Elucidation of Rapid Reduction of Water Flow through Concrete Crack Regarded as Self-healing Phenomenon

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ABSTRACT

The development of self-healing concrete has witnessed several strides in the last three decades. Among these is the understanding of the mechanisms of self-healing concrete, as well as the realization of new technologies of enhancing crack self-healing in concrete. Previous research suggests that crack closing mechanism occurs due to mainly 1) Hydration of anhydrous cement, 2) Formation and crystallization of Calcium Carbonate, 3) Swelling of cement matrix and 4) Sedimentation of particles in the crack interstices. In this research however, after a one by one investigation, it was found that these mechanisms do not fully explain the drastic water flow recovery that occurs in the initial stages of water permeation through cracked concrete. This preliminary finding then prompted direct visual observation of water flow through cracks' narrow spaces. This was achieved by using acrylic resin and glass as transparent media over the concrete surface of split and machine cut cracks respectively. With this, an interesting observation was made – the creation of air bubbles (waterless spaces inside the interstices) following the condition of full water saturation. It was observed that water flow through the narrow crack openings creates air bubbles by probably various water action mechanisms. The created air bubbles narrow water flow paths in the crack, causing significant water flow reduction in the initial and later stages of water supply condition.

1. INTRODUCTION

The challenges facing the development of concrete technology require an in-depth understanding of the mechanisms of the behaviours of the material itself under its immediate environment. As such, several mechanisms have been postulated to explain the occurrence of this phenomenon in concrete such as 1) Hydration of anhydrous cement, 2) Formation and crystallization of $CaCO_3$ and $Ca(OH)_2$ 3) Swelling of cement matrix and 4) Sedimentation of particles in the crack interstices [1]. Most researchers [1], [3], [5] etc., that approach self-healing by permeability tests especially where water is used as permeant report drastic water flow reduction and directly link it to self-healing recovery. Edvardsen (1999) attributes the initial (3- 5 days) water flow reduction (more than 70%) to formation of $CaCO_3$ within the crack. Hearn (1997) [6] analyses the several self-healing mechanisms and highlights the degree of influence of each, mentioning dissolution, deposition and crystallization as contributing mostly to self-healing. From visual observations and results of this research however, it was observed that the predominantly known mechanisms of self-healing do not explain the drastic water flow reduction that characterizes most permeability tests [3, 4, 5 & 6]

2. INVESTIGATION APPROACH

Initially, investigations were set out to quantify and understand the individual contribution of each of the supposed mechanisms of crack self-healing. In general, water permeability tests were performed through conducting water pass tests following the methodology adopted by Morita (2010) [4]. From experimental investigations, these mechanisms have a small effect on water flow reduction and thus do not explain the drastic water flow reduction. Therefore, direct observation of the water flow phenomenon through the crack by visualization technique was performed to understand self-healing mechanism further. All the tests were performed on 14days, 28days, 3, 6 months air cured specimens.

2.1 Test set up for water pass test measurements

The experimental set up involved measuring of water flow tests for a cracked concrete specimen. A cylindrical concrete specimen (200x 100dia) is cracked via the V-notch created on the long edge. The crack surfaces are cleaned and 0.2mm Teflon sheet strips are aligned along the crack surface and the concrete halves bound together with metal clamps. An average of 0.1 or 0.2mm crack width is maintained and confirmed by measurement with a microscope. A UPV pipe is then attached to the top of the specimen and through it water is supplied while maintaining a pressure head of 85mm. Water flow rate was determined by measuring amount of water flowing through the crack in 5 minutes over a given period of time. An average of 2-3 specimens is used for testing and average values obtained.

2.2 Effect of anhydrous cement on self-healing

Young concrete contains more unhydrated cement and this wanes out in relatively aged concrete. Tests were performed for 14days, 1, 3, and 6 months old specimens. From these results (Figure 1ⓐ & ⓑ), the contribution of unhydrated cement in the initial stages of water supply to the specimen is not clear. The water flow reductions for specimens of different curing ages are not coherent with expected diminishing quantity of unhydrated cement in longer curing periods.

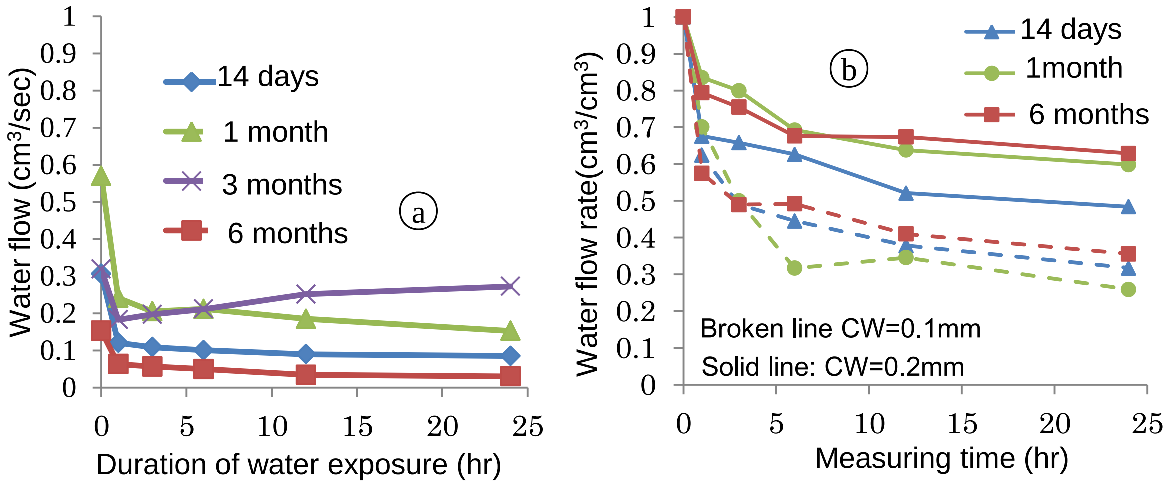


Figure 1: (a) Effect of unhydrated cement; (b) Effect of age and crack width

2.3 Effect of formation and crystallization of $CaCO_3$

$CaCO_3$ once formed should reduce the crack width, narrowing water flow path and thus reducing water flow. By measuring internal average crack width before and after water pass test, it was found that the contribution of the $CaCO_3$ to initial water flow reduction is indeed small. Prepared samples were checked for product filling in the crack. By injecting liquid epoxy which is allowed to solidify in the crack interstices and cutting the specimen at intervals to measure average crack widths, which are compared to crack size opening before water supply, effect of crack closure due to crystallization of $CaCO_3$ is compared. Crack width reduction was far less than that predictable from the modified Poiseuille water flow equation (Edvardsen 1999).

2.4 Effect of sedimentation on water flow reduction

Broken particles and sediments block water flow paths and thus reduced water flows. The effect of this phenomenon in the initial stage was investigated to quantify its contribution. By using liquid ethanol as a substitute for water, flow values were compared in the initial stages of application. The drastic flow reduction is not magnified to show any significant contribution of sedimentation (Figure 2 (a). Liquid ethanol is used to distinguish the contribution of broken particles from other possible water induced reactions.

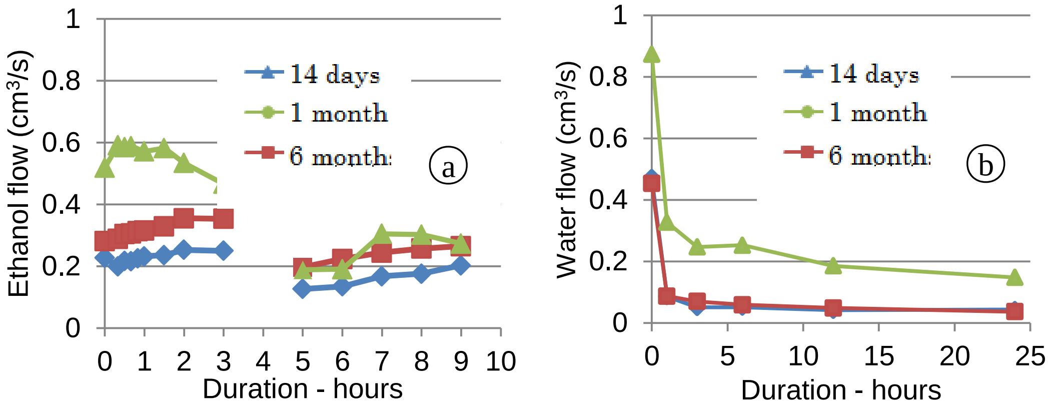
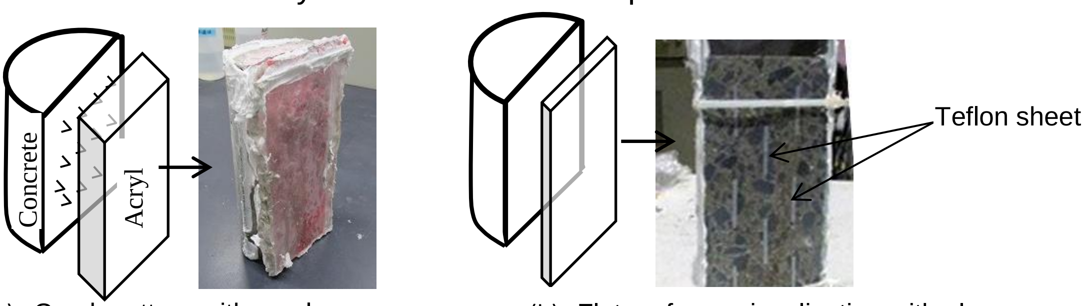


Figure 2: (a) Ethanol flow rate and (b) water flow rate characteristics

3. INVESTIGATION THROUGH VISUAL OBSERVATIONS OF WATER FLOW

Experimental investigations of primarily known mechanisms of self-healing show only a small effect on the initial water flow reduction. This then prompted the direct observation of water flow by a visualization technique.



(a) Crack pattern with acryl (b) Flat surfaces visualization with glass

Figure 3: Specimens for direct visual observation of water flow

The methodology involved using half crack surface concrete specimen with either glass or an acrylic resin to simulate the surface characteristics of the opposite crack side. The basic idea is to be able to visualise water flow through the crack interfaces (Figure 3). With glass, a flat surface is formed and similarly a flat concrete surface obtained by cutting specimen with a concrete cutter. On the other hand, with acryl resin, the opposite side of the cracked concrete is molded with acryl resin to produce a surface with similar crack pattern. Water flow through the interfaces is observed and with the use of coloured water and videography as well as photography, observation revealed oval shaped water-less spaces – air space/air bubbles. These air bubbles are initially non-existent and increase in number and size with time. It is this air bubble effect (Figure 4) that narrows the water flow space and thus water flow values in the early stages of water supply.

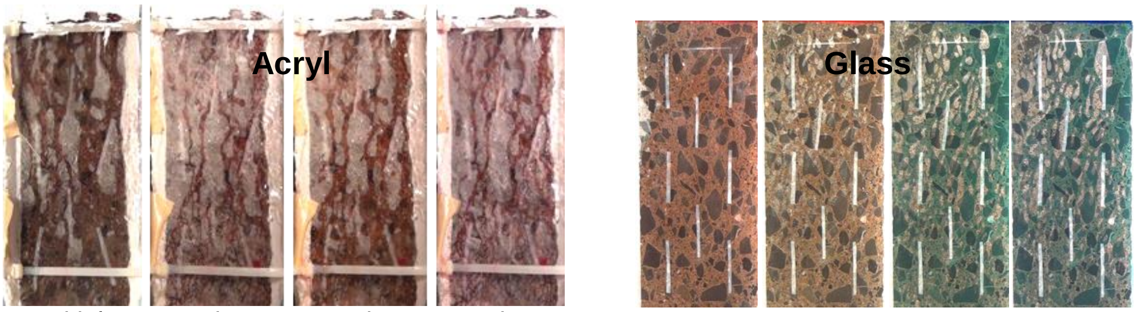


Figure 4: Air bubbles observed through acrylic resin and glass interfaces

The air bubble effect persists in the long term as long as water continues to flow through the crack. Its stability is supposedly attributed to the capillary and surface tension forces in the relatively narrow spaces. Conversely, specimens saturated with water through vacuuming and tested with de-aired water showed reduced effect of air bubbles. The treatment ensured that all sources of possible air bubble generation are minimized.

4. CONCLUSIONS

The observation of air bubble effect in drastically reducing water flow through a static penetrating crack in the initial and probably in long term range clarifies and contributes to previously known mechanisms of self-healing/self-sealing. The predominantly known mechanisms were separately investigated one by one by experimentation and found not to contribute significantly to the initial water flow reduction that characterizes most self-healing results that use water permeation.

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