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AN EXPERIMENTAL STUDY ON SELF-HEALING OF TENSION CRACKS IN ECC AND CONCRETE PANELS

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Abstract: A study on the leakage of pressurized water through direct tension cracks in Engineered Cementitious Composite (ECC) and concrete panels has been carried out. The findings are applicable to environmental structures such as Liquid Containing Structures (LCS), the design of which is based on serviceability limit states. Cracking plays a significant role in durability and functionality of these types of structures. ECC is considered to be of high self-healing potential because of its large quantity of cementitious materials, along with its self-controlled crack width. A test set-up was designed to simulate the leakage in a wall or a slab segment of LCS. This experimental program includes investigation into ECC and also a Normal Concrete (NC) panels. The panels were subjected to direct tensile force in order to form full depth cracks. Water leakage test was then performed on the cracked panels and the water leakage through the cracks was investigated. The leakage rate was recorded over time to study the short and long term self-healing of cracks. The results of the experiments highlight the water tightness and self-healing properties of using ECC in LCS.

1 INTRODUCTION

Concrete is a widely used material in the construction of environmental structures that are involved in storage or transmission of liquids, such as reservoirs, water and sewage tanks, etc. Concrete Liquid Containing Structures (LCS) are more vulnerable to adverse effects of cracking because it will affect both durability and functionality of these structures by facilitating corrosion of reinforcement and flow of the liquid in and/or out of the structure.

Among the different types of cracks, those created by direct tension are most vulnerable to allowing the leakage of liquid in/out of the structure. These cracks can penetrate through the wall or slab of the container and create a through path for the liquid. A vertical section of a circular tank carrying the tensile ring force produced by the internal hydrostatic pressure of the liquid is an example of a Reinforced Concrete (RC) member vulnerable to direct tension cracks. Other structural members also may be subjected to direct tensile stresses such as those subjected to restraint volume change due to temperature and shrinkage effects (Kianoush et al., 2008). In these situations, the formation of cracks in concrete appears to be inevitable due to its low tensile strength and limited self-healing ability.

Fortunately, concrete possesses self-healing ability that enables the cracks to remediate themselves with a series of chemical and physical reactions in the presence of water. In the last few decades, many extensive investigations have been performed in this area. Results show that self-healing in concrete is a complicated phenomenon, due to multiple mechanisms largely including the precipitation of CaCO_3 , continuous hydration of unhydrated cement particles, and pozzolanic reaction of supplemental cementitious materials (Edvardsen, 1999; Reinhardt and Jooss, 2003; Şahmaran et al., 2008). Most investigations highlight the self-healing phenomenon by means of water permeability test (Clear, 1985; Hearn and Morley, 1997). This test has been performed by Edvardsen (1999) on small concrete specimens with a single tension crack. He observed that cracks with 0.20 mm effective width completely sealed after seven weeks of water exposure. In another study conducted by Rashed A. et al. (2000), water leakage was examined through a crack in a prestressed RC element subjected to direct tensile load. The study found that cracks with effective width less than 0.15 mm might have healed completely before two days of water exposure and remarkable drop in leakage rate took place during the first few hours.

However, the quantity of the self-healing products is usually very limited and not sufficient to fully fill up large cracks (Reinhardt and Jooss, 2003; Yang et al., 2009). In order to ensure adequate self-healing and durability and functionality of the structure, crack widths should not exceed certain limits. However, protection of water retaining structures from cracking by limiting crack width cannot be assured. Employing new materials to construct water storage tanks can reduce the vulnerability of these structures. Engineered Cementitious Composite (ECC) can be an appropriate material to use in water storage tanks. ECC is a kind of High Performance Fiber Reinforced Cementitious Composite (HPFRCC), which was first developed by Victor Li based on the micro-mechanics theory (Li, 1992). Special characteristics of this type of material including high tensile strength, high tensile strain capacity, low permeability, and nontoxic fibres, make ECC a suitable option for water storage facilities (Fischer and Li, 2002; Lepech and Li, 2005; Li, 2011, 2003).

ECC is also considered to have great self-healing potential because of its large cementitious material quantity, which enhances the hydration reaction of cement and fly ash, and its self-controlled crack width (Ahn and Kishi, 2010; Kan et al., 2010; Wu et al., 2012; Yang et al., 2009; Zhang and Zhang, 2017). Yang et al. (2009) studied the magnitude of self-healing in ECCs exposed to different environments and found that crack damaged specimens showed effective self-healing when subjected to wet-dry cycles. This study also showed Resonant Frequency (RF) recovery can be used as a method to quantify the healing process of ECCs. Sahmaran et al. (2015) observed that RF recovery rates were lower at middle portions of specimens compared to measurements taken from the surfaces probably because of difficulty in diffusing moisture across longer distances. Although the self-healing mechanism was widely distributed over the entire area of the specimens, it was more prominent on a surface with easy exposure of cracks to water. Under different environmental exposure in direct water flow tests, Zhang and Zhang (2017) observed between 76% and 100% of water permeated through small ECC specimens after 10 days. Their observation suggests the self-healing ability of ECC decays over time. This could be due to less available unhydrated cement and fly ash for self-healing over time.

In addition to recovery of water transport properties, the mechanical properties of cracked ECC, including tensile and flexural stiffness/strength and tensile strain capacity, were also reported to have a distinct rebound to almost 100% of that of un-cracked specimens (Fischer and Li, 2003; Herbert and Li, 2013; Li and Li, 2011; Li, 2011; Yang et al., 2009). Herbert and Li (2012) observed that specimens recovered up to 90% of their original, pre-damaged RF values, and up to almost 30% and 70% of their initial stiffness after one and three months respectively. In an extended study, Herbert and Li (2013) observed more than 95% recovery of original RF after a year of exposure to the natural environment.

This experimental study examined the leakage and self-healing of direct cracks in full-scale ECC and NC panels representing a wall segment of circular tanks. For this purpose, panels were subjected to pressurized water simulating an elevation of water a number of panels and then tested under monotonic direct tensile load to develop tensile cracks. It was shown that direct tension cracks are detrimental to the serviceability of LCS as the water easily seeps through these cracks. The short- and long-term self-healing capability of tension cracks when exposed to positive water flow was investigated.

2 EXPERIMENTAL PROGRAM

This experimental study examined the permeability and self-healing of leakage through cracks in full-scale specimens made of ECC and NC. These panels represent a wall or slab segment of a liquid containing structure subjected to direct tensile force due to effects described in Section 1. The specimen details, test set-up and procedure are discussed here.

2.1 Test Specimens

The specimens of this experimental study represented typical segments of a circular-based tank wall. Each specimen in the form of panel measured 1500 mm (Length) × 400 mm (Width) × 250 mm (Height). The specimens were cast in place. This experimental program included testing of an ECC and one NC panels. These panels were subjected to an uniaxial tensile force to induce cracks followed by leakage and self-healing test. The longitudinal bar was 35M at the center providing 1% reinforcement ratio in specimen. The bar was Grade 400 steel conforming to the Canadian Standards Association (CSA) with a yield stress of 400 MPa and a modulus of elasticity of 200 GPa.

Table 1 presents the mix composition for ECC and NC panels. The results of compressive and tensile strength tests for each specimen are presented in Table 2. The compression tests include 100×200 mm cylinders and the tensile strengths are reported from the results of split test.

Table 1. Mix proportions for ECC and NC material.

Component	Cement	Silica Sand	River sand	Gravel	Slag	Water	Fiber (Vol. %)
ECC	1.0	1.2	-	-	0.8	0.58	1.2
NC	1.0	-	3.12	3.45	-	0.48	-

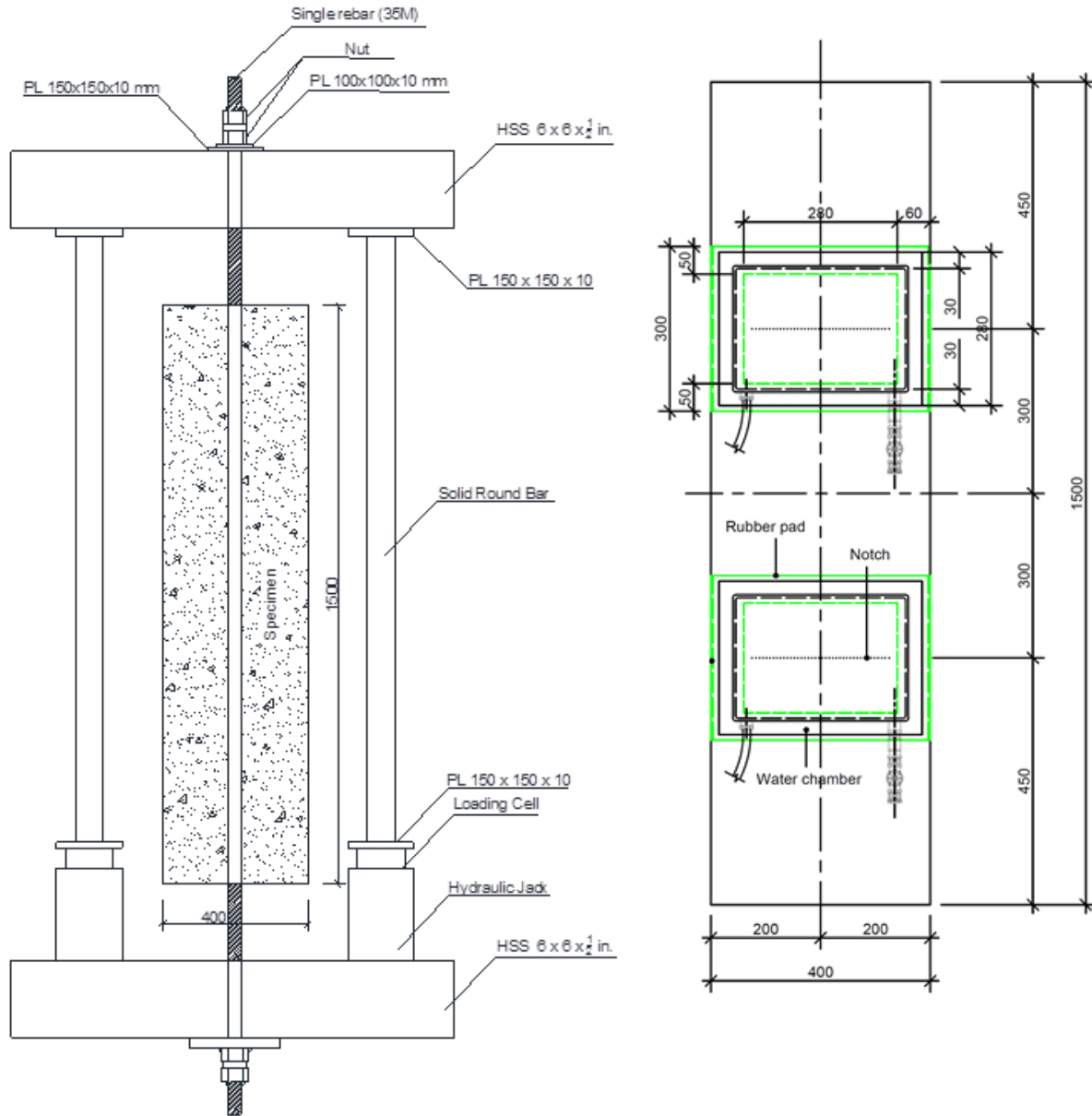
Table 2. Mechanical properties of ECC and NC specimens.

Material	7 days Cylinder	28 days Cylinder	Tensile strength
	Compressive strength (MPa)	Compressive strength (MPa)	(MPa)
ECC	66.5	71.9	7.8
NC	35.1	40.5	2.9

2.2 Test Set-up

Simulation of leakage and self-healing of direct tension cracks in LCS poses several challenges. First, pressurized water chambers must be attached and sealed to the surface of the specimen on one side of the crack while it would not resist any direct tensile force. During the loading process, resisting any tensile force by water chambers leads to unreal strength and cracking behaviour in the panel. Exposing the whole length of the crack to pressurized water presents another challenge. In the case of a water chamber installed only on a proportion of the crack at top, the water travels a diagonal path through the crack to reach the bottom surface, i.e., the crack leaks from a length larger than the length exposed to water. Applying pure tension on the panel is also problematic as even a small eccentricity disturbs uniform stress distribution, resulting in lifting the panel during loading, uneven crack width in cross section and the development of compression zone within the section. Due to these complications associated with water pressure chamber and loading, limited studies have been carried out on leakage and self-healing of tension cracks in LCS. However, in this study, a novel test set-up was designed to overcome these problems.

Figure 1(a) depicts the plan and side view of the distinctive test set-up, which applied the tensile force by pulling out an extruded rebar embedded at the centre of the specimens. Two 6 × 6 × 1/2 inch steel Hollow Structural Section (HSS) beams were used at both north and south ends to transfer the force to the rebar. This tensile force was applied by means of two identical manual hydraulic jacks on either sides of the panel. Each jack pushed an HSS via large diameter solid steel rounds. Each HSS transferred the loads from the jacks to the rebar. In order to apply pure tension and prevent any eccentricity during loading, a single rebar was placed at the center of the section. The rebar was passed throughout the center of the HSS and welded to fix the position of the HSS at both ends while being pushed by jacks. The panel was supported at both ends on rollers to ensure a free sliding boundary condition in the direction of loading. To ensure cracking at prescribed locations where water chambers were installed, two transverse notches (10 mm width and 20 mm depth) at top and bottom were created at 450 mm from each end of the panels.



(a) Specimen and loading set-up

(b) Arrangement of chambers on specimen

Figure 1. Test set-up.

Two water chambers were fabricated from 5 mm thick steel sheet. These chambers were placed on the top surface of panel, 450 mm from the center of chamber to North and South end of specimen (Figure 1 (b)). A layer of 25 mm gum rubber was placed between the edge of the chamber and the specimen surface. All edges of gum rubber and panel were sealed with a flexible water-proof concrete glue. This combination provided a seal between the water pressure chamber and the EEC panel while it would not resist any direct tensile force. To seal and prevent leakage from the sides of the cracked specimen, two thin membrane sheets were attached to sides of panel along the width of the water chambers. These measures ensured there was no leakage in these two sealed areas except from bottom face where the leakage was evaluated and collected.

The required water pressure was supplied by the city water system. However, the pressure in the water chamber normally dropped due to leakage from the bottom face or rose due to potential tolerance of pressure in city water. Therefore, the long-term self-healing study would not be possible unless measures were taken to keep a constant water pressure. For this reason, a pressure regulator was used along with a pressure gauge to monitor and control the water pressure inside each chamber. Each chamber was clamped to the specimen by two C channels at the top of the chamber and another two channels beneath the specimen. Each pair of top and bottom C channels was tightened together at each end by a 19 mm-diameter steel threaded rod to seal and resist the uplift pressure induced in the water chamber.

2.3 Test Procedure

Reinforcing rebar inside the panel was instrumented with 10 mm long electrical resistance strain gauges at four locations. Two strain gauges were placed at 450 mm from the ends of the panel (at the notch location) and two were placed on bare rebar outside the panel. After the initiation of the first major crack, the crack width was measured from bottom surface at various locations along the crack, using a crack scope with a magnification of 25X. Figure 2 shows the front and side view of the actual test set-up. The water chamber, water pressure regulator, hydraulic jack, HSS and water sealing components including rod, C channel, and membrane are specified in the figure.

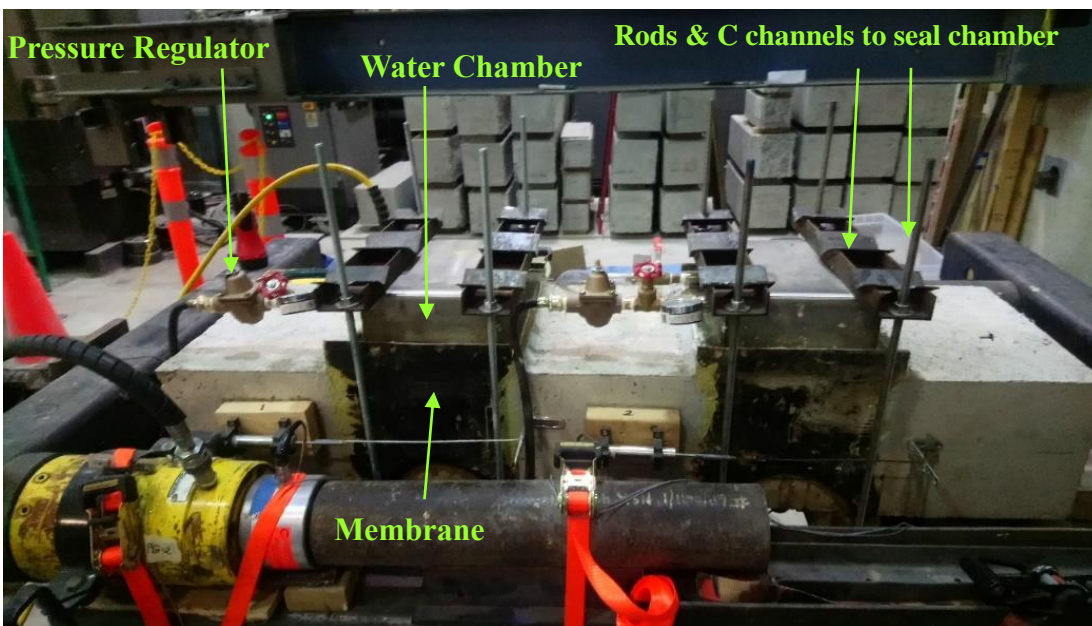


Figure 2. The actual side-view of specimen and test set-up.

As the first step, both water chambers were placed at the prescribed location and fully sealed as per section 2.2. Then, the panel was loaded incrementally to initiate cracking and subsequently cause leakage. The leaked water was gathered in two separate containers under the sealed area. The weight of the leaked water was measured over time using a digital scale with the sensitivity of 1 g.

At the final stage, the weight of the collected water was recorded over specific time intervals to study the short- and long-term self-healing. In the case of the short-term self-healing study, leakage was measured every one hour in the first 30 hours. Following that period, the leakage rate was recorded every six hours to study long-term self-healing. The leakage monitoring for the long-term self-healing study was continued to achieve 100% healing (zero water leakage) or to approach a steady leakage rate.

3 SELF-HEALING IN NORMAL CONCRETE (NC) PANEL

The NC panel were tested using the test set-up and test procedure outlined above. Each hydraulic jack was loaded simultaneously by increments of 10 kN. In the NC panel, the first crack was developed at 151 KN. This tensile force caused a single crack at the north notch with the average width of 0.40 mm. This brittle cracking was immediately followed by a high rate of flow while the pressure in water chamber was set to 27.6 kPa (4 psi).

As designed, applying more tensile load resulted in the formation of a second major crack at the south notch. This crack developed at the applied load of 178 KN with the average crack width of 0.25mm. However, this cracking did not cause a water flow at this load. This can be explained by the fact that water needs a path through the full depth of panel and even a few millimeters of un-cracked section in depth can completely prevent water flow. In order to create leakage from the south crack, the loading process resumed and the water from the south crack started to flow at 266 KN. At this stage, the crack width was 0.55 mm at the north notch and 0.4 mm at the south notch.

To study self-healing, the water pressure in both chambers was set to 48.3 (kPa) (7 psi) and the leakage rate was recorded over a specified time interval. As the cracks started to heal, the rate of leakage dropped over time. The NC panel experienced a high rate of leakages. Thus the employed approach to study the self-healing was recording the time required to completely fill a 10000 ml measuring cup with leaking water. Figure 3 shows that no significant decrease in water flow rate was developed after 25 hours, as a result, this self-healing investigation was stopped after 72 hours. The observed self-healing during the first 30 hours, which is considered here as short-term self-healing, was just 18% and 28% in north and south cracks, respectively. With these high flow rates, healing products were washed away. ACI 224.1R (ACI Committee 224) states that healing does not occur in an active crack and if the crack is subjected to movement during the healing period. Healing cannot occur while a positive water flow exists through the crack, which dissolves and washes away the lime deposit, unless the water flow is so slow that complete evaporation happens at the exposed face of concrete element causing redeposition of the dissolved salts.

Moreover, previous experimental studies (Reinhardt and Jooss, 2003; Yang et al., 2009) have shown the quantity of the self-healing products is very limited and not sufficient to fully fill cracks with large width.

4 SELF-HEALING IN ECC PANEL

In the ECC panel, micro-cracks were initiated at 157 KN and propagated along the panel by increasing the load but no significant leakage was observed at this level of loading. The loading continued up to 420 KN. At this level of loading the maximum crack widths were 0.15 mm and 0.20 mm at the south and north sealed areas, respectively. The ECC panel experienced several micro-cracks leaking at sealed areas. Figure 4 shows the leakage from cracks at the bottom surface during the test and the same area after a couple of days. During these days the applied load, water pressure and crack width were constant. As can be seen, a number of the cracks were sealed while others continued to leak.

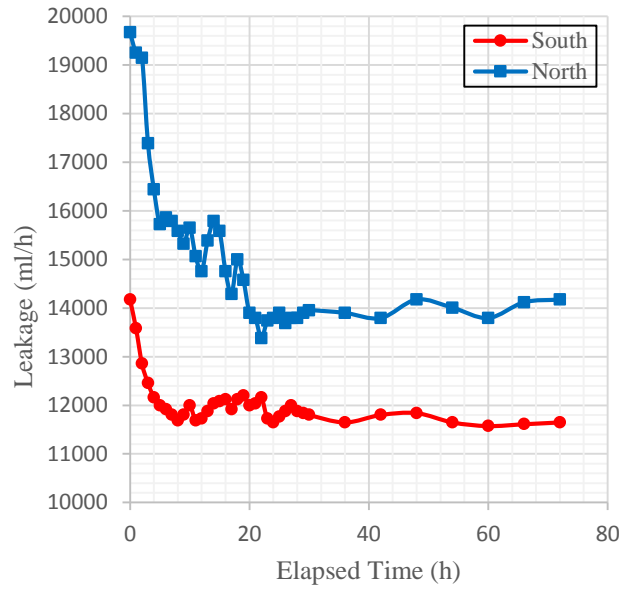


Figure 3. Water flow rate versus time (Self-healing in NC).

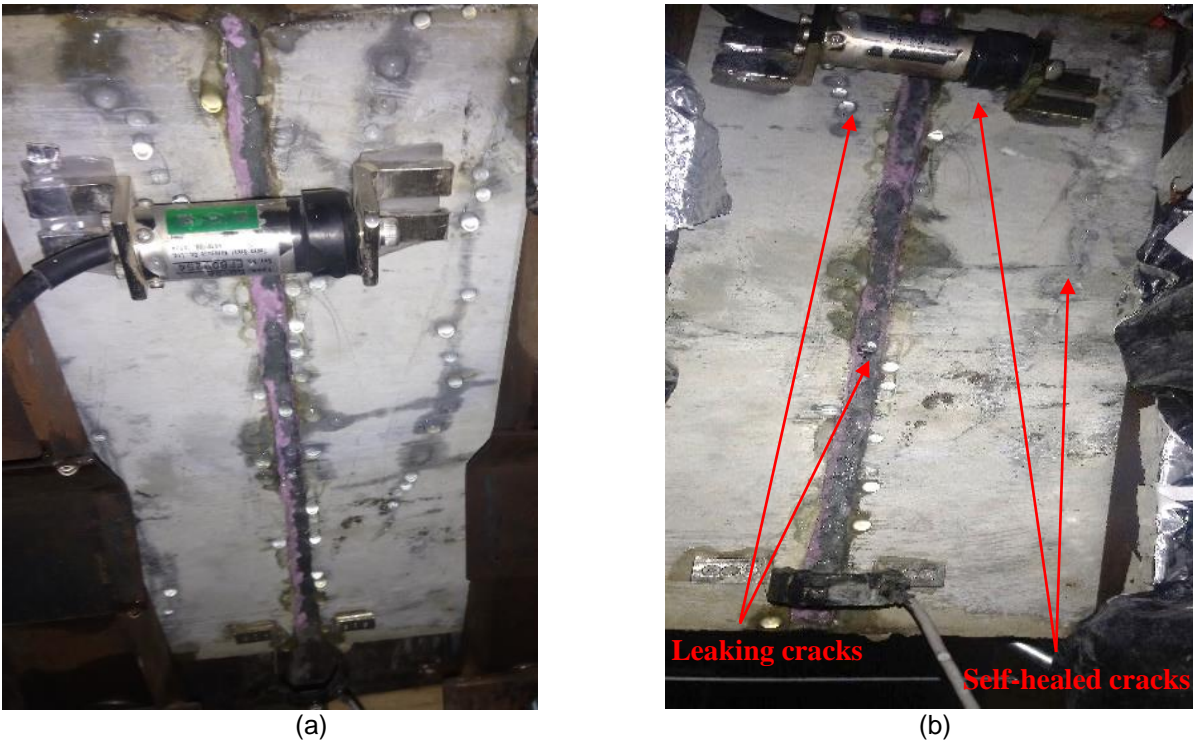


Figure 4. Self-healing of cracks in an ECC panel. (a) Leakage from cracks. (b) Self-healing of cracks.

In the short-term investigation of self-healing, the quantity of water permeating through the cracks over a one-hour time interval was studied. This leakage quantity from bottom face was recorded continuously for 30 hours. Figure 5 shows the results of short-term self-healing in the ECC panel. The leakage rate reduced gradually and after 30 hours reached 22% and 26% of the initial quantities in the north and south sealed areas, respectively. The water leakage in the south area experienced a sharp drop during the first 10 hours. This behaviour was accelerated in the north area, where a sharp drop in water leakage was observed in

the first six hours, after which the reduction rate continued with a lower intensity with some fluctuations. The fluctuation in leakage rates can be explained by the fact that self-healing of cracks in cementitious materials is a combination of complicated chemical and physical processes. In addition to the formation of calcium carbonate and hydration of the unreacted cementitious materials, blocking cracks by loose particles resulting from crack spalling materials can be the contributing factor for the self-healing (Schlangen, 2010). In the presence of positive flow in cracks due to water pressure, filling cracks with healing products and, on the other hand, washing away these products and loose particles could be the reason for these intermediate fluctuations. Investigation of the water leakage records revealed that this fluctuation mainly occurred after the sharp drop of leakage rates in first few hours. Approaching low rates of leakages, less fluctuation in leakage rate was observed.

The rate of leakage reduction dwindles over time as the self-healing ability of ECC decays. This finding is in agreement with previous studies (i.e. Zhang and Zhang, 2017). This would attribute to less available unhydrated cementitious material for self-healing over time.

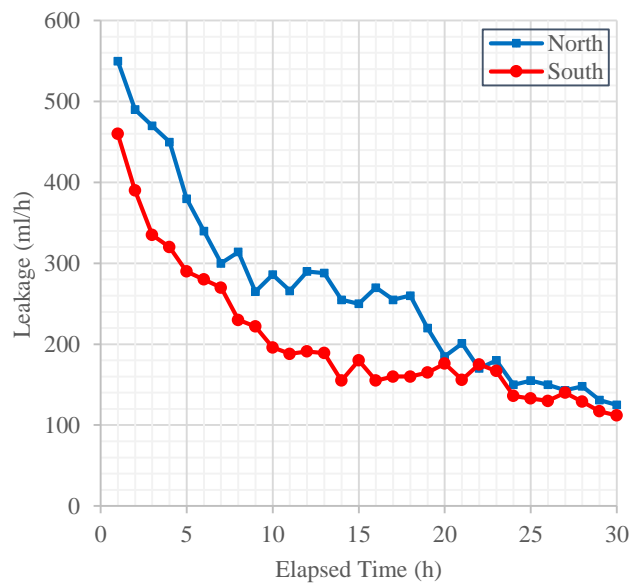


Figure 5. Leakage rate versus time (Short-term self-healing in ECC).

Figure 6 presents the leakage records over two weeks. Each leakage record presents the leakage during one hour which was continuously measured every six hours. The water leakage in the north area dropped to zero after nine days while this leakage rate in south was achieved in fifteen days. The zero value of leakage rate indicates that the cracks were almost sealed by self-healing products that completely blocked the water flow. However, it does not necessarily indicate 100% self-healing of cracks in full depth. Sealing a few centimeters in depth of cracks can block the water path from top face to bottom.

As can be seen, although the north area had a higher initial leakage rate, after 22 hours the leakage rate approached quantities identical to the south area. Interestingly, the north area was sealed earlier than the south area. Therefore the initial amount of leakage could not be relied upon to predict the time required for cracks to self-heal. This suggests self-healing is a complex phenomenon and different factors such as the number of cracks and crack widths affect the self-healing process.

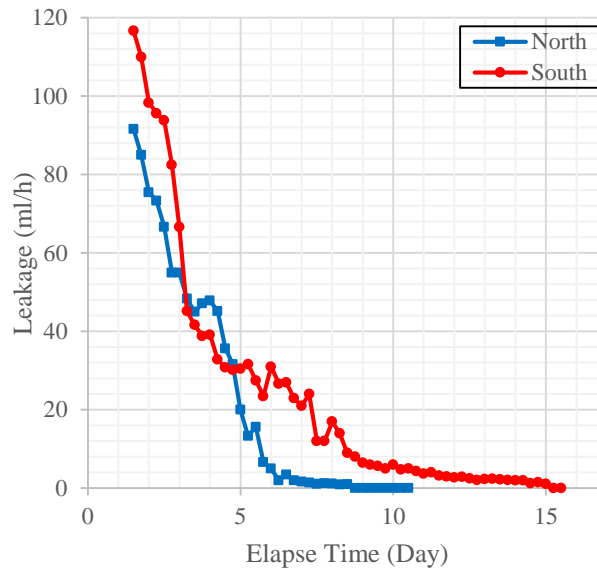


Figure 6. Leakage rate versus time (Long-term self-healing in ECC).

5 CONCLUSION

In this experimental study, direct tension was used to induce cracking of ECC and NC panels in order to investigate the resulting leakage from cracks. The results of this research are directly applicable to liquid containing structures or to any other structure in which liquid tightness is critical to maintain. Experimental tests were carried out on ECC and NC panels to study the leakage rate and self-healing of cracks.

The brittle cracking in concrete immediately followed by a high rate of water flow from a single crack while development of several narrow cracks in ECC panel results in much less water leakage rate. The self-healing investigation of cracks in ECC panel revealed that water leakage dropped sharply in the first few hours after which the reduction rate continued with a lower intensity with some fluctuations. The rate of leakage reduction dwindled over time as self-healing ability decayed. The ECC panel showed the ability to self-heal the cracks and seal the water leakage. The ECC panel reached almost 74 and 78% sealing ratio after 30 hours exposure to pressurized water at north and south ends respectively. The full sealing of cracks in the ECC panel was observed after nine and fifteen days of complete exposure to pressurized water from top surface. However, full self-healing did not occur in the NC panel with large crack widths and high rates of positive water flow. The maximum observed self-healing for a crack with effective crack width of 0.4 mm and initial flow rate of 14.2 lit/h was 28% after 30 hours. Overall, it can be concluded that ECC has superior advantages over NC due to better performance for water tightness and also higher self-healing characteristics.

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