Research Article

Study on Creep Mechanical Properties of Non-Water Reacting Polyurethane Grouting Material

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Non-water reacting polyurethane is a new type of grouting material for support reinforcement and emergency rescue, whose creep mechanical behavior is directly related to the stability and safety of the reinforcement project. To investigate the creep properties of non-water reacting polyurethane grouting material, a series of multistage loading creep tests were performed under uniaxial compression conditions. Then, the creep curves, creep strain rate, and creep failure modes of non-water reacting polyurethane grouting material were obtained. In addition, the effects of temperature and density on the creep properties of non-water reacting polyurethane grouting material were also analyzed. Finally, based on the finite difference program, the numerical simulation of the uniaxial compression creep test of non-water reacting polyurethane grouting material was conducted by employing the Burgers–Mohr creep model. The simulated creep curve was in good agreement with the test curve, which verified the feasibility of the model to describe the creep characteristics of non-water reacting polyurethane grouting material. The research results can provide a reference for studying the creep behavior of polyurethane grouting material and also contribute to the development and application of polyurethane material grouting technology.

1. Introduction

With the development of underground engineering, water inrush disasters occur frequently. The grouting technology is considered to be an effective means to prevent and control these engineering accidents [1–10]. Non-water reacting two-component polyurethane is a new type of grouting material, which is different from the traditional grouting material represented by cement mortar. It has the advantages of rapid hardening, large expansion, and a small permeability coefficient [11–15]. In recent years, it has gradually become a hot topic of international research. At present, it has been widely used in seepage prevention, infrastructure reinforcement, and as support materials in infrastructure engineering projects [16–24].

As non-water reacting polyurethane is a new type of material gradually emerging in recent years, the research on it is limited by test equipment and experimental data. Scholars have made slow progress in the study of its physical and mechanical properties, and the theoretical research is far behind the engineering practice [25–28]. Liu [29] conducted a uniaxial compression test and splitting test for low-density polyurethane materials ($\rho < 0.3 \text{ g/cm}^3$), and obtained the relationship between the density of polyurethane materials and the uniaxial compressive strength and splitting tensile strength. Pan [30] tested the expansion performance of non-water reacting polyurethane grouting material and obtained the law that the expansion force increases exponentially with the increase of density in fixed volume space. Shi et al. [31] studied the permeability, bending, and temperature characteristics of non-water reacting polyurethane grouting material and pointed out that the permeability of polyurethane materials decreases with the increase of density. Liu [32] tested the tensile properties of non-water reacting polyurethane grouting material by direct tensile test. The results showed that the tensile strength increased
exponentially with the increase in density. Aiming at non-water reacting polyurethane grouting material used for repairing highways, settlement lifting for ballastless track of high-speed rail, and impermeable reinforcement of dams or dikes in a seismic region, Li et al. [33] investigated dynamic viscoelastic properties of polyurethane grouting material and proposed a viscoelastic constitutive model based on the generalized Maxwell model. Sham [34] studied the relationship between the viscoelasticity of polyurethane and frequency or temperature by using the Dynamic Mechanical Thermal Analysis method. Bagley and Torvik [35] studied creep and relaxation behaviors of polyurethane materials and proposed a fractional viscoelastic model.

However, despite the recent improvements in the research on the mechanical properties of non-water reacting polyurethane grouting material by many scholars, the current research mainly focuses on the conventional mechanical behavior of polyurethane materials, and there are only a few research reports on the creep mechanical behavior. In practical engineering, the creep phenomenon of materials widely exists in all kinds of engineering. A large number of field measurements and engineering practices show that the grouting materials in highway and railway tunnels, large slopes, mine roadways, and tunnel surrounding rocks exhibit creep characteristics [12–14]. Therefore, it is of great significance to study the creep characteristics of non-water reacting polyurethane materials. The research results can provide a scientific basis for the analysis of long-term deformation characteristics of subgrade and provide theoretical guidance for jacking settlement pipeline and tunnel support.

Due to the similarity of the mechanical properties of non-water reacting polyurethane grouting material with geotechnical materials and asphalt mixtures, this study employed the rheological mechanical properties of geotechnical materials and asphalt mixtures to study the creep mechanical properties of non-water reacting polyurethane grouting material. First, a series of multistage loading creep tests were carried out to obtain the creep curves of non-water reacting polyurethane grouting material. Then, the effects of density and temperature on the creep rate and creep failure mode of polyurethane grouting material were analyzed. Finally, the viscoelastic mechanical parameters of polyurethane grouting material were obtained by the fitting method, and the creep test curve of polyurethane material was simulated by a finite difference program. The reliability of the Burgers–Mohr creep model to describe the creep behavior of non-water reacting polyurethane grouting material was verified.

2. Creep Tests

2.1. Testing Equipment. In our study, the uniaxial compression creep tests were conducted using the CMT5105 series microcomputer-controlled electronic universal testing system, as shown in Figure 1. The test system has high accuracy and sensitivity for the measurement and control of load, deformation, and displacement. It can also carry out the automatic control test of constant velocity loading, constant velocity deformation, and constant velocity displacement, and has the functions of low-frequency load cycle, deformation cycle, and displacement cycle. It can be competent for the tensile, compression, bending, shear, peeling, tearing, and other tests of various solid material samples. The maximum test force of the test equipment is 100 kN and the resolution of the test force is 1/300000 FS (full scale). The deformation measurement range is 0.2 ~ 100% FS and the relative error of deformation indication is ±0.5%. In order to study the temperature effect on creep characteristics of non-water reacting polyurethane, a high-low temperature test chamber was equipped with a temperature control range of −40°C to 150°C.

2.2. Sample Preparation. The non-water reacting polyurethane material is a two-component foam (polyls and isocyanate) that exhibits liquid properties before curing, with fluidity and expansion. The specimen used for the creep test was a cylinder with a diameter of 50 mm and a height of 50 or 100 mm. Therefore, the sample-making mold was specially developed, as shown in Figure 2.

Since the non-water reacting polyurethane grouting material can generate a large expansion force after mixing, the mold was made of steel to ensure sufficient rigidity. The grouting hole was set in the steel plate above the mold. In order to facilitate demolding, it is necessary to apply grease to the inner wall of the mold before grouting. It should be noted that the specimens with different densities were prepared by controlling the injection volume of polyls and isocyanate.

Due to the limitation of the testing equipment, some cylindrical samples with a height of 100 mm were cut into two cylindrical samples with a height of 50 mm by the numerical control punching machine. In order to ensure the smoothness of the end face of the specimen, the specimen with an uneven end face was polished with sandpaper. The surface deviation of the two ends was within a range of 0.05 mm. Figure 3 shows some of the prepared specimens.

The mass, height, and diameter of the specimen were measured by a digital display balance and vernier caliper with an accuracy of 0.1 g, and then the density of the polyurethane specimen was calculated. The uniaxial compressive strength
of each specimen was calculated according to the empirical formula, as listed in Table 1. The empirical formula for uniaxial compressive strength is as follows [32]:

\[ y = 67.289x^2 - 4.3758x + 1.1339, \]

where \( x \) denotes the density of the polyurethane specimen and \( y \) denotes the uniaxial compressive strength of the polyurethane specimen.

2.3. Creep Test Scheme. Previous studies have shown that density and temperature are important factors affecting the mechanical properties of polyurethane materials. Therefore, the effects of density and temperature were considered in this study. For creep tests to study the density effect, the multistep loading test method was used to reduce the influence of sample inhomogeneity. The axial stress was divided into several different levels. At present, no one has studied the creep mechanical properties of non-water reacting polyurethane grouting materials by laboratory tests. We also have no relevant literature for reference. Through a large number of tests, it is found that non-aqueous reactive polyurethane grouting materials have similar viscosity characteristics to asphalt mixture. Therefore, we searched the literature and relevant test procedures and referred to some test methods for the study of the rheological properties of asphalt mixture [25, 36–38]. The loading time for each step was tentatively determined to be approximately 1800 s (30 minutes). When the loading time of each step reached the predetermined value, the next step of the axial stress level was applied. The axial stress was increased step by step until the sample failed. In order to be consistent with the engineering environment as much as possible, the local average temperature (25°C) was taken as the reference temperature for creep tests. When considering the effect of temperature on the creep properties of the polyurethane grouting material, 25°C was taken as the initial temperature; the temperature increased or decreased by 10°C for each stage until the sample failed. It should be noted that the axial stress remained constant since loading throughout the creep experiment to study the temperature effect. After the temperature of each stage lasted for 1800 s, the temperature of the next stage was applied.

All of the creep test data were recorded during the test and the creep test scheme is outlined in Table 2. Before carrying out each creep test, a load of 50 N shall be pre-applied to the specimen at a loading speed of 1 mm/min, and the load shall be kept constant for 30 s.

3. Test Results Analysis

3.1. Creep Strain. Figure 4 illustrates the relationship curves of axial strain with time for the polyurethane grouting material. From Figure 4(a), it can be observed that the axial strain curves of polyurethane samples with different densities show typical creep characteristics, including attenuation creep, steady-state creep, and accelerated creep. When the axial stress was small, the polyurethane grouting material showed attenuation creep and steady-state creep behavior. With the gradual increase of axial stress, the creep of polyurethane grouting material gradually transited to the accelerated creep stage. In addition, polyurethane samples with higher density experienced a longer creep process. Taking the creep curves with densities of 0.141 and 0.357 g/cm³ as an example, the former creep loading time lasted for about 5800 s, while the latter lasted for nearly 11000 s, which was more than twice that of the former. Moreover, polyurethane samples with higher density experienced a higher creep failure strength. For lower density specimens (less than 0.233 g/cm³), the averaged creep failure strength is about 0.76 UCS. However, for the specimens with higher density (more than 0.233 g/cm³), their creep failure strength is basically above 0.9 UCS. This is because the polyurethane samples with higher densities showed larger strength, and thus the loading time was longer to reach higher creep failure strength. For lower density specimens (less than 0.233 g/cm³), the averaged creep failure strength is about 0.76 UCS. However, for the specimens with higher density (more than 0.233 g/cm³), their creep failure strength is basically above 0.9 UCS. This is because the polyurethane samples with higher densities showed larger strength, and thus the loading time was longer to reach higher creep failure strength. Therefore, in engineering practice, its service life can be improved by increasing the density of the polyurethane grouting material. Furthermore, it is also found that when the axial stress was less than 50% of the compressive strength, the polyurethane grouting material showed attenuated creep behavior. When it was 95% of the compressive strength, the polyurethane grouting material showed accelerated creep behavior. While it was 50% ~ 95% of the compressive strength, the polyurethane grouting material showed steady-state creep behavior.
Polyurethane samples with densities of 0.408 and 0.567 g/cm³ were taken as examples. Table 3 lists the axial total strain $\varepsilon_t$, axial instantaneous strain $\varepsilon_i$, axial creep strain $\varepsilon_c$, and at instantaneous elastic modulus $E_i$ different loading levels during the creep test.

From Table 3, the contribution of creep to axial total deformation increased with the increasing axial stress. In particular, the creep strain was less than 30% of the amount of axial total strain for the first loading level, when the axial creep strain exceeded 90% of the amount of axial total strain for the last loading level. In addition, it is also noticed that the elastic modulus of the polyurethane sample first increased and then decreased during the whole creep process. This is because the polyurethane grouting material had many internal voids, and with the increase of the axial stress, the elastic modulus of the polyurethane sample reached the maximum. Then, as the

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**Table 1: Physical and mechanical parameters of each specimen.**

| Specimen number | Mass (g) | Diameter (mm) | Height (mm) | Volume (cm³) | Density (g/cm³) | Uniaxial compressive strength (MPa) |
|-----------------|----------|---------------|-------------|--------------|----------------|------------------------------------|
| S1              | 29.4     | 50.0          | 49.9        | 97.93        | 0.300          | 5.86                               |
| S2              | 28.9     | 50.0          | 50.0        | 98.13        | 0.295          | 5.68                               |
| S3              | 55.6     | 50.0          | 49.9        | 97.93        | 0.567          | 20.26                              |
| S4              | 57.4     | 49.9          | 50.0        | 97.73        | 0.585          | 21.60                              |
| S5              | 39.9     | 50.0          | 49.9        | 97.93        | 0.407          | 9.08                               |
| S6              | 40.0     | 50.0          | 50.0        | 98.13        | 0.408          | 9.11                               |
| S7              | 22.9     | 50.0          | 50.0        | 98.13        | 0.233          | 3.78                               |
| S8              | 22.7     | 50.0          | 50.0        | 98.13        | 0.231          | 3.72                               |
| S9              | 44.1     | 49.9          | 49.9        | 97.53        | 0.449          | 12.76                              |
| S10             | 45.5     | 50.0          | 50.0        | 98.13        | 0.461          | 13.40                              |
| S11             | 9.0      | 49.9          | 49.9        | 97.53        | 0.092          | 1.30                               |
| S12             | 8.0      | 50.0          | 49.8        | 97.73        | 0.082          | 1.22                               |
| S13             | 19.2     | 50.0          | 49.8        | 97.73        | 0.196          | 2.85                               |
| S14             | 20.8     | 50.0          | 50.0        | 98.13        | 0.212          | 3.23                               |
| S15             | 35.0     | 50.0          | 50.0        | 98.13        | 0.357          | 8.13                               |
| S16             | 34.8     | 50.0          | 50.0        | 97.93        | 0.355          | 8.05                               |
| S17             | 13.8     | 50.0          | 50.0        | 98.13        | 0.141          | 1.85                               |
| S18             | 13.8     | 49.9          | 49.9        | 97.93        | 0.141          | 1.85                               |
| S19             | 61.8     | 50.0          | 50.0        | 98.13        | 0.630          | 25.7                               |
| S20             | 68.2     | 50.0          | 50.0        | 98.13        | 0.695          | 30.60                              |
| S21             | 17.4     | 50.0          | 50.0        | 98.13        | 0.177          | 2.47                               |
| S22             | 19.0     | 50.0          | 49.9        | 97.93        | 0.194          | 2.81                               |

**Table 2: Creep test scheme.**

| Factor | Specimen number | Density (g/cm³) | UCS (MPa) | Factor level |
|--------|-----------------|-----------------|-----------|--------------|
| Temperature | S18 | 0.141 | 0.92 | 25°C, 35°C, 45°C |
|         | S8  | 0.231 | 2.24 | 25°C, 35°C |
|         | S16 | 0.355 | 4.00 | 25°C, 15°C, 5°C, −5°C, −15°C, −25°C, −35°C |
|         | S17 | 0.141 | 1.85 | 0.4 UCS, 0.5 UCS, 0.6 UCS, 0.7 UCS, 0.8 UCS |
|         | S21 | 0.177 | 2.47 | 0.5 UCS, 0.6 UCS, 0.7 UCS, 0.8 UCS, 0.9 UCS |
|         | S22 | 0.194 | 2.81 | 0.45 UCS, 0.55 UCS, 0.65 UCS |
|         | S14 | 0.212 | 3.23 | 0.5 UCS, 0.6 UCS, 0.7 UCS, 0.8 UCS, 0.9 UCS |
|         | S7  | 0.233 | 3.78 | 0.55 UCS, 0.65 UCS, 0.75 UCS |
|         | S2  | 0.295 | 5.68 | 0.2 UCS, 0.3 UCS, 0.4 UCS, 0.5 UCS, 0.6 UCS, 0.7 UCS, 0.8 UCS, 0.9 UCS, 1.0 UCS, 1.1 UCS |
|         | S15 | 0.357 | 8.13 | 0.4 UCS, 0.5 UCS, 0.6 UCS, 0.7 UCS, 0.8 UCS, 0.9 UCS |
|         | S5  | 0.407 | 10.48 | 0.3 UCS, 0.35 UCS, 0.4 UCS, 0.5 UCS, 0.6 UCS, 0.7 UCS, 0.8 UCS, 0.9 UCS, 1.0 UCS |
|         | S6  | 0.408 | 10.53 | 0.6 UCS, 0.67 UCS, 0.74 UCS, 0.81 UCS, 0.88 UCS |
|         | S10 | 0.461 | 13.40 | 0.5 UCS, 0.57 UCS, 0.64 UCS, 0.71 UCS, 0.78 UCS, 0.85 UCS, 0.92 UCS |
|         | S3  | 0.567 | 20.26 | 0.4 UCS, 0.47 UCS, 0.54 UCS, 0.61 UCS, 0.68 UCS, 0.75 UCS, 0.82 UCS, 0.89 UCS, 0.96 UCS, 1.03 UCS, 1.1 UCS |
|         | S4  | 0.585 | 21.60 | 0.5 UCS, 0.6 UCS, 0.7 UCS, 0.8 UCS, 0.9 UCS, 0.95 UCS, 1.0 UCS, 1.05 UCS, 1.1 UCS, 1.15 UCS |
|         | S19 | 0.630 | 25.07 | 0.4 UCS, 0.48 UCS, 0.56 UCS, 0.64 UCS, 0.69 UCS, 0.74 UCS, 0.79 UCS, 0.84 UCS, 0.88 UCS, 0.92 UCS, 0.96 UCS, 1.0 UCS, 1.04 UCS |
|         | S20 | 0.695 | 30.60 | 0.5 UCS, 0.58 UCS, 0.66 UCS, 0.74 UCS, 0.82 UCS, 0.9 UCS, 0.98 UCS, 1.06 UCS |

Note: UCS represents uniaxial compressive strength.
Figure 4: Curves of axial strain with time for the polyurethane grouting material. (a) Different density conditions. (b) Density $\rho = 0.408$ g/cm$^3$. (c) Density $\rho = 0.567$ g/cm$^3$. 

Table 3: Axial strain and elastic modulus in each loading stage during the creep test.

| Density (g/cm$^3$) | Loading level | $\varepsilon_t$ | $\varepsilon_i$ | $\varepsilon_c$ | $\varepsilon_c / \varepsilon_t$ | $E_i$ (MPa) |
|-------------------|---------------|----------------|----------------|----------------|-----------------------------|-------------|
| 0.408             | Preloading    | 0.17           | 0.17           | 0              | 0                          | 192         |
|                   | 58.1%         | 4.70           | 3.48           | 1.22           | 25.96%                     | 235         |
|                   | 65.3%         | 1.52           | 0.30           | 1.22           | 80.26%                     | 233         |
|                   | 72.6%         | 2.41           | 0.31           | 2.10           | 87.14%                     | 225         |
|                   | 79.8%         | 4.62           | 0.33           | 4.29           | 92.86%                     | 217         |
|                   | 87.1%         | 6.18           | 0.36           | 5.82           | 94.17%                     | 217         |
|                   | Sum           | 19.60          | 4.95           | 14.65          | 74.74%                     | 220         |
axial stress continued to increase, a certain degree of damage occurred inside the polyurethane sample, resulting in the deterioration of its stiffness. On the whole, the density had a great influence on the elastic modulus of polyurethane grouting material. The average elastic modulus of a polyurethane sample with a density of 0.567 g/cm³ was nearly twice larger than that of a polyurethane sample with a density of 0.408 g/cm³.

3.2. Creep Strain Rate. In order to study the law of creep strain rate, Figure 5 shows the variation curve of axial strain with time during each loading level for polyurethane samples with different densities. It is clearly seen that the polyurethane grouting material exhibits an obvious creep stress threshold, that is, the creep phenomenon occurs only after the axial stress reaches a certain value. Moreover, the lower the density, the lower the creep stress threshold of polyurethane samples. For specimens with lower density (less than 0.295 g/cm³), when the axial stress is lower than 0.4 UCS, no creep phenomenon will occur. However, for specimens with higher density (more than 0.295 g/cm³), the creep stress threshold is about 0.5 ~ 0.6 UCS. In addition, it can also be seen that all specimens entered the accelerated creep stage before reaching the expected loading time (1800 s) during the final loading level. At the same time, the specimen did not fail when the axial load was applied. The final failure of the specimens occurred within 1800 s of the final loading level, i.e., creep failure. Moreover, the creep strain rate in the steady-state stage showed an increasing trend with the increase of density. However, when the density of the sample was too large, due to the compression of the voids in the sample, the deformation ability decreased, resulting in a decrease in the creep rate in the steady-state creep stage. Furthermore, with the increase of the axial stress, the creep strain rate in the steady-state creep stage also showed an increasing trend. The creep strain rate in the steady-state creep stage was usually 4% to 21% of the creep rate in the accelerated creep stage.

3.3. Creep Failure Characteristics. Figures 6~10 illustrate the failure forms of non-water reacting polyurethane samples.

It can be found that the creep failure modes of polyurethane specimens with different densities were significantly different. When the sample density was low, the sample was mainly a compressed deformation failure (see Figures 6 and 7). In addition, due to the difference in density and hardness, there were differences in the manifestations of compression failure of the specimens. The deformation of the two groups of samples with densities of 0.141 and 0.194 g/cm³ was only the wrinkle on the sample surface, without fracture failure on the sample surface (see Figure 7). For the sample with a density of 0.233 g/cm³, in addition to the same wrinkle, some wrinkles on the surface of the sample were broken (see Figure 7). When the density of the specimen was larger, there was a macro fracture surface. Vertical cracks appeared on the side surface of the sample with a density of 0.407 g/cm³. It indicates that the specimen occurred splitting tensile failure. For the samples with a density of 0.567 and 0.585 g/cm³, in addition to the vertical crack, there was a shear fracture surface with an inclination of 45°. When the density was large, the polyurethane sample showed tensile-shear composite failure.

3.4. Temperature Effect. Figure 11 shows the variation curves of axial strain with time for polyurethane samples with different densities under heating and cooling conditions. Clearly, the temperature had a significant effect on the creep behavior of polyurethane grouting material. When the temperature rose, the creep rate of the polyurethane sample was larger, and there was steady-state creep and accelerated creep stages. While the temperature decreased, the creep rate also decreased, and the polyurethane specimens only exhibited attenuated creep behavior. Therefore, it can be concluded that high temperature can enhance the creep of polyurethane grouting material, while low temperature can inhibit its creep behavior. The reason for this phenomenon is probably that the increase in temperature will increase the activity of the molecules in the polyurethane grouting material, causing the creep rate to increase significantly and thus inducing the accelerated creep behavior. In the low-temperature environment, the molecular activity inside the polyurethane grouting material was low, and thus the creep rate was greatly reduced, and only attenuated creep behavior occurs. In addition, by comparing Figures 11(a) and 11(b), it is found that the polyurethane specimen with a density of 0.231 g/cm³ had accelerated creep at 35°C, while the

| Density (g/cm³) | Loading level | ε_i | ε_i | ε_c | ε_c/ε_i | E_i (MPa) |
|---------------|---------------|-----|-----|-----|---------|----------|
| 0.567         | Preloading    | 0.18| 0.18| —   | 0       | —        |
| 40.2%         |               | 2.72| 2.48| 0.24| 8.82%   | 399      |
| 47.8%         |               | 0.58| 0.35| 0.23| 39.66%  | 450      |
| 55.3%         |               | 0.64| 0.35| 0.29| 45.31%  | 445      |
| 62.9%         |               | 0.78| 0.35| 0.43| 55.13%  | 435      |
| 70.4%         |               | 1.17| 0.35| 0.82| 70.08%  | 432      |
| 75.4%         |               | 2.80| 0.40| 2.40| 85.71%  | 260      |
| 83.0%         |               | 2.97| 0.39| 2.58| 86.87%  | 390      |
| 90.6%         |               | 4.12| 0.41| 3.71| 90.05%  | 374      |
| 98.1%         |               | 5.61| 0.41| 5.20| 92.69%  | 365      |
| 105.6%        |               | 7.13| 0.43| 6.70| 93.97%  | 357      |
| Sum           |               | 35.87| 6.54| 29.33| 81.77%  | 405      |

Table 3: Continued.
Figure 5: Continued.
specimen with a density of 0.141 g/cm$^3$ was only in the steady-state creep stage at 35°C, and the accelerated creep behavior occurred at 45°C. This further verified the above findings. The specimen with a smaller density contained less polyurethane grouting material, and the active energy of internal molecules was lower at the same temperature. Therefore, the temperature to reach the accelerated creep stage should be higher.

4. Numerical Simulation

4.1. Burgers–Mohr Creep Model. From the above analysis, the polyurethane grouting material had the three-stage characteristics of a typical creep curve, i.e., attenuation creep, steady-state creep, and accelerated creep. The Burgers creep model can well describe the viscoelastic characteristics of attenuation creep and steady-state creep. In order to better describe the accelerated creep characteristics, the FLAC3D finite difference program provided a Burgers–Mohr creep model which connects a Mohr–Coulomb plastic cell in series with the Burgers model [39], as shown in Figure 12. The Burgers part of the model was used to describe the first two stages of the creep curve. When the deviatoric stress exceeded yield strength and entered the accelerated creep stage, the Mohr–Coulomb plastic cell started to work. Next, the feasibility of using this model was explored to describe the creep mechanical behavior of polyurethane grouting material under uniaxial compression conditions. For the convenience of illustration, the polyurethane specimen with a density of 0.408 g/cm$^3$ was taken as an example.

4.2. Model Parameter Solution. From Figure 12, it is found that the Burgers–Mohr creep model includes five mechanical parameters, i.e., Kelvin module $E_1$, Kelvin visibility coefficient $\eta_1$, Maxwell module $E_2$, Maxwell visibility coefficient $\eta_2$, and yield strength $\sigma_s$. Since this study was limited to uniaxial compression, the yield strength here was taken as uniaxial compressive strength (9.11 MPa). In addition, in order to describe the lateral deformation, the mechanical parameter Poisson’s ratio was also needed. According to the uniaxial compression test results, the Poisson’s ratio was 0.25.

Under the one-dimensional condition, the creep equation of the Burgers creep model can be written as

$$\varepsilon = \frac{\sigma_0}{E_2} + \frac{\sigma_0}{\eta_2} t + \frac{\sigma_0}{E_1} \left(1 - e^{-\left(E_2/\eta_1\right)t}\right),$$

(2)

where $\sigma_0$ denotes the current stress level and $t$ denotes the loading time.

Referring to the previous study [40], (2) was adopted to fit the axial strain curve under each level of stress level, and the fitted model parameters are listed in Table 4. The creep parameters of each stress level varied greatly, indicating that the creep parameters of polyurethane grouting material were non-stationary in the whole creep test process.

Figure 13 shows the comparison between the fitted curves and the test value. It is found that the fitted curves were in good agreement with the test data at each stress level, and the correlation coefficient was close to 1. It indicates that the Burgers creep model can well describe the viscoelastic characteristics of polyurethane grouting material under uniaxial compression creep.
4.3. Model Verification. According to the parameters in Table 4, the Burgers–Mohr creep model built-in FLAC3D was employed to simulate the uniaxial compression creep of the specimen with a density of 0.408 g/cm³. The loading level classification and creep time in the numerical simulation were completely consistent with the actual test. Figure 14 shows the comparison between the test curve and the simulated curve. It is observed that the simulated curve was in good agreement with the experimental curve, and the accelerated creep stage was successfully obtained. It has strongly proved that the Burgers–Mohr creep model can better describe the viscoelastic plastic creep characteristics of polyurethane grouting material under uniaxial compression conditions.
Figure 8: Failure forms of the sample with a density of 0.407 g/cm³. (a) Fracture surface of the sample. (b) Vertical crack on the specimen side.

Figure 9: Failure forms of the sample with a density of 0.567 g/cm³. (a) Cracks with an inclination of 45° on the specimen side. (b) Vertical crack on the specimen side.

Figure 10: Failure forms of the sample with a density of 0.585 g/cm³. (a) Fracture surface of the sample. (b) Vertical crack on the specimen side.
Figure 11: Variation curves of axial strain with time for the polyurethane sample with different densities under heating and cooling conditions. (a) Density = 0.141 g/cm$^3$. (b) Density = 0.231 g/cm$^3$. (c) Density = 0.355 g/cm$^3$.

Figure 12: Schematic of the Burgers–Mohr creep model.

Table 4: Fitted parameters of the polyurethane specimen with a density of 0.408 g/cm$^3$.

| Stress level (MPa) | $E_1$ (MPa) | $\eta_1$ (GPa·s) | $E_2$ (MPa) | $\eta_2$ (GPa·s) | Correlation coefficient |
|-------------------|-------------|------------------|-------------|------------------|-------------------------|
| 6.1               | 1370        | 1850             | 163         | 1700             | 0.98                    |
| 6.9               | 1220        | 1430             | 132         | 1590             | 0.99                    |
| 7.7               | 880         | 700              | 115         | 830              | 0.99                    |
| 8.4               | 345         | 610              | 92          | 780              | 0.99                    |
Figure 13: Comparison between test data and fitted curves. (a) $\sigma_0 = 6.1$ MPa. (b) $\sigma_0 = 6.9$ MPa. (c) $\sigma_0 = 7.7$ MPa. (d) $\sigma_0 = 8.4$ MPa.

Figure 14: Comparison between the test curve and simulated curve.
5. Conclusions

In this study, a series of uniaxial compression creep tests were performed to study the creep properties of polyurethane grouting material. The main conclusions are as follows:

(1) Polyurethane grouting material showed typical creep characteristics under uniaxial compression. Density is the dominant factor affecting the creep behavior of polyurethane grouting material. Higher density can significantly increase the creep failure strength, stiffness, and creep failure time of polyurethane grouting material.

(2) The contribution of creep to polyurethane grouting material deformation increased with the increasing axial stress level. The steady-state creep strain rate increased with the increase of the axial stress level.

(3) The creep failure mode of polyurethane grouting material under uniaxial compression was significantly affected by the density. When the density was small (less than 0.2 g/cm³), the polyurethane sample showed the compression deformation failure mode with wrinkles on the surface. When the density was medium (0.2–0.5 g/cm³), the polyurethane sample shows splitting failure. When the density was high (more than 0.5 g/cm³), the polyurethane sample showed tensile-shear composite failure.

(4) The creep characteristics of polyurethane grouting material were significantly dependent on temperature. High temperature (more than 35°C) can enhance the creep of polyurethane grouting material, while low temperature (less than 35°C) can inhibit its creep behavior.

(5) Burgers–Mohr creep model can better describe the attenuated creep, steady-state creep, and accelerate the creep of polyurethane grouting material under uniaxial compression conditions. It will provide a reference for the research on the creep behavior of polyurethane grouting material, and contribute to the development and application of polyurethane grouting material grouting technology.

Data Availability

The data presented in this study are available on request to the corresponding author. The data are not publicly available due to the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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