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Elucidation of rapid reduction of water flow through concrete crack regarded as self-healing phenomenon

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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 investigating them one by one it was found that these mechanisms do not explain the drastic water flow recovery that occurs in the early stages of water permeation through cracked concrete. It then prompted direct visual observation of water flow through crack narrow space; and with this an interesting finding was observed-the air bubble effect. It was observed that water flow through the narrow crack openings creates air bubbles by 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.

Key words: Self-healing concrete, Water flow, Crack, Water permeation, Air bubble

Introduction

Concrete technology development is a cornerstone for sustainable and resilient infrastructural development especially in the 21st century. 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.

Self-healing concrete has developed over the last three decades to combat the problem of cracks in concrete. 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]. Through the occurrence of any or a combination of several of the above, crack closure can be achieved and thus recovery of the properties of concrete such as water transport and other structural aspects [2].

Fig. 1 shows the general trend of autogeneous healing depiction. Most researchers [3-5]… etc., that approach self-healing by permeability tests especially where water is used as permeant report drastic water flow reduction and directly relate it to self-healing recovery. Similarly, N. Hearn (1998), Morita (2011) obtained similar results of a drastic water flow reduction within the first hours of water exposure [6].

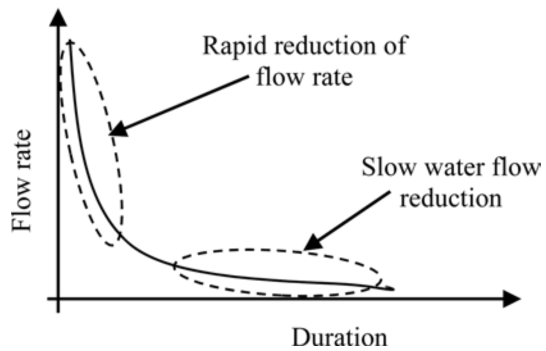

Fig. 1. Illustration of general water flow rate Vs duration graph for self-healing tests.

Edvarsen (1999) attributes the initial (3-5 days) water flow reduction (more than 70%) to formation of $CaCO_3$ within the crack. Hearn (1997) [7] 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 (Fig. 1). A one by one investigation of each of the previously proposed mechanisms was done to ascertain

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their contribution to water flow reduction in the earlier stages of water supply/flow.

This research clarifies the initial rapid reduction of water flow through a crack usually categorized as self-healing phenomenon. Through direct observation of the water flow through a crack in concrete, it was observed that water flow mechanisms through the crack created an air bubble effect. The created air bubbles cause reduced water flow paths within the crack interstices and in turn reduce water flows. It is this effect that's responsible for the initial drastic water flow reduction. Also, the stability of the air bubble within the narrow crack gaps further explains the persistent slow water flow reduction in the long term range.

Water flow through a static penetrating concrete crack

It is difficult to observe the real water flow scenario through the crack gaps in the real situation. Water flow in concrete as is usually characterized by modified Hagen-Poiseuille equation (Equation 1) assumes a saturated two dimensional flow that may not reflect the exact situation of water flow through concrete crack.

$$q = C \cdot \frac{b \cdot \Delta P}{12 \cdot u \cdot L} w^3 \tag{1}$$

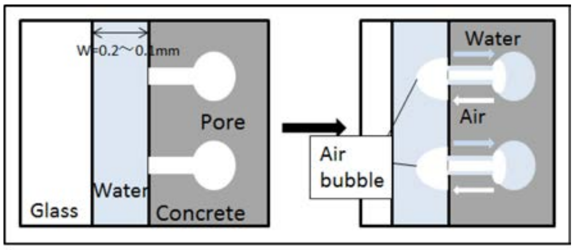
q, water flow rate m^3/s; w, crack width, m; L, Flow path length of crack, m; b, Length of the crack, m; C, Reduction factor for surface roughness; u, Absolute viscosity, Ns/m^2; Δ,P, Differential pressure head, N/m^2

The movement of water through narrow spaces is characterized by several mechanisms. For concrete in particular, these mechanisms also vary depending on the general characteristics of the material itself such as porosity, W/C ratio, and others [8]. The rough nature of concrete crack surfaces characterizes the flow to be significantly viscous at that the scale of crack opening. These surface imperfections within the crack interstices determine the water flow mechanisms in cracked concrete. Also water inherently contains dissolved air and this air often comes out depending on conditions such as temperature, flow pressure and water flow action. Gardner (2013) investigates the Hagen-Poiseuille flow characteristics of pozzolanic healing agent through a crack but doesn't highlight the actual situation of especially water flow in the initial stages [9].

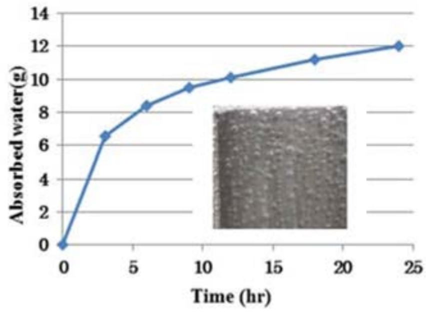
Mechanism of air bubble formation within concrete crack

Air bubble creation within the crack results from mainly water permeation into concrete and dissolved air in supplied water. Air bubbles may be generated through release of air dissolved in water (tap water) through various water flow actions. Also, the physical characteristics of the crack surface influence air bubble formation by acting as nucleation sites for the formation and agglomeration of the air bubble [10].

In addition, water permeation into concrete displaces



(a) Evolution of air bubble from within concrete



(b) Water absorption into concrete over time

Fig. 2. Illustration of air bubble formation through water permeation into concrete.

air in the pores. The air is ultimately forced out of the concrete and through nucleation; relatively larger air bubbles are created. These air bubbles are eventually trapped within the narrow cracks by capillary forces and other water flow characteristics. The illustration in Fig. 2 explains one of the contributions to the air bubble effect-air displacement from the inner depths of concrete. This too contributes to the total effect of water flow reduction by constricting flow paths inside the crack gaps.

It is the combined effect of these air bubbles that's responsible for the rapid water flow reduction within the initial stages of water leakage tests, which is often regarded as self-healing.

Methodology and Experimental Set up

Investigation approach

Initially, investigations were set out to quantify and understand the individual contribution of each of the supposed mechanisms of crack self-healing (Crystallization of $CaCO_3$ & $Ca(OH)_2$) Sedimentation of particles and rehydration of anhydrous cement. In general, water permeability tests were performed through conducting water pass tests following the methodology adopted by Morita [11] and Vu [12] (see Fig. 3).

From experimental investigations, these mechanisms were found to have a small effect on water flow reduction and thus do not explain the initial drastic water flow reduction. Therefore, direct observation of the water flow phenomenon through the crack by visualization technique was performed to understand the mechanisms further.

Table 1. Concrete mix design.

W/C	Air Content (%)	Kg/m3				
		W	C	S	A	Admixture
0.49	4.5	171	349	802	953	1.4

W-Water, C- Cement, S-Sand, A-Aggregate; Slump = 12 cm.

Table 2. Approach to understand self-healing mechanisms in initial stages of water flow.

Parameter	Approach	Known degree of influence*
Further hydration of cement	Testing of young and relatively older specimens 14, 28days, 3 & 6 months old.	Medium
Sedimentation of broken particle	Use of ethanol first followed by water for permeability tests	Medium
Crystallization of products $CaCO_3$&$Ca(OH)_2$	Visual checking of crystal products, crack width reduction; epoxy filling, microscopy	High
Swelling of cement matrix	Not considered	Not considered
Air bubbles	Visual observation, Microscopy, Photography + Video	Extent not known

*Based on characterization by Hearn et-al, 1997.

Tests were performed on concrete specimens cast with mix design as in Table 1. Averages of 2-3 specimens were used for each testing and measurements done especially for the initial 24 hours of water supply.

Table 2 highlights the approaches used to investigate the various causes of self-healing one by one to investigate their contribution to water flow recovery in the initial stage of water supply. All the tests were performed for 14 days, 28 days, 3, 6 months air cured specimens.

Test set up for water pass test measurements

The experimental set up involved measuring of water flows for a cracked concrete specimen. A cylindrical concrete specimen (200x 100mm in diameter) is cracked along the V-notch created on the long edge. The crack surfaces are cleaned and Teflon sheet strips are aligned along the crack surface and the concrete halves bound together with metal clamps. An average of 0.1 or 0.2 mm 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 85 mm.

Water flow rate was determined by measuring amount of water flowing through the crack in 5 minutes over given time intervals (0 ~ 24 hours). An average of 2-3 specimens was used for testing and average values obtained.

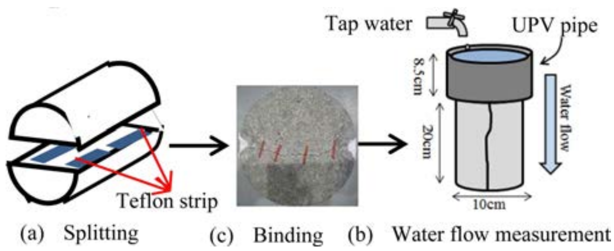


Fig. 3. Water flow test measurement procedure.

Results and Discussion

Effect of anhydrous cement on self-healing

Anhydrous parts of cement exist within the concrete matrix and crack rupture may expose this cement and in the presence of water cause rehydration products to be formed in the crack [13]. 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 (Figs. 4 & 5), the contribution of unhydrated cement in the initial stages of water supply to self-healing is not clear. This result is reflected for both 0.1 and 0.2 mm crack widths (Fig. 5).

The water flow reductions for specimens of different curing ages are not coherent with expected diminishing

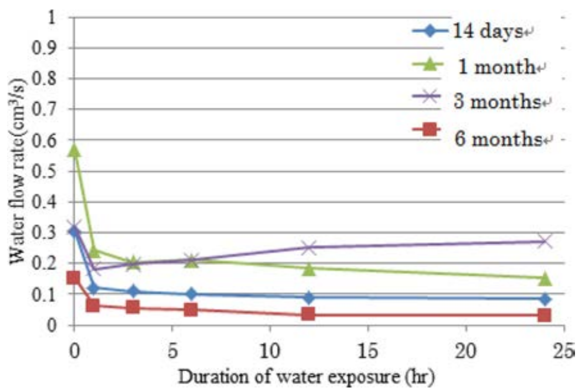


Fig. 4. Water flow graph to show possible effect of unhydrated cement content on self-healing.

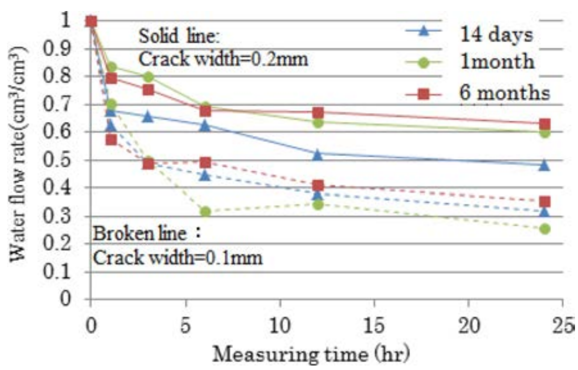
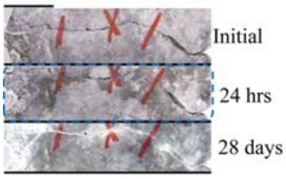
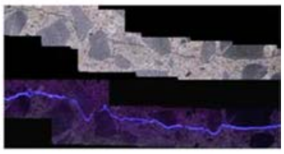
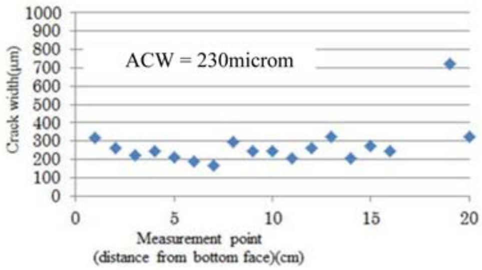


Fig. 5. Normalized flow rates to check effect of unhydrated cement on water flow.

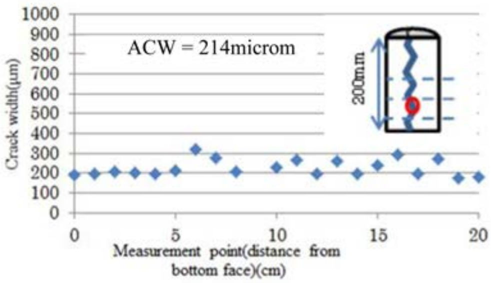




(a) Crack closure at bottom (b) Checking crack width change

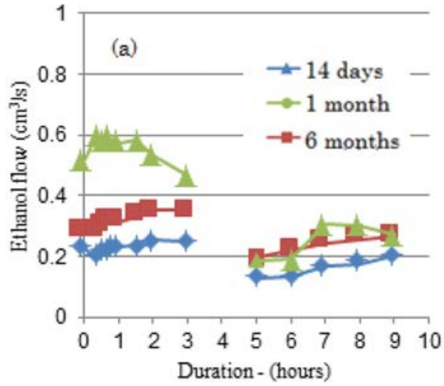


(c) Average crack width before water supply



(d) Average crack width after water supply

Fig. 6. Checking of crack closing action by measurement of average crack widths before and after water supply in the initial.



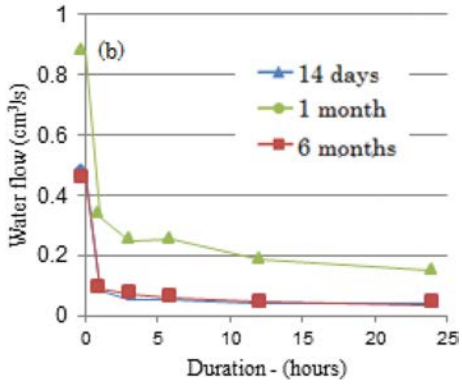


Fig. 7. (a) Ethanol flow rate and (b) water flow rate characteristics through concrete crack.

quantity of unhydrated cement for longer curing periods. Besides, significant water flow reduction rate is observed for all specimens irrespective of curing age.

Effect of formation and crystallization of $CaCO_3$

The formation and crystallization of calcium carbonate is thought to be one of the main contributing factors to crack self-healing in concrete [1-3]. This supposition too was investigated to check its effect on the drastic water flow reduction in the initial stages of water supply. The $CaCO_3$ once formed should reduce the crack width, narrowing water flow paths and thus reducing water flow. By measuring internal average crack width before and after water pass tests, it was found that the contribution of the $CaCO_3$ formation to initial water flow reduction is indeed small (Fig. 6). Prepared samples were subjected to water supply for 24 hours and later checked for product filling within the crack. By injecting liquid epoxy which is allowed to solidify in the crack interstices and cutting the specimen at several intervals to measure average crack widths, which are then compared to crack size opening before water supply, effect of crack closure due to crystallization of $CaCO_3$ is compared. Given that water flow reduction reduces by about 60-80% of initial flow, it would be expected from equation (1) that crack width reduces by 30 ~ 40%. However from Fig. 6 (c & d) of average crack widths before and after, this is not the case; further showing the small contribution of $CaCO_3$ formation and crystallization in the initial water supply stage. Besides, after 24 hours almost no noticeable self-healing products were observed at the bottom of the specimens.

Effect of sedimentation on water flow reduction

Sedimentation of broken particles is also thought to contribute to self-healing in cementitious materials. Broken particles and sediments block the flow path of water and thus reduced water flows. The effect of this phenomenon in the initial stage of water supply was investigated to quantify its contribution. Firstly by using liquid ethanol first as pearmeant, it was then followed with water after one day drying of specimen. The drastic flow reduction is not magnified to show any significant contribution of sedimentation (Fig. 7(a)) compared to one day later with water-Fig. 7(b). Liquid ethanol is used to bring out the effect of broken particles without engaging water initiated reactions.

Visual Observations of Water Flow

Experimental investigations of primarily known mechanisms of self-healing showed only a small effect on the initial water flow reduction. This finding

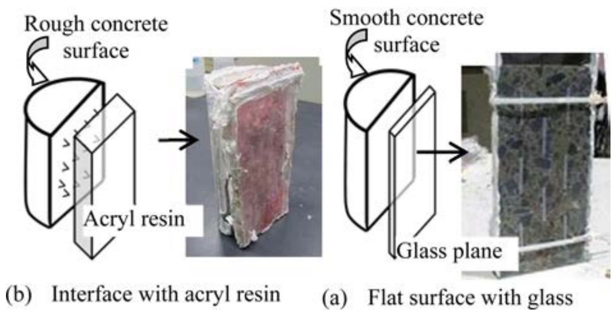


Fig. 8. Specimens layout for direct visual observation of water flow through concrete crack.

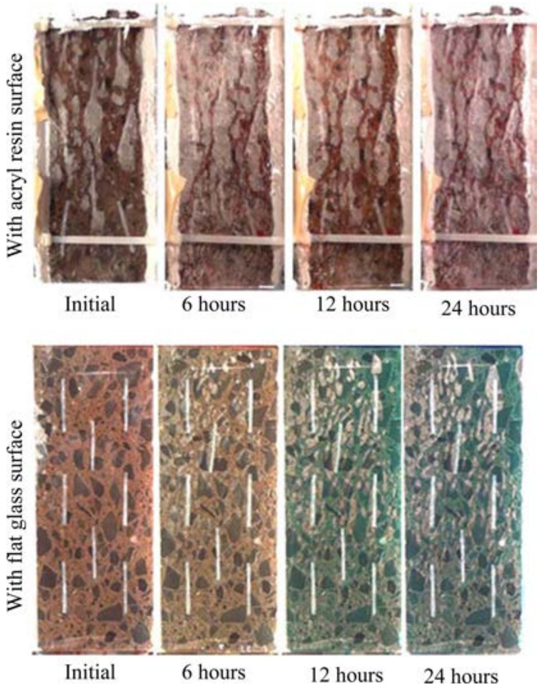


Fig. 9. Air bubbles observed through acrylic resin and glass-tap water is used as permeant.

Table 3. Degree of influence of self-healing mechanisms by experimentation approach (investigated one by one).

Parameter	Approach	Degree of influence based on findings
Further hydration of cement	Testing of young and relatively older specimens 14, 28days, 3 & 6 months old.	Low
Sedimentation of broken particle	Use of ethanol for permeability tests,	Low
Crystallization of products	Visual checking of crystal products, crack width reduction; epoxy filling, microscopy	Low
Air bubbles	Microscopy, Photography + Video; de-aired water, vacuuming & saturation	Very High

prompted the direct observation of water flow by a visualization technique. The methodology involved using half crack surface concrete specimen and another half made of either glass or an acrylic resin to simulate the surface characteristics of the opposite crack side. The basic idea is to be able to observe water flow through the crack interfaces (Fig. 8)

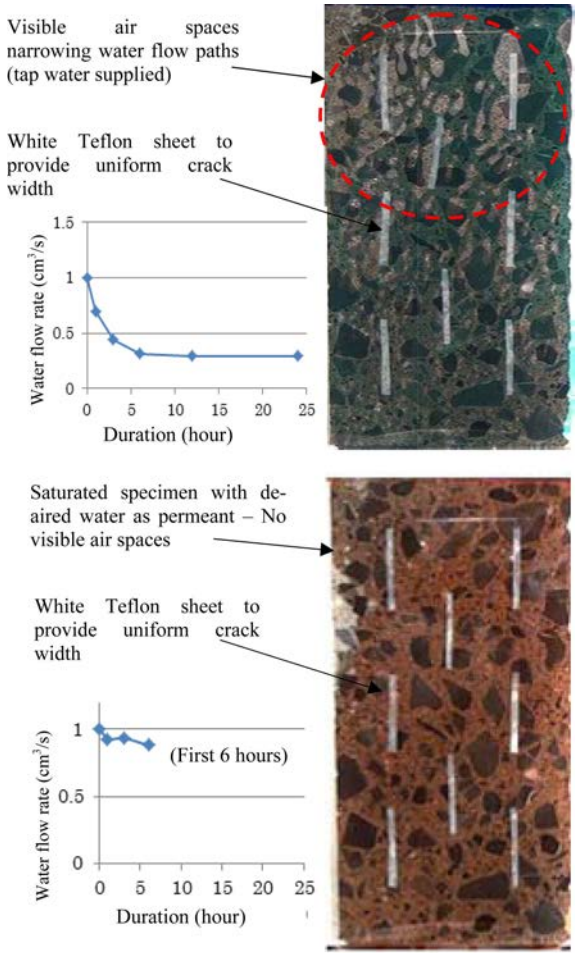


Fig. 10. Characteristic effect of air bubble in the initial stage of water supply under unsaturated condition and saturated condition with de-aired & tap water.

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 moulded with acryl to produce a surface with similar crack appearance. Water flow through the interfaces is observed and with the use of coloured water and videography plus photography, observations 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 (Fig. 9) that narrows the water flow space and thus water flow values in the early stage of water supply.

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 capillary and surface tension forces in relatively narrow spaces. The process of formation of air bubbles is partly explained by the presence of dissolved air in water and possibly the mechanism illustrated in Fig. 2. This mechanism is further heightened by the physical surface characteristics of concrete crack surfaces.

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Notably, specimens saturated with water by vacuuming and tested with de-aired water showed reduced effect of air bubbles (Fig. 10). This treatment ensured that all sources of possible air bubble generation are minimized. Even in conditions where saturated specimens are subjected to water flow, supply of tap water leads to creation of air bubbles. This is directly attributed to dissolved air in water being released by water flow action in the narrow crack gaps. Consequently, the results of this research are summarized in Table 3, showing findings of influence of different self-healing mechanisms in initial stages of water supply.

Conclusions

The observation of air bubbles 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. This research finding explains that the initial drastic water flow reduction is mainly attributed to the creation of air bubbles in the crack gaps, restricting water flow area and their remaining stably under possibly capillary forces and water flow action. The air bubbles are formed mainly through release of air dissolved in water-as observed with mainly tap water

The predominantly known mechanisms were separately investigated through experimentation and found not to contribute significantly to initial water flow reduction that characterizes most self-healing results by water permeation technique. Their contribution to self-healing could be slow and probably accumulates in longer time range comparison.

Acknowledgments

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