Research Article

Design and Experimental Verification of Asphalt-Based Material for Grouting of Prestressed Structure

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The quality of the grouting is an important factor affecting the durability of prestressed structures, especially in corrosive environment with stray current. Uncompacted grouting will lead to rapid corrosion and failure of steel strand. In this paper, an asphalt-based material as grouting material was designed to solve this problem due to the characteristics of asphalt material as impermeability, anticorrosion, and insulation. The viscosity and shear strength were considered as the main performance parameters of the grouting material for prestressed grouting. The composition and proportion of the asphalt-based material were determined through the tests, including natural asphalt (rock asphalt) being 12.5% and admixture (slaked lime and cement) being 40%. For this grouting material, the shear strength was 697.21 kPa at normal temperature, and the suitable grouting temperature was 115°C. Then, the grouting test of the prestressed concrete beam was carried out to verify the groutability of this material. The grouting slurry can be filled with prestressed duct, and the temperature stress of the concrete near the duct was lower than 1.4 MPa, which met the safety requirement of the concrete. This study provides a new option for guaranteeing the quality of grouting and improving the durability of prestressed structures in corrosive environment.

1. Introduction

The quality of prestressed duct grouting will directly affect the reliability of the prestressed concrete structure. In practical engineering, the use of cement slurry may lead to bleeding, resulting in uncompacted grouting. In recent years, the problems of prestressed duct grouting have been discovered in some existing prestressed bridges [1–3]. It becomes one of the main problems in the posttensioned prestressing system that leads to the lack of protection of prestressed strands in corrosive environment. The durability of the structure decreases because of premature corrosion failure of prestressed strands [4–8].

In solving the problem of the uncompacted grouting, the main methods are vacuum grouting and adding admixtures (such as water reducing agent, air entraining agent, and aluminum powder) to cement base grouting slurry. The study of new grouting material mainly focuses on the modification of grouting material, such as the use of ultrafine cement and high volume of fly ash to modify the grouting material [9–13]. Compared with traditional cement-based grouting material, asphalt-based grouting material has the advantages of no bleeding, no shrinkage, impervious, high adhesion, and self-healing ability [14, 15]. These properties of asphalt-based material make it suitable for some engineering applications as filling and anticorrosion [16–18]. However, there are few studies [19–21] on the application of asphalt-based material for grouting of prestressed duct. The method is to inject the preheated asphalt grouting material into the prestressed duct by the asphalt pump, and the slurry is cooled and solidified under the natural environment gradually, which is essentially different from the traditional grouting technology of using cement-based material. However, the pure matrix asphalt cannot transfer the pre-stress and form protection of the strand effectively, due to its low strength and high-temperature sensitivity. Due to the need of pumping, it is not possible to improve the strength of asphalt-based grouting material by increasing the size of
aggregates. Therefore, it is necessary to design a new polymer material for grouting based on asphalt.

The objective of this study is to investigate the composition and ratio of asphalt-based material to be suitable for prestressed concrete structure. The paper is organized as follows. Firstly, different proportions of natural asphalt and SBS asphalt were added to the matrix asphalt, and the optimum ratio was determined according to the modification effect of the natural asphalt and SBS asphalt on the matrix asphalt. Then, different ratios of admixture (cement, silicon powder, and slaked lime) were added to asphalt-based material. According to the viscosity test and shear strength test at different temperatures, the appropriate mix ratio of asphalt-based grouting material can be totally determined. After that the grouting test of concrete beam was carried out to verify the groutability of the material and the safety of concrete at grouting temperature. Finally, several conclusions were drawn based on the proposed study.

2. Material and Methods

2.1. Material and Specimens

2.1.1. Asphalts. The asphalts selected in this paper were AH70 asphalt, SBS asphalt, Trinidad lake asphalt (TLA), and Indonesian Budun rock asphalt (BRA), as shown in Figure 1. The basic properties of AH70 and SBS asphalt are shown in Table 1, and the properties of them meet the requirements of the specification [22]. The basic properties of TLA and BRA are shown in Table 2 and the contents of each component are shown in Table 3.

2.1.2. Admixtures for Asphalt. The admixtures to be used in this paper were cement, silicon powder, and slaked lime as shown in Figure 2. The basic properties of admixtures are shown in Table 4.

2.1.3. Specimen for Groutability Test. A posttensioned concrete beam was designed with a rectangular cross section of \( b \times h = 300 \text{ mm} \times 600 \text{ mm} \) and 6000 mm total length. Two plain bars of 20 mm diameter were at the bottom, two deformed bars of 20 mm diameter were on the top, and 8 mm stirrups with 150 mm spacing were used in the beam. Two ducts with 50 mm diameter were reserved inside the beam. The details of beam are shown in Figure 3. The mixing ratio of the concrete is given in Table 5.

2.2. Preparation Process of Asphalt-Based Material. For the preparation of natural asphalt mixture, the wet mixing method was adopted to make the natural asphalt react with the matrix asphalt sufficiently to improve its performance [23]. Firstly, the natural asphalt, matrix asphalt, and admixture were weighed and put into the incubator to melt. Then, the matrix asphalt was put into the stirring pot to heat up. The natural asphalt was added when the temperature reached 160°C and stirred quickly. It was necessary to ensure the stirring time during the heating process when preparing the asphalt-based grouting material to avoid the uncompacted grouting. After 20 minutes, the other admixtures were added and stirred to distribute evenly in the asphalt. Finally, the asphalt was placed in the incubator for 30 minutes to develop. The test groups are shown in Table 6.

2.3. Test Methods

2.3.1. Test for Ratio of Natural Asphalt. The modification effect of different contents of natural asphalt on base asphalt (AH70 asphalt) was tested by different ratios of natural asphalt including TLA and BRA. Through the analysis and comparison of penetration, ductility, viscosity, and softening point, the type of natural asphalt and its optimum content were finally determined, which would be prepared for the configuration of asphalt-based grouting materials in the next stage. For the test of SBS-modified asphalt to modify the base asphalt, the existing studies [24] had been carried out that the suitable ratio of SBS-modified asphalt was 7.5%. Therefore, this paper used this ratio for the test of modifying the matrix asphalt by adding SBS-modified asphalt. The mix proportion test scheme of asphalt-based materials is shown in Table 7.

2.3.2. Test for Ratio of Admixture. After the modified asphalt was obtained, the effect of different kind and ratio of admixtures on the performance of asphalt mortar would be studied. The main admixtures in the test were cement, silicon powder, and fly ash. Each kind of admixture was added in the proportion of 0%, 10%, 20%, 30%, 40%, and 50%, respectively. The viscosity of the asphalt cement increased rapidly with slaked lime added to it which inevitably caused difficulties in grouting, so slaked lime was used instead of some cement (10%) to explore its properties [25]. The suitable admixtures were determined according to the viscosity and strength index required by the grouting of prestressed structure. The mix proportion test scheme of asphalt-based material is shown in Table 8.

2.3.3. Test for Viscosity and Shear Strength of Asphalt-Based Material. The main influencing factor is the precipitation of the admixture during the performance test of the asphalt mortar. When the temperature of asphalt mortar is reduced from 155°C to 105°C, the maximum settlement distance of different admixtures in asphalt mortar is only 0.043 mm, which can be neglected [26]. Therefore, asphalt performance tests can be used for asphalt-based grouting material. The main performance indicators tested in this study were viscosity and shear strength. The tests were the Bush viscometer test for viscosity and the penetration test for the shear strength [27]. The shear strength of the penetration degree can be used to distinguish the influence of different admixtures and mixing ratios on the performance of asphalt-based grouting material. For the shear strength of asphalt-based material, it can be calculated as [28]

\[
\tau = \frac{0.981Q \cos^2 (\alpha/2)}{\pi h^2 \tan (\alpha/2)},
\]
where \( \tau \) is the shear strength of the asphalt-based grouting material, \( Q \) is the penetration weight (the total weight of the sinker, connecting rod, weight, and weight regulating steel ball), \( h \) is the penetration, and \( \alpha \) is the angle of the cone.

### 2.3.4. Test for Groutability of Asphalt-Based Material

After the composition and ratio of the asphalt material were determined through the tests, it was necessary to carry out the confirmatory test on the groutability of the material. Before the grouting, the heat-conducting oil was poured into the prestressed duct, and the electric cable was put in the oil for preheating the duct. As the heat-conducting oil was emulsified with the contacted asphalt after the slurry into the duct, it had no effect on the grouting. After energizing, the heat produced by the metal resistance wire was transmitted through the metal protection tube. When, the asphalt slurry was heated and grouted into the prestressed duct through the asphalt pump. For posttensioned prestressed structure, the diameter of grouting hole in prestressed duct was generally 28 mm. Therefore, asphalt pump with an outlet diameter of 25 mm was selected in this study. Considering the specification of asphalt pump and the distribution of slurry velocity in the duct, the grouting rate was selected as 50 L/min, and the working pressure of the pump was 0.8 MPa. The process of grouting is shown in Figure 4.

From the previous study on asphalt-based grouting material, it is apparent that for the posttensioned concrete
structure with asphalt-based grouting material, the slurry temperature is relatively high at the grouting stage, while the concrete of component is in the ambient temperature. When the temperature stress exceeds the tensile strength of concrete, cracks occur in the interior or surface of concrete members, which impacts on the durability of concrete structures. In order to measure temperature stress in the test beam under different conditions, the sensors were arranged in the test beam before pouring concrete to measure the temperature and temperature stress near duct at different slurry temperatures. The test time under each condition was 30 min, and the data was read once every 1 min. The sensors were embedded along the longitudinal section of the middle section as shown in Figure 5.

![Figure 2: Admixtures for test. (a) Cement. (b) Silicon powder. (c) Slaked lime.](image)

| Table 4: Basic properties of admixtures. |
|----------------------------------------|
| Content | Apparent density (g/cm³) | Specific surface area (m²/kg) | Particle size distribution (mm) | Loss on ignition (%) |
|----------|--------------------------|-------------------------------|-------------------------------|---------------------|
| Cement   | 3.21                     | 390                           | ≤0.075                        | 0.32                |
| Silicon powder | 2.33                 | 26000                         | ≤0.075                        | 8.24                |
| Slaked lime | 2.39                  | 1100                          | ≤0.075                        | 0.32                |

![Figure 3: Layout of the reinforcement of the test beam (mm).](image)

| Table 5: Mixing ratio of test beam concrete. |
|---------------------------------------------|
| Water-to-cement ratio (%) | Cement (kg/m³) | Water (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) |
|---------------------------|----------------|--------------|------------------------|--------------------------|
| 35                        | 388            | 137          | 748                    | 1126                     |

| Table 6: Slurry composition of test groups. |
|---------------------------------------------|
| Group | Slurry composition                        |
|-------|-------------------------------------------|
| R1    | Matrix asphalt BRA Cement                  |
| R2    | Matrix asphalt BRA Silicon powder          |
| R3    | Matrix asphalt BRA Slaked lime and cement  |
| R4    | Matrix asphalt SBS asphalt Cement          |

| Table 7: Test scheme of natural asphalt. |
|-----------------------------------------|
| Content | Ratio |
|--------|-------|
| BRA    | 0%    | 5%    | 10%   | 15%   | 20%   |
| TLA    | 0%    | 5%    | 10%   | 15%   | 20%   |

| Table 8: Test scheme of admixture. |
|-----------------------------------|
| Content | Ratio |
|--------|-------|
| Cement | 10%   | 20%   | 30%   | 40%   | 50%   |
| Silicon powder | 10%   | 20%   | 30%   | 40%   | 50%   |
| Slaked lime + cement | 10%   | 20%   | 30%   | 40%   | 50%   |
3. Results and Discussion

3.1. Determination of Type and Content of Natural Asphalt.
Compared with matrix asphalt, both BRA and TLA have good high temperature stability and aging resistance. Their physical and chemical properties are consistent with those of matrix asphalt, so they have good compatibility with matrix asphalt. The properties of the modified asphalt with different proportions of BRA and TLA were tested, and the results are shown in Tables 9 and 10, respectively.

According to the test results, the change trend of the modification effect of BRA and TLA on the matrix asphalt is basically the same with the change of the ratio. As the ratio increases, the penetration and ductility become smaller, and the viscosity and softening point increase. This is because the penetration and elongation of BRA and TLA are smaller than the matrix asphalt, and the viscosity and softening point are larger than the matrix asphalt.

Under the same ratio, BRA has more significant effect on the modification of matrix asphalt than TLA. Even the viscosity increases with the increase of the ratio, the value is still lower than 1 Pa·s. The asphalt-based grouting material needs a higher softening point to resist deformation under normal temperature of the prestressed structure. When the ratio of BRA is 10% to 15%, the improvement of the softening point is greater than that of other admixtures.

![Asphalt pump](Asphalt pump)
![Asphalt slurry](Asphalt slurry)
![Gate valve](Gate valve)
![Pipe](Pipe)

Figure 4: Grouting experiment of the asphalt-based material in concrete beam.

![Asphalt pump](Asphalt pump)
![Asphalt slurry](Asphalt slurry)
![Gate valve](Gate valve)
![Pipe](Pipe)

Figure 5: Arrangement of sensors (mm).

| Table 9: Properties of asphalt mixture with different ratios of BRA. |
|---------------------------------------------------------------|
| Content | Unit | 0% | 5% | 10% | 15% | 20% |
|----------|------|----|----|-----|-----|-----|
| Penetration (25°C) | mm | 69.5 | 66.8 | 62.9 | 54.2 | 48.3 |
| Ductility (15°C) | cm | 427 | 360 | 230 | 110 | 30.6 |
| Viscosity (135°C) | Pa·s | 0.33 | 0.41 | 0.47 | 0.65 | 0.75 |
| Softening point | °C | 47.3 | 49.5 | 51.1 | 54.5 | 55.6 |

| Table 10: Properties of asphalt mixture with different ratios of TLA. |
|---------------------------------------------------------------|
| Content | Unit | 0% | 5% | 10% | 15% | 20% |
|----------|------|----|----|-----|-----|-----|
| Penetration (25°C) | mm | 69.5 | 68.4 | 66.7 | 60.2 | 57.5 |
| Ductility (15°C) | cm | 427 | 330 | 190 | 70 | 20 |
| Viscosity (135°C) | Pa·s | 0.33 | 0.38 | 0.43 | 0.54 | 0.63 |
| Softening point | °C | 47.3 | 48.7 | 50.2 | 53.2 | 54.8 |
Therefore, BRA is selected as modified asphalt of the base asphalt, and the ratio is 12.5%.

3.2. Viscosity of Different Type and Content of Admixture. The viscosity of asphalt-based grouting material is not constant, but is related to temperature, pressure, time, and shear strain. Among these factors, temperature has the most significant effect on the viscosity. For the research object of this paper, the viscosity is described by the logarithmic coordinate and the single logarithmic coordinate of temperature. The relationship can be described as [29]

$$\log\log(\eta \times 10^3) = n - m\log(T + 273.13),$$

(2)

where $\eta$ is the viscosity, $m$ and $n$ are the regression coefficients, and $T$ is the absolute temperature.

The viscosity of asphalt-based grouting material is closely related to temperature. In this case, the viscosity for specific temperatures was tested, and the coefficients $m$ and $n$ were obtained according to the test results. Then, the viscosity at different temperatures (90°C, 110°C, and 130°C) can be calculated by (2). The viscosity of asphalt-based grouting material with different mixing ratios at different temperatures is shown in Table 11, the ratio of rock asphalt of each group is 12.5%, and the ratio of SBS-modified asphalt of each group is 7.5%.

The viscosity of asphalt-based grouting material with different ratios of admixture at 90°C and 110°C is shown in Figure 6. As the ratio of the admixture increases at 90°C, the viscosity of the mixing ratio of R1, R2, and R4 increases slowly, and the proportion increases substantially. This is due to that the asphalt-based grouting material is a diluted particulate reinforcing fluid in these ratios, and the ratio is linearly changed for the reinforcing effect of the material. The viscosity increases relatively slowly when the ratio of R3 is less than 30%, but it starts to increase rapidly when the ratio exceeds 30%. The viscosity changes of the mixing ratio of R1, R2, and R4 are similar at 90°C and 110°C, and the viscosity of R3 increases rapidly after the mixing ratio is 40%. As the ratio of the admixture increases, the growth trend of viscosity of R3 is much larger than the other three groups. This is because the slaked lime in R3 can produce physicochemical reaction with the carboxylic acid in the asphalt to produce bauxite salt, which exhibits strong interfacial bonding force to increase the viscosity of the asphalt-based grouting material. The effect of adding SBS-modified asphalt is not as obvious as that of BRA, and the segregation phenomenon is serious during the test. A similar phenomenon occurs when silicon powder is added, and it produced a lot of impurities. Therefore, the mixing ratios of R2 and R4 are not suitable as the grouting material for the prestressed structure.

3.3. Viscosity-Temperature Relationship of Asphalt-Based Material. The viscosity test results of the asphalt-based material at different temperatures are shown in Figure 7. According to the results, the viscosity-temperature relationship curves of the asphalt-based grouting material with different mixing ratios can be established, and the suitable mixing ratio and grouting temperature of asphalt-based material are discussed. At present, the grouting viscosity of asphalt pumps commonly used in the market ranges from 0 Pa·s to 10 Pa·s. Considering the winter construction, the ambient temperature is low, and the pump and the conveying pipeline may have a temperature drop even if there are insulation measures. With the safety factor of 2.5, the viscosity of the asphalt-based grouting material applied to the prestressed structure should be less than 4 Pa·s. Under the four ratios, the minimum grouting temperatures of the asphalt-based grouting material are 107°C, 104°C, 119°C, and 106°C.

3.4. Shear Strength of Asphalt-Based Material. At normal temperature, the penetration-intensity test was carried out on asphalt-based grouting material with different mixing ratios, and the penetration weight and penetration degree were measured, respectively. According to the measured data and (1), the shear strength of different proportions can be obtained as shown in Table 12.

As the ratio of the admixture increases, the growth trend of the shear strength of the asphalt-based grouting material is shown in Figure 8. On the whole, the shear strength increases with the increase of ratio of admixture, which indicates that the addition of the admixture can improve the shear strength of the asphalt-based grouting material.

It can be seen from Figure 8, as the ratio of the admixture increases, the shear strength of R3 increases much faster than the others. For the growth trend of the R3, the shear strength increases rapidly as the ratio of the admixture is less than 40%. When the ratio of the admixture increases from 40% to 50%, the growth rate of the shear strength begins to slow down. But as shown in Figure 6, when the ratio increases from 40% to 50% at 110°C, the viscosity growth is still fast, which was not conducive to the viscosity reduction of grouting at high temperatures. According to the results, the ratio of the admixture can be selected as 40%.

After material tests, the suitable slurry composition of the asphalt-based grouting material for prestressed duct is determined as follows: pure asphalt, natural asphalt (BRA), and admixture (lime and cement). The mix ratio of BRA is 12.5%, and the ratio of admixture (lime and cement) is 40%. The shear strength of asphalt-based grouting material at normal temperature is 697.21 kPa, and the suitable grouting temperature is 115°C.

3.5. Groutability of Asphalt-Based Material. The asphalt-based material prepared according to the obtained mix was heated to 115°C and then pumped into the duct in the test beam. The grouting process was smooth, and the slurry can be filled with duct. The temperature and temperature stress were tested at grouting time of 30 s and 120 s, respectively, and the results are as shown in Figure 9. From Figure 9(a), it can be seen that the temperature of the concrete at the measuring point decreases gradually from fast to slow after a peak value. The peak temperature of concrete was mainly affected by grouting time; it can reach almost 50°C when the
grouting time is 30 s, but only 40 °C when the grouting time is 120 s.

From Figure 9(b), it can be seen that the temperature stress of the concrete at the measuring point is consistent with the development of the grouting time. After a rapid growth, the temperature stress reaches the maximum value of the tensile stress and then drops quickly to reach the maximum value of compressive stress. With the development of time, the compressive stress of the concrete gradually decreases. Because of the thermal expansion at the beginning of the grouting, the tensile stress occurs in the concrete. Then, the concrete around the strain sensor is expanded with the diffusion of heat, and the trend of expansion is blocked by the surrounding concrete which

Table 11: Viscosity for asphalt-based grouting material with different ratios of admixture.

| Group | Slurry composition | Ratio of admixture | Viscosity (Pa·s) |
|-------|-------------------|--------------------|-----------------|
|       |                   | 0% | 10% | 20% | 30% | 40% | 50% |
| R1    | Matrix asphalt + BRA + cement | 4.13 | 6.11 | 8.42 | 9.97 | 11.21 | 12.35 |
|       |                   | 1.22 | 1.76 | 2.36 | 2.52 | 2.74 | 3.03 |
| R2    | Matrix asphalt + BRA + silicon powder | 4.13 | 4.38 | 7.01 | 8.23 | 9.83 | 11.05 |
|       |                   | 1.22 | 1.41 | 1.93 | 2.38 | 2.56 | 2.85 |
| R3    | Matrix asphalt + BRA + (slaked lime : cement = 1 : 9) | 4.13 | 9.36 | 13.61 | 16.60 | 24.02 | 32.91 |
|       |                   | 1.22 | 2.63 | 4.06 | 4.77 | 5.87 | 7.91 |
| R4    | Matrix asphalt + SBS asphalt + cement | 4.13 | 5.82 | 7.72 | 9.17 | 10.70 | 11.46 |
|       |                   | 1.22 | 1.67 | 2.16 | 2.42 | 2.63 | 2.91 |

Figure 6: Viscosity variation along different ratios of admixture at (a) the temperature of 90°C and (b) the temperature of 110°C.
Figure 7: Relationship between viscosity and temperature. (a) R1. (b) R2. (c) R3. (d) R4.

Table 12: Shear strength of asphalt grouting material with different ratio of admixture (kPa).

| Group | Shear strength |
|-------|----------------|
|       | 0%  | 10%  | 20%  | 30%  | 40%  | 50%  |
| R1    | 102.36 | 219.09 | 336.95 | 412.37 | 472.61 | 493.23 |
| R2    | 102.36 | 181.54 | 290.58 | 380.02 | 433.65 | 479.87 |
| R3    | 102.36 | 292.96 | 489.36 | 551.31 | 697.21 | 711.22 |
| R4    | 86.36  | 208.09 | 285.74 | 395.20 | 447.36 | 433.60 |
resulted in compressive stress. With the development of time, the amount of expansion decreases as the temperature drops; thus, the compressive stress of concrete is close to 0 MPa.

4. Conclusion

This paper presents the design and the experimental verification of an asphalt-based grouting material of prestressing structure in corrosive environment. Through the corresponding material test, the composition and proportion of the grouting material were determined, and the appropriate grouting temperature of the material was obtained. The grouting test of the material was carried out on the concrete test beam to determine its groutability. The following conclusions are made from this study:

(1) The appropriate composition of the asphalt-based grouting material was determined as pure asphalt, natural asphalt (BRA), and admixture (slaked lime and cement) after preliminary experimental study. Based on the requirements of prestressed grouting, the properties of viscosity and shear strength of the asphalt-based grouting material were considered as key performance parameters. The Bush viscometer

Figure 8: Variation of shear strength for test groups.

Figure 9: Comparison of the temperature and the temperature stress in the concrete at different grouting time. (a) Temperature. (b) Temperature stress.
test for viscosity and the penetration test for the shear strength were used in this study.

(2) Combined with the viscosity and the shear strength test results, the suitable mixing ratio for asphalt-based material was determined as matrix asphalt, BRA, and admixture (slaked lime and cement), where the ratio of BRA was 12.5%, and the total ratio of admixture was 40%. The shear strength of the asphalt-based grouting material was 697.21 kPa at normal temperature, and the suitable grouting temperature was 115°C.

(3) Through the verification test, the asphalt-based material was used for grouting in the test beam under our proposed technical indicators, and the temperature and temperature stress in the concrete near the slurry were measured. The whole pipeline was filled with the slurry after the grouting which met the basic requirement. The temperature stress caused by slurry decreased with the reduction of grouting time, and the peak value was lower than 1.4 MPa which met the ultimate strength requirement of the concrete. Based on the test results, the groutability of the material and the safety of the concrete with the grouting slurry were verified.

Data Availability
According to cooperation agreement, any type of date, including testing and recording, belongs to the unit and is therefore confidential to anyone else. The authors thank the readers for their understanding of the cooperation agreement.

Conflicts of Interest
The authors declare that they have no conflicts of interest regarding the publication of this paper.

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