Magazine of Civil Engineering. 2019. 88(4). Pp. 52–59
Инженерно-строительныйжурнал. 2019. №4(88). С. 52–59

Magazine of Civil Engineering

ISSN 2071-0305

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.18720/MCE.88.5

Factors effecting the recovery process of self-repairing concrete

***Q. Zhao*[*a,b],P.Cheng*[*a],Y.Wei*[c], J. Wang*[d]**
[a]Northeast Forestry University, Harbin, Heilongjiang, China
[b]Northeast Agricultural University, Harbin, Heilongjiang, China
[c]Yellow River Survey Planning and Design Co., Ltd., Zhengzhou City, Henan Province, China
[d]Harbin Dongan Automobile Engine Manufacturing Co.,Ltd., Harbin, Heilongjiang, China
** E-mail: 492954791@qq.com*

Keywords: self-repairing cement concrete, initial crack width, placement method, external environment, repair rate

Abstract. In order to explore the influence of external environmental factors, the initial width of cracks and the placement of glass fiber tubes on the repairing effect of self-repairing concrete, glass fiber tubes are built in self-repairing concrete specimens, Self-repair test using repair adhesive. The repair rate α is characterized by the ratio of the initial crack width l to the time t used for repair completion, and the effects of the above three factors on the repair rate were analyzed. The results show that at –15~30 °C, the repair rate increases with the increase of temperature; at 0~30 °C, the growth rate of repair rate is obviously less than the growth rate of –15~0 °C. When the temperature is below 0 °C, the temperature plays a leading role in the improvement of the repair rate; The repair rate increases first and then decreases with the increase of the initial crack width. When the crack width is from 0.4to 0.6mm, the repair rate increases significantly faster than the crack width from 0.6to 1.0mm. The rate of repair of the crack width from 1.0 to 1.5 mm is significantly higher than that of the crack width from 1.5 mm to 2.0 mm. And when the initial crack width is about 1.0 mm, the repair rate reaches the highest level. When the initial crack width and the repair temperature are between –15 and 30 °C, the repair rate of the glass fiber tube is slightly better than that of the diamond when the inverted trapezoid is placed. The initial width of the crack has the greatest influence on the repair rate. Followed by temperature conditions and placement of fiberglass tubes. The corresponding factor levels at the maximum repair rate are 1.0mm, 30 °C and inverted trapezoids.

1. Introduction

Cement concrete pavement can adapt to the requirements of large-scale transportation, high speed, large traffic flow, etc., which are necessary for the development of transportation, and has many advantages such as high strength, good stability, long service life and low maintenance costs, etc. A non-homogeneous brittle material can easily generate microcracks inside the component under the influence of the surrounding environment. If these micro-cracks cannot be repaired in time, these irregular and inconsistent micro-cracks will further develop under the influence of external factors. Macroscopic cracks that will greatly reduce the durability and safety of cement pavements [1, 2]. Therefore, how to prevent cracks on cement pavement is crucial. At present, the commonly used crack repair methods include surface repair method, grouting caulking plugging method, structural reinforcement method, concrete replacement method, electrochemical protection method and other passive repair methods, while bionic self-healing method is an active repair method, which can be timely repair concrete cracks and restore their compactness and mechanical properties [3,4]. At present, the self-healing method to repair concrete cracks, that is, self-repairing concrete is still in the primary stage of intelligent concrete [5, 6]. Many scholars have carried out various attempts and researches on self-repairing concrete technology. Victor Li [7] and other fibers and quartz sand were incorporated into the fiber-reinforced cementitious composite material to achieve control of crack dispersion. The maximum distance between the cracks was 0.3 cm, and the average spacing was only 60 μm. Carolyn Dry [8] selected a acetal polymer solution as a repairing agent, and the mechanical properties of the repaired test piece were

Zhao, Q., Cheng, P., Wei, Y., Wang, J. Factors effecting the recovery process of self-repairing concrete. Magazine of Civil Engineering. 2019. 88(4). Pp. 52–59. DOI: 10.18720/MCE.88.5.

Чжао Ц., Чен П., Вей Ю., Ван Д. Факторы, влияющие на процесс восстановления самовосстанавливающегося бетона // Инженерно-строительный журнал. 2019. № 4(88). С. 52–59. DOI: 10.18720/MCE.88.5.

improved and improved. Michelle Pelletier [9] used the reaction product of $Ca(OH)_2$ and Na_2SiO_3 to fill the cracks and achieve the purpose of repairing cracks. However, the research on the influencing factors of crack repair ability is limited to the internal factors such as repair materials and mix ratio. However, there are few studies on external factors such as temperature and load. Therefore, in order to achieve the best crack healing effect, the internal factors affecting the repair rate will be affected. It is necessary to conduct research in combination with external factors [10,11]. Self-repairing concrete with built-in fiberglass tube is a kind of self-repairing concrete. The reason why it can repair the crack is the combination of the initial width of the crack, the number and position of the fiberglass tube, the type of adhesive, and the external environment. In order to explore how each factor affects the self-repairing effect, the initial width of the crack, the placement of the fiberglass tube and the external environment (temperature) are selected as variables. The repair rate α is characterized by the ratio of the initial crack width l to the time t used for repair completion. The research was made in order to explore the influence of external environmental factors, the initial width of cracks and the placement of glass fiber tubes on the repairing effect of self-repairing concrete [12].

2. Methods

2.1. Repair materials and their carriers

The performance of the repair material is critical to the repair rate. The advantage of the adhesive is high bonding strength and good fluidity [13–16]. Select resin-based end isocyanate-based polyether-type single-liquid polyurethane as an adhesive, such as No. 717 adhesive produced by Great Wall manufacturers. The structural characteristics make it have the characteristics of normal temperature curing, temperature resistance, oil resistance, acid and alkali resistance. Therefore, test selected it as a repair material.

It is important to repair the effect of repairing the number of carriers and whether the mechanical properties of the repair carrier and the concrete matrix match. Since the coefficient of linear expansion of glass and concrete is very close, when the temperature changes, the glass and concrete will not break the bond between them due to the relative temperature deformation; and the glass is composed of various oxides, the calculation shows that the compressive strength is generally 500–2000 MPa, which is much higher than the compressive strength of concrete, which avoids the problem that the glass tube is broken before the concrete due to the load [17, 18]; in addition, the tensile strength of the glass is usually around 1/15 of compressive strength, in order to crack the glass tube while the specimen is cracked, a suitable glass tube size was calculated [19, 20]. In summary, the carrier used in this paper is an insulating glass fiber tube with a length of 25 cm, an inner diameter of 5 mm and a wall thickness of 0.5 mm.

2.2. Matrix materials and their mix ratio

The repaired fiber with a length of 25 cm, an inner diameter of 5 mm and a wall thickness of 0.5 mm was used for the test. The test substrate is a concrete anti-folding test piece with a size of 400 mm×100 mm×100 mm, and the tension zone is provided with 2 √ 8 fixtures. The cement is 42.5 grade ordinary portland cement; the fineness modulus of sand is 2.7; the gravel is 5–20 mm continuous gradation; the apparent density of concrete is 2406 kg/m^3; the water is tap water; the admixture is naphthalene efficient water reducing agent (FDN-C), water-to-binder ratio is 0.41. The concrete mix ratio is shown in Table 1.

Table 1. Concrete mix ratio.

Cement（kg/m^3）	Sand（kg/m^3）	Gravel（kg/m^3）	Water（kg/m^3）	Water Reducer（kg/m^3）
440	712	1068	180	6.6

2.3. Factors affecting repair capacity and evaluation indicators

Self-repairing concrete with built-in fiberglass tube is a kind of self-repairing concrete. The reason why it can repair the crack is the combination of the initial width of the crack, the number and position of the fiberglass tube, the type of adhesive, and the external environment. The factors affecting the repair rate can be generally divided into internal and external factors. The internal factors mainly include the content of various minerals (such as the amount of fly ash and silica fume), mix ratio, repair materials, repair carriers, etc. The external factors mainly include repair time, repair environment, initial crack width, external load, etc. Through the comparison of many internal and external factors, the initial crack size, the position of the glass fiber tube and the external environment (temperature) were taken as the influencing factors, and the internal and external factors were combined to study.

2.4. Influencingfactors

The initial width of the crack has a great influence on the repair rate. Studies have shown that self-repairing concrete can only repair micro-cracks within a certain width range, but does not explain the effect of the initial crack size on the repair rate and repair time of the repaired specimens. Therefore, it is very important to study the effect of the initial crack width on the repair rate. In order to make the initial crack have the same characteristics as the actual crack, referring to the crack prefabrication method in the existing research, the crack is obtained by applying a specific load to the test piece. The test shows that when the applied load is respectively 50, 55, 60, 65, 70 % of the failure load, the corresponding main crack width observed by the PTS-C10 intelligent crack width observer is about 0.4mm, 0.6 mm, 1.0 mm, 1.5 mm and 2.0 mm. The PTS-C10 intelligent crack width observer is shown in Figure 1. The reading view of the crack width is shown in Figure 2, the unit in Figure 2 is mm, the maximum range is 2 mm, and the minimum scale is 0.02 mm.

Figure 1. PTS-C10 intelligent crack width observer.

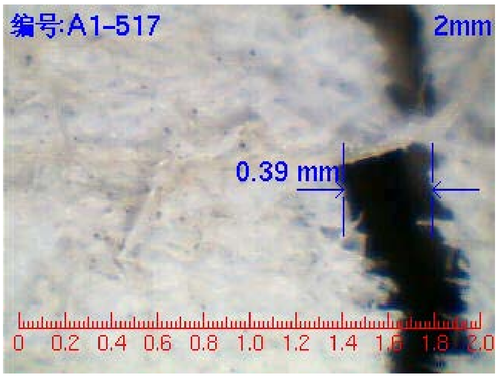
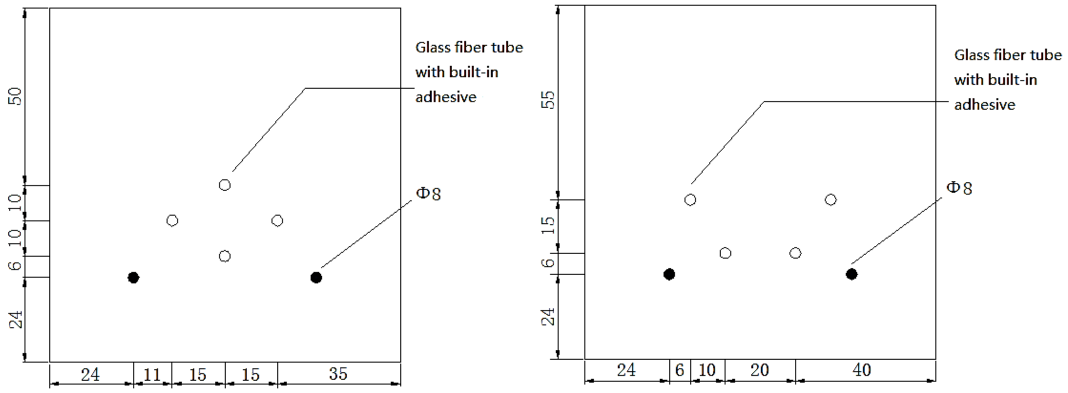


Figure 2. Crack width observation reading viewport.

The position of the fiberglass tube has a significant impact on the repair capacity. The hollow glass tube is added inside the test piece, and the flexural strength of the test piece will inevitably decrease. The test shows that the bending strength caused by placing four glass tubes is significantly lower than that when six pieces are placed. The placement is in the form of diamond and trapezoidal, where the reduction was the smallest compared with other placement methods, and the flexural strength decreased respectively by 5.7 % and 6.1 %, which was much lower than the lowest flexural strength recovery rate of 38.4 % in the test. In addition, the setting position is too low, the adhesive cannot repair the crack above the set position, the setting position is too high, and the adhesive capacity may not be enough to flow to the bottom of the crack. Therefore, it is important to properly set the position of the fiberglass tube. Studies have shown that the cracks are mainly produced in the longitudinal middle position of the test piece, and the development trend from bottom to top appears, so the position of the fiberglass tube in the test is selected in the middle to the lower position. In summary, the glass fiber tube is placed in the test in the form of a diamond and an inverted trapezoid as shown in Figure 3, the unit of measurement in Figure 3 is mm.



(a) (b)

Figure 3. How to place the glass fiber tube in the test piece:(a) the glass tube is placed in a diamond shape (b) the glass tube is placed in an invertedtrapezoid.

The external environmental conditions are one of the important factors affecting the self-repairing effect of cracks. China has a vast territory and a large difference in environmental conditions. In order to understand the repair rate of cracks under different environmental conditions, five different self-healing conditions are selected to represent the environmental conditions in different regions of China. The test data obtained can provides theoretical guidance on appropriate environmental conditions or areas for self-repairing concrete. In addition, for cement concrete pavement, at a certain moment, the road surface temperature is affected by three basic heat transfer modes of radiation, convection and heat conduction. It can be seen that the temperature of the road panel changes continuously with the temperature of the air. And cement concrete pavement as a pavement structure with specific thickness, the temperature along the thickness direction is also a certain regularity and constantly changing. The prediction model of temperature field of various cement pavement panels shows that the 22 cm thick cement road panel is taken as an example. The temperature of the pavement surface is nearly 15 °C higher than the temperature at the bottom of the pavement. At the same pavement depth, the highest temperature and the lowest temperature in the same day differ by about 20 °C.

Therefore, in order to make the temperature conditions of the test conditions coincide with the actual middle panel temperature conditions, it is very important to choose the temperature conditions reasonably. The meteorological statistics show that the temperature in Harbin is generally rising from February to June, and the humidity is decreasing. Based on the analysis of temperature and humidity data of various months in Harbin in recent years, and considering the environmental conditions must to a certain extent represent the average temperature conditions in various regions of China as well as the temperature conditions at different panel thicknesses in different seasons in Harbin. Finally, five environmental conditions as shown in Table 2 were selected.

Table 2. Crack self-healing environmental conditions.

Environmental condition number	Corresponding monthly average temperature (°C)	Description of environmental conditions in the test
1	–15	Outdoor environmental conditions in Harbin in February
2	0	Outdoor environmental conditions in Harbin in March
3	10	Outdoor environmental conditions in Harbin in April
4	20	Outdoor environmental conditions in Harbin from May to June
5	30	30 °C constanttemperatureoven

2.5. Evaluationindicators

Through the monitoring of the cracks during the repair of each test piece, it can be found that the repair of the crack mainly occurs in the first two days, that is, with the repair carrier breaks, the adhesive flows out from the flow and flows to the crack generating portion, and then gradually solidifies, and finally the crack Was fixed. Therefore, the crack monitoring results of the first two days of repair rate are the basis for calculation. The calculation formula of the time α used for the repair rate is as shown in Equation 1.

$$\alpha = \frac{1}{t}, \quad (1)$$

where α is repair rate (mm/d);

l is initial crack width (mm);

t is the time taken to complete the crack repair (d).

3. Results and Discussion

3.1. Preparation of test pieces

The filling and sealing of the adhesive in the glass fiber tube is carried out as follows: First, the end of the glass fiber tube is closed. Use GLUE GUN GT-10 hot melt glue gun to inject about 3 mm hot melt adhesive into the glass tube to seal one end of the glass tube. The operation is as shown in Figure 4. The glass tube sealed with hot melt adhesive is shown in Figure 5; After the molten rubber is solidified, the port sealed with hot melt adhesive is applied with epoxy resin AB glue to double seal; Secondly, the adhesive is injected into the glass fiber tube. Since the end of the glass fiber tube is closed, it is difficult to apply the adhesive. The infusion method of the adhesive in this test follows the lifting duct method used for pouring concrete in the bored pile, that is as shown in Figure 6. The syringe shown is used in conjunction with the sheared medical infusion belt for injection, so that the injection of the infusion belt can speed up the injection speed while avoiding the appearance of the air column. Finally, the other end of the glass fiber tube filled with the adhesive is closed. The sealing method is the same as the first step. The steel and the glass fiber tube filled with the adhesive can be placed in the corresponding position when pouring the concrete. The pouring process of the test piece is shown in Figure 7.

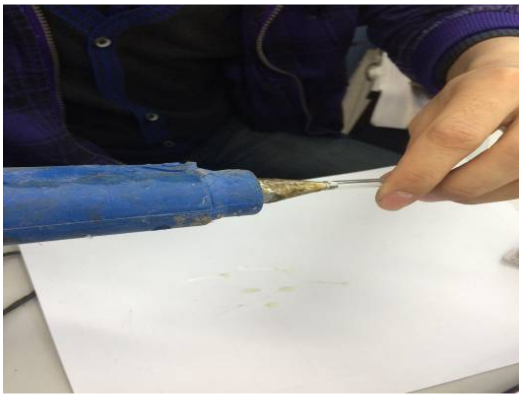


Figure 4. GLUE GUN GT-10 hot melt glue gun.

Figure 5. Hot melt glue closed glass tube.

Figure 6. Adhesive syringe.

Figure 7. Preparation of test piece.

3.2. Test technology route

In order to make the environmental conditions in the crack repair as consistent as possible in the actual environmental conditions, the test was carried out in five separate times, and 12 test pieces were prepared each time, 10 of which were test groups and 2 were control groups. Different degrees of load were applied to the test specimens to cause micro-cracks, and the test specimens were subjected to standard flexural strength tests. That is, when the environmental condition is 30 °C constant temperature oven, a total of 12 test pieces are required, wherein the glass fiber tube is placed in the test piece in a diamond shape, and the inverted test piece is 6 pieces each. Setting the destructive load of specimens placed in the diamond shape and inverted trapezoidal shape to be PA1 and PB1 in the standard flexural test, respectively, and the pre-applied loads of the other 10 specimens are 50 % P_{A1}, 55 % P_{A1}, 60 % P_{A1}, 65 % P_{A1}, 70 % P_{A1} and 50 % P_{B1}, 55 % P_{B1}, 60 % P_{B1}, 65 % P_{B1}, 70 % P_{B1} respectively. The initial cracks of the test pieces under the other four environmental conditions are prefabricated in the same way.

3.3. Analysis of test results

3.3.1. External environmental impact

In order to explore how the repair environment (temperature, humidity) affects the repair rate, the placement of the fiberglass tubes is diamond-shaped, inverted trapezoidal, Under the condition of the initial crack width is 0.4mm, 0.6mm, 1.0mm, 1.5mm, 2.0mm, the test pieces repaired in different repair environments are monitored and analyzed, and the relationship between the repair rate and temperature conditions is shown in Figure 8,9, the temperature unit is °C.

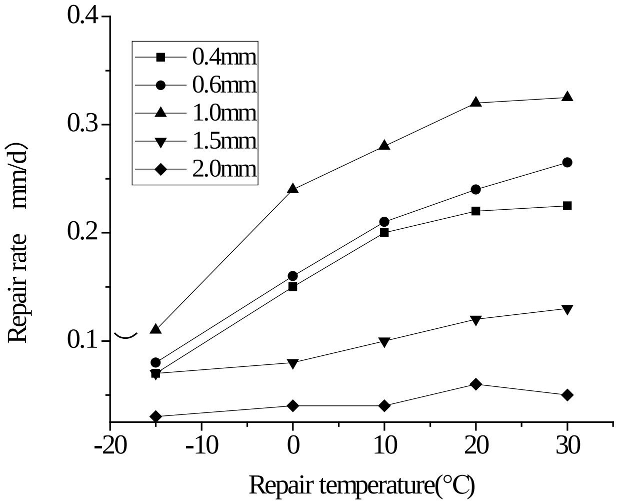


Figure 8. Change of repair rate with temperature when the glass fiber tube is placed in a diamond shape.

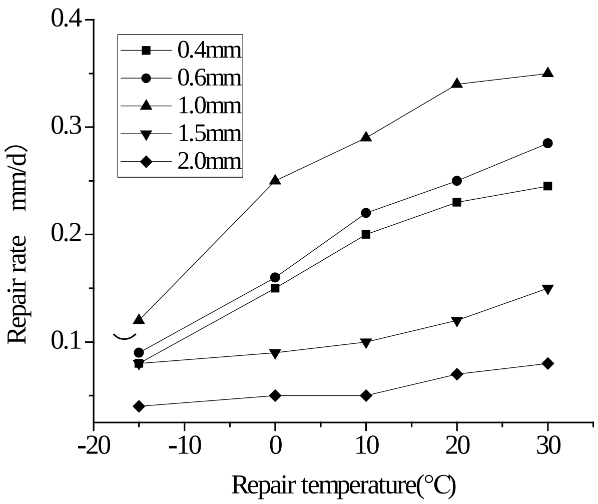


Figure 9. The change of repair rate with temperature when the glass fiber tube is placed in inverted trapezoid.

It can be seen from Figure 8 and 9 that no matter whether the glass fiber tube is placed in a diamond shape or an inverted trapezoidal shape, the repair rate increases with the increase of temperature in a certain temperature range, and the repair rate increases as the temperature increases. The speed gradually decreases. This shows that the change of temperature condition has a great influence on the repair rate. In a certain temperature range, the higher the temperature, the faster the repair rate is.

The above phenomenon occurs because the solidification of the selected adhesive is affected by various factors such as environmental conditions and the shape of the bonding surface etc. With the increase of temperature in the environmental conditions, the selected adhesive filled in the crack can be solidified earlier, and the reinforced concrete is re-established. Forming a solid whole, which in turn allows the crack to be repaired quickly, so the repair rate is higher. The rate of repair rate in each temperature range above 0 °C is significantly less than the growth rate of -15 °C to 0 °C. Due to a certain extent, when the temperature is below 0 °C, the temperature plays a leading role in the improvement of the repair rate. The temperature increases and the repair rate increases rapidly; When the temperature is above 0 °C, temperature is not the dominant factor affecting the repair rate.

3.3.2. Impact of initial crack width

In order to investigate how the initial crack width affects the repair rate, 50, 55, 60, 65 and 70 %, of the failure load of the control specimens are applied respectively under the conditions of the placement of the glass fiber tubes in the shape of diamonds and inverted trapezoids. Andthe corresponding initial crack widths are respectively 0.4, 0.6, 1.0, 1.5, 2.0mm. The relationship between the repair rate and the initial crack width is shown in Figures 10 and 11 after two days of repair under different curing conditions (temperature, humidity).

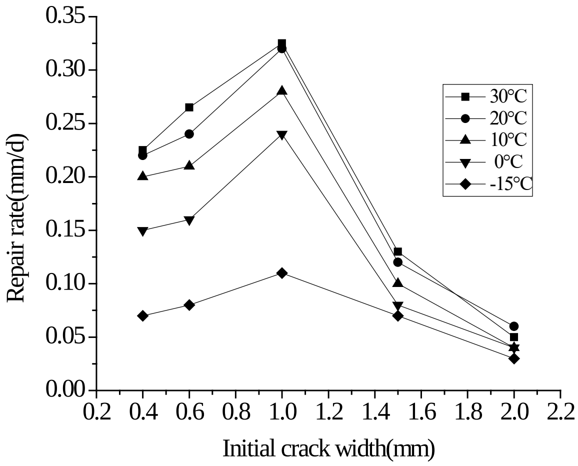


Figure 10. Repair rate as a function of initial crack width (diamond).

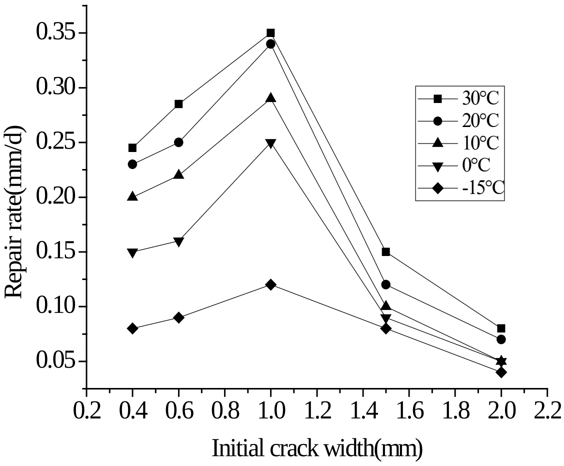


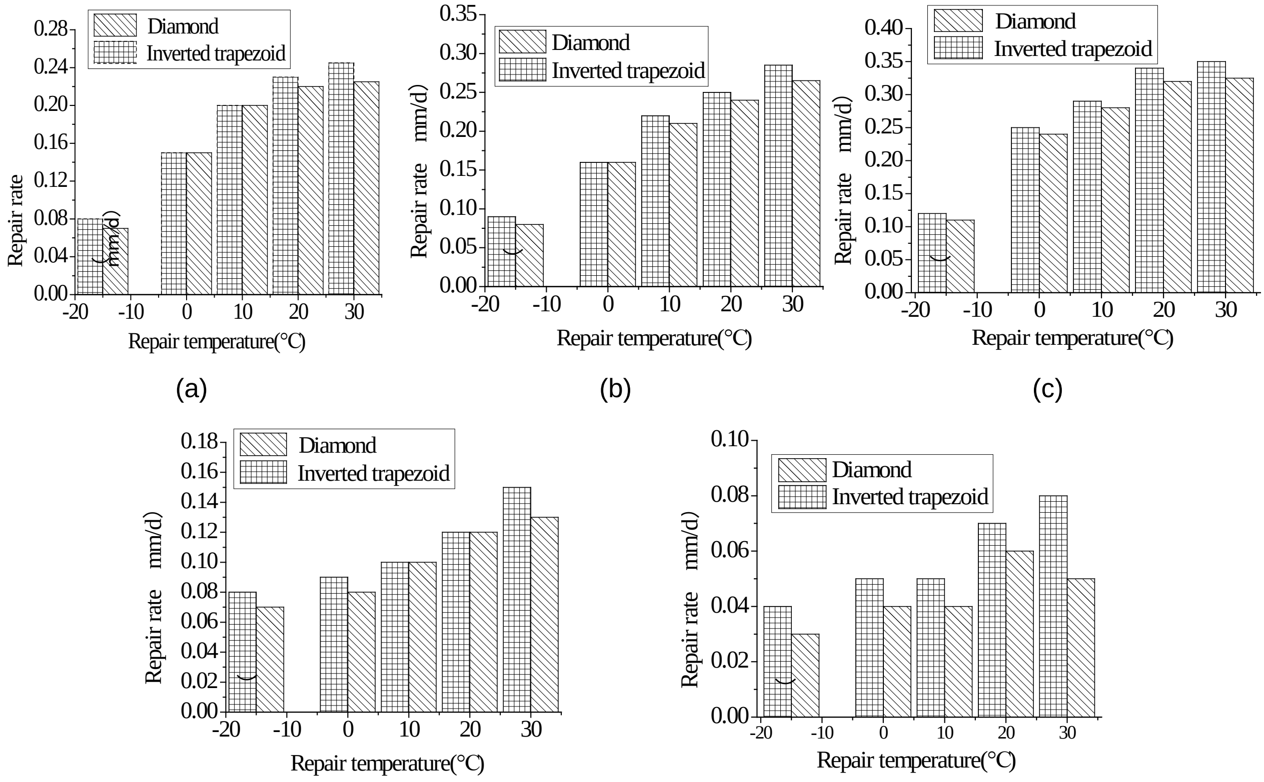
Figure 11. Repair rate as a function of initial crack width (inverted trapezoid).

It can be seen from Figures 10 and 11 that no matter whether the glass fiber tube is placed in a diamond shape or an inverted trapezoid, the repair rate increases first and then decreases with the increase of the initial crack width, and when the initial crack width is about 1.0 mm, the repair rate reached the highest level. Regardless of whether the glass fiber tube is placed in a diamond shape or a trapezoidal shape, the growth rate of the repair rate when the crack width is from 0.4 mm to 0.6 mm is significantly lower than that of the crack width from 0.6 mm to 1.0 mm; and the crack width is from 1.0 mm to the rate of repair rate at 1.5 mm is significantly higher than the rate at which the crack width decreases from 1.5 mm to 2.0 mm.

The occurrence of the above phenomenon is the result of the interaction of the fluidity of the adhesive and the capacity of the adhesive in the carrier. Because the fluidity of the adhesive is affected by the crack size, when the temperature conditions are the same, the fluidity of the adhesive increases with the increase of the crack width, so when the pre-cut crack width is less than 1.0 mm, the volume of the repair adhesive capacity is relatively larger and the fluidity is lower, so it can not flow to the crack better, and the repair rate is lower. As the crack width increases, the fluidity of the adhesive increases, and it can be quickly flowed to the interface of the crack at the crack to repair it. As the crack width is further increased, the adhesive capacity in the repair carrier is received. The limitation of the adhesive is that the viscosity increases and the fluidity increases, and the faster flow to the lower end of the crack, and the upper crack cannot be repaired, so the repair rate is greatly reduced. It can be seen that when the initial crack width is about 1.0 mm, the repair rate of the crack is the highest, and at this time, the capacity of the repair material in the repair carrier and the fluidity of the repair material in the crack are matched.

3.3.3. Influence of glass fiber tube placement

In order to explore how the placement of the glass fiber tube affects the repair rate, under the conditions of the initial crack width and the same curing conditions (temperature, humidity), the glass fiber tube is placed in a variable, placement includes diamonds and inverted trapezoids. The relationship between the repair rate and the initial crack width is shown in Figure 12.



(a) (b) (c) (d) (e)

Figure 12. Change in repair rate as the fiberglass tube is placed:a) Initial crack width is 0.4mm; b) Initial crack width is 0.6mm; c) Initial crack width is 1.0 mm; d) Initial crack width is 1.5 mm; e) Initial crack width is 2.0mm.

It can be seen from Figure12 that when the initial crack width and the temperature condition of the repair are given, the repair rate of the glass fiber tube placed in the inverted trapezoid is slightly better than that of the diamond. When the glass fiber tube is trapezoidal, the glass fiber tube is arranged at the lower part. When the test piece is subjected to an external action, the lower part first generates a crack, and the adhesive which flows out after the lower glass tube is broken can be better. Repair the lower crack, and the position of the glass tube is diamond-shaped, the lower part of the adhesive flows out, the amount of adhesive required for the lower crack can not be guaranteed, and the smaller the crack, the worse the fluidity, part of the adhesive solidifies gradually during the flow and the fluidity is reduced, so the crack cannot be repaired quickly.

According to the comparison with the existing research results, it can be concluded: The change of temperature condition has a great influence on the repair rate. In a certain temperature range, the higher the temperature, the faster the repair rate is. The repair rate increases firstly and then decreases with the increase of the initial crack width, and the repair rate reaches the highest level when the initial crack width is about 1.0 mm. When the initial crack width and the temperature condition of the repair are given, the repair rate of the glass fiber tube is slightly better than that of the diamond when the inverted trapezoid is placed. The initial width of the crack has the greatest influence on the repair rate, followed by the temperature condition and the placement of the fiberglass tube. The corresponding factor levels at the maximum repair rate are 1.0 mm, 30 °C and inverted trapezoids.

4. Conclusion

(1) At –15~30 °C, the repair rate increases with the increase of temperature; at 0~30 °C, the growth rate of repair rate is significantly lower than the growth rate of –15~0 °C. When the temperature is below 0 °C, the temperature plays a leading role in improving the repair rate. When the temperature rises, the repair rate increases rapidly; when the temperature is higher than 0 °C, the temperature is not the main factor affecting the repair rate. The above studies have important reference value for temperature-affected repair rate.

(2) When the crack width is 0.4 mm to 0.6 mm, the repair rate is significantly faster than the crack width of 0.6 mm to 1.0 mm. The repair rate of the crack width from 1.0 mm to 1.5 mm is significantly higher than the crack width of 1.5 mm to 2.0 mm. When the initial crack width is about 1.0 mm, the repair rate reaches the highest level. The study shows that as the initial crack width increases, the repair rate increases first and then decreases, which is important for the effect of the initial crack width on the repair rate.

(3) This study shows us that when the initial crack width and repair temperature is -15~30 °C, the repair rate of the glass fiber tube is slightly better than that of the diamond when the inverted trapezoid is placed. It is very valuable to study the effect of the location of the repair material on the repair effect.

(4) The initial width of the crack in this study had the greatest impact on the repair rate, followed by the temperature conditions and the placement of the fiberglass tube. The corresponding factor level under the maximum repair rate is 1.0mm, 30 °C and inverted trapezoid, which is of great significance for the study of the repair effect under the same conditions.

References

1. Shen, A.-Q., Zhu, J.-H., Wang, X.-F., Zhong, J.-C., Fu, Q. Performance and mechanism of polymer modified superfine cement for microcrack mending of concrete structure. China Journal of Highway and Transport. 2006.19(4). Pp. 46–51+58.
2. Wen, W.Key techniques study on cement pavement maintained. Dissertation. South China University of Technology,2009.
3. Shen,A.-Q.Study on the crack mending materials of cement concrete pavement.Dissertation. Chang'an University. 2005.
4. Yang, Q. The technology research on repairing cracks of prestressed concrete pavement. Dissertation. Changsha University of Science&Technology, 2013.
5. Liu, X., Yao, W., Zheng, X. et al. Experimental study on self-healing performance of concrete. Journal of Building Materials. 2005.No. 2. Pp.184–188.
6. Wang,G.. Studies on chemical change type self-healing material for cracks and its influence on durability of concrete. Dissertation.WuHan University of Technology, 2005.
7. Sahmaran, M., Li, M.V.C.Durability of mechanically loaded engineered cementitious composites under highly alkaline environments.Cement and Concrete Composites.2008. 30(2). Pp.72–81.
8. Jiao, J., Hongyu, X.U., Han, W.U. Construction theory and key technology of ultra-thick bottom plate of XindaInternation Finance Centre. Construction Technology, 2017.
9. Pelletier, M., Bose, A. Self-mending composites incorporating encapsulated mending agents.ACI.2011.16(3). P.456.
10. Zanotti, C., Borges, P.H.R., Bhutta, A., et al. Bond strength between concrete substrate and metakaolingeopolymer repair mortar: Effect of curing regime and PVA fiber reinforcement. Cement & Concrete Composites. 2017.No. 80. Pp.307–317.
11. Wei, S.S. Application of shallow grouting technology in maintenance and repair of cement concrete pavement of expressway[J]. Construction & Design for Engineering, 2017.
12. Wang, Y, Sun, D, Han, Q. Detection and treatment of corrosion in the side plate and bottom plate of converter gasholder. Metallurgical Power, 2018.
13. Skominas, R., Gurskis, V., Sadzevicius, R. et al. Evaluation of cement mortar suitability for repairing concrete in hydraulic structures. Ksce Journal of Civil Engineering. 2017.No. 6. Pp.1–7.
14. Cheng, P., Wei,Y.. Study on the performance of adhesive in the Self-healing concrete. Science Technology and Engineering. 2017. 17(17). Pp.292–296.
15. Ashofteh, Y.K., Bolhari, B., Sabetmoghaddam, T., et al. Effect of blood exposure on push-out bond strength of four calcium silicate based cements. Iranian Endodontic Journal. 2017. 12(2). Pp.196–200.
16. Jin, M., Feng, X., Feng, L., et al. Superhydrophobicaligned polystyrene nanotube films with high adhesive force. Advanced Materials. 2010. 17(16). Pp.1977–1981.
17. Drass, M., Schwind, G., Schneider, J. et al. Adhesive connections in glass structures—part I: experiments and analytics on thin structural silicone. Glass Structures & Engineering. 2018. 3(1). Pp.39–54.
18. Shen, C.The Research of Self-healing Concrete with PUA Fibers.Dissertation. Chong Qing Jiao Tong University, 2011.
19. Li, J.S., Guo, M.Z., Xue, Q. et al. Recycling of incinerated sewage sludge ash and cathode ray tube funnel glass in cement mortars. Journal of Cleaner Production. 2017. 152. Pp.142–149.
20. Kuang, Y., Ou, J. Experiments and Analyses of the Self-healing of Cracks in Reinforced Concrete Beams with Embedded Fibers Filled with Adhesive[刀.China Civil Engineering Journal. 2005. No. 4. Pp.53–59.
21. Karihaloo, B.L, Keer L.M., Nemat-Nasser, S. Crack kinking under nonsymmetric loading. Engineering Fracture Mechanics. 2016. Vol. 13(4). Pp. 879–888.

Contacts:

Qianqian Zhao, 045188028393; 492954791@qq.com
Peifeng Cheng(Corresponding Author), 13946139402; chengpeifeng@126.com*
Yuwei Wei, 13783869126; weiyuwei1991@qq.com
Jianwu Wang, 13603625185; nihaone@163.com