Creep, Shrinkage and Durability of Concrete and Concrete Structures

CONCREEP 7

September 12-14, 2005 – Nantes, France

Edited by
Gilles Pijaudier-Cabot
Bruno Gérard
Paul Acker

Hermes Science
PUBLISHING

Concrete creep at high temperature and its interaction with fracture: recent progress

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ABSTRACT. *Although the thermal effects on concrete creep and fracture have been studied for a long time, major progress has been taking place recently, facilitated by advances in computing power and driven mainly by problems of fire exposure of tall buildings and tunnel linings, decontamination of concrete walls and long-term radioactive waste storage. The paper first reviews the modeling concepts of concrete creep and drying shrinkage at elevated and high temperatures, and the thermal effect on fracture energy, process zone size and scale effects in quasibrittle failure. A recent generalization of microprestress-solidification theory for concrete creep at variable temperature is summarized and explained, and the dependence of brittleness and size effect on temperature is pointed out. Then attention is focused on a comprehensive computational model for estimating the feasibility of decontaminating from radionuclides a surface layer of concrete wall, a few millimeters in thickness, and optimizing the decontamination process. The decontamination is achieved by using a powerful microwave blast, of several seconds in duration, strong enough to ablate a thin surface layer of the concrete wall. Electromagnetic power dissipation is calculated on the basis of Maxwell equations and the rapid evolution of the temperature and pore pressure field within the concrete wall is simulated computationally. Due to order-of-magnitude jumps in the sorption isotherms of concrete and in the dependence of permeability on temperature, the finite volume (rather than finite element) method must be used, in order to enforce exact balance of water mass and heat. Short-time high-temperature creep is taken into account in calculating the thermal stresses produced by rapid heating, and the crack band model is used to capture the fracture mechanics aspects. It is concluded that ablation of the surface layer is driven mainly by high compressive stresses parallel to the concrete surface, while pore pressures serves only as a trigger of fracture but declines almost instantly as a crack begins to open. This conclusion is similar to that previously made for explosive spalling of building walls or tunnel linings in fire. The paper concludes by commenting on some profitable research directions.*

KEYWORDS: *Creep, fracture, decontamination, temperature.*

1. Temperature effect on concrete behavior

High temperatures in concrete can cause fracture or distributed cracking damage, as well as excessive or unstable deformation. These phenomena are of great concern for fire resistance of concrete buildings and tunnels (including fire resulting from terrorism), safety of nuclear reactor vessels and containments, use of concrete in radioactive nuclear waste storage and in chemical technology vessels, development of refractory concretes, performance and durability of massive concrete structures such as dams or thick walls of bridges and reactor containments susceptible to hydration heat. They are also important for some special modern processes such as accelerated microwave curing of concrete, development of rapidly hardening concrete, and ablation of thin surface layers from concrete floors and walls contaminated by radionuclides.

The main challenge in predicting the behavior of concrete structures is the formulation of constitutive and fracture laws. Without a realistic, physically based, mathematical formulation of these laws, structural stress analysis gives meaningless and misleading results. The main difficulty in formulating these laws lies in the thermodynamic coupling of viscoelastic stress-strain relation and damage-fracture model with the chemical aging processes, macroscopic water diffusion, local water diffusion through nanopores of hardened cement paste, thermodynamic equation of state for pore water consisting both of capillary water and adsorbed water, and possible ingress of deleterious chemical agents. Significant advances have been made since the dawn of computer era, but much still remains to be learned. The fastest progress in the modeling of heated concrete occurred in the U.S., Europe and Japan during 1965–1985, driven first by the design of nuclear power plants and then by nuclear waste storage. Today, research revival in the U.S. and Europe is motivated mainly by fire resistance of skyscrapers and tunnels, including fire due to terrorist attack, and in some other countries by the design of new large dams and new nuclear power plants.

There is a qualitative difference in the analysis of hygrothermal behavior at temperatures below and above 100°C. There are three basic reasons:

- Upon surpassing 100°C, the sorption-desorption isotherms of free pore water (capillary water and adsorbed water) develop a discontinuity (Fig. 1a) at the saturation point.
- The water permeability and diffusivity of concrete increases by almost two orders of magnitude as 100°C is surpassed (Fig. 1b).
- While below 100°C the diffusion equation for water transport has a negative sink term describing the rate of conversion of free pore water into water chemically combined in the calcium silicate hydrates, above 300°C there is a significant positive sink term describing the release of hydrate water as free water in the nanopores and capillary pores of concrete. This goes along with the fact that chemical reactions of hydration of cement, responsible for the aging property of creep and the gain of strength with time, progress only below 100°C (and slightl

more if water is pressurized), while above 300°C these reactions get reversed and cause dehydration, accompanied by negative aging in the creep law and a significant loss of strength.

One consequence of the aforementioned discontinuities is that the finite element approach to coupled heat and moisture transport at high temperatures breaks down. The reason is the development of sharp moving fronts of discontinuity between oversaturated and almost dry concrete. To achieve stable numerical simulation of such behavior, it is necessary for the computational model to exactly satisfy the mass balance condition within each control volume. Such exact mass balance is imposed in the finite volume method, originally developed for simulating the movement of solidification front in molten magma and of the phreatic surface in groundwater flow (Fig. 1c). In the early times (until about 1985), prior to the adoption of finite volume method, the finite element simulations of water transport and pore pressure in concrete at high temperature were plagued by development of unstable pressure oscillations near the fronts of discontinuity. The cause of these oscillations is intuitively clear upon noting in Fig. 1(a) that, just above the saturation point ($h > 1$), a very small error in pore water content w will cause a very large error in relative vapor pressure h (while below the saturation point it will cause only a small error in h).

The present paper attempts a (non-exhaustive) review of the main modeling problems, with emphasis on the results achieved at the author's home institution (see bibliography). The paper is focused on some new, recently published, results regarding the removal of thin surface layers of concrete walls by intense microwave radiation and on the coupling of creep and thermomechanical processes in the porous nanostructure of hardened cement paste. Admittedly, the appended bibliography is far from balanced or complete, but a detailed exposition of classical results, with a very broad review of literature up to 1994, is available in the book by Bažant and Kaplan (1996). The proceedings of SMiRT conferences during the 1970s and 1980s are the largest single source on the classical results.

2. Explosive thermal spalling

The explosive thermal spalling, which was first observed by Harmathy in normal concrete exposed to fire, has recently been identified as a major problem for high strength concretes. It is of great concern for survival of the core of a tall building in the case of a fire like that which doomed the World Trade Center. The explosive thermal spalling is a brittle failure, for which two different explanations have been offered and intensely debated in recent times:

- development of a high pore pressure caused by oversaturation in the region of concrete just in front of the heated zone (called the "moisture clog" by Harmathy); and
- brittle fracture and delamination buckling caused by compressive biaxial thermal stresses parallel to the heated surface.

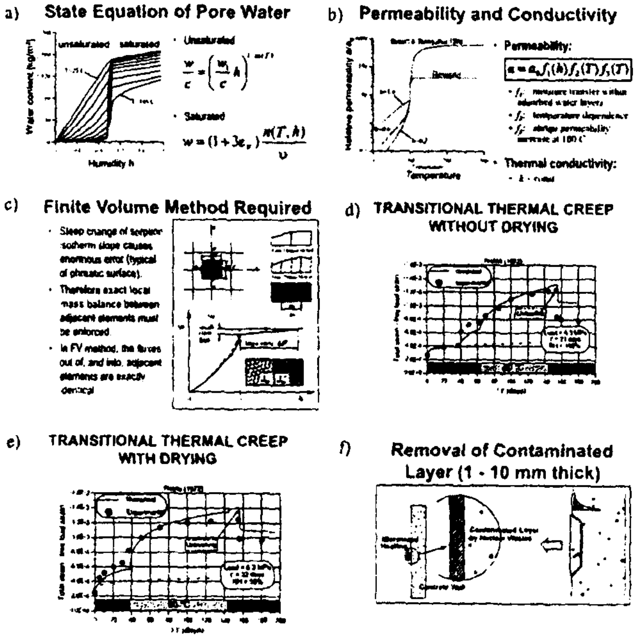

Figure 1. *a)-e) Basic thermal effects in concrete; f) Decontamination scheme*

On careful scrutiny it appears that the first mechanism, that is, the pore pressure, is not the major one. Pore pressures exceeding about 10 to 20 atm have never been measured, even if the thermodynamic equation of state of pore water at constant volume indicates pressures an order-of-magnitude higher. Nevertheless, the first mechanism, that is, the development of high pore pressure due to 'moisture clog', could contribute to the triggering of fracture.This mechanics cannot be neglected because recent experiments revealed that the explosive thermal spalling occurs only in wet concrete, in which over-saturation by water can develop. A high pore pressure a certain depth below the heated surface helps to trigger the opening of a crack. When the crack starts to open, the volume available to the water vapor and liquid within the crack is suddenly increased by several orders of magnitude. This means that the water contained within the crack is suddenly forced to expand enormously. Because additional water cannot flow into the crack from the surrounding concrete suddenly, the pore pressure must immediately drop to nearly zero, as soon as the crack starts opening up. The time required for a significant amount of water to flow into the crack from the surrounding concrete, and thus to repressurize the crack, is far longer than the duration of the explosive spall.

From this consideration, it appears that the pore pressure can only serve to trigger a crack but not to drive the explosion, not to force large dynamic opening of the crack. That must be caused by another supply of energy, which is of course available in the form of the potential energy of the thermal compressive stresses parallel to the heated surface. Such stresses can cause a splitting crack parallel to the surface, and a conical shear crack whose slip can expel a concrete plug (Fig. 1f). The slight initial deformation due to pore pressure may provide the imperfection that causes delamination buckling of the slab separated by the crack.

In this context, it is not surprising at all that the high strength concrete appears to be much more prone to explosive spalling than the normal strength concrete. The high strength concrete can store more strain energy, due to its higher strength, and is known to be far more brittle. The size effect method of the measurement of fracture energy revealed that an increase of the strength of concrete from 5,000 to 14,000 psi was accompanied by no increase in the fracture energy, G_f, and a decrease of the fracture process zone size, c_f (Bažant and Planas 1998, Bažant 2002).

It might be thought that fiber reinforcement should mitigate the propensity to explosive thermal spalling, but curiously the opposite is indicated by experiments (of limited scope, though). This might perhaps be explained by the fact that fiber reinforcement initially stabilizes a small enough developing crack until a large enough crack, driven by a greater stored energy, becomes unstable.

Thus it appears imperative to analyze the explosive thermal failure of high strength concrete on the basis of fracture mechanics. This of course further implies that the explosive thermal spalling should exhibit a pronounced size effect, which is observed in all brittle failures of concrete. Experiments checking the size effect in explosive thermal spalling ought to be conducted.

There are two curious phenomena not yet adequately explained physically. One is the aforementioned small value of measured pore pressures in saturated heated concrete, much smaller than indicated by the thermodynamic equation of state of bulk water. The explanation is complicated by the lack of understanding of the thermodynamic equation of state of hindered and unhindered adsorbed water layers. It may be that the pore space available to bulk free water expands upon heating (which may be due to redistribution of low and high density regions of calcium silicate hydrates, as recently suggested by F.J. Ulm). Another phenomenon that has been hard to explain physically is the enormous increase of permeability upon heating above 100°C, at no appreciable change of overall porosity. In the 1970's, the writer vaguely speculated that the microstructure changes so as to eliminate nano-pore necks on flow passages trough the cement paste. Recent work of F.J. Ulm at M.I.T. gives a clear explanation of this phenomenon: the low density C-S-H gets converted to high density C-S-H, which therefore shrinks, and this creates free space serving as a continuous capillary passage.

2.1. *Microprestress-solidification theory for aging viscoelasticity at variable temperature and humidity*

To separate the viscoelasticity of cement gel, the solid constituent of the hardene portland cement paste, from the chemical aging caused by the long-time solidificatio process of calcium-silicate hydrates characterized by the growth of volume fraction of hydration products in concrete, the solidification theory has been developed (Bažant and Prasannan 1989). This separation permits the viscoelastic constituent to be considered as non-aging, which yields a great modeling simplification. In this theory, the temperature dependence of the rates of creep and of volume growth is characterized by two transformed time variables based on the activation energies of hydration and of creep.

A further simplification and unification of the creep theory is obtained by the concept of microprestress, which achieves that the long-term aging and all the transient hygrothermal effects on creep simply become different consequences of one and the same physical phenomenon, the microprestress build-up and relaxation (Bažant and Hauggaard et al. 1997, Bažant and Cusatis 2004). The microprestress, which is independent of the applied load, is initially produced by incompatible volume changes in the microstructure during hydration, and later builds up when changes of moisture content and temperature create thermodynamic imbalance between the chemical potentials of vapor and adsorbed water in the nanopores of cement gel. This simultaneously captures three basic phenomena: (1) the creep decrease with increasing age at loading in mature concrete, in which the growth of the volume fraction of hydrated cement has already ceased; (2) the drying creep, i.e., the transient creep increase due to drying (Pickett effect) which overpowers the effect of steady-state moisture content (i.e, less moisture—less creep); and (3) the transitional thermal creep, i.e., the transient creep increase due to temperature change (Fig. 1d,e).

The microprestress relaxation is a nonlinear and temperature dependent process. The separation of aging makes it possible to formulate an efficient time-step numerical integration algorithm, based on reducing the creep law to a system of first-order differential equations in time for internal variables. Extensive finite element simulations, in which the apparent creep due to microcracking has been taken into account separately, has been used in inverse analysis to identify the constitutive parameters, and a satisfactory agreement with a broad range of test data on creep at variable temperature and humidity has been achieved.

2.2. *Ablation of contaminated surface layer by microwave heating*

In nuclear laboratories, there are many acres of concrete penetrated to a depth of 1 to 10 mm by radionuclides of strontium, cesium, cobalt and uranium. The contamination is very light, but nevertheless potentially harmful for humans after decades of exposure. Efforts to remove the surface layer are under way. One innovative approach is to decontaminate the concrete walls and floors by spalling the contaminated surface layer by rapid heating achieved by means of a powerful microwave blast of about 10 s in duration (Figs. 1f, 2a-f).

Analysis of the most effective approach must deal with two aspects of the problem: (1) The hygrothermal aspect, which consists in calculating the evolution of the temperature and pore pressure fields, and (2) the fracturing aspect, which consists in predicting the stresses, deformations, stored energy release and fracturing. The former can be assumed to be independent of the latter, as an approximation, but the latter is coupled to the former. The heat and moisture transfer governing the temperature and pore pressure fields induced by the decontamination process has been numerically simulated by an improved form of Bažant and Thonguthai's (1978) model for heat and moisture transfer in concrete at high temperatures.

The rate of the distributed source of heat due the interaction of microwaves with the water contained in concrete has been calculated from Maxwell's equation on the basis of the standing wave normally incident to the concrete wall. Since the microwave time period is much shorter than the time a heating front takes to propagate over the wavelength of microwave, and since concrete is heterogeneous, the Ohmic power dissipation rate may be averaged over both the time period and the wavelength, in agreement with Lambert's law. The reinforcing bars parallel to the surface are considered to block microwave passage. Microplane constitutive model M4 is used for realistic simulation of triaxial nonlinear behavior and fracturing.

The mathematical formulation consists of (1) a model for heat generation in the bulk of concrete by microwave power dissipation, (2) a model for heat and moisture transfer with build-up of pore pressure, (3) a constitutive model for nonlinear triaxial behavior and fracturing of concrete, and (3) numerical algorithm. The aim of numerical simulation is to determine the required microwave power and predict whether and when the contaminated surface layer of concrete spalls off. The effects of wall thickness, reinforcing bars, microwave frequencies and microwave power can thus be studied numerically.

The computations confirm that the wave frequency, power and efficiency of the microwave applicator are key factors for the decontamination process (Fig. 2c). For the maximum power efficiency considered, the heat generation per unit volume of the wall is almost three-times greater than it is for minimum efficiency. Therefore the efficiency should be accurately measured. The calculations confirm that a 5 mm thick surface layer of typical concrete can be spalled off within about 10 seconds of microwave heating of frequency 18.0 GHz and power 1.1 MW/m^2.

Computations further show that the thickness of concrete wall has a negligible effect on the evolution of pore pressure and temperature. This is explained by the short heating duration. The electromagnetic power carried by the microwaves is found to be almost exhausted when the waves reach the depth of the reinforcing bars in typical concrete structures. Therefore, the same decontamination process can be used for both unreinforced and reinforced concrete walls.

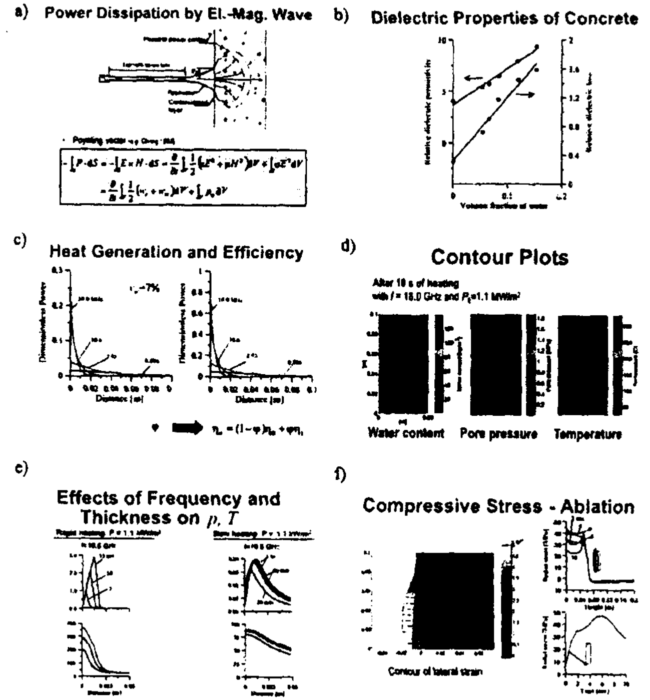

Figure 2. *Microwave induced ablation of surface layer of concrete*

Computer simulations confirm that the pore water pressure caused by heating is not a major factor. The main cause of spalling is found to be high compressive stress along radial lines emanating from the heated zone, and high tensile stress along circumferential lines, produced by thermal expansion of the heated zone (Fig. d,e,f).

2.3. *Cohesive fracturing in nuclear containment and chunnel fire*

In assessing the damage due to hydration heat, particular attention should be paid to crack spacing. The most important characteristic of cracking is the crack opening width, which is determined by the crack spacing. The estimation of crack spacing requires taking into account what is known about the the stability of parallel crack systems. As previous studies showed, the spacing of open cracks increases roughly in proportion to the crack depth unless there is a strong and dense reinforcing mesh. This property needs to be embedded in the cracking model based on the smearing of cohesive cracks (Bažant Kim and Jeon 2003).

In another study, the fire in the "Chunnel", which destroyed a part of the concrete tunnel rings by thermal spalling, was simulated (Ulm et al. 1997). The aim of this study was (1) to evaluate the effect of thermal damage (loss of elastic stiffness) and thermal decohesion (loss of material strength), and (2) to check whether restrained thermal dilatation can explain the thermal spalling observed. The thermal damage at temperatures up to 700° C resulted mainly from the dehydration of concrete, which degraded all the mechanical properties of concrete. The dehydration-process was described by a kinetic law which relates the degradation to the dehydration rate.

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