Properties of high performance concrete: the effect of cracks

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Abstract

The moisture transport and storage parameters of high performance concrete belong to the most critical parameters in designing and using complex reliability based models for service life prediction of concrete structures. However, mostly it is supposed that the material is compact without any significant cracks, which is not always true. In this paper, the effect of thermally induced cracks on the basic moisture transport and storage properties is analyzed. Experimental results show that the presence of cracks in hardened high performance concrete mixtures dramatically changes all measured hygric parameters. Also, the effects of both microsilica and the size and presence of aggregates on moisture transport and storage parameters are very important. The liquid water transport is found to be affected by cracks, microsilica and aggregates in a much more significant way than water vapour transport.
Keywords: high performance concrete, moisture transport and storage properties, cracks.

1   Introduction

The progressive building materials development improves their quality and utility value. In order to achieve better material properties, besides the new technologies also specific admixtures are employed. The accurate admixtures dosage and technological conditions observation can improve the material parameters like strength and durability. Most frequently, the mineral admixtures, for example pozzolana, fly ash or flue cinder, are used in concrete production. Fine siliceous materials usually called silica fume belong to relatively newly applied materials improving concrete quality.

Silica fume can influence the hydration process on the one hand physically, ultra fine elements fill space between hydrating cement grains, on the other one chemically; they can react together with calcium hydroxide to form qualitatively different binding products. It leads to lower porosity, it changes the micro-pores distribution, the cementing agent is compacting and the strength, insolubility and corrosion durability of final product are improved.

Despite the gradual shift in the HPC design and application philosophy towards a generally recognized necessity to measure a wider scale of HPC parameters the mechanical properties still remain the far most frequent parameters investigated in the research work being done on HPC. Water and water vapor transport and storage properties of HPC were not yet in the center of interest of most researchers until now although they possess a very high predicative potential concerning the HPC quality.

In this paper, we analyse the influence of cracks on moisture transport and storage parameters of two different types of concrete, namely the high performance concrete C90/105 containing microsilica and the same material C60/75 without microsilica.

2   Materials

Basic tested material was high performance concrete C90/105 containing silica fume suspension, microsilica, denoted as BI in subsequent text. For the sake of comparison, the same concrete mixture C60/75 (denoted as BII) was prepared without microsilica. In order to analyse the effect of aggregates on moisture transport and storage parameters, two other mixtures based on BI and BII were prepared. The first one (denoted as BBI and BBII) was cement mortar without the 8-16 mm aggregate fraction. The second one was cement paste denoted as PI and PII. Table 1 presents the composition of the studied cement mixtures.

Table 1:   Composition of studied cement mixtures.

Type of concrete	Composition in g							
	CEM I 52.5 R	[*]SiO_2 suspension	Aggregates			[**]Woerment FM 794	[***]Lentan VZ 33	w/c
			0-4 mm	4-8 mm	8-16 mm			
BI	480	72	664	207	995	7.74	2.58	0.36
BII	470	0	668	209	1001	5.17	2.35	0.33
BBI	480	72	664	1202	0	7.74	2.58	0.38
BBII	470	0	668	1210	0	5.17	2.35	0.35
PI	2346	352	0	0	0	38	12.67	0.31
PII	2348	0	0	0	0	26	12	0.34

[*]SiO_2 suspension – water suspension consisting of 88-95% of SiO2 and small amounts of calcium oxide, magnesium oxide and nitrogen oxide.
[**]FM 794 – plasticizer on the basis of polycarboxylateether.
[***]Lentan VZ 33 – hydration retarder on the saccharose basis.

Each mixture was cast into the forms, after one day the samples were removed from the forms and then varnished using curing solution. After the hardening period of 28 days, the samples were cut to required dimensions. These samples were then heated up to 600°C in an oven to reach cracks, see Figure 1.
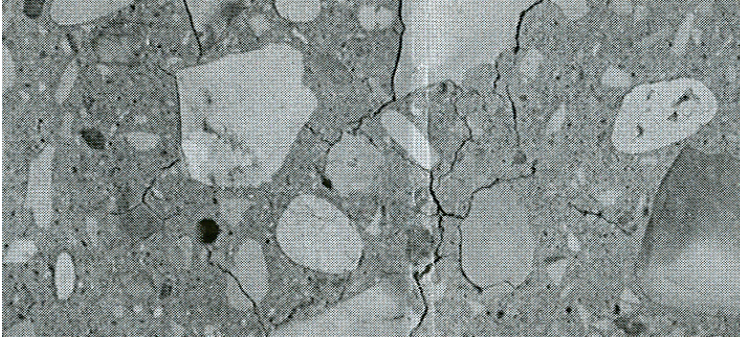

Figure 1:   The HPC BI sample after thermal loading.

3   Experimental methods

3.1 Basic material parameters

As fundamental physical material characteristics, bulk density ρ_b [kgm^{-3}], vacuum saturation moisture content w_{sat} [kgm^{-3}], porosity [Vol.-%] and matrix density ρ_m [kg m^{-3}] were determined. They were obtained using the gravimetric method and the vacuum saturation method. The vacuum saturation moisture content was calculated according to the equation

$$w_{sat} = \rho_w \frac{m_{sat} - m_0}{m_{sat} - m_a} = \rho_w \psi \, , \tag{1}$$

where ρ_w is the water density [kg m^{-3}], m_0, m_{sat} and m_a are the mass of dry sample, water- saturated sample and mass of the immersed water - saturated sample [kg], respectively, and ψ is the open porosity, which is defined as the ratio of the volume of open pores in material to its total volume. Matrix density was calculated as

$$\rho_{mat} = \frac{m_0}{V(1-\psi)} \, , \tag{2}$$

where V is sample volume [m^3].

The measurement of basic parameters took place in a conditioned laboratory at the temperature of 22±1 ˚C and 25-30% relative humidity. Each result represents the average value from three to five measured values.

3.2 Water vapour and water transport parameters

Two versions of the common cup method were employed in the measurements of the water vapor diffusion coefficient [1]. In the first one the sealed cup containing silica gel (5% relative humidity) was placed in a controlled climatic chamber with 97% relative humidity and weighed periodically. In the second one the cup containing the saturated solution of K_2SO_4 (97% relative humidity) was placed in the 25% relative humidity environment. The measurements were done at 20°C in a period of two weeks. The steady state values of mass gain or loss were determined by linear regression for the last five readings.

The water vapor diffusion coefficient D [m^2s^{-1}] was calculated from the measured data according to the equation

$$D = \frac{\Delta m \cdot d \cdot R \cdot T}{S \cdot \tau \cdot M \cdot \Delta p_p}, \tag{3}$$

where Δm the amount of water vapor diffused through the sample [kg], d the sample thickness [m], S the specimen surface [m^2], τ the period of time corresponding to the transport of mass of water vapor Δm [s], Δp_p the difference between partial water vapor pressure in the air under and above specific specimen surface [Pa], R the universal gas constant, M the molar mass of water, T the absolute temperature [K].

On the basis of the diffusion coefficient D, the water vapor diffusion resistance factor μ was determined:

$$\mu = \frac{D_a}{D}, \tag{4}$$

where D_a is the diffusion coefficient of water vapor in the air.

The water sorptivity was measured using a standard experimental setup. The specimen was water and vapor-proof insulated on four edges and the face side was immersed 1-2 mm in the water, constant water level in tank was achieved by a Mariott bottle with two capillary tubes. One of them, inside diameter 2 mm, was ducked under the water level, second one, inside diameter 5 mm, was above water level. The automatic balance allowed recording the increase of mass. The water absorption coefficient A [$kgm^{-2}s^{-1/2}$] was then calculated using the formula

$$i = A \cdot \sqrt{t}, \tag{5}$$

where i is the cumulative water absorption [kg/m^2], t is the time from the beginning of the suction experiment. The water absorption coefficient was then employed for the calculation of the apparent moisture diffusivity in the form [2]

$$\kappa_{app} \approx \left(\frac{A}{w_c - w_0} \right)^2, \tag{6}$$

where w_c is the saturated moisture content [kgm^{-3}] and w_0 the initial moisture content [kgm^{-3}].

In the experimental work, the following samples were used: water vapor diffusion coefficient – 10 cylinders with the diameter 105 mm and thickness 20 mm, water sorptivity - 5 specimens 50 x 50 x 20 mm.

3.3 Sorption isotherms

The water adsorption and desorption in a porous material are based on van der Waals forces between the surface of the porous matrix and water molecules. The dry material mass increases after a contact with moist air because of gradual bonding of water molecules from the air to the pore walls, in the case of adsorption. Desorption is reversed physical phenomenon, the initial state is capillary saturated sample. At the moment of achieving the equilibrium state between the water vapour pressure in the moist material and in the surrounding air this process is stopped.

The mass of samples was measured in specified periods of time until steady state value of mass was achieved. Then, the moisture content by mass was calculated according to the equation

$$u_m = \frac{m_w - m_0}{m_0}, \tag{7}$$

where m_w is the mass of wet sample and m_0 is the mass of dry sample [kg].

The samples were placed into the desiccators with different salt solutions to simulate different values of relative humidity, see Table 2.

Table 2:   Relative humidity over saturated salt solutions.

Salt	Temperature/Relative humidity [-]		
	20°C	23°C	25°C
LiCl	0.111	-	0.111
MgCl$_2$.6H$_2$O	0.330	0.329	0.328
NaNO$_2$	0.654	-	0.643
NaCl	0.755	0.754	0.753
NH$_4$Cl	0.792	0.788	0.786
KCl	0.851	0.845	0.843
K$_2$SO$_4$	0.979	-	0.976

In the measurements of adsorption and desorption isotherms, for each relative humidity 3-10 test specimens of each material with overall dimensions of 40 x 40 x 10 mm were prepared. The measurements were done at 23±1°C. The initial

states were dry samples in the case of adsorption, and capillary saturated samples in the case of desorption.

4 Experimental results and discussion

The results of basic parameter measurements are presented in Table 3.

Table 3: Basic material parameters.

Type of mixture	Without cracks				With cracks			
	ρ_b	ρ_{mat}	w_{sat}	ψ	ρ_b	ρ_{mat}	w_{sat}	ψ
	[kgm^{-3}]			[%]	[kgm^{-3}]			[%]
BI	2423	2760	122.0	12.20	2391	2856	162.2	16.30
BII	2388	2647	95.1	9.80	2350	2713	133.2	13.40
BBI	2240	2652	150.6	15.60	2147	2627	182.0	18.30
BBII	2210	2578	140.5	14.30	2205	2669	174.8	17.40
PI	1988	2809	248.4	29.20	1942	3068	375.8	36.70
PII	1991	2779	285.2	28.30	2019	3088	355.7	34.60

The highest bulk density exhibited the hardened HPC mixture BI. The second highest had the BII mixture without microsilica. Nearly the same values had mixtures denoted BBI and BBII, cement pastes had the lowest values. The bulk density of cement mixtures with cracks was lower then of the same without cracks. The matrix densities differed only in the range of about 5% and increased about 10% in the case of mixtures with cracks compared to mixtures without cracks. The highest vacuum saturated moisture content had the cement pastes PI and PII, where the difference was within the error range, and increased about 30 % in the case of mixtures with cracks compared to mixtures without cracks. The most porous materials were cement pastes PI and PII, the presence of microsilica and admixtures did not have a significant effect. The porosity increased from 3 to 6% in the case of mixtures with cracks compared to mixtures without cracks.

The results of measurements of water and water vapour transport parameters of the studied hardened cement mixtures are presented in Tables 4 and 5.

The water vapour diffusion coefficient was affected by the addition of microsilica only for cement paste PI in a remarkable way where it decreased three to four times. However, for the mixture BII its effect was within the error range of the measuring method. The cracks caused dramatic increase of the water vapour diffusion coefficient in all cases.

The effect of microsilica on the liquid moisture transport parameters was more pronounced than on water vapour transport. The water sorptivity for the

basic mixture BI decreased five times due to the microsilica addition, and for the cement paste PI by about 30%. The moisture diffusivity of mixtures with microsilica decreased in a corresponding way. In the case of cement mixtures with cracks the moisture diffusivity increased one order of magnitude compared to mixtures without cracks.

Table 4: Water vapour transport properties of cement mixtures.

Type of mixture	Without cracks				With cracks			
	$D\ [10^{-6}\ m^2 s^{-1}]$		$\mu\ [-]$		$D\ [10^{-6}\ m^2 s^{-1}]$		$\mu\ [-]$	
	97-25% RH	5-97% RH	97-25% RH	5-97% RH	97-25% RH	5-97% RH	97-25% RH	5-97% RH
BI	1.06	0.397	22.5	59.3	1.48	1.55	15.8	15.4
BII	1.10	0.375	20.9	61.4	2.22	1.76	10.4	13.2
BBI	0.287	0.132	80.3	175.4	1.73	1.96	13.8	12.3
BBII	0.288	0.151	81.4	152.1	2.11	2.23	11.0	10.6
PI	0.136	0.079	170.7	295.9	2.29	3.20	10.2	7.2
PII	0.357	0.291	65.4	81.7	2.22	1.76	10.4	13.2

Table 5: Water transport properties of cement mixtures.

Type of mixture	Without cracks		With cracks	
	$A\ [kg\ m^{-2}s^{-1/2}]$	$\kappa_{app}\ [m^2 s^{-1}]$	$A\ [kg\ m^{-2}s^{-1/2}]$	$\kappa_{app}\ [m^2 s^{-1}]$
BI	3.63E-03	8.9E-10	4.84E-02	9.2E-08
BII	1.80E-02	3.3E-09	4.23E-02	1.1E-07
BBI	1.76E-02	1.5E-08	8.08E-02	2.5E-07
BBII	4.04E-02	8.3E-08	6.21E-02	2.0E-07
PI	2.36E-02	7.0E-09	2.77E-01	5.5E-07
PII	3.52E-02	1.8E-08	1.59E-01	2.0E-07

The effect of aggregate presence was found to be quite different for liquid water transport than for water vapour transport. The water sorptivity was for the basic hardened HPC mixture BI several times lower than for the cement pastes. On the other hand, the water vapour diffusion coefficient of cement pastes was always lower than for the basic hardened HPC mixtures. The 5-97% RH values of the water vapour diffusion coefficient were always lower than the 97-25% RH values, which is in accordance with the previous measurements on many other materials including concretes and cement pastes.

Figure 2a-f shows the measured adsorption (lower curves) and desorption (upper curves) isotherms. We can see that cement pastes had higher water adsorption capacity than the basic hardened HPC mixtures. This is an expected behaviour due to absence of the inert aggregates in cement pastes. The presence of microsilica slightly increased the water adsorption capacity of basic hardened

HPC mixture but for cement pastes an opposite behaviour was observed. Therefore, any clear effect of microsilica on water adsorption capacity was not evidenced. The sorption curves are almost the same for the mixtures without and with cracks.
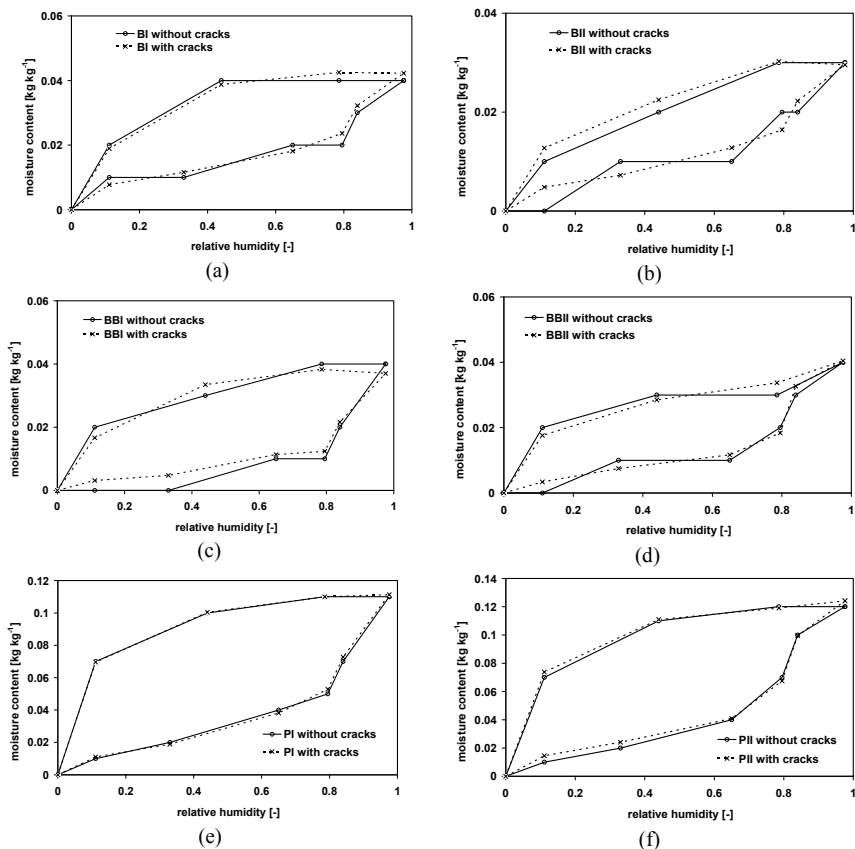

Figure 2:   Sorption isotherm of mixture (a): BI, (b): BII, (c): BBI, (d): BBII, (e): PI and (f) PII.

5   Conclusions

The experimental work performed in this paper has shown that the presence of cracks in hardened HPC mixtures dramatically changed all measured parameters. Also the effect of both microsilica and aggregates on the moisture transport and storage parameters was very important. The liquid water transport was found to be affected by cracks, microsilica and aggregates in a much more significant way than water vapour transport.

Acknowledgement

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