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/cm³, 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
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/cm³ 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 × 100 × 50 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
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 \( \tau_u \) 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 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 \( \nu_c \)       | 0.22       | 0.22       | 0.23       |
| Surface roughness (mm)               | 0.187      | 0.168      | 0.147      |
| Specimen | \( P \) (MPa) | \( \rho_p \) (g/cm\(^3\)) | \( f_p \) (MPa) | \( E_p \) (MPa) | \( \tau \) (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       |
|          |                |                |               |               | 0.858         | 2.317       |
| C30P36   | 0.0            | 0.36           | 5.02          | 194.94        | 0.751         | 1.780       |
|          |                |                |               |               | 0.663         | 1.650       |
|          |                |                |               |               | 0.974         | 1.228       |
| C30P43   | 0.0            | 0.43           | 7.80          | 242.72        | 1.032         | 1.560       |
|          |                |                |               |               | 1.146         | 1.666       |
|          |                |                |               |               | 0.937         | 1.103       |
| C30P54   | 0.0            | 0.54           | 10.64         | 350.14        | 1.101         | 1.213       |
|          |                |                |               |               | 1.166         | 1.368       |
|          |                |                |               |               | 1.426         | 2.286       |
| C30P69   | 0.0            | 0.69           | 27.19         | 422.46        | 1.365         | 1.052       |
|          |                |                |               |               | 1.297         | 0.952       |
|          |                |                |               |               | 1.675         | 1.001       |
|          |                |                |               |               | 1.672         | 1.080       |
| C30P92   | 0.0            | 0.92           | 41.06         | 539.61        | 1.435         | 1.128       |
|          |                |                |               |               | 0.491         | 3.419       |
|          |                |                |               |               | 0.425         | 2.754       |
| C30P23   | 0.1            | 0.23           | 2.43          | 77.13         | 0.522         | 3.222       |
|          |                |                |               |               | 0.866         | 1.761       |
|          |                |                |               |               | 1.103         | 1.254       |
| C30P36   | 0.1            | 0.43           | 2.43          | 194.94        | 0.903         | 1.560       |
|          |                |                |               |               | 0.998         | 3.064       |
|          |                |                |               |               | 1.418         | 1.505       |
| C30P43   | 0.3            | 0.23           | 2.43          | 77.13         | 0.663         | 4.059       |
|          |                |                |               |               | 0.501         | 4.185       |
|          |                |                |               |               | 1.403         | 1.169       |
| C30P23   | 0.5            | 0.23           | 2.43          | 77.13         | 0.974         | 1.768       |
|          |                |                |               |               | 1.148         | 1.049       |
|          |                |                |               |               | 0.600         | 5.411       |
| C30P43   | 0.5            | 0.36           | 5.02          | 194.94        | 0.993         | 1.731       |
|          |                |                |               |               | 0.917         | 1.925       |
|          |                |                |               |               | 1.134         | 1.827       |
| C30P23   | 1.0            | 0.23           | 2.43          | 77.13         | 1.225         | 4.629       |
|          |                |                |               |               | 1.062         | 3.885       |
|          |                |                |               |               | 1.209         | 4.566       |
| C30P36   | 1.0            | 0.36           | 5.02          | 194.94        | 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        | 1.554         | 1.566       |
|          |                |                |               |               | 1.791         | 1.032       |
|          |                |                |               |               | 2.576         | 1.011       |
| C30P69   | 1.0            | 0.69           | 27.19         | 422.46        | 2.336         | 1.143       |
|          |                |                |               |               | 2.243         | 1.397       |
between \( r_u \) 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 0.54, 0.69, and 0.92 g/cm\(^3\) 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

### Table 2: Continued.

| Specimen | \( P \) (MPa) | \( \rho_p \) (g/cm\(^3\)) | \( f_p \) (MPa) | \( E_p \) (MPa) | \( \tau \) (MPa) | \( s_0 \) (mm) |
|----------|-------------|-----------------|-------------|--------------|---------|----------|
| C30P92   | 1.0         | 0.92            | 41.06       | 539.61       | 2.397   | 1.694    |
| C30P23   | 2.0         | 0.23            | 2.43        | 77.13        | 1.443   | 5.843    |
| C30P36   | 2.0         | 0.36            | 5.02        | 194.94       | 2.112   | 3.932    |
| C30P43   | 2.0         | 0.43            | 7.80        | 242.72       | 2.272   | 4.699    |
| C30P54   | 2.0         | 0.54            | 10.64       | 350.14       | 2.313   | 4.764    |
| C30P69   | 2.0         | 0.69            | 27.19       | 422.46       | 2.441   | 2.673    |
| C25P23   | 0.0         | 0.23            | 2.43        | 77.13        | 1.891   | 1.708    |
| C25P36   | 0.0         | 0.36            | 5.02        | 194.94       | 2.78    | 2.704    |
| C25P69   | 0.0         | 0.69            | 27.19       | 422.46       | 2.636   | 1.899    |
| C25P92   | 2.0         | 0.92            | 41.06       | 539.61       | 2.507   | 1.375    |
| C25P23   | 1.0         | 0.23            | 2.43        | 77.13        | 2.112   | 2.633    |
| C25P36   | 1.0         | 0.36            | 5.02        | 194.94       | 1.819   | 1.708    |
| C25P69   | 1.0         | 0.69            | 27.19       | 422.46       | 2.78    | 2.704    |
| C25P92   | 2.0         | 0.92            | 41.06       | 539.61       | 2.897   | 1.313    |
| C55P23   | 0.0         | 0.23            | 2.43        | 77.13        | 3.188   | 1.579    |
| C55P69   | 0.0         | 0.69            | 27.19       | 422.46       | 3.292   | 1.579    |
| C55P23   | 0.0         | 0.23            | 2.43        | 77.13        | 1.937   | 1.937    |
| C55P69   | 0.0         | 0.69            | 27.19       | 422.46       | 2.002   | 1.137    |
| C55P23   | 1.0         | 0.23            | 2.43        | 77.13        | 1.146   | 1.146    |
| C55P69   | 1.0         | 0.69            | 27.19       | 422.46       | 1.553   | 1.553    |
| C55P23   | 2.0         | 0.23            | 2.43        | 77.13        | 1.146   | 1.146    |
| C55P69   | 2.0         | 0.69            | 27.19       | 422.46       | 2.065   | 1.868    |
| C25P92   | 2.0         | 0.92            | 41.06       | 539.61       | 2.011   | 0.935    |
| C25P23   | 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    |
Figure 3: Schematic diagrams of modified direct shear apparatus.

Figure 4: Continued.
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 $\tau/\tau_u$ 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 $\tau_u$ 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...
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.
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.
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.
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/cm³. For specimens with a polymer density lower than 0.43 g/cm³, 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/cm³, 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 represented 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
- $\nu_c$: 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
- $\tau$: Bond strength
- $\tau_u$: 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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