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THERMAL DEGRADATION OF CONCRETE IN THE TEMPERATURE RANGE FROM AMBIENT TO 315°C (600°F)

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ABSTRACT

This report is concerned with determining the effect of elevated temperatures on the behavior of concrete. Emphasis is placed on quantifying the degree of potential degradation of the physical properties of concrete in high-level waste storage tanks. The range in the temperature elevation of interest covers from ambient to 315°C (600°F). The literature has been reviewed to examine the applicable experimental data and quantify the degradation in the concrete and reinforcing steel. Since many variables and test conditions control the results in the data base, upper and lower bounds of the degraded properties at temperatures applicable to the environments of the storage tanks are summarized and presented in explicit forms. Such results are useful in assessing the effect of elevated temperatures on the structural behavior of the tanks. Also, they provide the technical basis for a parametric study that may be necessary to investigate the thermal aspects of the structural integrity of the tanks.

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EXECUTIVE SUMMARY

The compressive strength and modulus of elasticity of concrete tend to decrease when concrete is subjected to elevated temperatures. Also, repeated thermal cycling causes increase in the nonrecoverable maximum strain, and could affect the bond strength between the concrete and the steel reinforcement. Other physical properties of concrete are also degraded because of the exposure to elevated temperatures. Undoubtedly, such degradation could have a strong impact on the structural behavior of those waste storage tanks that have been subjected to high temperatures during their service lives.

The objective of this study is to provide a quantitative interpretation of the response of the concrete vaults of the high-level waste storage tanks to elevated temperature. Since the wastes in many tanks are reported to have achieved a temperature range of 150-180°C (302-356°F), and in a few tanks the temperature is suspected to have reached 200-315°C (392-600°F), attention is focused on quantifying the effects of temperature rise from ambient to 315°C (600°F) level.

An independent literature review of the laboratory test data has been undertaken and the applicable degradation in the physical properties of concrete is examined and quantified. These properties include compressive strength, modulus of elasticity, time-dependent properties (creep and shrinkage), thermal properties (expansion, conductivity, diffusivity, and specific heat), thermal cycling and characteristics of stress-strain relation. The influences of elevated temperature on the yield strength and modulus of elasticity of the reinforcing steel as well as the bond strength between concrete and steel are also discussed. Because many variables and test conditions govern the test data, upper and lower bounds of the degraded properties are provided. The results are essential in order to assess the structural response of the storage tanks to elevated temperatures. The threshold of significant degradation of concrete is around 65-93°C (150-200°F). For this reason, current codes and industry standards dealing with reinforced concrete structures specify a temperature limit of about 65-93°C (150-200°F) to ensure predictable concrete behavior.

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1.0 INTRODUCTION

The concrete vaults of the high-level waste storage tanks have been exposed to sustained high temperatures for a long period due to decay heating of the wastes obtained as a result of chemical processing of nuclear materials. The wastes in many tanks are reported to have achieved a temperature range of 150-180°C (302-356°F). The waste temperatures in a few tanks are suspected to have attained even a higher range, e.g., 200-315°C (392-600°F). It is well known that concrete materials degrade at elevated temperatures. The purpose of this report is to discuss the results of a literature search and present generic bounding experimental data that can be used to verify the structural integrity of the concrete components in the waste storage tanks. In order to provide an independent verification, the limited test data that exist for waste storage tanks are not included in the current study except for the creep behavior.

When conventional concrete is exposed to elevated temperatures, it begins to experience dehydration reactions in the hydrated cement paste, possible thermal incompatibilities between paste and aggregate, and eventual physiochemical deterioration of the aggregate. Typically, such degradation is accompanied by a decrease in the compressive strength, and in the stiffness (modulus of elasticity) of the concrete. In the temperature range of interest for the waste storage tanks, very little degradation is expected to occur in the mechanical properties of the steel reinforcement. The stress-strain curve for concrete is also influenced by the rise in temperature. Moreover, repeated thermal cycling due to fluctuating temperatures reduce the peak strength and could loosen the bond between the concrete and the reinforcing bars. The thermal gradients and induced thermal stresses could trigger microcracking, crumbling and spalling of the concrete, and depending on the available cover, it could expose the embedded reinforcing steel.

The purpose of this study is to quantify the influence of a rise in temperature from ambient to 315°C (600°F) on the physical properties of the concrete. The results can be used to estimate the influence of high temperature on the structural behavior and integrity of concrete components. The properties investigated for this purpose include compressive strength, stiffness, time-dependent properties (creep and shrinkage), thermal expansion, thermal conductivity, thermal diffusivity, specific heat and characteristics of the stress-strain relations. These parameters are the principal ones by which the structural behavior of reinforced concrete can be judged. They provide the technical basis for numerical modeling of a concrete tank needed for its structural integrity analysis. The compressive strength affects the load-carrying capacity of a structural component while the stiffness influences the deformation and load distribution. For the small strain analysis of concrete structures, a knowledge of

the strength and the elastic modulus is sufficient. However, when large strains are involved, as in a structural integrity analysis, a knowledge of the stress-strain relationship of the concrete at elevated temperatures is also required.

An independent literature review has been undertaken for this purpose and the applicable manifestations of degradation are quantified. When there is doubt about the direct applicability of a given set of experimental data to the tank situation, lower bound estimates of the degradation are made for the sake of conservatism. The results are summarized in the following sections.

2.0 PHYSICAL PROPERTIES

The properties of concrete (strength and stiffness) are generally degraded when concrete is exposed to elevated temperatures. Experimental data supporting such degraded behavior of concrete have been extensively studied in the literature (References 1-20). The level of degradation is influenced by many variables including concrete mixing and test conditions. The primary conditions include the following:

- Conditions of testing: Whether the concrete is tested while hot or after cooling; whether it is quenched or allowed to cool slowly before testing.
- Conditions of loading during specimen heating: Whether the concrete specimen is restrained during heating.
- Moisture content of concrete when heated.
- Prevention of moisture loss: Whether free moisture is contained (sealed specimen) or allowed to evaporate during heating (unsealed specimen).
- Specifics of concrete mixture proportions, specimen size, degree of curing, and length of time the specimen was heated and allowed to stabilize before load testing.

Other physical properties of concern to the behavior of concrete at elevated temperatures are thermal expansion, thermal conductivity, thermal diffusivity, and specific heat. These properties determine the nature of the heat transfer through the concrete and, as a consequence, affect its load bearing and load transfer capabilities.

Comprehensive reviews of the effects of elevated temperatures, ambient to about 982°C (1800°F), on concrete used in nuclear power plant structures and components are available in References 21 and 22. These review documents also contain a list of the original references in which the actual specimen test data were published. More recent data are available in Reference 23. A review of the laboratory data base indicates that concrete specimens of many

sizes and shapes were heated for varying periods and temperatures and tested using many of the variables and conditions mentioned above. The important test conditions which can be identified as having the most influence on the degradation of concrete in the present application include the following: First, the "cold" and "hot" test conditions. In "cold tests," the specimens are heated to the specified temperature, allowed to stabilize at that temperature for a prescribed time, cooled down slowly to room temperature, and then tested to determine the mechanical properties. In "hot tests," the specimens are gradually heated to the specified level, allowed to stabilize at that level for a prescribed time and then tested while hot at that temperature. Second, the period of sustained heating and level of temperature rise affect the degree of degradation. Other contributory factors influencing the degradation are concerned with the moisture path during the testing. The specimens in the data base are tested in either an open environment (unsealed specimen) where moisture can escape to the atmosphere or a closed environment (sealed specimen) where moisture is contained. The influence of elevated temperatures, ambient to 315°C (600°F), on the properties of these parameters is summarized in the following sections.

2.1 Strength

As mentioned previously, the compressive strength of concrete generally decreases with a rise in temperature. A review of the technical data, based mostly on laboratory testing, reveals the following:

- (a) There is less strength degradation in laboratory specimens tested under "hot" conditions compared to those tested under "cold" conditions.
- (b) Sealed specimens loose more strength than unsealed ones. This is because the moisture is not allowed to escape during heating and subsequent testing.
- (c) The type of aggregates and mixture proportions influence the degradation in the strength of heated concrete. In particular, lean concrete (low cement content) shows smaller reduction in the compressive strength than rich concrete. Also, limestone aggregates degrade less than siliceous ones when the specimen is heated. Thus, if the concrete in the tanks is fabricated from high cement content mixtures then this has a negative influence on its degraded strength.

Based on these observations, the variation of the residual compressive strength of concrete (expressed as % of the initial strength) with rise in temperature up to the 600°F level is shown in Figure 1. The experimental data were obtained for specimens

Figure 1. Reduction of Compressive Strength of Concrete at Elevated Temperatures

tested under both cold and hot conditions (Reference 21). It is clear from this figure that the upper bound of the test data indicates almost no reduction in the concrete strength for elevated temperatures through almost 600°F. The lower bound data, however, indicate a reduced strength for temperatures above 100°F. For example, for specimens tested at 300°F, the reduced strength is 68% of the initial compressive strength at room temperature. The reduced strength for specimens tested cold is 62% at the same temperature.

2.2 Stiffness (Modulus of Elasticity)

The modulus of elasticity, E_c , which is the ratio of stress to strain, is an important parameter to describe the structural behavior of concrete components. At elevated temperatures, the modulus experiences a permanent reduction in its value. Like the strength parameter, several factors influence the value of the modulus of elasticity in laboratory specimens tested at high temperatures. The major factors include the method of test conditions (hot or cold) and prevention of moisture loss (sealed or unsealed specimens).

Figure 2 shows the variation of the modulus of elasticity (expressed as % of the initial room temperature value, E_c) with increase in temperature (Reference 21). The upper and lower curves envelope the data obtained from specimens tested in hot and cold conditions and at various moisture paths. At 100°F, the upper bound envelope indicates no reduction in the modulus while the lower bound curve reveals a reduction of about 5%. At 300°F, the upper bound curve indicates a modulus of $0.9 E_c$ while the lower bound curve shows a modulus of $0.45 E_c$. This indicates that in the temperature range of concern for the waste storage tanks, the degradation is more pronounced for the stiffness of concrete than the compressive strength. As shown in Figure 2, the reduction in modulus of elasticity at temperatures higher than 300°F is significantly greater.

2.3 Stress-Strain Relations

In order to investigate the structural integrity of the waste storage tanks, elastic-plastic analyses resulting in large strains are sometimes required. Thus, in addition to variation in the modulus of elasticity, one needs to examine the stress-strain characteristics of concrete at the applicable elevated temperature.

The shape of the stress-strain curve of concrete does not change when it is heated. However, because of the induced degradation, the peak in the curve may be reduced and occur at a higher strain especially when the moisture path is constrained. Figure 3a illustrates this point with typical stress-strain diagrams obtained by testing sealed specimens fabricated using limestone aggregate and subjected to temperature rise through the 180°C (356°F) level (Reference 18). The curves reveal significant

Figure 2 Variation of the Modulus of Elasticity of Concrete with Temperature

(a) Sealed Specimens

(b) Unsealed Specimens

Figure 3 Stress-Strain Diagrams of Limestone Aggregate Concrete

and progressive increase in the strain corresponding to the peak stress. At 180°C (356°F), the corresponding strain has increased by about 50%. However, as shown in Figure 3b, when similar laboratory specimens were tested in an unsealed environment through the same temperature range, the results revealed practically no influence of the rise in temperature on the ductility of the concrete (Reference 18). This indicates that certain test conditions, specifically, the moisture retention capability and evaporation paths have strong influence on the characteristics of the stress-strain diagrams. Stress-strain curves for lightweight aggregate concrete specimens tested to failure are shown in Figure 4 (References 6 and 22).

Stress-strain experimental data applicable for concrete made using other types of aggregates at elevated temperature are scarce. Because of this, lower and upper bound stress-strain diagrams illustrating the influence of elevated temperatures on conventional concrete have been postulated by use of the limited existing data and are shown in Figure 5 (Reference 20). Such stress-strain diagrams have been used to assess the load bearing capacity of structural members. *At 150°C (302°F), the lower bound data show a reduction in strength by 30% and an increase in strain at the peak strength by 20%.*

2.4 Creep

Creep is defined as an increase in strain with time under a constant stress. It affects the distribution of stress and deformation in structural members. In concrete, the magnitude of creep in compression is the same as that in tension (Reference 24). At room temperature, the primary factor influencing the development of creep in concrete structures is the type of aggregate used. Concrete made using basalt and sandstone aggregate exhibits three (3) times more creep than that made using limestone aggregate (Reference 7).

Like all solids, creep in concrete increases with temperature. It is caused by the diffusion of solid particles and moisture into the gaps of the material. At elevated and room temperatures, creep typically varies exponentially with time under constant load and increases linearly with increasing applied stress up to a ratio of stress over strength of about 0.5 (Reference 25). Creep also increases with increasing moisture content. However, it decreases with increasing maturity of concrete. A comprehensive study on the time-dependent deformation behavior of concrete when subjected to varying temperatures, moisture contents and load conditions similar to those found in prestressed concrete reactor vessels is available in Reference 26. A concrete of constant specified strength (about 6,000 psi) made with different coarse aggregates exhibits different creep strains (Reference 26). Other factors which influence creep in concrete at elevated temperatures include the size and shape of the structure and the duration and magnitude of the load. In massive and partially confined structures like the waste storage tanks an extended period of time is required for the moisture to diffuse out to the soil.

Figure 4 Stress-Strain Behavior of Lightweight Aggregate Concrete

(a) Lower Bound Data

(b) Upper Bound Data

Figure 5 Typical Stress-Strain Diagrams for Modeling Concrete

The effect of elevated temperatures on creep in concrete specimens for a period extending to one hundred (100) days is shown in Figure 6 (Reference 13). There is a steady increase in the creep rate until a stable moisture condition is reached. Limited experimental data (Reference 27) indicate that the rate of creep in sealed specimens is greater than that in unsealed ones by a factor of 0.5 - 5.0 at temperatures above 200°F. Mathematical relations to predict long term creep effects in concrete structures subjected to elevated temperatures have been developed in the literature. Two such relations are included here.

(a) Gross Model (Reference 28):

In this model, the strain as a function of the applied stress σ (psi), temperature T (°C), and time t (days) is given by

$$\epsilon(\sigma, T, t) = \epsilon_{initial} + \epsilon_{creep} \quad (1)$$

where the creep strain is given by the exponential function

$$\epsilon_{creep} = [1+b(\sigma, T)]^{-1} e^{2.3025a(\sigma, T)} t^{1+b(\sigma, T)} \quad (2a)$$

with

$$a(\sigma, T) = 0.20 + \log_{10}(\sigma/s) + [0.0028 - 0.001(\sigma/s)] T \quad (2b)$$

$$b(\sigma, T) = -0.55 - 0.25(\sigma/s) \quad (2c)$$

where s is the specified compressive strength. The initial strain appearing in Equation (1), which is developed after the load and temperature have been applied is given by

$$\epsilon_{initial} = (\sigma/E_c) g(T) \quad (3a)$$

where E_c is Young's modulus at room temperature and the function $g(T)$ is given by

$$g(T) = \begin{cases} 1.0 + 0.00833(T-30), & 30 < T < 60^\circ\text{C} \\ 1.25 - 0.0025(T-60), & 60 < T < 110^\circ\text{C} \\ 1.125 + 0.00349(T-110), & 110 < T < 350^\circ\text{C} \end{cases} \quad (3b)$$

Figure 6 Creep of Porphyry Aggregate Concrete at Various Temperatures

The Gross model is based on experimental data involving cylindrical specimens fabricated from conventional concrete with a specified strength of about 6000 psi. The specimens were loaded by three stress ratios, $\sigma/f'_c = 0.2, 0.4$ and 0.6 , and heated to various temperatures in the range $(20 - 400)^\circ\text{C}$. Additional details are available in Reference 28.

(b) Rashid Model (Reference 29)

In this model the creep strain, which is a function of the applied stress level, σ (psi), temperature, $T(^{\circ}\text{C})$ and time t (days) is computed from the equation

$$\epsilon_{\text{creep}} = [1.11 \times 10^{-4} (1 - e^{-0.23t}) + 3.8265 \times 10^{-7} t] \sigma e^{-(2194.44/T)} \quad (4)$$

The present model is incorporated in a computer code, ANACAP-U, which can be used as a pre-processor in standard finite element codes. It is partially based on experimental results obtained by Portland Cement Association (PCA) concerning the Hanford Waste Project. The PCA project involved creep of a concrete with a design strength of 4,500 psi for a two-year period. Three sets of loads and temperatures were used to generate the creep data. These sets are: (i) 1,500 psi load at 250°F , (ii) 500 psi load at 500°F , and (iii) 1,500 psi load at 350°F . Additional details are available in Reference 29.

2.5 Shrinkage

Shrinkage in concrete occurs because of drying and autogenous volume change. Several factors influence the amount of shrinkage including the type of aggregates, richness of mixture, consistency, etc. The magnitude of shrinkage generally increases with a temperature rise and the process is usually completed when the temperature reaches the level of about 105°C (221°F). For the temperature range of interest for this study, the rise in temperature does not increase the shrinkage in concrete by significant amounts as compared to room temperature. Therefore, for the high-level waste storage tanks *the shrinkage does not play a major role in assessing the structural behavior at elevated temperatures.*

2.6 Coefficient of Thermal Expansion

The coefficient of thermal expansion, α , represents the change in length per unit length per degree of temperature change. A relatively lower value of α means lower induced thermal stress and strain. In concrete, the magnitude of the coefficient is influenced by the type of aggregates and moisture condition. For typical concrete materials, the coefficient varies between $\alpha = 2.2 \times 10^{-6}$ to $3.9 \times 10^{-6}/^\circ\text{C}$ (i.e., 4.1×10^{-6} to $7.1 \times 10^{-6}/^\circ\text{F}$) with an

average value of $3.1 \times 10^{-6}/^{\circ}\text{C}$ (i.e., $5.6 \times 10^{-6}/^{\circ}\text{F}$) at room temperature (Reference 22). *The coefficient of thermal expansion remains approximately constant through a temperature rise of 300°C (572°F) and then increases with further elevation of temperature (Reference 30).*

2.7 Thermal Conductivity

Thermal conductivity is the ability of the material to conduct heat. It is measured by the rate of heat flux per temperature gradient. In concrete, the thermal conductivity, k , depends on its composition and degree of saturation. Concrete with high thermal conductivity is desirable because it permits rapid dissipation of the heat flux so that the thermal gradients through the thickness are minimum; this results in lower thermal stresses. *For a temperature level from ambient to 315° (600°F), the influence of temperature on thermal conductivity of concrete is insignificant and can be neglected (Reference 7).* For concrete with specific weights varying between 150 to 160 lb/ft³, typical values of the conductivity coefficient applicable to the waste storage tanks are $k = 0.75\text{--}2.13$ Btu/(ft.hr $^{\circ}\text{F}$) (i.e., 13-37 MW/(cm $^{\circ}\text{C}$) (Reference 22).

2.8 Thermal Diffusivity

The thermal diffusivity, h , measures the rate at which temperature changes take place within a material. Concrete aggregates with increasing values of diffusivity include basalt and limestone. *For the waste storage tanks, the rise in temperature has insignificant influence on the diffusivity.* Typical thermal diffusivity values for conventional concrete vary between 0.002 to 0.007 m²/hr (i.e., 0.02 to 0.07 ft²/hr) (Reference 22).

2.9 Specific Heat

The specific heat, c , is a measure of the heat capacity of a material and is related to the thermal conductivity, k , and thermal diffusivity, h , by the expression, $k = hc\rho$ where ρ stands for the mass density of the material. Experimental data indicate that the values of the specific heat of concrete increase slightly with rise in temperature as shown in Figure 7 (Reference 31).

3.0 EFFECT OF ELEVATED TEMPERATURE ON REINFORCING STEEL

A temperature rise in concrete also influences the properties of the embedded reinforcing steel (Reference 16). Moreover, since the structural capacity of the waste storage tanks is a direct function of the strength and other mechanical properties of the steel reinforcement, an assessment of these properties at elevated temperatures is required. Like concrete, the yield strength and modulus of elasticity of the steel will reduce with increasing temperatures. However, the reduction is not as detrimental as in

the concrete. This section summarizes the available data in the temperature range of interest on this topic.

3.1 Yield Strength and Modulus of Elasticity

Up to a temperature of about 371°C (700°F), experiments have shown that hot-rolled reinforcement steels show a *linear decrease in yield strength amounting to a maximum value of 15%* (Reference 16). More pronounced reductions are observed at higher temperatures. In the same temperature range, ambient to 371°C (700°F), insignificant variations are observed for the coefficients of thermal expansion and thermal conductivity in the reinforcing steel.

3.2 Bond Strength

Since concrete and reinforcing steel have different coefficients of thermal expansion, the bond strength and consequently the structural behavior could be influenced by a rise in temperature. Results presented in References 32 and 33 have indicated that for exposure to temperatures in the range ambient to 150°C (302°F) and under controlled laboratory conditions, *the loss in bond strength between the concrete and reinforcement steel amounts to less than 15%*. However, other limited data indicate that the residual bond strength is only 50% after subjecting the specimens (made from river gravel concrete with plain round steel bars) to 300°C (572°F) for 90 days and then cooling to room temperature before testing (Reference 34). Ribbed and deformed bars obviously experience less loss in resistance to pull out than plain bars.

4.0 THERMAL CYCLING

Thermal cycling causes progressive degradation of concrete with increasing number of cycles though most of the damage occurs in the first few cycles. Reference 8 indicates that cyclic heating generally causes greater reduction in mechanical properties than a single heating even at a relatively moderate temperature rise (65°C). At higher temperatures, 200 to 300°C (392 to 572°F), most of the damage is caused in the first few thermal cycles and is usually associated with a loss of bond between aggregates and the matrix (Reference 35). Apparently, the extent of damage depends on the aggregate type. In one test program (Reference 35), the breakdown of bond between aggregate and mortar was least for fireclay brick aggregates and greatest for limestone aggregates. Figure 8 shows the effects of temperature cycles on concrete specimens made with limestone (Reference 35). Effects of thermal cycling on the stress-strain behavior of sealed limestone specimens are shown in Figure 9 (Reference 21).

Figure 7 Variation of Specific Heat with Temperature

Figures 8 Effects of Thermal Cycling on Unsealed Limestone Concrete

Figure 9 Effect of Thermal Cycling on Sealed Limestone Aggregate Concrete

5.0 SUMMARY

An independent literature review has been performed to determine the influence of elevated temperatures from ambient to 315°C (600°F) on the behavior of concrete materials. The physical properties which control the behavior of concrete at elevated temperatures include the mechanical properties (compressive strength and modulus of elasticity), time-dependent properties (creep and shrinkage) and the thermal properties (coefficients of thermal expansion, conductivity, diffusivity and specific heat). Thermal cycling as well as the influence of elevated temperatures on the steel reinforcement is also investigated. Since many variables and test conditions control the results in the data base, upper and lower bounds of the degraded properties at the elevated temperatures of interest are summarized and presented in explicit forms. Such results are useful in assessing the effect of elevated temperatures on the structural behavior of the waste storage tanks. Also, they provide the technical basis for assessing the structural integrity of these tanks when subjected to thermal excursions in addition to other operating loads.

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