Research Article

Bond Behavior between Concrete and Self-Expansion Polymer Material under Normal Pressures

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Self-expansion polymer grouting technology is a new rapid trenchless method for repairing leakage and subsidence of underground concrete structures. The bond between polymer and concrete is critical to determine the ultimate conditions of repaired concrete. In this paper, a series of direct shear tests were performed to investigate the influence of normal pressure on the shear bond properties between self-expansion polymer and concrete with different polymer density and concrete strength. Results indicate that failure modes and bond strength are greatly influenced by the normal pressure for specimens with a lower polymer density. For a given normal pressure, the bond strength linearly increases with the increasing polymer density. As the polymer density increased up to 0.43 g/cm^3 , the increased ratio decreases with the polymer density. Moreover, the displacement at the peak point reduces with an increase in polymer density. Finally, a finite element model is proposed to evaluate the bond strength for specimen failure in concrete and verified with the test results.

1. Introduction

A polyurethane polymer material with the characteristics of self-expansion [1], lightweight [2], early strength [3], high tensile strength [4], and excellent water resistance [5] has been successfully and effectively used to repair underground structures such as tunnels, road foundations, dams, and concrete pipelines [6, 7]. As shown in Figure 1, for a buried concrete drainage pipeline, when the polymer is injected into the outside wall of the pipe by grouting apparatus, the volume of polymer expands quickly and fills the voids and cracks between the pipe wall and soil. Then, the pipelines are lifted by the hardened polymer in 15 minutes [8]. Finally, the leakage, subsidence, and disengagement of the buried defective concrete pipelines have been restored. Based on the full-scale field tests and numerical analysis, Fang et al. [2] and Wang et al. [5] found that the self-expansion polymer grouting can improve the stress distribution and

deformation of bottom hollow defective pipelines effectively. However, under the influence of vertical traffic loading or seismic loading, the pipeline-polymer interface may be subject to shear stress. Therefore, it is critical to study the shear bond performance of the self-expansion polymer and concrete for accurately evaluating the response of polymer reinforced underground concrete structures under external loading [9].

Existing studies found that the bond performance between concrete and polymer adhesive material such as epoxy is influenced by many factors [10–12]. Ivano and Andrea [13] observed that the bond quality between epoxy and concrete is greatly improved with larger interfacial roughness, and sandblasting is an effective way to increase the surface roughness of concrete. For a given surface roughness of the concrete substrate, Zhang et al. [14] pointed out that the bond resistance is increased by incrementing the strength of materials between the interfaces. Ouyang and

FIGURE 1: Polymer grouting technology.

Wan [15] and Zhou et al. [16] revealed that the bond capacity is greatly decreased and the failure model shifts from concrete to the epoxy-concrete interface as the interface is subject to moisture invasion. Yuan et al. [9, 17] discovered that the shear bond strength decreased with a larger size of the coarse aggregate. As to the self-expansion polyurethane polymer material, the chemical reaction involves a substantial increase in volume and exerts huge compressive stress on the concrete interface. Shi [8] found that the expansion pressure and polymer strength are extremely improved with a higher polymer density. For polymer with designed densities of 0.29, 0.35, 0.48, 0.53, 0.67, 0.79, and 0.84 g/cm^3 , the corresponding maximum expansion pressure is 0.36, 1.22, 1.97, 2.72, 3.10, 4.38, and 4.83 MPa, respectively. Therefore, during the self-expanding diffusion process of polymer, a higher grouting volume results in a larger expansion force at the polymer-concrete interface. Moreover, the soil cover depth and traffic load above the pipelines also exert different compressive stress around the bond region. The existence of normal stress around the bond region exerts a great influence on the shear bond strength [18, 19]. Therefore, to accurately evaluate the overall performance of polymer-repaired pipelines, the effect of normal stress on the shear bond performance between the self-expansion polymer and concrete should be considered. However, researches about this topic are limited.

This paper aims to present an experimental investigation to quantify the normal pressure on the shear bond behavior between self-expansion polymer and concrete. The effects of polymer density, the magnitude of normal pressure, and the strength of concrete on the failure mode, bond parameters, and shear bond stress-slip curves are analyzed. Then, a shear bond strength model for specimen failure in concrete is proposed.

2. Experimental Program

2.1. Specimens. Concrete with dimensions of $100 \times 100 \times 50 \text{ mm}$ was adopted as the substrate for the direct shear tests. The concrete substrates were cured for 28 days in the standard curing room at a constant temperature and relative humidity of 20°C and 90%. All concrete was cast in one batch, and the surface roughness of different strength of concrete was measured by the sand filling method with five specimens. The average surface roughness of different strength of concrete is shown in Table 1. When the concrete substrate was horizontally placed in a special steel model with inner dimensions of $100 \times 100 \times 100 \text{ mm}$, a

bicomponent liquid polyurethane polymer material with a temperature of 95°C was pumped into the steel model by grouting system. The polymer was then expanding and hardening rapidly in the model and squeezed the air out of the model through the air vent. About 60 minutes later, all specimens were demolded. As depicted in Figure 2, composite cubic specimens with half concrete and half polymer were formed. Thus, the bond section area A was 0.01 m^2 . After that, all the specimens were stored in the laboratory until testing.

2.2. Materials. Concrete with three designed compressive strengths was used to fabricate the composite specimens during the test. Coarse aggregate with a maximum size of 20 mm, P.O 42.5 ordinary Portland cement, medium sand, and tap water were selected as the concrete mixture. The mixture proportions and mechanical properties of concrete are listed in Table 1. Polyurethane polymer materials with six different densities of 0.23, 0.36, 0.43, 0.54, 0.69, and 0.92 g/cm^3 were designed. The density of the polymer was determined by the amount of polymer grouted in a steel mold. The average compressive strengths and elastic modulus of each density of polymer are listed in Table 2.

2.3. Testing Apparatus and Procedure. Polymer-concrete interfacial bond tests were performed on a retrofitted direct shear test apparatus. As illustrated in Figure 3, two steel boxes with internal dimensions of $100 \times 100 \times 50 \text{ mm}$ were fastened on the horizontal pistons to apply horizontal shear stress, and a load cell with an accuracy of 0.01 kN was connected between the horizontal piston and left part of the lower shear box to measure the shear load P . Besides, two linear voltage displacement transducers (LVDTs) were attached on the bottom shear box to monitor the horizontal displacement between polymer and concrete. Thus, the average slip s between polymer and concrete can be calculated as $s = (s_1 + s_2)/2$, where s_1 and s_2 are the measured slip value of the two LVDTs. Steel support was fixed between the bottom part of the lower shear box and the guide plate to bear the vertical force of the device, and a row of rollers was placed between the guide plate and the base of the test machine to reduce the friction between them. During the test, the concrete part of the specimen was first placed in the lower shear box.

After the required normal pressures were applied to the polymer by the vertical piston, the shear force was applied at a rate of 0.01 mm/s . Specimens were classified into three

TABLE 1: Mix proportions and mechanical properties of concrete.

Type	C20	C30	C45
Compressive strength f_c (MPa)	38.24	43.06	57.32
Cement : water : sand : coarse aggregate	1 : 0.64 : 2.18 : 4.05	1 : 0.60 : 1.91 : 3.54	1 : 0.43 : 1.28 : 2.38
Elastic modulus E_c (GPa)	32.9	33.7	36.1
Poisson's ratio ν_c	0.22	0.22	0.23
Surface roughness (mm)	0.187	0.168	0.147

FIGURE 2: Schematic of specimen.

groups to examine the effect of the polymer density, normal pressure, and concrete strength on bond behavior. In group I, specimens with designed polymer densities of 0.23, 0.36, 0.43, 0.54, 0.69, and 0.92 g/cm³ (P23, P36, P43, P54, P69, and P92) were prepared to examine the influence of the polymer density. In group II, specimens with normal pressures of 0, 0.1, 0.3, 0.5, 1.0, and 2.0 MPa were tested to study the normal pressure effect. In group III, specimens with designed compressive strength of 25, 30, and 45 MPa (C25, C30, C45) were tested to evaluate the effect of the strength of concrete. Therefore, C30P23 represents a specimen with designed concrete compressive strength of 30 MPa and a polymer density of 0.23 g/cm³. The combinations of normal pressures, polymer density, and concrete strength are shown in Table 2.

3. Testing Results and Discussions

3.1. Failure Modes. For FRP strengthened structures, the bonding system is comprised of three types of materials (concrete, epoxy, and FRP) and two interfaces [20–22]. During the test, FRP and epoxy failures can be observed for specimens with poor FRP quality or poor surface preparation, whereas failure in concrete is the dominant failure models for specimens with good bond quality [23].

Figure 4 shows the failure modes between self-expansion polyurethane polymer and concrete with different polymer density and normal pressure. Under no normal stress, the failure mainly occurs in the polymer-concrete interface (Model A) for specimens with low polymer density. As shown in Figure 4(a), it can be observed that most of the polymers that penetrated into the voids of the concrete soundly adhere to the polymer part of the specimen and a

thin layer of cement paste has been sheared off. When the density of polymer increases up to 0.43 g/cm³, the interfacial shear cracks propagate in the concrete substrate (Model B) rather than along the interface, and more concrete will be adhered off with the increasing of polymer density. Moreover, a certain amount of aggregates can be observed in the concrete matrix. This indicates that the roughness of the failure surface is increased with the increasing of polymer density, which results in a larger friction resistance between polymer and concrete.

When normal pressure is applied, as presented in Figure 4(b), for specimens with a polymer density of 0.23 g/cm³, the failure model is changed into a new pattern, in which the debonding primarily occurs in the polymer and a thin polymer layer above the interface is sheared off (Model C). Besides, with the increment of normal pressure, more polyurethane polymer material will be sheared off. As illustrated in Figure 4(c), for specimens with a polymer density of 0.36 g/cm³, the failure model is not changed with the increase of normal pressure, and the failure surface roughness is reduced with a higher normal pressure. When polymer density increased up to 0.43 g/cm³, the failure mode is less influenced by normal pressure, and the dominant failure is Model B.

3.2. Ultimate Bond Strength. Figure 5 shows the relationship between polymer density and shear bond resistance of specimens under different normal pressure. It can be found from Figures 5(a) and 5(b) that, for a given normal pressure, the ultimate bond strength τ_u almost linearly increases with the increasing of polymer density. As the polymer density increased up to 0.43 g/cm³, the increased ratio decreased with the increase of polymer density. Thus, the relationship

TABLE 2: Test parameters.

Specimen	P (MPa)	ρ_p (g/cm ³)	f_p (MPa)	E_p (MPa)	τ (MPa)	s_0 (mm)
C30P23	0.0	0.23	2.43	77.13	0.316	2.940
					0.487	3.869
					0.552	3.465
C30P36	0.0	0.36	5.02	194.94	0.858	2.317
					0.751	1.780
					0.663	1.650
C30P43	0.0	0.43	7.80	242.72	0.974	1.228
					1.032	1.560
					1.146	1.666
C30P54	0.0	0.54	10.64	350.14	0.937	1.103
					1.011	1.213
					1.166	1.368
C30P69	0.0	0.69	27.19	422.46	1.426	2.286
					1.365	1.052
					1.297	0.952
C30P92	0.0	0.92	41.06	539.61	1.675	1.001
					1.672	1.080
					1.435	1.128
C30P23	0.1	0.23	2.43	77.13	0.491	3.419
					0.425	2.754
					0.522	3.222
C30P36	0.1	0.36	5.02	194.94	0.866	1.761
					0.903	1.560
					0.998	3.004
C30P43	0.1	0.43	7.80	242.72	1.418	1.505
					1.271	1.422
					0.826	1.629
C30P23	0.3	0.23	2.43	77.13	0.662	2.976
					0.663	4.059
					0.501	4.185
C30P36	0.3	0.36	5.02	194.94	1.103	1.254
					1.005	1.481
					1.230	1.686
C30P43	0.3	0.43	7.80	242.72	1.403	1.169
					0.974	1.768
					1.148	1.049
C30P23	0.5	0.23	2.43	77.13	0.600	5.411
					0.718	5.890
					1.008	5.287
C30P36	0.5	0.36	5.02	194.94	1.326	1.212
					0.993	1.731
					0.917	1.925
C30P43	0.5	0.43	7.80	242.72	1.134	1.827
					1.592	1.430
					1.640	1.968
C30P23	1.0	0.23	2.43	77.13	0.901	3.405
					1.225	4.629
					1.062	3.885
C30P36	1.0	0.36	5.02	194.94	1.209	4.566
					1.169	3.431
					1.516	3.218
C30P43	1.0	0.43	7.80	242.72	1.656	2.539
					1.668	2.965
					2.177	3.391
C30P54	1.0	0.54	10.64	350.14	1.519	0.941
					1.554	1.566
					1.791	1.032
C30P69	1.0	0.69	27.19	422.46	2.576	1.011
					2.336	1.143
					2.243	1.397

TABLE 2: Continued.

Specimen	P (MPa)	ρ_p (g/cm ³)	f_p (MPa)	E_p (MPa)	τ (MPa)	s_0 (mm)
C30P92	1.0	0.92	41.06	539.61	2.397	1.694
					1.614	0.908
					2.138	1.308
C30P23	2.0	0.23	2.43	77.13	1.005	5.002
					1.443	5.843
					1.153	4.482
C30P36	2.0	0.36	5.02	194.94	1.563	1.448
					2.112	3.932
					2.272	4.699
C30P43	2.0	0.43	7.80	242.72	2.313	4.764
					2.441	2.673
					2.035	2.633
C30P54	2.0	0.54	10.64	350.14	1.819	1.708
					2.873	2.713
					2.78	2.704
C30P69	2.0	0.69	27.19	422.46	2.636	1.899
					2.507	1.375
					2.210	2.464
C30P92	2.0	0.92	41.06	539.61	2.504	1.276
					2.897	1.313
					3.188	1.579
C25P23	0.0	0.23	2.43	77.13	0.381	2.170
C25P36	0.0	0.36	5.02	194.94	0.665	3.476
C25P69	0.0	0.69	27.19	422.46	0.806	1.143
					0.752	0.894
C25P92	0.0	0.92	41.06	539.61	0.889	1.85
C25P23	1.0	0.23	2.43	77.13	0.714	—
C25P36	1.0	0.36	5.02	194.94	1.419	2.638
					1.208	3.118
C25P43	1.0	0.43	7.80	242.72	1.792	1.933
C25P69	1.0	0.69	27.19	422.46	1.805	1.553
					2.002	1.137
C25P23	2.0	0.23	2.43	77.13	1.146	—
C25P36	2.0	0.36	5.02	194.94	1.292	—
					1.169	—
C25P43	2.0	0.43	7.80	242.72	1.922	1.937
C25P69	2.0	0.69	27.19	422.46	2.065	1.868
C55P23	0.0	0.23	2.43	77.13	0.562	3.149
C55P69	0.0	0.69	27.19	422.46	1.207	0.912
					1.123	0.929
C55P92	0.0	0.92	41.06	539.61	2.011	0.935
C55P23	1.0	0.23	2.43	77.13	0.841	5.662
C55P69	1.0	0.69	27.19	422.46	1.760	1.188
C55P23	2.0	0.23	2.43	77.13	1.211	—
C55P69	2.0	0.69	27.19	422.46	2.642	1.962

between τ_u and polymer density under different normal pressure can be represented by two straight lines. When no normal pressure is applied, for the comparison specimens C30P23, the increasing percentage of the average bond strength with polymer density of 0.36 to 0.43 0.54, 0.69, and 0.92 g/cm³ is 67, 133, 130, 202, and 253%, respectively. Thus, the bond resistance is highly sensitive to the density of the polymer, and the failure modes discussed in the above section can be used to judge the bond quality of concrete and polymer.

From Figures 5(a) and 5(b), it can also be found that the ultimate bond strength increases significantly as normal pressures increase for a given polymer density. As the

normal pressure increased up to 2.0 MPa, compared with the specimens of C30P23, C30P36, C30P43, C30P54, C30P69, and C30P92 under no normal pressure, the bond strength increased about 166, 162, 115, 140, 80, and 79%, respectively. The test results further manifest that the effect of normal pressure on the bond resistance decreases with increasing polymer density. Moreover, it can be seen from Figures 5(c)–5(e) that, for a given polymer density and normal pressure, the bond strength is decreased with a lower strength of concrete.

When the polymer was injected into the steel model, the chemical reaction between the two-component liquid polyurethane materials results in a substantial increase in

FIGURE 3: Schematic diagrams of modified direct shear apparatus.

FIGURE 4: Continued.

FIGURE 4: Typical morphology of fracture surface after bonding test. (a) Specimens of C30 without normal pressure; (b) C30P23; (c) C30P36.

volume, and a certain amount of foaming polymer has been squeezed into the pores, voids, and cracks of the concrete grouting surface by the self-expansion force. Thus, as shown in Figure 6, the voids in the concrete are fulfilled by the polymer, the polymer-concrete interface is contacted soundly, and no cracks are observed between the interfaces even though the scanning electron microscope specimens are suffering cutting process. Therefore, the bond resistance of concrete polymer can be considered composed by chemical adhesion generated by the chemical reaction of polymer on concrete and the mechanical interlocking of the polymer keys provided by the penetration of polymer into the pores and cracks of the concrete interface. Previous studies demonstrated that the strength and expansion force of polyurethane polymer are extremely improved with a higher polymer density [8]. Hence, with the increasing of polymer density, more polymers can be squeezed into the indentations of the concrete grouting surface and result in a larger chemical adhesion and mechanical interlocking between the interfaces. Moreover, as listed in Table 2, the polymer compressive strength is significantly increased with the density. Therefore, the bond strength rises with the increase of polymer density. When normal pressure is applied to the polymer material, the interface between concrete and polymer has been compacted, and the mechanical interlocking of the polymer is pretightened and strengthened. Moreover, the friction resistance generated by the wedging action of polymer and concrete particles at the polymer and concrete interface as slip begins to increase with the normal pressure. Therefore, the normal pressures exert a positive influence on the bond behavior.

3.3. Slip at the Peak Bond Strength. The slip at the peak bond point s_0 is plotted in Figure 7. It can be found that s_0 is a decreasing function of polymer density. However, for a

given polymer density, s_0 increases with increasing the increment of normal pressure, and the increasing percentage becomes less pronounced for specimens with larger polymer density. Figure 6 also shows that the strength of concrete has a slight influence on the slip s_0 .

3.4. Shear Bond Stress-Slip Curves between Polymer and Concrete. The relationship between shear bond stress and average horizontal displacement for specimens is illustrated in Figure 8. For specimens under no normal stress, each curve is composed of ascending and descending branches. The bond stress in the ascending branch increases significantly as the polymer density increases. When the chemical adhesion and mechanical interlocking between the interfaces have been overcome, the bond stress drops rapidly, and the specimen is sheared into two pieces along with the interface. Figure 9 gives the normalized bond stress-slip relationship for specimens under different polymer density, where it can be observed that the relations between τ/τ_u and s/s_0 can be represented by two straight lines. As the polymer density increases, the ascending branch nearly keeps unchanged, while the descending branch decreases more dramatically with a lower polymer density. The test results further manifested that the ascending branch can be defined by τ_u and s_0 , and the descending branch is mainly influenced by normal pressure and polymer density.

As normal pressure is applied, the polymer-concrete interface has been compacted and the friction action between the interfaces becomes an important part of the bond resistance. As illustrated in Figure 10, ascending and descending branches are closely related to normal pressure. For a given polymer density, the bond stress in the ascending branch increases more dramatically while decreasing more

▼ 0.1 MPa
* 0.3 MPa
△ 0.5 MPa

(a)

▼ 0.0 MPa
* 1.0 MPa
△ 2.0 MPa

(b)

▼ C15
* C30
◁ C45

(c)

▼ C15
* C30
◁ C45

(d)

FIGURE 5: Continued.

FIGURE 5: Relationship between bond strength and polymer density. (a) C30-1; (b) C30-2; (c) 0.0 MPa; (d) 1.0 MPa; (e) 2.0 MPa.

FIGURE 6: SEM micrograph of microstructure of the interface.

FIGURE 7: Relationship between s_0 and polymer density.

FIGURE 8: The stress-slip curves of specimens under different polymer density. (a) 0.23, 0.43, and 0.69 g/cm³; (b) 0.36, 0.54, and 0.92 g/cm³.

FIGURE 9: Normalized bond stress-slip curves for specimens under no normal pressure.

slowly in the descending branch with increasing normal pressure. As described in Figure 11, when the density of the polymer is in the range of 0.23~0.43 g/cm³, the increase in normal pressure leads to the normalized ascending branch changes from straight to concave, and the descending branch decreases even more slowly with a lower polymer density. As the polymer density larger than 0.43 g/cm³, the

effect of normal pressure on the shape of the ascending curves becomes less pronounced.

3.5. FE Model for Polymer-Concrete Interface. As illustrated in Figure 4, when no normal pressure is applied, for specimens with polymer density larger than 0.43 g/cm³, the

FIGURE 10: Continued.

FIGURE 10: The load-slip curves of specimens with different normal pressure. (a) C40P23; (b) C40P23; (c) C40P36; (d) C40P43; (e) C40P54; (f) C40P69; (g) C40P92.

failure location in concrete is consistent with epoxy-concrete under good bond conditions. To study the shear failure mechanism at the polymer-concrete interface with a good bond condition, a 2D FE model of the specimen was established employing the ABAQUS software. As presented in Figure 12, the specimen was divided into the polymer layer, adhesive layer, and concrete layer with depths of 50 mm, 0 cm, and 50 mm, respectively. Owing to the interfacial failure that takes place in concrete, the polymer is treated as a linear elastic material in the FE model, and its

elastic modulus varies with the density. The polymer and concrete are connected with the sharing nodes and keep intact during the failure process. The Concrete Damaged Plasticity (CDP) model proposed by Lee and Fenves [24] was applied to model the concrete, and the detailed parameters are listed in Table 3. The vertical and horizontal direction of concrete is restrained along with the lower shear box to simulate the restraints of the shear box. The shear load is applied on the left surface of the polymer in a displacement-controlled manner. The predicted shear bond strength of

FIGURE 11: Normalized bond stress-slip curves for specimens with different polymer density. (a) C40P23; (b) C40P36; (c) C40P43.

FIGURE 12: FE model.

TABLE 3: Model parameters.

Density (kg/m ³)	Elastic modulus (GPa)	Poisson's ratio	Dilatancy angle	Eccentricity	f_{b0}/f_{c0}	κ
2500	33.7	0.22	38	0.1	1.16	0.6667

FIGURE 13: Comparisons between test and simulation results.

specimens under different polymer density is presented in Figure 13. It shows that the predicted results agree with the test value, especially for polymer density larger than 0.43 g/cm^3 . For specimens with a polymer density lower than 0.43 g/cm^3 , failure occurs in the interface. Therefore, the predicted value is larger than the test results.

4. Conclusions

A total of 105 composite specimens have been prepared and tested to evaluate the effect of normal pressure on the shear bond behavior of concrete and self-expansion polyurethane polymer under different polymer density and concrete strength. The conclusions can be drawn as follows:

- (1) The failure mode is mainly related to the magnitude of polymer density and normal pressure. For specimens with a lower polymer density, the failure mode changes with the increase of normal pressure. As the normal pressure rises to 0.36 g/cm^3 , the influence of normal pressure on the failure mode is negligible.
- (2) Polymer density, normal pressure, and concrete strength all positively affect the bond capacity. For a given normal pressure, the relationship between shear strength and polymer density can be repressed by two straight lines, and the increment in the bond strength gradually decreases for a higher polymer density.
- (3) When no normal pressure is applied, with increasing polymer density, the bond stress increases rapidly to the peak point and then drops sharply on the descending branch. The normalized bond-slip curves

can be represented by two straight lines. When normal pressure is applied, the bond stress increases dramatically to the peak point and then drops sharply to the residual strength with a higher polymer density.

- (4) The finite element model proposed in this study can be used to predict the shear bond strength between self-expansion polymer and concrete failure in concrete mode.

Abbreviations

- E_c : Elastic modulus of concrete
 f_c : Compressive strength of concrete
 f_p : Compressive strength of polymer density
 ν_c : Poisson's ratio of concrete
 P : Shear load
 s : Average slip between the interfaces
 s_0 : Slip at peak bond strength
 s_1 : Slip at lower shear box
 s_2 : Slip at lower shear box
 A : Cross-sectional area of the bond region
 τ : Bond strength
 τ_u : Ultimate bond strength
 p : Normal pressure.

Data Availability

All data used to support the findings of this study are included within the article, and the data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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