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Effect of initial moisture content on wick action through concrete

J.M. Aldred[a,*], B.V. Rangan[a], N.R. Buenfeld[b]

[a]*Department of Civil Engineering, Curtin University of Technology, GPO Box U1987, Perth, Western Australia 6845, Australia*
[b]*Department of Civil and Environmental Engineering, Imperial College, London SW7 2BU, UK*

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Abstract

Wick action is the transport of water through a concrete element from a face in contact with water to a drying face. Wick action tests were conducted on concrete specimens of varying thickness and initial moisture condition over a period of 300 days. The rate of wick action was inversely proportional to thickness regardless of the specimen preparation. Initial moisture condition was found to significantly influence wick action with vacuum-saturated specimens having the highest rate followed by saturated and then dried specimens. Possible reasons are discussed.

Keywords: Drying; Diffusion; Transport properties; Wick action

1. Introduction

Wick action is defined as the transport of water (and any species it may contain) through a concrete element from a face in contact with water to a drying face [1]. Wick action has been considered a combination of capillary absorption and water vapour diffusion with evaporation being the linking process as shown in Fig. 1. If a concrete element was initially dry, early water transport would be determined by sorptivity. If initially saturated, water vapour diffusion would dominate. Regardless of the initial moisture condition, the expectation was that approximately the same steady state flux would be eventually established with the distance of the wet/dry interface from the drying face and the rate of water transport at steady state being determined by the intrinsic sorptivity and vapour diffusivity of the concrete. Research by Buenfeld et al. [1] showed wick action also to be a function of section thickness. A model based on the sorptivity and vapour diffusivity of the concrete was developed to describe the depth of the wet/dry interface as well as the rate of wick action. These tests were conducted on initially saturated mortar specimens.

Tests by Aldred et al. [2] on wick action through initially saturated and dried concrete showed a higher rate of wick action in the saturated specimens. This relationship was found for both plain ordinary Portland cement (OPC) and hydrophobic concrete with water/cement ratios of 0.4 and 0.6. These data suggest that the initial moisture state may play an important role in wick action.

Moisture content is known to strongly influence water transport in concrete. However, the drying of concrete tends to increase, rather than decrease, penetrability due to microcracking within the concrete matrix [3]. Studies by Powers et al. [4], Vuorinen [5] and Hearn [6] showed the permeability coefficient increased by one to two orders of magnitude when cement paste and concrete had been dried prior to testing. Powers et al. [4] observed that the permeability of hardened cement paste increased by nearly 70 times after gradual drying to 79% relative humidity. Vuorinen [5] found that oven drying increased permeability by two orders of magnitude. The volume of water absorbed by a dry concrete surface is also greatly increased by the degree of drying [7]. Parrott [8] found that ‘‘drying at intermediate relative humidities, particularly in the range from 0.2 to 0.6, causes a partial collapse in the smaller pores (diameters less than about 40 Å) and a corresponding increase in the volume of larger pores’’. Accordingly, pore structure changes due to drying are complex and should not be considered simply coarsening the larger pores.

The current research investigated wick action through forced and air-dried, saturated and vacuum-saturated speci-

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* Corresponding author. Tel.: +61-413-150945; fax: +61-8-94296555.
E-mail address: jaldred@ghd.com.au (J.M. Aldred).

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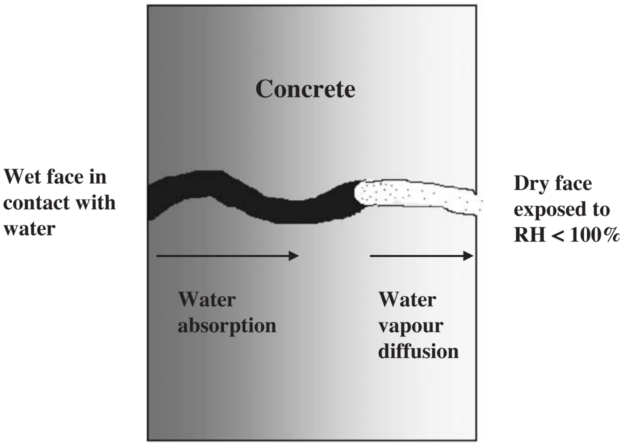

Fig. 1. Wick action through concrete [1].

mens of varying thickness to help clarify the influence of initial moisture state on wick action.

2. Experimental methods

2.1. Materials

The concrete used in this study contained 400 kg/m^3 of OPC, 765 kg/m^3 of natural sand, 267 kg/m^3 of 5- to 10-mm crushed granite and 790 kg/m^3 of 10- to 20-mm crushed granite with a free water/cement ratio of 0.4. The aggregate gradings complied with the requirements of ASTM C33-93 [9]. A superplasticiser was added as required to achieve a target slump of 100 mm. The superplasticiser was "Daracem 100", supplied by W.R. Grace, a retarding sulphonated napthalene-based product conforming to the requirements of ASTM C494-92 Type G [10].

2.2. Test environment

The environmental conditions during testing were controlled within a temperature range of 30 ± 2 °C and relative humidity range of 75 ± 5%. The test environment was ventilated with fans to prevent humidity gradients and provided a minimum evaporation rate for free water of more than twice the maximum measured evaporation rate from the specimen with the highest initial rate of moisture loss. Accordingly, the level of ventilation was considered adequate to prevent the build up of humidity at the concrete surface. Unfortunately, the fans at the location of the 100-mm specimens were left off for the week before the measurement at 108 days reducing the measured value.

2.3. Specimen preparation

After casting, the concrete specimens were covered with polythene and demoulded after 24 h. The specimens were placed in a fog room at 30 °C for a minimum of 16 weeks to reduce effects associated with continued hydration during testing. Prior to sealing into the test cells, all specimens had 3 mm removed from the flat surfaces by grinding to reduce the gradients associated with cast or trowelled finishes [1]. Three types of concrete specimen were used in this study: 145 mm in diameter and nominally 50 or 100 mm in thickness after grinding and 100 mm in diameter and nominally 180 mm in thickness after grinding. The 100- and 180-mm-thick specimens both had a surface area to volume (SA/V) ratio of 0.5 cm^{-1} while the 50-mm-thick specimens had a SA/V ratio of 0.7 cm^{-1}. Two specimens were prepared for each preparation procedure for the 50-mm-thick specimens and one for the 100- and 180-mm-thick specimens. The results for the 50-mm specimens are presented as the average value.

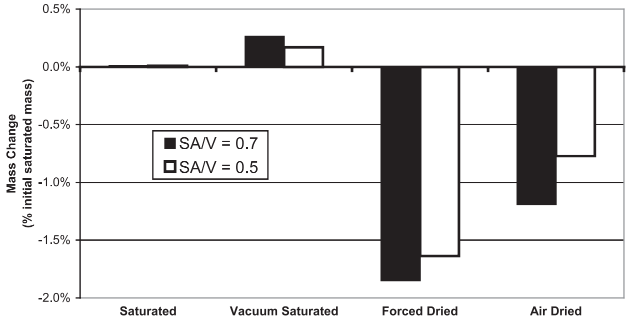

Fig. 2. Changes in mass for different preparation procedures compared with initial saturation.

The forced drying procedure attempted to avoid the severe microcracking associated with drying at 105 °C [11] and the inconvenience of prolonged ambient drying [12]. The procedure adopted was similar to RILEM CPC 11.2 [13] with additional ambient exposure. Accordingly, "forced dried" specimens were oven dried at 40 °C and 45% relative humidity for 14 days then left in the ventilated

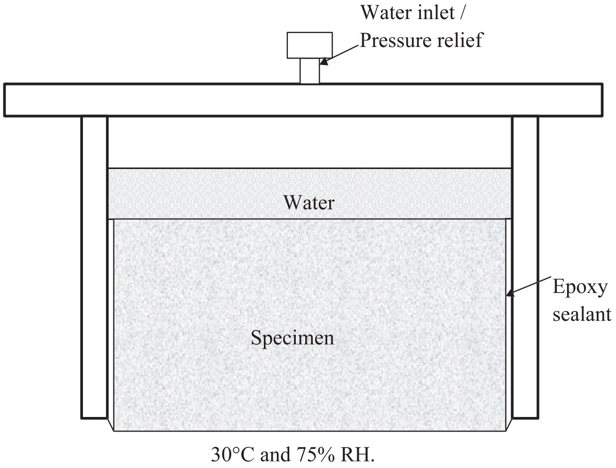

Fig. 3. Wick action test cell.

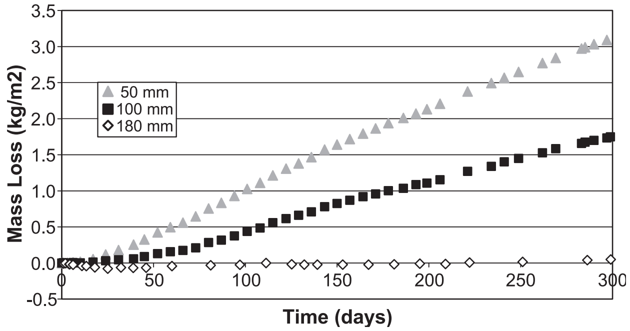

Fig. 4. Mass loss due to wick action through forced dried specimens.

racks within the test environment for a further 14 days. Forced drying of the specimens with SA/V ratios of 0.5 and 0.7 had respectively achieved 88% and 100% of the moisture loss achieved by long-term ambient drying within the test environment. “Air-dried” specimens were taken from the fog room and left within the test environment for a further 28 days to dry naturally. This drying procedure achieved approximately 41% and 64% of the moisture loss achieved by long-term ambient drying for the specimens with SA/V ratios of 0.5 and 0.7, respectively. “Saturated” specimens were taken from the fog room and directly immersed in water for 24 h before testing. During the installation of saturated (and vacuum-saturated) specimens into the wick action cells, great care was taken to ensure that the surface to be in contact with water was kept saturated until the test commenced. This procedure simulates field conditions under which concrete is unable to dry before exposure. “Vacuum-saturated” specimens were forced dried as described above before being vacuum saturated in accordance with the specimen preparation requirements of ASTM C1202 [14]. The procedure resulted in a slight increase in mass compared with initial saturated mass. This is presumably due to air-filled voids becoming water filled under vacuum. The effect of the various preparation procedures for the specimens on mass changes compared with initial saturation is shown in Fig. 2.

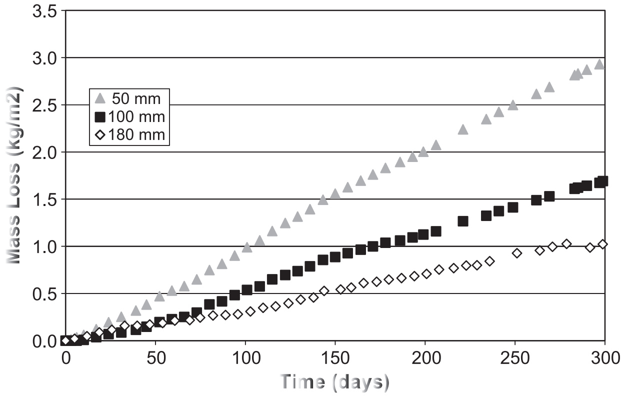

Fig. 5. Mass loss due to wick action through air-dried specimens.

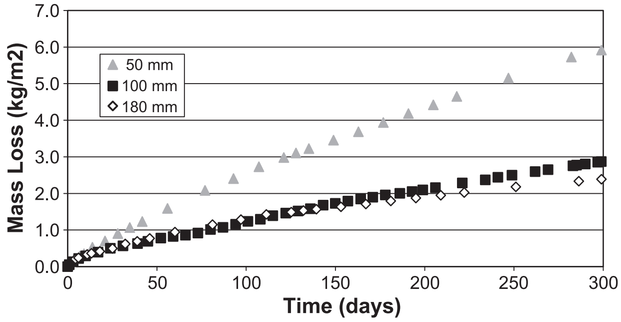

Fig. 6. Mass loss due to wick action through saturated specimens.

2.4. Wick action test

The wick action test procedure was similar to that developed by Buenfeld et al. [1]. Dried and saturated specimens of 100-mm thickness were sealed into the test cell using epoxy paste. A nominal hydrostatic head of 20 mm of water was poured onto the top surface of the concrete specimen. By using a cell in which the dry surface of the specimen was an external surface of an otherwise sealed cell, evaporation from the dry surface could be monitored by monitoring the mass of the entire cell. The test setup is shown in Fig. 3. Mass loss, which was assumed to be entirely water loss due to wick action, was measured to the nearest 0.01 g on an electronic balance. Water was replaced as required and any negative pressure due to water loss from the cell was released weekly. Dried specimens initially had low rates of water loss as water vapour had to diffuse through the dried specimen to the exposed surface. Saturated specimens initially had high rates of water loss as water evaporated from the exposed surface.

The cumulative mass loss measured (reported as kg/m^2) for the four preparation procedures is shown in Figs. 4–7. The rate of wick action (reported as kg/m^2/s) is shown in Fig. 8. The rate of wick action shown in Fig. 9 is the apparent steady state rate attained after 300 days of testing when the rate of in- and outflow were assumed to have converged, independent of their initial moisture content.

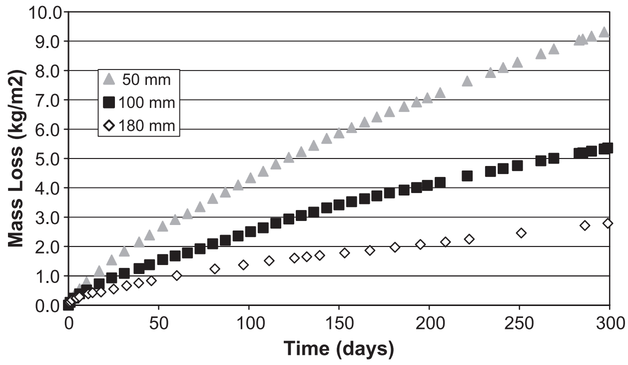

Fig. 7. Mass loss due to wick action through vacuum-saturated specimens.

3. Test results

3.1. Effect of thickness

The influence of specimen thickness on water loss due to wick action during the test programme is shown in Figs. 4–7. There is a clear trend of decreasing wick action for increasing specimen thickness for each of the four preparation procedures (Fig. 9). There was no measurable moisture loss through the forced dried specimen of 180-mm thickness until 220 days after the start of the test showing how slow moisture loss by vapour diffusion can be when the saturation front is distant from the drying face. Indeed, this specimen had not reached a stable rate of water loss even after 300 days. For the saturated specimens, the 100- and 180-mm specimens exhibited comparable wick action for the first 150 days thereafter the thicker specimen had a slightly lower rate. A steady rate of wick action appeared to have been established by approximately 200 days. The rates of wick action for all specimens after 300 days of testing are summarised in Fig. 9. For each preparation procedure, the rate of wick action was approximately inversely proportional to thickness.

3.2. Effect of initial moisture content

The influence of initial moisture content on the rate of wick action for the 50-mm-thick specimens is shown in Fig. 8. The vacuum-saturated and saturated specimens had high rates of initial moisture loss. This would be explained by the rapid evaporation of the exposed saturated concrete into the neighbouring ambient environment. At all stages during the experiment, the rate of moisture loss from the vacuum-saturated specimens was significantly greater than the saturated specimens. At steady state, the wick action flux for the former was approximately 50% higher than that for the latter.

The initial rates of moisture loss from forced and air-dried specimens were low. The distance from the wetting front at the face in contact with water to the ambient environment at the drying face combined with the low water vapour diffusivity of concrete would have limited evaporation and vapour transport. Initially, the forced dried specimens exhibited lower rates of moisture loss than the air-dried specimens. However, from approximately 50 days onwards, both forced and air-dried specimens had similar rates of wick action, which were significantly less than the saturated specimens. The summary in Fig. 9 shows that the apparent steady state rates of wick action were strongly influenced by initial moisture content for all three specimen thicknesses; vacuum-saturated specimens had the highest rates followed by saturated and then the dried specimens.

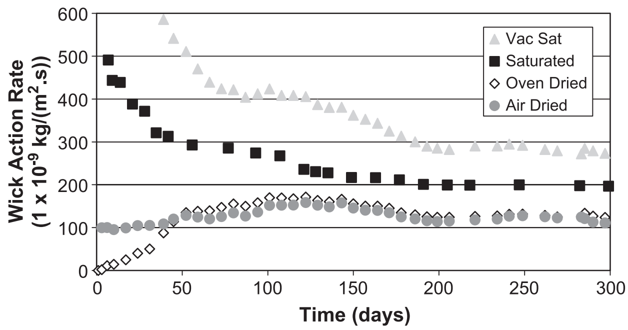

Fig. 8. Rate of wick action through 50-mm specimens with different initial moisture content.

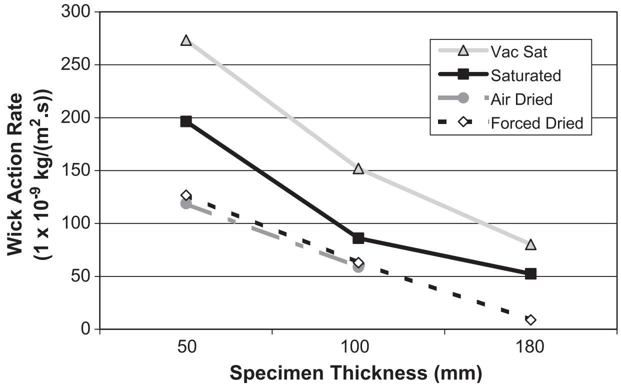

Fig. 9. Rate of wick action at 300 days for different specimen thickness and preparation.

The effect of initial moisture content is best illustrated by a comparison of forced dried and vacuum-saturated specimens. Both were from the same batch of concrete that had received long-term water curing before being exposed to the same drying cycle. Accordingly, these concrete specimens can be considered comparable in all respects except initial saturation. Yet the initial presence of liquid water more than doubled the rates of wick action at 300 days for the 50- and 100-mm-thick specimens as shown in Fig. 9. The forced dried 180-mm specimen had not reached a steady rate within 300 days, but the results suggest a similar trend.

4. Discussion of results

The rapid initial moisture loss from the vacuum-saturated and saturated specimens is consistent with vapour diffusion from the drying face being the dominant transport mechanism at early stages. The slow initial moisture loss from forced and air-dried specimens is consistent with limited vapour diffusion due to the distance of the wetting front fromfrom from the drying surface. Therefore, sorptivity would appear to dominate early transport in dried specimens as proposed by Buenfeld et al. [1]. Yet the results presented in this paper show that the initial presence of liquid water within the capillary network increased the subsequent rate of wick action through concrete even when it appeared that steady state had been achieved. Vacuum-saturated and saturated specimens invariably exhibited higher steady state flux than otherwise comparable dried specimens.

If water transport through a porous material (with a pore structure that did not change during wetting or drying) was defined by vapour diffusion and sorptivity, the same steady state wick action would be expected to eventually be achieved irrespective of whether the material starts wet or dry [1]. As discussed in the Introduction, drying of concrete actually causes microstructural damage which, under most circumstances, is associated with an increase in penetrability and so the rate of wick action through dried specimens might be expected to be higher than through initially saturated ones. Indeed, this trend is observed when comparing the wick action rate of vacuum-saturated and saturated specimens where the former, which had been forced dried prior to saturation, had significantly greater wick action.

There are three possible hypotheses for the increased rate of wick action in initially saturated specimens:

1. Pore structure changes during drying caused some pores to be inaccessible to water unless under vacuum.
2. Some mechanism(s) operated to augment flow through the initially saturated specimens compared to the initially dried specimens.
3. A true steady state had not been achieved in spite of the readings having apparently stabilized.

As mentioned in the Introduction, drying changes the pore structure by causing the collapse of smaller pores [8]. The first hypothesis would suggest that the resultant disruption might have prevented flow through some pathways reducing the rate of wick action. Parrott [8] found that pore structure changes and collapse of smaller pores was most prevalent when drying at relative humidities between 20% and 60% and that restricted micropore filling occurred in specimens dried at relative humidities less than 70%. As the forced and air-dried specimens were dried at relative humidities of 45% and 75%, respectively, any pore structure changes due to drying would have been very different. But the forced and air-dried specimens were found to have comparable rates of wick action suggesting that possible changes to pore structure during drying did not provide an explanation for reduced flow in initially dried specimens.

There are two mechanisms potentially affecting the initially saturated specimens that could result in an increase in wick action. The first relates to meniscus curvature. The curvature of the meniscus, which defines the interfacial tension that it induces, is dependent on the vapour pressure over its downstream surface [15]. Accordingly, tensile stresses would be expected to be greater where there is a greater rate of evaporation. The higher rate of evaporation from the vacuum-saturated and saturated specimens may have increased tension drawing water from the water reservoir at the input face to the meniscus, thereby slowing the rate at which the wet/dry interface receded and so modifying the steady state condition.

The second mechanism relates to the dependence of contact angle on whether a water front is advancing or receding. While it is difficult to accurately determine contact angles for complex, porous materials like concrete, the receding and advancing contact angles of water on glass, which could be considered an "idealized" concrete, have been measured at 36° and 64°, respectively [16]. The contact angle is a measure of the competing tendencies of water to spread so as to cover the solid surface and to round up so as to minimise its own surface area [17]. Thus, a lower receding contact angle indicates greater adhesion to the surface and therefore a greater ability to resist the forces that may be applied. This effect is illustrated in Fig. 10 [18]. In the case of the one-sided drying of an initially saturated specimen, a low receding contact angle may resist the tendency for the wet/dry front to retreat from the drying surface, thereby also increasing flow under steady state conditions.

Both mechanisms would result in increased hydraulic tension through water-filled capillaries. This hydraulic tension effect is well documented in relation to trees, where thin columns of water have been shown to have a tensile strength of at least 30 atm [19,20] and drying from the leaves is able to suck water from relatively dry soil with tensile stresses up to 2.5 MPa [19].

The third hypothesis is that a true steady state had not been achieved, despite the readings having apparently stabilised. The above hydraulic tension mechanisms may have merely delayed the attainment of true steady state and resulted in a very gradual convergence. However, if these mechanisms did operate to augment flow in concrete with a receding waterfront, they would be expected to constantly increase the rate of flow, albeit at a reducing rate as the front moved further away from the drying face. Hence, they would shift the wet/dry interface and change the steady state. A wick action environment is not a closed system where convergence to equilibrium would be a thermodynamic certainty [21].

The hydraulic tension hypothesis appears to explain why the vacuum-saturated specimens had the highest rate of

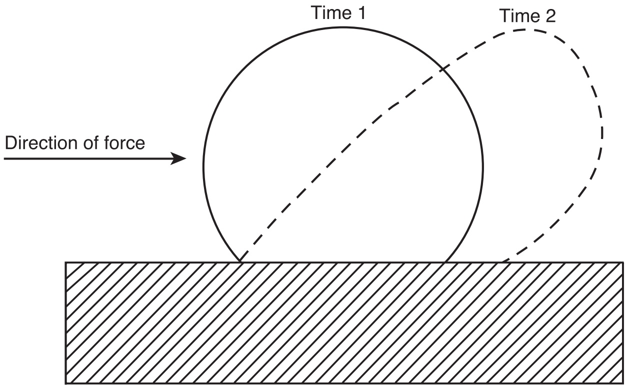

Fig. 10. The effect of receding and advancing contact angles on drop motion [18].

wick action followed by the saturated and then the dried specimens. If true, the fact that the forced and air-dried specimens had comparable rates of wick action in spite of significant differences in their initial moisture contents must be considered. A possible explanation is that air-drying for 28 days, in common with forced drying, eliminated continuous liquid pathways through which hydraulic tension forces could act. Consequently, in both cases flux would have been defined by the depth of water penetration and the rate of vapour diffusion through the unsaturated concrete. Ho and Lewis [11] found that the depth of penetration of water was relatively unaffected by the degree of drying as long as the specimens had received a minimum of 21 days of air-drying. Accordingly, while the volume of water penetration may have differed between forced and air-dried specimens, the depth of the saturation front would be expected to be similar. As the initial moisture content has little influence on the rate of water vapour diffusion [2], the rate of wick action would be expected to be similar.

The fact that long-term wick action flow rates through initially water-saturated concrete may be higher than through initially dry concrete has important practical implications. In situations where it is necessary to limit water transport through concrete into an environment that is meant to be dry, there may be reason to avoid using construction techniques, such as diaphragm walling, that prevent drying of the concrete prior to groundwater exposure. However, in situations where ingress of dissolved salts is a concern, the longer term advantage of low near steady state wick action rates associated with predried concrete will be somewhat offset by greater initial absorption.

5. Conclusions

i. In wick action tests on specimens of well hydrated OPC concrete, the initial moisture state of the specimens influenced the subsequent rate of wick action even after 300 days when it appeared that steady state conditions had been achieved. Specimens that had been vacuum saturated after drying had the highest flux followed by initially saturated specimens, with the lowest flux associated with specimens that had been forced or air-dried. Forced and air-dried specimens had comparable rates of wick action in spite of significant differences in moisture content.
ii. The apparent steady state rate of wick action was approximately inversely proportional to thickness, regardless of initial moisture content.
iii. The observed behaviour appears consistent with wick action involving hydraulic tension with flux dependent on the continuous liquid-filled capillaries able to support tensile forces and indicates that continuity of water pathways is more critical than absolute moisture content.
iv. Mechanisms related to meniscus curvature and the reduced contact angle of a receding wetting front may have augmented flow, increasing the steady state flow for initially saturated specimens.

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