SELF-HEALING OF CRACKS IN CONCRETE SUBJECTED TO WATER PRESSURE

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ABSTRACT

This paper presents findings of experimental investigation carried out on self-healing process of cracks in concrete under percolation of water. A test method was developed to study the effect of crack width, crack length and water pressure on self-healing process of cracks in concrete. In this test, flow of water through a cracked concrete specimen under constant head was monitored with time. Rapid reduction of flow rate followed by gradual reduction was observed in all specimens indicating self-healing process of the crack. Most of the specimens got sealed completely after several weeks of exposure to water flow. It was found that the time taken to seal a crack depends not only on crack width but also on hydraulic gradient. For selected hydraulic gradients, sealing times for different crack widths were obtained. It was found that, for a given hydraulic gradient there is a optimum crack width which would get sealed within minimum duration. Furthermore, it was found that this critical crack width decreases with the increase of pressure gradient.

1. INTRODUCTION

Self-healing or autogenous healing of concrete is very important for the satisfactory functioning of reinforced concrete water retaining structures. Since the primary requirement of a water retaining structure is free from leakage, few decades ago, the structures were designed based on limiting concrete stress to prevent cracking which resulted in very thick sections. Even though cracks were not developed in those structures due to imposed loads there were cracks due to moisture and temperature movements because of excessive thickness. It is now understood that it is difficult to construct a concrete structure without any kind of cracking. Even though it is not possible to prevent cracking in concrete structures, the water tightness can be achieved by controlling cracking. The limitation on crack width depends on the sealing of the crack when it is subjected to percolation of water and without any external action. This is known as self-healing or autogenous healing of cracks in concrete.

Most of the current Codes of practice (BS 8007, 1987; AS 3735,1991) adopt the limit state design philosophy in design of reinforced concrete water retaining structures and the governing limit state is the limit state of cracking. This was possible due to development of a method to calculate crack width due to imposed loads, thermal and moisture movement. Most of the Codes limit the crack width to 0.1mm or 0.2mm in order to achieve water-tightness irrespective of the crack length and water head. Based on practical experience Lohymeyer has published some figures concerning the relation between critical crack width and the hydraulic gradient (i.e. ratio between water head and crack length). If the crack width is less than the critical crack width self-healing would be liable to occur (Breugel, 1984). In Netherlands, water tightness is assumed to be guaranteed if the calculated crack width is less than 0.1mm, the wall thickness is grater than 200 mm, and the water height is less than 4m (Breugel, 1984).

Some research works have been carried out recently on factors affecting self-healing of concrete (Ramm,1998; Edvardsen, 1999; Reinhardt, 2003). According to the literature (Naville, 2002), the chemical reactions of self-healing process have not been established conclusively. The most significant factor that influences the self-healing is the precipitation of calcium carbonate crystals on the crack surface (Edvardsen, 1999). The other mechanisms that can contribute to healing are:

- Continued hydration of cement at cracked surface as well as continued hydration of already formed gel and also inter-crystallization of fractured crystals (Turner, 1937; Ramn, 1998).
- Blocking of flow path by water impurities and concrete particles broken from the crack surface due to cracking (Ramn, 1998; Edvardsen, 1999).

The main purpose of the research described in this paper was to investigate the self–healing process and to find out the effect of hydraulic gradient (i.e. ratio of water head to crack length) and crack width to self-healing.

2. EXPERIMENTAL INVESTIGATION

The main requirement of an experimental investigation on self-healing is simulation of the self-healing process under controlled conditions. Out of the main parameters that would affect the self-healing process, the most difficult one to control is the crack width. A simple test method was developed to study the self-healing process by using a cracked cylindrical concrete specimen with a known crack width.

2.1 Test specimens

A cylindrical concrete specimen was selected to introduce a crack as cylindrical specimens can be split easily by applying a compressive force across the diameters as in the indirect tensile test (BS 1881, 1983). All concrete specimens were cast with grade 25 concrete and cured for 28 days. After splitting the cylindrical specimen the two halves were joined again by using steel straps while maintaining the required crack width. Before joining the two parts, loose particle were removed by brushing. This was carried out to eliminate the possible contribution of broken particles on self-healing process. A crack width-measuring microscope was used to measure surface crack widths on end faces of the cylindrical specimen. After obtaining the required crack width by adjusting the screws of the steel straps, the two longitudinal sides of the cylindrical specimen were sealed with epoxy resin (see Figure 1). Then the specimen was connected to a constant head water supply. The water used was drinking water from the main water supply line with zero total hardness (expressed as $CaCO_3$ mg/l) and pH of 6.5. After applying constant water pressure to the specimen the amount of water flowing through the crack was measured with time. Initially outflow was measured at shorter time intervals and once the flow rate was reduced, time interval was increased appropriately.

The selected length of the specimens and crack widths are given in Table 1. The applied pressure head for all these specimens was 2m.

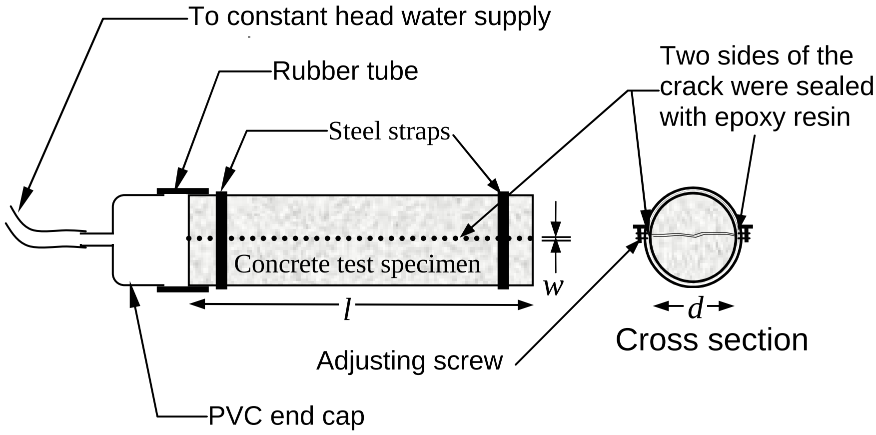

Figure 1: Cylindrical test specimen

Table 1:Test parameters

Specimen	Crack width w (mm)	Crack length l (mm)	Water head (m)	Diameter of specimen d (mm)
A1, A2	0.10	200	2	110
A3, A4	0.15	200	2	110
B1, B2	0.15	600	2	160
B3	0.20	600	2	160
B4	0.25	600	2	160

2.2 Equivalent crack width

Even though the surface crack width can be measured using optical crack width measuring microscope, the actual crack width varies along the length of the specimen as well as across the specimen. Therefore, in order to obtain equivalent crack width the initial flow rate (i.e. flow rate during the first 5 minuets after exposing the crack to water flow) was used. Assuming that the flow through the crack is laminar flow, the equation (1) for flow through parallel plates was used to calculate the equivalent crack width.

$$q = \Delta p \, d \, w^3 / 12 \, \eta \, l \qquad (1)$$

Where
q = initial water flow rate (m^3/s)
Δp = differential water pressure between inlet and outlet of the crack (N/m^2)
d = surface crack length (m)
w = crack width (m)
l = flow path length of a crack (m)
η = absolute viscosity of water (Ns/m^2) ($=0.801\times10^{-3}$ Ns/m^2 at 30 °C)

The measured and calculated equivalent crack widths are given in Table 2. It can be seen that there is a considerable variation between the measured crack width and calculated crack width as there are variation in the crack width cross the specimen as well as due to the roughness of the inner surface of the crack (Ramn, 1998; Edvardsen, 1999). Since calculated crack width is more realistic than the measured surface crack width, the rest of the analysis is based on the calculated crack width and it is referred as equivalent crack width.

Table 2: Equivalent crack widths

Specimen	Measured crack width (mm)	Initial flow rate (ml/h)	equivalent crack width (mm)
A1	0.1	71.72	0.026
A2	0.1	337.39	0.044
A3	0.15	2048.66	0.080
A4	0.15	7202.93	0.121
B1	0.15	1330.59	0.088
B2	0.15	2851.90	0.113
B3	0.2	4360.0	0.131
B4	0.25	9734.8	0.171

2.3 Variation of flow rate through the crack with time

Figure 2 shows a typical variation of flow rate with time. It can be seen that there is a rapid drop in flow rate initially and then a gradual decrease in flow rate. Edvardsen also reported this behaviour. When water passes through the crack surface, $CaCO_3$ is deposited on the crack surface as well as on the outer surface of the crack. $CaCO_3$ is produced from the reaction between Ca^{++} derived from the hydrated cement and bicarbonate HCO_3^- or CO_3^{2-} available in the water. Since the rate of formation of $CaCO_3$ is high at the initial stage, there is a rapid drop in flow rate at the beginning. But after formation of $CaCO_3$ layer on the crack surface, the rate of releasing Ca^{++} from the hydrated cement paste is reduced. As a consequence, gradual reduction of flow rate can be seen (Edvardsen, 1999).

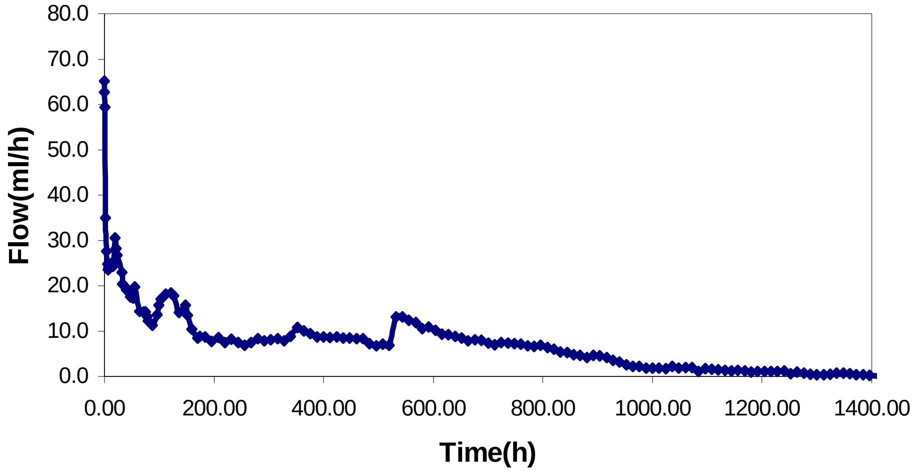

Figure 2: Variation of flow rate with time

2.4 Variation of sealing time with crack width

The time taken to seal the crack for different crack widths under two different pressure gradients are given in Table 3 and shown in Figure 3. It can be seen that, for a given hydraulic gradient, time taken for total self-healing is more for small crack widths as well as large crack widths. This means that, for a given hydraulic gradient, there is an optimum crack width for which total self-healing would take place at the shortest time period. This behaviour can be explained as follows.

Table 3: Time taken for total self-healing

Specimen	Hydraulic gradient ($\Delta p/l$)	Equivalent crack width (mm)	Sealing time (h)
A1	10	0.026	1528
A2	10	0.044	1216
A3	10	0.080	484
A4	10	0.121	1152
B1	3.3	0.088	2680
B2	3.3	0.113	1312
B3	3.3	0.131	715
B4	3.3	0.171	1912

When the crack width is small initial flow rate is also small. Therefore removal of Ca^{++} from the hydrated cement paste is slow. As a result, the rate of formation of $CaCO_3$ would be slow and it would take longer time for total self-healing. On the other hand, when the crack width is large, the rate of formation of $CaCO_3$ would be high. However, part of the deposited $CaCO_3$ would have got washed away due to high flow rate of water. Because of this reason, wider cracks take longer time to seal completely. This can be clearly seen by comparing the normalized flow rates (normalized with respect to the initial flow rate) of the specimens. Figure 4 shows the normalized flow rate for specimens A1, A2, A3 and A4. It can be seen that flow of A3 (c.w.= 0.08mm) specimen was reduced to 18% of the initial flow rate while flow rates of specimens A2 (c.w.= 0.044mm) and A4 (c.w.= 0.121mm) were reduced to only 72% of the initial flow. Similar behaviour can be seen in series B where the hydraulic gradient was 3.3 (see Figure 5). This means that, for a given pressure gradient, there is optimum crack width for which rate of deposition of $CaCO_3$ will be maximum and therefore the crack will undergo total self-healing with minimum time. Based on Figure 3, the optimum crack width for hydraulic gradients of 3.3

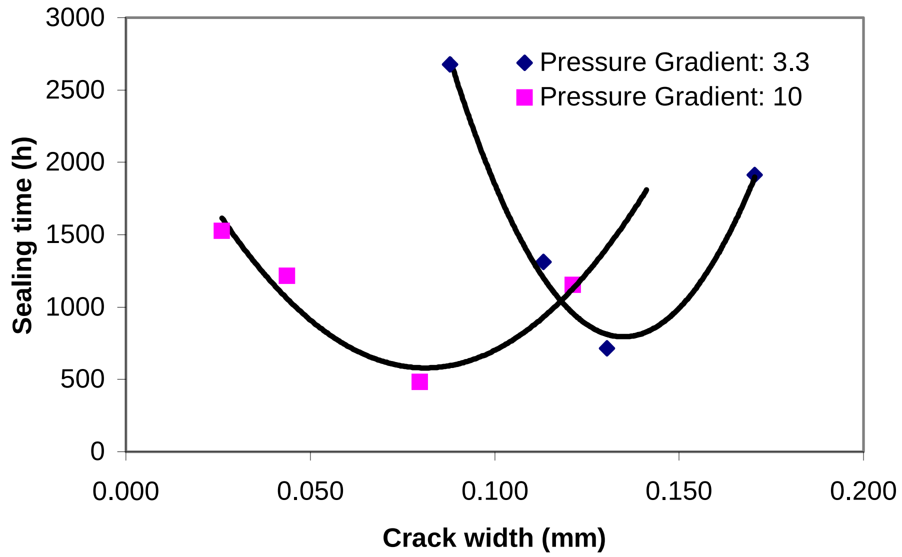

Figure3: Variation of sealing time with crack width

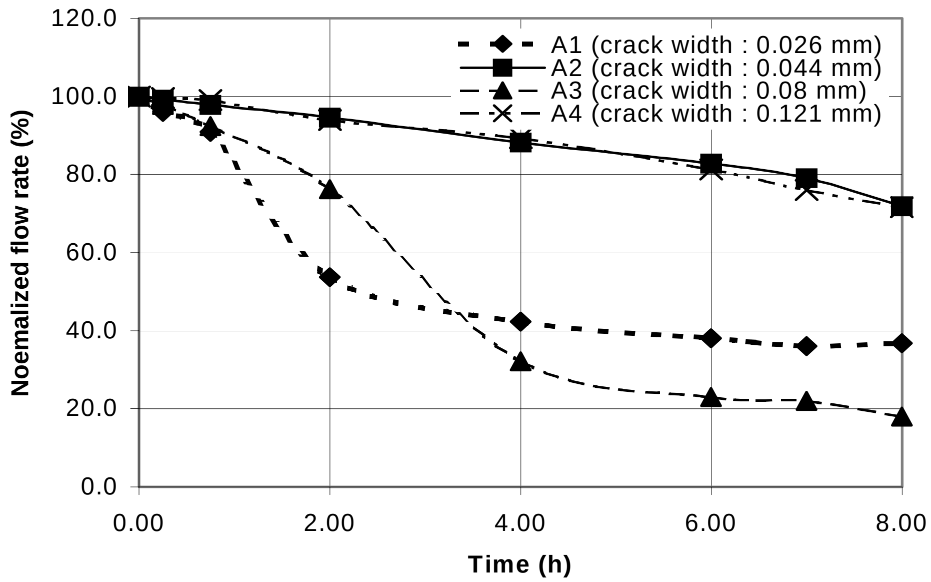

Figure 4: Normalized flow rate during first 8 hrs for series A

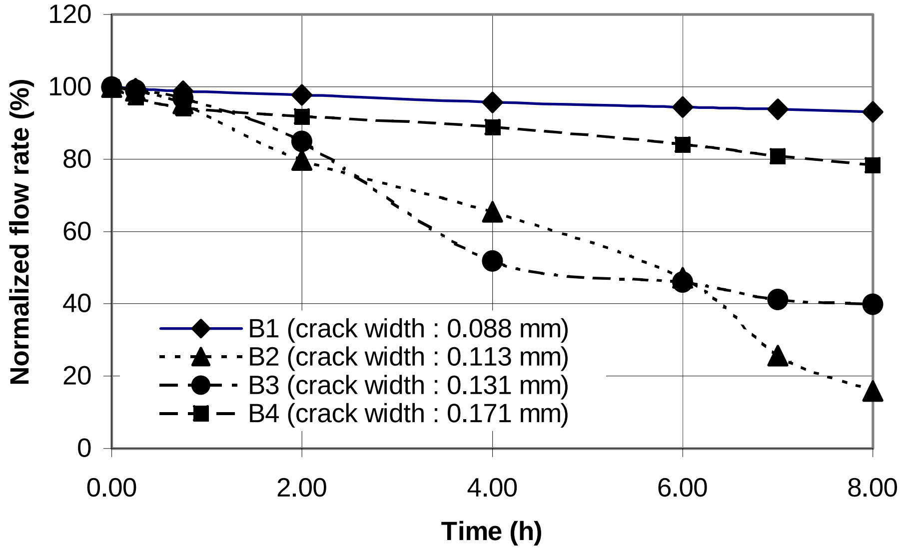

Figure 5: Normalized flow rate during first 8 hrs for series B

and 10 are 0.135 mm and 0.08 mm respectively. These values are in close agreement with the Lohmeyer's recommendations for self-healing (i.e. for crack widths less than critical crack width, self-healing would be liable to occur) given in Table 4 (Breugel, 1984).

Table 4: Relation between critical crack width and hydraulic gradient

Hydraulic gradient (Liquid height/crack length)	Critical Crack width (mm)
< 2.5	<0.2
<5	<0.15
<10	<0.10
<20	<0.05

3. CONCLUSIONS

The test method developed is capable of simulating the self-healing process of cracks in concrete when exposed to water pressure. Test results clearly indicated the self-healing process when water passing through the crack. The rate of self-healing is very rapid during the first 2 to 3 days of water exposure. The complete self-healing depends on the crack width and hydraulic gradient. For a given hydraulic gradient, there is an optimum crack width that would be getting sealed in minimum time. The cracks wider or narrower than the optimum crack width would take much longer time to seal. The optimum crack width can be considered as the permissible crack width for self-healing.

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