Influence of High Temperature on Water Content, Permeability and Pore Pressures in Concrete

G. L. ENGLAND
Imperial College, London, UK
R. J. GREATHEAD
Principia Mechanica, London, UK
S. A. KHAN
Nuclear Electric, Gloucester, UK

ABSTRACT

The influence of temperatures to 600°C on the performance of containment vessel concrete is studied in relation to pore pressures; moisture migration causing drying and physically saturated zones; and permeability for various types of cure and post-cure treatments. It is concluded that pore pressures to 10 MN/m² can exist in non-uniformly heated concrete; water migration and drying take place rapidly during the first hour of heating; and permeability values may vary by more than seven orders of magnitude.

1 INTRODUCTION

The results relate to raised temperature studies on a containment vessel concrete. The mix contained sulphate resisting Portland cement, blast furnace slag (Cemsave), quartz dolerite aggregate; calcarious quartzite sand; and a water reducing agent.

The objectives were to obtain data on permeability, pore pressure/temperature relationships and pore/pressure moisture migration behaviour for concrete at a range of temperatures and moisture contents similar to those experienced in a reactor containment vessel during normal service life and during a thermal accident. Modelling techniques depend on these source data for making reliable predicitons. The work has:

(A) recorded the variation of pore pressure with temperature to 350°C for a wide range of water contents: from'as cast'(w/c=0.39) to'dry'(w/c=0.06)

(B) characterised the movement of moisture under thermally and hydrostatically induced potentials.

(C) assessed the significance of cure and subsequent temperature and moisture treatments on water permeability.

(D) assessed the importance of pore pressures and moisture migration at the liner/concrete interface of a containment subject to a 400°C temperature excursion.

Figures 1 to 5 highlight some of the findings of two recent research studies, (Greathead 1986, Khan 1990), and extend some earlier work on this subject (England & Sharp 1972, Chapman & England 1977).

SMiRT 11 Transactions Vol. H (August 1991) Tokyo, Japan, © 1991

2. RESULTS

2.1 Pore Pressures

A common theme of all pore pressure experiments is that the pore pressures for sealed concrete exceed those due to saturation vapour pressure (SVP) of water alone. During a controlled release, water vapour and air escape together initially and pressures fall to a plateau corresponding to the SVP of water; Figure 1. Continued releases cause pressures to fall eventually below SVP. Moisture expulsion becomes slower as drying progresses, and the final equilibrium water content at 350°C is for a water/cement ratio, w/c=0.06. The evaporable water content marked on the figure is that recorded after drying a separate sample to constant weight at 105°C and atmospheric pressure.

Additional data were sought from the 'release tests' by introducing temperature perturbations and then observing the pressure/temperature (P/T) changes at various states of dryness, for that part of the response below the SVP. For release tests covering the temperature range 240°C to 350°C the P/T results exhibited considerable non-linearity. This feature supports existing knowledge from drying experiments, namely that more water is released from the hydrated structure when the temperature is increased. Without loss of this water from the pore structure, pressures increase due to temperature rise <u>and</u> due to an increase in the mass density of water molecules present in the pores.

2.2 Permeability

Figure 2 illustrates the importance of curing and the post-cure histories of moisture content and temperature on the permeability of concrete. Tables 1,2 and 3 give the details of cure and post-cure treatments.

The permeability values quoted relate to the Darcy Equation, Eq.(1), for which dm/dt is the mass flow rate; A is the cross-sectional area over which flow occurs; dP/dx is the pressure gradient; and and are respectively the density and dynamic viscosity of water. k is then a solid phase parameter the permeability in m^2.

$$dm/dt \quad = \quad kA \quad dP/dx \qquad (1)$$

After curing and post-cure treatment, all tests were carried out at 26°C using distilled water, for periods ranging from several weeks to more than 200 days in a few cases.

Two distinct types of performances can be identified; namely those associated with:

(i) Adequate water for curing and subsequent treatment.

(ii) Insufficient water during air curing or subsequent drying.

In the first category well-formed stable hydration products are created and these lead to permeabilites which are unaffected by flow and remain time-invariant; (a) and (b) of Figure 2. Concrete of the second category suffers either impeded hydration or damage during drying, and consequently undergoes flow-related permeability changes with the formation of more hydration products and some healing; (c) and (d) of Figure 2.

2.3 Liner/Concrete Interface Pressures

Experiments were staged to simulate a thermal accident, where the 'liner' was subjected rapidly to a temperature of approx.400°C. Measurements of pressure adjacent to the liner and at distances from it were made immediately afterwards and for periods of up to 12 hours. Deformations of the 'liner' were also monitored to provide an independent check on the pressures from a previous calibration test under hydrostatic pressure. Figures 3 to 5 show a sketch of the test assembly and the results obtained. Figure 4 infers that rapid moisture migration occurs close to the liner (stations 1 and 2) and pressures there fall below SVP after as little as 10 mins from time of accident. Thereafter, pressures rise as temperatures increase but remain always below SVP. The superposed SVP P/T curve in Figure 4 indicates that a water saturation front exists between monitoring stations 2 and 3 for most of the test period and moves continuously towards station 3. The zone of moisture saturation is shown in Figure 5.

3. CONCLUDING REMARKS

- Temperatures, to 400°C, will generate high pore pressures (26MN/m² at 350°C) in excess of SVP values in a sealed situation.
- For non-uniform temperature states moisture migration mitigates pore pressures significantly; the extent depending on the spatial temperature distribution, the temperature/time history and the permeability of concrete. Zones of physical water saturation are created.
- For a liner accident to 400°C, pressures up to 10 MN/m² can result in normal concrete, i.e. not previously dried. Considerable drying takes place adjacent to the liner during the first few hours following an accident.
- Permeability is dramatically affected by type of cure and subsequent temperature and moisture treatment; changes of seven orders of magnitude between continuous water cure and severe drying at 600°C. Stable permeability values result from adequate water during cure and post-cure treatment, while unstable values result from water deficiencies.

4. REFERENCES

England, G.L. and Sharp, T.J. (1971). Migration of Moisture and Pore Pressures in Heated Concrete. 1st SMiRT Conference, Berlin. Paper H2/4.

Chapman, D.A. and England, G.L. (1977). Effects of Moisture Migration on Shrinkage, Pore Pressures and other Concrete Properties. 4th SMiRT Conference, San Fransisco. Paper H5/3.

Greathead, R.J. (1986). Permeability of Concrete containing Blast Furnace Slag as affected by Temperature, Moisture and Time. PhD Thesis, University of London.

Khan, S.A. (1990). Pore Pressure and Moisture Migration in Concrete at High and Non-uniform Temperatures. PhD Thesis, University of London.

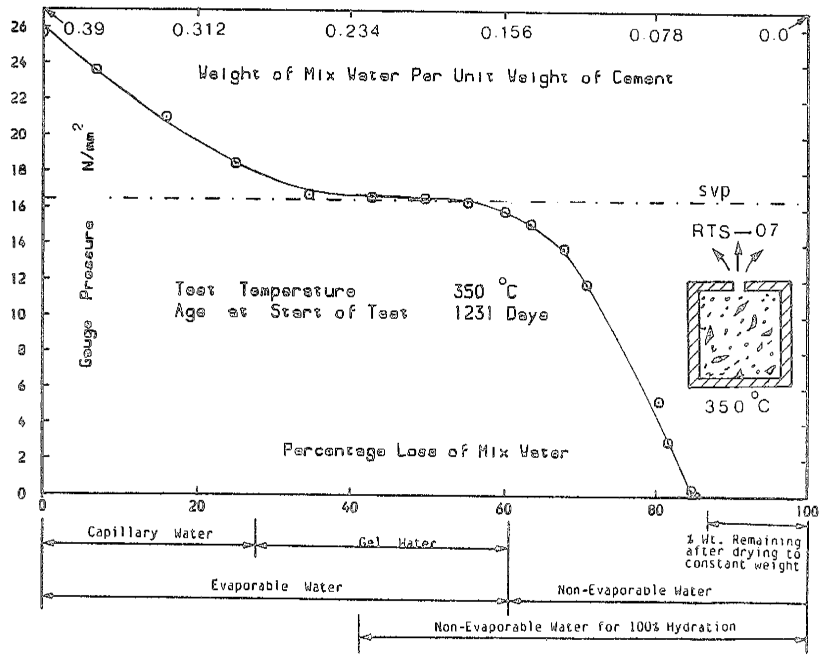

FIGURE 1. Variation of pore pressure with moisture loss from sealed specimen.

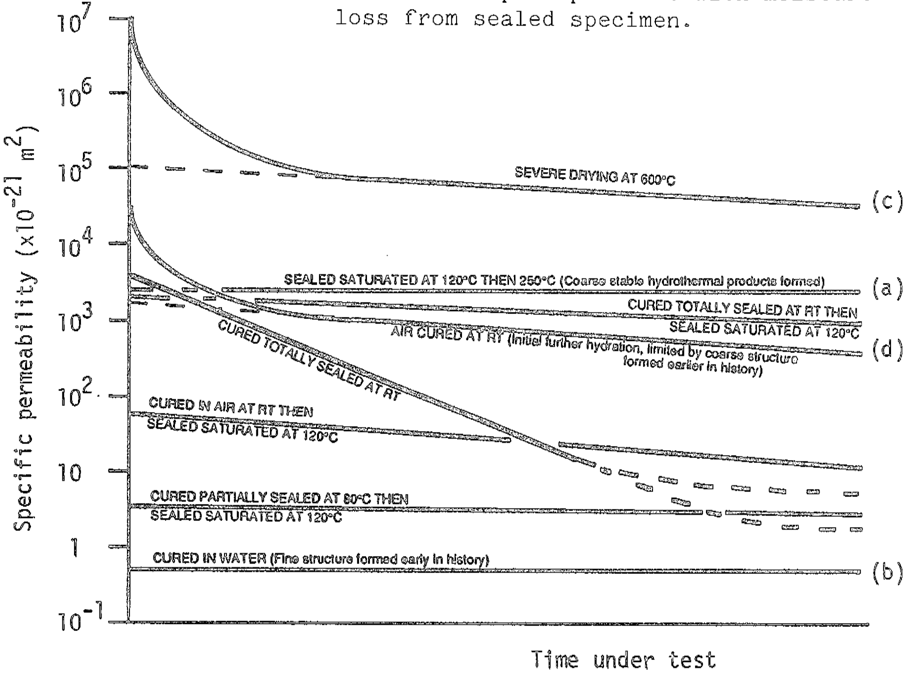

FIGURE 2. Variation of permeability with type of cure and post-cure treatment.

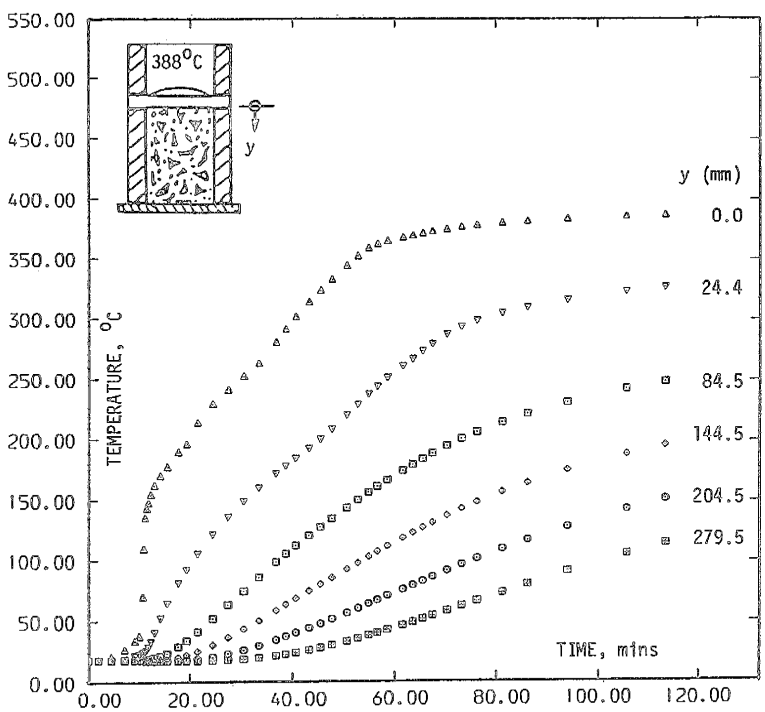

FIGURE 3. Variation of temperature with time in concrete behind 'liner'.

TABLE 1. CURING: Duration Greater than 100 Days.

Environment	Air	Water	Totally Sealed	Partially Sealed
Temperature	26°C or 80°C	26°C or 80°C	4°C or 26°C	80°C

TABLE 2. TREATMENT: Normally 6 hr Hold Time.

Environment	Oven Drying at	Sealed Saturated at
Temperature	120°C, 250°C, 400°C or 600°C	120°C or 250°C

TABLE 3. Initial, k_i, & End of Test, k_f, Specific Permeabilities for Various Cure and Post-Cure Treatments ($\times 10^{-21}$ m²) RT = 26°C

Specimen Ref:	CURE	TREATMENT	k_i	k_f
3H1C5B	Water, 80°C	None	0.5	0.5
1H1C2B	Totally Sealed, RT	"	4000	3
5H1C6E	Partially Sealed, 80°C	"	47	3
1H1C4B	Air, RT	"	22000	700
1H1C2D	Totally Sealed, RT	Sealed Saturated, 120°C	1700	1500
1H1C4D	Air, RT	Sealed Saturated, 120°C	60	10
5H1C6D	Partially Sealed, 80°C	Sealed Saturated, 120°C	4	1.5
1H1C4E	Air, RT	Dried, 120°C	55000	1000
5H1C6B	Partially Sealed, 80°C	Dried, 120°C	4000	<600
1H1C3B	Totally Sealed, RT	(Sealed Saturated, 120°C + Sealed Saturated, 250°C)	2000	2000
1H1C3D	Totally Sealed, RT	(Dried, 120°C + Dried, 250°C)	19000	100
3H1C2B	Totally Sealed, RT	Dried, 250°C	680000	10000
3H1C2D	Totally Sealed, RT	Dried 400°C	2300000	15000
3H1C2E	Totally Sealed, RT	Dried, 600°C	9500000	30000

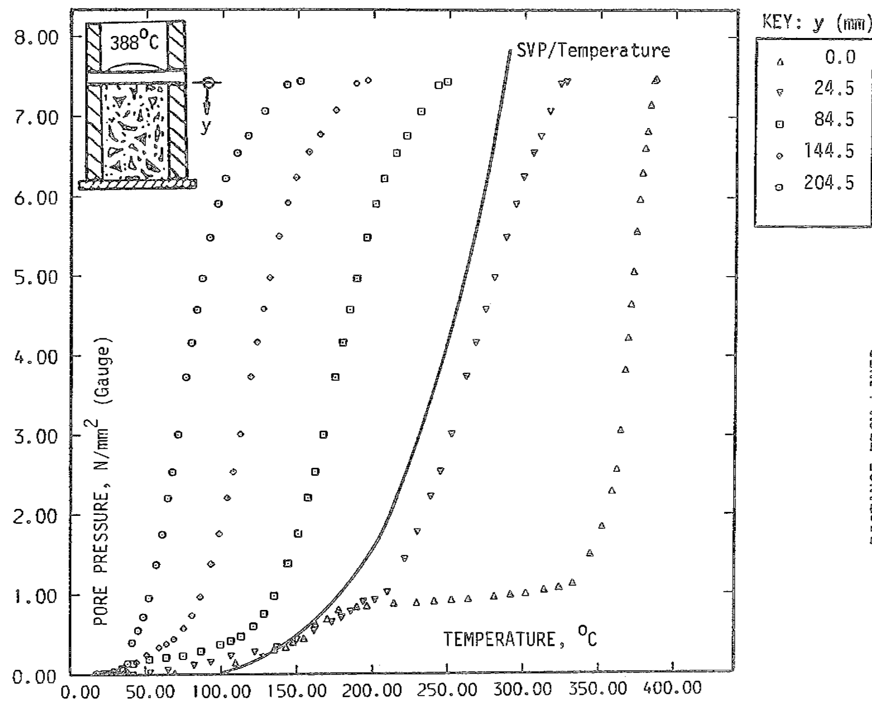

FIGURE 4. Temperature and pore pressure variation in concrete behind 'liner'.

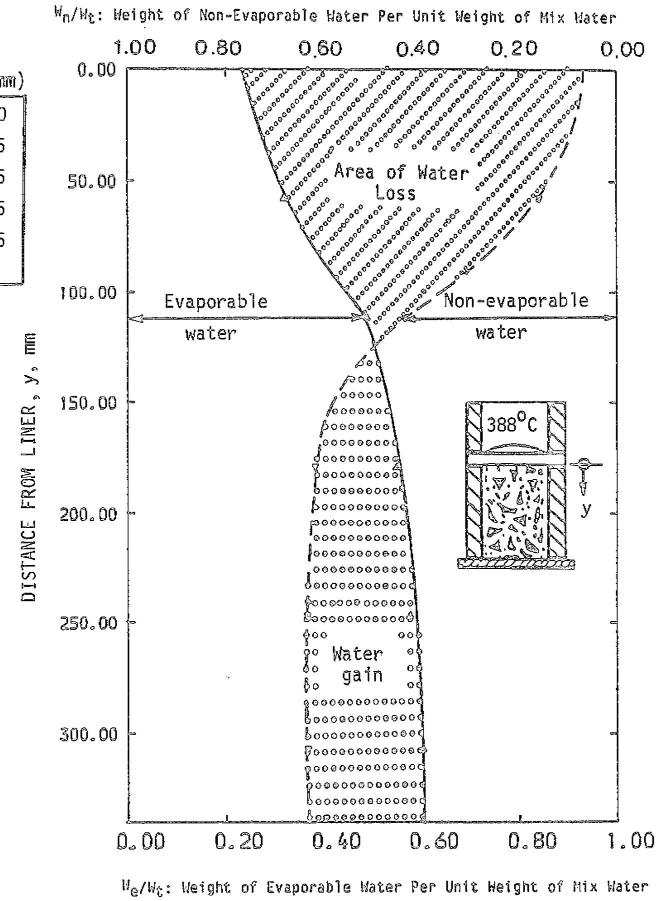

FIGURE 5. Phase diagram for water in concrete behind 'liner' at 121 minutes from Accident.