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Relationship between liquid sorptivity and capillarity in concrete

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Abstract

Neutron radiography (NR) was applied to study liquid transport processes in concrete. With this method, it is possible to monitor the liquid distribution inside specimens and to measure the height of the liquid front for liquids of high hydrogen content inside concrete. The experiment was performed with water and fuel oil for three different types of concrete. The results are compared with the sorptivity measured by the gravimetric method. It is shown that the ratio between the capillarity coefficient and sorptivity depends upon the combination of liquid and solid phases. For water, this value was found to be 5.5 ± 0.6, 5.8 ± 0.6 and 7.1 ± 0.7 in concrete without additives, concrete with an air-entraining agent and concrete with a plasticizer, respectively. For fuel oil, the value is about 50% higher than that for water.

Keywords: Admixture; Concrete; Neutron radiography; Transport properties

1. Introduction

Water is the main cause of the degradation of building materials. It penetrates into porous media, transports harmful substances and freezes inside. When a homogeneous porous material has a constant hydraulic potential at wet front, liquid can mount to considerable heights due to the capillary absorption. If evaporation takes place, equilibrium between capillary absorption and evaporation is reached at a certain height. For this reason, in technical practise heights of approximately 1 m above ground level are considered in moisture degradation of building constructions [1].

To monitor moisture in materials, several methods are available. A simple and therefore widely used technique of moisture determination is the gravimetric method. With this method, it is possible to detect moisture distribution in a structure at a certain time, but it is impossible to observe its movement. When this method is applied to laboratory specimens, it is possible to collect data about the quantity of moisture inside the specimen, but its distribution cannot be established. Dynamic processes of moisture movement can be observed by nuclear magnetic resonance [2], gamma rays [3,4] or neutron radiography (NR) [5]. However, in order to select the most appropriate method, it is essential to be acquainted with their limitations. Nuclear magnetic resonance is useful when observing materials like clay or sand, but for basic building materials like concrete or fired-clay brick, the signal is too weak [2]. Gamma rays cannot give satisfactory results when moisture content is less than 5 g in a volume of 100 cm^3, which excludes the early phase of transport process [4]. With NR, it is possible to distinguish between substances with low and high hydrogen content [5]. NR is based upon the fact that the neutron attenuation coefficient changes abruptly according to the atomic number of the element [6]. Elements with the highest attenuation coefficient are gadolinium, boron, hydrogen, samarium, europium, cadmium, lithium and dysprosium, which are, except for hydrogen, very rare in nature. Aggregate and the cement matrix, which are the dominant ingredients of concrete, mostly consist of calcium, silicon, aluminum, iron, magnesium, oxygen and carbon, so concrete is evidently a material with a low attenuation coefficient for neutrons. This also holds for fired-clay brick. Therefore, this method is very appropriate for the observation of moisture movement inside concrete or brick [7], although the specimen thickness is limited by the neutron flux intensity.

However, water is not the only liquid to which building materials are exposed. For some liquids, deep penetration is even desired (e.g., hydrophobic impregnation agents). With NR, it is possible to monitor all sorts of liquids with high hydrogen content inside concrete or brick. Hence, besides

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Table 1
Composition of mixture for the preparation of specimens

Type of additive	Sand [g]	Cement [g]	Water [g]	Additive	
				[%][a]	[g]
None	1350	450	225	0	0
Air-entraining agent	1350	450	225	0.3	1.35
Plasticizer	1350	450	225	3	13.5

[a] According to the mass of cement.

water, the presence and distribution of all kinds of organic liquids can be observed.

Capillary rise is usually described with the relationship:

$$h = k\sqrt{t} \quad (1)$$

where h is the height to which the liquid rises in time t, and k is the capillarity coefficient. The capillarity coefficient covers the relationship between the solid and liquid phases, as well as the pore structure inside the solid phase, and should be determined experimentally. The lack of an adequate method for the determination of liquid height at a given time requires an alternative measurement of the sorptivity S, which can be calculated according to the relationship:

$$i = S\sqrt{t} \quad (2)$$

where i is the volume of liquid absorbed per unit cross section in time t [8]. The use of sorptivity as a measure of the capillary absorption properties of porous construction materials is now widespread [9]. It can be easily measured by the gravimetric method, but it will not give us a very good picture of the distribution of absorbed liquid.

In this paper, results of capillarity coefficient measurement for concrete in combination with water and fuel oil using NR are presented. Results are compared to sorptivity measurements performed by gravimetric method.

2. Experimental

Experiments were performed on three different concrete specimens and with two liquids. All specimens were prepared as a standard mixture for cement testing with a mass ratio of 6:2:1 of aggregate–cement–water, which gives a water–cement ratio of 0.5. Aggregate quartz sand with grain sizes from 0 to 2 mm was used. The difference between the specimens was only in the type of additive. Compositions of specimens are presented in Table 1. Six specimens with a thickness of about 20 mm, width of 40 mm and height of 160 mm were prepared from each mixture. They were treated at

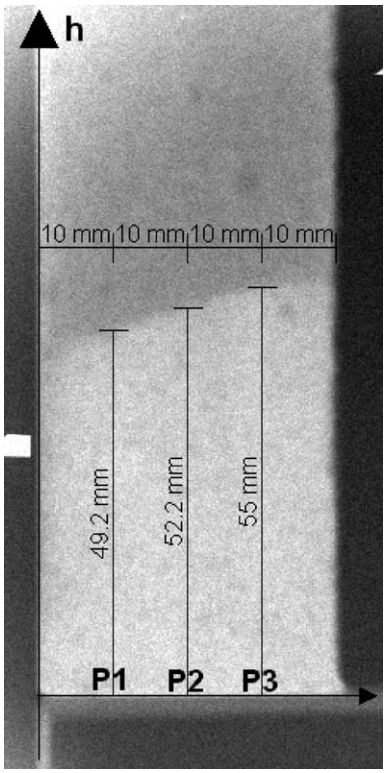

Fig. 1. Neutron radiograph of a concrete specimen without additives at 43.42 h. Height of liquid front h is measured in three profiles, P1, P2 and P3, with the computer program TINA 2.10g.

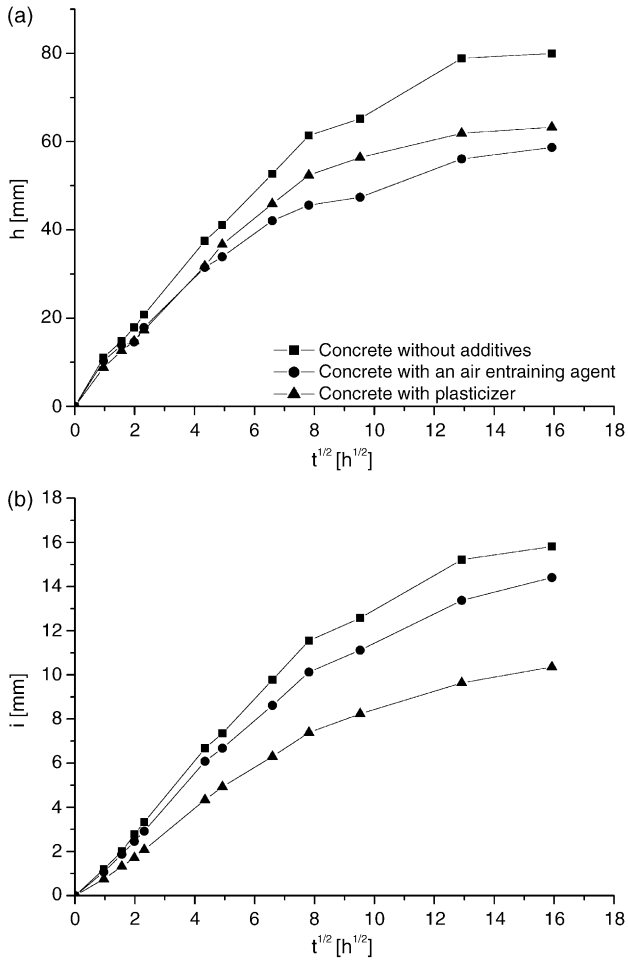

Fig. 2. Height of water raised h (a) and volume of water absorbed per unit cross section i (b) versus square root of soaking time t for three different types of concrete.

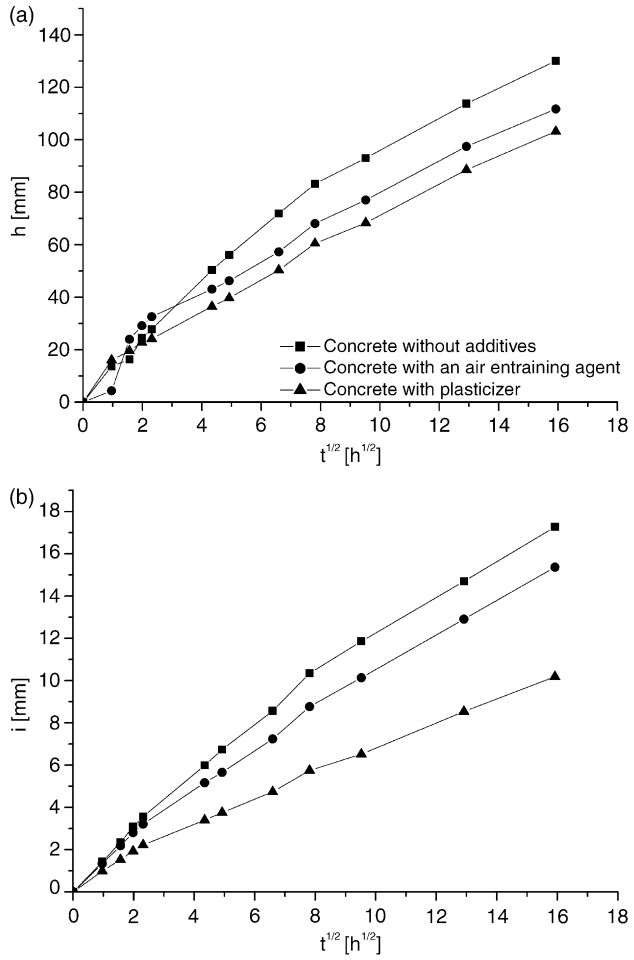

Fig. 3. Height of fuel oil raised h (a) and volume of fuel oil absorbed per unit cross section i (b) versus square root of soaking time t for three different types of concrete.

22 °C and 100% moisture for 28 days. Then the specimens were dried at 105 °C, their masses were established and NR images of dry specimens were obtained.

Liquid transport experiments began when the bottom parts of the specimens (approximately 5 mm) were placed into the liquid and time was defined as zero. One specimen of each kind was placed into water and the second one into fuel oil. Specimens were covered to avoid evaporation. During the next 11 days, NR images of the soaked specimens were made at certain time intervals. Liquid rise was measured in three profiles on each neutron radiograph as presented in Fig. 1. At the same time, specimen masses were determined.

Table 2
Normalised values of the height to which liquid rises h and the volume of liquid absorbed per unit cross section i measured after soaking time of 253.5 h for three different types of concrete

	h (1 ± 0.1)		i (1 ± 0.05)	
	Water	Fuel oil	Water	Fuel oil
Concrete without additives	0.6	1	0.9	1
Concrete with an air-entraining agent	0.5	0.9	0.8	0.9
Concrete with a plasticizer	0.5	0.8	0.6	0.6

Table 3
Capillarity coefficient k and sorptivity S for water in three kinds of concrete

	k (1 ± 0.1) [mm h$^{-1/2}$]	S (1 ± 0.05) [mm h$^{-1/2}$]
Concrete without additives	8.1	1.5
Concrete with an air-entraining agent	7.5	1.3
Concrete with a plasticizer	6.8	1.0

Values are valid for $t < 60$ h.

The neutron radiographic experiments were performed at the TRIGA Mark II reactor of the Jožef Stefan Institute in Ljubljana [10]. At the irradiation point, the functional diameter of the beam was 9 cm and the thermal neutron flux was 4×10^5 n/cm^2 s (measured with Au foil). The specimen was placed 10 cm in front of the image detector. Neutrons that passed through the specimen were captured on the imaging plate, where a gadolinium converter absorbed them. As the result of absorption, the gadolinium released secondary radiation of charged particles, which photostimulated the dielectric crystals mixed with gadolinium on the imaging plate. Afterwards, the imaging plates were scanned with a thin laser beam (633 nm) that caused relaxation of the dielectric crystals through which a light flash was produced. The scanner registered this light and the digital image obtained from the process was saved in the computer memory. Digital images were further processed with a computer program that enabled us to measure distances with a precision of 0.1 mm.

3. Results and discussion

Results are presented in Figs. 2 and 3, where liquid height and volume of the absorbed liquid per unit cross section are plotted against the square root of soaking time. If Eqs. (1) and (2) are valid, the graphs should be a straight line and the capillarity coefficient and sorptivity would be the slope of the straight line. This is true for specimens soaked in fuel oil, as can be seen from Fig. 3. However, a significant variation from linearity for water was observed. This anomaly has already been noticed by Hall et al. [11]. They explained this phenomenon by a new hydration, which takes place in the presence of water and causes an increase of effective grain size and tends to block the micropores. Consequently, water movement through concrete is hindered.

Table 4
Capillarity coefficient k and sorptivity S for fuel oil in three kinds of concrete

	k (1 ± 0.1) [mm h$^{-1/2}$]	S (1 ± 0.05) [mm h$^{-1/2}$]
Concrete without additives	10.8	1.2
Concrete with an air-entraining agent	9.0	1.0
Concrete with a plasticizer	7.5	0.7

Table 5
Measured value of $C = k/S$ for three different kinds of concrete in combination with water and fuel oil

	C (1 ± 0.1)	
	Water	Fuel oil
Concrete without additives	5.5	8.1
Concrete with an air-entraining agent	5.8	8.8
Concrete with a plasticizer	7.1	10.6

The symbols k and S denote capillarity coefficient and sorptivity, respectively.

From Fig. 2b, it can be inferred that concrete with an air-entraining agent absorbed considerably more water than concrete with a plasticizer, but the height to which the water climbed is approximately the same, as can be seen in Fig. 2a. A similar occurrence can be observed in Fig. 3. The density of concrete with plasticizer is about 20% higher than the density of concrete with an air-entraining agent, since concrete with an air-entraining agent is characterized by uniformly distributed air bubbles (diameter of 0.01–0.3 mm). These bubbles cause an increase in the absorbed volume of liquid, but they simultaneously decrease capillary rise due to the disconnection of the capillary network.

For comparison of the volume of absorbed water and fuel oil per unit cross section, final values of i (at $t = 253.5$ h) were normalised. For a given type of concrete, these values are approximately the same for both studied liquids. On the other hand, normalised values of h show considerable discrepancy, as can be seen in Table 2. These observed deviations indicate that methods that enable direct measurements of height to which the liquid rises are more suitable to study transport phenomena in porous materials.

From the collected data, the capillarity coefficient and sorptivity for water and fuel oil in concrete can be calculated. Results are presented in Tables 3 and 4, respectively. From Eqs. (1) and (2) it follows that:

$$h = Ci \tag{3}$$

where constant C correlates capillarity and sorptivity as follows:

$$C = \frac{k}{S} \tag{4}$$

Although there is linear dependence between capillarity and sorptivity, the correlation factor strongly depends upon the combination of liquid and solid phases, as can be perceived in Table 5. Hence, from a sorptivity measurement alone, one cannot make conclusions about capillarity and vice versa if the value of C is not known.

4. Conclusions

NR using imagining plates proved to be a very good method for the determination of capillary rise of liquids with high hydrogen content inside concrete. From the results of the experiment we can make the following conclusions:

1. For concrete soaked into water, Eqs. (1) and (2) are valid only when $t < 60$ h.
2. If two materials in combination with certain liquid have similar sorptivity, it does not necessarily mean that they will have similar capillarity and vice versa.
3. The ratio between the capillarity coefficient and sorptivity depends upon the combination of liquid and solid phases. For water, this value was found to be 5.5 ± 0.6, 5.8 ± 0.6 and 7.1 ± 0.7 in concrete without additives, concrete with an air-entraining agent and concrete with a plasticizer, respectively. For fuel oil, this value is about 50% higher compared to that for water.

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