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Self-healing and leakage performance of cracks in the wall of a reinforced concrete water tank

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Abstract. A reinforced concrete water tank is a typical functional liquid storage structure and cracks are the greatest threat to the liquid storage structure. Tanks are readily cracked due to seismic activity, thereby leading to the leakage of the stored liquid and a loss of function. In order to study the effect of cracks on liquid storage tanks, self-healing and leakage tests for bending cracks and through cracks in the walls of a reinforced concrete water tank were conducted. Material performance tests were also performed. The self-healing performance of bending cracks in a lentic environment and through cracks in a lotic environment were tested, thereby the self-healing width of bending micro-cracks in the lentic environment in the short term were determined. The through cracks had the capacity for self-healing in the lotic environment was found. The leakage characteristics of the bending cracks and through cracks were tested with the actual water head on the crack. The effects on liquid leakage of the width of bending cracks, the depth of the compression zone, and the acting head were determined. The relationships between the leakage rate and time with the height of the water head were analyzed. Based on the tests, the relationships between the crack characteristics and self-healing as well as the leakage were obtained. Thereby the references for water tank structure design and grading earthquake damage were provided.

Keywords: bending crack; leakage; reinforced concrete water tank; self-healing; through crack

1. Introduction

The self-healing of concrete cracks refers to the self-repairing capacity of cracks in concrete without any intervention (Chai 2008, Muhammad 2016). Many studies have investigated the self-healing performance and leakage characteristics of concrete cracks with various conclusions. Edvardsen (1999) tested several concrete specimens with tension cracks and the results showed that the water leakage decreased very rapidly and self-healing of the cracks occurred quickly. It was also shown that cracks with an initial width of 0.2 mm healed completely after remaining in contact with the aqueous phase for seven consecutive weeks. For cracks with a width of 0.3 mm, the water leakage decreased by half after 15 days compared with that before healing.

Rashed *et al*. (2000) reported a series of experiments in 2000 and 2002, where they studied the crack and leakage characteristics of the partial prestressed concrete tank wall under different stress combinations. They showed that cracks with a width of less than 0.15 mm could self-heal completely after remaining in contact with water for 2 days. Moreover, the water leakage rate decreased greatly in the first few hours. They suggested that the liquid storage structure could satisfy the corresponding leakage standards by defining the minimum height limit in the compressive zone. When the diameter of the partial prestressed circular tank was calculated as greater than the height (the height was greater than or equal to 6m) and the allowable head loss per second was 0.05%, the lowest depth for the compression zone was determined as 15.6 mm. Based on comparisons of the self-healing processes for concrete cracks under conditions comprising 95% relative humidity and complete immersion in water, Neville (2002) reported that there were great differences in the extent of self-healing, where the cracks self-healed rapidly when the specimen was completely immersed in the water. Thus, water is a necessary condition of self-healing for concrete cracks. Reinhardt and Jooss (2003) showed that decreasing the leakage from cracks depended on the crack width and environmental temperature. The self-healing was faster for narrow cracks and a higher temperature could accelerate the self-healing process.

Li *et al*. (2004) studied the factors that influence leakage for concrete cracks, where they established a crack leakage model and determined the relationship between the leakage and crack width, as well as the self-healing time with different crack widths. Moreover, they investigated the

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crack self-healing mechanism. Liu *et al*. (2005) studied the effects of the cement strength grade, admixture, fiber, and other components on the self-healing performance of concrete damage. Yao *et al*. (2006) characterized the concrete damage produced under various ultrasonic velocities before and after applying a load on the concrete. They also established the relationship between the amount of damage and the healing conditions. Thereby, the damage threshold for concrete self-healing was determined, where the self-healing capacity of damaged concrete at an early age was better under the same damage degree.

In Article 3.13 of American Concrete Institute Standard ACI 224.1R-07 (2007), the description of the concrete crack self-healing phenomenon states the following: “When the water through the crack has a flow velocity, the water can dissolve and wash away the newly generated hydration product on the crack surface, and crack self-healing will not occur. Unless the water velocity is very slow, the water on the crack surface evaporates completely and the dissolved salts are deposited”. Ziari *et al*. (2009a) reported a series of crack and leakage tests with reinforced concrete specimens under monotonic normal tension, and determined the correlations between the behavior of the cracks and the amount of water leakage (Ziari and Kianoush 2009b). They demonstrated that the crack self-healing capacity could be tested by placing a crack in a moist or wet environment (Suleiman *et al*. 2018). The special attention is also paid to the types of healing agents and capsules used for self-healing in cementitious materials (Van Tittelboom and De Belie 2013).

Most previous studies of crack self-healing have focused on cracks in concrete test blocks, whereas few have considered the self-healing performance of bending cracks and through cracks in a solid concrete structure or component. Moreover, a value has not been proposed for the healing width of a concrete micro-crack in the short term. In leakage tests, the water pressure instrument employed can only apply the water head and it cannot retain a large amount of water, and thus it cannot simulate the liquid leakage degree and leakage rate through the crack in a realistic manner. Therefore, studies of the leakage characteristics of through cracks are still inadequate. A limiting value also needs to be determined for the depth of the compression zone in order to control the leakage from a bending crack in a normal concrete tank. At the same time, the effects of water environment including lentic environment and lotic environment on cracks self-healing and leakage performance have not been considered in the existing researches.

Factors such as internal liquid and body cracks should be considered during water tank structure design and earthquake damage grading (Yazdabad 2018). The Chinese code GB/T 24336-2009 (2009) and some literatures (Gao 2012, Guo *et al*. 1998) use the crack width of the tank wall as an influencing factor when dividing the earthquake damage classification of the tank. However, the self-healing properties of concrete cracks are not taken into consideration when determining the crack width value. For the tank wall damage phenomenon with micro-cracks, it is possible to amplify the damage degree of tank structure. In the present study, two identical reinforced concrete water tank wall slabs were designed to simulate the stress state of the tank wall under seismic action, as well as to study the effects of bending cracks and through cracks on the function of the liquid storage structure. Under the action of static load, the vertical section of the wall for reinforced concrete rectangular tank is subjected to the axial tension and the out-of-plane bending moment. Under the action of seismic load, the tank wall may also be subjected to shear force in addition to the internal forces generated by the static load action. For specimen 1, bending cracks were formed by applying eccentric force, and the self-healing performances of the micro-cracks in lentic environment as well as the leakage characteristics of the bending crack were tested. For specimen 2, through cracks were formed by simultaneously applying eccentric force and mid-span vertical force, self-healing performances and leakage characteristics of through cracks in lotic environment were investigated. The test results may provide a reference for tank structure design specification and relevant parameters for the grading of seismic damage to tanks (Vui *et al*. 2014).

2. Specimen design and measuring and loading scheme

2.1 Specimen design

The test concrete mix ratio was designed to be cement: grip tape: rubble: water: waterproofing agent=1: 2.66: 3.25: 0.52: 0.03. The concrete water-cement ratio is 0.52, and the maximum aggregate size is 40mm. The test rebars included ribbed steel bar and plain round bar with nominal diameter of Φ12 and Φ8, respectively. According to test measurements, the average 28d compressive strength of the standard concrete test block was 33.95 MPa, and thus it was designated as concrete grade C25. The impermeability grade was P12. The average yield strength of the Φ12 ribbed steel bars was 288.17 MPa and the average tensile strength was 416.69 MPa. For the Φ8 plain round bar, the average yield strength and tensile strength were 267.73 MPa and 393.23 MPa, respectively.

The specimen was designed based on the “Specification for Structural Design of Reinforced Concrete Water Tank of Water Supply and Sewerage Engineering” (CECS 138:2002). The unit-height water tank wall was selected as the test object. C25 concrete and a Φ12 longitudinal carrying bar were employed. The thickness, width, and length of the tank wall were 250 mm, 1.0 m, and 2.8 m, respectively. The thickness of the protective layer was 35 mm. In order to obtain bending cracks and through cracks in the concrete slab, and to compare the development of the bending crack under the bending tensile and bending shear load, the specimens were designed as shown in Fig. 1 and Fig. 2. In Figs. 1 and 2, the symbol a represents the concrete slab of the tank wall and the symbol c represents the side wall, which is perpendicular to a. The height, width and length were 0.5 m, 0.4 m, and 1 m, respectively. To ensure that the external force was correctly transmitted to concrete slab a, c was allocated several rebars at the two rigid ends of the specimen. The symbol b represents the axillary angle and it was strengthened at the corner of concrete slab to

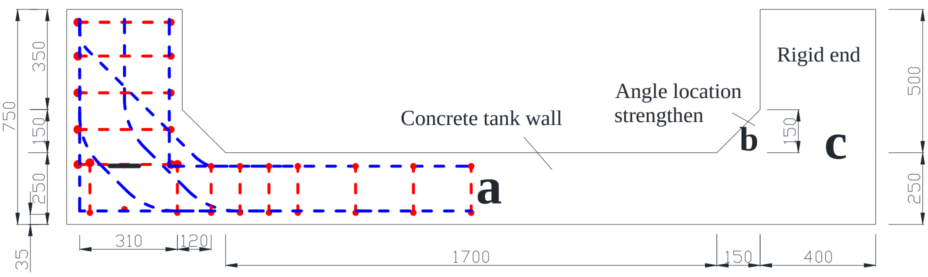


Fig. 1 Elevation of test specimen (unit: mm)

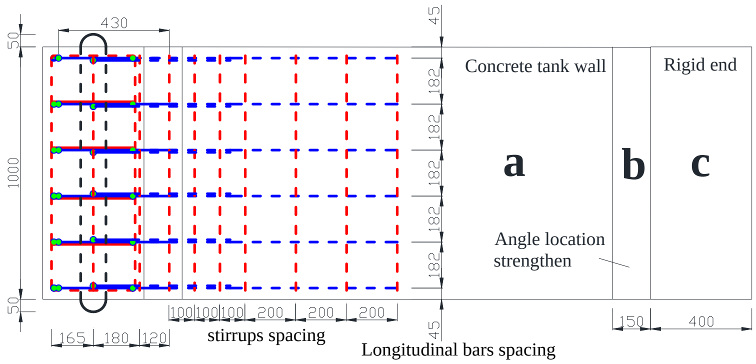


Fig. 2 Plan view of test specimen (unit: mm)

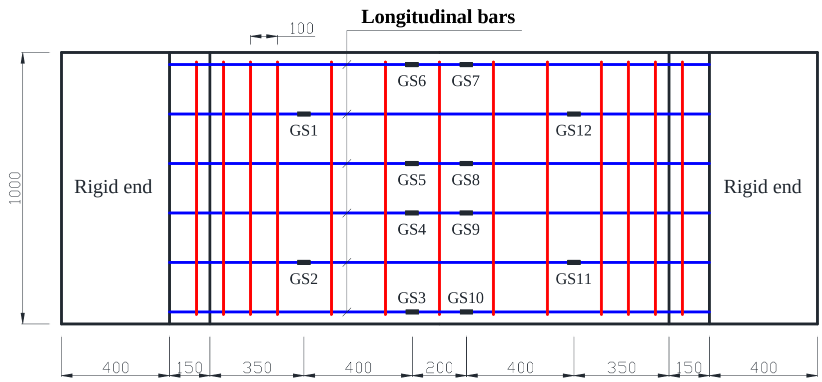


Fig. 3 Schematic diagram showing the arrangement of the strain measurement points in the upper layer of the test specimen

avoid initial damage at the corner, thereby preventing it from affecting the crack development in the whole concrete slab. The specimen was reinforced as follows: the diameter of the longitudinal carrying bar and stirrup was 12 mm and 8 mm, respectively, and the rebars were distributed uniformly in the upper and lower layers of the slab. Figs. 1 and 2 only show schematic diagrams of the reinforcement on the left-hand side of specimen, and the right-hand side was symmetric with the left-hand side. The specimen was maintained after binding the steel bar. All of the parameters conformed to the relevant specification requirements.

2.2 Measurement scheme

The measurements comprised measurements of the strain, deformation, and crack.

2.2.1 Strain measurement

The rebar strain gauges were used to measure the strains under external force. The strain gauges were arranged according to the following principles: The strain gauges were arranged at such positions where the force is larger and the cracks may occur, and were evenly arranged in the width and length of the slab. At the same time, the strain gauges were ensured on each of the longitudinal rebar. In order to avoid the damage of a rebar strain gauge when casting concrete slabs affect data acquisitions, all strain gauges should be arranged symmetrically.

The arrangement of the strain measurement points for the rebar is shown in Fig. 3. In Fig. 3, only the strain measurement points for the top bars are presented, but the strain measurement points in the lower layer bars were in the same positions as those in the upper layer.

The strain measurement points in the concrete were basically in the same area as those in the rebar. The strain gauges were pasted to the top surface of the concrete slab. The strain data obtained from the measurement points in the concrete were employed to determine the moment and location for the micro-cracks that appeared on the slab’s surface. The positions where the concrete strain gauge were

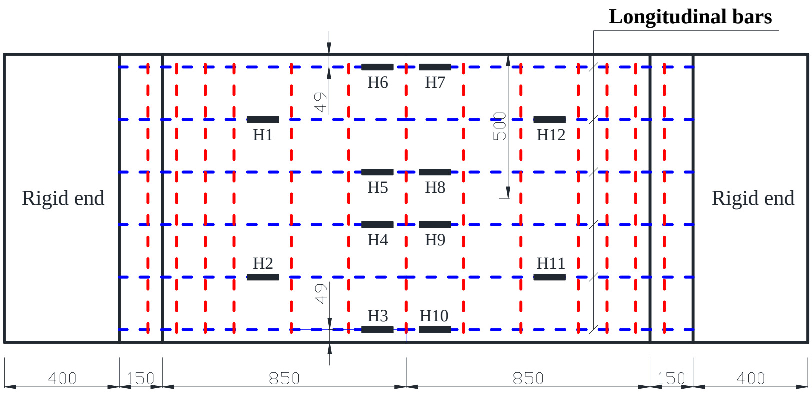
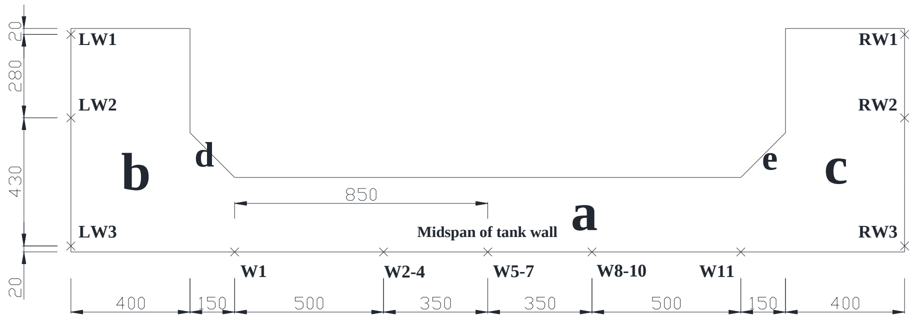
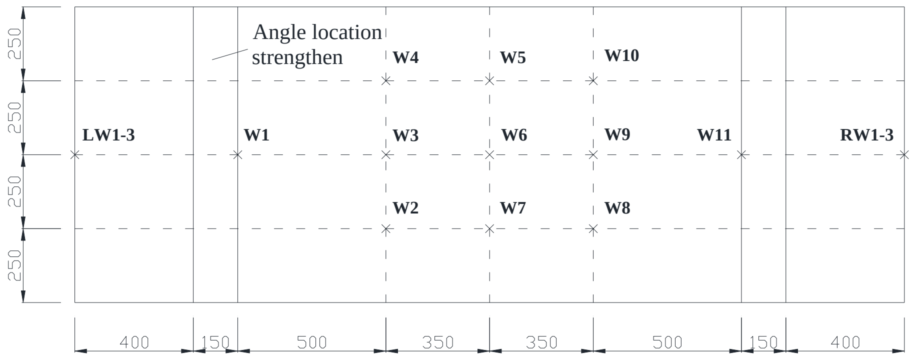


Fig. 4 Schematic diagram showing the position where the strain gauge was pasted onto the surface of the concrete specimen



(a) Arrangement of displacement meters on the lateral side of the slab



(b) Arrangement of displacement meters on the bottom of the slab

Fig. 5 Locations and numbers of displacement meters on specimen 1

pasted is shown in Fig. 4. To facilitate convenient crack observations, thin layer white paint was brushed on the upper surface and two side faces of the concrete slab before testing.

2.2.2 Deformation measurement

The deformation of the whole specimen was measured using a displacement meter in real time during the test process. For specimen 1, the deformation measurement points were specified as six horizontal displacements and 11 vertical displacements. The location "×" and the numbers of displacement meters are shown in Fig. 5. When the test specimen deformed, the displacements were positive on the left of measurement point LW, on the right of measurement point RW, and above measurement point W.

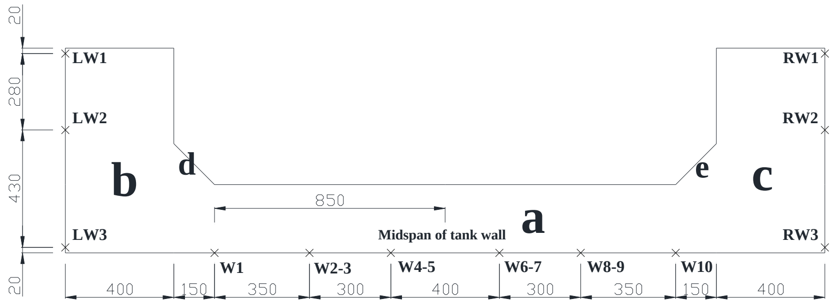
The locations of the displacement meters on specimen 2 are shown in Fig. 6. A jack was placed at the mid-span of the bottom of the slab to apply the vertical force, so a mid-span displacement meter was placed on both sides of the jack, i.e., displacement meters W4-W7.

2.2.3 Crack measurement

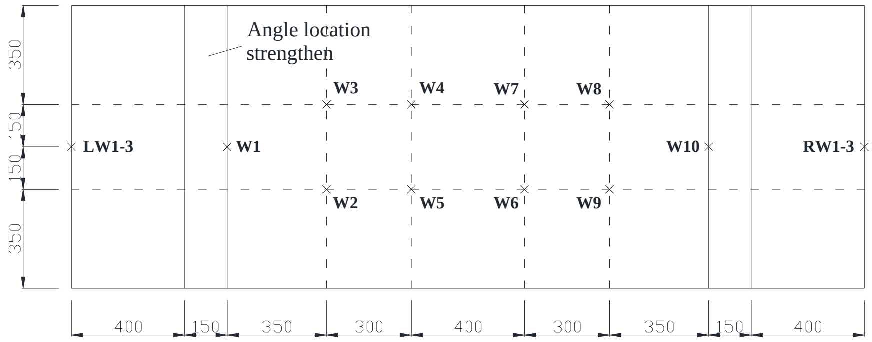
The crack width was measured using an HC-CK102 crack width gauge. The measurement range was 0-8 mm and the reading accuracy was 0.01 mm. The crack length and crack spacing were measured using steel rulers.

2.3 Loading scheme

According to a previous study (Chen *et al*. 1992), the theoretical cracking moment of the test concrete slab was calculated as 25.43 KN•m. The loading rate was slowed down when the test specimen was loaded to close to the theoretical cracking moment in order to investigate the development of the crack in the concrete slab in greater details.

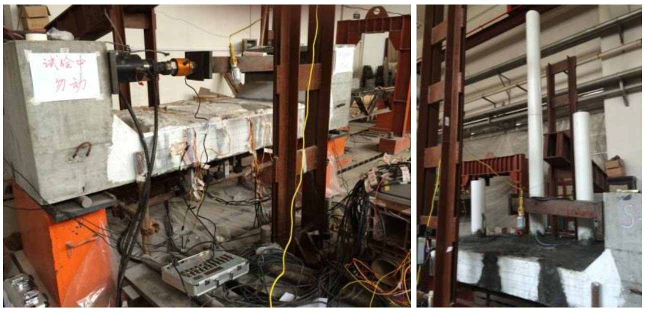


(a) Arrangement of displacement meters on the lateral side of the slab



(b) Arrangement of displacement meters on the bottom of the slab

Fig. 6 Locations and numbers of displacement meters on specimen 2



(a) Loading and self-healing testing device (b) Leakage testing device

Fig. 7 Testing device for specimen 1

(a) Horizontal loading testing device

(b) Vertical loading testing device

Fig. 8 Testing device for specimen 2

2.3.1 Loading on specimen 1

Specimen 1 was placed in the steel loading frame system for loading. The bending tensile load (dominated by the bending stress with a smaller positive tensile stress) was applied to the concrete slab by the hydraulic jack in order to push the two rigid ends of the specimen along the length of the slab. The horizontal force acting point was 0.485 m away from the middle of the concrete slab's surface. When the horizontal load was smaller, it was unloaded after the bending micro-crack appeared on the upper surface of the slab. The strain value of the rebar was stable, so the self-healing test was conducted for the micro-crack. The loading was continued and the leakage test was performed for the bending crack. The testing device for specimen 1 is shown in Fig. 7.

2.3.2 Loading on specimen 2

The eccentric load in the horizontal direction loaded on specimen 2 was identical to that for specimen 1. The jack was used to apply a vertical upward load at the vertical mid-span of the bottom slab. The vertical load and horizontal load at the mid-span were applied at the same time and the value was maintained at 1:5.

A steel beam was placed at the top of two vertical rigid ends to provide the support for the endpoint of the vertical load at the mid-span. The steel beam and top beam of the steel frame were connected tightly by a jack. Therefore, a high shear force could develop in the concrete slab (Fig. 8(a)). First, a bending crack formed on the upper surface of

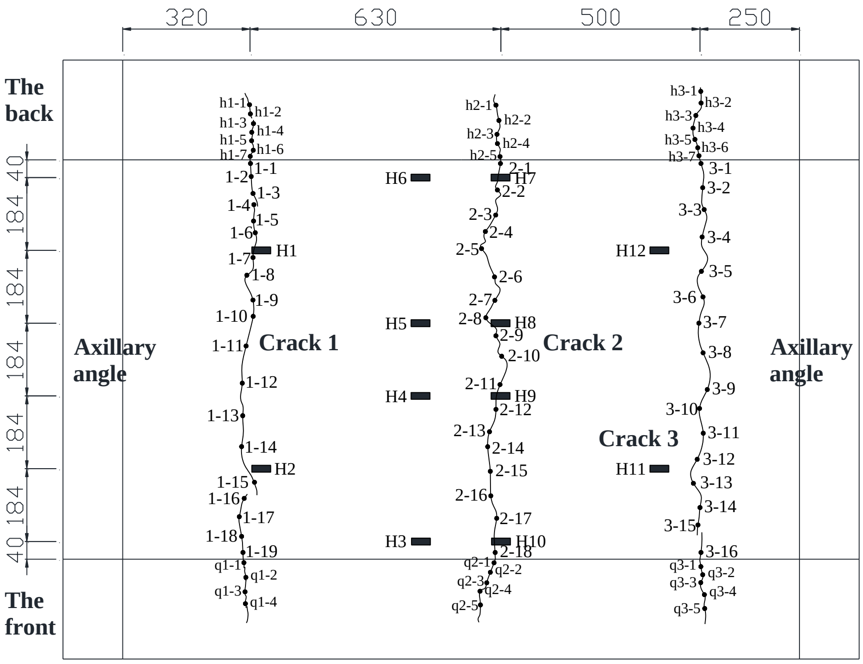


Fig. 9 Spacing and measurement point width for the three cracks in specimen 1

the slab due to the horizontal load and vertical load applied at the mid-span of specimen 2. A through crack then formed as the downward vertical force was applied to the concrete slab (Fig. 8(b)). After the strain value of the rebar stabilized, the self-healing and leakage tests were conducted for the through crack.

3. Self-healing of the micro-crack in a lentic environment

Loading on specimen 1. When the horizontal force was 53.35 KN, cracks 1 and 2 appeared simultaneously in the concrete slab. Moreover, the strain value for the rebar changed suddenly and the cracking moment of the concrete slab was 25.87 KN•m. Due to measurement errors and the nonuniformity of the concrete, the measured cracking moment was slightly higher than the theoretical value. Crack 3 appeared after loading continuously to 57.22 KN. After unloading, the strain values for the rebar were monitored continuously. After the rebar strain stabilized, the deformation and crack widths were measured. At this time, the displacements of measurement points LW2, RW2, W5, W6, and W7 were all 1 mm and the remaining measurement points exhibited no deformation. After cracking, residual deformation occurred during unloading. The widths of the two sides on the upper surface expanded in the plane, and the crack spacing and measurement point locations indicating the crack width were as shown in Fig. 9. The crack widths according to each measurement point were listed in Table 1. The degree of crack self-healing was assessed based on the crack width measurements.

For the three bending micro-cracks in Table 1, the self-healing process was tested to assess the self-healing performance of the micro-cracks in solid concrete in a lentic environment. During the self-healing test, the ambient

Table 1 Summary of the crack widths (mm) at each crack measurement point

Measurement point for crack 1	Crack width (mm)	Measurement point for crack 2	Crack width (mm)	Measurement point for crack 3	Crack width (mm)
h1-1	<0.10	h2-1	<0.10	h3-1	<0.10
h1-2	<0.10	h2-2	<0.10	h3-2	<0.10
h1-3	0.12	h2-3	<0.10	h3-3	<0.10
h1-4	0.10	h2-4	<0.10	h3-4	<0.10
h1-5	0.16	h2-5	0.10	h3-5	<0.10
h1-6	0.14	/	/	h3-6	0.10
h1-7	0.18	/	/	h3-7	0.10
1-1	0.18	2-1	0.10	3-1	<0.10
1-2	0.16	2-2	0.10	3-2	<0.10
1-3	0.16	2-3	<0.10	3-3	<0.10
1-4	0.14	2-4	<0.10	3-4	<0.10
1-5	0.12	2-5	0.10	3-5	<0.10
1-6	0.12	2-6	0.10	3-6	<0.10
1-7	0.14	2-7	<0.10	3-7	<0.10
1-8	0.18	2-8	<0.10	3-8	<0.10
1-9	0.10	2-9	<0.10	3-9	0.10
1-10	0.14	2-10	<0.10	3-10	0.10
1-11	0.10	2-11	<0.10	3-11	0.10
1-12	0.12	2-12	0.10	3-12	0.10
1-13	0.14	2-13	0.10	3-13	0.12
1-14	0.12	2-14	0.12	3-14	<0.10
1-15	0.10	2-15	<0.10	3-15	<0.10
1-16	0.10	2-16	0.10	3-16	<0.10
1-17	0.10	2-17	0.10	/	/
1-18	0.12	2-18	0.12	/	/
1-19	0.14	/	/	/	/
q1-1	0.14	q2-1	0.10	q3-1	0.10
q1-2	0.10	q2-2	0.10	q3-2	<0.10
q1-3	<0.10	q2-3	<0.10	q3-3	<0.10
q1-4	<0.10	q2-4	<0.10	q3-4	<0.10
/	/	q2-5	<0.10	q3-5	<0.10

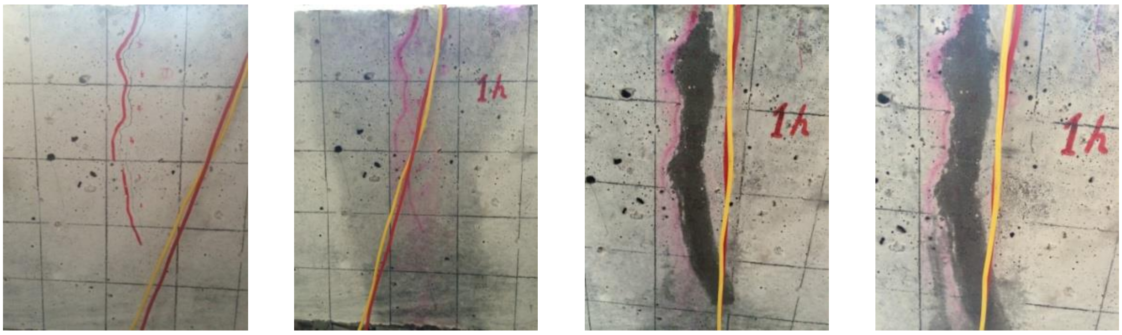
Table 2 Self-healing of concrete bending crack with time

Number of test days	Crack 1	Crack 2	Crack 3
First day	Width of each crack measurement point (see Table 1 for details)		
Fourth day	Crack width of 0.14 mm for points h1-5 and h1-6, and 0.16 mm for point h1-7,1-1, and 1-8, but less than 0.1 mm for the remaining points	Widths of all measurement points less than 0.1 mm and visible to the naked eye	Widths of all measurement points less than 0.1 mm. Fine micro-cracks that are apparent to the naked eye. Original connected and longer micro-cracks self-healed in some positions
Seventh day	Crack width of 0.12 mm for point h1-5, h1-6, h1-7, 1-1 and 1-8, and smaller than 0.1 mm for the other points	Width of each measurement point smaller than 0.1 mm and visible to the naked eye. Cracks self-healed in some positions	Widths of each measurement point less than 0.1 mm and apparent to the naked eye. Cracks self-healed in most positions
Tenth day	Widths of all measurement points less than 0.1 mm and apparent to the naked eye	Widths of all measurement points less than 0.1 mm and cracks self-healed in most positions	Widths of all measurement points less than 0.1 mm and cracks self-healed in most positions

temperature ranged from 25-34℃ and the ambient humidity was 65-80%. The volume of the whole test specimen was very large so the specimen with cracks could not be immersed completely in the water for the self-healing test. Thus, water was sprayed onto the crack's surface so it remained in contact with water. In addition, the surface of the crack was covered with absorbent cotton to retain water, thereby ensuring that the crack remained continuously in a wet environment, as shown in Fig. 7(a). During the micro-crack self-healing test, the crack width was measured and recorded in real time. In addition, the degree of crack self-healing was compared based on photographs. The self-healing test for the micro-crack was conducted after maintaining the specimen in a lentic environment for 21 days. The number of test days was used to replace the test date to represent the test result in order to understand the degree of self-healing of bending crack in a convenient and intuitive manner. The crack widths after self-healing are listed in Table 2. Photographs of the self-healed crack in some positions are shown in Figs. 10 to 16.

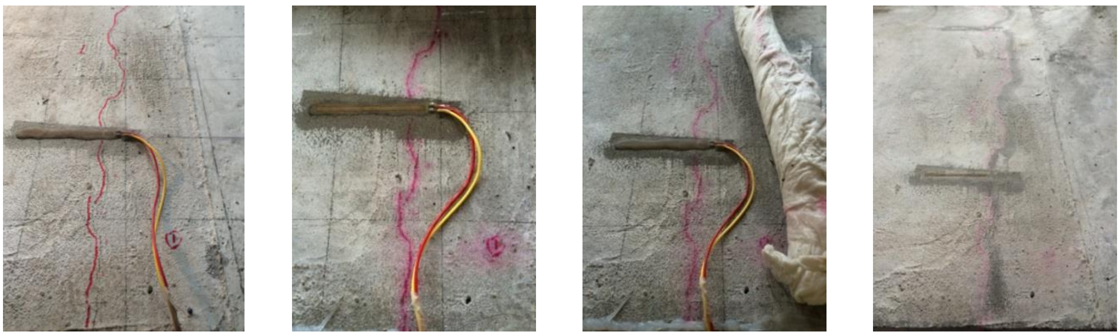
According to the descriptions in Table 2 and the photographs of crack self-healing, the bending micro-cracks in solid concrete self-healed in the lentic environment were observed. According to the self-healing test for the bending micro-cracks, the relationship between the crack self-healing width [W] and healing phase under the test conditions were determined, as shown in Table 3. The variation in the crack width was equal to the ratio of the difference between the crack width and the minimum crack width relative to the minimum crack width. The change in the crack width was greater when the value was higher.

Table 2 and Table 3 show that crack 2 and crack 3 both had widths of about 0.1 mm. The variations in the crack width were less 30%. The cracks self-healed within 3 days. The width of crack 1 was less than 0.2 mm and the variation in the width was less than or equal to 100%. In the healing phase, the crack healed to 0.1 mm after 10 days. This suggests that the concrete microcracks exhibited better self-healing performance in the lentic environment based on test



(a) First day (b) Fourth day (c) Seventh day (d) Tenth day

Fig. 10 Self-healing at the measurement points h1-1→h1-7 for crack 1



(a) First day (b) Fourth day (c) Seventh day (d) Tenth day

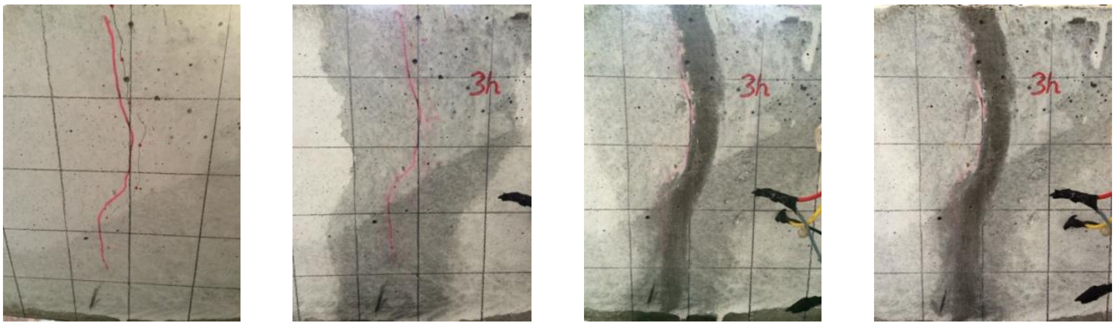
Fig. 11 Self-healing at the measurement points 1-1→1-19 for crack 1

(a) First day (b) Fourth day (c) Seventh day (d) Tenth day

Fig. 12 Self-healing at the measurement points q1-1→q1-4 for crack 1

(a) First day (b) Fourth day (c) Seventh day (d) Tenth day

Fig. 13 Self-healing at the measurement points q2-1→q2-5 for crack 2



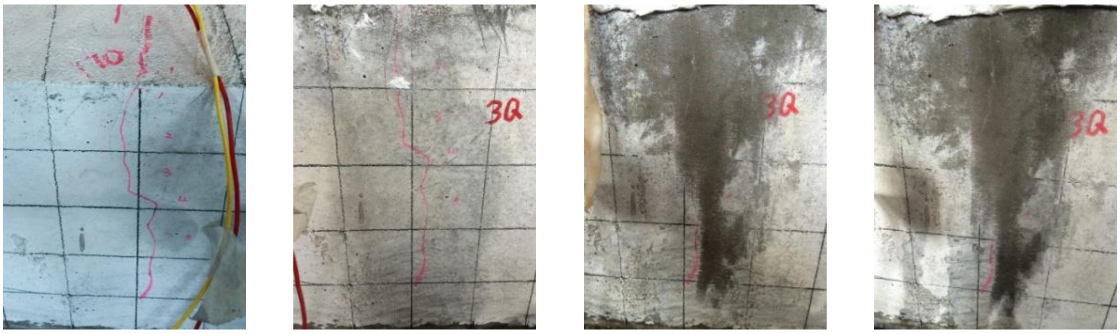
(a) First day (b) Fourth day (c) Seventh day (d) Tenth day

Fig. 14 Self-healing at the measurement points h3-1→h3-7 for crack 3

(a) First day (b) Fourth day (c) Seventh day (d) Tenth day

Fig. 15 Self-healing at the measurement points 3-1→3-16 for crack 3

temperature ranged from 25-34℃ and the ambient humidity was 65-80%. The volume of the whole test specimen was very large so the specimen with cracks could not be immersed completely in the water for the self-healing test. Thus, water was sprayed onto the crack’s surface so it remained in contact with water. In addition, the surface of the crack was covered with absorbent cotton to retain water, thereby ensuring that the crack remained continuously in a



(a) First day (b) Fourth day (c) Seventh day (d) Tenth day

Fig. 16 Self-healing at the measurement points q3-1→q3-5 for crack 3

Table 3 Healing phase and self-healing width [W] (mm) of the bending micro-crack in the lentic environment

Main test conditions	Variation in crack width ≤ 30%		Variation in crack width ≤ 100%	
	Healing phase	Self-healing width [W]	Healing phase	Self-healing width [W]
Age of concrete ≥ 28 days, Initial crack width ≤ 0.2 mm, Ambient temperature 25-34°C, Humidity 65-80%	1 day	0.02	1 day	0.02
	3 days	0.02	3 days	0.04
	/	/	6 days	0.06
	/	/	10 days	0.1

wet environment, as shown in Fig. 7(a). During the micro-crack self-healing test, the crack width was measured and recorded in real time. In addition, the degree of crack self-healing was compared based on photographs. The self-healing test for the micro-crack was conducted after maintaining the specimen in a lentic environment for 21 days. The number of test days was used to replace the test date to represent the test result in order to understand the degree of self-healing of bending crack in a convenient and intuitive manner. The crack widths after self-healing are listed in Table 2. Photographs of the self-healed crack in some positions are shown in Figs. 10 to 16.

According to the descriptions in Table 2 and the photographs of crack self-healing, the bending micro-cracks in solid concrete self-healed in the lentic environment were observed. According to the self-healing test for the bending micro-cracks, the relationship between the crack self-healing width [W] and healing phase under the test conditions were determined, as shown in Table 3. The variation in the crack width was equal to the ratio of the difference between the crack width and the minimum crack width relative to the minimum crack width. The change in the crack width was greater when the value was higher.

Table 2 and Table 3 show that crack 2 and crack 3 both had widths of about 0.1 mm. The variations in the crack width were less 30%. The cracks self-healed within 3 days. The width of crack 1 was less than 0.2 mm and the variation in the width was less than or equal to 100%. In the healing phase, the crack healed to 0.1 mm after 10 days. This suggests that the concrete microcracks exhibited better self-healing performance in the lentic environment based on test results. Under the test conditions, the micro-crack healed to 0.1 mm in the short term. In an actual water tank, a micro-crack would be in contact with water for a long time (De Belie *et al*. 2018, Melika *et al*. 2018). Furthermore, using the conventional treatment method, a crack with a width of less than 0.5 mm can be repaired easily (Song *et al*. 2010). Thus, the self-healing performance of concrete cracks should be considered when assessing the seismic damage grade to a clean-water reservoir in a water supply system, and the limiting value of the crack width at the basically intact and slight damage grade must be increased in an appropriate manner for an existing clean-water reservoir (Gao 2012, Guo *et al*. 1998). In a water treatment pond in a water supply system, a chemical reagent that is mixed in the stored water may permeate to the surface of the rebar through the crack to cause its corrosion and reduce the structure-bearing capacity. Therefore, the limiting value for the crack width when grading the seismic damage to a water treatment tank does not need to consider the self-healing performance of the crack.

4. Leakage performance of a bending crack

The aim of leakage assessments for a bending crack is to test the leakage characteristics of a bending crack with a larger crack width and a smaller depth for the compression zone at a certain water head. The water head is applied to the crack by installing a water pipe. After the application of the water head, reloading may lead to the pipeline leaning or the sealing effect between the pipeline and crack may fail. In addition, during the loading process, the sealing of the crack affects the measured crack width and depth of the compression zone. Considering all of these reasons, the loads were unloaded as the bending crack was loaded to a larger width and smaller depth for the compression zone, and the water pipe was then installed to apply the water head in the leakage test for the bending crack. The main steps were as follows. After the self-healing test for the bending crack, the horizontal load was applied to the test specimen continuously. As the horizontal load increased, only two short cracks appeared in the front of the concrete slab. Moreover, the length and width did not develop fully in the loading process. However, as described in Section 3, the widths of the three existing bending cracks increased gradually, whereas the depths of the compression zones decreased gradually in the loading process. The depths of the compression zones for the three bending cracks were

Table 4 Bending crack characteristics and leakage test results

Working condition	Height of water head (m)	Installation location of water head	Crack width of water head (mm)	Average crack depth (mm)	Unconnected height at the front (mm)	Unconnected height at the back (mm)	Leakage of water head after stabilization
(1)	0.64	Middle in the slab width of crack 1	8-12	217.5	23	42	No soakage, no leakage
(2)	0.64	About 25 cm from the back of crack 2	5-6	215	35	35	No soakage, no leakage
(3)	1.25	About 25 cm from the back of crack 2	5-6	215	35	35	No soakage, no leakage
(4)	2.54	About 25 cm from the back of crack 2	5-6	215	35	35	Some drops leaked from the slab bottom
(5)	0.64	About 25 cm from the back of crack 3	5-6	229.5	18	23	No soakage, no leakage
(6)	1.25	About 25 cm from the back of crack 3	5-6	229.5	18	23	No soakage, no leakage

measured in real time. When they were close to 35 mm, the load was unloaded up to the stable strain value of the rebar. After measuring the widths of the three bending cracks and the heights of the unconnected region, an unplasticized polyvinyl chloride (PVC-U) solid wall tube was installed in the crack at the corresponding height, and the cracks on the surface and two sides of the slab were sealed with silicon sealant and cement. After adding water via the pipeline, the effects of water head application on the crack were determined. The diameter and wall thickness of the PVC-U solid wall tube were 160 mm and 40 mm, respectively, and it could bear a water head of 3 m without breaking. The heights of the solid wall tube in cracks 1, 2, and 3 were 0.64 m, 2.54 m and 1.25 m, respectively. After adding water, the height of the water head increased by 0.1 m due to the flow. After the water head stabilized, the leakage from the slab bottom was observed for 20 min. If there was no leakage from the slab bottom, the water head was increased constantly. The test was stopped if leakage was observed. The maximum head applied to each crack was the height of the solid wall tube. The leakage characteristics of the bending cracks were analyzed by comparing the different heights of the water head for the same crack and the same height of the water head for different cracks. The installation of the solid wall tube and water adding device are shown in Fig. 7(b), respectively. Table 4 shows the bending crack characteristics and the leakage test results.

When the height of the water head on crack 1 was less than 0.64 m, no soakage or leakage occurred. The height of the water head on crack 2 was less than 2.40 m, so there was also no soakage or leakage. For crack 3, there has no soakage or leakage when the height of the water head was less than 1.25 m. According to the comparison of working conditions (1), (2), and (5) with working conditions (3) and (6) in Table 4, when the crack was very wide and the unconnected height was relatively small, no soakage or leakage occurred under the influence of a small water head. By contrast, according to the comparison of working conditions (2), (3), and (4) with working conditions (5) and (6), when the crack width and unconnected height were the same and the water head was small, no soakage or leakage occurred at the slab bottom. Soakage and slight leakage occurred at the slab bottom only under working condition (4) when the height of the water head was very large and it reached 2.54 m. Thus, the height of the water head was the decisive factor that determined liquid leakage from the bending crack. After unloading, the unconnected area of the crack or the compressive stress area generated by the bending stress effect during loading could effectively mitigate the liquid leakage, thereby maintaining the basic function of the liquid storage structure. The high head required a larger compressive zone to prevent leakage than the low water head.

The current tank design codes and specifications strictly prohibit the generation of the structural component through the crack due to tensile stress. The maximum allowable crack width is stipulated for a bending crack. In the "Specification for Structural Design of Reinforced Concrete Water Tank of Water Supply and Sewerage Engineering," article 5.3.4 states that the maximum limiting value for the crack width in a reinforced concrete clean-water tank component is 0.25 mm. In Table 4.1 of American Concrete Institute Standard ACI 224.1R-01 (2001), under the working load, the maximum allowable crack width for a reinforced concrete liquid storage structure is 0.1 mm (0.004 in). In ACI350M-06 (2006), it is suggested that the limiting value for the bending crack width of a concrete structure in environmental engineering is 0.23 mm (0.009 in) in a severe exposure environment and 0.28 mm (0.011 in) in a general environment. According to the leakage test results for the bending crack, no wetting or leakage occurred when the crack width was 5-6 mm with an unconnected height of 35 mm and water head of 2.40 m was observed, i.e., the bending crack width was not the decisive factor that determined whether leakage occurred from the liquid storage tanks. At a certain water head, the leakage from the liquid storage was determined mainly by the height of the unconnected area or the depth of the compression zone. In the "Specification for Structural Design of Reinforced Concrete Water Tank of Water Supply and Sewerage Engineering," the limit for a smaller bending crack width mainly considers the issue of preventing the rebar from corroding. Thus, in order to consider preventing the corrosion of the rebar and liquid storage leakage, the crack width and depth of the compression zone should be restricted simultaneously, rather than only regulating the

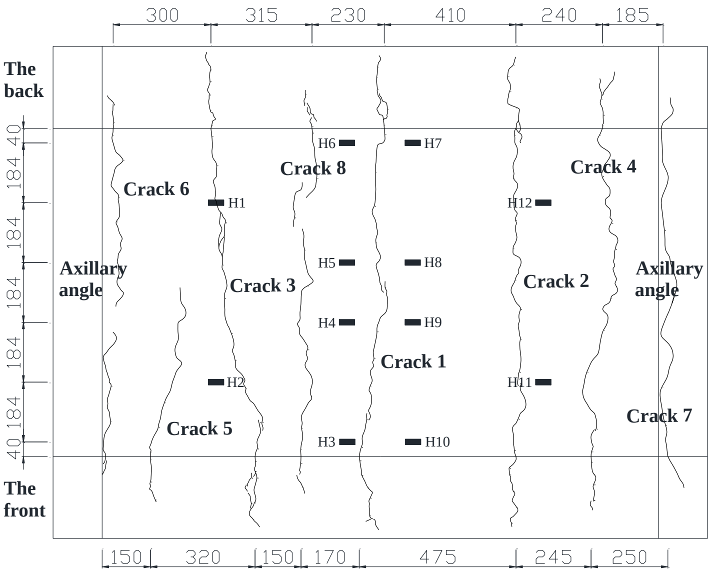
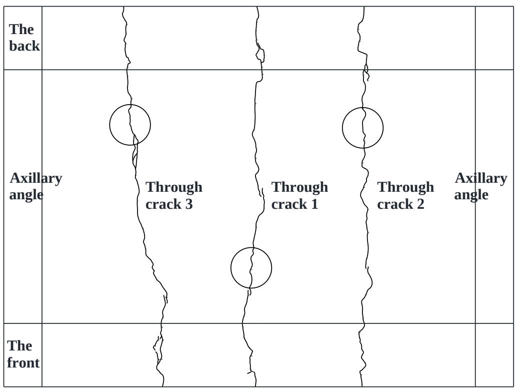


Fig. 17 Development of the bending crack in specimen 2



(a) Locations of through cracks and water heads

(b) Testing device

Fig. 18 Self-healing and leakage test devices for the through cracks

crack width. The regulations for crack width and the depth of compression zone are not suitable for calculating and checking the structural design as well as evaluating the functional status, and they also focus on the role of the structure or component. Thus, in order to estimate the damage grade for a liquid storage structure such as a water tank, it is necessary to comprehensively assess the seismic damage grade according to the distribution, location, density, and length of cracks, as well as the leakage.

5. Self-healing performance of the through crack in a lotic environment

In Section 3, the concrete cracks self-healed in a lentic environment were showed. In this section, the self-healing performances of through cracks in concrete in a lotic environment were assessed. The self-healing test for a through crack was conducted after 41 days of complete maintenance in a lotic environment. For specimen 2, the horizontal load and vertical load were applied simultaneously to the concrete slab at a ratio of 5:1. A bending crack appeared on the upper surface of the slab. The loading was stopped when the displacement value of the measurement point reached 25 mm, and the widths of the bending cracks 1, 2, and 3 were larger at this time. The bending cracks that appeared in the slab are shown in Fig. 17. The upper and lower numbers denote the spaces between the cracks. The numbers of the cracks were designated according to their order of appearance. After comparing the development of the bending cracks in specimens 1 and 2, the crack distribution in specimen 2 was more even due to the existence of the vertical force, and the spaces between the adjacent cracks were similar.

After the formation of the bending crack, vertical force was applied to the concrete slab and bending cracks 1, 2, and 3 formed through cracks 1, 2, and 3 along the direction of the slab thickness. The strain value of the rebar strain gauge was monitored continuously when the through cracks appeared. After the strain value of the rebar stabilized completely, the self-healing and leakage tests were performed for the through crack, while avoiding the effects of steel and concrete retraction on the follow-up test results after unloading. The through cracks and location of the water head are shown in Fig. 18(a). The self-healing and leakage test devices used for assessing the through cracks

Table 5 Properties of three through cracks and maximum height of the water head

Number of cracks	Interval of crack width at the location of water head	Maximum crack width on the lower surface of slab	Maximum allowable water head
1	2.18-2.30	0.40	1.25
2	2.18-2.30	0.86	2.54
3	2.18-2.30	0.26	0.64

Table 6 Samples of data in terms of the time required for 1000 ml of water leakage in the self-healing test for through crack 1 on the third day

Number of test records	1st	5th	10th	15th	20th	25th	30th	35th	40th	45th	50th
Leakage time (sec)	94	104	118	122	131	134	145	157	162	197	211

Table 7 Samples of data in terms of the time required for 1000 ml of water leakage in the self-healing test for through crack 3 on the third day

Number of test records	1st	5th	10th	15th	20th	25th	30th	35th	40th	45th	50th
Leakage time (sec)	98	107	121	128	135	139	152	160	167	202	220

Table 8 Time required for 1000 ml of water leakage in the repeated tests for through crack 1 at a constant water head of 1.25 m

Number of test days	1st day	2nd day	3rd day	4th day	5th day	6th day	7th day	8th day	9th day	10th day
Leakage time (sec)	78.3	79.2	135.0	136.7	139.1	198.4	209.5	393.5	1203.5	2309.5

Table 9 Time required for 1000 ml of water leakage in the repeated tests for through crack 3 at a constant water head of 0.64 m

Number of test days	1st day	2nd day	3rd day	4th day	5th day	6th day	7th day	8th day	9th day	10th day
Leakage time (sec)	92.8	97.9	137.0	153.3	241.3	833.7	1316.2	2324.7	4269.9	7763.8

are shown in Fig. 18(b).

The widths of three through cracks at the location of the water head and the maximum allowable height of the water head are shown in Table 5.

Before adding water, the contact sites at the bottom of the pipeline and slab, the cracks on the upper surface of the slab, the location of the water head, and the two sides were sealed completely, so the water could only leak out from the lower surface of the slab. At the bottom of each through crack, the drainage system was prepared from waterproof plastic cloth. The heights of both sides of the device were not the same, so the water flowed to one side and into a measuring cylinder. The time corresponding to the water yield in full flow was recorded directly in this test. A constant water head was applied to the through crack by measuring the time when the required amount of water

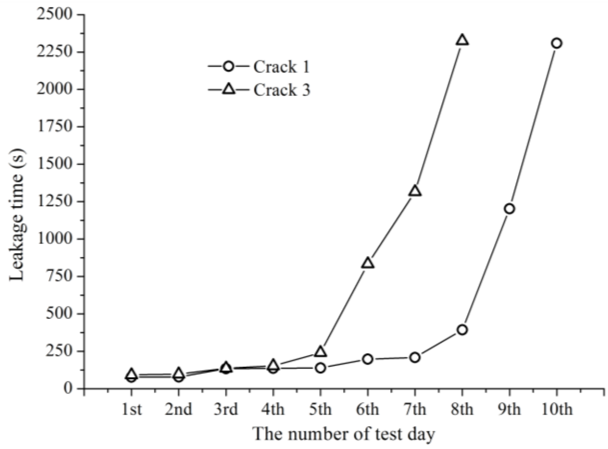
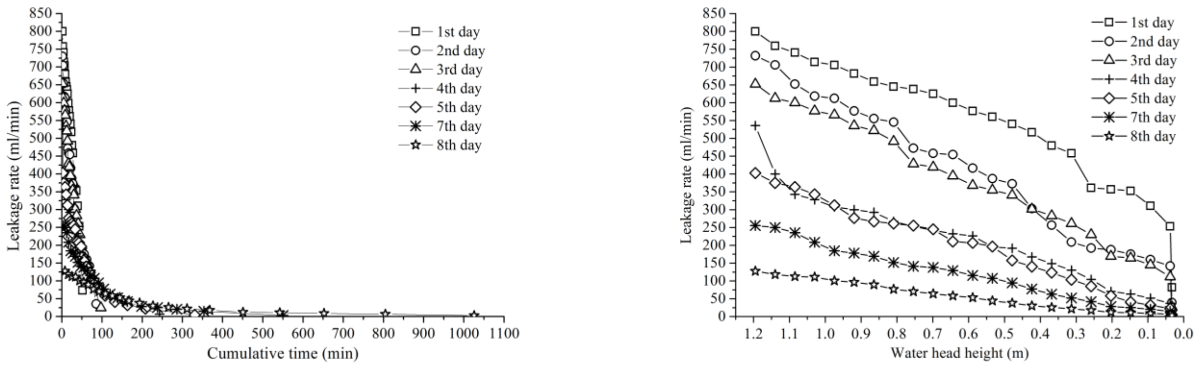


Fig. 19 Number of test days and time required for 1000 ml of water leakage for through cracks 1 and 3 in repeated tests

leaked out from the crack, and the self-healing performance of the through crack in the lotic environment was then studied. Due to the large height of the water head for through crack 2 and the wide crack on the bottom of the slab, it was difficult to maintain a constant water head and accurately measure the time required for leakage at a certain water head. Thus, the maximum water head was only applied to through cracks 1 and 3 in the self-healing test. In the self-healing test for through crack 1, the height of the water head was maintained at 1.25 m by continuously adding water. For through crack 3, the height of the water head remained unchanged at 0.64 m. The time was measured for 1000 ml of water leakage at a constant water head. In the daily test, the time required for 1000 ml of water leakage was recorded 50 times. The self-healing test was conducted for 10 consecutive days at a constant water head. Similar to the regulations in the self-healing test for a bending crack, the number of test days represented the corresponding test results in this case. In the test, the environmental temperature was 25-34℃ and the humidity ranged from 55-80%. Tables 6 and 7 show some of the test data in terms of the time required for 1000 ml of water leakage, which was recorded 50 times on the third day at a constant water head in a single trial for through cracks 1 and 3, respectively. The average time required for 1000 ml of water leakage was recorded 50 times in a single trial each day and it was used as the daily test result. Tables 8 and 9 shows the repeated self-healing test results for through cracks 1 and 3, respectively.

Tables 6 and 7 show that in the single self-healing tests for through cracks 1 and 3, as the number of records increased, the time required for 1000 ml of water leakage increased continually, which indicates that the water leakage rate decreased continually. The leakage times of less than 2500 seconds in Tables 8 and 9 are shown in Fig. 19 in order to compare the self-healing of the two cracks.

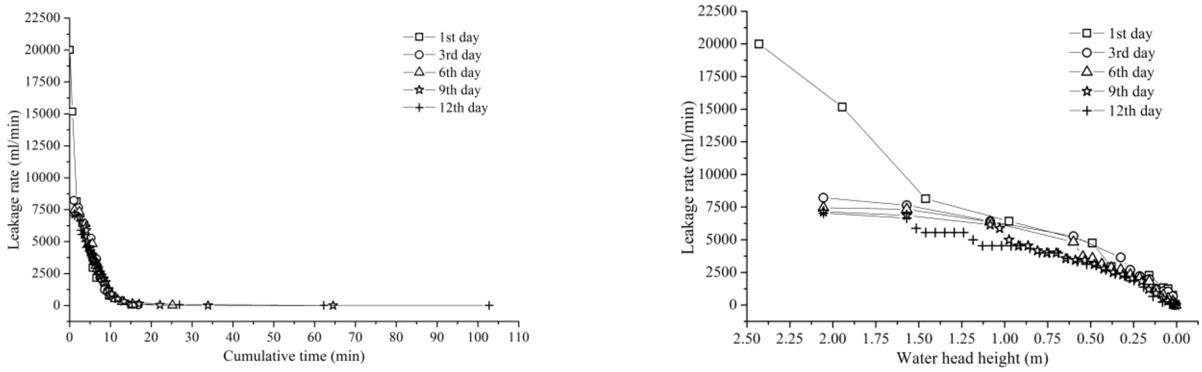
Fig. 19 shows that as the test continued, the time required for 1000 ml of water leakage increased continually. In the same number of test days, the time required for 1000 ml of water leakage from through crack 1 was shorter than that from through crack 3, and the flow velocity for through crack 1 was larger than that for crack 3.



(a) Relationship between the leakage rate and cumulative time

(b) Relationship between the leakage rate and water head height

Fig. 20 Correlation curve for leakage rate from through crack 1



(a) Relationship between the leakage rate and cumulative time

(b) Relationship between the leakage rate and water head height

Fig. 21 Correlation curve for leakage rate from through crack 2

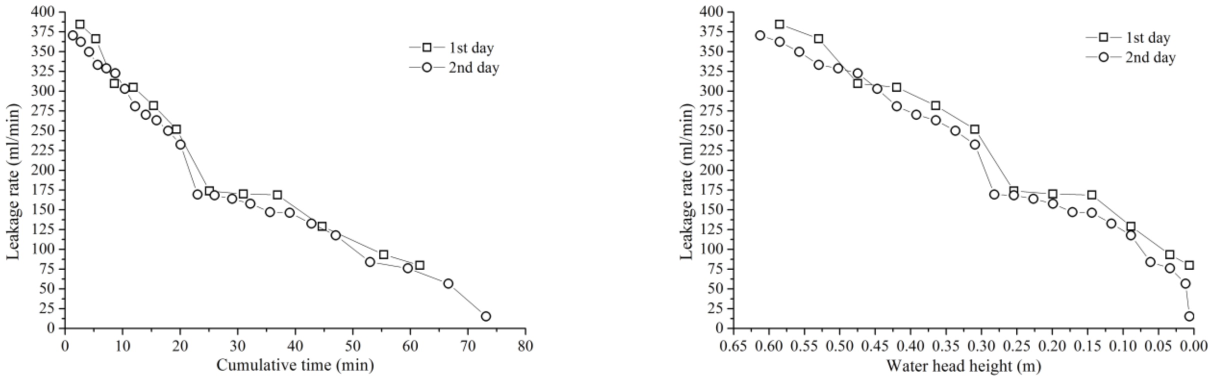
For through crack 1, the maximum leakage time occurred on the ninth day and the self-healing effect was obvious. For through crack 3, the leakage time increased to the maximum on the sixth day and the healing effect was also remarkable. In addition, the crack width decreased gradually on the slab bottom. Thus, the self-healing test data showed that the through cracks exhibited self-healing in the lotic environment. By contrast, according to the self-healing tests for the cracks in the lentic environment, under the great scouring force, some of the hydration products generated in the self-healing process were washed away and dissolved, but not all of the hydration products. The water flow slowed down the crack self-healing process. Comparisons of the self-healing processes for through cracks 1 and 3 showed that the crack width was smaller, the water flow velocity lower, and the scouring action of the hydration products was smaller, and thus the crack self-healing process was faster.

6. Leakage performance of through cracks

In Section 5, the results of self-healing tests for through cracks under a constant water head were presented, where the leakage tests for the through cracks were conducted under conditions with a decreased water head. Leakage tests were performed for through cracks 1 and 3 after each self-healing test, and performed directly for through crack 2. As the water head reduced, the time corresponding to the water leakage was measured and the water leakage was determined based on both the water flow velocity and leakage. The cracks 1, 2 and 3 were measured continuously 8 days, 20 days and 6 days respectively.

The leakage test results shown for the three through cracks demonstrate that as the water leaked out continuously, the height of the water head decreased in a constant manner, and the time required for the same amount of water leakage increased. In addition, the total leakage was smaller than the total water added via the pipe and the difference was mainly due to the chemical reaction with unhydrated cement particles in the slab, i.e., self-healing of the concrete crack, and the remainder was lost via water evaporation. In Figs. 20 to 22, the cumulative time is the time required for light leakage of the stored water in a single trial. The cumulative time required for the same amount of water leakage also increased with the number of test days. Thus, the through cracks exhibited self-healing in the lotic environment.

The leakage rate (ml/min) was equal to the quantity of water leakage (ml) divided by the time required for leakage of the corresponding amount of water. The cumulative time was the total time required to reduce the water head to a certain height. The descending height of the water head was calculated according to the water leakage, which was equal



(a) Relationship between the leakage rate and cumulative time

(b) Relationship between the leakage rate and water head height

Fig. 22 Correlation curve for leakage rate from through crack 3

to the total water head minus the descending water head, i.e., the height of the water head at some point. According to the leakage test results in Figs. 20 to 22 shows the relationships between the leakage rates for through cracks 1, 2, and 3 with the cumulative time and the height of the water head. Only parts leakage data are shown since the very small leakage rates are not drawn.

The relationship between the leakage rate and cumulative time for the through cracks showed that with different water heights and crack widths, the leakage rate decreased as the cumulative time increased, where it decreased rapidly initially and then more slowly. In the repeated test, the leakage rate in the later test period was lower compared with that in the early stage, and the increase in the total cumulative time required for leakage of the same amount of water in the later period was greater than that in the early period. The variations in the leakage rate and cumulative time required in this and previous tests confirmed that the self-healing of through cracks actually occurred.

The relationship between the leakage rate for the through cracks and the water head height was linear according to the results obtained with different water heights and crack widths in repeated tests. The change rate in the leakage rate with the water head height was obtained by fitting the slope of the correlation curve between these two parameters. The slope was smaller in the later period and the decrease in the leakage rate was slower as the water head height increased. The widths of through crack 2 and through crack 3 were the maximum and minimum, respectively. When the water head heights were the same, the maximum leakage rate occurred for through crack 2, followed by through crack 1, and the minimum for through crack 3. Thus, under the same water head height, the leakage rate was higher when the crack width was larger. Therefore, the water leakage rate was related to the water height and crack characteristics.

7. Conclusions

In this study, reinforced concrete tank slab specimens were constructed to investigate the self-healing performance and leakage characteristics of bending and through cracks. Our main conclusions are as follows.

- Under the test conditions, a bending crack in concrete healed by 0.1 mm after 10 days in a lentic environment. In addition to demonstrating the feasibility of water tank crack repair by self-healing, the appropriate limit for crack width grading according to the basic integrity under slight damage to a clean-water tank in a water supply system were determined.
- Considering the need to prevent corrosion of the reinforcement and liquid storage leakage, the bending crack width and compressive zone height should both be restricted in the component design process.
- Leakage rate tests for the through cracks under a constant water head demonstrated that self-healing still occurred for the through cracks in a lotic environment. When the through crack width was smaller, the water flow velocity was lower and the self-healing of the through crack occurred more rapidly.
- According to the leakage rate from through cracks under variable water head levels, the water leakage rate decreased over time continuously. There was a linear relationship between the leakage rate and water height head. Repeated leakage tests for through cracks under various water head levels also demonstrated that the through cracks exhibited self-healing in a lotic environment.

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