AN UNEXPECTED OBSERVATION AFTER DRYING AAR-AFFECTED CONCRETE

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Abstract

After completing the first phase of an investigation into the effect of ambient relative humidity (RH) on the swelling or shrinking of AAR-affected concrete, the specimens were oven-dried at 50°C to establish their water contents. As the surface temperature of concrete exposed to the sun in South Africa can exceed 50°C, this temperature was not considered excessive.

When the same specimens were exposed to a different range of RHs, higher than before, they absorbed water as expected, but unexpectedly shrank rather than swelling. The observations are described in detail, and a theoretical explanation for the unexpected shrinkage is given, in terms of capillary stresses acting on porous materials subjected to drying and subsequent wetting.

Keywords: Absorption, drying, shrinkage, suction, swelling

1 INTRODUCTION

Cores of concrete are routinely drilled from structures apparently affected or damaged by AAR, with the object of confirming the occurrence of AAR as the cause of damage, to determine the potential for further expansion (e.g. Hobbs, [1]) or to assess future potential swelling pressure (e.g. Alexander, et al., [2]). The usual practice has been to core-drill using water as a coolant. After the surface wetness of the core has been dried off by exposure to air at room temperature (usually about 20°C), the cores are strain-gauged, either with electric resistance gauges or Demec targets, and then subjected to further testing. Occasionally, a core will be cut longitudinally to form rectangular slabs 10 to 15mm thick in order to reduce their least dimension and hasten equilibration with test relative humidities, absorption of water, etc. Initial air-dry masses are measured, changes of mass are recorded during the tests and finally, the specimens are oven-dried (usually at 105°C) to ascertain the water contents of the concrete relative to oven dryness before and during the tests.

2 THE PRESENT EXPERIMENT

Several cores, taken from structures affected by AAR, were sawn into 10mm-thick slabs and Demec targets were affixed to each slab at a gauge length of 100mm. Five groups of four specimens each were then exposed, within sealed glass desiccators, to atmospheres maintained at various relative humidities by means of saturated salt solutions. The temperature of the laboratory was controlled at 20° ± 1°C. Initially, RHs of 32%, 76% and a nominal 100% were used by means of saturated solutions of calcium chloride, sodium chloride and over distilled water. After 60 days, equilibrium had been reached and this stage of the test was terminated. Although it had been decided to proceed with further tests using the same specimens, but a different range of RH, the initial water contents were required and the specimens were dried in an oven maintained at 50°C. As this temperature is well within the range of surface temperatures to which concrete can be exposed in South Africa, it was not considered excessive.

In the second series of tests, the groups of specimens were exposed to a range of higher relative humidities (RH 86 to 98%), the nominal RH 100% over distilled water of the previous tests being replaced by 98% over a saturated solution of potassium sulphate. It was now found that all of the specimens at first shrank, before eventually expanding. The behaviour is graphed in Figures 1 to 3. In these diagrams, specimens "A" and "B" had each been cut from a different core and both cores had been drilled from structures that had been damaged by AAR. Specimens "C" had been cut from a core taken from concrete made with dolomite aggregate, which is not affected by AAR. The AAR-affected concrete contained reactive Witwatersrand quartzite aggregate (Blight, et al., [3]). For all three of the cores, maximum initial shrinkage occurred at a controlled RH 86% with less shrinkage occurring at higher temperatures.

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At 60 days, none of the specimens had yet regained their initial length. In addition to the groups of specimens A, B and C, two similar groups of four specimens (D and E, not illustrated here) both behaved in a similar way. Each group consisted of slabs cut from one core, the total number of cores being five in all.

After 60 days, the specimens that had been exposed to RH 98% were wrapped in paper towelling, the ends of which dipped into a tray of distilled water in the bottom of the desiccator, thus allowing the cores to absorb liquid water. The specimens previously exposed to RH 93% were exposed to RH 86% and those previously exposed to RH 86%, to RH 98%.

The specimens with access to liquid water (H_2O in Figures 1 to 3) absorbed water very rapidly and also expanded, but not to the extent of expansion of the same specimens exposed to a nominal RH 100% prior to drying at 50°C. Obviously, the process of drying at 50°C had been more severe than expected, but the intriguing aspect is that the concrete shrank as it was simultaneously absorbing water.

3 FURTHER TESTING

To further investigate and confirm the phenomena recorded in Figures 1 to 3, after 83 days the specimens were again oven-dried at 50°C for seven days and the original measurements were repeated, except that all specimens were now exposed to RH 98%. The results of the first seven days of this third stage of testing are shown in Figure 4. In this figure, the zeros of measurement for strain and water content are the same as in Figures 1 to 3. The measurements at 90 days were recorded after removing the specimens from the 50°C oven, placing them into a sealed desiccator over silica gel to cool and, when at 20°C, measuring initial masses and strains. After this, the silica gel in the desiccator was replaced with a saturated solution of potassium sulphate to provide the RH 98% atmosphere.

Comparing Figure 4 with Figures 1 to 3, it will be seen that the residual shrinkage at 90 days was approximately equal to the maximum shrinkage originally recorded at about three days, while the residual water content at 90 days was also approximately the same as the water content at three days. Thereafter, further shrinkage took place up to 92 to 95 days, after which the specimens again began to swell.

4 A TENTATIVE EXPLANATION FOR THE UNEXPECTED SHRINKAGE

Concrete is a porous material in which the pores may be saturated with water or partly filled with air and water. Free water in unsaturated concrete (i.e. water that is not chemically bound) exists in capillary form at the boundaries of air-filled voids between solid constituents of the concrete. Because of the curvature of the capillary water menisci, the pressure in the water is less than that of the air (Marshall, [4]). If the air is at atmospheric pressure, the water will be in a state of tension relative to atmospheric pressure. The difference between air and water pressure is termed the suction, p'', i.e.

$$p'' = u_a - u_w \text{ (units N/mm}^2\text{ or MPa)} \quad (1a)$$

where u_a = air pressure in pores and u_w = water pressure in interstices between air-filled pores. The suction is also given by:

$$p'' = 2T/r \quad (1b)$$

where T is the surface tension of water and r is the radius of curvature of the air-water menisci. T has units of N/mm length of surface, hence with r in mm the units in equation (1b) are also N/mm^2.

Alternatively, the suction can be represented by the weight per unit area of a suspended column of water what would balance the upward pull of one of the menisci. This is illustrated in Figure 5, which shows that

$$p'' = h\gamma_w \quad (1c)$$

where γ_w is the unit weight of water in N/mm^3 and with h in mm, p'' also has units of N/mm^2.

Referring to Figure 5:

The work done in transporting unit weight of water vapour from the free water surface to the water meniscus is

$$\Delta w = \int_o^h v dp \quad (2a)$$

where v is the volume of unit weight of water vapour and dp is the change in pressure experienced in going from 0 to h. The units of v are mm^3/N and those of dp are N/mm^2. Hence, the units of Δw are mm. Assuming that water vapour behaves as a perfect gas, it can be shown that

$$\Delta w = \frac{R\theta}{m_w} \log_e \frac{p}{p_o} \qquad (2b)$$

in which R is the universal gas constant, θ is the absolute temperature and m_w is the molecular mass of water. p/p_o is the relative humidity H of the air in the air-filled pores of the concrete and since the water vapour is in equilibrium with the liquid water, it must have equal potential energy per unit weight, i.e.

$$\Delta w = h$$

$$\text{or} \quad \frac{R\theta}{m_w} \log_e H = \frac{p''}{\gamma_w} \qquad (2c)$$

This is the well-known Kelvin equation, which at a standard temperature of 20°C can be expressed as

$$p'' = 311 \log_{10} H \ N/mm^2 \qquad (2d)$$

It is obvious from equation (2) that as concrete dries and the water menisci withdraw, r will decrease, p" will increase and H decrease. Table 1 gives some values of H and the corresponding values of p".

The negative sign of p" shows that the water may be subjected to very large tensions that result in corresponding compressions in the solid skeleton of the concrete. Because the water tensions, pulling the solid skeleton together, only act over the surface area of the water-filled parts of the pores, the value of p", i.e. that giving rise to an average isotropic compressive stress in the concrete is:

$$p''(eff) = \chi (u_a - u_w) = \chi p'' \qquad (3a)$$

where χ is a factor of less than unity if the concrete is unsaturated. The linear compressive strain in the concrete in a given direction will be:

$$\varepsilon = \frac{\chi p''}{E(1-2\nu)} \qquad (3b)$$

where E is the elastic modulus and ν is Poisson's ratio. Equation (3b) provides an explanation for the shrinkage strains undergone by concrete as it is dried, and also the swelling strains that occur when it is wetted. An interesting situation must occur when the concrete becomes so dry that the water menisci disappear. $\chi p''$ must disappear simultaneously and so must the compression stress to which the concrete was subjected. As the concrete absorbed water vapour after being placed in controlled RH environments, the absorbed water vapour condensed and the menisci were re-established in the fine-pored part of the concrete solid skeleton. Initially, the re-established menisci were of very small radius and hence (in terms of equation (1b) and Table 1), corresponded to very large water tensions (p"). However, initially the factor χ would also have been small. As the radii of the menisci increased, p" would have decreased and χ increased. About five days after the specimens had been placed in the new controlled RH atmospheres (see Figures 1 to 3), the maximum compressive stress and strain were reached in the concrete.

Taking the elastic modulus of concrete as 20000 MPa and Poisson's ratio as 0.1, $\chi p''$ can be calculated from equation (3b) as $\chi p'' = E(1-2\nu) = 0.016\ \varepsilon$ MPa with ε in microstrain.

The range of maximum compressive strains measured in the test series was from 370 to 600 microstrain, hence maximum values of $\chi p''$ would have varied from 5.9 to 9.6 MPa.

As water continued to be absorbed by the concrete, the radii of the menisci continued to flatten, $\chi p''$ started to reduce and the concrete began to swell, as shown by Figures 1 to 3. When given access to free water, all of the initial compression was recovered, but the concrete did not swell to anything approaching the extent of its original swelling when exposed to water vapour.

5 DISCUSSION AND CONCLUDING REMARKS

It is not known if the phenomena described in this paper have been observed before. No reference to this type of behaviour has been found in the literature. Care must clearly be taken in making measurements of the water content of concrete, especially if such measurements represent an intermediate stage of a longer test. The fact that both AAR-affected cores and the control core of dolomite aggregate concrete behaved similarly, shows that the phenomenon of shrinkage while absorbing water vapour after drying is a general one and has little or no connection with the process of attack by AAR.

It has long been known [5] that AAR can be arrested if the affected concrete can be dried out to below a relative humidity in the pores of 95% or less. Reference to Table 1 shows that this corresponds to a value of $\chi p''$ of about 5 to 7 MPa. Relative humidities have been measured in situ, in exposed reinforced concrete structures in South Africa [6], that correspond to p''=5MPa and more, and which persist for periods of a month or more if the concrete is not re-wetted by rain. It is also well known that drying shrinkage of concrete is only partly reversible on re-wetting, e.g. [7], and that swelling caused by AAR can be severely inhibited by applied mechanical stress. Also, that removing the stress results in only partial recovery of the swelling that would have occurred had the concrete not been loaded. These related phenomena, together with the results described in this paper, are aspects of the behaviour of concrete that is periodically loaded and unloaded by drying and re-wetting, a subject that has been researched relatively little, but deserves more attention. What little research has been done, has been physical in nature, and the chemistry of the processes should also receive attention.

6 REFERENCES

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TABLE 1: Values of H and corresponding values of p'' calculated from equation (2d).

H%	p'' N/mm^2 (MPa)	Meniscus radius R mmx10^{-3} (micron)
100	0	Menisci planar
98	-2.7	5.3
95	-6.9	2.1
85	-21.9	0.66
75	-38.8	0.37
60	-68.9	0.21
45	-108	0.13
30	-163	0.09
15	-256	0.06
5	-405	0.04

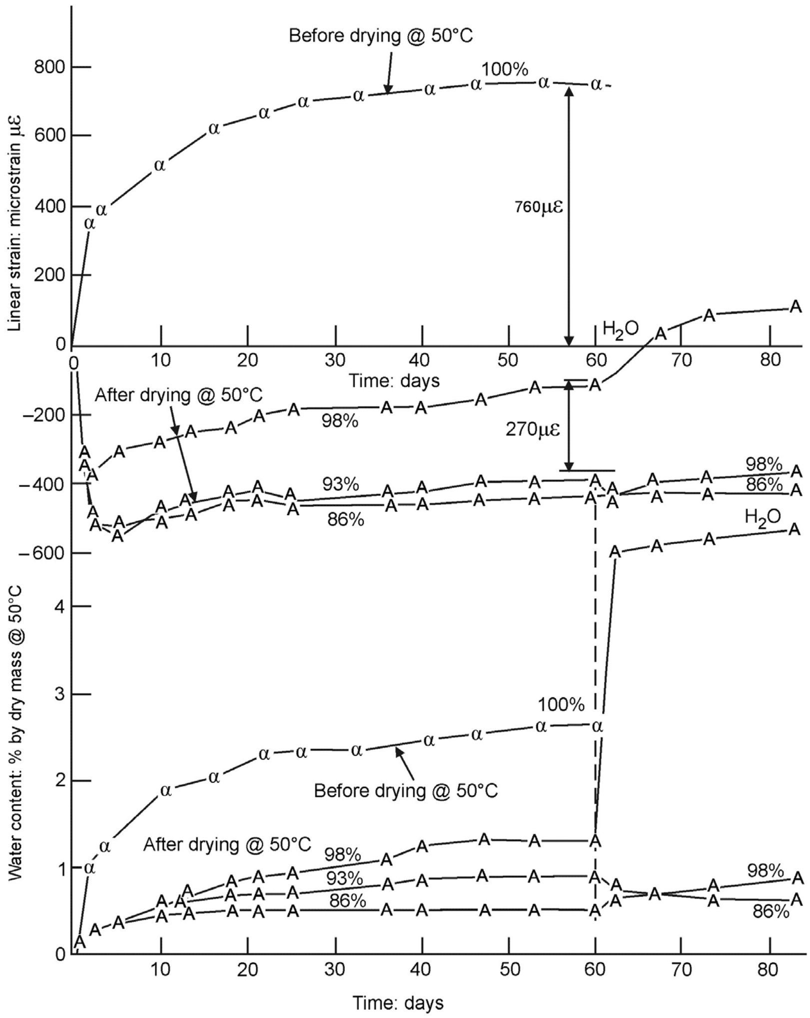

Figure 1: Behaviour of specimens "A" during exposure to relative humidities of 86%to 98% at 20°C after drying at 50°C. ("α" shows behaviour of specimen exposed to nominal 100% RH before drying at 50°C.)("A") specimens were AAR-affected.

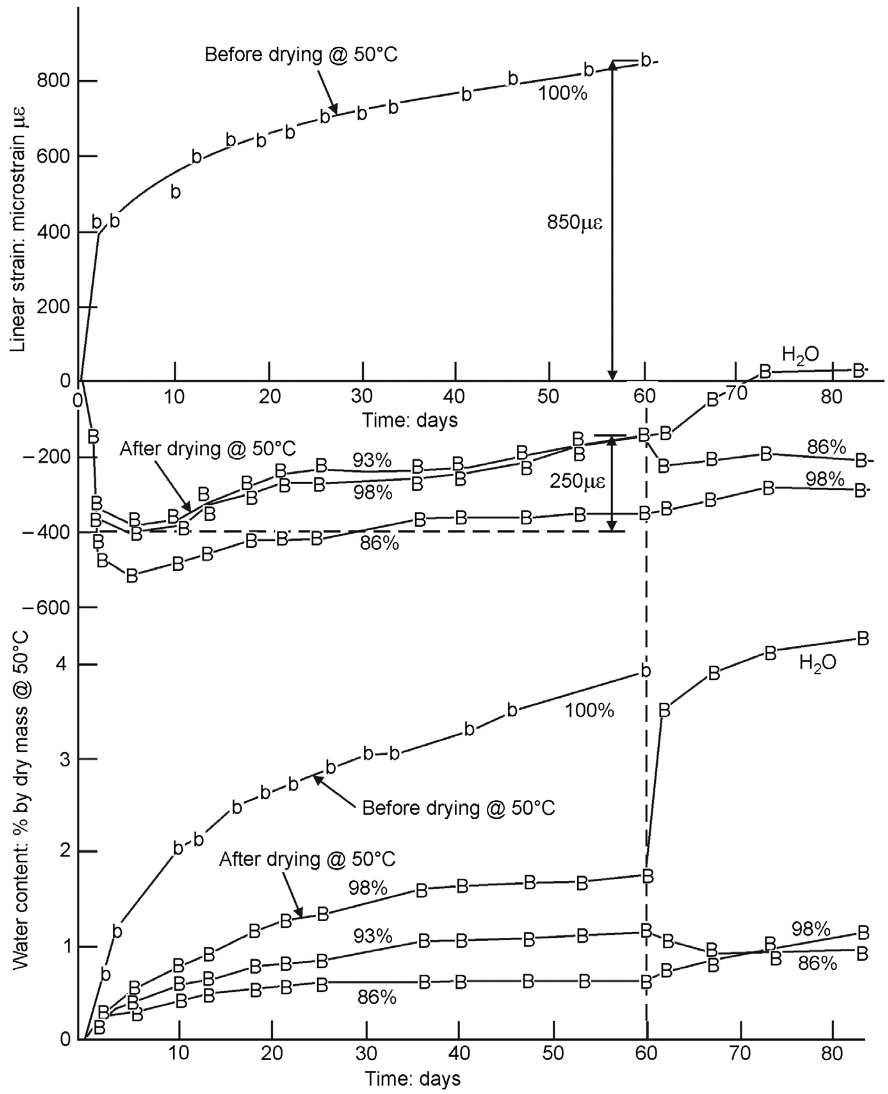

Figure 2: Similar to Figure 1, but for specimens "B" ("B" specimens were AAR-affected).

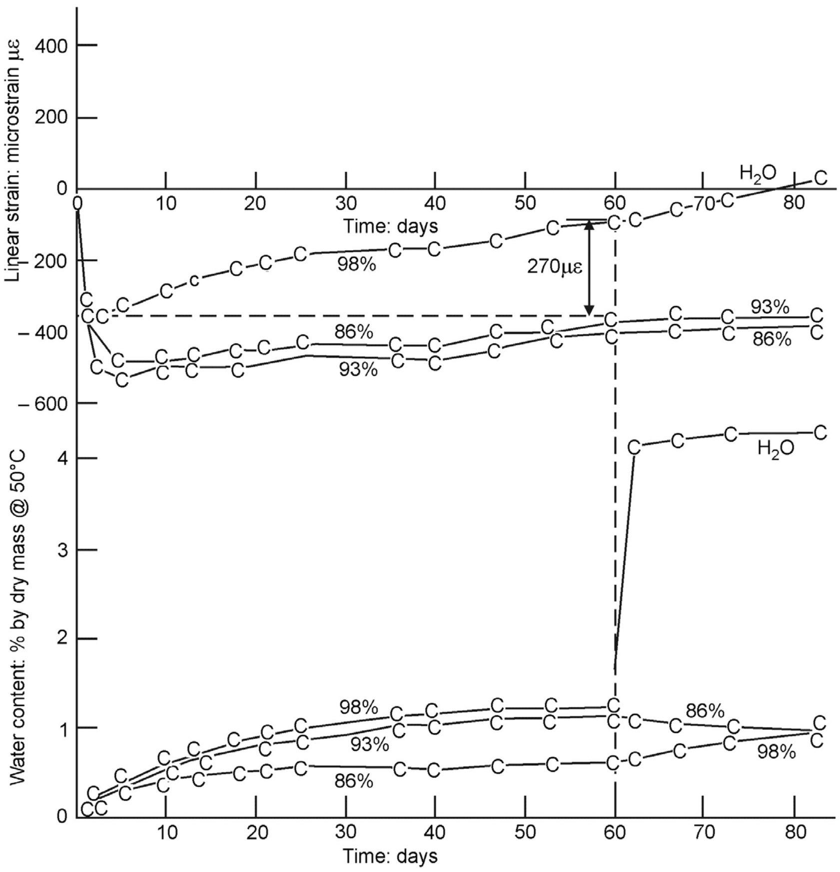

Figure 3: Similar to Figures 1 and 2, but for specimens "C" (Specimens "C" have dolomite aggregate and are not affected by AAR).

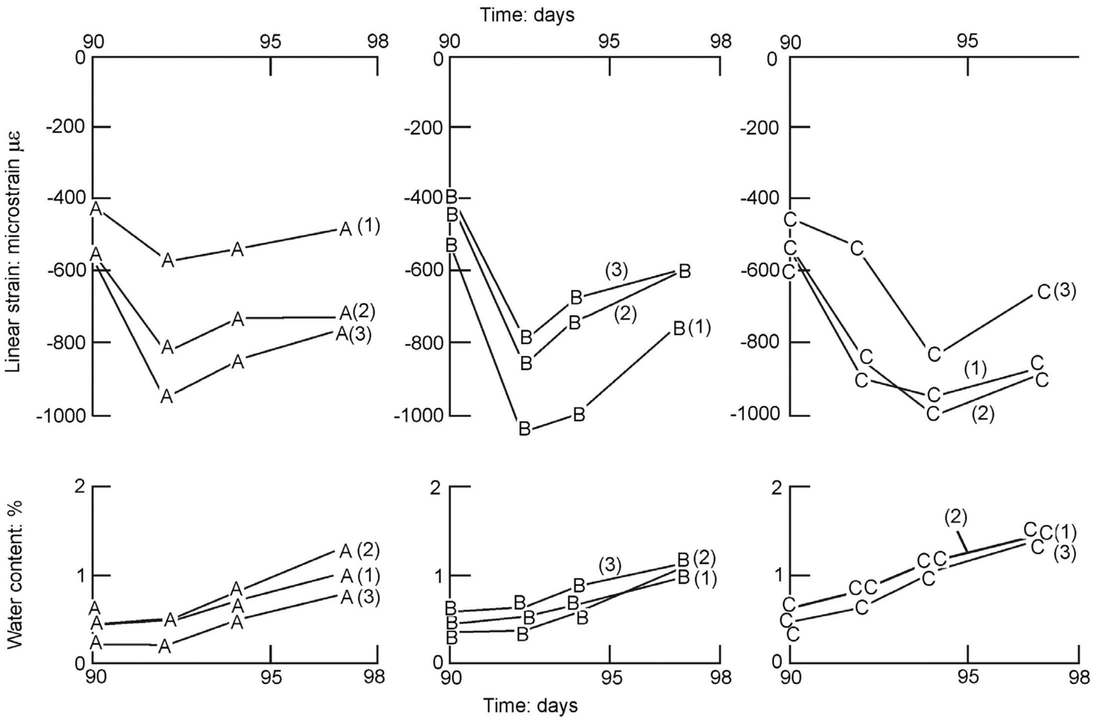

Figure 4: Behaviour of specimens after re-drying at 50°C followed by exposure to 93% relative humidity, at 20°C. In each case, zero strain and water content are the same as in Figures 1, 2 and 3. (The numbers (1), (2) and (3) allow water content and linear strain curves to be matched).

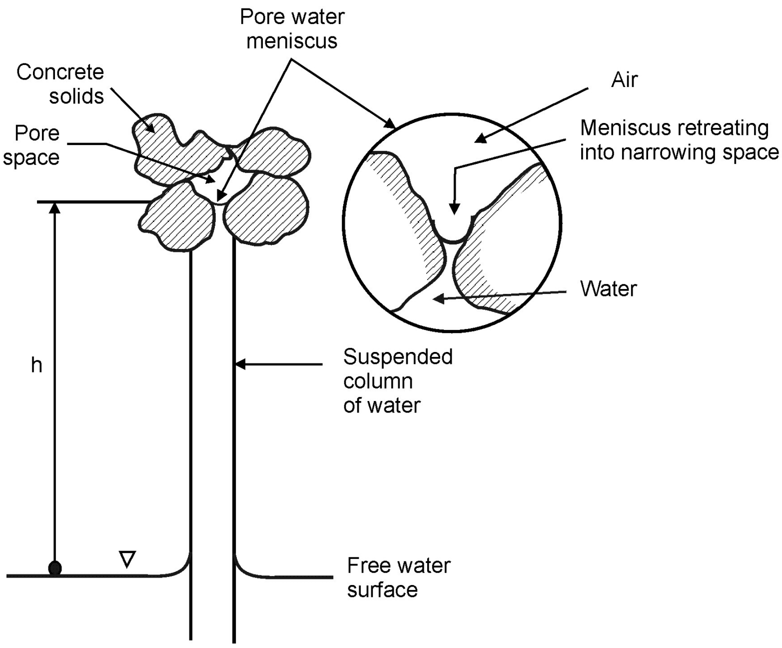

Figure 5: Capillary model of partly saturated concrete.