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MOISTURE MIGRATION IN THICK CONCRETE SECTIONS AT RAISED TEMPERATURES UP TO 400°C

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ABSTRACT

Moisture migration in non-uniformly heated concrete at temperatures in excess of 100°C is controlled dominantly by pore vapour pressures. In a totally sealed condition water is forced to migrate away from the most severely heated zones and to collect in cooler regions, causing physical saturation of the pores there. The presence of an unsealed boundary at atmospheric pressure creates a flow of water towards this boundary with a resultant loss of water from the concrete. The rate of drying during moisture migration, is a complex phenomenon related to several parameters, including permeability, length of moisture path, temperature and temperature gradient, and vapour pressure gradient with respect to temperature (ie the slope of the water saturation vapour pressure curve with respect to temperature.)

Experimental results are presented for two concretes, containing *limestone* and *basalt* aggregates. They illustrate two sets of overheat conditions in containment walls: (i) long-term service conditions at steady-state liner temperatures in the range 105°C to 200°C, with and without pressure venting close to the liner. (ii) short-term transient behaviour for an accident with temperatures to 400°C. The results show the amount of drying and the distributions of free and bound water throughout the wall thickness for 10 concrete walls of two thicknesses, (1.55m and 3.1m), after approximately 1.5 years from heating one face to the following temperatures; 105°C, 125°C, 150°C, 175°C, and 200°C. The results of a further five *vented* walls (1.55m thickness), confirm significantly higher rates of drying, and the ability of water to migrate *towards* higher temperature locations when driven by pore pressure gradients that are in opposition to the local temperature gradients. Finally, some short-term results (1 hour duration) for *sealed* and *vented* concrete heated to 400°C are presented.

1. INTRODUCTION

Moisture migration in non-uniformly heated concrete is a complex phenomenon when water flows contra to, or in the direction of, the temperature gradients. At temperatures above 100°C the initial flow is away from the hottest zones where pore pressures are highest. The free pore volume in *as cast* concrete (2% to 4%) plays an important role in the migration process:

(i) it acts to permit the development of water saturation vapour pressures on first heating,

(ii) it acts as a reservoir to the influx of moisture and is therefore instrumental in mitigating the highest initial saturation vapour pressures in nearby high pressure zones.

Later during this migration some of the free pore volume becomes physically saturated and the flow of water in these zones is then controlled by the pressure differentials across the length of the saturated zone. Conditions in these saturated zones are often ideal for the creation of additional cement hydration products. In turn, these reduce the permeability to water migration and reduce moisture loss to the surroundings.

In a wall heated and sealed from water loss at one face, and with free moisture loss permitted at the other, drying is dependent on the thickness of the section, the permeability of the concrete and its changes with temperature and moisture condition [1-3] , on the temperature crossfall and local temperature gradients within the wall, and whether or not physical pore saturation has developed anywhere.

2. DRYING OF THICK SECTIONS

The drying process of a reactor containment wall can be described in the following way, when pore pressures are taken to be the dominant driving forces and when the temperature crossfall is taken, for simplicity, to be linear throughout the thickness of the wall.

The higher inner temperature of the containment will cause a flow of moisture towards the outside. The local migration rates initially will depend on the local pressure gradients, dP/dx. For a linear temperature crossfall (i.e. dT/dx = constant), dP/dx will be highest initially at the location of the highest temperature, T, since dP/dT is highest there, when P is taken to be the saturation vapour pressure (SVP) of water at the local temperature. The one-dimensional rate of moisture flow, dm/dt, for concrete with permeability, k, may then be written,

$$\frac{dm}{dt} = k.\frac{dP}{dx}, \qquad \text{or,} \quad \frac{dm}{dt} = k.\frac{dP}{dT}.\frac{dT}{dx} \tag{1}$$

The term dT/dx of Eq.(1) implies that for a given permeability, k, and linear temperature crossfall, dm/dt will be greater (everywhere) in the thinner wall section. However, the term dP/dT plays an equally important role when walls of different thicknesses are being considered. Because P is a non-linear function of temperature, T, the influence of dP/dT in two walls of different thicknesses, but subjected to the same temperature crossfall, is to create faster migration in the thicker wall. This may be explained by considering a general location, distance x say, from the liner and noting the values of dP/dT at this location in each wall. Because the temperature crossfalls are the same, the temperature at location x in the thicker wall is greater than that at the same location in the thinner wall , thus illustrating that dP/dT, at x, is greater in the thicker wall.

Finally, because of the strong dependence of the coefficient of permeability on temperature [2,3] any assessment of drying rates in walls of different thicknesses, will depend on the product of the three separate ratios,

$$\frac{k_2}{k_1}; \qquad \frac{\left(dP/dT\right)_2}{\left(dP/dT\right)_1}; \qquad \frac{\left(dT/dx\right)_2}{\left(dT/dx\right)_1};$$

Here, the suffices 1 and 2 relate to the thinner and thicker wall respectively.

The ratio, R, of instantaneous migration rates - at location x - is then defined for the two walls as,

$$R = \frac{k_2}{k_1} \cdot \frac{\left(dP/dT\right)_2 \cdot \left(dT/dx\right)_2}{\left(dP/dT\right)_1 \cdot \left(dT/dx\right)_1} \qquad (2)$$

For linear temperature crossfalls (i.e. same hot face and same cold face temperatures in both walls), Eq.(2) reduces to;

$$R = \frac{k_2}{k_1} \cdot \frac{L_1}{L_2} \cdot \frac{\left(dP/dT\right)_2}{\left(dP/dT\right)_1} \qquad (3)$$

where L_1 and L_2 are the two wall thicknesses.

Eq.(3) represents the ratio, R, of the initial moisture migration and drying rates for the two wall thicknesses. R may be greater or less than unity and depends on the product of the geometrical ratio L_1/L_2, the temperature-dependent ratio $(dP/dT)_2/(dP/dT)_1$, and the temperature- and moisture-dependent permeability ratio, k_2/k_1. Because of this feature, it is not possible to say simply whether moisture movement will be faster in any one wall thickness with respect to the other. However, some information regarding the individual ratios is available for the example considered. $L_1/L_2 < 1$; $k_2/k_1 > 1$, close to the heated liner *, and

$$\frac{\left(dP/dT\right)_2}{\left(dP/dT\right)_1} \geq 1$$ always, because $T_2 > T_1$ everywhere, within the wall.

It is readily observed from the SVP/Temperature curve for water vapour that this ratio increases with temperature difference, while dP/dT increases with increase of temperature.

2.1. Simplified Example

Eq.(2) has been used [3] to demonstrate for two walls having the same permeability to water flow, wall thicknesses L_1 and $L_2 = 2L_1$, and subjected to the same temperature crossfall, that the initial migration ratio R is less than unity for approximately $0.5L_1$ from the hot face and for the remainder of the wall thickness R>1. In other words the initial migration rates are faster in the thinner over approximately the first half of the thickness of the thinner wall (first quarter of the thickness of the thicker wall), and thereafter the migration rates are faster in the thicker wall

As moisture migration continues, pore pressures in the hotter regions reduce and approach uniformity. This behaviour is coupled with the release of some bound water and the creation of a pore structure with increased permeability. A totally different situation develops in cooler regions where due to the reduced pore pressures and migration rates there, water accumulates and causes physical saturation of the pore structure. When this occurs further migration is controlled primarily by the pressure gradients (hydraulic) across the zone of saturation and the local permeability values. The thermal and moisture conditions in the saturated zones are ideal for the creation of additional cement hydration products. These formations reduce the local permeability and restrict further moisture migration. This feature plays a dominant role in the drying of thick wall sections. Surface drying at the outer face of the wall is a separate phenomenon and is governed by the local external environment.

* Generally the permeability, k, increases with temperature and for hot dry concrete its value may be several orders of magnitude greater than conventionally moist-cured concrete [4].

3. INFLUENCE OF TEMPERATURE

3.1. Steady-state liner temperatures, 105°C - 200°C; limestone concrete.

Figures 1 to 5, Parts (a) (3.1m thick wall) show clearly that both the amount of drying local to the liner and the extent of drying into the wall increase with increase of liner temperature. Drying to a distance of 1.5 to 2m has occurred at the highest temperatrue after 400 days heating and about 90% of the evaporable water has been expelled from the 1.5m layer close to the liner. In contrast to this behaviour, at a liner temperature of 105°C, only about 20% of the evaporable water was lost at 1.0m into the concrete, and 50% still remained at the location of the liner itself after 525 days of heating. Concrete details are given in Table 1.

The influence of temperature is similar in the thinner wall sections (1.55m) although the variations are somewhat "blurred" for the *vented* specimens in that the duration of heating was not the same in all experiments.

Evaporation drying from the cold face was essentially unaffected by the influence of temperature, thus indicating that the rate of migration close to the exposed boundary is controlled more by the local external environment than by the liner temperature or the temperature crossfall. Moisture migration in the zone of excess water is clearly slow compared to the *suction* effect of the external environment on water close to the outer face of the wall.

3.2. Short-term transient temperatures to 400°C; basalt concrete.

A short-term accident situation is considered for which the liner temperature is subjected to sudden heating to 400°C and thereafter sustained. The transient pore pressures were monitored for several hours into the accident. Because only short-term responses were sought, short specimens (0.34m) were used. Three sealing conditions were investigated at the end remote from the liner; totally sealed, partially sealed and unsealed. The purpose was to determine the influence of the downstream boundary conditions on moisture migration and pore pressure changes. Indications were that during the first hour of heating the sealing conditions did not influence either pore pressure development or drying. Therafter, drying conditions were different. Figure 6, parts (a), (b) and (c), show the evaporable and non-evaporable water distributions throughout the 0.34m thickness of concrete at the end of each experiment. Part (a) is representative of the water distributions at one hour into the accident, while parts (b) and (c) show the extent of drying after periods of soaking at the high temperatures, for the partially sealed and unsealed cases. Concrete details are given in Table 1.

4. INFLUENCE OF WALL THICKNESS

Comparison of Figures 1 to 5, parts (a) and (b), show that for two wall thicknesses, the amount of drying - for approximately the same periods of heating and same temperature crossfalls - as a proportion of the wall thickness, is similar, thus indicating that more drying has occurred in the thicker wall.

The form of the evaporable and non-evaporable water distributions is also similar for the two wall thicknesses, both showing zones of excess wetting and probable physical saturation in the cooler parts of the wall.

The evaporation drying from the cold face of the wall is essentially independent of wall thickness.

5. CONCLUDING REMARKS

In non-uniformly heated concrete the rate of moisture migration is dependent upon several parameters, including, permeability, temperature, temperature gradient, moisture content and time. In as cast concrete the saturation vapour pressures of the pore water help to define the initial mass movements. Later, continued drying in the hottest zones causes water to migrate from these locations and form zones of physical saturation and low permeability. These lower temperature saturated zones play a major part in controlling the long-term moisture migration process. Evaporation drying from an exposed boundary at ambient temperature is essentially independent of the moisture migration caused by the temperature gradients in thick sections.

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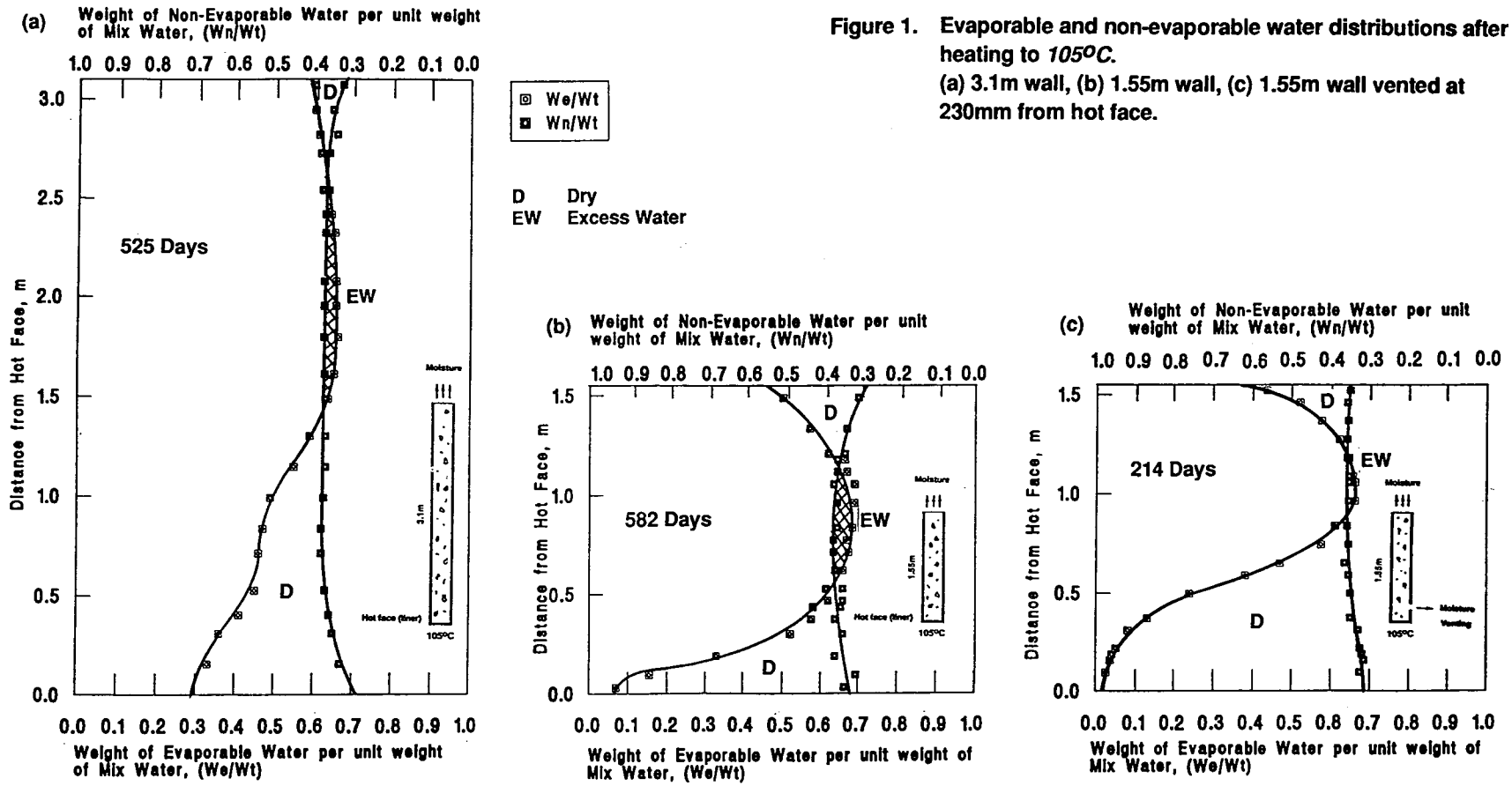


Specimen R18, Length 3.1m (105°C)

Specimen A1, Length 1.55m (105°C)

Specimen O15, Length 1.55m (105°C and Vented)

Figure 1. Evaporable and non-evaporable water distributions after heating to *105°C*.
(a) 3.1m wall, (b) 1.55m wall, (c) 1.55m wall vented at 230mm from hot face.

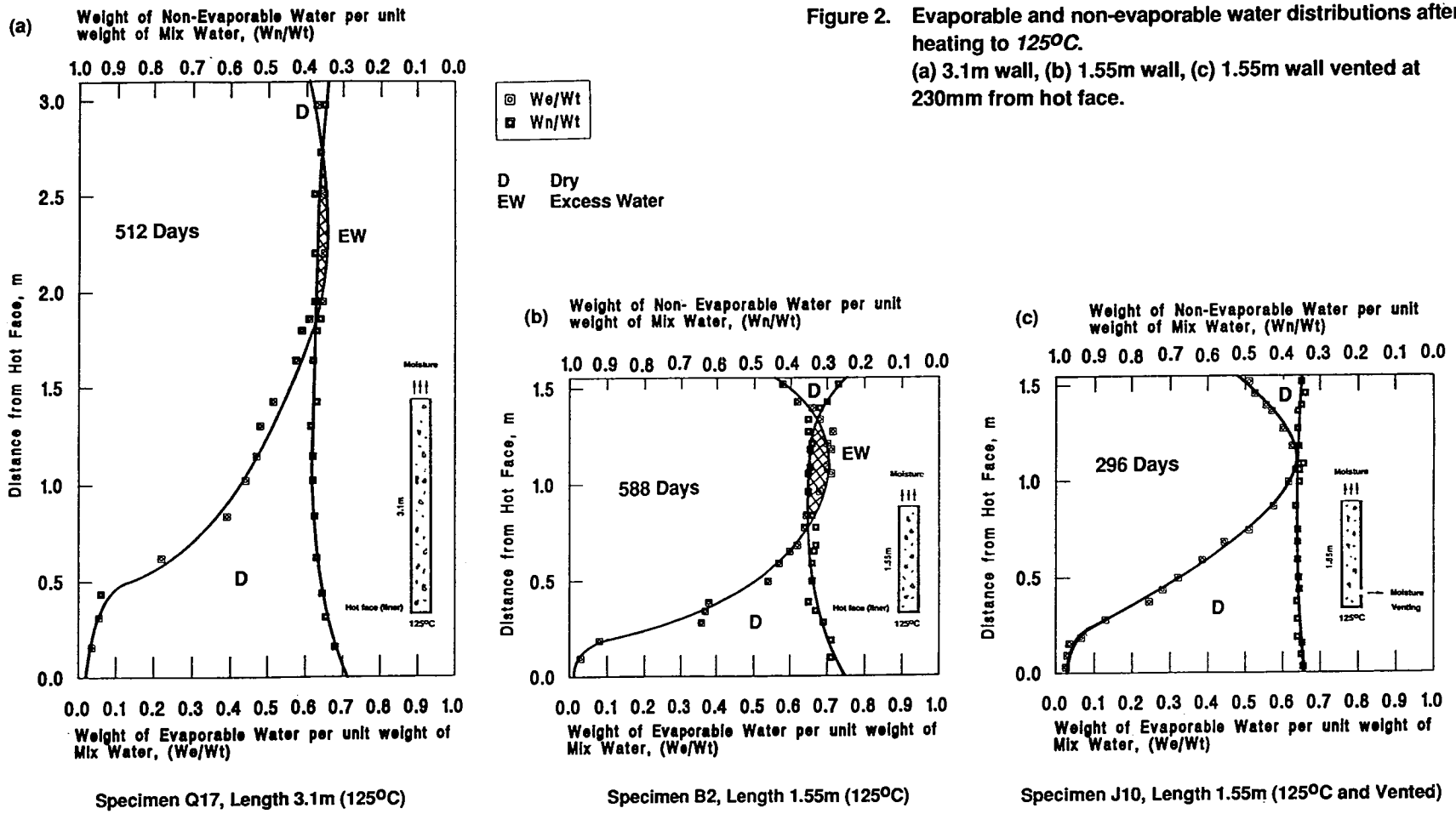
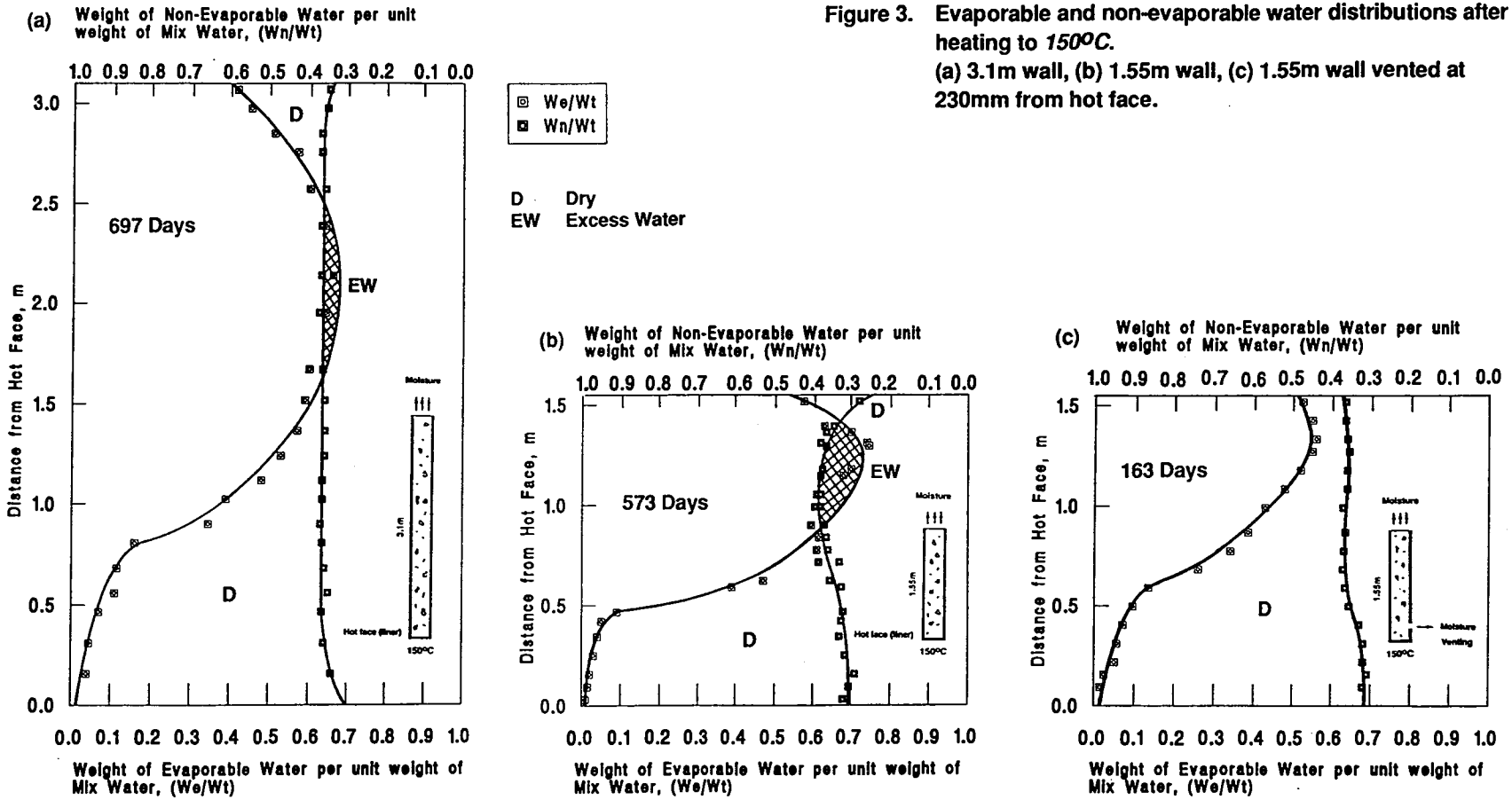


Figure 2. Evaporable and non-evaporable water distributions after heating to *125°C*.
(a) 3.1m wall, (b) 1.55m wall, (c) 1.55m wall vented at 230mm from hot face.

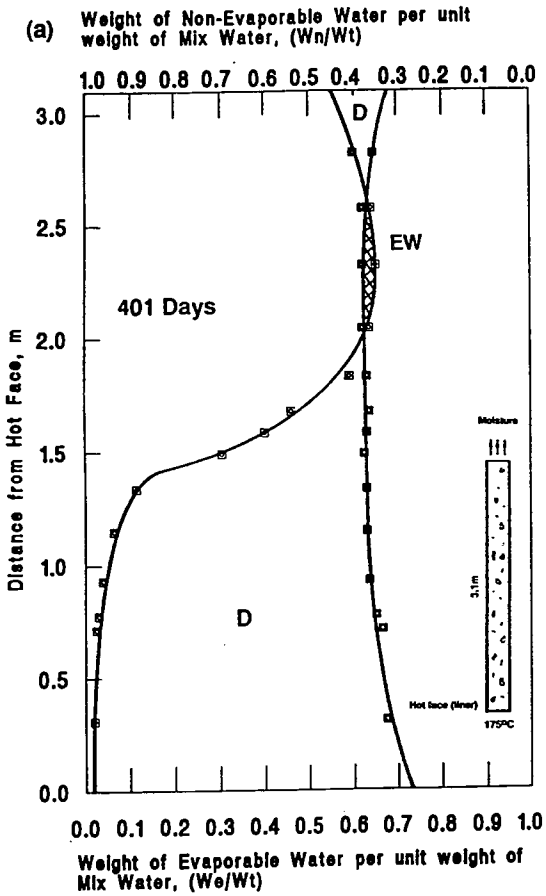


Specimen P16, Length 3.1m (150°C)

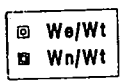
Specimen C3, Length 1.55m (150°C)

Specimen F6, Length 1.55m (150°C and Vented)

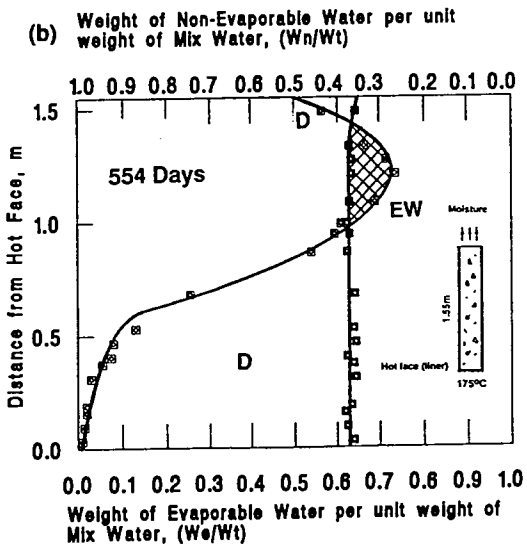
Figure 3. Evaporable and non-evaporable water distributions after heating to *150°C*.
(a) 3.1m wall, (b) 1.55m wall, (c) 1.55m wall vented at 230mm from hot face.



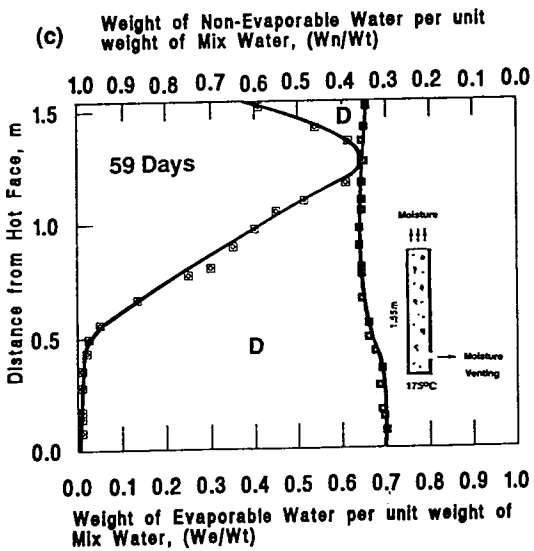
Specimen T20, Length 3.1m (175°C)



D Dry
EW Excess Water

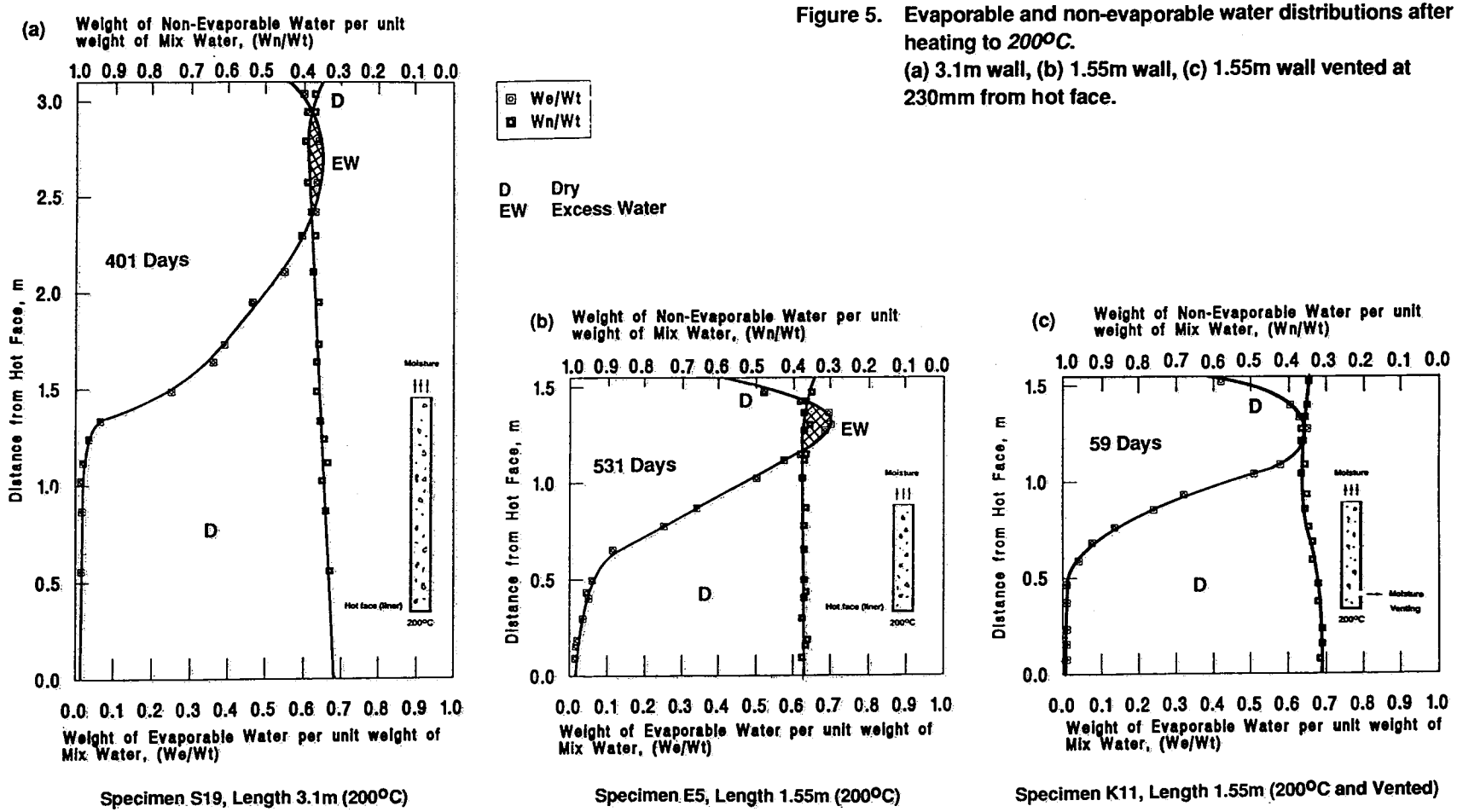


Specimen D4, Length 1.55m (175°C)



Specimen N14, Length 1.55m (175°C and Vented)

Figure 4. Evaporable and non-evaporable water distributions after heating to *175°C*.
(a) 3.1m wall, (b) 1.55m wall, (c) 1.55m wall vented at 230mm from hot face.



Specimen S19, Length 3.1m (200°C)

Specimen E5, Length 1.55m (200°C)

Specimen K11, Length 1.55m (200°C and Vented)

Figure 5. Evaporable and non-evaporable water distributions after heating to *200°C*.
(a) 3.1m wall, (b) 1.55m wall, (c) 1.55m wall vented at 230mm from hot face.

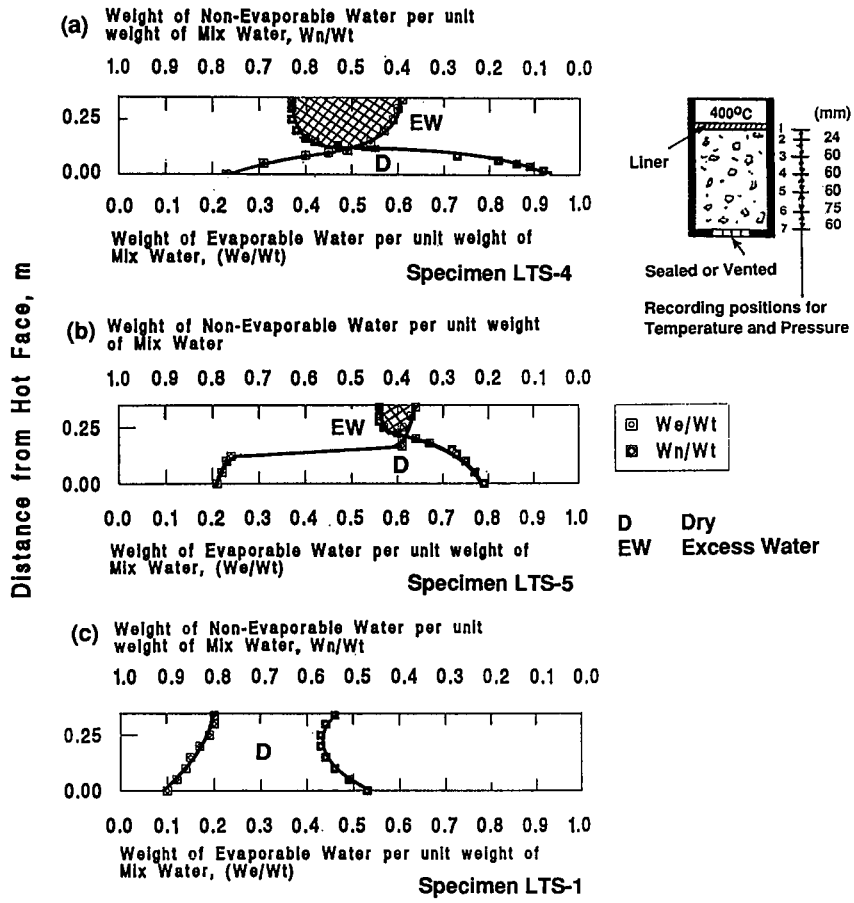


Figure 6. Evaporable and non-evaporable water distributions after heating to *400°C*. Length of specimen, 340mm. (a) Totally sealed (b) Partially sealed (c) Unsealed at cold face.

Constituent	Limestone	Basalt
Cement (OPC)	1.00	-
Cement (SRPC)	-	0.5
Cemsave	-	0.5
Sand	2.67	1.46
Coarse Aggregate	4.00	2.51
Water	0.60	0.39
Plasticiser	-	0.0057
28 Day Cube Strength (N/mm^2)	42	52

Table 1: Mix proportions by weight of two concretes tested.