BONDING BEHAVIOUR AND FAILURE MECHANISM OF DAMAGED CEMENT CONCRETE REPAIRED USING EPOXY-BASED CONCRETE

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In this paper, the strength grade and surface roughness of damaged concrete are used as controlling factors to explore their influence on the bonding behaviour of concrete repaired using epoxy-based concrete. Using X-ray photoelectron spectroscopy (XPS) analyses and phenomenological methods, the essence of the bonding force and the mechanism for bonding failure between the epoxy-based concrete and damaged concrete are revealed. As shown by the results, the bonding strength of the repaired concrete increases with an increase in the average sand-filling depth and the strength grade of the damaged concrete. However, when the sand-filling depth exceeds 17 mm, the bonding strength no longer increases. The chemical bonding force between the epoxy-based concrete and damaged concrete essentially comes from coordination bonds formed at the bonding surface. Based on the experimental phenomena and test results, a bonding strength model is established for the repaired concrete, and it provides a basis for predicting the interface bond strength in practical repair engineering.

INTRODUCTION

Epoxy-based concrete is a kind of polymer concrete, using epoxy resin as the cementitious system and coarse and fine aggregates as fillers, which has the advantages of high early strength, low shrinkage deformation, strong adhesion, excellent water resistance, a large ultimate deformation capacity and rapid solidification. Therefore, epoxy-based concrete is suitable for the rapid repair of structures, which has broad application prospects for improving the structural bearing capacity and structural durability [1-3].

Most studies have been devoted to improving the mechanical properties of epoxy-based concrete [4, 5]. The research results of Jiaqing Wang [6] and Shu Xingwang [7] show that the addition of rubber can improve the mechanical properties and durability of epoxy-based concrete. The research results of Zuo Lian [8] show that a reasonable ratio of cementitious material to sand is from 15 ~ 30 %. Within the range of reasonable ratios, the greater the ratio and the amount of curing agent are, the higher the compressive strength of the epoxy-based concrete is. The above modification methods can improve the mechanical properties of epoxy-based rapid repair concrete to a certain extent, but research regarding the essence of the bonding force has not been systematic to date.

There are two main sources of bonding between epoxy-based concrete and cement concrete that can be used for repairs (damaged concrete). The first one is the mechanical occlusal force formed at the intersection of a bulge, hole or crack on the surface of the repaired concrete and epoxy-based concrete. The second one is the chemical adhesion force produced by the epoxy cementitious system. For the mechanical occlusal force, the mechanical properties of the repaired component can be improved by increasing the roughness of the bonding surface, but the determination of the roughness parameter is still unclear, and for the chemical adhesion force, the essence of its source is also unclear. In addition, there are few models for the adhesion between epoxy-based concrete and damaged concrete [5, 9]. Therefore, this paper explores the influence of the strength and roughness of damaged concrete on the bonding performance of concrete repaired using epoxy-based concrete, reveals the mechanism of the mechanical occlusal force and chemical adhesion force, and establishes a bonding strength model of the repaired components through experiments.

EXPERIMENTAL

Materials

A mix proportion design method for stone mastic asphalt (SMA) was adopted for the preparation of the epoxy-based concrete. The fine and coarse aggregates used were basalt with particle sizes of 1-3, 3-5, 5-10 and 10-15 mm. The mineral powder used was limestone powder, the proportion of particles less than 0.075 mm was 85.3 %, and the proportion of particles less than 0.15 mm was 95 %. The binder used was Type NPEL128(E51) epoxy composed of two a/b components, which was produced by Ningbo Tianyi Steel Deck Pavement Technology Co., Ltd. According to the grading range SMA-13 in the Chinese standard JTG F 40-2004 "Technical specifications for construction of highway asphalt pavements", the median value of the grading range was selected as the reference grade for the trial mixing, the amount of aggregate in each grade was calculated, and finally the grading curve described herein was determined. The mix proportions and compressive strength of the epoxy-based concrete are shown in Table 1.

The designed compressive strength grade of the cement concrete specimens for the rapid repair was 30 MPa (C30), 40 MPa (C40) and 50 MPa (C50). The mixing proportions of the cement concrete are shown in Table 2, and the chemical composition of cement is shown in Table 3. In total, twelve cement concrete specimens for rapid repair were prepared, including six C30 specimens, three C40 specimens and three C50 specimens. The size of each specimen was 150 × 150 × 150 mm. After 28 days of standard curing, the damaged concrete was prepared by splitting the cement concrete specimens in half.

Preparation of specimens and the testing method

To explore the influence of the different roughness of the repaired surface on the bonding performance of the epoxy-based concrete, twelve damaged concrete specimens were prepared by splitting six C30 concrete specimens. The splitting test was carried out according to the Chinese Standard GB/T50081-2019 "Standard for test methods of concrete physical and mechanical properties", and the splitting tensile strength of the specimen was obtained. Four different roughness levels were constructed by controlling the water pressure and action time of the high-pressure water gun, as shown in Figure 1. The construction mode of the roughness is shown in Table 4.

There were three specimens for each roughness, and the sand-filling method was used to evaluate the roughness. The specific operation steps are as follows: Surround the four sides of the damaged concrete specimen with four plastic plates. Adjust the height of the four plastic plates so that the top of the plastic plate is consistent with the highest point of the four

a) Split specimen (b) High-pressure water gun roughening
Figure 1. Construction of the rough surface.

Table 4. Construction mode of the roughness.

Roughness (mm)	Hydraulic pressure (MPa)	Action time (min)
11	5	30 - 60
14	10	30 - 60
17	20	30 - 60
21	25	30 - 60

Table 3. Chemical composition of the cement.

SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	Loss
21.5	6.0	57.3	3.6	2.7	3.2	2.6

Table 2. Mixing proportions for the cement concrete (kg·m^{-3}).

Strength grade	Cement	Fly ash	Slag	Sand	Gravel	Water	Superplasticiser
C30	217	78	61	739	1063	178	3.92
C40	279	62	70	702	1098	164	5.74
C50	353	50	94	616	1096	164	6.96

Table 1. Mix proportion and compressive strength of the epoxy-based concrete

Mix proportion						Compressive strength (MPa)	
Aggregate				Mineral powder	Epoxy		
0~3 mm	3~5 mm	5~10 mm	10~15 mm			1 d	28 d
1.56	1.41	2.26	1.88	0.702	0.624	45.2	92.4

sides of the bonding surface. Then, fill standard sand to the top of the plastic plate, and measure the volume of the filled standard sand with a measuring cylinder. The average sand-filling depth was calculated, as shown in Equation 1:

$$h = \frac{V_0}{S_0} \tag{1}$$

where h is the average sand-filling depth (mm), V_0 is the volume of the standard sand (mm^3), and S_0 is the cross-sectional area of the specimen (mm^2).

To explore the influence of the different strengths of the damaged concrete on the bonding performance of the epoxy-based concrete, specimens C40 and C50 were split into specimens to be repaired (damaged concrete specimens), and the same roughness was formed by a high-pressure water gun. The split tensile strength of all the cement concrete specimens is shown in Table 5.

Table 5. Split tensile strength of the cement concrete specimens.

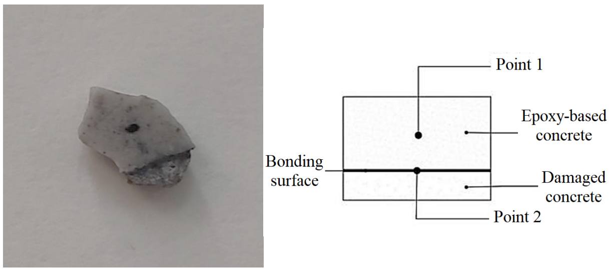
Original cement concrete specimen	Split tensile strength (MPa)
C30	3.5
C40	4.6
C50	5.5

The prepared damaged concrete specimen was put into a 150 × 150 × 150 mm steel mould and injected with the epoxy-based concrete. After vibrating and compacting, the specimen was placed into a standard curing room for 18 hours and then demoulded. After 1 day, the split tensile strength (bonding strength) was measured, as shown in Figure 2.

a) Preparation of the repaired specimens　b) Testing the split tensile strength

Figure 2. Preparation and testing of the repaired specimens.

X-ray photoelectron spectroscopy (XPS) can determine the elemental composition on the surface of the specimen and the chemical state of the element; this technique has the characteristics of high sensitivity and causing little damage to the bonding surface of the specimen. To explore the essence of the chemical adhesion force between the epoxy-based concrete and the damaged concrete, an XPS analysis was carried out on the bonding surface and epoxy-based concrete. The test elements were C and O, as shown in Figure 3.



a) Testing sample for the XPS　b) Layout of the measuring points

Figure 3. XPS testing.

RESULTS

Effect of the different surface roughness values and strengths of the damaged concrete on the bonding strength of the repaired concrete

Under the condition that the strength of the damaged concrete remained the same, a total of four different roughness values for the bonding surface were constructed, and the average sand-filling depths were 11, 14, 17, and 21 mm. The split tensile strength was used as the key index (bonding strength) to evaluate the bonding performance of the epoxy-based concrete. Figure 4 shows the effect of the average sand-filling depth on the bonding strength of the repaired concrete. When the sand-filling depth reaches 14 mm, the bonding strength of the repaired concrete specimen reaches more than 80 % of that of the original cement concrete. When the sand-filling depth is less than 17 mm, there is a positive correlation between the bonding strength and the sand-filling depth. When the sand-filling depth exceeds 17 mm, the bonding strength will no longer increase, and the bonding strength of the repaired concrete specimen

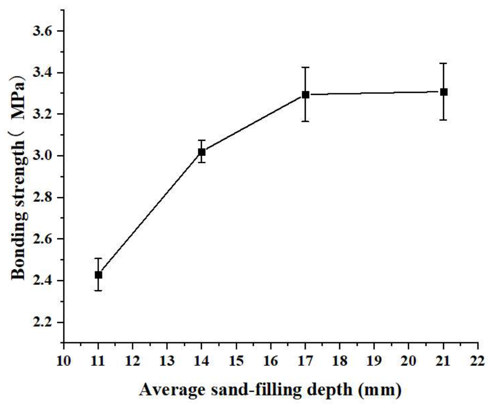


Figure 4. Effect of the average sand-filling depth on the bonding strength.

can reach more than 90 % of that of the original cement concrete. According to the Chinese specification "Code for construction and quality acceptance of roadworks in city and town" (CJJ 1-2008), cement concrete pavement can be opened to traffic when the strength reaches more than 70 % of the design strength. Therefore, in an actual repair project, the sand-filling depth of the repair surface of the damaged concrete is controlled at 14 mm, which can meet the repair requirements.

Under the condition of keeping the sand-filling depth of the damaged concrete at 17 mm, epoxy-based concrete was used to repair the C30, C40 and C50 damaged concrete specimens. Figure 5 shows the effect of the strength grade of the damaged concrete on the bonding strength of the repaired concrete. With an increase in the strength of the damaged concrete specimen, the bonding strength of the repaired concrete also increases, and the relationship between them is approximately linear. In this case, the bonding strength of the repaired concrete can reach more than 90 % of the original concrete. The failure surface of the repaired concrete specimen occurred on the side of the damaged concrete, so the strength of the original cement concrete determines the bonding strength of the repaired concrete, which is consistent with the measured results.

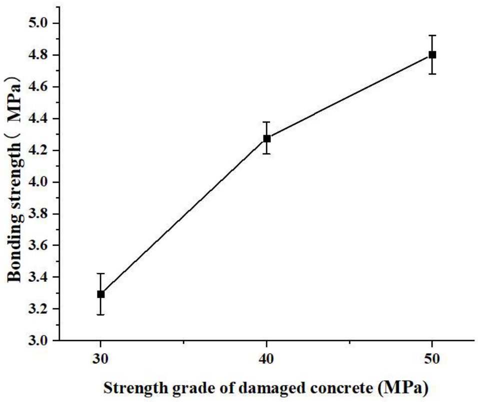


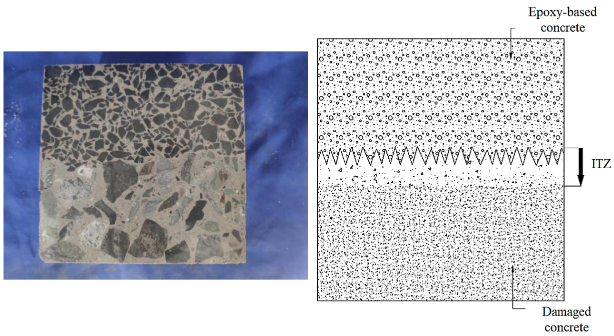
Figure 5. Effect of the strength grade of the original cement concrete on the bonding strength

Bonding mechanism analysis

Mechanical occlusal force

Figure 6 shows the failure mode of the repaired concrete specimens with the different sand-filling depths. In the case of the splitting tensile failure of the repaired concrete specimen, bonding failure occurs on the side of the damaged concrete close to the bonding surface, and within a certain range, the distance between the failure surface and the bonding surface increases with the increasing surface roughness.

Based on the above test phenomena and results, the bonding structure model between the epoxy-based concrete and damaged concrete can be established, as shown in Figure 7. There are two reasons for the formation of the interface transition zone (ITZ) in the bonding structure model. First, when the original cement concrete specimen is subjected to a splitting tensile test, the test fixture will disturb the failure surface, resulting in a certain number of microcracks in the specimen. Second, when chiselling the repair surface with a high-pressure water gun, although the loose cement paste and aggregates on the damaged surface will be removed, the number of microcracks will be increased to a certain extent. The mechanical properties of the ITZ increase gradually from top to bottom along the bonding surface until they reach the same level as the mechanical properties of the damaged concrete. When epoxy-based concrete is combined with the ITZ of the bonding



a) Cross section of the repaired concrete specimen
b) Schematic illustration of the bonding structure model

Figure 7. Bonding structure model between the epoxy-based concrete and the damaged concrete

a) Sand-filling depth of 11 mm
b) Sand-filling depth of 14 mm
c) Sand-filling depth of 17 mm

Figure 6. Failure mode of the repaired concrete.

surface, the good mechanical properties of epoxy-based concrete have a certain enhancement effect on the mechanical properties of the ITZ, making the splitting tensile strength of the repaired concrete reach more than 90 % of the original concrete. Moreover, within a certain range, this enhancement effect increases gradually with the increasing bonding surface roughness.

When the surface roughness is not more than 17 mm, the repaired surface area will increase with the increasing roughness, which increases the mechanical occlusal force between the epoxy-based concrete and the damaged concrete, thus improving the mechanical properties of the repaired concrete. If the roughness continues to increase, then the bond strength of the repaired concrete will not increase. The reason is that, while using an external force to increase the roughness of the repaired surface, although it will increase the mechanical occlusal force between the epoxy-based concrete and the damaged concrete, it will also further increase the weak area in the ITZ. This results in an enhancement effect of the interface bond strength that is less than the weakening effect, which reduces the mechanical properties of the repaired concrete. Therefore, in the actual repair engineering, it is particularly important to select the appropriate roughness.

Chemical adhesion force

There are three classical bonding theories [10-12]. The adsorption theory postulates that when the distance between the molecules of two substances is sufficiently small (0.5 nm), the polar groups are close to each other through the movement of molecular chains, and the molecules will bond to each other, resulting in adhesion. The chemical bond theory refers to the chemical reaction between two substances when they are combined; a new substance is formed on the bonding surface, and the strength of the new substance determines the bonding strength. Coordination bond theory refers to the formation of a shared electron pair between the binder molecule and the substance to be bonded due to the strong polarity, resulting in a coordination bond.

The cured epoxy resin molecule has three polar groups, namely, hydroxyl, an ether bond and epoxy groups. Therefore, it is preliminarily assumed that a coordination bond is formed between the epoxy-based concrete and the damaged concrete, resulting in a chemical binding force. To verify the above assumptions, the repaired concrete specimen was tested by XPS, and the results are shown in Figure 8. The abscissa in the figure represents the orbital electron binding energy. The electron binding energy on each orbital of atoms of different elements is different. Therefore, a combined state of the element can be found through the electronic energy spectrum comparison table; the ordinate represents the number of electrons received per unit time. The greater its value is, the higher the content of the combined state of the element is. Similarly, in Figure 6b, the spectral line of O 1 s on the epoxy-based concrete has only one peak, and the electron binding energy is 532 eV. At this time, the combination state of O element is C-O-C, so it is inferred that the group of O element is the epoxy group. On the bonding surface, however, there are two peaks in the O 1s spectrum, corresponding to the electron binding energies of 532 eV and 532.5 eV. A comparison of the electron energy spectra shows that the electron binding energy is 532.5 eV, the state of the corresponding element is not found, and the value is close to 532 eV. The epoxy group in the epoxy resin molecule forms a coordination bond with the Ca or Si elements on the bonding surface.

Establishment of the bonding strength model of the repaired concrete

In the Materials and Methods sections, the effects of the different roughness, strength grades of the damaged concrete and bonding surface treatment methods on the

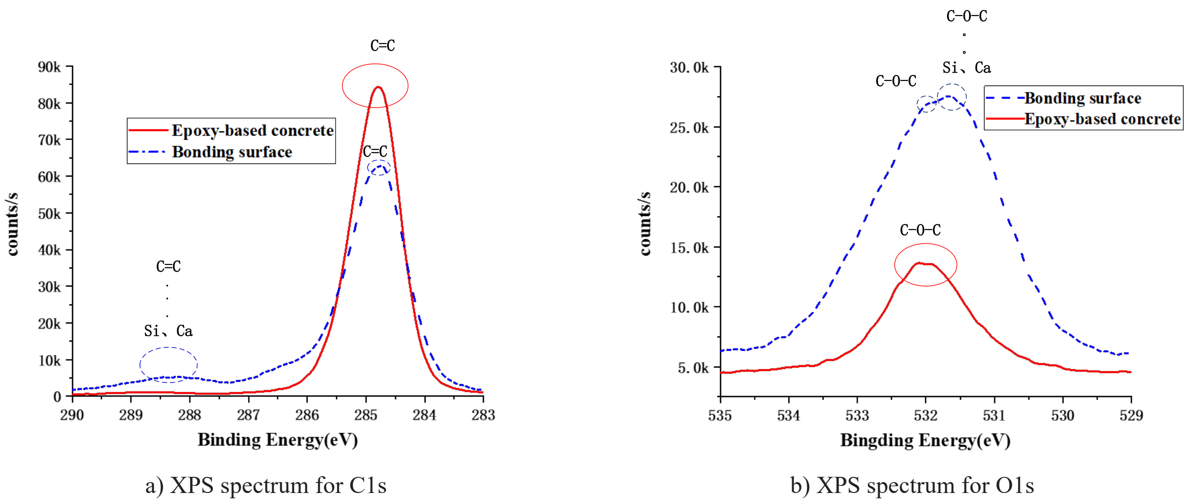
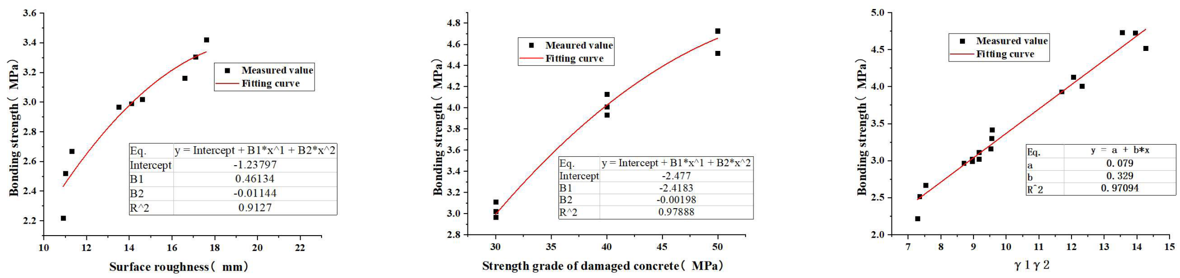


Figure 8. XPS spectrum.



a) Bonding strength formula considering the different roughness

b) Bonding strength formula considering the different strength grades

c) Bonding strength formula considering the different roughness and strength grades

Figure 9. Bonding strength model of the repaired concrete.

bonding performance of the epoxy-based concrete are explored. Based on the above test data, the test results were fitted and analysed, as shown in Figure 9.

Taking the roughness of the bonding surface and the strength grade of the damaged concrete as variables, the influence of the different factors on the bonding strength of the repaired concrete was fitted, and Equation 2 and Equation 3 are obtained, respectively.

$$\gamma_1 = -0.1144\, h^2 + 0.46134\, h - 1.23797 \quad (2)$$

$$\gamma_2 = -0.00198\, f_c^2 + 0.24183\, f_c - 2.477 \quad (3)$$

where h is the average sand-filling depth, f_c is the strength grade of the damaged concrete, and γ_1 and γ_2 are influencing factors of the different variables.

Let $$\sigma = \beta \times \gamma_1 \times \gamma_2 \quad (4)$$

Then

$$\sigma = 0.329 \times (-0.01144\, h^2 + 0.4613\, h - 1.2379) \times \times (-0.0019\, f_c^2 + 0.2418\, f_c - 2.477) \quad (5)$$

where σ is the bonding strength of the repaired concrete and β is the fitting coefficient.

To verify the accuracy of Equation 5, two groups of repaired concrete specimens with different bonding surface roughness and strength grades were prepared, and the verification results are shown in Table 6. The maximum error of the established bonding strength model is 10.2 %, and the minimum error is 1.38 %, which shows that the model is highly accurate.

CONCLUSIONS

(1) When the average sand-filling depth of the repaired surface is less than 17 mm, the bonding strength of the repaired concrete increases with the increasing sand-filling depth. With the increasing strength grade of the damaged concrete, the bonding strength of the repaired concrete also increases, and the mechanism of mechanical occlusal force is explained.

(2) The chemical bonding mechanism between the epoxy-based concrete and the damaged concrete was analysed. The XPS results showed that a coordination bond is formed between the epoxy-based concrete and the damaged concrete.

(3) Based on the experimental phenomena and results, the bonding strength model of the repaired concrete was established. The predicted results were consistent with the experimental results.

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Table 6. Verification of the bonding strength model.

ID	Strength grade of damaged concrete	Roughness of the bonding surface	Observed bonding strength	Calculated bonding strength	Relative error
	(MPa)	(mm)	(MPa)	(MPa)	(%)
1	40	10.9	3.369	3.223	4.53
2	40	11.6	3.089	3.412	9.47
3	40	12.3	3.219	3.586	10.2
4	50	19.2	5.067	5.222	2.97
5	50	18.7	4.949	5.201	1.38
6	50	20.6	4.896	5.235	6.48

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