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HW/9

Pore pressures and moisture flow in concrete : steady and transient temperatures

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ABSTRACT

A numerical model is proposed and used to predict the pore pressures and redistribution of moisture in thick concrete containment walls under the influence of long-term service temperatures and during short-term over-temperature incidents. The mass transfer computations reflect both pressure-induced and diffusion-based flow components. Rapid temperature transients are shown to lead to pore saturation, excessive pore pressures and possible loss of material/structural integrity.

INTRODUCTION

The imposition of a temperature crossfall through the concrete wall of a nuclear reactor containment causes a redistribution of the internal moisture and long-term drying to take place. The nature and extent of these changes are of interest during service life; 30 years or more. Of additional interest is the integrity of the vessel/liner system during an over-temperature incident or operational upgrade. The effect of a temperature increase late in life will generally be very different from an early application of the same temperature state.

In situations where high pore pressures may develop in the concrete, due to vapour, steam, or hydraulic pressures it is important to assess their effects on liner performance and integrity and for those containments where services and/or facilities are housed within the containment walls, it is necessary to determine whether they or their environments are at risk.

MOISTURE FLOW

Experiments [1] which were staged to simulate the flow of moisture in thick concrete sections (up to 3.1m) and a range of liner temperatures (up to 200^{o}C) have revealed a number of important features of the mass flow processes.

Pore Pressures:

The pressures monitored in the hottest regions usually do not reach the saturation vapour pressures, P_{svp}, at the local temperatures [2]. This is simply because there is simultaneous migration occurring during the heat-up period producing *dry* concrete (i.e. concrete for which the water content is insufficient to sustain P_{svp}) where temperatures are highest. Elsewhere, in regions of lower temperature, P_{svp} pore pressures have been recorded. The water migration which mitigated the highest pore pressures is able to occur because 'as cast' concrete contains a small volume of voids which act as receptors or reservoirs during the transfer process. Without this initial unfilled pore volume, V_{uf}, typically 2% to 4% of the bulk concrete volume, considerably higher pore pressures would be experienced. The experimental evidence [3] shows that the core of the wall is characterised by *wet* (sufficient water to sustain P_{svp}) and *saturated* pores (those pores for which their initial unfilled pore volume has become filled). Pressures in these water-filled pores are *hydraulic* and exceed P_{svp} at the local temperature.

Near to the cold unsealed face of the wall where both temperatures and pore pressures are low, drying occurs to the surrounding atmosphere. Pores in this region are generally *wet*. Typical pore pressure distributions are given in Figure 1, for two walls heated to 200°C at the liner face.

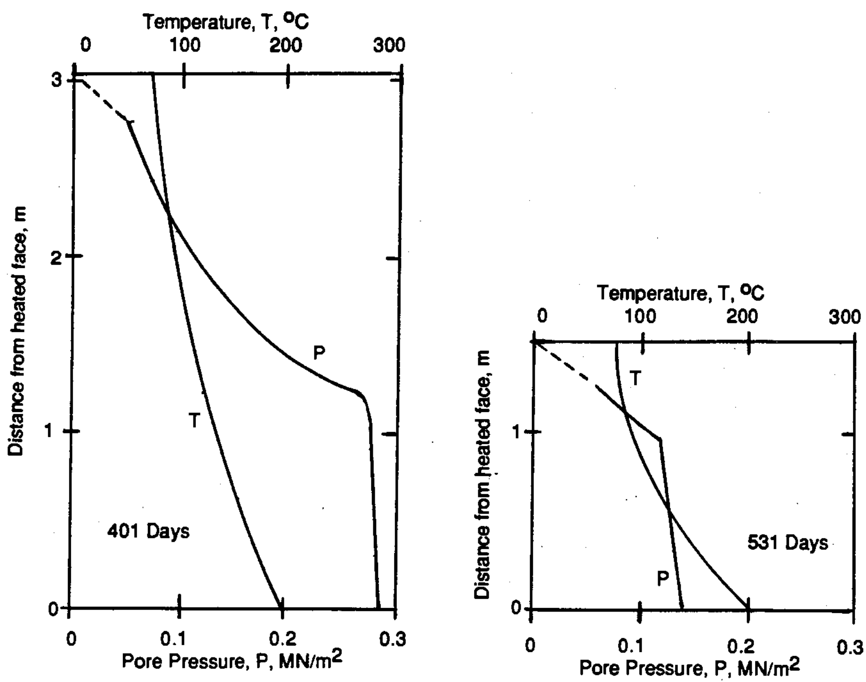

FIGURE 1. Typical pore pressure and temperature distributions for two walls heated to 200°C at the liner [1].

Redistribution of Moisture

Typical transient water distributions are shown in Figure 2. They correspond to the problems and pore pressures of Figure 1 and show clearly: (a) the two zones of drying, at the exposed face and adjacent to the liner, and (b) the zone of physical saturation in the core of the wall.

During prolonged heating, the zone of saturation migrates slowly towards the cold face as water continues to condense at the upstream face. The migration rate steadily reduces in this condition because the driving pressure at the upstream face of the water 'plug' continuously decreases during the flow process, and because simultaneous reductions occur to the concrete permeability in the saturated zone.

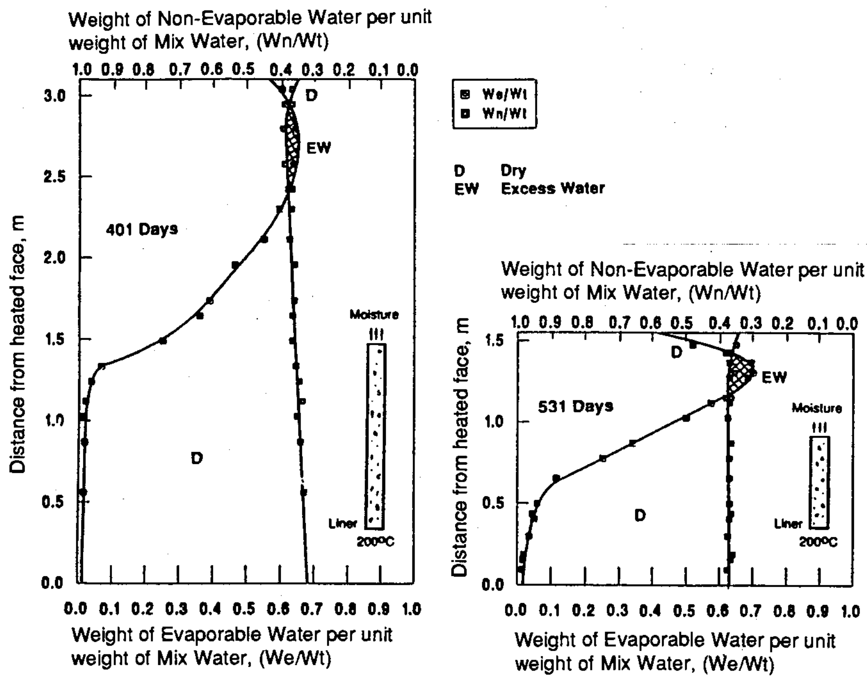

FIGURE 2. Distributions of evaporable and non-evaporable water in two walls heated to 200°C at the liner [1].

Concrete permeability is also influenced by temperature and drying. Experimental data for a limestone aggregate concrete [4] indicate that permeability can be expected to increase by two orders of magnitude when temperatures rise above 100°C. Other evidence reveals increases of seven orders of magnitude for a basalt aggregate concrete [5] over the temperature range, 20°C to 600°C.

FEATURES TO BE INCLUDED IN THE NUMERICAL ANALYSIS

If reliable estimates are to be made of moisture distribution and pore pressures the following features must be addressed and quantified.

Permeability, k: the magnitude and variation of k with temperature and water content must be known.

Diffusion, D: allowance must be made for the temperature-dependence of the diffusion coefficient D.

Water Content: it is necessary to differentiate between the volumes of free, gel and hydrated water and to know their inter-relationships with temperature variation.

Unfilled Pore Volume, V_{uf}: Initially the 'as cast' unfilled pore volume must be known. Thereafter changes to V_{uf} based on the release of gel and bound water must be taken into account.

Pore Pressures, P: In the absence of partial air pressures, the pores generally contain dry vapour (superheated steam for which the pressure $P_{sst}<P_{svp}$), wet vapour (supporting P_{svp}), or water at physical saturation of the pore, $P>P_{svp}$.

Thermal Expansion: the differential thermal expansion between water and the pore skeleton must be taken into account, particularly at temperatures in excess of 250°C.

NUMERICAL ANALYSIS

The numerical analysis has been carried out for a unidirectional moisture and temperature flow problem, modelled by representing the flow path as a series of connected elements, or chambers, through which the flows of moisture and heat pass. Equations governing the mass flow rates between adjacent pairs of chambers have been written in terms of the pressure differentials (Pressure-Induced Flow, PIF) and in terms of their respective states of moisture saturation (Diffusion-Based Flow, BDF). Additional compatibility equations relating to moisture content help to control the flow processes and define the appropriate pore pressures based on temperature and moisture content. The calculation proceeds in a step by step manner in time computing the incremental mass transfers between the chambers and revising the pore pressures to be consistent with the new moisture contents. Special checks are required when pores become physically saturated and their internal pressures are then governed by other factors, e.g. the pore pressures at each end of the saturated 'plug', or the differential thermal expansion between water and pore skeleton during a temperature transient.

DESCRIPTION OF MODEL

The behaviour of the model is described in several stages.

1. Volume components of porous element.
2. Mass flow between adjacent porous elements at non-uniform temperatures, for;
   (a) unsaturated pores,
   (b) saturated pores
3. Influence of transient heating

The mass transfer modelling can proceed at the *material* level so long as the internal pore pressures remain below the critical value which causes fracture of the porous skeleton in tension. At pressures at or above this value the problem can only be solved at the *structural* level, when details of the constraint geometry and constraining actions need to be considered.

Volume Components of Porous Element

A porous concrete element is considered at 20°C and at a temperature T>105°C, Figure 3. At 20°C the volume components in the hardened state are shown in part (a) of the figure. They can be seen to differ from those of an inert porous material by the existence of water associated with the contained cement, namely the volume of gel water, V_{gw}, and bound water, V_{bw}. Gel and bound water are released into the pore structure as temperatures are raised and thereby sustain higher pore vapour pressures than would be experienced in an inert material, [3].

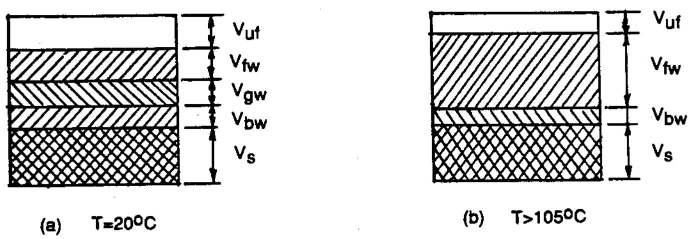

FIGURE 3. Definition of volume components in unsaturated concrete element; volume of solids, V_s; bound water, V_{bw}; gel water, V_{gw}; capillary or free water, V_{fw}; and unfilled pore volume, V_{uf}.

During an increase of temperature to T<105°C there is a progressive release of gel water, until none remains held by the gel at 105°C. At temperatures T>105°C bound water is released progressively until all hydraulic bonding is lost at around 850°C. Because the gel and bound water components are at higher effective densities in the confined states their release at elevated temperature reduces the unfilled pore volume, V_{uf}, and creates an increase in the degree of pore filling (DPF). Additionally the differential expansion between the contained water and the solid skeleton of the pores must be taken into account. When this is done the DPF increases further. The detailed nature of these modelling features is given in [6] and is shown schematically in Figure 3(b).

Mass flow between adjacent porous elements

When the flow path is modelled by a series of connected porous elements, or chambers, the flow properties are defined by the connections between elements as shown in Figure 4. The flow rate between adjacent chambers is then defined in terms of two transport mechanisms, namely (i) a pressure-induced flow (PIF) which is defined by the pressure gradient between the two elements, and (ii) a diffusion based flow (DBF) which is determined from the concentration gradient between the two elements. These two gradients may or may not be in the same direction during the mass flow process; however, the net flow is always the algebraic sum from the two mechanisms.

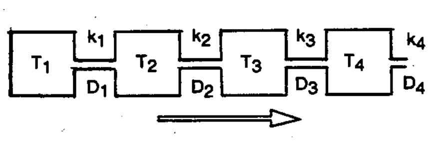

FIGURE 4. Schematic layout of connected elements showing location in the model of the permeability and diffusion parameters.

For PIF the pore vapour pressures in *unsaturated* pores will be either, (i) saturated vapour pressures, P_{svp}, corresponding to

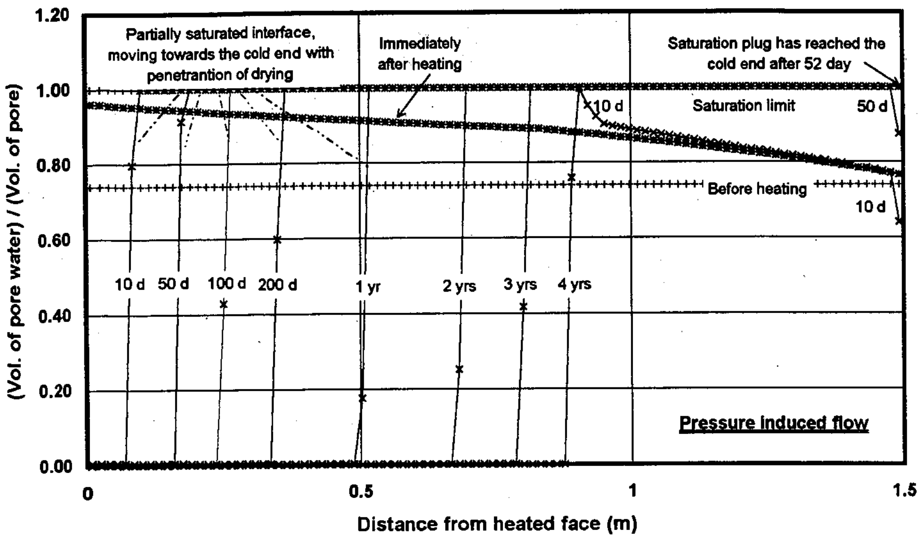

FIGURE 5. Predicted moisture content distributions and their variation with time, for *pressure-induced* flow in 1.5m thick wall. Permeability, $k=10^{-18}m^2$

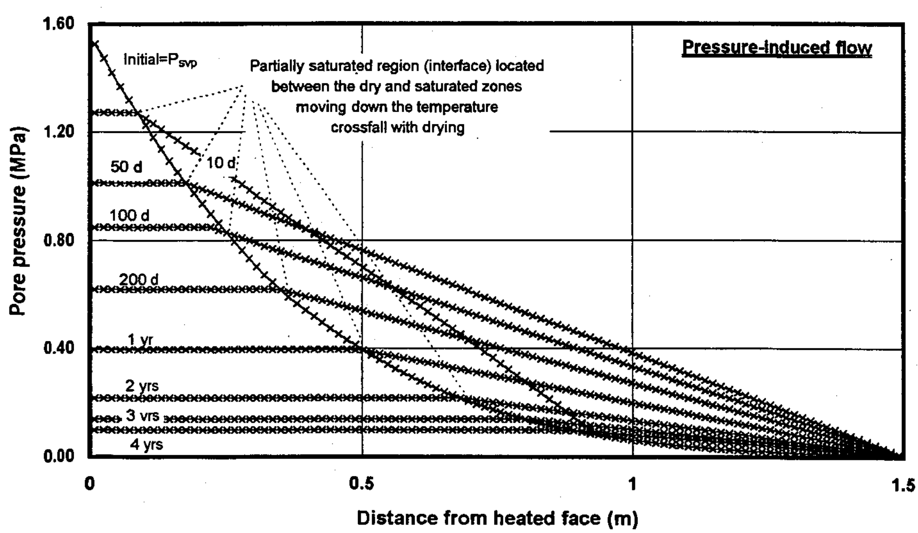

FIGURE 6. Pore pressure distributions for wall of Fig.5.

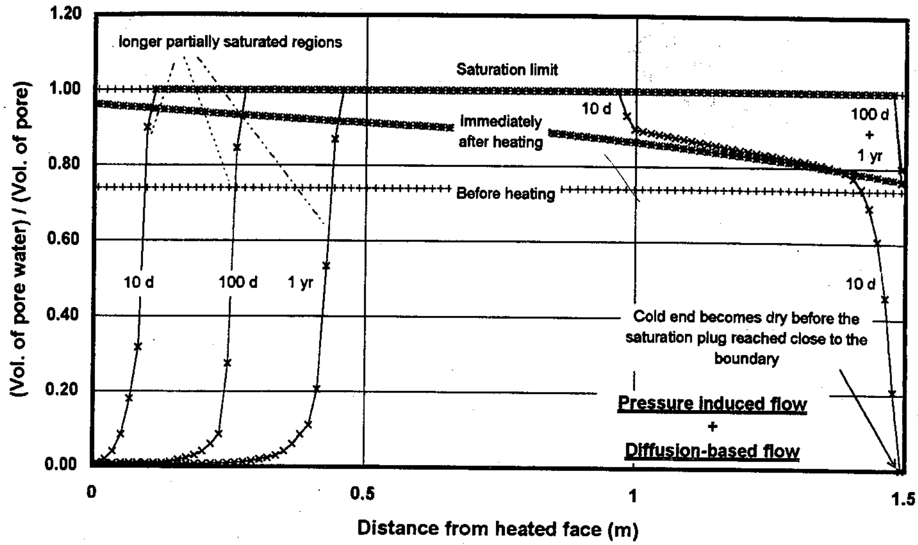

FIGURE 7. Predicted moisture content distributions and their variation with time, for *pressure-induced and diffusion-based* flows in 1.5m thick wall. Permeability, $k=10^{-18}m^2$, and $D/k=10^8$/sec.

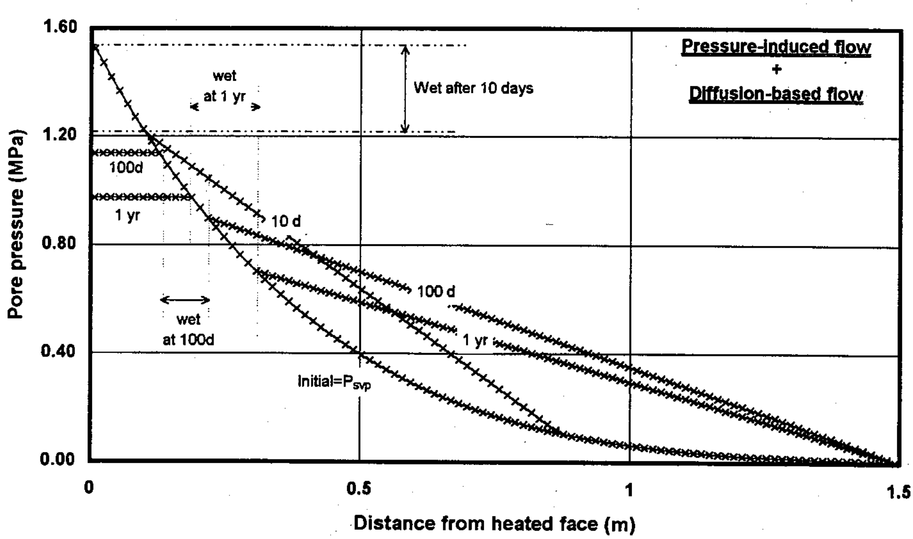

FIGURE 8. Pore pressure distributions for wall of Fig.7.

the local temperatures when the pores are *wet*, i.e. containing free water, or else, (ii) superheated steam pressures, $P_{SSt}<P_{SVP}$, when the pores are *dry*, i.e. they contain no free water, but water vapour only. The PIF in *saturated* pores will be controlled by hydraulic pressure gradients defined by the interface pressures of the non-saturated pores at each end of the saturated zone.

Influence of Transient Heating

During heating, the associated pore vapour pressures cause drying and a flow of water and vapour away from the hottest locations, leading to excess wetting and possible saturation elsewhere. When steady-state temperatures have been established before pore saturation occurs, the migration process can be adequately described in terms PIF and DBF.

However, when heating continues after saturation has occurred it is necessary to investigate the potentially high *strain-imposed* hydraulic pore pressures generated by the differential expansion of water and the restraining pore skeleton. At temperatures in excess of 250°C the high differential thermal expansion of the water can lead to tensile fracture of concrete when the structural restraint to the pressurised pores is insufficient. This type of damage usually occurs close to a free surface as can be experienced in a fire or over-temperature accident. This behaviour is frequently described as spalling [7] when linked to the behaviour of concrete structures in fire. During slow heating, hydraulic fracture will not occur whenever the release rate of water from the saturated pore structure is sufficient to mitigate the build up of very high pore pressures.

CHECKS ON THE ANALYSIS

Because there are no fundamental procedures available to check the transient performance of the numerical model when used to predict moisture flow for cases where there can be a loss of moisture from the system, two forms of checking were adopted.

For problems that have well-defined steady-state solutions, e.g. completely sealed systems, it has been possible to check that the time-step transient mass flow solution does converge to the steady-state solution as derived from a direct analysis.

For cases without useful steady-state solutions a step-by-step thermo-dynamic check was made. At each step of the analysis an assessment was made of the entropy produced during the transient analysis. The production rate was kept as low as possible and close to the minimum which characterises the thermo-dynamic solution. This was achieved by a suitable choice of time step and geometrical subdivision of the flow path.

SELECTED RESULTS AND DISCUSSION

The results have been selected to demonstrate a range of features of the moisture flow problem. The analysis in each case is for a wall of 1.5m in thickness.

Figures 5 to 8 show moisture content profiles and pore pressures for a wall sealed and heated at one face (200°C) and unsealed at the other (30°C). Separate analyses for PIF (Figure 5 and 6) and DBF (Figures 7 and 8) are presented. The influence of diffusion is readily apparent in these Figures. In the 0.5m zone close to the liner, Figure 7, drying has been impeded by the reverse flow component of diffusion, i.e. towards the liner. At the unsealed cold face of the wall diffusion has increased the degree of drying to the atmosphere. Observation of the corresponding pressure distribution, Figure 8, shows that the inclusion of diffusion has produced *wet* zones between the *dry* and *saturated* zones. This feature is consistent with experimental observations [3]. For PIF alone, Figure 5, the *wet* zones have degenerated to become simply interfaces between the *dry* and *saturated* zones.

Figures 9 to 12 illustrate the effects of rapid transient heating to an exposed face. The heating rates and transient temperatures have been generated from the application of a *standard fire curve* taken from the British Standard BS 476 [8]. The two examples differ only in that the initial degree of pore filling is for the concrete 'as cast' in Figures 9 and 10, and for a partially dried concrete in Figures 11 and 12. In both examples moisture migration occurs into the core of the wall where is causes pore saturation. Continued heating then creates pressures associated with P_{svp} in wet regions, P_{sst} in dry zones, and very high hydraulic pressures from the thermal incompatibility of the saturated pores. When the heating rate is sufficiently high the hydraulic pressures build up at a rate greater than can be mitigated by the flow of water away from the saturated regions. These pressures rapidly overtake the nearby saturated vapour pressures and can cause damage and cracking close to a free concrete surface. This would be the case also adjacent to the main containment liner or close to any in-wall services. Figures 10 and 12 show the existence of high hydraulic pressures at a depth of less than 10mm when the wall face temperatures had reached approximately 190°C and 280°C respectively.

From the examples of Figures 9 to 12 it may be inferred that the drier the concrete is before being subjected to severe heating, the higher is the face temperature that is required to cause pore saturation and the development of high hydraulic pressures and possible material damage. When damage occurs close to the heated surface it does so in a short time, e.g. a few minutes. Longer delay times can be expected for walls which have become partially dried during service.

For a containment wall, dried to a depth of 0.5m say, and subsequently subjected to a hypothetical liner/concrete interface temperature of 600°C (and sustained thereafter), several days will elapse before the saturated region in the core of the wall experiences a temperature rise which is sufficient to develop significant hydraulic pressures. The safety of the containment under these conditions depends on its structural integrity and can no longer be guaranteed from material considerations alone. Important parameters to be considered in these situations are the relative rates of temperature increase and mass flow in the saturated regions, and the nature of the surrounding geometrical and structural constraints.

CONCLUDING REMARKS

The migration of water in thick concrete walls can be estimated using the numerical model proposed, for long-term service conditions or short-term temperature transients.

The model can be used to assess potential damage to containments which are subjected to over-temperature incidents.

Numerical predictions over very long periods of time are sensitive to spatial variations of material properties and these must therefore be sought from appropriate programs of control testing.

Comparisons of predicted moisture profiles with those obtained in experiments have confirmed the need to include both pressure-induced and diffusion-based flow mechanisms into the analysis.

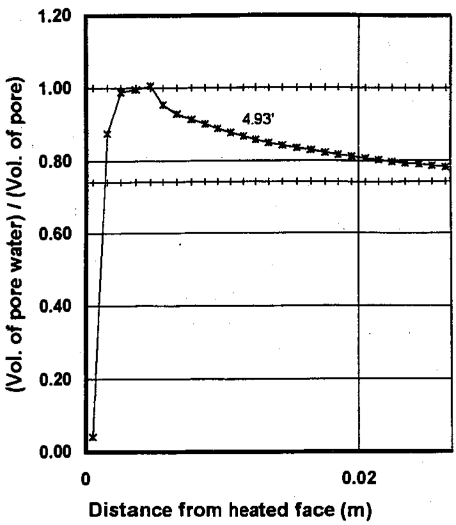

FIGURE 9. Water distribution close to the liner at first pore saturation (after 4.93 min) of *'as cast' concrete*, following fire heating.

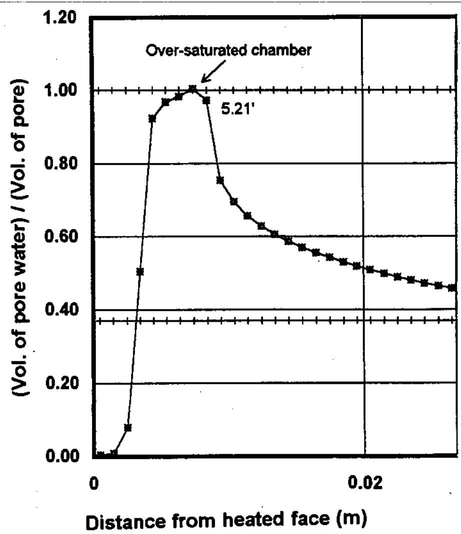

FIGURE 11. Water distribution close to the liner at first pore saturation (after 5.21 min) of *partially pre-dried concrete*, following fire heating.

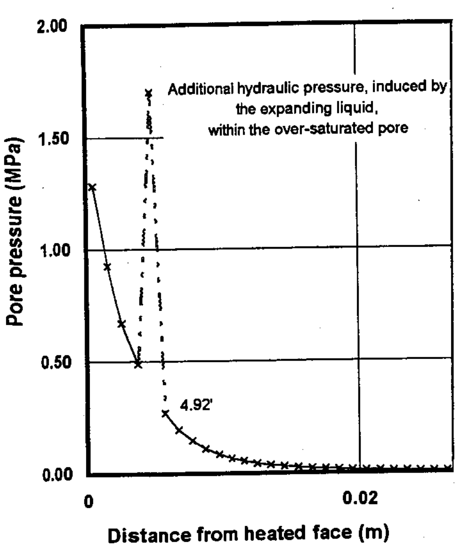

FIGURE 10. Pore pressures close to liner for wall of Fig.9. Location of potential damage is defined by location of rapidly increasing hydraulic pore pressure.

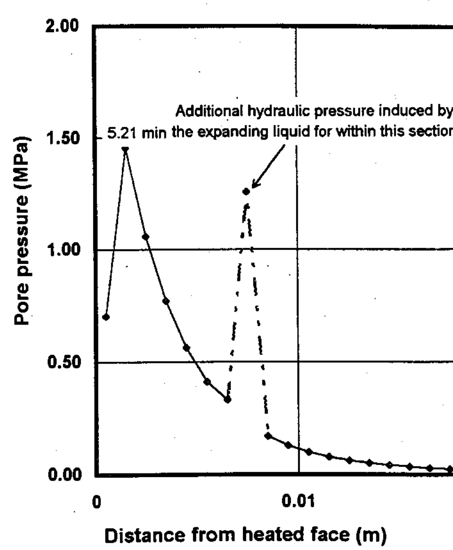

FIGURE 12. Pore pressures close to liner for wall of Fig.11. Location of potential damage is defined by location of rapidly increasing hydraulic pore pressure.

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