A New Soil Conditioner for Highly Permeable Sandy Gravel Stratum in EPBs

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Abstract: Full-face water-rich gravel stratum is a large challenge during tunnel excavation with earth pressure balance shields (EPBs) because of accidents such as water spewing from the screw conveyor and ground collapse. Slurry and polymer have been used as conditioning agents to avoid such problems and thus ensure a successful tunneling. However, limited improvement of sandy gravel was achieved when traditional soil conditioner were applied. This study proposes a new conditioner (modified slurry) consisting of bentonite slurry, viscosity modifier, sodium silicate and polymer, which will enhance the properties of sand gravel stratum. Low reaction time, high apparent viscosity, good plastic behavior and low permeability were employed for investigating the optimum ratio of the ingredients. The proposed modified slurry has a good performance in conditioning sandy gravel soils and can be the reference for EPBs’ excavation in highly permeable, non-adhesive coarse-grained soil stratum.

Keywords: modified slurry; EPBs; sandy gravel; plasticity; permeability

1. Introduction

In recent years, with the increasing demand for underground space, underground tunnel excavation technology has transitioned from open excavation to underground excavation and has become a research hotspot [1–3]. Among all excavation technologies, the earth pressure balance shield (EPBs) is the most commonly used [4]. Under different stratum conditions, specific accidents may occur in the application of EPBs, which makes it difficult to apply this method. For example, different from tunneling in clayey soil, in a sandy gravel stratum accidents, such as groundwater spew and ground collapse, may occur when EPBs is used [5–7]. Furthermore, since Beijing, Chengdu and other cities that are vigorously developing the metro are rich in sandy pebble stratum, a new soil conditioner for highly permeable sandy gravel to prevent water spewing has become a key technology problem to be solved in underground tunnel construction and in the application of EPBs in China [8].

To ensure the successful excavation of a tunnel in the process of EPBs, an improvement technology to obtain the “ideal soil” (low permeability, moderate compressibility, small shear strength and certain fluidity) by adding soil conditioners was proposed [9]. Large particle size, low clay content and low cohesion lead to poor plastic paste and the high permeability of sandy gravel soils. Soil conditioners can decrease the permeability and improve the plastic paste of sandy gravel soils, and many successful cases were obtained [10].

Considerable studies on the improvement of sandy gravel soils have been conducted by researchers. A foam agent was added to enhance the plastic paste of the soil. Peila et al. (2009) [11] studied the effect of different ratios of foam injection on the soil slump of various non-viscous coarse-grained soils. According to the foam loss, slump and water loss, the
improvement results were divided into the non-suitable, the suitable, and the borderline. Mori et al. (2018) [12] concluded that a foam agent can effectively fill the granular soil void, reduce the friction and shear strength between soil particles and improve the plasticity of soil. In the conditioned soil, qualitative evaluation standard considers the slump to be mainly related to the foam injection ratio and water content [13].

However, enhancing the plastic and reducing the permeability are required to prevent water spewing in water-rich sandy gravel stratum [14,15]. When excavating in a coarse-grained stratum, it is insufficient to obtain a satisfactory conditioning by simply adding a foam agent. Some researchers proposed polymer or bentonite slurry for reducing soil permeability [15]. Adding polymer material to the slurry not only increases the viscosity of the liquid, but also the polymer’s long-chain structure can enhance the adhesion between the fine particles of the slurry, so that the conditioned slurry has a better sealing effect on the large-grit sand-gravel soil [16].

During the construction of the earth pressure balance shield tunnel in the high permeability stratum, some methods have been proposed to improve its permeability by adding water-insoluble fine particle solids (such as fine sand, calcium carbonate powder, etc.) or polymer materials. Fritz (2007) [17] added fine sand (<1 mm), vermiculite (0.7–4 mm) and a small amount of high-polymer material to the soil of high permeability, which significantly reduced the permeability. In addition, filtration problems always occur in the formation of slurry. Bosshard (2011) [18] used slurry and high polymer to improve the high-permeability (k > 3 × 10⁻³ m/s) of gravel stratum in the process of Weinberg tunnel construction. Carrieri (2006) [19] injected a turbid liquid of calcium carbonate powder as a filler into the excavation chamber, which improved high-permeability coarse sand formation in Turin Metro Line 1. Zhao (2018) [20] improved the viscosity of sodium bentonite by sodium carbonate and carboxymethyl cellulose sodium (CMC) and obtained S1 bentonite slurry (the ratio of bentonite, water, Na₂CO₃ and CMC is 6:1:0.042:0.056), which was successfully applied to the waterless sand-pebble stratum of Urumqi Metro Line 1.

Previous studies concluded that the polymer can increase the cohesion by filling in the voids between the gravel particles, while the bentonite slurry or filler mainly filled in voids between the fine-grained particles and forms a slurry film, consequently reducing the permeability of the stratum.

To ensure a successful tunneling by EPBs in a water-rich sandy gravel stratum, this study proposed a new soil conditioner that is capable of effectively improving the plasticity and impermeability of sand and gravel. The main objects were: (1) to study the effect of ammonium chloride as a viscosity modifier on the apparent viscosity and rheology of sodium bentonite slurry; (2) to study the improvement effect of modified slurry on the plasticity of non-cohesive sand and gravel; and (3) to study the impermeability improvement of sandy gravel conditioned by sodium silicate solution, high molecular polymers and modified slurry.

2. Materials and Methods

2.1. The Modified Slurry Modifier Components

The traditional slurry is commonly the aqueous solution of sodium bentonite with 10–18 wt%. The preparation method added the weighted sodium bentonite powder to distilled water several times. It should be noted that the incorporation quality of sodium bentonite was less than 5 g to avoid an uneven blend and the solution was stirred at 1000 r/min.

In this study, ammonium chloride, sodium silicate and high molecular polymers were mixed into the traditional slurry to modify and improve it, in which ammonium chloride was the viscosity modifier to adjust the reaction time. In order to distinguish the traditional slurry, the mixed solution of modifier and slurry was called modified slurry. In addition, high molecular polymers were helpful for enhancing the impermeability of the mixed system.

In this study, the modified slurry preparation process mainly included two mixed solution systems, namely, the mixed solution of bentonite and sodium silicate as well as
the mixed solution of ammonium chloride and high polymers. The sodium bentonite (Henan Zhongyuan Mining Company, Henan Province, China) chemical components and physical characteristics are shown in Tables 1 and 2. Ammonium chloride (Beijing Chemical Reagent Factory, Beijing, China) formed the viscosity modifier for modified materials. The ammonium chloride was analytically pure (>99%), the sodium silicate solution (Shandong Dongyue Group, Shandong Province, China) had a Baume Degree of 40, and the content was 34 wt%. There were 6 kinds of polymers. They are carbomer (97%, Sumitomo Chemical Co., Ltd., Tokyo, Japan), guar gum (99%, Guangzhou Feirui Chemical Co., Ltd. Company, Guangzhou, China), xanthan gum (99%, Fufeng Group, Jinan, China), carboxymethyl cellulose sodium (99%, Yixing Tongda Chemical Co., Ltd., Yixing, China), hydroxyethyl cellulose (99%, Shanghai Huguang Fine Chemical Co., Ltd., Shanghai, China) and polyacrylamide (99%, Shandong Baomo Biochemical Co., Ltd., Dongying, China). Details of the components are shown in Table 3. Code B represents a solution of 13 wt% bentonite, other codes have similar meanings, and the solvent was water. In the process of polymer solution preparation, it should be noted that the weighed reagent was slowly added into the 50–60 °C distilled water and then the solution was stirred at 2000 r/min for more than 30 min until the solution was clear.

Table 1. Main chemical constituents of sodium bentonite.

| Ingredient | SiO$_2$ (Content %) | Al$_2$O$_3$ | Fe$_2$O$_3$ | Na$_2$O | MgO | K$_2$O | TiO$_2$ |
|------------|---------------------|-------------|-------------|---------|------|--------|--------|
|            | 63.43               | 17.88       | 2.06        | 0.98    | 3.05 | 0.9    | 0.13   |

Table 2. Sodium bentonite properties.

| Expansion Capacity (mL/g) | Gum Price (mL/15 g) | Wet-Heat Tensile Strength (KPa) | Steady State Tensile Strength (KPa) | Blue Absorption Power (mmol/100 g) | 200 Mesh Throughput (%) |
|--------------------------|--------------------|-------------------------------|-----------------------------------|-----------------------------------|------------------------|
| 30                       | >100               | 1.4                           | 45                                | 25                                | 95                     |

Table 3. Experimental materials.

| Material Category/Use | Name                      | Concentration (wt%) | Density (g/mL) | Code  |
|-----------------------|---------------------------|---------------------|----------------|-------|
| Slurry                | Sodium bentonite          | 13                  | 1.11           | B     |
| Water shutoff agents  | Sodium silicate           | 34                  | 1.37           | S     |
| reaction material     |                           |                     |                |       |
| Viscosity modifier    | Ammonium chloride         | 20                  | 1.04           | A     |
| Polymers / Water      | Carboxomer                | 0.5                 | 1.06           | Carbo |
| shutoff agents        | Guarr gum                 | 0.5                 | 1.02           | Guar  |
|                       | Xanthan gum               | 0.5                 | 1.04           | Xan    |
|                       | Carboxymethyl cellulose   | 0.5                 | 1.04           | CMC   |
|                       | Sodium Hydroxyethyl cellulose | 0.5          | 1.08           | HEC/H |
|                       | Polyacrylamide            | 0.5                 | 1.04           | PAM   |

Four different grades of sandy gravel soil samples were prepared in the laboratory, in which the coarse sand was selected from standard sand, the main mineral component was quartz, and the gravel was a natural breccia-like cobblestone whose main mineral composition was quartz and carbonate minerals. The gradation curve and dry density information are shown in Figure 1 and Table 4.
Figure 1. Experimental sandy gravel particle grading curve.

Table 4. Sand gravel material physical characteristics.

| Sand Gravel Size | Coarse Sand | Gravel |
|------------------|-------------|--------|
|                  | 0–2 mm      | 2–4 mm | 4–6 mm | 6–9 mm | 10–20 mm |
| Dry Density (g/mL) | 1.77        | 1.77   | 1.78   | 1.71   | 1.66     |

2.2. Slurries Conditioner Preparation

Modified slurry is a mixed material prepared by adding ammonium chloride, sodium silicate and high molecular polymer into traditional slurry. In the preparation process of the modified slurry, the traditional slurry and each modifier solution were separately configured. Before the relevant tests, the solutions were mixed according to the experimental design ratio, and then stirred evenly with a glass rod.

In engineering applications, all fluid materials (such as slurry, foam, polymers solution, etc.) must be pumped into the excavation chamber, which consequently requires the materials to have good fluidity. On the one hand, the high apparent viscosity and non-flowing state of the modified slurry are the key to improving the plasticity and water blocking of sand and gravel soil. On the other hand, the fluidity of the slurry is a prerequisite for actual engineering use. Based on that, the traditional slurry and modifier solution involved in this article need fluid composition with good fluidity to ensure that the material can be easily pumped into the excavation cabin to mix and react to form a modified slurry.

In this study, the main objective was to obtain the traditional slurry with moderate apparent viscosity, good time stability and fluidity. The apparent viscosity of traditional slurry samples with four bentonite concentrations (i.e., 10 wt%, 13 wt%, 15 wt% and 18 wt%) over time (0–50 h) are measured. The dumping method was used to compare with and analyze the slurry flow corresponding to different apparent viscosity values, and then the fluidity of each experimental group was evaluated. Afterwards, the optimal bentonite concentration was obtained. In order to study the apparent viscosity and fluidity of the mixed system after adding ammonium chloride solution to the traditional slurry, the experimental goals were to obtain the modified slurry with high apparent viscosity and low fluidity. In this study, five ratios of bentonite slurry and ammonium chloride solution were selected (B:A = 20:1, 10:1, 5:1, 10:3 and 5:2).
To study the effect of ammonium chloride on the water absorption time of bentonite slurry, six modifiers were prepared with different ammonium chloride concentrations, one modifier was used (i.e., Ammonium Chloride) but in six different ratios, one containing no ammonium chloride as a control. At this stage, no further additive was included in the mixture. The details are shown in Table 5. The preparation process was as follows: a certain amount of water was added to the beaker, then bentonite with 13 wt% was added slowly to the beaker and the solution was stirred for another 30 min until there were no lumps on the surface and no sediment at the bottom of the solution (note that, through the process, the stir rate of the magnetic stirrer was 1500 r/m)). According to the solution dissolution efficiency and the experiment results, the optimum dissolved concentration of ammonium chloride was 20 wt%. In this study, the slurry solution was mainly composed of bentonite (B) and ammonium chloride (A), which is called B/A modified slurry. B/A refers to the mixture mainly formed by B and A.

Table 5. B/A modified slurries modifier samples.

| Sample No. | Bentonite (mL) | Ammonium Chloride (mL)/Concentration (wt%) | Remarks |
|------------|----------------|------------------------------------------|---------|
| B-A-0      | 100            | 0/0                                      | Control sample |
| B-A-10     | 100            | 10/10                                    | Study the effect of ammonium chloride concentration on the degree of expansion |
| B-A-15     | 100            | 10/15                                    |         |
| B-A-20     | 100            | 10/20                                    |         |
| B-A-25     | 100            | 10/25                                    |         |
| B-A-30     | 100            | 10/30                                    |         |

In addition, to study the influence of sodium silicate concentration and polymers types on the impermeability improvement degree of soil, the conditioners containing different concentrations of sodium silicate and different types of polymers were prepared.

2.3. Analysis Method

2.3.1. Apparent Viscosity Test

The concentration and hydration time of bentonite play the key roles in affecting the fluidity of traditional slurry. Traditional slurry is the basic composition of modified slurry. The main targets for optimizing the composition of the traditional slurry are to be equipped with higher viscosity value, better viscosity stability and fluidity.

Apparent viscosity (i.e., effective viscosity) is an important parameter that characterizes fluid flow performance and can be used as an evaluation index for fluid pumping performance. The apparent viscosities of the conditioners prepared were tested by a ZNN-D6 six-speed rotational viscometer [21]. In this study, the apparent viscosity values of the slurry samples were measured after the samples prepared 5–20 min. The test procedure was as follows: (1) the cup of the sample (350 mL) was placed on a tray that subsequently was elevated until the scale line outside the rotary sleeve was completely immersed in the sample; (2) stable readings at 600 r/m, 300 r/m, 200 r/m, 100 r/m, 6 r/m and 3 r/m were recorded. Steps (1) and (2) were repeated twice. The interval time of each experiment should not exceed 2 min. Half of the average value of three readings at a rate of 600 r/m is the apparent viscosity.

2.3.2. Slump Test

Slump test is a commonly used method to evaluate the effect of soil flow plasticity improvement during the construction of the earth pressure balance shield. Based on the results of the traditional slurry and the ammonium chloride optimization experiments, in order to compare with and analyze the plasticity improvement effects of traditional slurry and modified slurry on soil flow, the effects of the traditional slurry and ammonium chloride modified on the slump of six soil samples were studied. The flow plasticity of the improved soil is classified according to its slump value. Combining with the improvement
of the goal of sand and gravel soil in actual engineering, the reasonable flow plasticity state of sand and gravel are discussed in this study.

In this study, the slump test was adopted to evaluate the flow plasticity of conditioned soil by modified slurry. Before the slump test, the soil samples (6 L) and the modified slurry were mixed with different experimental ratio (5%, 10%, 15%, 20%, 25% and 30%) and stirred with a mixer for 3 min. According to the slump test standard [22], the test procedure was as follows: (1) the conditioned soil samples were loaded into the slumping cylinder three times until the cylinder was full, with 25 instances of tamping at each load, so that the thickness of each layer was approximately one third of the cylinder height; (2) the cylinder was elevated vertically and smoothly (within 5–20 s). The height difference $s_1$ (before and after the test) was recorded, and the test was repeated two more times to obtain $s_2$ and $s_3$, respectively. The average value of the three slump tests is the result. In addition, the slump experiment was completed after the slurry samples had been prepared for no more than 20 min.

2.3.3. Permeability Test

Based on the apparent viscosity and slump test, decreasing the permeability of soil sample plays the key role in preventing the spewing problem of the screw machine in the excavation process of the earth pressure balance shield on the sand and gravel ground. In order to find a slurry additive material and a better ratio decrease to reduce the permeability of the slurry-soil mixture, a large number of experiments show that the permeability of mixing system is decreased with the sodium silicate solution or polymers solution is added into the traditional slurry-ammonium chloride mixing system. It is mainly caused by the fact that the silicate ions ionized by the sodium silicate solution can not only react with the calcium and magnesium ions in the slurry to form calcium silicate, magnesium silicate and other water-insoluble fine particles, but also react with chlorination the ammonium ion in the ammonium solution to produce water-insoluble silicic acid. The formation of insoluble matter, such as silicic acid, magnesium silicate and calcium silicate can increase the water-insoluble fine particulate matter in the slurry mixing system to reduce the permeability of the mixing system. Due to the special long-chain molecular structure of the polymer, the integrity of the bentonite particles was increased at the microscopic level, thereby improving the water blocking ability of the slurry.

Based on the experimental phenomena, the types and ratios of sodium silicate solution and polymer solution were optimized. This study investigated the change curve of the penetration rate and time of the slurry-soil mixed system when sodium silicate solution and polymer materials are used as slurry additives. Taking the minimum permeation amount of the mixing system per unit time as the preferred index, the ratio of sodium and sodium silicate solution and the type and ratio of polymer materials are optimized, respectively.

A permeability test device was developed, which mainly consists of a sealing cover, rubber pad, pressure-maintaining vessel, metal filter, high-pressure gas pipe, pressure regulator valve, air compressor, metering container, and electronic weighing platform (see Figure 2). The pressure maintaining vessel is made of pressure-resistant acrylic material, and the cylinder is 260 mm high, 70 mm in diameter, 5 mm in wall thickness and 60 mm in inner diameter. The pressure vessel was designed to withstand a pressure of 5 bar.

The test procedure was as follows: (1) a gravel (2–4 mm) permeable layer was placed at the bottom of the pressure-maintaining vessel, and subsequently the conditioned soil sample was packed into the vessel until it was 15 cm in height. The sample was loaded every 2–3 cm of height with compaction; (2) 200 mL of water was poured into the vessel, which was subsequently sealed up; (3) The pressure was adjusted to 2 bar; (4) The pressure regulator valve was opened and timed at the same time; and (5) the water seepage volume was recorded every 1 min. When the water seepage volume was greater than 200 mL or the test time was greater than 30 min, the experiment was stopped and the pressure was relieved.
3. Results and Discussion

3.1. Apparent Viscosity Test

3.1.1. Difference between Traditional Slurry and B/A Modified Slurry

Viscosity tests of traditional bentonite slurry at different concentrations, including 10 wt%, 13 wt%, 15 wt%, and 18 wt% were performed. As shown in Figure 3a, the viscosity is closely related to time regardless of which slurry concentration is used. More specifically, the viscosity of traditional slurry increases first and then remains stable over time. For example, the viscosity of traditional slurry at a concentration of 15 wt% sharply increases from 24 mPa·s to 41 mPa·s within 0–10 h. Subsequently, its viscosity remains stable at approximately 43 mPa·s after 10 h. This is because the main component of bentonite is a clay mineral (i.e., montmorillonite), which has a multilayer crystal structure. When water was added into bentonite, the water molecules easily entered the smectite layers and thus lead to the lattice expanding. As hydration time increases, the water molecules were transformed into a hexagonal ring structure through hydrogen bonding, and thus the interaction force montmorillonite crystal was enhanced [23]. In addition, it can be seen from Figure 3b that the fluidity of slurry is great when its viscosity is less than 35 mPa·s, while the fluidity deteriorates as its viscosity increases to larger than 40 mPa·s, and then the slurry exhibits a slow flow state when the viscosity exceeds 50 mPa·s.

According to the construction experience [24], proper pumpability of bentonite slurry is necessary to ensure smooth tunneling. Since bentonite slurry at 13 wt% concentration exhibited proper viscosity and sufficient hydration degree, the concentration was used to prepare the B/A modified slurry sample. Figure 3c is the schematic diagram of the mixture of 13 wt% bentonite slurry and 20 wt% ammonium chloride solution. Compared with the traditional slurry (Figure 3b), the viscosity of bentonite slurry rapidly increases after adding ammonium chloride solution and the B/A modified slurry exhibits a nonflowing state. Therefore, the ammonium chloride solution can be used as a viscosity modifier for traditional slurry.

Figure 3d illustrated that the ammonium ions can exchange with calcium, magnesium and sodium in bentonite and are not easily occluded by other ions, which is caused by ammonium ions that have a small hydration radius, low hydration energy, similar ionic radius with a six-membered ring radius in a clay crystal lattice [25]. Therefore, ammonium chloride solution can act as a viscosity modifier of traditional slurry. The apparent viscosity of traditional slurry increased and the fluid loss of sand gravel samples reduced after adding solution containing ammonium ions. Subsequently, the solution added with excess ammonium ions would lead to aggregation of montmorillonite particles and then the aggregates were surrounded by water molecules to form high consistency and viscosity copolymer slurry.
3.1.2. Optimization of Viscosity Modifier Concentration

As mentioned above, the incorporation of ammonium chloride solution can increase the apparent viscosity of traditional slurry instantaneously. In order to investigate the effect of ammonium chloride solution volume on the viscosity of B/A modified slurry, the blend of 13 wt% bentonite slurry and 20 wt% chlorine with different volume ratios was prepared, including 20:1, 10:1, 5:1, 10:3 and 5:2. The viscosity of the B/A modified slurry was measured and the results were shown in Figure 4a and Table 6. It can be observed that, as the volume fraction of ammonium chloride solution increases, the consistency of the B/A modified slurry first increases and then decreases. The depth change of the cone (tested by mortar consistency meter) is consistent with the apparent viscosity. When the ratio is 10:1, the initial consistency of the slurry is the largest and shows a non-flowing state compared with other samples. In addition, Figure 4b shows the viscosity changes of various B/A modified slurry samples over time. It can be seen that the viscosity of
B/A modified slurry slightly increases and then shows a stable trend over time, but the increasing degree does not exceed 10 mPa·s during the first 30 min. Among them, the B/A modified slurry with 10:1 volume ratio has the greatest plasticity and its viscosity is the largest. According to the experiment’s results, the B-A-20 sample (B/A = 10:1, 20 wt% NH₄Cl) was selected as the basic sample because of its great effectiveness.

![Figure 4](image-url)  
**Figure 4.** (a) Effect of the B/A modified slurry dumping state under different ratios, and (b) Change of apparent viscosity with time.

### Table 6. Apparent viscosity and cone penetration of different sample groups.

| Match Ratio | Apparent Viscosity (mPa·s) | Status Description                  |
|-------------|-----------------------------|-------------------------------------|
| 13 wt% bentonite (B) | 18                          | Good liquidity.                    |
| 20 wt% NH₄Cl (A)   | 0.5                         | Very fluid, equivalent to water.    |
| 13 wt% bentonite: 20 wt% NH₄Cl = 20:1 | 127                         | Moderate consistency, inverted microflow. |
| 13 wt% bentonite: 20 wt% NH₄Cl = 10:1 | 146                         | Consistency is high, inverted does not flow. |
| 13 wt% bentonite: 20 wt% NH₄Cl = 5:1 | 118                         | Moderate consistency, inverted microflow. |
| 13 wt% bentonite: 20 wt% NH₄Cl = 10:3 | 79                          | Less consistency, inverted flow.    |
| 13 wt% bentonite: 20 wt% NH₄Cl = 5:2 | 56                          | Small consistency, flowing after dumping. |

3.2. **Slump Test**

3.2.1. **Comparison of Traditional Slurry and B/A Modified Slurry**

A slump test, a common method for conditioned soil, was used in this study to evaluate the modification effectiveness of traditional and B/A modified slurry to sandy gravel samples with different diameters, including 0–2 mm, 2–4 mm, 6–9 mm and 10–20 mm. The results of the slump tests on the mixtures of various sandy gravel and slurry of 5%, 10% and 20% (volume ratio) are shown in Table 7 and Figure 5. The following results were observed:

### Table 7. Comparison of slump between slurry and B/A modified slurry.

| Sample Group | Injection Ratio | Additive     | 5%  | 10%  | 20%  |
|--------------|-----------------|--------------|-----|------|------|
|              |                 | Average Slump (mm) |     |      |      |
| 2–4 mm Gravel| Traditional slurry | 158   | 170 | 178  |
|              | B/A modified slurry | 155  | 136 | 0    |
| 6–9 mm Gravel| Traditional slurry | 177   | 180 | 196  |
|              | B/A Modified slurry | 172  | 162 | 0    |
| 10–20 mm Grave| Traditional slurry | 162  | 168 | 174  |
|              | B/A Modified slurry | 150  | 146 | 135  |
6–9 mm (particle size) and 10–20 mm sand gravel samples mixed with 20% traditional slurry. In addition, the larger the size of sand gravel, the greater the loss degree of slurry occurs. This is because the increasing gravel diameter increases the porosity of the gravel.

(3) As shown in Figure 5, the addition of B/A modified slurry significantly improved the cohesiveness of sand gravel particles. As the B/A modified slurry injection ratio increases the plasticity of the sand gravel samples gradually increases and its fluidity decreases.

| Sample Group | Injection Ratio | 5% | 10% | 20% |
|--------------|----------------|-----|-----|-----|
| 2–4 mm Gravel Traditional slurry | 158 | 170 | 178 |
| B/A modified slurry | 155 | 136 | 0 |
| 6–9 mm Gravel Traditional slurry | 177 | 180 | 196 |
| B/A Modified slurry | 172 | 162 | 0 |
| 10–20 mm Grave Traditional slurry | 162 | 168 | 174 |
| B/A Modified slurry | 150 | 146 | 135 |

Figure 5. Comparison of slump between traditional slurry and B/A modified slurry at various injection ratios.

(1) As shown in Table 7, B/A modified slurry shows a positive effect on improving the plasticity of sandy gravel sample, while traditional slurry has the opposite effect. Furthermore, as the traditional slurry injection ratio increases, the slump of sand gravel sample gradually increases, because traditional slurry is fluid and thus its incorporation increases the flow ability of sand gravel. The addition of B/A modified slurry reduces the slump value because the voids of sand gravel are filled by B/A modified slurry and the cohesion between sand gravel particles is enhanced by B/A modified slurry. The slump value of the mixture of 20% B/A modified slurry and sand gravel samples with 2–4 mm and 6–9 mm diameter decreased to 0.

(2) It can be seen from Figure 5 that slurry is prone to flow away from sand gravel pores and the amount of slurry loss increased with its injection ratio increasing, due to the large fluidity of traditional slurry and large voids of sand gravel sample, such as for the 6–9 mm (particle size) and 10–20 mm sand gravel samples mixed with 20% traditional slurry. In addition, the larger the size of sand gravel, the greater the loss degree of slurry occurs. This is because the increasing gravel diameter increases the porosity of the gravel.

(3) As shown in Figure 5, the addition of B/A modified slurry significantly improved the cohesiveness of sand gravel particles. As the B/A modified slurry injection ratio increases the plasticity of the sand gravel samples gradually increases and its fluidity decreases.
3.2.2. Effect of the Injection Ratio and Particle Size of the Gravel on Slump

The gravel slump is not only related to the type of bentonite slurry, but is also affected by the B/A modified slurry concentration and the size of the sand gravel sample. Therefore, the slump experiments of different sand gravel samples mixed with different injection ratios of B/A modified slurry were conducted and the results are shown in Figure 6. Peila et al. (2013) proposed that the modification state of sand gravel can be classified into three categories according to the flow, suitable and stiff states, as shown in Table 8.

![Figure 6](image-url)

Figure 6. Changes of slump with various injection ratio on different sandy gravel particle sizes.

Table 8. Conditioned sandy gravel state classification.

| Major Class     | Class              | Slump Range (mm) | Illustration         |
|-----------------|--------------------|------------------|----------------------|
| flow state      | Self-flowing state | 250–300          | Water, milk, etc.    |
|                 | Dumping flow state | 200–250          | Yogurt, cream, etc.  |
| suitable state  | Flow plasticity    | 150–200          |                      |
|                 | Plastic flow state | 100–150          |                      |
| stiff state     | Moderate plastic   | 50–100           |                      |
|                 | Plastic state      | 0–50             |                      |
As seen from Figure 6, the slump value of differently sized sand gravel samples without the addition of modifier is between 170 mm and 180 mm. When the injection ratio of B/A modified slurry is 5%, the slump value of sand gravel with a diameter of 0–2 mm sharply decreases to 132.5 mm, while the flow plasticity state almost does not change for the sand gravel samples of 2–20 mm in size. As the slurry injection ratio increases to 10%, the slump value of the sand gravel a size of 0–2 mm decreases to zero, and the flow plasticity state reaches a plastic non-flow state. For the sand gravel sample with a diameter of 2–6 mm, the flow plasticity state is transformed from flow plasticity to plastic flow, while the state of the sand gravel of 6–20 mm in size is still the flow plasticity state. When the slurry concentration continually increases to 15%, the 2–6 mm sand gravel sample changes from plastic flow state to medium plastic state, and the mixture of 6–20 mm sand gravel and B/A modified slurry changes from flow plasticity state to plastic flow state. Furthermore, the slump value of the sandy gravel sample with a diameter of 0–10 mm decreases to nearly zero, and the plasticity paste state is the plastic state with the addition of 20% B/A modified slurry.

It can be concluded that, as the slurry concentration increases, the slump value of various sand gravel samples gradually decreases and finally the flow plasticity reaches the plastic state. However, the injection ratio of B/A modified slurry that makes sand gravel sample with different size reach plastic state is different. Specifically, the smaller the sand gravel diameter is, the lower the slurry concentration is. As for sand gravel sample with 0–2 mm size, the plastic state is reached when B/A modified slurry injection ratio is between 5% and 10%, while the injection ratio is 15–20% for 2–10 mm sand gravel samples. Sand gravel with a diameter larger than 10 mm reaches a plastic state with a mixture of 20–30% B/A modified slurry. In addition, the voids of the 0–20 mm sand gravel sample can be completely filled when the addition of B/A modified slurry injection ratio is 30%. For the earth pressure balance shield, some scholars believe that the suitable slope of the soil should be between 100 mm and 200 mm. But for the full-face water-rich gravel, how to maintain the stability of the excavation surface and reduce the penetration is the main consideration. Therefore, by enhancing the cohesion of sand and gravel to achieve a plastic (flow) state is an effective way of improving the self-stability of the excavation face and preventing the instability of the formation.

### 3.3. Permeability Test

As mentioned above, the 0–20 mm void of sand gravel can be filled by B/A modified slurry. Therefore, the addition of B/A modified slurry (13 wt% bentonite: 20 wt% NH₄Cl = 10:1) has a positive effect on improving plasticity of sand gravel to reach a plastic non-flow state. However, whether the impermeability of sand gravel can be enhanced with the incorporation of B/A modified slurry is not certain (Figure 7). Sodium silicate or high molecular polymer, as additives of traditional slurry, were often used to improve the impermeability of soil [26,27]. As a result of the chemical reaction between sodium silicate and ammonium, calcium, magnesium ions of B/A modified slurry, silicic acid, calcium silicate and magnesium silicate can be formed to fill the voids and then to enhance the impermeability of sandy gravel. Therefore, the influences of the concentration of sodium silicate and the type of polymer on the impermeability of sand gravel were investigated, which aims to provide a proper mix ratio of B/A modified slurry.
3.3.2. Effect of Polymer Type and Concentration on Permeability of Modifier

To study the effect of B/A modified slurry injection ratios on the impermeability resistance of sand gravel, the impermeability of coarse sand with 0–2 mm diameter conditioned by different injection ratio B/A modified slurry (i.e., 0–50% with 10% interval) was obtained by impermeability tests under 2 bar air pressure. The results are shown in Figure 7a. It is observed that, with the addition of B/A modified slurry into a coarse sand sample, its impermeability was significantly enhanced compared with the sample without modifier. With the injection ratio of B/A modified slurry increasing from 10% to 40%, the permeation value reduced from 46.6 mL/min to 16.2 mL/min. With the combination of impermeability of conditioned coarse sand and economic effectiveness, the proper B/A modified slurry injection ratio is 30%. In the following experiments, the injection ratio of the B/A modified slurry is 30% if not specified.

The blends of B/A modified slurry and different mix ratios of sodium silicate aqueous solution (i.e., B:A:S = 10:1:0–3 with 0.5 interval) were used as coarse sand conditioner to improve its permeability. The permeability tests of conditioned coarse sand samples were conducted under 2 bar air pressure to investigate the effect of sodium silicate concentration on impermeability. Results were shown in Figure 7b. It is observed that the addition of sodium silicate solution can significantly improve the impermeability of coarse sand. For example, the permeability test result of the B:A = 10:1 (volume ratio) sample is 18.5 mL/min, while the result of the B:A:S = 10:1:0.5 sample is 9.4 mL/min. In addition, as the sodium silicate concentration increases, the permeation of the modified coarse sand sample first decreases and then increases. More specifically, as the concentration of sodium silicate solution increases from 10:1:0.5 to 10:1:2, the permeation value decreases from 9.4 to 3.6 mL/min, and when the concentration continually increases to 10:1:3, the permeation value increases to 5.3 mL/min.

3.3.2. Effect of Polymer Type and Concentration on Permeability of Modifier

In this study, the effect of high molecular polymer type, including Kapom, Guar, Xanthan, Carboxymethyl cellulose Sodium (CMC), Hydroxyethyl cellulose (HEC) and Polyacrylamide (PAM), on the impermeability of coarse sand was investigated. Among them, the solubility of Xanthan is lowest, 0.5 wt%, which was used as the concentration of various polymers to study the effect of polymer type on the impermeability property. Therefore, coarse sand is conditioned by 30% modified slurry consisting of B, A, S and X (i.e., 0.5 wt% polymer) and their volume ratio is 10:1:2:2. The permeability tests under 2 bar
In this study, the effect of high molecular polymer type, including Kapom, Guar, Xanthan, CMC, PAM, and Guar, on the permeability of coarse sand was investigated. The permeability was measured using controlled pressure and concentration studies. The permeability of conditioned coarse sand was found to be significantly improved with the addition of high polymer types. The order of improvement performance degree of polymer from high to low is HEC, CMC, Kapom, PAM, Guar, Xanthan.

Further, in order to verify whether different types of high polymer blends will produce better impermeability, based on the above experimental results, the impermeability of HEC samples mixed with Kapom, CMC and Xanthan was tested. The results were shown in Figure 8a. It is observed that the improvement degree of impermeability of coarse sand with addition of HEC is the greatest compared to that of the sand sample with the addition of other polymers. The order of improvement performance degree of polymer from high to low is HEC, CMC, Kapom, PAM, Guar, Xanthan.

![Figure 8](image_url)

**Figure 8.** (a) Effect of high polymer types on B/A/S seepage flow. (b) Effect of HEC content on B/A/S seepage flow.

In order to study the effect of HEC concentration on the impermeability of coarse sand, coarse sand samples were prepared by adding different concentrations of HEC (i.e., 0–4 volume concentration with 0.5 interval). Permeability tests were conducted under 2 bar air pressure. The results were shown in Figure 8b. It is observed that the higher the HEC concentration, the greater the obtained impermeability of conditioned coarse sand. When the HEC proportion is 2, the volume of fluid per unit time is the lowest (<1 mL/min). However, with the HEC proportion is 2–4, the impermeability of coarse sand shows a reversed trend.

### 3.3.3. Polymer Compounding and Verification of Conditioned Gravel Permeability

Further, in order to verify whether different types of high polymer blends will produce better impermeability, based on the above experimental results, the impermeability of HEC samples mixed with Kapom, CMC and Xanthan was tested. The results were shown in Figure 9a. It can be seen from the experimental results that the permeation of the three groups of compound experiments were larger than that of the pure HEC sample group. The impermeability improvement performance in decreasing order is CMC, Kapom and Xanthan. The experimental results were consistent with the preferred experiment results shown in Figure 8a. Therefore, it can be concluded that the single component of the sealing water effect of HEC on bentonite is better than the compounding component, and there is no significant difference in the performance of compounded polymers with better performance.
According to the permeability tests, the optimal ratio of the proposed conditioner was: B:A:S:H = 10:1:2:2. To verify the impermeability effect of the modified slurry on the gravel under the ratio, experiments were carried out on 2–4 mm, 4–6 mm, 6–9 mm, 9–12 mm and 10–20 mm gravel, respectively, and the results were compared with the coarse sand group. The experimental results were shown in Figure 9b, it can be seen that when the gravel particle size is within 12 mm, the impermeability improvement effect of the modified slurry is gradually weakened, and when the particle size ranges from 10 to 20 mm, the volume of fluid is close to that of coarse sand. The average permeation value of each samples was less than 1 mL/min, indicating that the modified slurry showed good impermeability on the gravel under different particle sizes.

4. Conclusions

When EPB is used in the excavation of full-face water-rich sandy pebble stratum with high permeability, applying traditional conditioner may be insufficient, which will lead to accidents such as the spewing of the screw machine and ground collapse. In view of it, a new conditioner, modified slurry, was proposed in this paper. Modified slurry was prepared by using ammonium chloride as a viscosity modifier and sodium silicate solution and polymer as water shutoff agents. Two main aspects were studied: (1) viscosity modifier effect of modified slurry conditioner’s performance on the plasticity of sandy gravel soils with different particle sizes; (2) the effect of concentration and type of water shutoff agent on the improvement of conditioned soil impermeability.

Ammonium chloride can act as the viscosity modifier of traditional slurry and instantaneously increased the apparent viscosity of traditional slurry. The developed new modified slurry has an effect on improving the plasticity of sandy gravel soils. Sodium silicate and high-molecular polymer as the main water shutoff agents for modified slurry greatly enhanced the impermeability of conditioned samples. The optimum slurry is composed of B:A:S:H = 10:1:2:2 and its suggested injection ratio is 30%.

In addition, the suggested field application method is, separately, the injection of B, A, S and H (A and H should better be premixed) at the ratio of 10:1:2:2 into the excavation chamber through the slurry pipelines. After stirring through the cutterhead, these components react rapidly to form a modified slurry, which will consequently increase the plasticity and impermeability of the conditioned soils.
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