Investigations on Water Penetration and Autogenous Healing of Cracked Concrete

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Abstract: On many construction projects in Australia and in other parts of the world, structural elements are designed where limits on design crack width are specified. In many cases, the need for watertightness in the element and the structure is highlighted, resulting in tighter specifications of design crack width. In practice, the reasons for crack propagation in concrete are complex and cracks themselves form and orient themselves in a myriad of ways. In this paper, results from studies on the relationships between water penetration, concrete properties and cracking is presented. Controlled cracks with predefined widths of 0.1 mm to 0.4 mm were induced in concrete specimens through the application of feedback-controlled splitting-tensile loads. Cracked and uncracked specimens were placed into a permeability apparatus where water at a significant head was applied to determine water penetration rates. The permeability characteristics of cracked concrete specimens was determined and compared with that reflective of comparable uncracked concrete specimens. Crack healing was also investigated over time in conventional concretes and with those containing specialty admixtures. Relationships were developed between crack width and water penetration. As expected, larger crack widths resulted in increased water penetration. Cracks in all concretes were found to heal under the conditions examined when they were below 0.15 mm, consistent with current standard provisions for water retaining structures. Cracks in some concretes containing certain permeability-reducing admixtures were found to heal at widths of up to 0.3 mm.

Keywords: crack width, permeability-reducing admixture, water penetration, permeability, durability.

1. Introduction

Watertightness in a structure can be achieved through proper concrete mix design, construction practice and structural design and detailing (1). Structural design and detailing are aimed at crack control, joint and fitting detailing and element set out. In the absence of cracks, resistance to water penetration determines the ability of water to flow into the concrete structure. It is affected by concrete porosity and the different types, sizes and connectivity of pores.

Over the past two decades, chemical admixtures (particularly permeability-reducing admixtures – PRAs) have been widely used in construction to improve the watertightness and durability of concrete. The exact role of these admixtures in concrete and the benefits they might provide is complex and has been discussed in the literature (2). ACI 212.3R (3) subdivides permeability-reducing admixtures into two main groups: admixtures for concrete exposed to hydrostatic (PRAH) and nonhydrostatic (PRAN) conditions. ACI 212.3R classifies PRAs into several categories including those that are hydrophobic pore blockers (HP) and those that are crystalline products (CP).

Whilst water penetration into uncracked concrete can be assessed and modelled, the issue of modelling water penetration in cracked concrete is further complicated by crack geometry and its usually non-uniform distribution. Kermani (4) studied the influence of cracking and crack distribution on water ingress into concrete. He reported on water permeability of concrete under a uniaxial compressive stress and observed a very high variation of water flow when concrete specimens experienced stresses higher than 40% of ultimate compressive strength (F_u) (**Error! Bookmark not defined.**). This study found that the permeability of concrete increased from an initial value of 8×10^{-13} m/s to more than 1000 times that value under stress levels between 40% and 70% of F_u. Park et al. (5) used the split tensile test to induce a controlled single crack in concrete and compared water permeability of cracked concrete specimens with that of uncracked concrete specimens. They found that the permeability in concrete containing a 0.4 mm crack was three orders of magnitude higher than the permeability in a comparable uncracked concrete.

Most standards and codes of practice define design procedures to limit the crack width in structural members and therefore limiting permeability. Australian Standard AS 3600-2018 (6) specifies specific crack control measures for different member types (beams, slabs and non-flexural members). On the other hand, the Australian Standard for liquid retaining structures, AS 3735 (7) specifies minimum requirements for reinforcement ratio and stress in reinforcing steel.

Permeability models for concrete integrating a single crack model have been found to be more reliable and closer to experimental data when compared with those having distributed cracks (22). On many projects, engineers design for a maximum crack width in an element and limit crack width in construction specifications. The link between a crack width in design versus what might be found on a structural element in service is unclear. In this paper, a single crack technique was used to examine the influence of crack width on water penetration. Predefined crack widths of 0.1 mm, 0.2 mm, 0.3 mm and 0.40 mm were induced in standard concrete cube specimens. The concretes evaluated in this study covered conventional as well as those incorporating integral permeability-reducing admixtures as described in Australian Standard AS1478.1 (**Error! Bookmark not defined.**). The variation in permeability rates of concrete caused by cracking and healing were evaluated by applying water pressure. Numerical relationships were developed to relate the permeability of concrete to the crack width and comments are made on what the data show in relation to current design practices for watertight concrete elements.

2. Experimental Investigation

In this study, cracking and its influence on water penetration was investigated in a range of concretes made using a range of binders and chemical admixtures. Concretes studied in this investigation were as follows:-

- Binders covering General Purpose Portland Cement (GP- conforming to Australian Standard AS3972) (8), fly ash (FA - conforming to Australian Standard AS3582.1) (9) and ground granulated blast furnace slag (GGBFS - conforming to Australian Standard AS3582.2) (10); and
- Permeability reducing admixtures (PRAs) – specific materials selected were a hydrophobic pore blocker (HP) and two different crystalline products (CP1 and CP2);

Three sets of concretes were prepared, the first incorporating GP cement, the second incorporating a binder composed of GP and FA and the third incorporating a binder composed of GP and GGBFS. For each set, four concretes were compared, the first being a control (denoted “C”) that included no PRA. The other three concretes incorporated a liquid hydrophobic pore blocker (HP) and two powdered crystalline products (CP1 and CP2). Such PRAs are commonly specified and used in projects within Australia where watertightness is desired. Mix proportions for the three sets of concretes are given in Table 1 for GP concretes, Table 2 for FA concretes and Table 3 for GGBFS concretes.

Table 1. Mix Proportions for GP Concretes.

Mix Description	C	HP	CP1	CP2	C	HP	CP1	CP2	C	HP	CP1	CP2
Target slump (mm)	100				100				100			
W:B ratio	0.40				0.50				0.60			
Binder content (kg/m^3)	387				340				300			
GP (kg/m^3)	387				340				300			
20 mm aggregate (kg/m^3)	640				630				620			
10 mm aggregate (kg/m^3)	370				360				350			
Nat. fine aggregate (kg/m^3)	590				718				742			
Manufactured fine agg (kg/m^3) aggregate (kg/m^3)	130				83				85			
Water (kg/m^3)	153				170				180			
Water Reducer (wt % binder)	1.07	0.84	0.84	1.24	0.73	0.64	0.63	0.72	0.56	0.44	0.28	0.44
HP, CP1, CP2 (wt % binder)		1.00	1.00	0.80		1.00	1.00	0.80		1.00	1.00	0.80

“C” denotes control concrete mix without any PRAs. “HP” denotes a hydrophobic pore blocker. “CP1” and “CP2” are crystalline products. PRA dosage was 1% of cementitious material content by weight.

Table 2. Mix Proportions for GP - FA Concretes.

Mix Description	C	HP	CP1	CP2	C	HP	CP1	CP2	C	HP	CP1	CP2
Target slump (mm)	100				100				100			
W:B ratio	0.40				0.50				0.60			
Binder content (kg/m^3)	450				351				284			
GP (kg/m^3)	338				263				213			
FA (kg/m^3)	112				88				71			
20 mm aggregate (kg/m^3)	640				625				620			
10 mm aggregate (kg/m^3)	370				365				350			
Uncrushed fine aggregate	625				670				750			
Manufactured fine	105				75				85			
Water (kg/m^3)	180				175				170			
Water Reducer (wt % binder)	0.46	0.44	0.19	0.56	0.43	0.48	0.32	0.19	0.65	0.53	0.47	0.70
HP, CP1, CP2 (wt % binder)		1.00	1.00	0.80		1.00	1.00	0.80		1.00	1.00	0.80

C" denotes control concrete mix without any PRAs. "HP" denotes a hydrophobic pore blocker. "CP1" and "CP2" are crystalline products. PRA dosage was 1% of cementitious material content by weight.

Table 3. Mix Proportions for GP - GGBFS Concretes.

Mix Description	C	HP	CP1	CP2	C	HP	CP1	CP2	C	HP	CP1	CP2
Target slump (mm)	100				100				100			
W:B ratio	0.40				0.50				0.60			
Binder content (kg/m3)	450				350				284			
GP (kg/m3)	270				210				171			
GGBFS (kg/m3)	180				140				114			
20 mm aggregate (kg/m3)	640				625				620			
10 mm aggregate (kg/m3)	370				365				350			
Uncrushed fine aggregate	625				670				750			
Manufactured fine	105				75				85			
Water (kg/m3)	180				175				170			
Water Reducer (wt % binder)	0.45	0.21	0.07	0.48	0.48	0.21	0.16	0.50	0.64	0.38	0.35	0.67
HP, CP1, CP2 (wt % binder)		1.00	1.00	0.80		1.00	1.00	0.80		1.00	1.00	0.80

C" denotes control concrete mix without any PRAs. "HP" denotes a hydrophobic pore blocker. "CP1" and "CP2" are crystalline products. PRA dosage was 1% of cementitious material content by weight.

The HP admixture consists of active components that reportedly form non-soluble materials throughout the pore and capillary structure of the concrete and seal the concrete against penetration of water. The CP admixture reportedly reacts with moisture present in the cementitious matrix and generates pore-blocking substances. It improves water impermeability as well as self-healing properties of the concrete.

To carry out the experimental tests, concrete cubes measuring 150 mm square were cast and cured for 28 days prior to being subject to a water pressure test described later in this section. This conditioning was chosen to reflect common site conditions. Whilst the presence of other conditions on site is acknowledged, these were beyond the scope of this study. Cracked specimens were tested for water permeability under 0.4 MPa water pressure. In addition, uncracked concretes were also tested for water permeability under 3.0 MPa water pressure. Higher water pressure was used for uncracked concrete specimens to accelerate the procedure. To examine the self-healing properties of different concrete types, the cracked specimens were further cured for 28 days after the initial measurement of water permeability. After 28 days additional curing, the water permeability test was repeated and compared with the initial permeability measurement. Any recovery of water permeability was thought to be a result of the self-healing of cracks.

2.1 Feedback controlled splitting test

In order to carry out the water permeability test on cracked concrete, first, it was necessary to induce a controlled crack in the concrete specimen. A feedback controlled splitting test was used to do this. The test specimens were obtained by saw cutting concrete cubes into a section measuring 50 mm thick. These specimens were loaded under a splitting uniaxial compressive load and the lateral displacement (crack width) was reached. The process was controlled by means of two LVDTs attached to both sides of the specimen. Figure 1 shows the feedback controlled test setup.

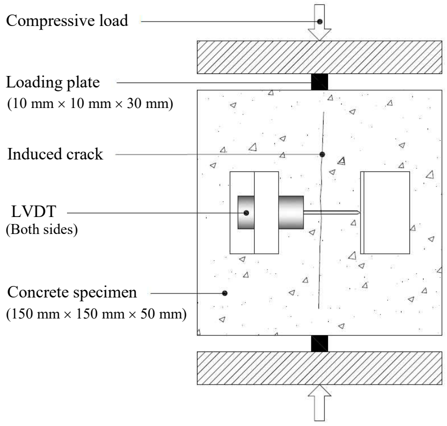

Figure 1. Feedback controlled splitting test setup.

2.2 Steady-state water permeability test

Permeability testing was carried out using a pressure cell capable of applying variable water pressure up to 3.0 MPa. In this test, the side surfaces of the cube specimens were sealed by epoxy to have a one-dimensional flow in the specimens. These were subjected to the hydrostatic pressure for a pre-set period of time. Water penetration through the specimen was collected and measured to determine the coefficient of permeability in m/sec (Darcy coefficient) which is expressed as:

$$K_{S-Measured} = \frac{Ql}{tA\Delta h} \qquad (1)$$

where K_s is coefficient of water permeability (m/s); Δh is pressure head (m); Q is volume of liquid flowing (m^3), t is time (s); l is thickness of penetrated section (m) and A is penetrated area (m^2).

2.3 Cracks in concrete specimens

In Figure 2, a concrete specimen with a crack of width 0.4 mm is shown. The crack width is also known as crack opening displacement (COD), which is defined as the distance between two parallel walls of the crack at the point of examination. Figure 2 illustrates an image of the crack width.

3. Analytical Investigation

Water penetration through an uncracked concrete matrix was almost negligible when compared with the penetration of water through cracks. Thus, the permeability through a section of cracked concrete section is controlled by the characteristics of the cracks rather than the permeability of the concrete matrix. Current permeability prediction models generally give larger values for cracked concrete when compared with measured values in practice. This difference is attributable to variation in crack characteristics such as roughness and tortuosity. A reduction factor was introduced by Fauchet to modify the models empirically (11). The author of the Fauchet study showed that the permeability of concrete with multiple single cracks can be written as:

$$K_S = \sum \frac{w^3 \rho g}{12\Delta \, \eta} \qquad (2)$$

where, w is crack width (m); η is fluid dynamic viscosity (kg/m/s); P is hydrostatic pressure (Pa); ρ is density of the fluid (kg/m^3); Δ is the average spacing between the cracks; or, $1/\Delta$ is cumulated crack length per area (m/m^2), and ζ is the reduction factor of the crack which accounts for the defects of the crack geometry.

In a concrete specimen with a single crack, the cumulated crack length per area can be written as:

$$\frac{1}{\Delta} = \frac{l}{A} \tag{3}$$

where, l is crack length (m), and A is specimen area (m^2). Accordingly, the permeability of a cracked concrete specimen with a single crack can be written as:

$$K_{S-Calculated} = \zeta \frac{w^3 l \rho g}{12A\,\eta} \tag{4}$$

In this study, $K_{S\text{-}Measured}$ for each concrete specimen was determined during the steady-state water permeability test. In addition, $K_{S\text{-}Calculated}$ was determined for each predefined crack width, and the reduction factor (ζ) for each concrete specimen was determined using the following formula:

$$\zeta = \frac{K_{S-Measured}}{K_{S-Calculated}} \tag{5}$$

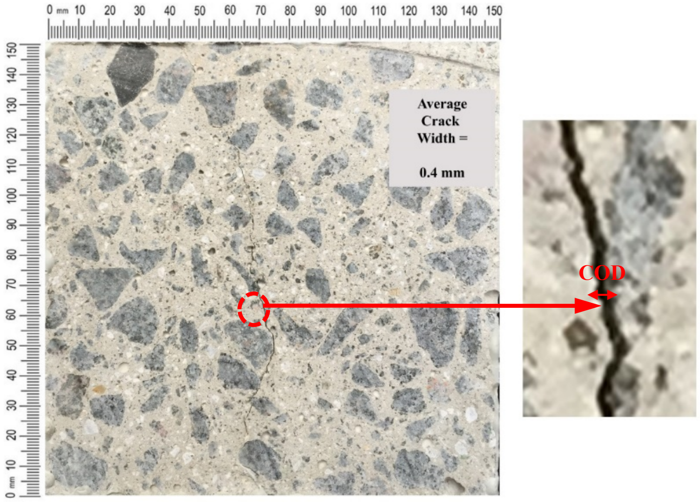

Figure 2. Typical crack formation in the concrete specimen and definition of crack opening displacement (COD).

4. Experimental Results and Discussion

4.1 Influence of crack width on water permeability

In Figure 3, the results for water permeability in the different concretes and crack widths investigated in the study are shown. It was found that the water permeability increased significantly for increasing crack width in all specimens. The results indicated that the type of concrete did not affect the water permeability when the repeatability of the test was considered. For example, in concretes with 0.1 mm predefined crack width, the water permeability of C, HP and CP concretes were approx. 1.5×10^{-8} m/s. When comparing the permeability of uncracked concrete with that of cracked concrete, cracking significantly influences the permeability.

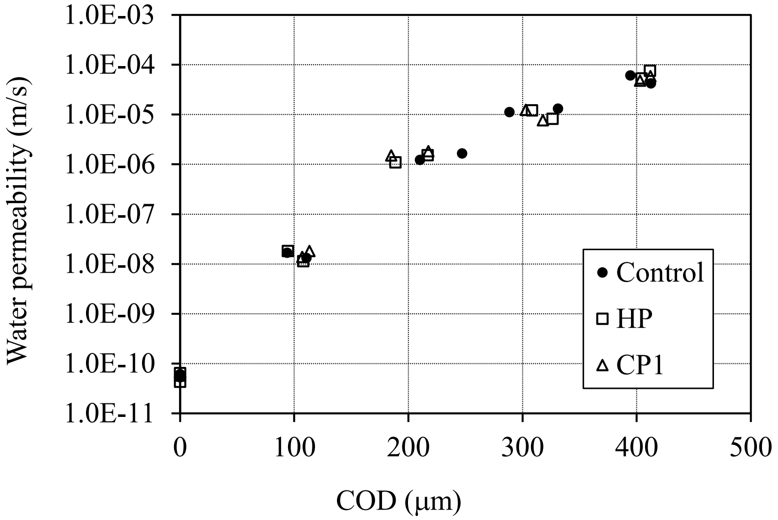

Figure 3. Effect of crack width on water permeability of conventional concrete and concretes incorporating specialty admixtures after cracking.

When the effect of crack width on water permeability is considered, the results obtained in the current study showed good correlation with the previous studies carried out by Aldea et al. (12), Wang et al. (13) and Park et al. (14). In Figure 4, the results of the current study are compared with the results from the work reported by others.

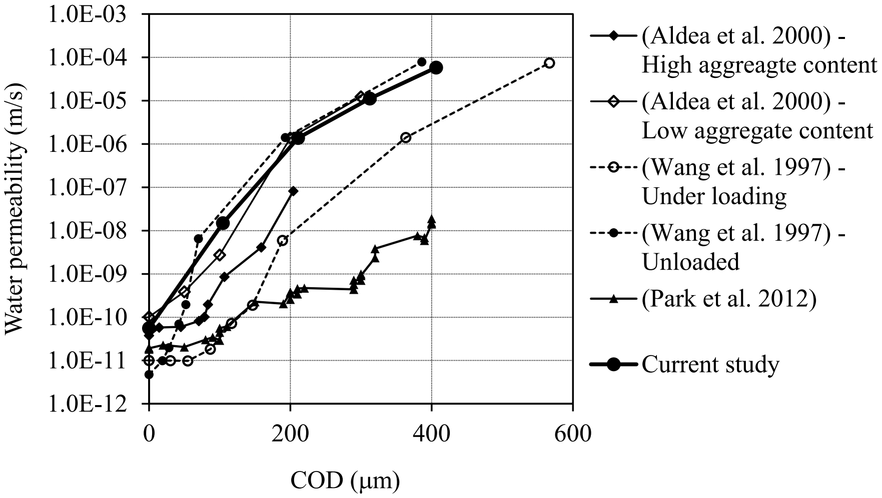

Figure 4. Effect of crack width on permeability of concrete – comparison between previous and current findings.

4.2 Self-healing properties of concretes

The water permeability test is used as a technique to verify the self-healing properties of concrete. The recovery of water permeability was examined after 28 days water curing. The average water permeability (average of two repetitions) is shown in Figure 5. It was observed that the reduction of water permeability was higher in narrower cracks when compared with wider cracks. It is thought that additional hydration products may have formed in narrower cracks during additional hydration, thus, bridging and blocking the cracks more efficiently and resulting in lower permeability.

The data in Figure 5 show that concrete having the HP admixture did not improve the self-healing properties of the concrete when compared with the control concrete. In contrast, concrete containing the CP admixture showed a reduction in permeability of concrete for cracks having a crack width of 0.3 mm. Reductions in permeability for crack widths of 0.1 mm of 99% when compared with control concrete were found. However, as the crack width increased, concrete with the CP admixture could not heal the cracks fully as reflected by the measured permeability.

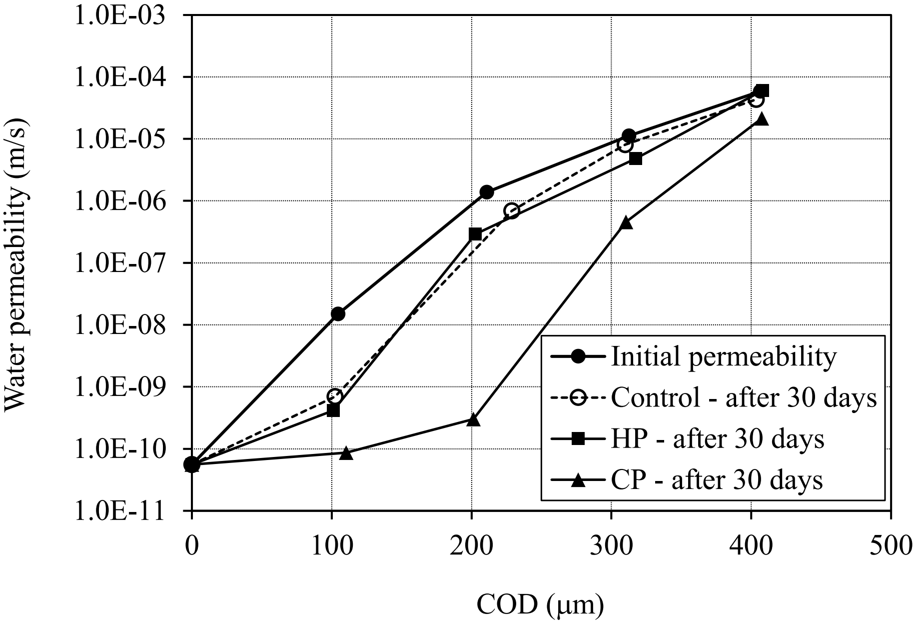

Figure 5. Effect of crack width on water permeability of conventional concrete and concretes incorporating specialty admixtures after 28 days addition curing (self-healing).

5. Comparison of Predictions and Experimental Results

The reduction factor of ζ calculated in accordance with Equation (5) are presented in Table 4 for different concrete types and crack widths after 28 days additional curing (self-healing). These reduction factors can be used to modify the permeability models and predict the realistic permeability of cracked concrete.

Table 4. Reduction factor (ζ) for different concrete types and crack widths, to be used in permeability models of cracked concrete.

	Concrete type		
Crack width, mm	C	HP	CP
0.1	12.0E-05	7.1E-05	1.2E-05
0.2	10.2E-03	6.2E-03	6.5E-06
0.3	4.7E-02	2.2-02	2.6E-03
0.4	1.10E-01	1.5E-01	0.54E-01

6. Conclusions

The influence of cracking on water penetration into concrete specimens is evaluated. The water permeability of concrete specimens with predefined crack widths of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were investigated. In addition, the self-healing properties of conventional concrete and concretes modified with permeability-reducing admixtures were explored.

The influence of cracking on concrete permeability was much more significant on water permeability (by orders of magnitude) when compared with reductions in permeability of uncracked concrete.

At crack widths of 0.3 mm and over, significantly higher rates of water penetration in all concretes were observed when compared with concretes having smaller crack widths. The water penetration results for crack widths over 0.3 mm suggested that there was limited opportunity for healing to occur. At crack widths of 0.2 mm, reduced rates of water penetration were found in concretes incorporating crystalline pore blockers when compared with control concrete. At crack widths of 0.1 mm, all concretes tested were found to heal under the conditions modelled.

7. Acknowledgement

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