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A Numerical Investigation of the Influence of Pore Pressures and Thermally Induced Stresses for Spalling of Concrete Exposed to Elevated Temperatures

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Abstract

Although in past years extensive experimental and numerical investigations have been carried out in order to gain better understanding of the phenomenon of spalling of concrete exposed to elevated temperatures, there still exists controversy as to the driving mechanisms of spalling. This paper presents a numerical investigation aimed at determining the significance of pore pressures and thermally induced stresses for spalling of a concrete. A mathematical model for the coupled hygro-thermal-mechanical-damage behaviour of the concrete is briefly presented together with its finite element solution procedure. Although not intended for design purposes at this stage, the model provides insight into the interactions of the physical process that occur when concrete is exposed to elevated temperatures and can provide impetus for further development of numerical solutions for accurate prediction of spalling. The model is here employed to investigate the significance of pore pressures and thermally induced stresses for spalling of concretes with different initial permeabilities and moisture contents through the numerical simulation of a wall and a square column exposed to fire. The numerical results reveal that thermally induced stresses are a primary factor in causing damage and hence spalling in concrete, while pore pressures, at most, play a secondary role.

KEY WORDS: *concrete, spalling, hygro-thermal-mechanical, damage model.*

1. Introduction

On close inspection concrete is seen to be a multi-phase material, consisting of a porous solid skeleton, liquid (and adsorbed) water and a mixture of gases, typically consisting of water vapour and dry air. When concrete elements are exposed to elevated temperatures, numerous complex phenomena will occur, such as heat conduction and convection, transport of liquid water and gases, evaporation of liquid water in pores, dehydration of cement paste and thermal expansion of the solid skeleton. All of these processes will result in a build-up of pore pressures and of thermally induced stresses inside the concrete elements, which, if high enough, could lead to the fracturing and loss of material from the surface of the concrete elements, i.e. spalling. At the same time, the problem is exacerbated as the increase in temperature results in the chemical and mechanical degradation of the concrete, causing the development of micro-fractures, reducing its elastic stiffness and strength, and changing various other properties including its fracture energy, thermal conductivity, permeability, porosity, etc.

Spalling, which has been observed to occur in various explosive or non-explosive forms, can ultimately threaten the integrity of the overall structure if sufficient cross-section is lost from structural members or if reinforcing steel is exposed directly to heat as cover material is lost.

In past years, extensive experimental studies have been conducted in order to gain a better understanding of the driving mechanisms underlying spalling behaviour, e.g. [1-4], and at the same time, various numerical models have been presented for simulation of these complex phenomena at different levels of simplification, e.g. [5-11]. Based on this previous work, consensus has generally been achieved that spalling is influenced by a combination of heating rate, section shape and size, moisture content, permeability and restraint of concrete structure. However, there still exists controversy over the main driving mechanism of spalling. Some researchers state that pore pressure is

the most important factor (e.g. [4, 12-14]) while some emphasise the significance of thermally induced stresses (e.g. [15-18]), and others believe spalling is jointly caused by these two factors (e.g. [2, 3, 19]).

In this paper, a coupled hygro-thermo-mechanical-damage finite element model capable of capturing the complex behaviours described above is employed to investigate the significance of pore pressures and thermally induced stresses for the development of damage and spalling in concrete. The mathematical formulation, together with its finite element solution procedure is briefly described before the results of various numerical experiments are presented. Taking the examples of a concrete wall and a square column exposed to fire, the damage development for concretes with different combinations of initial permeabilities and moisture contents was analysed. These numerical experiments allowed the effects of pore pressures and thermally induced stresses to be isolated and the relative significance of each to be determined.

Specifically this work sought to examine the three commonly cited theories: that spalling is caused by thermally induced stresses (developed through differential thermal expansion resulting from thermal gradients); that spalling is caused by macro-scopic pore pressures associated with the ‘moisture clog’ concept (where gas pressures build up as they are prevented from dissipating due to the condensation of moisture in cooler parts of the concrete ‘clogging’ the pore system)¹; or that spalling is caused by a combination of both of these processes.

In conducting these analyses and drawing conclusions from the results, it is recognised that, as with most models for concrete, the macro-scopic formulation of the model represents a simplification of the true heterogeneous nature and micro-scopic processes that may occur. However, the model represents the state-of-the-art for concrete at elevated temperatures and it is argued that since numerous

¹ It should be noted that the build up of pore pressure due to the macro-scopic ‘moisture clog’ phenomenon (extensively cited in the literature) is considered a separate issue to the micro- or mesoscopic build up of pressure in closed pores. Although it has been suggested that these may be associated with the occurrence of explosive spalling, as will be clear from the following, they are beyond the scope of this work to consider.

physical and chemical aspects of concrete, (such as heat and mass transfer of solid, liquid and gas phases, phase changes between liquid water and vapour, hydration/dehydration of chemically bound water, free thermal expansion, load induced thermal strain, thermal and mechanical degradation of material properties, coupled hygro-thermo-mechanical interaction of transport properties and the thermal dependencies of more than 20 material properties), are represented in the model [9, 10], and as many as possible of these are modelled physically and mechanistically, rather than empirically, the model presented here may be considered a comprehensive tool with which to study the macroscopic behaviour of concrete exposed to elevated temperatures.

The model is part of a very small group of models for concrete at elevated temperatures published to date that consider three phases in a fully coupled manner [5, 10, 20, 21], which has been shown to be critical in capturing accurately the behaviour of concrete at elevated temperature (e.g. [22]). Other Authors have also published in this area (e.g. [11, 23-25]) but their models are either less sophisticated or tend to be based on the formulations developed in [5, 8, 10].

These three phase coupled models, although similar, differ in a number of key ways concerning the primary formulations, state equations and constitutive laws employed. Crucially, where the model used in this work differs particularly from others is in its consideration of mechanical failure. While other models either make no attempt to model mechanical failure of the material (e.g. [20]) or make assumptions about the occurrence of spalling based on pore pressures (e.g. [11]) or stress criteria (e.g. [15]), this model makes no prejudgement of the processes driving spalling. Furthermore, the Modified von Mises damage formulation employed in the model has been demonstrated to be better suited to reproducing the patterns of damage observed in spalling than other formulations [26]. Thus it may be considered that the model is well placed to shed light on the process occurring during the spalling process.

Nonetheless, it should be made clear that it is not intended, at this stage, that this model be used as a tool for design or quantitative analysis, but as a numerical laboratory through which a better understanding of the interactions of the various processes may be gained, with which to identify both what can and cannot be explained at this level of representation and to provide inspiration for future development of numerical solutions for the spalling phenomenon.

2. Mathematical model

In the mathematical formulation, concrete is treated at a macro-scopic level, as a multiphase system consisting of solid, liquid and gas phases. Micro-scopic phases, properties and behaviours are considered as overlapping continua averaged across a representative elemental volume (REV) [27]. The solid skeleton is assumed to develop isotropic elastic-damage deformations under mechanical and thermal loadings. The liquid phase consists of free liquid water in pores and adsorbed water physically bound to the surface of solid skeleton. The dehydrated water is considered as a part of free liquid water since chemically bound water is assumed to be initially released as liquid water. The gas phase is a mixture of dry air and water vapour, both of which are assumed to behave as ideal gases. Most of the material properties are variable (typically, either directly or indirectly, as a function of temperature). The complete description of the material properties can be found in [9, 10, 28]. Herein, only the governing equations, aspects of the transport equations, the mechanical constitutive equations and the damage model, which are the essential parts of the mathematical model, are briefly described.

2.1 Governing equations

The model consists of four governing equations (Eqs. (1) - (4)) defining the conservations of mass of dry air, mass of moisture (i.e., vapour and liquid), energy [9] and linear momentum [5], respectively.

$$\frac{\partial(\varepsilon_G \tilde{\rho}_A)}{\partial t} = -\nabla \cdot \mathbf{J}_A \quad (1)$$

$$\frac{\partial(\varepsilon_G \tilde{\rho}_V)}{\partial t} + \frac{\partial(\varepsilon_L \rho_L)}{\partial t} - \frac{\partial(\varepsilon_D \rho_L)}{\partial t} = -\nabla \cdot (\mathbf{J}_V + \mathbf{J}_L) \quad (2)$$

$$(\underline{\rho C}) \frac{\partial T}{\partial t} - \lambda_E \frac{\partial(\varepsilon_L \rho_L)}{\partial t} + (\lambda_D + \lambda_E) \frac{\partial(\varepsilon_D \rho_L)}{\partial t} = \nabla \cdot (k \nabla T) + \lambda_E \nabla \cdot \mathbf{J}_L \quad (3)$$

$$\nabla \cdot (\boldsymbol{\sigma}' - \eta P_{Pore} \mathbf{I}) + \mathbf{b} = 0 \quad (4)$$

where, ε_θ is the volume fraction of a phase θ ($\theta = L, V, A, G, D$ refer to liquid water, water vapour, dry air, gas mixture and dehydrated water phases, respectively), ρ_θ is the density of a phase θ , $\tilde{\rho}_\theta$ the mass of a phase θ per unit volume of gaseous material, $\mathbf{J}_\theta$ the mass flux of a phase θ , $\underline{\rho C}$ the heat capacity of concrete, k the effective thermal conductivity of concrete, λ_E and λ_D are the specific heats of evaporation and dehydration, $\boldsymbol{\sigma}'$ is the Bishop's stress (also known as the effective stress in geomechanics), $\mathbf{I}$ the identity matrix, η is the Biot coefficient, P_{Pore} the pore pressure and $\mathbf{b}$ the body force.

2.2 Fluid transport equations

In the concrete, the liquid water flow is assumed to be driven by the pressure gradient under Darcy's law, while the gas flow is assumed to be driven by both the pressure gradient under Darcy's law and the concentration gradient under Fick's law. Therefore, the mass fluxes of dry air ($\mathbf{J}_A$), water vapour ($\mathbf{J}_V$) and liquid water ($\mathbf{J}_L$) per unit area of concrete are given by Equations (5) - (7).

$$\mathbf{J}_A = \varepsilon_G \tilde{\rho}_A \left(-\frac{k_g K K_G}{\mu_G} \right) \nabla P_G - \varepsilon_G \tilde{\rho}_G D_{AV} \nabla \left(\frac{\tilde{\rho}_A}{\tilde{\rho}_G} \right) \quad (5)$$

$$\mathbf{J}_V = \varepsilon_G \tilde{\rho}_V \left(-\frac{k_g K K_G}{\mu_G} \right) \nabla P_G - \varepsilon_G \tilde{\rho}_G D_{AV} \nabla \left(\frac{\tilde{\rho}_V}{\tilde{\rho}_G} \right) \quad (6)$$

$$\mathbf{J}_L = \varepsilon_L \rho_L \left(-\frac{KK_L}{\mu_L} \right) \nabla P_L \quad (7)$$

where, K is the intrinsic permeability of the dry concrete, K_θ , μ_θ and P_θ are the relative permeability, dynamic viscosity and pressure of the phase θ , k_g is the gas-slip modification factor and D_{AV} is the coefficient of diffusion for the dry air/water vapour mixture within the porous concrete.

2.3 Mechanical constitutive equations

The total strain ($\boldsymbol{\varepsilon}$) of the solid skeleton is considered to consist of elastic strain ($\boldsymbol{\varepsilon}^e$), free thermal strain ($\boldsymbol{\varepsilon}^{ft}$) and load induced thermal strain ($\boldsymbol{\varepsilon}^{lits}$), i.e.,

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^{ft} + \boldsymbol{\varepsilon}^{lits} \quad (8)$$

The free thermal strain rate is calculated by way of Equation (9):

$$\dot{\boldsymbol{\varepsilon}}_{ij}^{ft} = \alpha \dot{T} \delta_{ij} \quad (9)$$

where, α is a non-linear, temperature dependent coefficient of thermal expansion [10, 28], $\dot{T}$ is the rate of temperature change and δ_{ij} is the Kronecker delta.

The load induced thermal strain rate is calculated as shown in Equation (10):

$$\dot{\boldsymbol{\varepsilon}}_{ij}^{lits} = \frac{\beta}{f_c^0} \left((1 - \nu_c) \sigma'_{ij} - \nu_c \sigma'_{kk} \delta_{ij} \right) \dot{T} \quad \text{for } \dot{T} > 0 \quad (10)$$

where, β is the coefficient of load induced thermal strain, f_c^0 is the initial compressive strength, ν_c is the lateral component of the load induced thermal strain (similar to Poisson's effect) and σ'_{ij} is the negative (compressive) projection of the Bishop's stress tensor, σ'_{ij} [10, 28].

The fracture and the reduction of stiffness of the concrete are accounted for by an isotropic damage model as described in the following, where a scalar damage parameter, Λ , is used to represent the failure state of the concrete, i.e. $\Lambda = 1$ indicating complete failure, while $\Lambda = 0$ indicates intact

material. Assuming that the solid skeleton undertakes elastic-damage deformation and adopting the Bishop's stress concept, the stress-strain relationship can be written as

$$\boldsymbol{\sigma}' = (1 - \Lambda) \mathbf{D}_0 : \boldsymbol{\varepsilon}^e \quad (11)$$

where, $\boldsymbol{\sigma}'$ is the Bishop's stress, consisting of elastic stress ($\boldsymbol{\sigma}$) and pore pressures (P_{pore}), i.e.,

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} + \eta P_{pore} \mathbf{I} \quad (12)$$

where, η is the Biot coefficient, $\mathbf{I}$ is the unity matrix, $\mathbf{D}_0$ is the initial elasticity matrix, and Λ is the scalar damage parameter, which can be further expressed as:

$$\Lambda = 1 - (1 - \omega)(1 - \chi) \quad (13)$$

where, ω is the mechanical damage parameter, accounting for the loss of the elastic stiffness caused by the micro-fracturing of concrete that develops under loading and χ the thermal damage parameter, accounting for the reduction of the elastic stiffness due to thermally induced degradation of the cement paste. Considering that the occurrence of spalling, whether explosive or non-explosive spalling, is always accompanied by fracture of the concrete, it can be shown that the mechanical damage parameter, ω , can be used as a straightforward indicator for assessing the development of spalling (although it recognised that a continuous scalar representation cannot fully reflect the discrete and potentially explosive nature of the spalling).

The thermal damage parameter, χ , is defined as:

$$\chi = 1 - \frac{E(T)}{E_0} \quad (14)$$

where, E_0 is the Young's modulus at a reference temperature (normally 20 °C) [5].

The mechanical damage parameter, ω , is defined as:

$$\omega = 1 - \frac{\kappa_0^{md}(T)}{\kappa^{md}} e^{-\gamma(T)(\kappa^{md} - \kappa_0^{md}(T))} \quad (15)$$

where, κ_0^{md} , which defines the threshold for the onset of fracture, is a function of the tensile strength, $f_t(T)$, and elastic modulus, $E(T)$, i.e.,

$$\kappa_0^{md} = \frac{f_t(T)}{E(T)} \quad (16)$$

where, $f_t(T)$ and $E(T)$ are both temperature dependent [28].

$\gamma(T)$ is the softening parameter, representing brittleness of the concrete. The higher $\gamma(T)$, the more brittle is the concrete. κ^{md} is the mechanical damage history parameter and reads as:

$$\kappa^{md} = \max\{\kappa_0^{md}, \max(\bar{\varepsilon})\} \quad (17)$$

where, $\bar{\varepsilon}$ is the equivalent strain measure. As described in [29] a modified von Mises definition is adopted for $\bar{\varepsilon}$, as shown below:

$$\bar{\varepsilon} = AI_1 + \sqrt{A^2 I_1^2 + BJ_2} \quad (18)$$

where, I_1 and J_2 are the first and second invariant of the strain tensor and the deviatoric strain tensor respectively, and which can be written as:

$$I_1 = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \quad (19)$$

$$J_2 = (\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 \quad (20)$$

where, ε_1 , ε_2 and ε_3 are principal strains.

The coefficients A and B in Eq. (18) are defined as

$$A = \frac{(g-1)}{2g(1-2\nu)} \quad (21)$$

$$B = \frac{3}{2g(1-2\nu)} \quad (22)$$

where, g is the ratio between the compressive and tensile strength and ν is the Poisson's ratio.

2.4 Numerical Solution

Finally, for solution of the governing equations (1) - (4), the initial and boundary conditions must be defined. The initial conditions specify the full fields of displacements ($\mathbf{u}$), temperature (T), gas pressure (P_G) and vapour content ($\tilde{\rho}$) at time instant $t = 0$ and the boundary conditions for the primary variables can be of Dirichlet, Neumann or Cauchy types.

The governing equations are discretised in space using the standard finite element approximation, with the chosen primary variables of displacements, $\mathbf{u}$, temperature, T , gas pressure, P_G , and vapour content, $\tilde{\rho}_v$, and in time by a generalised mid-point finite difference scheme. Details of the formulation may be found in [9, 10]. The numerical solution procedure was implemented in FEAP [30].

2.5 Model Validation

The model described here has been applied extensively to numerous problems ranging from isothermal drying, through problems related to the relatively slow heating of nuclear power plant structures, to problems related to rapid fire loading, such as those detailed in this work.

The validity of the model and its ability to accurately represent the multi-phase, macroscopic behaviour of concrete exposed to elevated temperatures has been specifically demonstrated in [10] and [26] where it was shown capable of accurately capturing experimentally measured mass losses, moisture movements, magnitudes and shapes of temperature and gas pressure profiles in time and with depth from the heated surface in different concretes, as well as capturing qualitatively and quantitatively, in terms of time and depth of occurrence, the development of spalling in walls and columns. The necessity of a fully coupled hygro-thermo-mechanical formulation in order to capture

this behaviour was also demonstrated in that poor results were obtained when the model was decoupled.

It is therefore considered that the model employed here is highly suitable for the purposes of the work reported where underlying coupled hygro-thermo-mechanical phenomena are considered key to understanding the overall behaviour.

3. Numerical analyses

For numerical investigation of the roles played by thermally induced stresses and pore pressures in the development of concrete damage and thus the occurrence of spalling, two typical concrete elements, a concrete wall and a square concrete column, both exposed to fire on all sides, were herein studied. For each of these a number of numerical experiments were conducted as described in the following.

It is well understood that the magnitude of the pore pressures built-up in the concrete during heating is significantly influenced by the permeability and moisture content of the concrete and that, through the effective stress concept, these pressures could theoretically result in the development of damage in the concrete. To investigate the significance of this behaviour several combinations of initial permeabilities and relative humidities were used in the analyses, in order to produce different levels of pore pressure peaks (i.e., low, medium and high levels of pore pressures). The range of permeabilities chosen for these analyses are typical of those reported in the literature and are representative, at their high end, of normal strength concretes, with relatively open pore structures, and at their lower end, of the dense pore structures characteristic of high performance concretes.

In addition, to isolate the contributions of thermally induced stresses from those of the pore pressures a parallel set of analyses were conducted in which the pore pressure term, P_{pore} , was switched off in the momentum equation (Eq. (4)). It may be noted that this could not be done in a physical experiment and represents an advantage of the numerical modelling approach.

Table 1 summarises the initial permeabilities, relative humidities and on/off options of the P_{pore} term as used in the various simulation cases. Typical initial values for other key parameters were chosen from the literature, and set as shown in Table 2 for all of the simulations.

Furthermore, in all of the simulations, the concrete elements are assumed to be exposed to the ISO834 standard fire, the far-field temperatures of which can be expressed as:

$$T_{\infty} = 20 + 345 \log_{10}(8t + 1) + 273.15 \quad (23)$$

where, t is time in minutes.

3.1 Concrete wall exposed to fire

For the first set of analyses a concrete wall exposed to fire on both sides was modelled as a one-dimensional problem in central-plane symmetry, as illustrated in Figure 1. As can be seen, one (left) side was constraint-free and heated by the standard ISO834 fire curve, while the other (right) side was a symmetry plane and was therefore fixed and isolated and had no heat or mass transfer across it.

Figure 2 shows the predicted distributions of mechanical damages and pore pressures at different times for the concrete with an initial permeability of $1 \times 10^{-17} \text{m}^2$ and an initial relative humidity of 1% (Case 1). As can be seen, the mechanical damage initially occurs after about 1200s, increasing with time and developing towards the inside of the wall. It is noted that this pattern matches very well with the location and depth to which spalling is typically observed to occur (e.g. [4, 26, 31-34]) and hence the mechanical damage is seen as a very good analogue for spalling behaviour.

In Figure 2, the highest peak of the pore pressures is less than $\sim 0.2 \text{MPa}$, which is much lower than the tensile strength of the concrete (initially 3MPa). Figure 3 shows the behaviour predicted for Case 2, which is the same as Case 1 but for the isolation of the pore pressure effects from the thermal

induced stresses. As can be seen, the damage pattern² is almost identical to that of Case 1 and hence it is proven that, in this case, it is the thermally induced stresses that predominantly caused the development of the damage zone. Physically, the damage is due to the high temperature gradient near the heated surface, which results in a high strain gradient and thus thermally induced stresses ultimately in excess of the concrete strength.

Similarly, Figure 4 shows distributions of mechanical damage and pore pressures for the concrete wall with an initial permeability of $1 \times 10^{-19} \text{m}^2$ and initial relative humidity of 65% (Case 3) and Figure 5 gives the corresponding results without pore pressure effects (Case 4). Again it can be observed that, although the peaks of pore pressures are higher than those in Cases 1 and 2 due to the lower permeability and higher moisture content, the pore pressure still has little effect on the development of mechanical damage since the pattern development is almost identical in the two plots.

Finally, to maximize the influence of the pore pressures, concrete with an initial permeability of $1 \times 10^{-21} \text{m}^2$ and initial relative humidity of 90% was considered (Cases 5 & 6). Comparing Figure 6 and Figure 7 (respectively with and without pore pressure effects), the difference in the development pattern of the mechanical damage due to the pore pressures is very obvious. Initially, the mechanical damage observed in Figure 6 is a result of thermally induced stresses caused by restrained thermal expansion. This results in high mechanical damage near the heated surface, which decreases with increase in distance from the heated face. However, under the conditions of Case 5, with increase of heating time, pore pressure builds up with a peak value occurring at some distance beneath the heated surface. When the pore pressure peak is high enough (i.e. it exceeds the local strength), it causes the development of mechanical damage in an area of the concrete ahead of the initial stress induced

² It may be noted that the mechanical damage reaches maximum values of around 0.6 in the results presented (i.e. up to a time of 2400s). However, the total damage, consisting of both mechanical and thermal damage, has reached 1.0 at this time, indicating total failure of the material and representing what may be considered an open fracture. Mechanical damage is here plotted in isolation for clarity.

damage zone. This combination results in the double peaked mechanical damage profile seen in the results.

Examination of Figure 7 shows that the pore pressures also increase the magnitude of the overall mechanical damage³. However, as can be seen in Figure 8 where the contributions from thermally induced stresses and pore pressures are separated out, it may still be considered that pore pressures play a secondary role in the development of spalling in terms of magnitude of mechanical damage.

It may be observed that the findings noted above are consistent with those of a number of experimental studies of concrete slabs (e.g. [35, 36]) that showed spalling occurred even where high pore pressures did not develop.

3.2 Square column exposed to fire

For the second set of analyses a concrete column exposed to fire on all sides was modelled as a two-dimensional problem in quarter-plane symmetry, as shown in Figure 9. Similarly to the wall model (above), two (top and right) sides were constraint-free and heated by the standard ISO834 fire curve, while the other (bottom and left) sides were symmetry planes and were therefore fixed and isolated and had no heat or mass transfer across them.

Figures 10 -12 show the development of mechanical damage, first principal stresses and pore pressures in the concrete column with an initial permeability of $1 \times 10^{-19} \text{m}^2$ and initial relative humidity of 65% (Case 7). It can be observed in Figure 10 that the mechanical damage starts just after 160s, developing quickly and extending to the heated boundaries after 200s. The damage pattern can clearly

³ It may be noted that the peaks of pore pressures shown in Figure 6 are significantly lower than their counterparts in Figure 7. This is because the occurrence of mechanical damage increases the permeability of the concrete which then facilitates the dispersal of gas, thus alleviating the build-up of the pore pressures.

be interpreted as defining a fracture across the corner of the column which is highly reminiscent of the phenomenon of corner spalling, often observed in both experimental and real case fires (e.g. [2, 33, 37-40]), where a triangular corner piece is lost.

Similarly to the findings of the analysis of the concrete wall (above) Anderberg [2], suggests that corner spalling is also mainly caused by thermally induced stresses and this is again supported by the numerical results of these analyses.

Firstly, it can be seen in Figure 11 that during heating tensile stresses are built-up and concentrated quickly at the corner, causing mechanical damage once they exceed the tensile strength of the concrete, before decreasing significantly in the damaged zones due to the unloading effect and concentrating at the ends of the fracture, as would be expected.

Secondly, as can be seen in Figure 12, the gas pressure build-up is concentrated in a very small area at the corner of the column. It can further be seen that the pressure has a maximum value of just over 1MPa at the time of 200s, which is much lower than the tensile strength of the concrete (initially 3MP_a) and that this occurs at some distance from the area of damage seen in Figure 10. These results indicate that the thermally induced stresses play a more important role than the pore pressures in the development of the mechanical damage.

Further support for this conclusion can be found in the results of Case 8, which, as before was the same as Case 7 but for the numerical isolation of the pore pressure effects from the thermally induced stresses. As can be seen in Figure 13, the developed pattern of damage is almost identical to that in Case 7 (Figure 10), indicating that the pore pressures had very little effect on the development of damage and that thermally induced stresses were the primary factor.

For a more complete understanding of the significance of pore pressures in this behaviour, a case using a low initial permeability ($5 \times 10^{-21} \text{m}^2$) and high relative humidity (80%) was also

investigated (Case 9), where pore pressures higher than those in Cases 7 & 8 were expected to build-up. As can be seen in Figure 14b, at the time of 200s, a damage pattern typical of those seen in Cases 7 & 8 is again present. However, it may also be seen that there is a small patch of damage in the very corner of the column and that this corresponds to the location of the peak gas pressures ($\sim 2.5\text{MPa}$) that can be seen in Figure 14a.

It may therefore be concluded that, although pore pressures of magnitude similar to that of the concrete strength are present, the effects of thermally induced stresses are more significant in the development of damage, and hence spalling, of the concrete. Although high pore pressures are shown to contribute to damage on the concrete they do not significantly affect the major damage zone that can be associated with observed spalling behaviour and, again, play only a secondary role.

4. Conclusions

This paper presents a numerical investigation of the significance of pore pressures and thermally induced stresses for spalling of concrete and specifically examines the three commonly cited theories: that spalling is caused by thermally induced stresses; that spalling is caused by macro-scopic pore pressures associated with ‘moisture clog’; or that spalling is caused by a combination of both of these processes.

A series of numerical experiments were carried out using a macro-scopic coupled hygro-thermo-mechanical-damage finite element model to analyse the behaviour of two typical concrete elements, a concrete wall and a square concrete column, exposed to fire. An isotropic damage model was used to account for the degradation and fracture of the concrete material due to both thermal and mechanical loadings and the mechanical damage parameter was considered to be an indicator of potential spalling behaviour.

Both the wall and column problems demonstrated that thermally induced stresses play a primary role in spalling of concrete, while the pore pressure, at most, plays a secondary role. For the concrete with high initial permeability and/or low relative humidity, it was shown that the maximum pore pressures that develop are too low to directly affect the mechanical integrity of the concrete, and therefore, have negligible contribution to spalling. For the concrete with low initial permeability and/or high relative humidity, high pore pressure may be built-up and these can directly cause mechanical damage beneath the heated surfaces of the concrete. However, even in such a case, the effect of the pore pressures is still secondary to that of the thermally induced stresses, as, firstly, they tend not to occur in the locations associated with observed spalling phenomena and, secondly, the magnitude of damage caused by thermal induced stresses is significantly higher than that caused by the pore pressures. With the other conditions the same, the higher the strength of concrete, the less significant are the pore pressures.

Nonetheless, it is acknowledged that the conclusions drawn above must be considered in the context of the limitations of the model, as described in Section 1. Particularly it must be considered that due to the averaging processes associated with the macro-scopic representation the effects of localised micro-scale phenomena, such as closed areas of the pore structure, cannot be explicitly accounted for. Although it may be noted that the damage predicted in these results tends to occur in relatively cool areas of the concrete, not conducive to the evaporation or expansion of water and the build up of pore pressures, it is recognised that the pressures that may build up in a closed pore structure could be much more significant than those predicted in this work (which, even at very low permeabilities, makes the inherent assumption of an open pore system) and are potentially a factor in the phenomenon of explosive spalling. Similarly, the model cannot capture the effects of full saturation with liquid water, and although this work would suggest that this situation is reasonably

unlikely to occur, it is again recognised that, where it does occur, the effects of the associated pore pressures may be very significant for the development of spalling [12]. It is intended that both these situations be investigated in the future.

However, most importantly it must also be noted that the results presented here match very well both qualitatively, in terms of geometry, and quantitatively, in terms of the time taken for damage to develop, with observed results (e.g. [2, 31-33, 37-39]). They are also consistent with the findings of a number of experimental studies (e.g. [35, 36]) that showed spalling to occur even where high pore pressures did not develop. Given that the results presented in this paper were produced not by making empirical assumptions but by modelling physical processes, this would tend to indicate that the findings of this work are valid.

What is without doubt is that more work is required in this area.

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References

1. Phan, L.T., *Fire Performance of High-Strength Concrete: A Report of the State-of-the-Art*, NISTIR 5934. 1996, Building and Fire Research Laboratory, National Institute of Standards and Technology: Gaithersburg, MD, USA.
2. Anderberg, Y., *Spalling Phenomena of HPC and OC*, in *International Workshop on Fire Performance of High-Strength Concrete Proceeding*, NIST Special Publication 919, L.T. Phan, et al., Editors. 1997, NIST: Gaithersburg, MD.
3. Kalifa, P., F.-D. Menneveau, and D. Quenard, *Spalling and Pore Pressure in HPC at High Temperatures*. Cement and Concrete Research, 2000. **30**: p. 1915 - 1927.
4. Hertz, K.D., *Limits of Spalling of Fire-Exposed Concrete*. Fire Safety Journal, 2003. **38**: p. 103 - 116.
5. Gawin, D., C.E. Majorana, and B.A. Schrefler, *Numerical Analysis of Hygro-Thermal Behaviour and Damage of Concrete at High Temperature*. Mechanics of Cohesive-Frictional Materials, 1999. **4**: p. 37 - 74.
6. Stabler, J., *Computational Modelling of Thermo-mechanical Damage and Plasticity in Concrete*. 2000, PhD Thesis, The University of Queensland, Australia.
7. Khoury, G.A., et al., *Modelling of Heated Concrete*. Magazine of Concrete Research, 2002. **54**(2): p. 77 - 101.
8. Tenchev, R.T., L.Y. Li, and J.A. Purkiss, *Finite Element Analysis of Coupled Heat and Moisture Transfer in Concrete Subjected to Fire*. Numerical Heat Transfer - A, 2001. **39**: p. 685 - 710.
9. Davie, C.T., C.J. Pearce, and N. Bicanic, *Coupled Heat and Moisture Transport in Concrete at Elevated Temperatures - Effects of Capillary Pressure and Adsorbed Water*. Numerical Heat Transfer, Part A, 2006. **49**(8): p. 733 - 763.
10. Davie, C.T., C.J. Pearce, and N. Bicanic, *A Fully Generalised, Coupled, Multi-Phase, Hygro-Thermo-Mechanical Model for Concrete*. Materials and Structures, 2010. **43**(Supplement 1).
11. Dwaikat, M.B. and V.K.R. Kodur, *Hydrothermal model for predicting fire-induced spalling in concrete structural systems*. Fire Safety Journal, 2009. **44**(3): p. 425-434.
12. England, G.L. and N. Khoylou, *Moisture Flow in Concrete Under Steady State Non-Uniform Temperature States: Experimental Observations and Theoretical Modelling*. Nuclear Engineering Design, 1995. **156**: p. 83 - 107.
13. Phan, L.T., J.R. Lawson, and F.L. Davis, *Effects of Elevated Temperature Exposure on Heating Characteristics, Spalling and Residual Properties of High Performance Concrete*. Materials and Structures, 2001. **34**: p. 83 - 91.
14. Ichikawa, Y. and G.L. England, *Prediction of moisture migration and pore pressure build-up in concrete at high temperatures*. Nuclear Engineering and Design, 2004. **228**(1-3): p. 245-259.
15. Gawin, D., F. Pesavento, and B.A. Schrefler, *Towards prediction of the thermal spalling risk through a multi-phase porous media model of concrete*. Computer Methods in Applied Mechanics and Engineering, 2006. **195**(41-43): p. 5707-5729.
16. Ulm, F.-J., O. Coussy, and Z.P. Bazant, *The "Chunnel" Fire. I: Chemoplastic Softening in Rapidly Heated Concrete*. Journal of Engineering Mechanics, 1999. **125**(3): p. 272 - 282.
17. Msaad, Y. and G. Bonnet, *Analyses of Heated Concrete Spalling due to Restrained Thermal Dilation: Application to the "Chunnel" Fire*. Journal of Engineering Mechanics, 2006. **132**(10): p. 1024 - 1132.
18. Bazant, Z.P., *Analysis of Pore Pressure, Thermal Stresses and Fracture in Rapidly Heated Concrete*, in *International Workshop on Fire Performance of High-Strength Concrete Proceeding*, NIST Special Publication 919, L.T. Phan, et al., Editors. 1997, NIST: Gaithersburg, MD.
19. Consolazio, G.R., M.C. McVay, and J.W. Rish, *Measurement and prediction of pore pressures in saturated cement mortar subjected to radiant heating (vol 95, pg 529, 1998)*. Aci Materials Journal, 1998. **95**(6): p. 761-761.
20. Chung, J.H., G.R. Consolazio, and M.C. McVay, *Finite element stress analysis of a reinforced high-strength concrete column in severe fires*. Computers & Structures, 2006. **84**(21): p. 1338-1352.
21. Tenchev, R. and P. Purnell, *An application of a damage constitutive model to concrete at high temperature and prediction of spalling*. International Journal of Solids and Structures, 2005. **42**(26): p. 6550-6565.
22. Gawin, D., F. Pesavento, and B.A. Schrefler, *What physical phenomena can be neglected when modelling concrete at high temperature? A comparative study. Part 1: Physical phenomena and mathematical model*. International Journal of Solids and Structures, 2011. **48**(13): p. 1927-1944.
23. Hozjan, T., et al., *Fire analysis of steel-concrete composite beam with interlayer slip*. Computers & Structures, 2011. **89**(1-2): p. 189-200.
24. Mounajed, G. and W. Obeid, *A New Coupling F.E. Model for the Simulation of Thermal-Hydro-Mechanical Behaviour of Concretes at High Temperatures*. Materials and Structures, 2004. **37**: p. 422 - 432.

25. Yuen, R.K.K., et al., *Heat and mass transfer in concrete at elevated temperature*. Numerical Heat Transfer Part a-Applications, 2007. **51**(5): p. 469-494.
26. Davie, C.T., H.L. Zhang, and A. Gibson, *Investigation of a continuum damage model as an indicator for the prediction of spalling in fire exposed concrete*. Computers & Structures, 2012. **In Press**(0).
27. Lewis, R.W. and B.A. Schrefler, *The Finite Element Method in the Static and Dynamic Deformation and Consolidation of Porous Media*. 2nd ed. 1998, Chichester: Wiley.
28. Pearce, C.J., C.V. Nielsen, and N. Bicanic, *Gradient enhanced thermo-mechanical damage model for concrete at high temperatures including transient thermal creep*. International Journal for Numerical and Analytical Methods in Geomechanics, 2004. **28**(7-8): p. 715-735.
29. Peerlings, R.H.J., et al., *Gradient-enhanced damage modelling of concrete fracture*. Mechanics of Cohesive-Frictional Materials, 1998. **3**(4): p. 323-342.
30. Taylor, R.L., *FEAP - A Finite Element Analysis Program. Version 7.5 User Manual*. 2005, Berkeley, California: University of California at Berkeley.
31. Zeiml, M., R. Lackner, and H.A. Mang, *Experimental insight into spalling behavior of concrete tunnel linings under fire loading*. Acta Geotechnica, 2008. **3**(4): p. 295-308.
32. Jansson, R. and L. Bostrom, *Spalling in Concrete Exposed to Fire*. 2008, SP Technical Research Institute of Sweden
33. Bailey, C., *Holistic behaviour of concrete buildings in fire*. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 2002. **152**(3): p. 199-212.
34. Ali, F., A. Nadjai, and A. Abu-Tair, *Explosive spalling of normal strength concrete slabs subjected to severe fire*. Materials and Structures, 2011. **44**(5): p. 943-956.
35. Jansson, R. and L. Bostrom, *The Influence of Pressure in the Pore System on Fire Spalling of Concrete*. Fire Technology, 2009.
36. Mindeguia, J.-C., et al. *Experimental Study on the Contribution of Pore Vapour Pressure to the Thermal Instability Risk of Concrete. Concrete Spalling due to Fire Exposure*. in *1st International Workshop on Spalling due to Fire Exposure*. 2009. Leipzig.
37. HITECO, *Brite Euram III BRPR-CT95-0065, Understanding and Industrial Application of High Performance Concrete in High Temperatures Environment, Final Report*. 1999.
38. Aldea, C.-M., J.-M. Franssen, and J.-C. Dotreppe, *Fire Test on Normal and High-Strength Reinforced Concrete Columns*, in *International Workshop on Fire Performance of High-Strength Concrete Proceeding, NIST Special Publication 919*, L.T. Phan, et al., Editors. 1997, NIST: Gaithersburg, MD.
39. Jau, W.C. and K.L. Huang, *A study of reinforced concrete corner columns after fire*. Cement & Concrete Composites, 2008. **30**(7): p. 622-638.
40. Kodur, V. and R. McGrath, *Fire endurance of high strength concrete columns*. Fire Technology, 2003. **39**(1): p. 73-87.

Figures

Figure 1 Schematic diagram of model representing concrete wall exposed to fire on both sides

Figure 2 Distributions of mechanical damage and pore pressure (Case 1 - $K_0=1 \times 10^{-17} \text{ m}^2$; R.H.=1%)

Figure 3 Distributions of mechanical damage and pore pressure without pore pressure effects in elastic deformation (Case 2 - $K_0=1\times 10^{-17}\text{m}^2$; R.H. =1%)

Figure 4 Distributions of mechanical damage and pore pressure (Case 3 - $K_0=1\times 10^{-19}\text{m}^2$; R.H. = 65%)

Figure 5 Distributions of mechanical damage and pore pressure without pore pressure effects in elastic deformation (Case 4 - $K_0=1\times 10^{-19}\text{m}^2$; R.H. = 65%)

Figure 6 Distributions of mechanical damage and pore pressure (Case 5 - $K_0=5\times 10^{-21}\text{m}^2$; R.H. = 90%)

Figure 7 Distributions of mechanical damage and pore pressure without pore pressure effects elastic deformation (Case 6 - $K_0=5 \times 10^{-21} \text{ m}^2$; R.H. = 90%)

Figure 8 Mechanical damage separately caused by pore pressures and by thermally induced stresses

Figure 9 Schematic diagram of model representing concrete square column exposed to fire on all sides

Figure 10 Evolution of mechanical damage in the concrete at: (a) 160s; (b) 180s and (c) 200s. (Case 7 - $K_0=1 \times 10^{-19} m^2$; R.H.=65%)

Figure 11 Evolution of stresses in the concrete at: (a) 160s; (b) 180s and (c) 200s. (Case 7 - $K_0=1 \times 10^{-19} m^2$; R.H.=65%)

Figure 12 Evolution of pore pressures in the concrete at: (a) 160s; (b) 180s and (c) 200s. (Case 7 - $K_0=1 \times 10^{-19} m^2$; R.H.=65%)

Figure 13 Evolution of mechanical damage in the concrete at: (a) 160s; (b) 180s and (c) 200s, without pore pressure effects in elastic deformation (Case 8 - $K_0=1\times 10^{-19}\text{m}^2$; R.H.=65%)

Figure 14 Distributions of: (a) pore pressures and (b) mechanical damage (Case 9 - $K_0=1\times 10^{-21}\text{m}^2$; R.H.=80% and $t = 200\text{s}$)