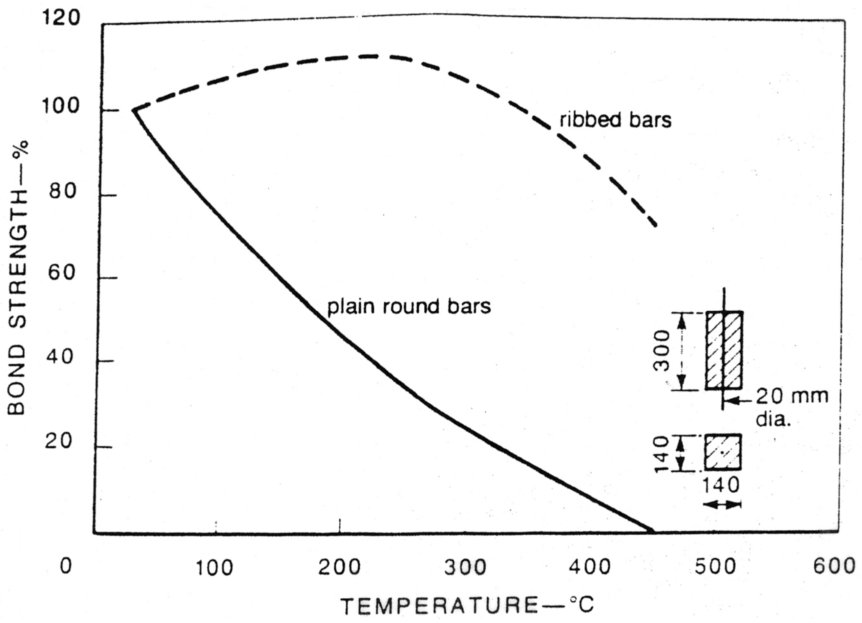


Figure 54 Bond strength of ribbed and plain round bars. *Source*: A. F. Milovanov and G. D. Salmanov, “The Influence of High Temperature Upon the Properties of Reinforcing Steels and Upon Bond Strength Between Reinforcement and Concrete,” *Issledovanija po zharoupornym betonu I zhelezobetonu,* pp. 203–223, 1954.

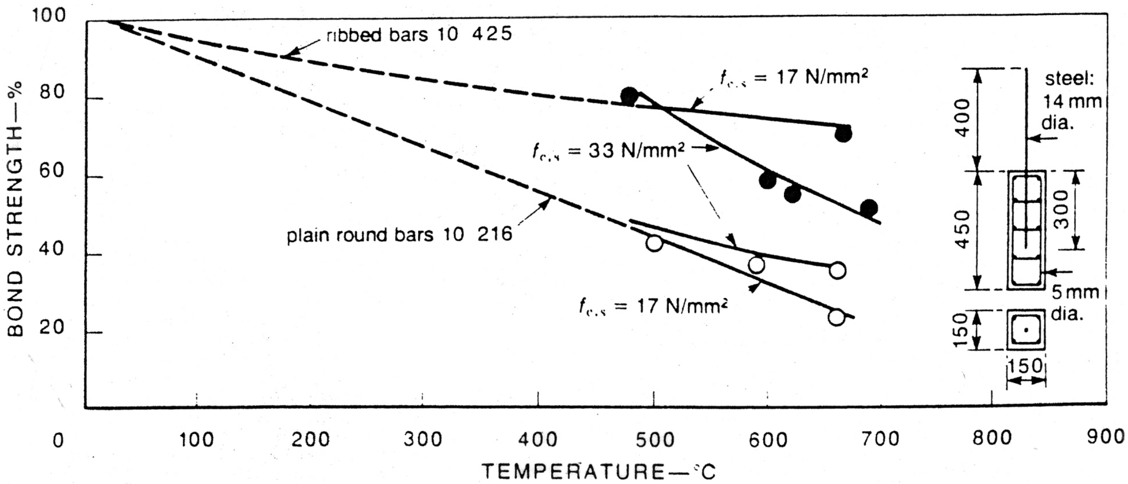
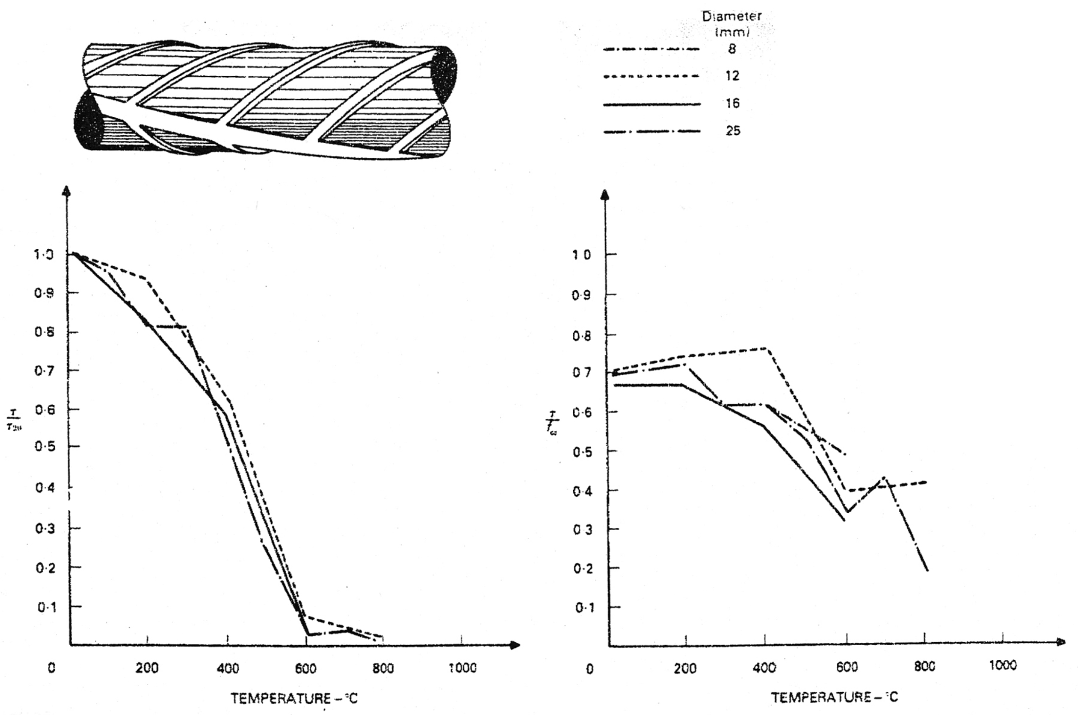


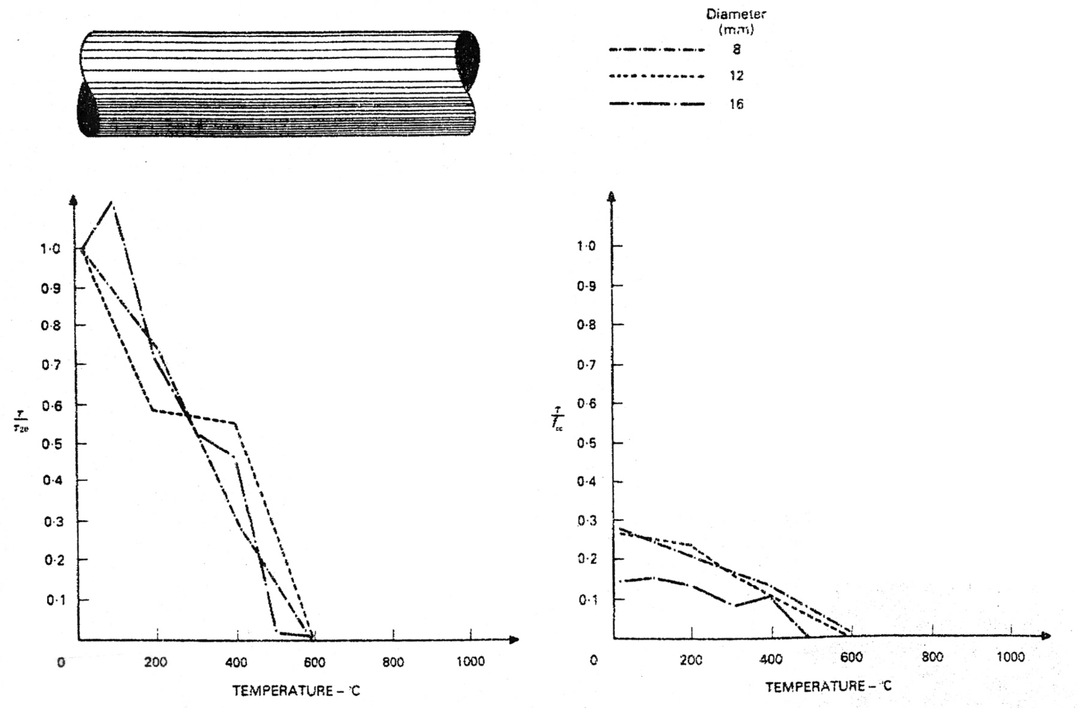
Figure 55 Bond strength of ribbed and plain round bars for different concrete compressive strengths. *Source*: H. V. Reichel, “How Fire Affects Steel-to-Concrete Bond,” *Building Research and Practice* **6**(3), 176–186 (May/June 1978).



(a) Variation of bond strength with temperature

(b) Variation of the relation between bond strength and compressive strength with temperature

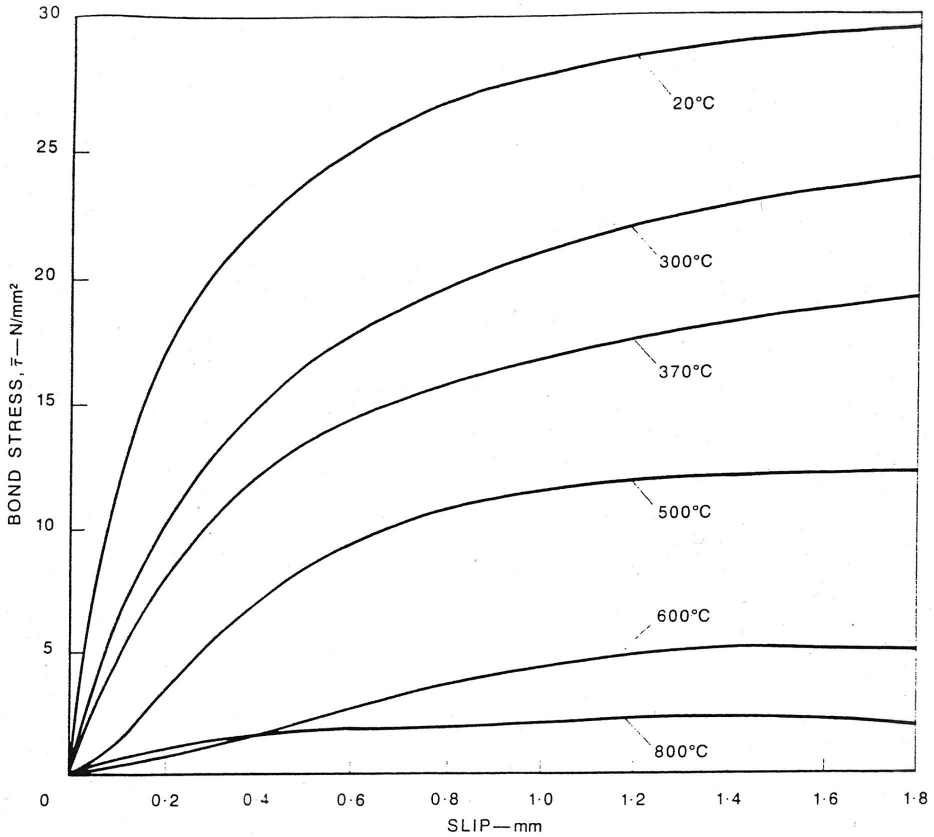
Figure 4: Results of tests on Danish Tentor bars.



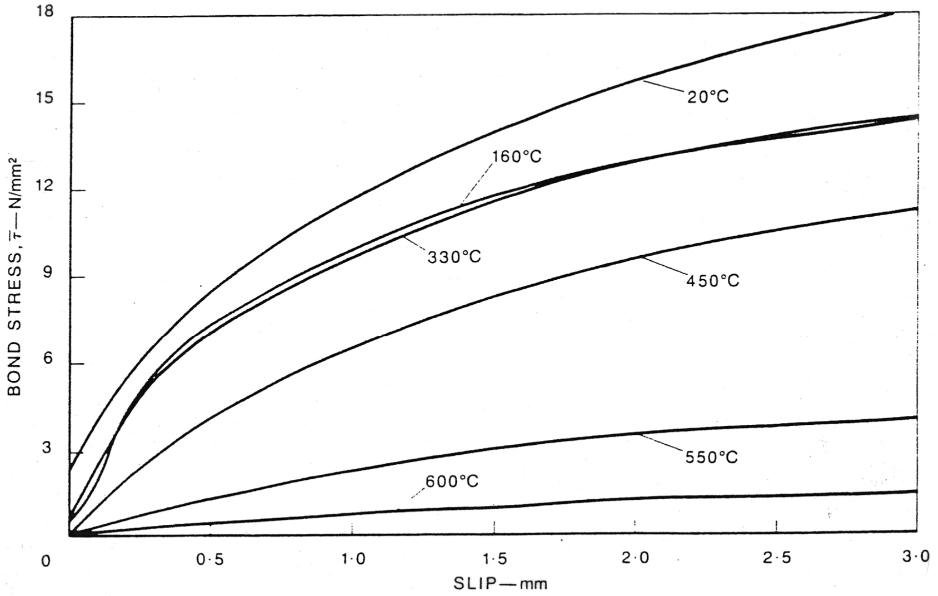
(a) Variation of bond strength with temperature

(b) Variation of the relation between bond strength and compressive strength with temperature

Figure 56 Effect of bar diameter on bond strength after elevated-temperature exposure for ribbed and plain round bars. *Source*: K. Hertz, "The Anchorage Capacity of Reinforcing Bars at Normal and High Temperatures," *Magazine of Concrete Research* **34**(121), 213–220 (December 1982).

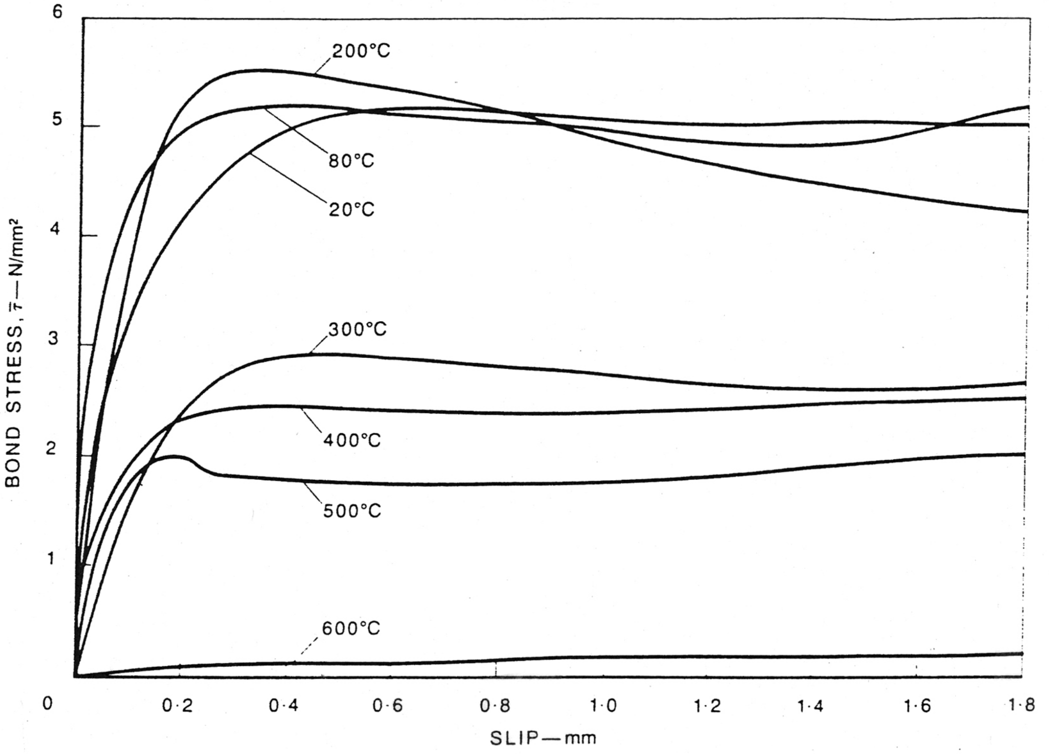


Deformed steel

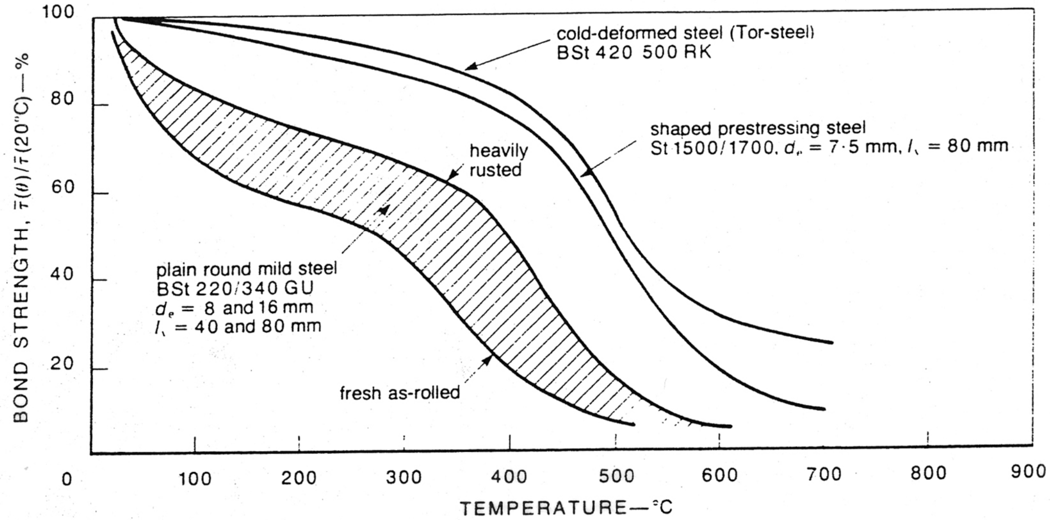


Deformed prestressing steel

Figure 57 Bond-slip relationship at elevated temperature for cold deformed steel and deformed prestressing steel. *Source*: U. Diederichs and U. Schneider, "Bond Strength at High Temperature," *Magazine of Concrete Research* **33**(115), 75–83 (June 1981).



Rusted plain round mild-steel bars.



Relative bond strength of various reinforcing bars

Figure 58 Relative bond strength as a function of temperature. *Source*: U. Diederichs and U. Schneider, "Bond Strength at High Temperature," *Magazine of Concrete Research* **33**(115), 75–83 (June 1981).

(0.5 to 3 h) on the residual bond strength of No. 3 bars embedded in a concrete cube is presented in Fig. 59.[86] A substantial decrease in bond strength was observed at temperatures greater than 200°C, and the bond strength decreased with increasing exposure time. The influence of type aggregate on the bond strength is presented in Fig. 60.[87] The effect of curing conditions (e.g., in water unsealed, sealed, in air

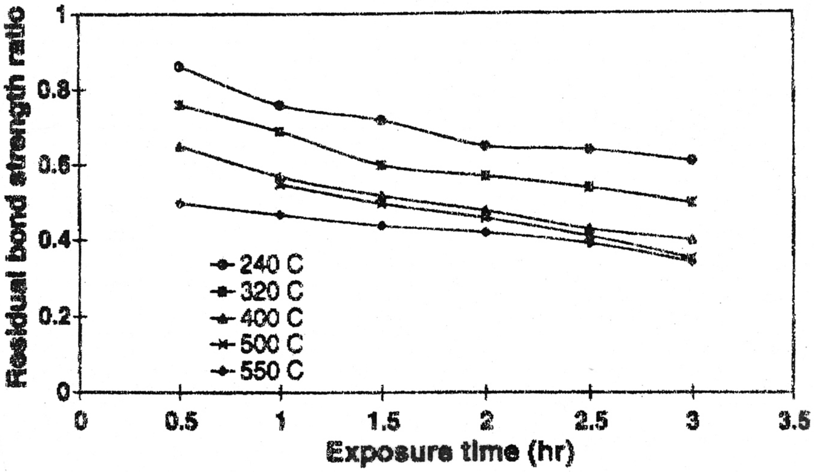


Figure 59 The effect of elevated-temperature exposure time on the residual bond strength of No. 3 bars embedded in a concrete cube. *Source*: C-H. Chiang and C-L. Tsai, "Time-Temperature Analysis of Bond Strength of a Rebar After Fire Exposure," *Cement and Concrete Research* **33**, 1651–1654 (2003).

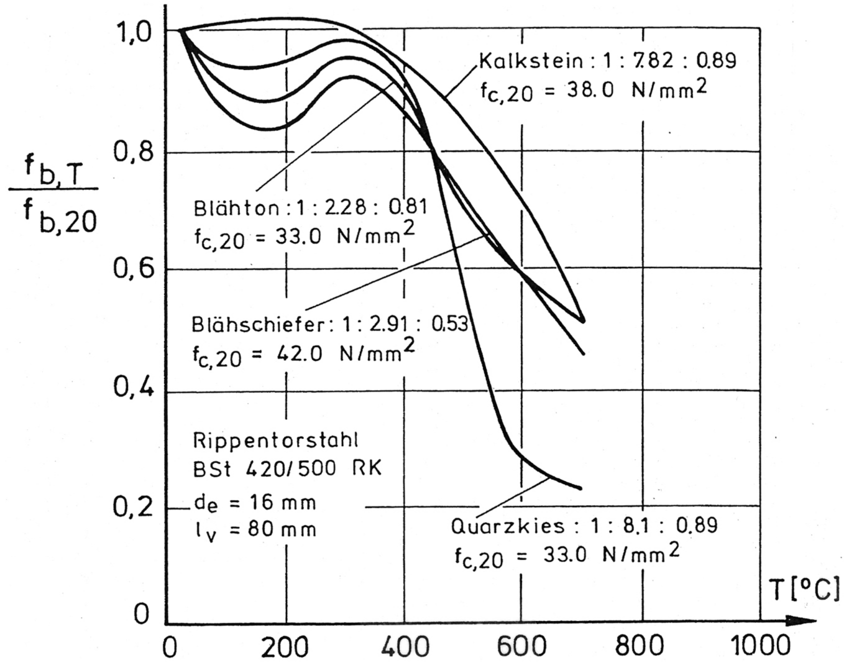


Figure 60 Bond between concrete and deformed bars exposed to high temperature. *Source*: H. Sager et al., "High Temperature Behavior of Reinforcing and Prestressing Steels," *Sonderforschungs-Bereich* **148**, Part II, pp. 51–53, Technical Universitat Braunschweig, Germany, 1980.

unsealed) prior to elevated-temperature exposure on the relative variation in bond strength at start of pull-out for a hard sandstone aggregate concrete after various heating periods at 175°C is presented in Fig. 61.[36] The bond strength for specimens unsealed during heating exhibited up to about a 30% decline for heating exposures of 3 d or less, but specimens that were sealed exhibited practically no reduction as a result of temperature exposure. Prolonged elevated-temperature exposure for sealed specimens exhibited a positive effect on the bond strength, and for the unsealed specimens a recovery in bond strength to the point that at 91-d exposure it was reduced by 10 to 15% relative to control results. Other results[85,88] indicate that the loss in bond strength between concrete and steel reinforcement at temperatures < 65°C is small (≤15%).

Conclusions from results presented in the literature specific to concrete-reinforcing steel bond at elevated temperature are that ribbed bars exhibit improved performance relative to plain round bars, surface roughness increases the performance for plain round bars, the bond strength decreases as the exposure temperature increases, at high temperatures (≥200°C) the time at temperature affects the bond strength, the diameter of ribbed steel reinforcement (8 to 25 mm) does not have a significant effect on bond strength, residual bond strengths of specimens sealed during temperature exposure perform better than unsealed specimens (≤175°C), curing conditions are important at moderate elevated-temperature exposures (≤400°C), a clear influence of the water/cement ratio and concrete strength on bond strength at elevated-temperature exposure has not been observed, the type of aggregate has a significant effect on the high-temperature bond strength, and at temperatures < 65°C the bond strength is relatively unaffected.

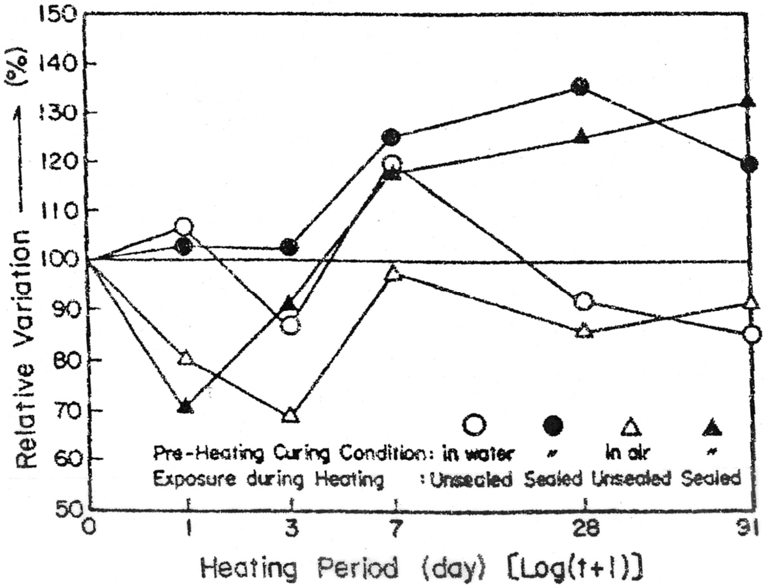


Figure 61 Relative variation in bond strength at start of pull-out for a hard sandstone aggregate concrete after various heating periods at 175°C. *Source*: K. Hirano et al., "Physical Properties of Concrete Subjected to High Temperature for MONJU," Paper P2-25, Power Reactor and Nuclear Fuel Development Corporation, Tokyo, Japan.

Long-Term Exposure (Aging)

During the nominal 40-year design life of nuclear power plants, certain concrete components may be subjected to moderately elevated temperatures that could affect the concrete's mechanical properties. In conducting safety evaluations for these components, the significance of concrete component aging needs be taken into account. Unfortunately, only a limited number of data have been identified related to the effects of long-term elevated-temperature exposure on concrete properties. Surprisingly, although Portland cement concretes have been in existence for more than 160 years, relatively little documented information is available on the aging of concrete structures that are not being acted upon by environmental stressors.[89] When concrete is fabricated with close attention to the factors related to the production of good concrete (e.g., material selection, production control, desirable properties, and costs), the concrete will have infinite durability unless subjected to extreme external influences (e.g., overload, elevated temperature, industrial liquids and gases).[31]

An investigation has been conducted to determine the changes in mechanical properties of a limestone aggregate concrete after exposure to temperatures of 75°C and 300°C for periods up to 8 months and 600°C for 1 month.[90] For thermal exposure to 75°C, compressive and splitting-tensile strengths after 8 month's exposure were 98 and 94%, respectively, of their reference values. However, on exposure to 600°C for just 1 month, compressive and splitting-tensile strengths were only 23 and 38%, respectively, of their reference values. In companion mixes where either fly ash or blast furnace slag was used, improvement in retention of mechanical properties occurred after exposure to sustained high temperatures as a result of partial replacement of the cement.

The effect of long-term exposure (up to 13 years) at moderate elevated temperature (65°C) on the mechanical properties of a limestone aggregate concrete was investigated.[91] These tests were somewhat unusual because the specimens were first subjected to a simulated temperature-vs-time cement hydration cycle. Also, because the concrete mix was being evaluated for an application that experienced exposure to sulfate-bearing groundwater at elevated temperatures (~65°C), both ordinary and sulfate-resistant Portland cements were investigated. Specimens, after being subjected to the simulated cement hydration cycle, were stored either in water at 19°C (control specimens) or in a sodium sulfate solution of 2000 ppm at 65°C. Frequently during the test program, the sodium sulfate solution was changed, which required cooling to room temperature; the specimens were therefore also subjected to thermal cycling. Results of the study indicated that there was no evidence of long-term degradation in compressive strength for any of the concrete mixes and heat treatments utilized, and that for a given compressive strength the dynamic modulus of elasticity was lower for the concrete that had been heated. Cooling down and reheating the limestone and flint aggregate mixes for a total of 87 cycles did not appear to cause a degradation in strength.

A 5-year testing program was conducted to determine the effects of long-term exposure to elevated temperature on the mechanical properties of concrete used in constructing the radioactive underground storage tanks at Hanford Engineering Development Laboratory (HEDL).[92] Tests were conducted using specimens fabricated from the same mix proportions and materials specified for the concrete used to fabricate the tanks (20.7- and 31.0-MPa design compressive strengths). Concrete strength, modulus of elasticity, and Poisson's ratio values were determined from specimens subjected to either 121, 177, or 232°C for periods of up to 33 months. The effect of thermal cycling was also investigated. Results showed that the compressive strengths in general tended to decrease with increasing temperature and also with length of exposure; however, with the exception of the cylinders exposed to 232°C, all compressive strength results obtained after a 900-d exposure exceeded the design values noted previously. Splitting-tensile strength results also decreased somewhat with increasing temperature and length of exposure. Modulus of elasticity was affected most significantly by the elevated-temperature exposure; after 920 d of heating at 232°C, it had a value of only 30% the value obtained from an unheated control specimen. Poisson's ratio, although exhibiting somewhat erratic values, was relatively unaffected by either the magnitude or the length of elevated-temperature exposure. Thermal cycling (~18 cycles) to 177°C produced moderate reductions in compressive strength (5 to 20%), significant reductions in modulus

(30 to 50%), and slight reductions in Poisson's ratio (0 to 20%). Time-dependent (creep) and physical property data were also obtained from specimens cast from the concrete mixes.

Associated with the laboratory investigation described in the previous paragraph was a study to confirm the laboratory results by testing samples removed from the underground storage tanks and process buildings at HEDL.[93] Cores 76-mm in diameter were obtained over the length of the haunch wall, and footing of a single-shell tank that was built in 1953; contained waste for about 8 years; reached temperatures in the range of 127°C to 138°C; and experienced a radiation field of 0.10 to 0.13°C/kg/h (400 to 500 R/h). Although considerable scatter was obtained from the data because of different concrete pours and different environmental exposure, after about 29 years of exposure only one data point fell below the 20.7-MPa design compressive strength. Figure 62 presents compressive strength results from cores obtained from structures at HEDL and compares them to values based on the laboratory results.

A study has been carried out to examine the effect of temperature on sealed and unsealed air-entrained concrete containing fly ash, conventional water reducer, and superplasticizer.[94] The properties of compressive strength and modulus of elasticity were studied at seven different temperatures ranging from –11°C to 232°C and at seven different exposure periods from 1 to 180 d. Local crushed aggregates of 19-mm maximum size consisting primarily of dolomite and hornblend were used in the concrete

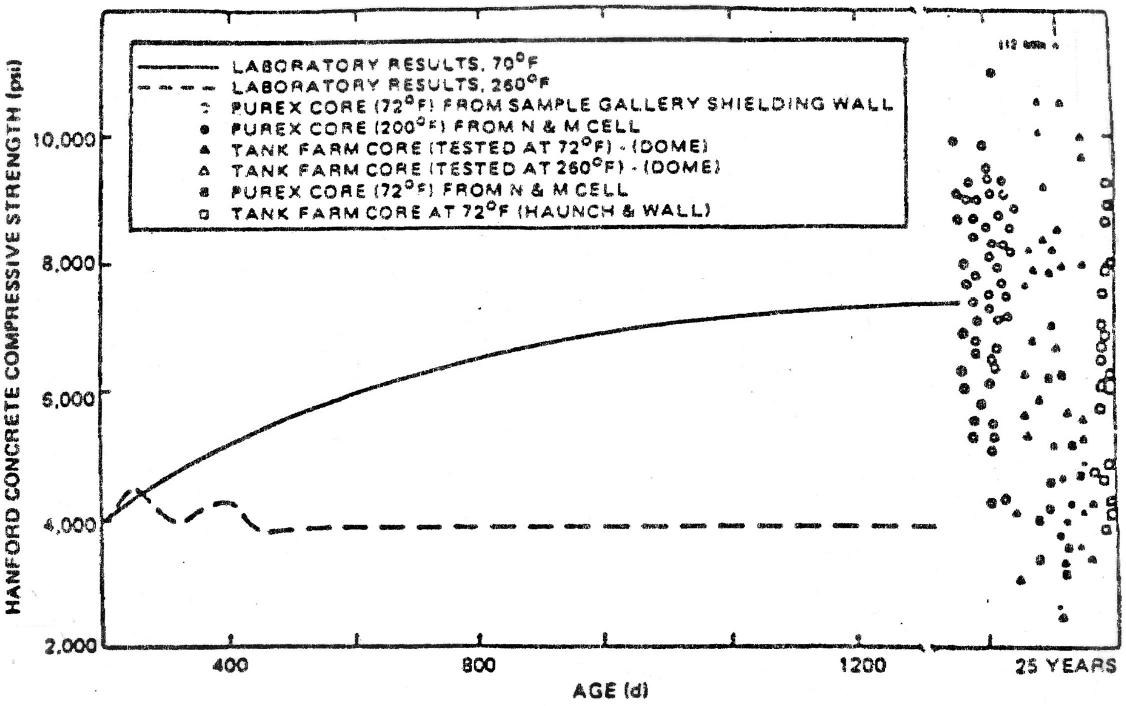


Figure 62 Comparison of laboratory and actual sample long-term compressive strength data.
Source: M. P. Gillen et al., "Strength and Elastic Properties of Concrete Exposed to Long-Term Moderate Temperatures with High Radiation Fields," RHO-RE-SA-55 P, Rockwell Hanford Operations, Richland, Washington, 1984.

mixtures. Figure 63 presents the relationship of strength ratio (ratio of compressive strength at temperature to that obtained from unheated control specimens) and exposure time for the temperatures investigated that was obtained from sealed specimens. The corresponding relationship of the elasticity ratio (ratio of modulus of elasticity at temperature to that obtained from unheated control specimens) and exposure time obtained from sealed specimens is presented in Fig. 64. The results indicate that up to a temperature of 121°C there was no degradation in compressive strength for exposures up to 180 d. With increasing temperature, the strength decreased with the extent of strength reduction generally proportional to the exposure temperature and time at temperature (e.g., at 232°C and 180-d exposure the strength was about 50% its reference value). The modulus of elasticity started to decline monotonically at temperatures ≥ 71°C with the decline in modulus proportional to the exposure temperature and time at temperature (e.g., at 232°C and 180-d exposure the modulus was about 25% its reference value). Strength and elasticity ratios for unsealed specimens are presented in Fig. 65 and indicate improved performance relative to the sealed specimens. An explanation of the greater effect of elevated-temperature exposure on sealed (mass concrete) specimens was that in a closed system saturated steam pressure develops at high temperatures, which causes deterioration in structural properties of the cement gel.

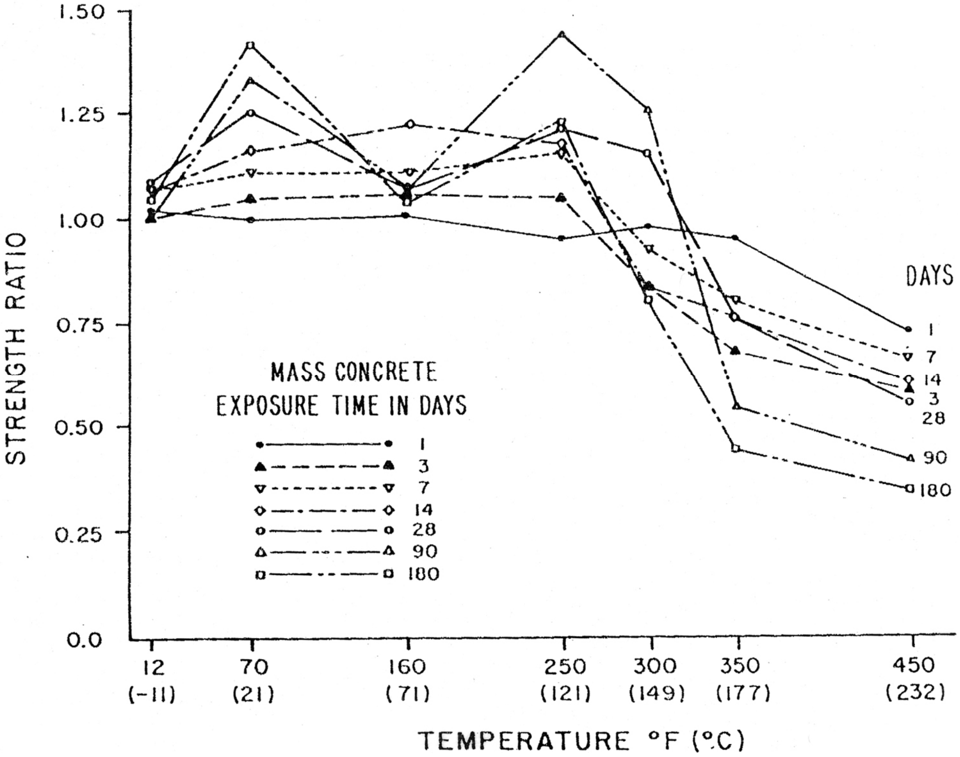


Figure 63 Relationship of strength ratio and temperature of mass concrete (sealed).
Source: K. W. Nasser and M. Chakraborty, “Temperature Effects on Strength and Elasticity of Concrete Containing Admixtures,” *Proceedings of Symposium Temperature Effects on Concrete*, ASTM Special Technical Publication 858, American Society for Testing and Materials, West Conshohocken, Pennsylvania, 1985.

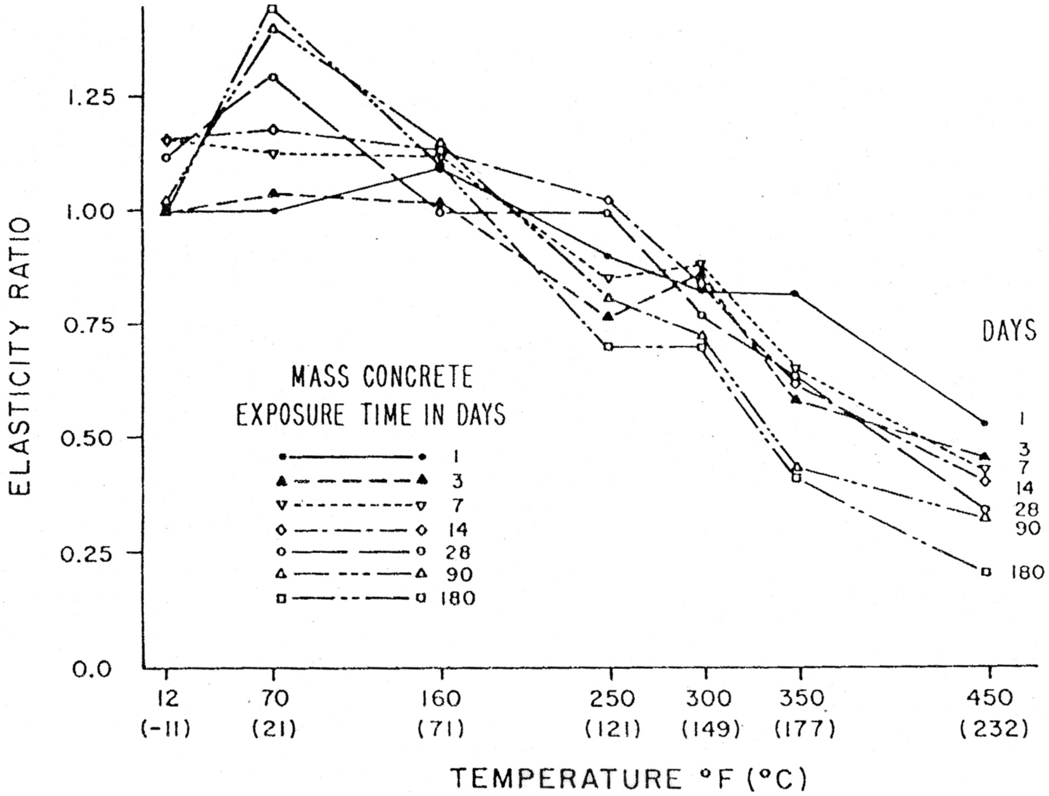


Figure 64 **Relationship of elasticity ratio and temperature of mass concrete (sealed).** *Source*: K. W. Nasser and M. Chakraborty, "Temperature Effects on Strength and Elasticity of Concrete Containing Admixtures," *Proceedings of Symposium Temperature Effects on Concrete*, ASTM Special Technical Publication 858, American Society for Testing and Materials, West Conshohocken, Pennsylvania, 1985.

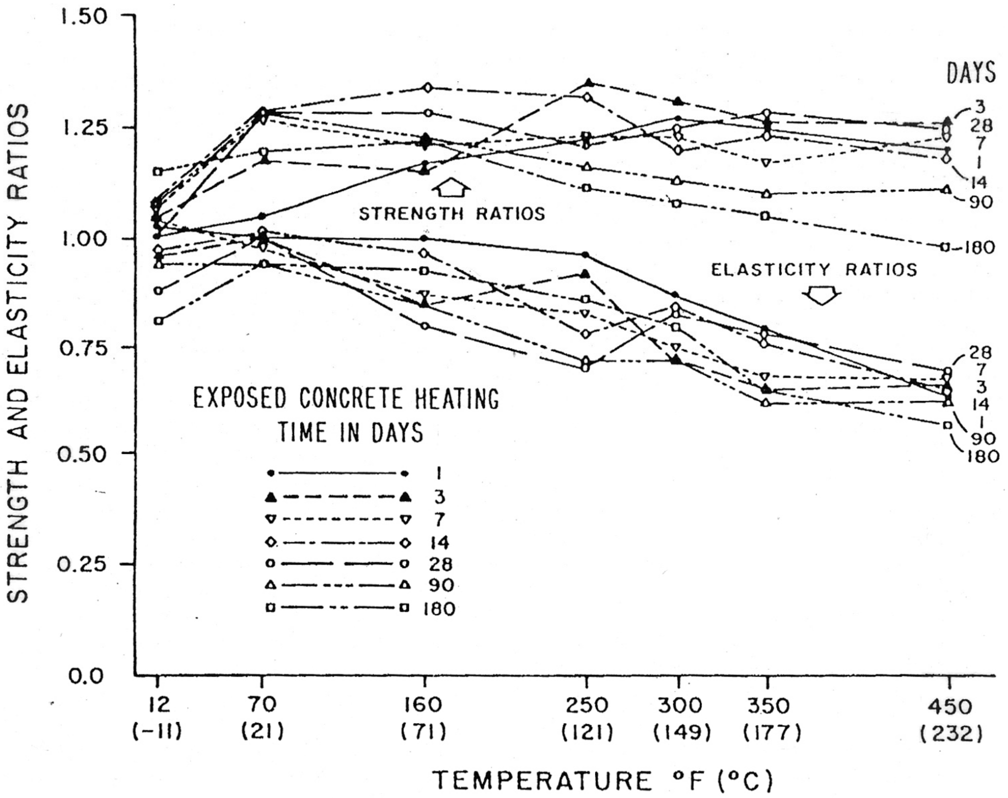


Figure 65 **Relationship of strength and elasticity and temperature of unsealed concrete.** *Source*: K. W. Nasser and M. Chakraborty, “Temperature Effects on Strength and Elasticity of Concrete Containing Admixtures,” *Proceedings of Symposium Temperature Effects on Concrete*, ASTM Special Technical Publication 858, American Society for Testing and Materials, West Conshohocken, Pennsylvania, 1985.

A laboratory study has been conducted to evaluate the relative performance of limestone and dolostone aggregate ordinary Portland cement concretes under sustained exposure to high temperature.[95] After 28-d moist cure followed by 26 weeks of room temperature curing, the test specimens were exposed for up to 4 months to temperatures ranging from 76°C to 450°C, and 1 month for a 600°C exposure. Figure 66 presents residual compressive strength versus conditioning temperature (up to 450°C) after 4 months exposure for the limestone concrete.* The loss of compressive strength of specimens exposed to elevated temperature was proportional to the exposure temperature. At temperatures of 150°C and higher, an increase in length of exposure from 48 h to 4 months resulted in further decreases in strength. In all cases, any major loss in strength was found to occur within the first month of exposure. In general the leaner concretes (water/cement ratio = 0.6) were slightly less affected than the richer concretes in terms of relative strength loss after exposure.

The effect of elevated-temperature exposures either at 65°C, 90°C, or 110°C for periods up to 3.5 years was investigated in Japan in support of nuclear power plant facilities.[96] Either basalt or sandstone coarse aggregates were utilized in the concrete mixtures. Cementitious materials studied included Class B fly

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*The dolostone aggregate results are not discussed because pyrite was contained in some of the aggregate particles, and it underwent slow oxidation that produced a disintegrating expansion of the aggregate and cracking of the concrete.

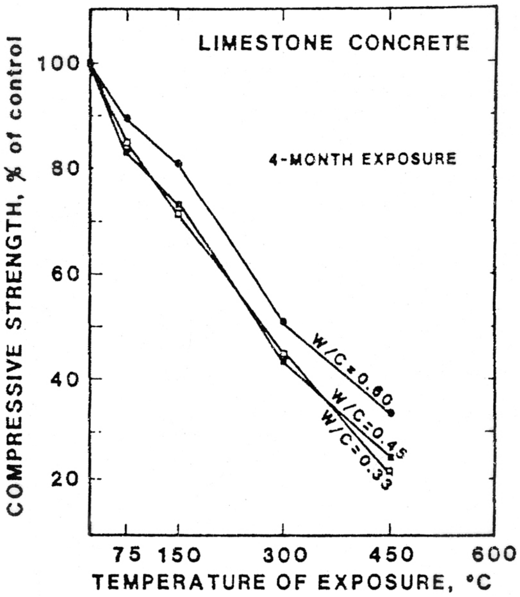


Figure 66 Compressive strength of limestone concrete after 4-month exposure to various temperatures (up to 450°C). *Source*: G. G. Carrette and V. M. Malhotra, "Performance of Dolostone and Limestone Concretes at Sustained High Temperatures," *Proceedings of Symposium Temperature Effects on Concrete,* ASTM Special Technical Publication 858, pp. 38–67, American Society for Testing and Materials, West Conshohocken, Pennsylvania, 1985.

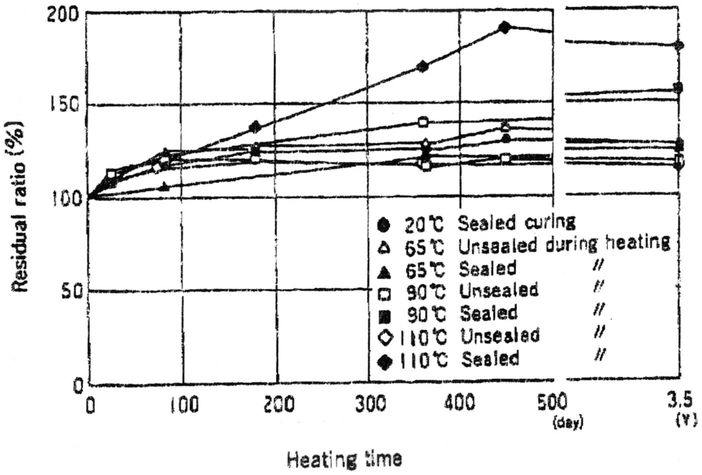
ash, moderate heat cement plus fly ash, and normal Portland cement. Heating conditions adopted were (1) long-term heating tests [allowable temperature except for local areas (long-term) (65°C), allowable local temperature (long-term) (90°C), temperature at which water is considered to evaporate rapidly (110°C)], (2) short-term heating tests [allowable temperature (short-term) (175°C)], and (3) thermal cycling tests for up to 120 cycles [cycled heating temperatures (20°C to 110°C to 20°C) to simulate temperature variations during operation periods]. Three cylindrical specimens were prepared for each test condition and put under either sealed conditions, where evaporation of water was prevented, or unsealed conditions, where evaporation was allowed. From the results of heating tests, the following conclusions were obtained:

1. Under long-term heating at 65°C, 90°C, and 110°C, compressive strength after heating was greater than before heating, under both sealed and unsealed conditions. This was especially true under sealed conditions at 110°C in which the compressive strength increased for 1.5 years reaching approximately 200% that of unheated control specimens. These results are considered to be caused by the effect of autoclave curing. Under unsealed conditions, it is considered that microcracking in concrete, which was caused by moisture migration and evaporation under high temperatures, caused a degradation of compressive strength. However, the acceleration of hydration at high temperatures in any nonhydrated sections of the concrete increased the compressive strength more than degradation caused by microcracking. The results after 3.5 years were relatively unchanged from that measured after 1 year. Therefore, it was found that the compressive strength ceased to fluctuate at an early stage.

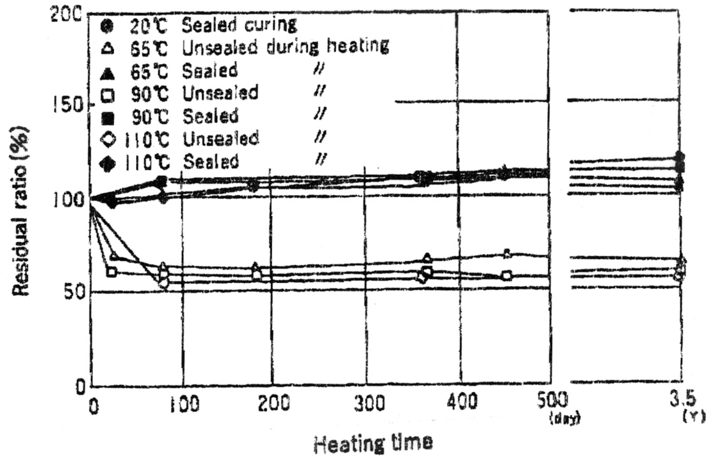
2. Under sealed conditions during heating, the increase in the elastic modulus due to heating had a tendency to increase slightly, though not as much as the compressive strength. The elastic modulus under sealed conditions remained relatively unchanged under heating, even after 3.5 years. Under unsealed conditions during heating, the modulus at temperature relative to that obtained from unheated control specimens was reduced about 50%. The reduction of the elastic modulus under unsealed conditions can be explained by the closing of microcracks at an early stage of stress. Thus, the elastic modulus of concrete heated to high temperatures, with moisture migration and evaporation present, was markedly reduced. In addition, it was found that the elastic modulus became stabilized at an early stage, not changing much from 91 d through 3.5 years, even under heating.
3. During the thermal-cycle heating test, compressive strength after heating was greater than before heating under both sealed and unsealed conditions. However, the ratio of increase was smaller than under constant heating, suggesting the influence of thermal-cycle heating. For the same number of thermal cycles, the compressive strength was consistently higher for the sealed specimens relative to that obtained from unsealed specimens. Under unsealed conditions, specimens exhibited little influence of number of cycles on compressive strength for thermal cycle numbers greater than five (i.e., little change in compressive strength value for cycles greater than five). Under unsealed conditions the modulus of elasticity exhibited a similar trend to that obtained for constant heating in that it was reduced by about 50%. A major part of the reduction occurred in the early stages of the thermal-cycle heating. Under sealed conditions during thermal cycling, the elastic modulus showed a tendency similar to that of the compressive strength, but the modulus of elasticity did not increase as much as the compressive strength of the sealed specimens.
4. The greater the weight reduction became, the greater the decrease in the elastic modulus tended to be, which indicated that moisture migration and evaporation during heating affected the reduction of elastic modulus. Therefore, to estimate the properties of massive concrete structures subjected to high temperatures accurately, it is necessary to study moisture migration in mass concrete members that are subjected to high temperatures over long periods of time.

Figure 67 presents the residual compressive strength and modulus of elasticity results, and Fig. 68 the effect of thermal cycling for the sealed and unsealed concretes.

A series of studies was conducted to evaluate the drying effect of elevated-temperature exposure on the properties of concrete.[81] Specimens made from four concrete mixes of ordinary Portland cement and river-gravel aggregate were tested to investigate the compressive, tensile, and bond strengths, moduli of elasticity, and weight loss after 90-d exposure to temperatures of 20, 35, 50, 65, 80, 110, 200, and 300°C. Moisture in specimens was allowed to evaporate freely. Residual strength tests of unheated and heated concretes were conducted at room temperature on both dried and wet specimens presoaked in water for 2 d. Exposure to sustained elevated temperature higher than 35°C showed remarkable deteriorating effects on the physical properties of concrete when moisture in concrete was allowed to evaporate. Greater reductions of strengths and weights after exposure were associated with mixes having higher mix water contents. Strengths did not decline linearly as the temperature rose and were minimal at around 50°C. Dry compressive strengths of heated concretes indicated approximately 10% loss when heated at 50°C with practically no change when heated at higher temperatures up to 110°C, 20% loss at 200°C, and 30% loss at 300°C. Wet compressive strengths of heated concretes indicated larger losses than dry strengths, and more than 20% loss when heated at only 35°C. Reductions in tensile and bond strengths and modulus of elasticity of heated concretes were greater than obtained in compressive strengths. Tensile strength tests indicated approximately 30% loss upon exposure to temperatures of 50°C to 65°C, and less strength loss at higher temperatures. Bond strengths showed approximately 15% loss when heated at only 35°C, and smaller loss for higher temperatures of 50°C to 80°C, 25% loss at 110°C and more than 50% loss at 300°C. Moduli of elasticity of heated concretes indicated a tendency to decline linearly with rising

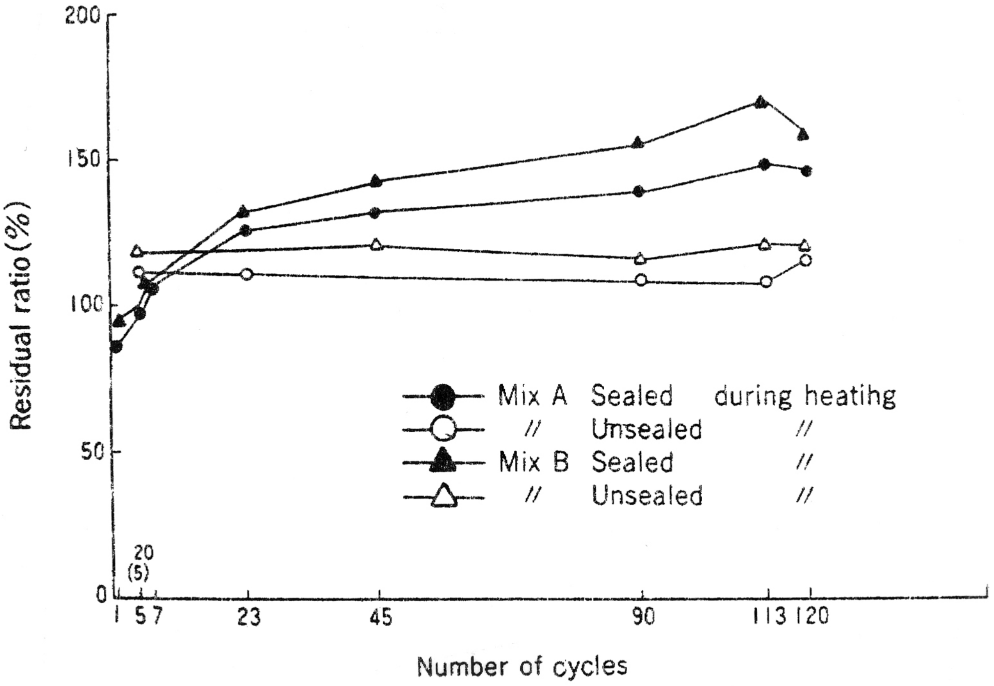


Compressive strength

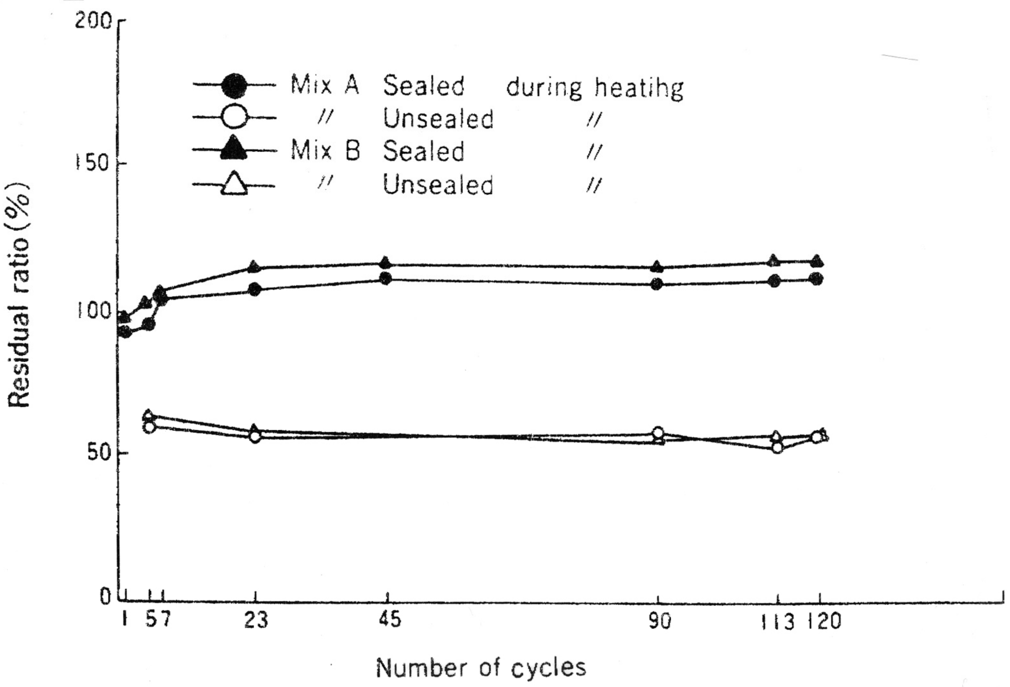


Modulus of elasticity

Figure 67 Long-term (3.5-year) heating effect on compressive strength and modulus. *Source*: T. Suzuki et al., “Study on the Degradation of Concrete Characteristics in the High Temperature Environment,” *Concrete Under Severe Conditions: Environment and Loading*, Vol. 2, pp. 1119–1128, E & FN Spon Publishers, 1995.



Compressive strength



Modulus of elasticity

Figure 68 Effect of thermal cycling on compressive strength and modulus. *Source*: T. Suzuki et al., "Study on the Degradation of Concrete Characteristics in the High Temperature Environment," *Concrete Under Severe Conditions: Environment and Loading*, Vol. 2, pp. 1119–1128, E & FN Spon Publishers, 1995.

temperature, experiencing a 15% loss at 50°C, 25% loss at 110°C, and 50% loss at 300°C. The unusual deterioration at around 50°C in compressive, tensile, flexural and shear strengths was also indicated in subsequent investigations regardless of the kind of aggregates. However, the influence of aggregate on the properties of heated concrete was significant. Sandstone and basalt aggregate concretes indicated smaller reductions, while limestone, andesite, and serpentine aggregate concretes showed greater reductions in strengths after exposure. Changes in chemical composition in the cement paste were not noticeable under 100°C. However, the porosity was found to be affected by the exposure temperature. The unusual deterioration in strengths at around 50°C can be due to either the expansion of cement paste or to the change in porosity caused by evaporation of free water. Figure 69 presents the effect of exposure

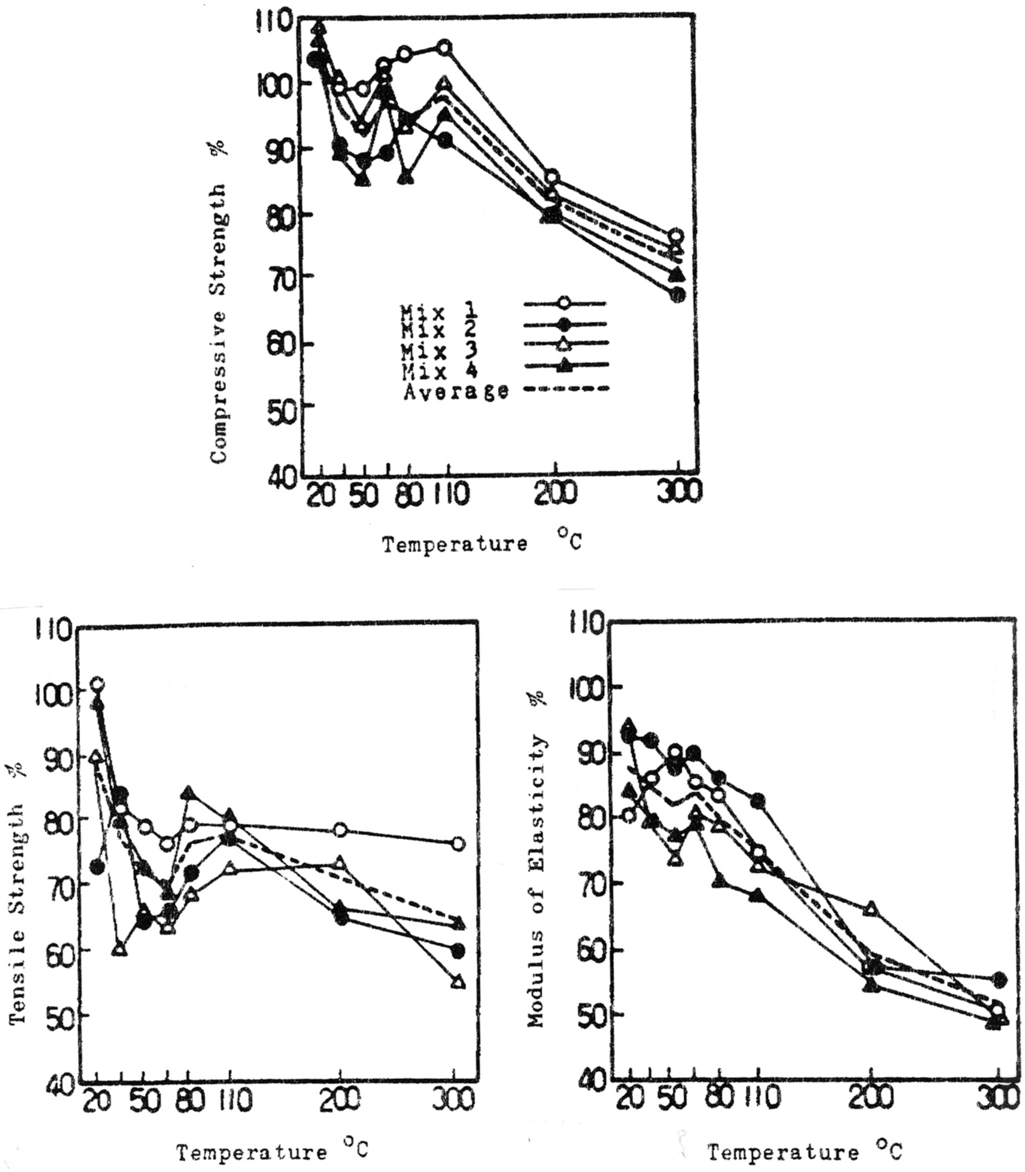


Figure 69 Effect of exposure temperature on residual compressive strength, tensile strength, and modulus of elasticity results after 90-d exposure. *Source*: H. Kasami, T. Okuno, and S. Yamane, “Properties of Concrete Exposed to Sustained Elevated Temperature,” Paper Hl/5 in *Proc. 3rd International Conference on Structural Mechanics in Reactor Technology*, Elsevier Science Publishers, North-Holland, The Netherlands, 1975.

temperature on residual compressive strength, tensile strength, and modulus of elasticity results after 90-d exposure for each of the concrete mixtures investigated. Figures 70 and 71 present bond strength and weight loss results, respectively, for the different concrete mixtures. Residual compressive strength and moduli of elasticity results showing the effect of aggregate material type are presented in Fig. 72. The effect of aggregate type and temperature exposure level on shear strength* is presented in Fig. 73.

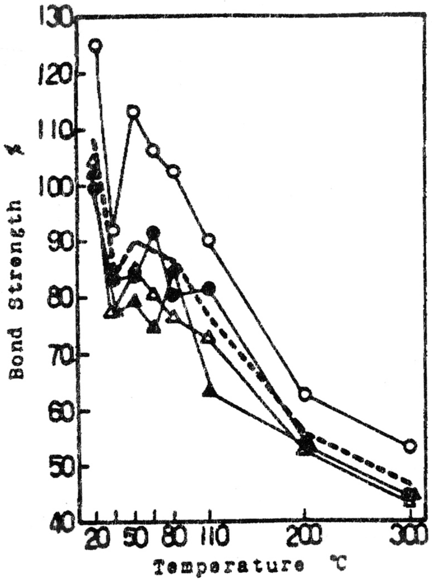


Figure 70 Bond strengths of heated concretes. *Source*: H. Kasami, T. Okuno, and S. Yamane, “Properties of Concrete Exposed to Sustained Elevated Temperature,” Paper Hl/5 in *Proc. 3rd International Conference on Structural Mechanics in Reactor Technology*, Elsevier Science Publishers, North-Holland, The Netherlands, 1975.

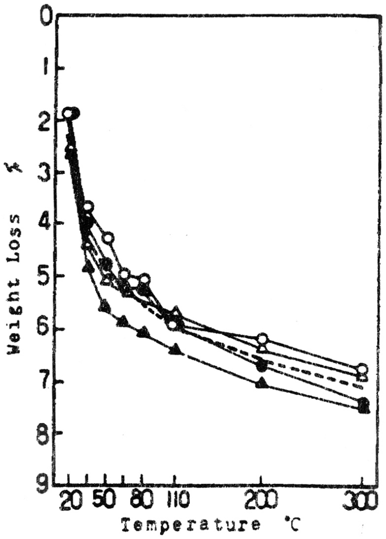


Figure 71 Weight loss of heated concrete. *Source*: H. Kasami, T. Okuno, and S. Yamane, “Properties of concrete Exposed to Sustained Elevated Temperature,” Paper Hl/5 in *Proc. 3rd International Conference on Structural Mechanics in Reactor Technology*, Elsevier Science Publishers, North-Holland, The Netherlands, 1975.

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*Shear is the action of two equal and opposite parallel forces applied in planes a short distance apart. Shear stresses cannot exist without accompanying tensile and compressive stresses (pure shear is applied only through torsion).

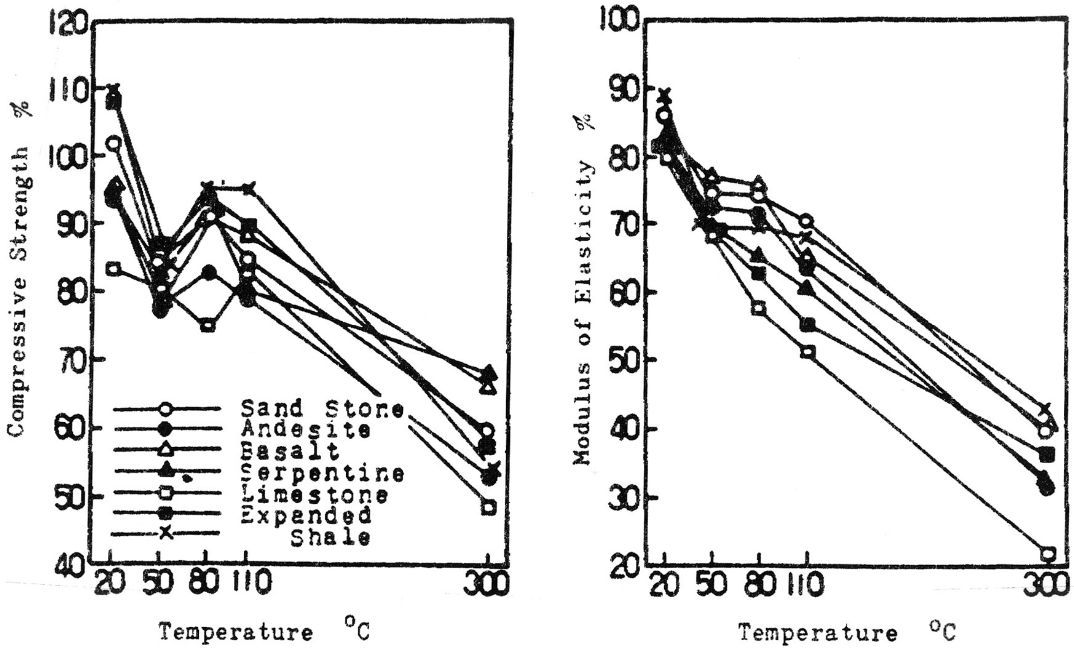

Figure 72 Compressive strength and modulus of elasticity of heated concretes. *Source*: H. Kasami, T. Okuno, and S. Yamane, "Properties of concrete Exposed to Sustained Elevated Temperature," Paper H1/5 in *Proc. 3rd International Conference on Structural Mechanics in Reactor Technology*, Elsevier Science Publishers, North-Holland, The Netherlands, 1975.

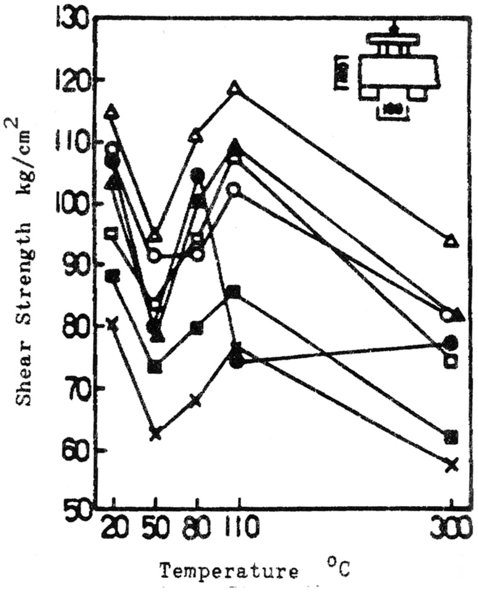

Figure 73 Shear strength of heated concrete. *Source*: H. Kasami, T. Okuno, and S. Yamane, "Properties of concrete Exposed to Sustained Elevated Temperature," Paper H1/5 in *Proc. 3rd International Conference on Structural Mechanics in Reactor Technology*, Elsevier Science Publishers, North-Holland, The Netherlands, 1975.

Radiation Shielding Effectiveness

Portland cement concrete possesses many of the physical qualities of an ideal radiation shield. It is a polyphase material consisting of particles of aggregate contained in a matrix of Portland cement paste. Gamma rays are absorbed by the high-density aggregate materials, and neutrons are attenuated by hydrogen atoms in the cement paste. A concrete shield is exposed to two sources of heat: heat transferred from hot parts of the reactor system and heat produced internally by the attenuation of neutrons and gamma rays.[97] Energy captured from slowed down fast neutrons and gamma rays entering the shield from the reactor core is deposited within the shield material and liberated as heat. The total amount of heat generated can be considerable. Different types of concrete perform differently under radiation exposure, although if heated to relatively high temperatures they all will lose waters of crystallization and become somewhat weaker and less effective in neutron attenuation.[98]

The effectiveness of concrete as a shield may be reduced under service conditions (elevated temperature) as drying reduces the hydrogen content or cracking occurs. Results of elevated-temperature exposure on shielding of heavyweight aggregate (iron limonite and magnetite limonite) concretes are presented in Fig. 74.[99] Significant changes in attenuation effectiveness were found as the concrete was heated to 100°C and 200°C, with little additional change effected on heating to 300°C. Despite the loss of neutron and gamma attenuation efficiency with increasing temperature, it was concluded that the concrete would serve as a satisfactory shield material. If increasing efficiency were required at higher temperatures, it could be accounted for in the design. The effect of different durations (1, 2, and 3 h) of high temperature (250, 500, 750, and 950°C) on the physical, mechanical, and radiation properties of heavyweight concrete has been studied.[100] Results showed that ilmenite concrete had the highest density and modulus of

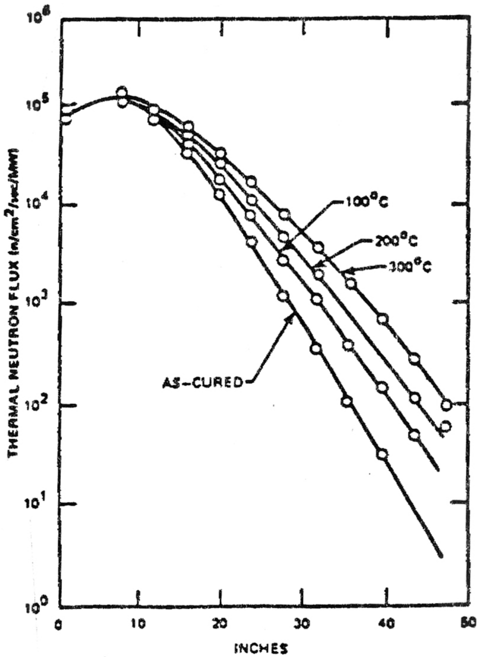

Figure 74 Thermal neutron distribution in ordinary concrete as a function of temperature. *Source*: E. G. Peterson, "Shielding Properties of Ordinary Concretes as a Function of Temperature," HW-65572, Hanford Atomic Products Operation, Richland, Washington, August 2, 1960.

elasticity and lowest percent absorption, and it also had higher values of compressive, tensile, bending, and bond strength than that obtained from either the barite or gravel concretes. Ilmenite also showed the highest attenuation of transmitted gamma rays and was most resistant to elevated temperature. As the magnitude of thermal exposure increased, the attenuation coefficient decreased.

Shielding effectiveness of concrete is also reduced if through-cracks develop. Reference 101 investigated the effect of gamma rays through a concrete shield containing straight and crooked cracks. In the immediate vicinity of the concrete surface, leakage of gamma rays through a slit contributed significantly to γ-dose rate, but diminished rapidly with distance from the surface as a result of shield thickness and scattering effects. Reference 102 investigated the shielding effectiveness of cracked concrete and developed formulas to define the resulting effects. Guidelines developed to compensate for cracking note that it might be economically advantageous to allow a concrete shield to crack and then shield the resulting radiation by other means.

Multiaxial Conditions

In large structures such as prestressed concrete pressure vessels, the concrete is stressed either biaxially or triaxially. Only limited investigations, however, have been conducted to study the multiaxial behavior of concrete at elevated temperature.

Biaxial tests of a quartzite concrete and mortar using plate-shaped specimens (200 × 200 × 50 mm) were conducted.[103] After a 2-h hold time at temperatures of either 20, 150, 300, 450, or 600°C, the specimens were loaded to failure at constant displacement rate. Specimen heating was applied at the free surfaces. A comparison of uniaxial and biaxial results for tests at 300°C and 600°C is shown in Fig. 75. Results have

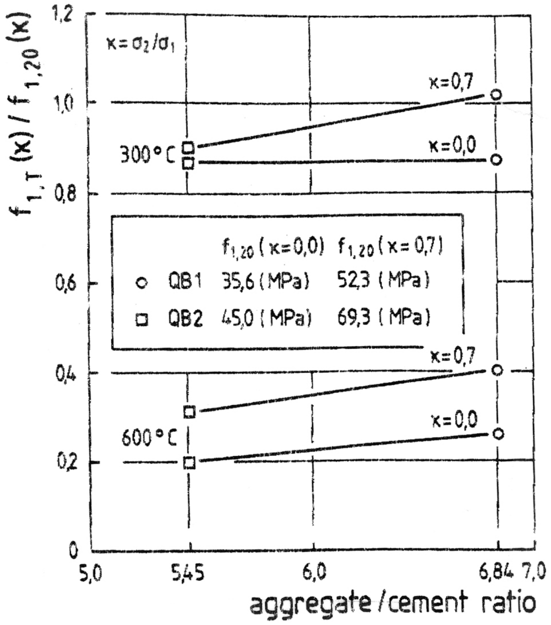

Figure 75 Comparison of uniaxial and biaxial results for tests at 300°C and 600°C. *Source*: K.-Ch. Thienel and F. S. Postasy, “Strength of Concrete Subjected to High Temperature and Biaxial Stress; Experiments and Modeling: Materials and Structures,” **28**, 575–581 (1995).

been normalized with respect to corresponding strength values at room temperature and same stress ratio. The tests exhibited a smaller decrease in compressive strength for concrete with higher aggregate contents at both temperatures. Under biaxial loading, an increase in strength even appears at 300°C for the leaner mix. The strength of mortar was reduced less than that of concrete at temperatures above 300°C. The influence of stress ratio on the compressive strength for various temperatures is shown in Fig. 76. The stress ratio of the compressive strength was varied between 0 and 1, where the stress ratio represents the ratio of the applied stresses in the two principal directions. The solid and dashed lines in the figure represent the mean biaxial behavior (predicted) at each temperature noted. The failure envelopes are similar for each temperature with increasing temperature producing a larger loss of biaxial strength. The difference between uniaxial and biaxial strength increased as the temperature increased. The temperature-dependent decrease in strength was affected by the composition of the concrete in the entire range of biaxial compressive stress. The maximum aggregate size had a significant influence on behavior, while the aggregate content and water/cement ratio were less influential.

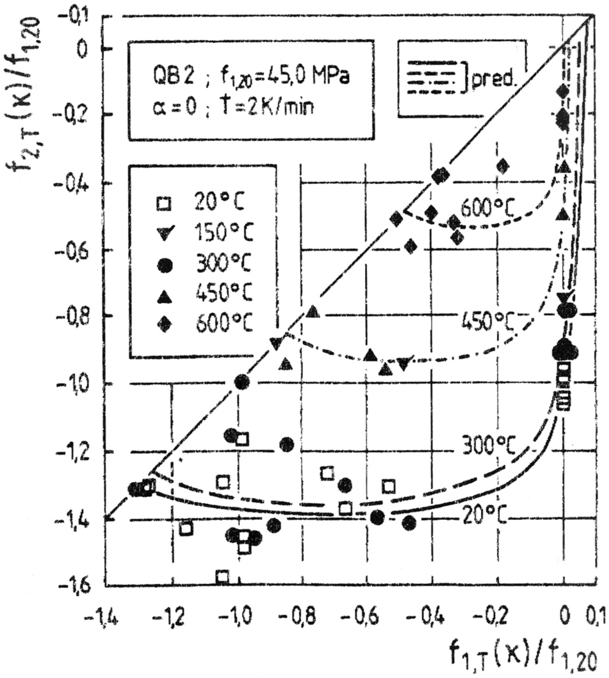

Figure 76 **Biaxial compressive strength at different temperatures.**
Source: K.-Ch. Thienel and F. S. Postasy, "Strength of Concrete Subjected to High Temperature and Biaxial Stress; Experiments and Modelling: Materials and Structures," **28**, 575–581 (1995).

Reference 104 notes that when the principal stress ratio remains constant, the biaxial strength of the concrete decreased with an increase in temperature. Loss of strength was observed at 150°C under biaxial conditions but was much lower than that obtained under uniaxial loading. Under the same elevated temperature, the biaxial strength of concrete varied with different values of principal stress ratio. When the principal stress ratio equaled 0.5, the biaxial strength of concrete at high temperature reached a maximum.

The time-dependent deformation of concrete was investigated by subjecting 15.2-cm-diameter by 40.6-cm cylindrical specimens to various stress conditions and elevated temperatures (Fig. 77). Variables included temperature (23.9°C and 65.6°C), age at loading (90, 183, and 365 d), a variety of axial and

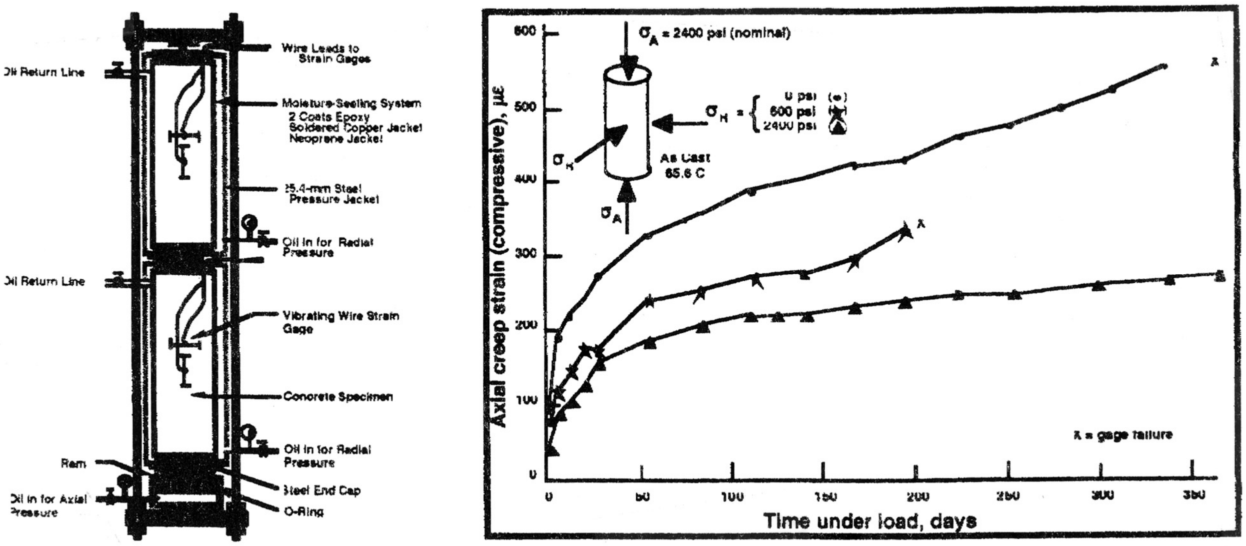

Figure 77 Investigation of the time-dependent deformation of concrete. *Source*: J. E. McDonald, "Creep of Concrete Under Various Temperature, Moisture, And Loading Conditions," SP 55, *Douglas McHenry International Symposium on Concrete and Concrete Structures,* American Concrete Institute, Farmington Hills, Michigan, 1978.

radial load combinations from 0 to 24.8 MPa, and two curing histories (air-dried and as-cast). Strains were measured using vibrating wire gages. In the investigation it was found that compressive and tensile total creep strains were generally larger for (1) a test temperature of 65.6°C than for 23.9°C, (2) an air-dried concrete than an as-cast concrete (except for low tensile creep), (3) increased time after loading, and (4) uniaxial than biaxial states of stress, and that the axial creep strains decreased with increasing confining stress.[79,105]

Thermal Spalling and Fire Resistance

The effects of very rapid and localized heating of a concrete wall or floor element is of interest in nuclear power plants in the unlikely event of a fire or where response of a structure to low probability hypothetical core disruptive accidents is considered [(e.g., molten core debris and liquid sodium coolant melt through the reactor vessel and guard vessel into the reactor area of a liquid-metal fast breeder reactor (LMFBR)]. Research on transient behavior of concrete elements under fire conditions has been conducted for many years,[106–108] with most of the tests to determine the fire resistance of specific concrete elements.

Concrete spalling tests—Spalling of concrete exposed to fire is understood to be the explosive detachment of large or small pieces of concrete from the concrete surface subjected to heating. Spalling can be divided into four categories:[108] (1) explosive dislodging of a few large pieces of concrete from the surface that can result in failure of the member affected, (2) local dislodging of relatively minor portions of the surface or the edges, (3) gradual reduction of the cross section, or (4) explosive dislodging of small pieces of concrete from the surface, which primarily occurs at high material temperatures and can expose the steel reinforcement. Factors influencing spalling include the moisture content, whether heat is applied at one or two faces, rate of temperature increase, aggregate material, the member thickness, state of stress, and presence of reinforcement. Because of the relatively high permeability of NSC, spalling is generally not a safety risk except during initial curing when concrete is in the process of drying or in some tunnel applications. Spalling, however, is of primary importance to high-performance concrete, which exhibits reduced permeability.[*]

Reference 108 presents results of an extensive study conducted to evaluate spalling of concrete exposed to fire. Twenty-five tests were conducted on beam- and plate-like elements primarily to investigate the influence of the concrete moisture content. Other parameters included type aggregate (gravel and lightweight coarse aggregates), compressive stress, concrete compressive strength, thickness of element, steel reinforcement content, and one- or two-sided heating. Results of the study indicated that a high moisture content [>7% (v/v)] can give rise to severe spalling only, if in addition, one or more other unfavorable working conditions are present at the same time (i.e., two-sided heating, small thickness, compressive stress, and reinforcement). Also, it was noted that inspections of buildings after real fires revealed that the spalling that occurred was never as severe as may be expected from fire tests. This was possibly due to the heating rate being lower than that which corresponds with the standard fire-test conditions and that the concrete moisture content in these buildings was relatively low because they had been in service for several years.

Fire resistance of concrete elements—The fire endurance of materials and assemblies is established based on national and international standards.[109-111] In ASTM E 119,[109] a standard time-temperature relation is specified for use in evaluating the fire resistance of structural elements for buildings. Also provided is the furnace time-temperature for a short-duration high-intensity (SDHI) fire, which is used by many fire protection engineers where conditions are postulated that a fire will burn intensely, but die down quickly as available fuel is exhausted.[112,113] Typical unexposed surface temperatures recorded during standard fire tests for concrete slab and beam elements have been published.[114] For concrete assemblies such as these, the temperature rise depends mainly on the thickness and unit weight of the concrete, but it is also influenced by aggregate type, concrete moisture condition, air content, maximum aggregate size, and aggregate moisture condition at time of mixing.

A summary of practical information intended for use by architects, engineers. and building officials who must design concrete structures for particular fire resistances or evaluate structures as designed is given in Ref. 21. Additional information on determination of fire endurance for slabs, two-course roofs and floors, columns, and walls is available.[114] Computer program are available (e.g., FIRETEST) that estimate the temperature distribution through normal weight and lightweight concrete slabs and on the unexposed surface during either an ASTM E119 or SDHI fire test.[112] Also information is available relative to modeling the thermal behavior of concrete.[61,115–117]

Due to the unique conditions under which many of the fire tests reported in the literature were conducted (e.g., thermal gradients, use of insulating material, and structural element type), the results probably have limited application to safety evaluations of reinforced concrete structures in current and new generation nuclear power plants. However, some general conclusions that can be derived from structural fire endurance tests are pertinent: (1) fire endurance increases with increasing moisture content of the concrete; (2) fire endurance of a concrete slab increases with an increase in air content, particularly for air contents >10%, but below 7% air content the effect is not significant; (3) fire endurance of concrete slabs increases as the amount of mortar (cement, water, and sand) in the concrete increases (concretes with smaller maximum size aggregates have longer fire durations than those with larger sizes); (4) factors such as water-cement ratio, cement content, and slump have almost no influence on fire endurance within the normal ranges for structural concretes; (5) structural fire endurance of a complete concrete wall section is seldom a governing factor because it is generally much longer than the fire endurance evaluated based on the temperature rise of the unexposed surface; (6) fire endurance of slabs increases with an increase of

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[*] High-strength (or high-performance) concretes will be discussed later.

slab thickness; and (7) in general, fire endurance increases with a decrease in unit weight (lightweight aggregate concretes have superior fire endurance relative to normal-weight concretes).[114,21]

2.2.2 Physical Properties

The physical, or thermal, properties of concrete are important both in the planning of mass concrete construction (thermal changes) and the dissipation of heat buildup during operation. The thermal expansion coefficient and modulus of elasticity data are prerequisite to computing the thermoelastic stresses that result from nonuniform heating.

As water is added to cement, an exothermic chemical reaction takes place. If the heat is generated at a faster rate than it can be dissipated, a temperature rise occurs. Factors affecting the amount and rate of heat generated during this reaction are the cement type, temperature at placement, water-cement ratio, and cement content. In mass concrete structures where there can be significant heat buildup, cracking can occur upon cooling because the exterior of the structure will cool faster than the interior. However, by using low (Type IV) or moderate (Type II) heat of hydration cements and following the procedures recommended in Ref. 118, this problem can be minimized.

Temperature variations produce expansions or contractions of concrete structures. If movement of a structure is restrained, significant internal stresses can develop, thus leading to cracking, distortions, or even destruction. In general, the density, conductivity, and diffusivity of concrete will increase with an increase in temperature. The coefficient of thermal expansion α is used as a measure of the volume change of a material subjected to a temperature differential. Dissipation of heat is important to nuclear power plant structures such as a PCPV because it affects the development of thermal gradients and the resulting thermal stresses. The basic quantities involved are (1) the coefficient of thermal conductivity k, (2) the thermal diffusivity a, and (3) the specific heat c. These quantities are related by the term $a = k/cp$, where p is the material density.

Density

The density of concrete depends on the density of its aggregate materials and its moisture content in the temperature range from 20°C to 150°C. Figure 78 presents the effect of aggregate type on the density of concretes in the temperature range from room temperature to 1400°C (Ref. 5). Storage (curing or preconditioning) conditions at lower temperature are also important because moist specimens will lose water and thus experience a greater decrease in density upon heating than specimens that have experienced drying. At temperatures from 150°C to 600°C (limestone decarbonation) the density of limestone concrete is relatively constant. Upon decarbonation weight loss occurs[119] as the concrete porosity increases until at higher temperatures when sintering take place the density may increase slightly.[5] Siliceous aggregates exhibit a somewhat steeper decrease in density with heating in the range from room temperature to 700°C. The sharper decline in density at higher temperatures is due to the large thermal expansion of the quartz. Basalt exhibits the smallest decline in density because of its lower thermal expansion.[5] Figure 79 presents bulk density as a function of temperature for a 38-MPa basalt aggregate concrete utilized for Korean nuclear power plants.[120]

Coefficient of thermal expansion

The coefficient of thermal expansion represents the volume change of a material due to temperature changes and is expressed as a change in length per degree of temperature change. The coefficient is important as a measure of the structural movement and thermal stresses resulting from a temperature

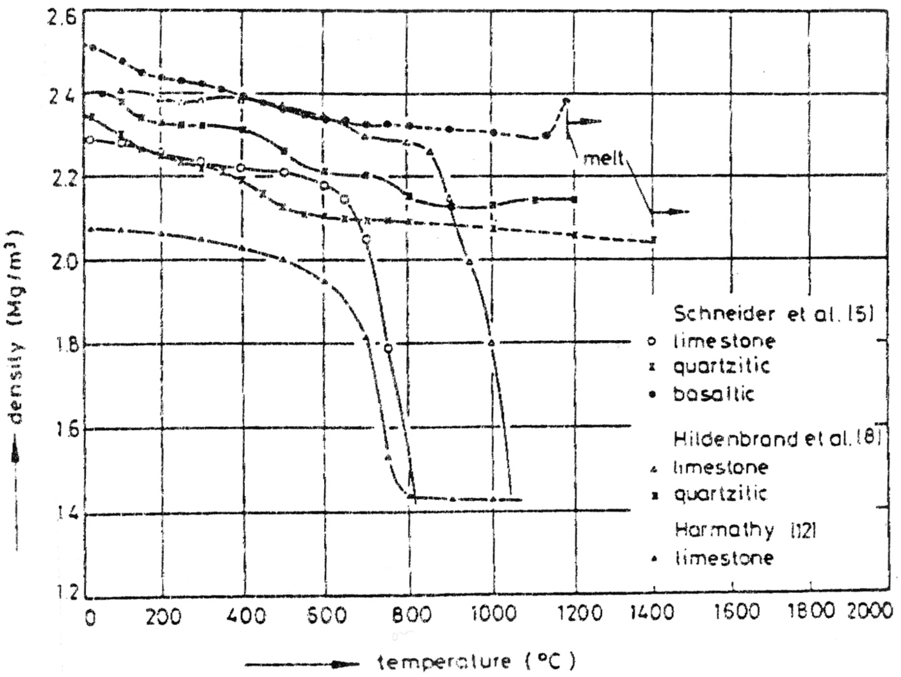

Figure 78 Density of different concretes. *Source*: U. Schneider, C. Diererichs, and C. Ehm, "Effect of Temperature on Steel and Concrete for PCRV's," *Nuclear Engineering and Design* **67**, 245–258 (1981).

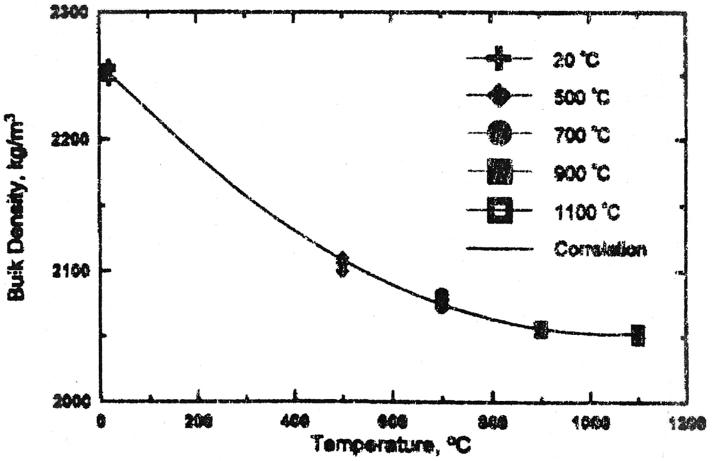

Figure 79 Density of a nuclear power plant concrete. *Source*: K.-Y. Shin et al., "Thermo-Physical Properties and Transient Heat Transfer of Concrete at Elevated Temperatures," *Nuclear Engineering and Design* **212**, 233–241 (2002).

change. Concrete's thermal expansion is a complicated phenomenon because of the interaction of its two main components—cement paste and aggregate—which each have their own coefficients of thermal expansion. Because the aggregate generally constitutes a major proportion of the mix, it primarily influences the resultant coefficient of thermal expansion. Figure 80[121] presents thermal coefficient of expansion values for neat cements, mortars, and concretes. As illustrated, values of the coefficient for concrete range from $\sim 2.2 \times 10^{-6}$ to 3.9×10^{-6} mm/mm/°C with 3.1×10^{-6} mm/mm/°C being a typical value. The coefficient is influenced by the moisture condition (applies to paste component) and has minimum values for the two extremes: dry and saturated.[119] The coefficient of linear expansion also apparently increases with increasing temperature (Fig. 81);[119] however, the effects of specimen moisture condition at test initiation (i.e., the number of thermal cycles that have been applied to the specimen) also has to be taken into consideration in determining the net specimen length change with temperature.[122]

Thermal expansion coefficients for limestone and siliceous aggregate concretes are presented in Figs. 82 and 83, respectively.[4] Results indicate an almost monotonic increase in thermal expansion coefficient for the limestone concrete until decarbonation ($CaCO_3 \rightarrow CaO + CO_2$) leads to a decrease in the coefficient. The thermal expansion of the siliceous concrete is greater than that for the limestone concrete. Basalt, due to its fine crystalline structure, exhibits a lower expansion than the siliceous concrete. Figure 84 presents the influence of temperature (20°C to 200°C) on thermal expansion coefficient of a siliceous aggregate concrete from the French Penly Nuclear Power Plant.[123]

Results presented in the literature indicate that the main factor influencing the coefficient of thermal expansion is the aggregate type; at high temperatures (600°C to 800°C) most concretes no longer exhibit an expansion and in some cases contract; moisture content, water/cement ratio, and cement type influence results at relatively low temperatures with moist concretes exhibiting higher thermal expansion values than dry concretes; and thermal expansion coefficient is inversely proportional to aggregate content.

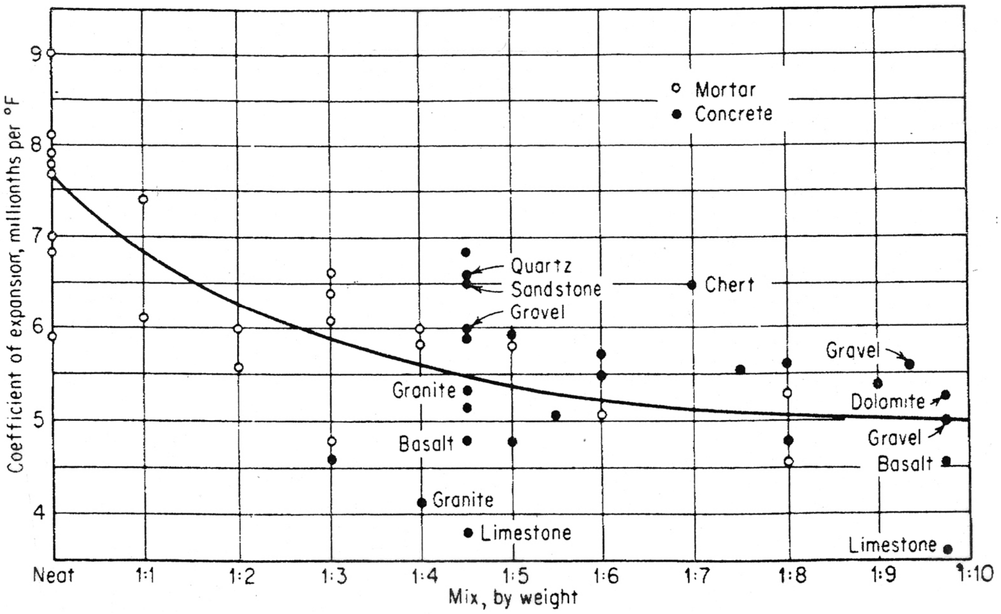

Figure 80 Coefficients of thermal expansion of neat cements, mortars, and concretes. *Source*: *Concrete Manual,* 7th Ed., U.S. Bureau of Reclamation, Denver, Colorado, 1963.

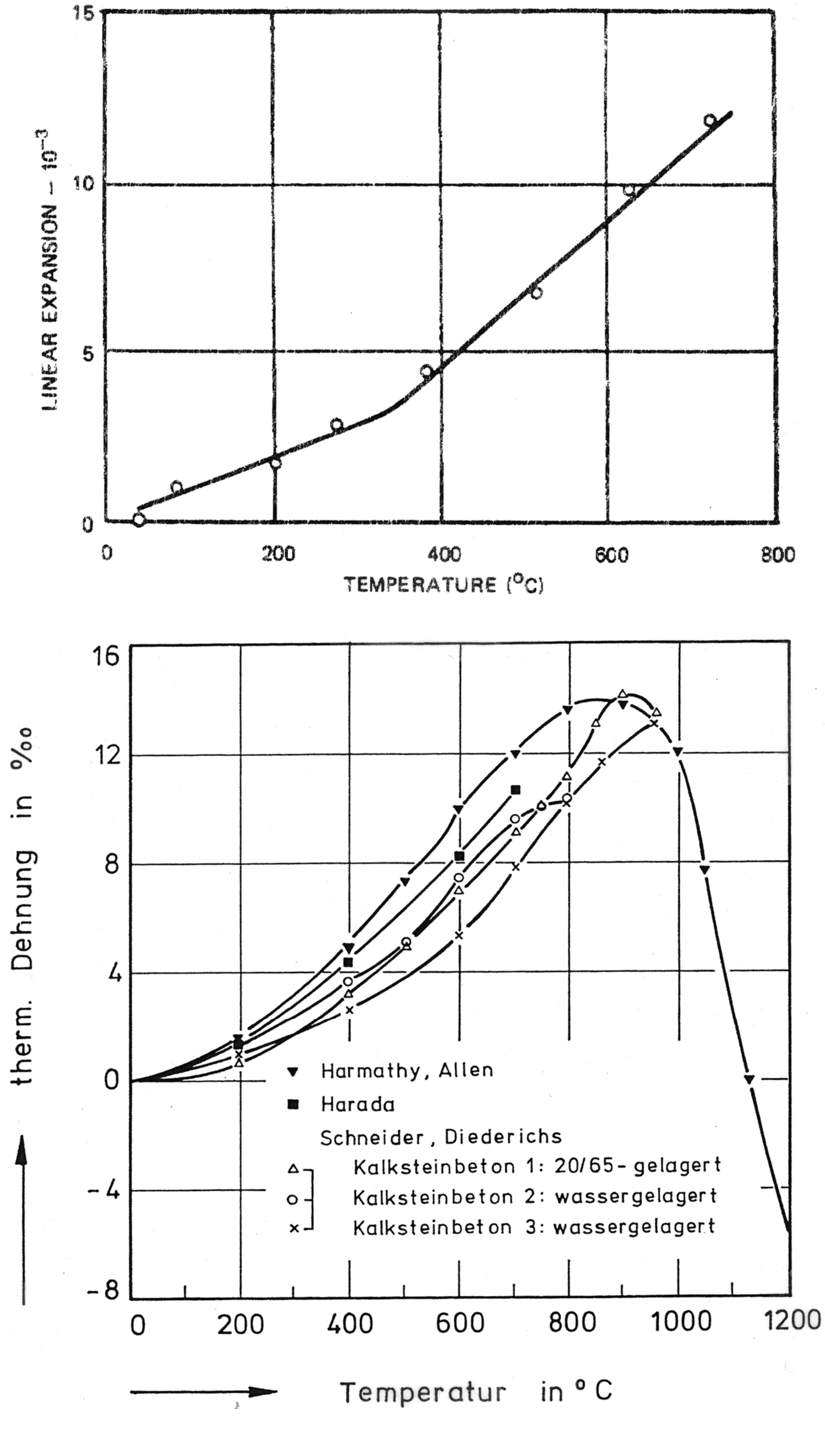

Figure 81 Linear expansion of concrete on heating. *Source*: R. Philleo, "Some Physical Properties of Concrete at High Temperature," *Research Department Bulletin 97,* Portland Cement Association, Skokie, Illinois, October 1958.

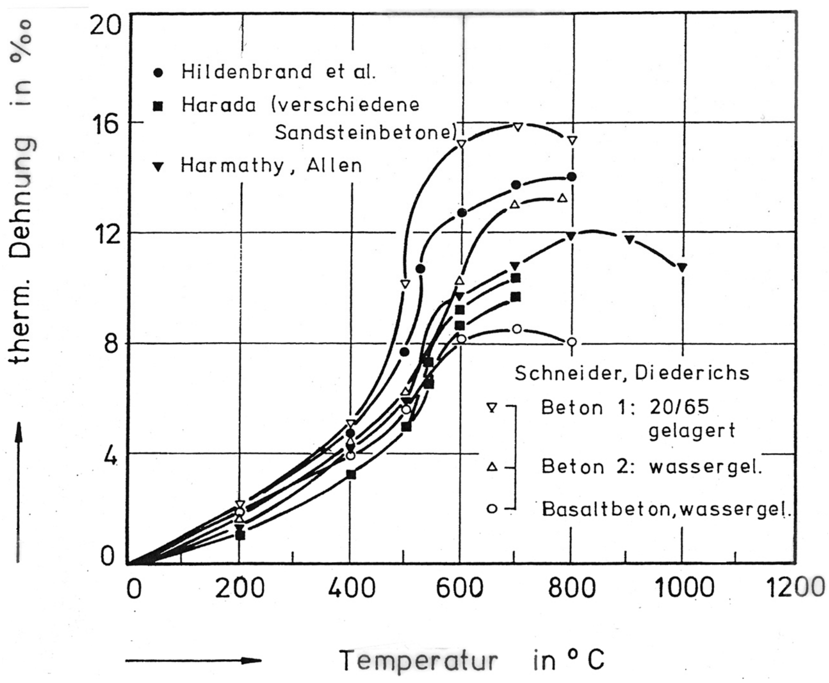

Figure 82 Thermal expansion of limestone aggregate concretes. *Source*: U. Schneider, "Behaviour of Concrete at High Temperature," HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

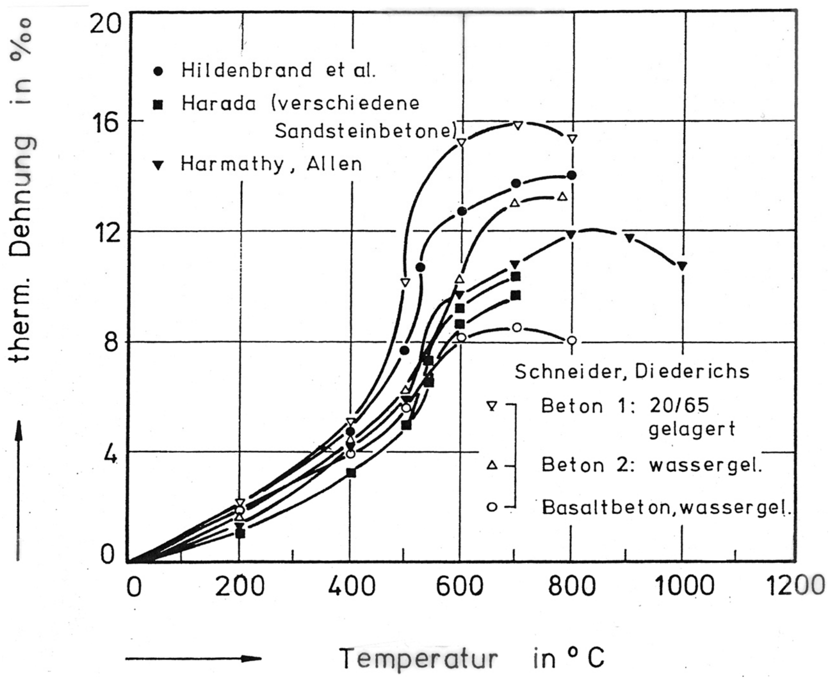

Figure 83 Thermal expansion of siliceous aggregate concretes. *Source*: U. Schneider, "Behaviour of Concrete at High Temperature," HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

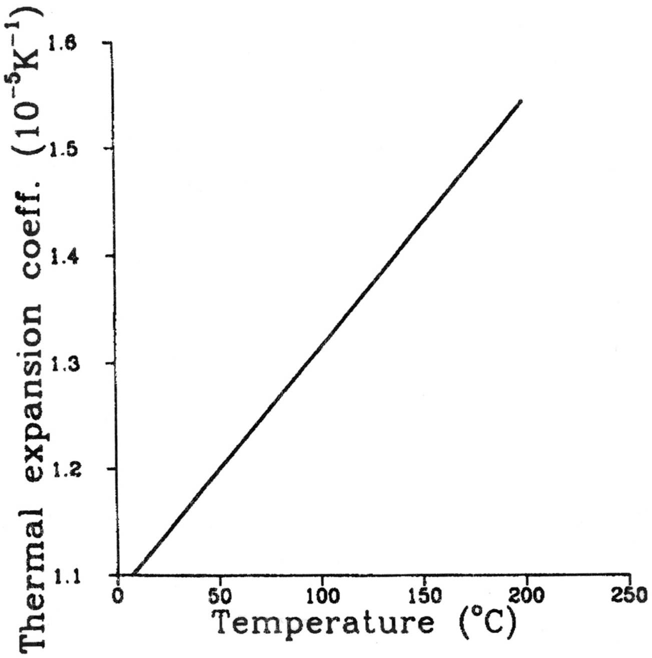

Figure 84 Temperature dependence of linear thermal expansion coefficient of nuclear power plant concrete. *Source*: F. Vodak et al., "The Effect of Temperature on Strength—Porosity Relationship for Concrete," *Construction and Building Materials* **18**, 529–534 (2004).

Thermal conductivity

Thermal conductivity is a measure of the ability of the material to conduct heat and is measured in British thermal units per hour per square foot of area of body when the temperature difference is 1°F per foot of body thickness. For PCPVs, concrete with a high thermal conductivity is generally desirable but not always used to allow a rapid dissipation of heat flux, so thermal gradients through the thickness will be minimal.

Important factors influencing the thermal conductivity of concrete are the hardened cement paste, the pore volume and distribution, and the water content. At low temperatures and with moist concrete very high values for thermal conductivity exist.[5] At higher temperatures the thermal conductivity increases slightly (see next paragraph), but decreases as it approaches 100°C. Up to 300°C to 400°C, the thermal conductivity decreases further, and as the temperature increases beyond 300°C increasing cracking develops.

Table 2 lists typical values of thermal conductivity for several concretes fabricated using a wide variety of aggregates.[124] Because the conductivity of water is approximately half that of cement paste, the lower the mix-water content, the higher the conductivity of the hardened concrete.[125] As shown in Fig. 85, thermal conductivities of concrete made with highly crystalline aggregate decrease with temperature up to 100°C, while those of concrete made with amorphous aggregate are essentially constant.[8] Figure 86 presents thermal conductivities for normal concretes having different aggregate types.[5] Figures 87 and 88 presents thermal conductivities of concrete as a function of density and moisture content and the variation of thermal conductivity as a function of temperature for several mortars and concretes, respectively.[120]

Table 2 Typical Values of Thermal Conductivity

Type aggregate	Concrete density [lb/ft^3 (kg/m^3)]	Conductivity [Btu/ft^{2}h°F/ft (MW/cm°C)]
Barite	227 (3640)	0.80 (13.9)
Igneous	159 (2550)	0.83 (14.4)
Dolomite	160 (2560)	2.13 (37)
Limestone or gravel	150 (2400)	0.75–1.00 (13–17)
Lightweight No. 1	30 (481)[a]	0.08 (1.4)
Lightweight No. 2	110 (1760)[a]	0.35 (6.1)
Pumice		0.02 (0.3)
Foam	20 (320)	0.04 (0.7)
Cinder		0.43 (7.4)
Expanded clay		0.23–0.36 (4–6.2)
Perlite or vermiculite		0.04–0.07 (0.7–1.2)

[a] Oven dried.

Source: L. L. Mitchell, “Thermal Properties,” ASTM Special Technical Publication 169, pp. 129–135, American Society for Testing and Materials, West Conshohocken, Pennsylvania, October 1962.

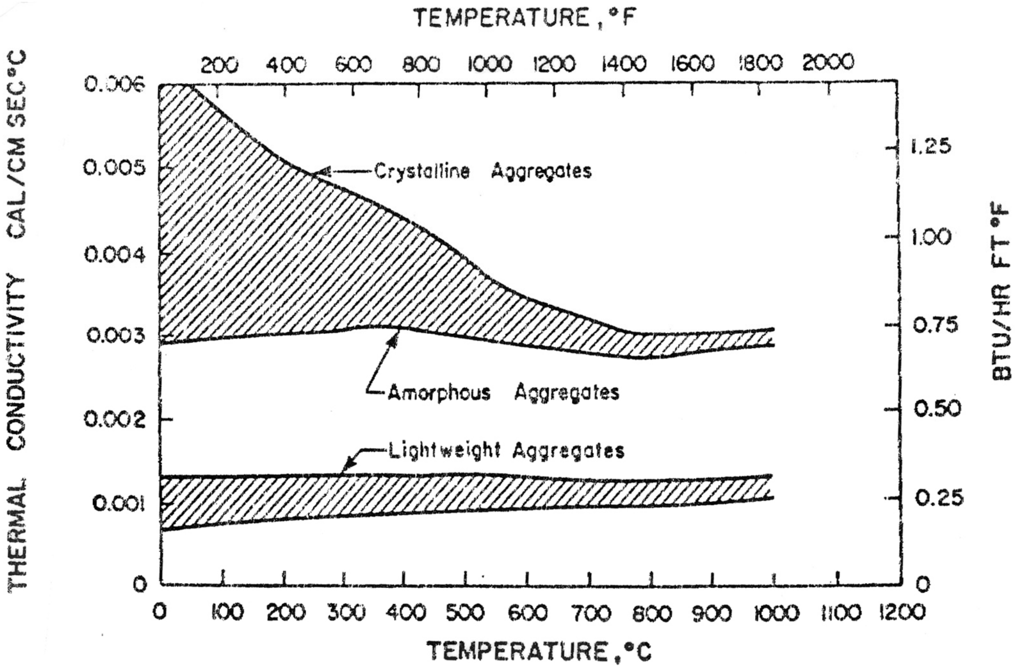

Figure 85 **Thermal conductivity of Portland cement concretes.** *Source*: T. Z. Harmathy and L.W. Allen, “Thermal Properties of Selected Masonry Unit Concretes,” *J. American Concrete Institute* **70**, 132–142 (1973).

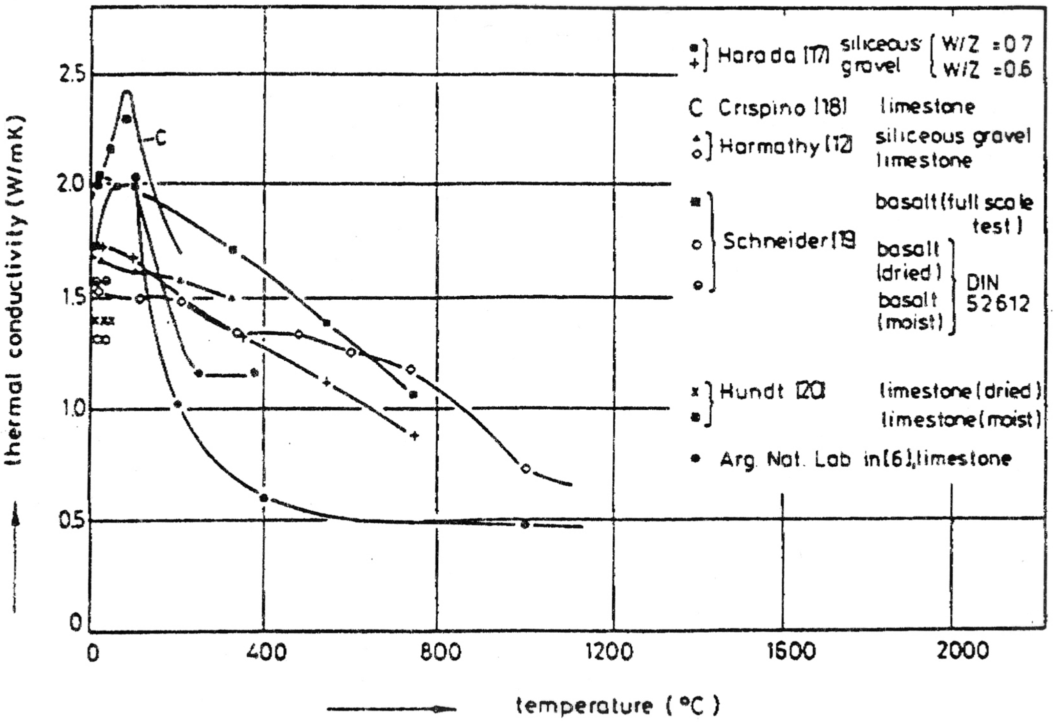

Figure 86 **Thermal conductivity of ordinary concretes with different aggregates.** *Source*: U. Schneider, C. Diererichs, and C. Ehm, "Effect of Temperature on Steel and Concrete for PCRV's," *Nuclear Engineering and Design* **67**, 245–258 (1981).

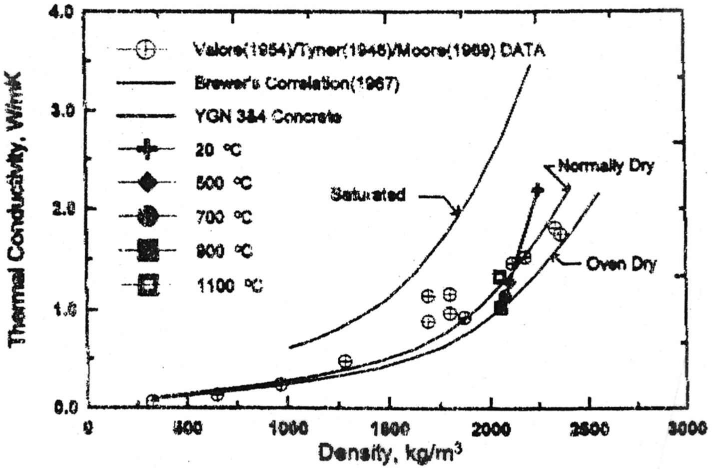

Figure 87 **Thermal conductivity as a function of density and moisture content.** *Source*: K.-Y. Shin et al., "Thermo-Physical Properties and Transient Heat Transfer of Concrete at Elevated Temperatures," *Nuclear Engineering and Design* **212**, 233–241 (2002).

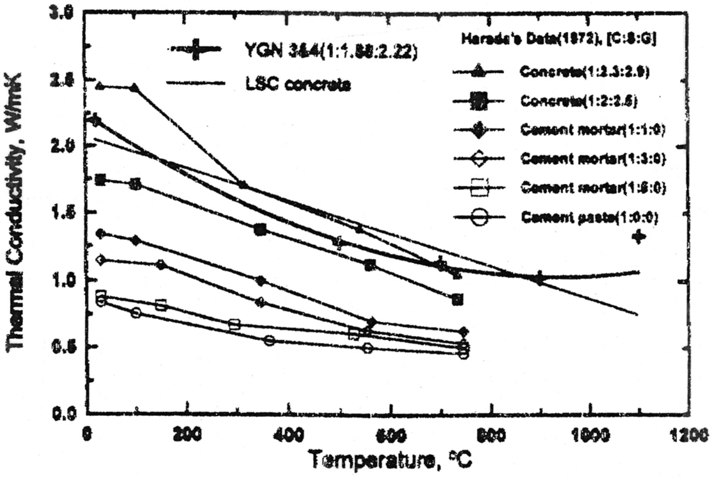

Figure 88 Thermal conductivity as a function of temperature. *Source*: K.-Y. Shin et al., "Thermo-Physical Properties and Transient Heat Transfer of Concrete at Elevated Temperatures," *Nuclear Engineering and Design* **212**, 233–241 (2002).

Figure 89 presents the influence of temperature on thermal conductivity of a siliceous aggregate concrete from the French Penly Nuclear Power Plant.[123] Results presented in the figure are based on 40 measurements at each of the test temperatures (30, 60, 90, 150, and 200°C) and are comparable to those obtained by other researchers for siliceous aggregates in this temperature range.[125,126]

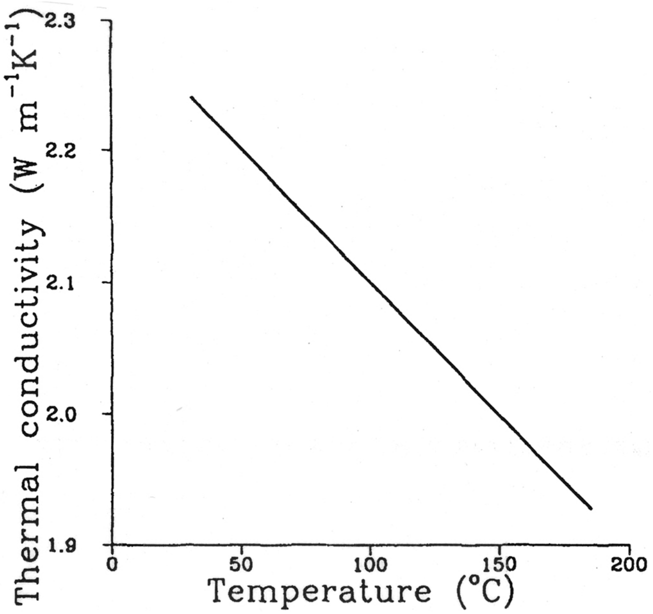

Figure 89 Temperature dependence of thermal conductivity of a nuclear power plant concrete. *Source*: F. Vodak et al., "Thermophysical Properties of Concrete for Nuclear Safety-Related Structures," *Cement and Concrete Research* **27**(3), 415–426 (1997).

Results presented in the literature indicate that the major factors influencing concrete thermal conductivity are moisture content, type of aggregate material, hardened cement paste, and pore volume and distribution. The conductivity varies linearly with moisture content. As the conductivity of the aggregate material increases, the concrete thermal conductivity increases. Concretes with lower cement paste content can be expected to have a lower conductivity than lean concrete mixtures.

Thermal diffusivity

Thermal diffusivity is a measure of the rate at which heat will diffuse through a material in all directions due to a temperature change and is thus an index of the facility with which the material will transfer heat due to a temperature change. Thermal diffusivity is important to nuclear power plant structures such as PCPVs for the same reasons cited for thermal conductivity. Thermal diffusivity of concrete is determined by the thermal properties of its constituents. Aggregates with increasing values of thermal diffusivity include basalt, rhyolite, granite, limestone, dolerite, and quartzite.[127] Factors that affect thermal conductivity generally have the same influence on thermal diffusivity. Thermal diffusivity of limestone and siliceous aggregate concretes is presented in Figs. 90 and 91, respectively.[4] Figure 92 presents the influence of temperature on thermal diffusivity of a siliceous aggregate concrete from the French Penly Nuclear Power Plant[123] and is noted to be similar to other results presented in the literature for siliceous aggregate concretes in the temperature range investigated (30°C to 200°C).[128] Figure 93 presents the thermal diffusivity of several mortars and concretes as a function of temperature.[120]

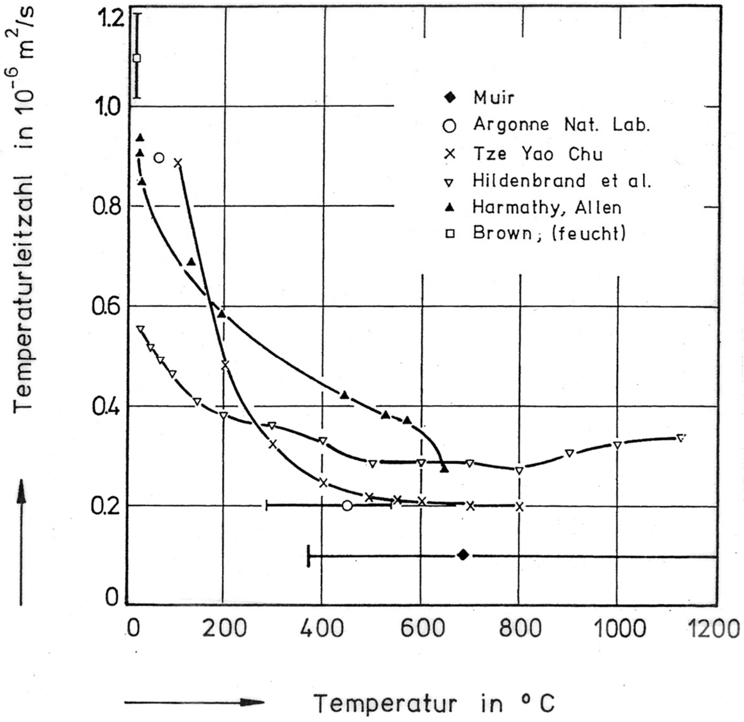

Figure 90 Thermal diffusivity of limestone concrete. *Source*: U. Schneider, “Behavior of Concrete at High Temperature,” HEFT 337, Deutscher Ausschuss fur Stahlbeton, Wilhelm Ernst & Sohn, Berlin, Germany, 1982.

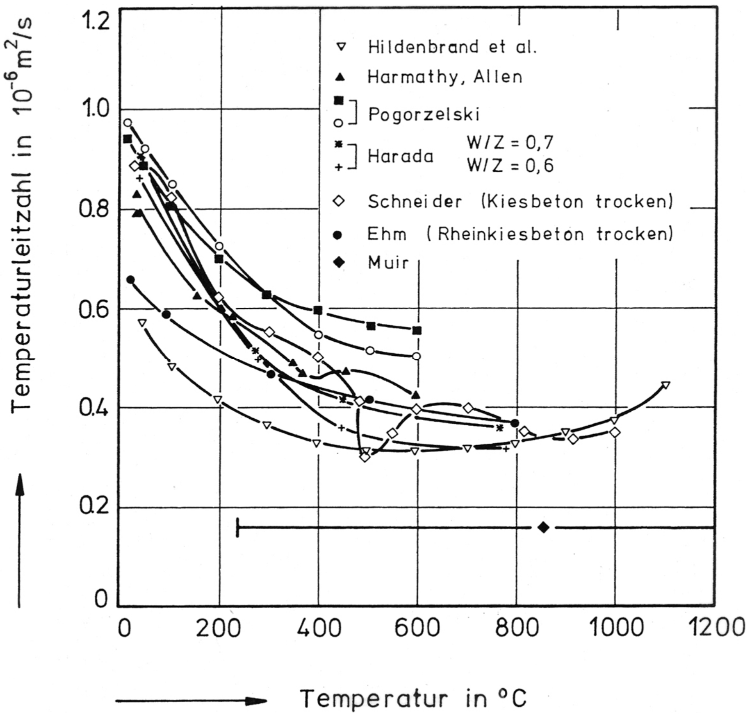

Figure 91 **Thermal diffusivity of siliceous aggregate concrete.** *Source*: U. Schneider, “Behaviour of Concrete at High Temperature,” HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

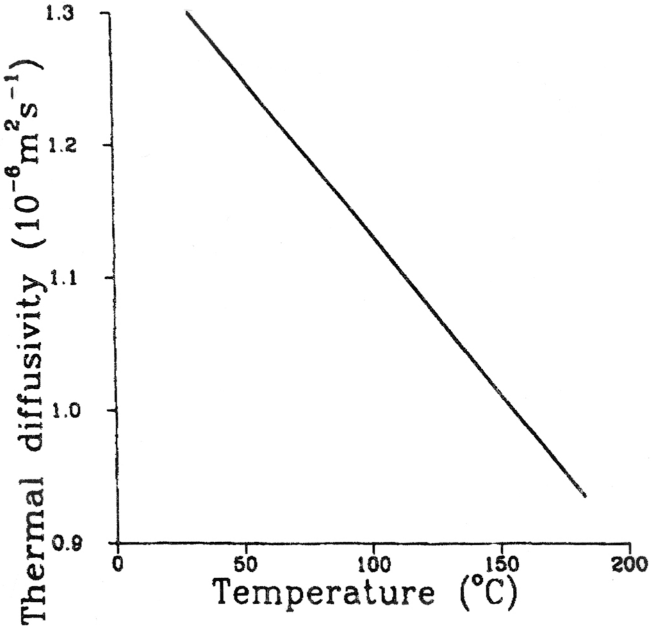

Figure 92 **Temperature dependence of thermal diffusivity of a nuclear power plant concrete.** *Source*: F. Vodak et al., “The Effect of Temperature on Strength—Porosity Relationship for Concrete,” *Construction and Building Materials* **18**, 529–534 (2004).

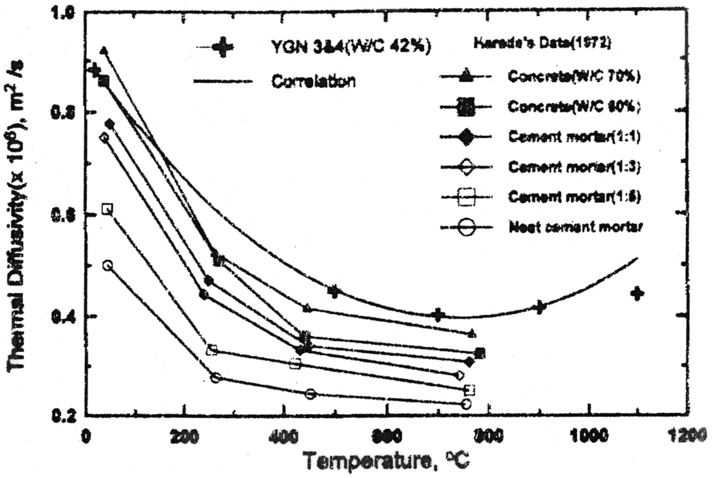

Figure 93 Thermal diffusivity variation of concrete as a function of temperature. *Source*: K.-Y. Shin et al., "Thermo-Physical Properties and Transient Heat Transfer of Concrete at Elevated Temperatures," *Nuclear Engineering and Design* **212**, 233–241 (2002).

Specific Heat

Specific heat is the amount of heat required to change the temperature of 1 lb (0.45 kg) of material 1°F (0.56°C) and thus represents the heat capacity of the material. As the moisture content in the concrete increases, the specific heat capacity increases at lower temperatures. Concrete's heat capacity rises with temperature up to about 500°C and then levels out or declines up to 1000°C as shown in Fig. 94.[8]

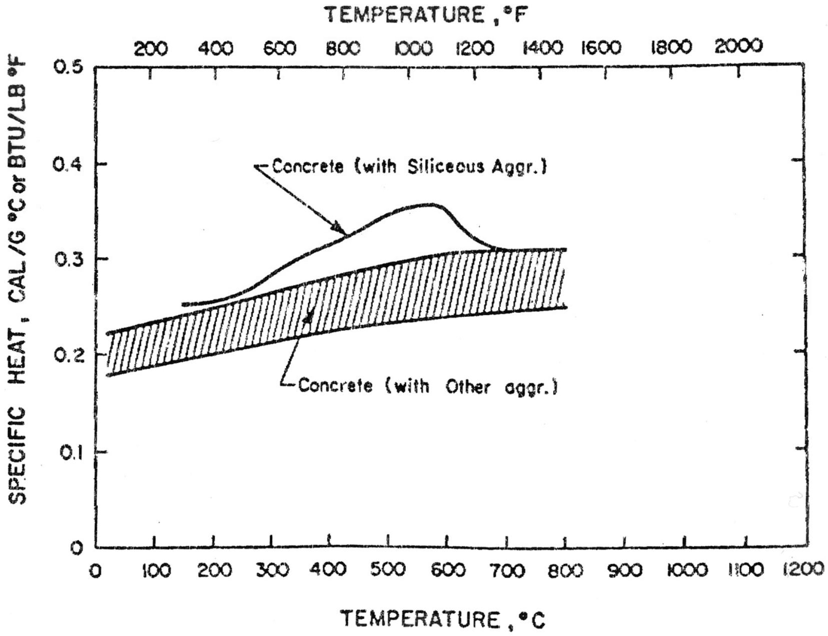

Figure 94 Thermal conductivity of Portland cement concrete. *Source*: T. Z. Harmathy and L. W. Allen, "Thermal Properties of Selected Masonry Unit Concretes," *J. American Concrete Institute* **70**, 132–142 (1973).

Figures 95 and 96 present heat capacities of limestone and siliceous aggregate concretes, respectively.[4] Additional information is provided in Figure 97, which presents the influence of temperature on the specific heat of a siliceous aggregate concrete from the French Penly Nuclear Power Plant.[123]

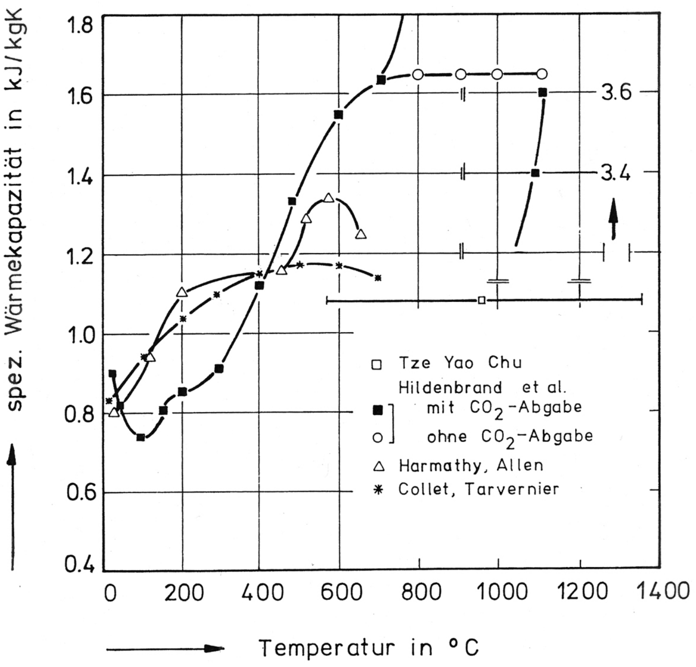

Figure 95 Specific heat capacity of limestone aggregate concrete.
Source: U. Schneider, “Behaviour of Concrete at High Temperature,” HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

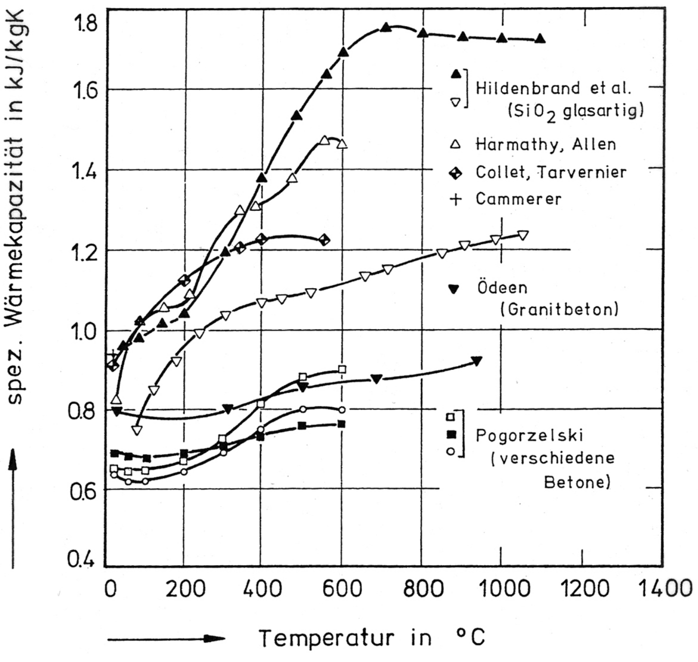

Figure 96 Specific heat capacity of siliceous aggregate concrete.
Source: U. Schneider, “Behaviour of Concrete at High Temperature,” HEFT 337, Deutscher Ausschuss für Stahlbeton, Wilhelm Ernst & Sohn, Munich, Germany, 1982.

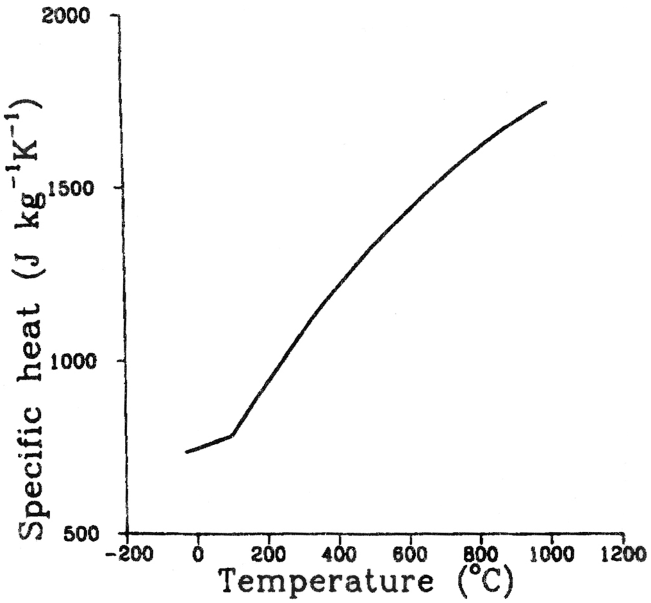

Figure 97 Temperature dependence of specific heat of a nuclear power plant concrete. *Source*: F. Vodak et al., "The Effect of Temperature on Strength—Porosity Relationship for Concrete," *Construction and Building Materials* **18**, 529–534 (2004).