Experimental Needs in Structural Analysis of High Temperature Concrete

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Abstract
The needs of experimental data on concrete structures under high temperature, ranging up to about 370°C for operating reactor conditions and to about 900°C and beyond for hypothetical accident conditions, are described. This information is required to supplement analytical methods which are being implemented into the finite element code TEMP-STRESS to treat reinforced concrete structures. Recommended research ranges from material properties of reinforced/prestressed concrete, direct testing of analytical models used in the computer codes, to investigations of certain aspects of concrete behavior, the phenomenology of which is not well understood.

1. Introduction
The ultimate concern of nuclear reactor containment is to guard the public from radioactive contamination. Concrete containment integrity is challenged during accidental conditions when concrete is exposed to extraordinary pressure and/or temperature conditions. One such accident condition would be the spillage of hot materials which could limit the full strength capability of the concrete structure.

The finite element code TEMP-STRESS [1] is being developed at Argonne National Laboratory (ANL) to assess the concrete containment capability during thermal and mechanical attack. This code involves not only thermal stress considerations but also the prediction of temperature and moisture distribution within the structure. Much of the needed information at high temperatures of concrete are not known at the present time, and estimates are often made to enable analytical treatment of concrete structures.

In order to help the analytical development in the high-temperature environment, it is essential to understand concrete behavior under these conditions. Much of this is possible only by means of well controlled experiments. The required experimental data would increase the capability of the analytical tools thereby enabling optimal design of concrete containments. Thus, the intent of this paper is to describe the concrete data needed in the area of high temperature.

2. The TEMP-STRESS System of Codes
The analytical modeling of concrete structure experiencing high temperatures and other deleterious effects have evolved into several directions at ANL. The following set of codes,
comprising the TEMP-STRESS system, either have been developed or will be in the very near future.

2.1 Explicit Time Integration Version

The explicit time integration scheme has been adopted at ANL for stress analysis of concrete under high temperatures and relatively short durations (several hours or days). This explicit time integration scheme was supplemented by a dynamic relaxation procedure which provides a better means to treat static problems. Furthermore, thermal conduction calculations which determine the temperature in the structure were also incorporated using the explicit time algorithm.

In the explicit time algorithm, the maximum value of the time step is controlled by a stability criterion depending on the discretization of the model and material properties. The real time of the thermal conduction problem can be decreased (by increasing the diffusivity of concrete) making it compatible with the structural solution.

A simple elastic-plastic stress-strain constitutive relation is used to model concrete response up to failure. The von Mises loading surface is used with an associated flow rule. Failure of concrete is established by a four-parameter surface. The failure surface is used in the tension-compression and compression-compression range as a cap model to the von Mises loading surface. Reinforcement is modeled by a uniaxial elastic-plastic stress-strain relation. The effect of reinforcement is smeared throughout the area of the continuum concrete elements.

The code accepts stress-strain input for variable temperatures. Automatic interpolation between the supplied data is done internally. Variation of thermal properties and mechanical properties with respect to temperature and moisture content can be accommodated as well.

2.2 Implicit Integration Version

A newly developed constitutive relation [2], based on an efficient exponential algorithm of time integration, has been recently adopted with the TEMP-STRESS system. This formulation includes the conventional elastic and thermal strain contributions plus those due to creep, drying shrinkage, cracking, and volumetric strain resulting from pore pressure. It is based on a rheological model composed of a Maxwell chain unit, a cracking unit, and a unit reflecting shrinkage, dilatation, and volume changes. A continuous stress-strain relation is used for strain softening in tension and compression. This is facilitated by a relation between the stress and the component of cracking strain in the form of a secant modulus.

The analytical uniaxial relations are generalized for high temperatures and for multiaxial analysis. These will be used for comprehensive evaluations of concrete structures when subjected to high temperatures. When fully operational, this code will require viscoelastic properties input on basic creep, activation energy coefficients for creep rate and for hydration. Strain softening information for tensile cracking with variable temperature and moisture will be necessary.

2.3 Calculation of Moisture Distribution

The computer program TEMPOR2 [3] is used to calculate (and provide supporting information to structural codes) pore pressure, moisture content, and temperature in heated concrete. It does this by solving a system of governing differential equations for the coupled heat and moisture transfer in concrete. These equations are complemented by the
equation of state which relates the water content, pressure, and temperature. Saturated and unsaturated concrete are treated differently. For saturated concrete, the equation of state is based on the thermodynamic properties of water. In the unsaturated region, the capillary and adsorption phenomena in the pores are assumed to govern the equation of state; a semi-empirical equation of state has been developed for this case. The temperature is presumed to be a very important factor in the sorption relation, but more basic research is needed to ascertain this point. A very important part of this code is the relationship of permeability with temperature and pore pressure.

3. Recommended Research

The experimental data of concrete sought to help extend the range of analytical predictions to high temperatures can be divided into three distinct categories. These are described in the subsequent sections.

3.1 Material Properties

The stress-strain data for different temperatures and moisture conditions, derived from complete load-deflection diagrams of uniaxial specimens, would be the most important information for stress analysis. This information would include the modulus of elasticity, the compressive and tensile strengths, and the corresponding ultimate strains.

Another important set of input are the coefficients of thermal expansion and shrinkage due to change in moisture. These coefficients have been found to be stress-dependent and are indispensable in correlating analysis with experimental data. The importance of the stress-dependent coefficients was demonstrated in [4,5].

The contribution of creep at high temperature can be very significant to the overall deformation of a concrete structure. This effect is modeled by treating the aging of concrete by an equivalent hydration time, which is a function of temperature based on activation energy and also a function of pore humidity. Several coefficients involved in the calculation, such as the activation energy for hydration, activation energy for creep rate, and humidity effect on hydration, must be determined with respect to change in temperature and humidity.

Thermal properties of concrete are essential for temperature prediction. A fair amount of data have already been accumulated for the variation of thermal conductivity, diffusivity, and specific heat with respect to change in temperature. However, their variation with the change in humidity has not been well established. Testing of thermal properties with variable humidity and the effect of cracking would have to be realized.

Permeability plays an important part in the analytical prediction of moisture transport. It is essential to know the variation of permeability for the entire range of temperatures. Also important to determine is the permeability of concrete for water, air, and other gases which will be formed in concrete when heated. Microcracking induced by thermal gradient seems to be another key factor that causes the drastic increase of permeability. It is necessary to bring cracking into the calculation of permeability to obtain the correct moisture and pore pressure predictions. Because cracking of concrete in a high-temperature environment is unavoidable, a genuine effort must be made to extend the permeability testing up to and including the presence of cracks.
It has been shown that if fracture concepts are applied in concrete cracking, then the element-size dependency associated with the strength criterion can be avoided. It is, therefore, necessary to establish the dependence of fracture parameters, such as fracture energy and the characteristic size of the failure zone on temperature and also on the pore pressure. Fracture tests like Mode I, Mode II, Mode III, and specimen size effect have to be studied to understand the cracking phenomena which exists at high temperature.

3.2 Tests for Code Verification

The present predictions of cracking in the codes are based on uniaxial test data at room temperatures. With the presence of multiaxial stress conditions and high temperatures, the prediction of cracking becomes questionable. Furthermore, under thermal loading, the initiation of cracking may well be internal to the hot temperature boundary. It is necessary, therefore, to correlate the analytical cracking predictions with experiments.

From existing tests at high temperatures, it is established that the creep of concrete is greatly magnified. Typical results of steady-state creep tests show that the creep strain at 650°C is about 40 times higher than strain obtained at room temperature after five hours of compressive creep tests. It is also found in transient thermal creep tests that transient temperature causes a substantial increase of creep rates in the concrete. In many of these tests, a surge of creep strain is observed near 100°C. Some attribute this phenomenon to the influence of moisture content on the strength of concrete. Many, if not all, of these tests are carried out by using unsealed specimens which result in moisture loss during the test. Attention must be paid to restrict the movement of moisture which would increase the creep rates. Furthermore, direct tensile test data at high temperature is nonexistent. Since creep is known to be important, it would be essential to establish the nonlinearity of creep on stress. It is suspected that the assumption of linear dependence of creep on stress and its history is probably more in error at high temperatures than it is at room temperatures.

The interaction of concrete and reinforcement is especially questionable at high temperatures. For example, the bonding between reinforcement and concrete is quite strong at ambient temperatures, and at about 600°C it is practically non-existent. The bond strength between concrete and steel at high temperature has been intensively studied recently. All these tests, however, were performed under the hot condition of specified temperature. A more critical study is necessary by carrying out tests at transient high temperature. Furthermore, the effect of state of moisture of concrete on bond strength should be investigated.

The relationship of the degree of bonding with temperature must be determined so that the effect can be incorporated in the computations. Another remarkable feature of bond between steel and concrete at high temperatures is bond-relaxation under imposed constant slip, as well as the increase of slip under constant bond-stress (i.e., bond-slip creep). Strain softening phenomenon may also exist for the concrete reaction with the rib of reinforcing steel. Results on dowel action, the effect of shear resistance of reinforcement with the appearance of cracking, must also be obtained.

3.3 Phenomenological Tests

One important aspect of concrete analysis and correlation with experiment is the principle of superposition. The analysis usually assumes that the principle of superposition
holds and the variation of different parameters obtained from tests can be taken into account. In a classic case, known as the Pickett effect, it was shown that the principle of superposition does not hold. It is generally suspected that the principle of superposition in concrete may be in greater error at high temperatures than it is at ambient temperatures. A special effort must be made to resolve the applicability of superposition for concrete at high temperatures. This issue is very important because the known analytical methods hinge on this assumption. Therefore, transient thermal tests of concrete would be necessary to resolve the question of the degree to which the principle of superposition could be applied.

Spalling can have a serious effect on the stability of the structure due to the extensive removal of concrete from reinforcement, thereby reducing the cross-section. At the present, there is no generally accepted theory for the occurrence of spalling. The most fruitful investigation regarding concrete spalling may well involve the type of aggregate used in concrete [6]. If the culprit of spalling indeed is the type of aggregate used, then spalling would not be subject to analytical macroscopic simulation and prediction. Spalling could be predicted from the characteristics of aggregate alone. Otherwise, investigation of the hypothesis [7] where differential thermal expansion of the aggregate and cement under compressive stress causes cracking parallel with the surface and the internal pore pressure triggers the instability of material layers may be fruitful. In particular, the quantification of cracking due to differential thermal expansion between aggregate and cement would be very helpful in pinpointing the true cause of spalling.

4. The Testing Approach

It should be understood that testing at high temperatures also includes testing at room temperature. Test data at ambient temperature and moisture content would be used as reference for high-temperature data.

In the past, structural analysis has been done in a deterministic way where the material and loads were assumed to be known. However, increasing importance is being placed on the probability of occurrence of extreme values in many practical cases (e.g., nuclear accident evaluation), where the probabilistic approach is used. Regarding the structural safety design of nuclear containment, there exists uncertainty in the strength and deformation of concrete due to the stochastic nature of material properties [8]. Many statistical approaches [9,10] have been developed which are now applicable to structural analysis. In order to achieve a good prediction, work must be done to obtain the realistic material or strength distribution on which the calculation is based.

In planning the high-temperature tests, the stochastic behavior of concrete should be considered. A selective and representative number of tests would need to be repeated or carried out at the same time under identical conditions. This would be a worthwhile additional investment towards the assurance of safety of the nuclear containment.

5. Final Remarks

The simulation of concrete structural response at high temperatures has advanced quite far. Not only temperature, but also the disposition of moisture content has been brought into the structural calculations. The expansion and shrinkage of concrete with stress dependency have also been incorporated into the stress analysis. Creep simulations for aging
materials at very high temperatures have been introduced. Tensile softening is presently being considered to simulate concrete cracking. Compressive softening under variable temperature and moisture are also being introduced.

Much of the needed experimental data for the analytical models at the present time are somewhat incomplete. Hence, the resultant solutions possess an even lower degree of uncertainty. With the addition of new analytical developments, the uncertainties are being compounded. An impasse is being approached where the results of these efforts of the analytical development efforts will begin to diminish. In the limit, the analytical modeling could become meaningless without experimental backup.

Verification of certain computational models incorporated within the analytical formulations is indispensable. Much testing needs to be done at high temperatures and varied moisture contents. Only with good agreement between the experiment and analysis will confidence in the analytical codes be established. These codes would then be used to advance the design and assess the safety of nuclear reactor containment.

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