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Permeability and self-healing of cracked concrete as a function of temperature and crack width

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Abstract

Tests have been carried out on a high-strength concrete establishing permeability and self-healing behaviour of cracked concrete as a function of temperature between 20 and 80 °C and crack width between 0.05 and 0.20 mm. The results show a considerable increase of water transport with temperature. Theoretical prediction on the basis of thermodynamics showed reasonable to good agreement between theory and experiment.

Keywords: Temperature; Hydration products; Permeability; Blended cement; High-performance concrete

1. Introduction

Self-healing of concrete and reinforced concrete is a well-known phenomenon. It is also known as autogenous healing. Numerous publications show a high level of knowledge [1,2,6–8]. Edvardsen [2], Meichsner [6] and Ripphausen [8] have tested the self-healing of concrete under various influences. However, the correlation between self-healing and temperature has received only little attention. This is surprising since water transport and leaching processes are often accompanied with temperature variation. The investigation was initiated by the design and construction of hot water storage of solar energy. Water is heated by solar collectors and pumped into a buried storage vessel. The water has a maximum temperature of 95 °C, the stored energy should be saved for the colder season of the year. The question arose about the self-healing of concrete at temperatures between 20 and 80 °C. This paper presents the testing methods and results of the investigation as well as some theoretical considerations. It does only deal with one type of high-performance concrete (HPC). A detailed test description and summary as well as the other investigated mixtures can be found in Jooss and Reinhardt [5].

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2. Specimen, concrete and measuring device

2.1. Scope of investigations

The investigations deal with the preparation of the cracked specimens, the experimental method and the results of the permeability measurements. Three categories of cracks were produced, i.e., with crack widths of 0.05, 0.10 and 0.15 mm. One type of HPC was used. The hydraulic gradient amounted to 1 MPa/m and was the same throughout the tests. The temperature levels were kept to 20, 50 and 80 °C.

2.2. Specimen

The test specimens are circular slices with 150 mm diameter and a thickness of 50 mm which were ground flat on both sides and sealed with epoxy resin on the perimeter surface. Since the influence of reinforcement on the crack formation was not known before the tests, the steel diameter, the number of rods and the position of the reinforcement were varied in the first specimen series (see Fig. 1 and Table 1).

After the first tests, it turned out, that the rod diameter as well as the steel surface did not have a noticeable influence on the crack formation. In Series I, the specimens with a diameter of 150 mm were each reinforced with all four types of reinforcement. The position of the

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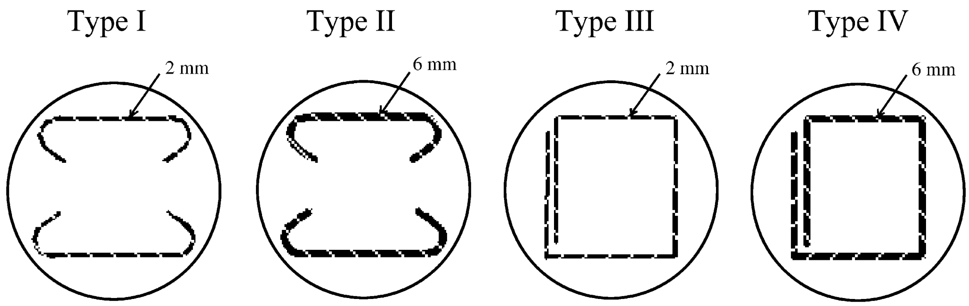

Fig. 1. Schematic illustration of the various types of reinforcement, reinforcing length 100 mm, diameter of specimen 150 mm.

steel, in contrast, had a great influence. The specimens with only one centric reinforcement showed large differences in the crack width between front and backside, so it was decided to use only reinforcement type I for all tests to come.

2.3. Calibration of cracks

The calibration of cracks with well anticipated position and predictable crack width in concrete is one of the most difficult ventures at all, because a multitude of parameters influence the crack formation. In this case the calibration of the cracks was carried out by a splitting tensile test to form cracks perpendicular to the reinforcement. The crack width could almost exactly be adjusted to the preset values and the specimens rejected were below 5%. However, it is very difficult to draw a conclusion on the position of the crack. Especially in case of a very small crack, it has to be anticipated that the crack width, which was measured externally, is not constant over the complete specimen height.

2.3.1. Classification of crack categories

It was not possible to adjust cracks exact to 1/100 mm by the splitting tensile test. The crack width was measured with a measuring magnifier at different points on the front and backside of the specimen. To minimize subjective influences, these operations were all carried out by the same person. The classification of cracks is given in Table 2.

Table 1
Schematic representation of the various types of reinforcement of the concrete slices for the splitting tensile test

Type of reinforcement	Rod diameter (mm)	Position of reinforcement	Number of rods	Steel surface
I	2	third[a]	4	smooth
II	6	centric	2	ribbed
III	2	third[a]	2	smooth
IV	6	centric	1	ribbed

[a] Two layers of reinforcement on one third and two third of the height of the specimen.

2.4. High-performance concrete

A standard mixture, which was optimized under the aspects of impermeability, workability and costs in the course of the tests, was the starting point. As in other types of concrete, several components (type of cement, additives and aggregates) were varied during the tests. Altogether, five different mixtures of HPC were produced for the test program. This paper deals with the one which was very workable and got high strength (about 90 MPa) reliably. The composition of the concrete is given in Table 3. Standard properties are summarized in Table 4.

All concrete specimens were cured wet during 6 days and then stored in a constant climate room with 20 °C and 65% RH until testing at 28 days.

The HPC reached a compressive strength of 93 MPa after 28 days. The flexural tensile strength was 8.1 MPa.

2.5. Measuring devices

2.5.1. Permeability and self-healing with water

Since test procedures for the measuring permeability are not standardized in Germany, a test device was designed and constructed. The test device consists of the test cell and the control unit. The test cell consists of a housing made of aluminium, a contact pressure tube made of rubber, a seal pressure sleeve made of polyurethane as well as a measuring capillary with a scaling at the inlet and the outlet end (see Fig. 2).

The test set-up has originally been designed by Gräf and Grube [3,4] for isothermal conditions of 20 °C. The system

Table 2
Classification of crack width categories

Crack width category (mm)	w_{min}	$w_{average}$	w_{max}
0.05	0.000	0.050	0.074
0.10	0.075	0.100	0.124
0.15	0.125	0.150	0.174
0.20	0.175	0.200	0.224

Table 3
Composition of the concrete mixture used

Mix	w/c ratio	Cement (kg/m^3)	Aggregate (kg/m^3)	Additions and admixtures (kg/m^3)
HPC	0.37	360 (CEM II/ A-L 32. 5 R)	1956	40 MS, 40 FA, 9.0 FM 30

FM, water-reducing agent; MS, microsilica; FA, fly ash.

Table 4
Properties of the concrete mixture used

Mix	Density (kg/m^3)	Air content (%)	Compressive strength after 28 days (MPa)	Flexural strength (four-point) after 28 days (MPa)
HPC	2450	1.0	93	8.1

has been adjusted to an option up to 80 °C with special attention to the sealing materials. Up to the required temperature of about 80 °C, all parts of the system work without difficulties. To simulate temperatures of 50 and 80 °C, the test cells were put into large climatic chambers with a temperature tolerance of ±1 °C. The water used was drinking water from the Lake of Constance water supply with a hardness of 7–14 (hardness 1 equals to 10 g CaO or 7.14 g MgO in 1 m^3 water).

3. Experimental investigations and results of HPC

3.1. Initial flow rate

At the beginning of the permeability test, a flow rate was measured according to Table 5. The temperature influence at a crack width of 0.05 mm is not significant.

Table 5
Initial flow rate [l (liter) h^{-1} m^{-1}], hydraulic gradient [1.0 MPa/m]

Crack width (mm)	Temperature (°C)		
	20	50	80
0.05	10	11	12
0.10	22	39	56
0.15	110	155	190

However, with increasing crack width, the influence of temperature is remarkable. The higher the temperature, the larger is the thermal influence. All tests were performed on five specimens, the following graphs are the mean of five results. It should be noted that the emphasis of the investigations was more laid on the temperature dependency of permeability than on the absolute values.

3.2. Self-healing with water

Figs. 3–6 show the normalized flow rate as function of crack width and temperature. The curves are the mean of all relevant specimens. The flow rate is normalized with respect to the initial flow rate at the beginning of the test.

It can be seen from Fig. 3 that in case of ambient temperature (T=20 °C), cracks with an average crack width measured at the surface of 0.05 mm shows the fastest self-healing. After only 25 h the flow rate q_t amounts to about 45% of the initial flow rate q_0. In case of a crack width of 0.15 mm, q_t, in contrast, amounts to approximately 75% of q_0 after 25 h. After approximately 336 h (2 weeks) a q_t of just approximately 2% of the original flow rate can be recognized at a crack width of 0.05 mm. In case of a crack width of 0.15 mm, the flow rate has reduced to approximately 14% of the initial flow rate after 2 weeks.

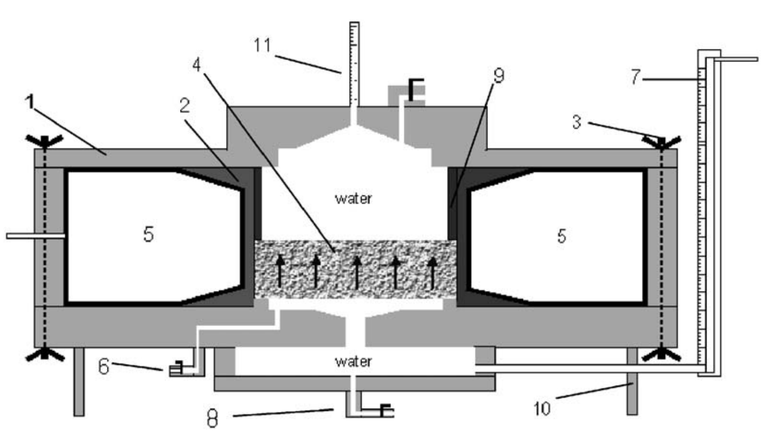

Fig. 2. Schematic illustration of the test cell for the determination of the self-healing behaviour of concrete. (1) Aluminium housing; (2) seal pressure sleeve; (3) fixing screw; (4) concrete specimen; (5) pressure tube; (6) deairation valve; (7) measuring capillary (water pressure); (8) water inlet; (9) backup ring; (10) support; (11) measuring capillary (flow rate).

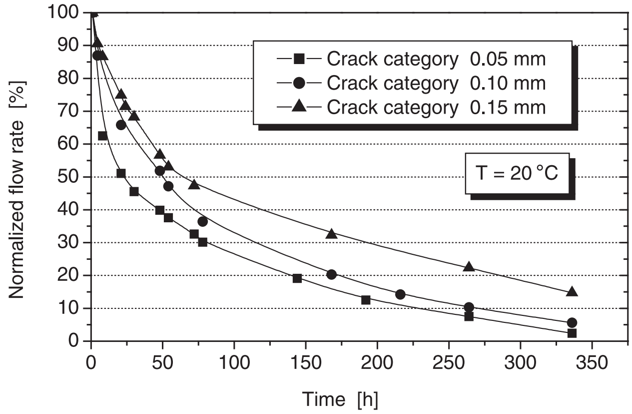

Fig. 3. Decrease of the normalized flow rate because of the self-healing of the crack for HPC at various crack widths and a pressure gradient of 1 MPa/m and a temperature of 20 °C.

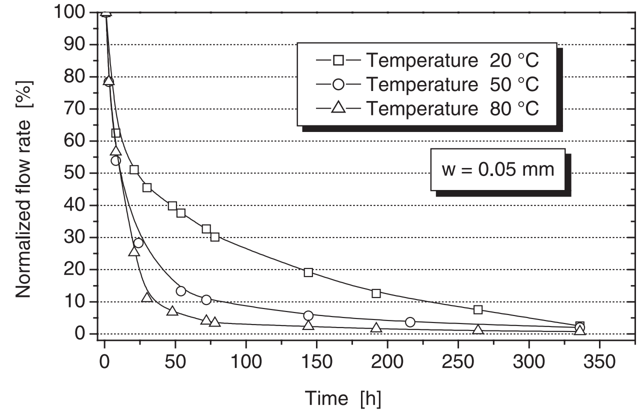

Fig. 6. Decrease of the normalized flow rate because of the self-healing of the crack for HPC at various temperatures and a pressure gradient of 1 MPa/m and a crack width of 0.05 mm.

Fig. 4 shows the situation for 50 °C. It shows a faster healing of cracks that have a smaller crack width, whereas the curves have generally shifted to a lower level. Comparing it to the curve for a crack width of 0.05 mm, as mentioned above, a decrease of the flow rate after 25 h to 45% of the initial flow rate can be stated in Fig. 3, while the decline already amounts to 29% in Fig. 4.

A clear tendency to a faster self-healing process in case of an increase in temperature can be recognized. This tendency also continues in Fig. 5 for 80 °C, where the flow rate of the 0.05-mm curve already fell to 10% of the initial flow rate after 25 h. This tendency can likewise be observed at different crack widths, but it is not quite as distinct.

In Fig. 6, the reduction of the normalized flow rate as function of temperature is described. Equal crack widths were drawn in one diagram. It is clearly visible from Fig. 6 that in case of an equal crack width of 0.05 mm for all temperatures, those specimens that were installed at 80 °C show the best self-healing behaviour. After 75 h, the 20 °C specimen still was at approximately 30%, the 50 °C specimen at approximately 10% and the 80 °C specimen at merely 3% of its initial flow rate. Similar graphs could also

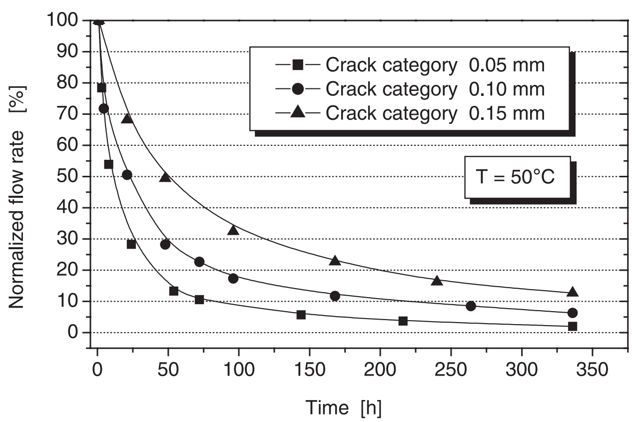

Fig. 4. Decrease of the normalized flow rate because of the self-healing of the crack for HPC at various crack widths and a pressure gradient of 1 MPa/m and a temperature of 50 °C.

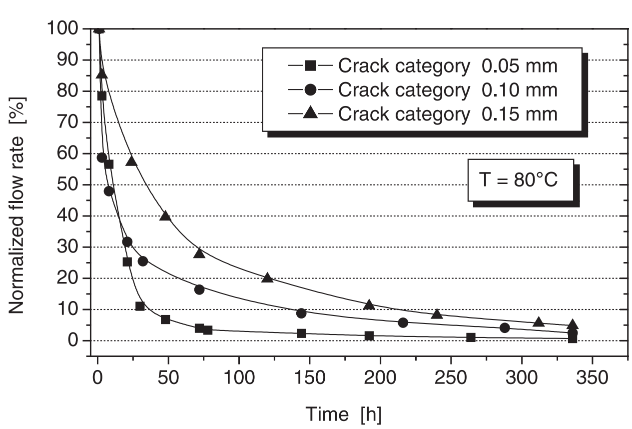

Fig. 5. Decrease of the normalized flow rate because of the self-healing of the crack for HPC at various crack widths and a pressure gradient of 1 MPa/m and a temperature of 80 °C.

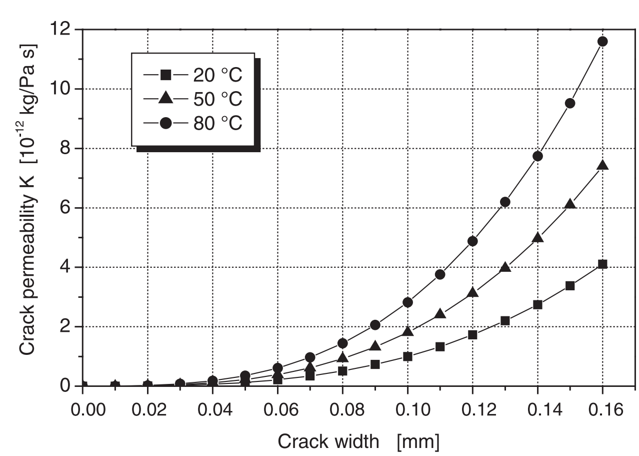

Fig. 7. Representation of the dependency of K of Eq. (4.3) on crack width and temperature.

Table 6
Comparison of the flow rates normalized to 20 °C and a crack width of 0.08 mm from theory and test

Flow rate determination	Crack width (mm)	Temperature (°C)		
		20	50	80
By theory	0.05	0.24	0.44	0.67
	0.08	1.00	1.80	2.82
	0.10	1.95	3.52	5.50
By test	0.05	0.21	0.38	0.60
	0.08	1.00	1.61	2.90
	0.10	2.12	3.62	4.87

be plotted for $w = 0.10$ mm and $w = 0.15$ which are not shown due to space limitation.

4. Discussion of the results

The influence of temperature on the permeability can be predicted by theoretical considerations. The following equation based upon the law of Hagen–Poiseuille is used in this paper:

$$Q_{r0} = \xi \frac{w^3 \Delta p l}{\eta d} \quad [\mathrm{m^3/s}] \tag{4.1}$$

with: Q_{r0} = flow rate; ξ = parameter of roughness; w = crack width; l = length of crack; d = thickness of the specimen; η = viscosity of water; ρ = density of water; g = acceleration due to gravity; h_1 = hydraulic head with $\Delta p = \rho g h_1$ it results in:

$$Q_{r0} = \xi h_1 \frac{g w^3 l}{d} \frac{\rho}{\eta} \tag{4.2}$$

Eq. (4.2) can be rewritten to:

$$Q_{r0} = \xi h_1 \frac{gl}{d} w^3 \frac{\rho}{\eta} \Rightarrow Q_{r0} = \xi h_1 \frac{gl}{d} K \tag{4.3}$$

The crack permeability K depends on the viscosity of water and, to a smaller extent, on the density of water. The viscosity drops from 1.00 at 20 °C to 0.35 mPa s at 80 °C. The density is reduced from 1000 to 970 kg/m^3. On the other hand, the dependence of these quantities on temperature is not linear. In this formula, the influence of temperature and crack width are represented as crack permeability K. The following Fig. 7 illustrates the dependency of K on crack width and temperature.

From Fig. 7 it is visible that the flow rate rises nonlinearly in case of an increase of the crack width. Besides this, the influence of temperature is also well recognizable. The following table compares the test results and theoretical prediction by normalizing the flow rates to the value of 0.08 mm crack width and 20 °C.

It can be recognized from Table 6 that the theoretical prediction and the test results of the dependency of the flow rate through a crack on temperature correspond very well.

5. Summary

Tests have been performed with the aim to establish the dependency of permeability and self-healing behaviour of cracked concrete on temperature. Test cells that were specially developed for the permeability tests were available. In the tests the temperature was kept constant at 20, 50 and 80 °C. It has been shown that the decrease of the flow rate depends on crack width and temperature. Smaller cracks do heal faster than greater ones and a higher temperature favours a faster self-healing process. In regard to self-healing of cracks in HPC, the conclusion can be drawn that at a hydraulic gradient of approximately 1 MPa/m and under the assumption of nonmoving crack edges, cracks of ≤ 0.10 mm can be regarded as smooth and can be closed by self-healing processes. In all tests, the theoretical predictions are in close agreement with the average values of the experiments.

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