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Mechanism of conditioning EPB shield soil

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ABSTRACT

Large internal friction angle and small cohesion for sand result in engineering problems such as difficulty in soil dumping and excessive torque during Earth Pressure Balance (EPB) shield tunneling in sandy strata. Therefore, it is necessary to change the mechanical characteristics of the excavated shield soil by adding conditioning agents. However, the conditioned soil containing a variety of the agents could cause environmental contamination. In order to make a workable conditioning scheme to ensure the shield construction and to reduce environmental risk, it is necessary to understand the mechanism of soil conditioning. This study investigated the influence of the addition and combinations of conditioning agents on the workability of sand, and analyzed the rheology and mechanical properties of sands with adequate workability by using workable agent combinations to condition sands, in order to analyze the influence of the agent combinations on the properties of sand. The results show that the addition and combination of conditioning agents have a significant influence on the workability of sand. The combination of bentonite slurry, foam and Na-CMC can effectively improve the workability of sand, and reduce the addition of bentonite slurry and foam to reduce costs and mitigate environmental contamination. The sand conditioned by the combination of bentonite slurry, foam and Na-CMC has workable rheology, shear strength and compressibility. The results will provide theoretical guidance for making the workable conditioning scheme and green treatment scheme of the shield soil.

Keywords: Earth Pressure Balance (EPB) shield, soil conditioning, workability, rheology, mechanical properties

1 INTRODUCTION

Sand has poor workability and large shear strength due to its small cohesion and large internal friction angle. When Earth Pressure Balance (EPB) shield tunneling in sandy strata, it is easy to cause difficulty in soil dumping and excessive torque (Anagnostou & Kovári, 1996). In order to solve the problems, conditioning agents are usually used to condition the properties of sand. Foam is a common agent for sand. The common main component of foam is sodium dodecyl sulfate (SDS). SDS is a kind of anionic surfactant with certain toxicity, which is irritant to human eyes and skin and has negative effects on the growth of some aquatic organisms (Najim et al., 2022). SDS with good water solubility and foaming is easy to enter the water environment and form foam on the water surface, which affects the oxygen exchange between the water and the atmosphere and causes water quality deterioration. If the soils containing foam are directly piled, SDS will be brought into the groundwater by rainwater under the effect of rainfall leaching, which will cause environmental contamination. In order to obtain a workable conditioning scheme to ensure the shield construction and to reduce environmental risk, it is necessary to carry out a systematic study on the conditioning mechanism of sand.

At present, the commonly used conditioning agents include bentonite slurry, foam and sodium carboxymethyl cellulose (Na-CMC) (Gharahbagh et al., 2014; Vinai et al., 2008). Bentonite slurry has the functions of lubrication and bonding. It can form a layer of lubricating film on the surface of sand particles, reduce the friction between particles, and enhance the bonding force between particles (Ghadr & Assadi-Langrodi, 2018), which will improve the workability of soil and reduce the shear strength. Foam is compressible. When foam exists in soil pores, it can share part of the contact force between soil particles, and weaken the direct contact between soil particles (Ma et al., 2012), which will improve the flowability of soil and reduce the shear strength. Na-CMC is a kind of environment-friendly, biodegradable water-soluble polymer, and has the functions of lubrication and bonding (Lan et al., 2018). Na-CMC can adsorb on the surface of sand to form a lubricating film, and bridge the particles with its own long chain structure, which will improve the workability of soil and reduce the shear strength.

The previous research showed that the conditioning effect of multiple agents is better than that of a single agent. Compared with bentonite slurry, the agent combination of bentonite slurry and Na-CMC significantly reduce the shear strength and internal friction angle of sand, and improve its cohesion (Sun, 2019). Compared with bentonite slurry or foam, the agent combination of the two can effectively improve the workability of sand (Zhao et al., 2018). In addition, the combinations of bentonite slurry and Na-CMC or foam and Na-CMC can effectively improve the workability of sand, and achieve good application results in the project (Tang et al., 2016). At present, two or more conditioning agents are usually used in the shield construction. However, the existing research has not carried out a systematic analysis of the influence of agent combinations on the workability, rheology and mechanical properties of sand.

In this study, the properties of conditioning agents were measured to select workable agent combinations. The influence of the addition and combinations of the agents on the workability of sand was analyzed by the slump test, and the conditioned sands with adequate workability and their conditioning scheme were obtained. The vane shear test was used to measure the rheology and mechanical properties of conditioned sands with adequate workability. According to the test results, this study analyzed the influence of different agent combinations on the workability, rheology and mechanical properties of sand.

2 TEST MATERIALS

2.1 Soil

The unconditioned sand in this study was collected in the shield construction section of Xi'an Metro Line 10. The mechanical and grading parameters of air-dried sand are listed in Table 1. The sand has large internal friction angle and poor grain gradation, which result in poor workability and high shear strength of the sand in EPB shield construction. It is difficult to improve the construction efficiency.

Table 1. *Physical and mechanical parameters of the sand*

Soil type	Internal friction (°)	Average particle size (mm)	Nonuniform coefficient	Curvature coefficient
Sand	38	0.43	3.3	1.3

2.2 Conditioning agents

The bentonite and foam agent from the shield construction of Xi'an Metro Line 10 were used in this study. The bentonite is produced by Yangxian Qiyanquan Bentonite Plant, and its swelling capacity is 12 mL/g. The foam agent produced by Taihe Fengshun Engineering Materials Company is light yellow and no peculiar smell, and can be mixed with water in any proportion. The mass ratio of bentonite to water is recorded as m_1. The mass percentage of foam agent to water is recorded as m_2. During the test, the mass ratio of bentonite to water and the mass percentage of foam agent to water in the shield construction of Xi'an Metro Line 10 were used to prepare the bentonite slurry and foam agent solution, and m_1 = 1:8, and m_2 = 3%.

Sodium carboxymethyl cellulose (Na-CMC) produced by Mreda Technology Company was used in this study. Na-CMC is a white powdery and water-soluble polymer, and the viscosity of 2% Na-CMC solution is 300 – 800 mPa·s. Na-CMC is usually added into bentonite slurry or foam and injected into the tunnel face. The addition of Na-CMC in the bentonite slurry or foam agent solution is recorded as c. With reference to the research of Li (2020), the addition of Na-CMC in the bentonite slurry and foam agent solution was 0.06% in this study. The influence of Na-CMC on the properties of bentonite slurry and foam agent solution is as follows.

2.2.1 Bentonite slurry

During the test, bentonite and water were mixed to form slurry under continuous stirring. After 24h of stirring, the funnel viscosity and filtration properties of slurry were measured with a Markov funnel viscometer and a medium pressure filtration meter respectively. After the above tests were repeated for three times, the average values were taken. The properties of bentonite slurry and slurry with 0.06% Na-CMC are listed in Table 2. The funnel viscosity of slurry is required to be about 30s in the project. The filtration loss of workable slurry is generally less than 15 mL, and the slurry cake thickness is less than 2 mm. The properties of slurry with c = 0.06% is significantly improved. Na-CMC as a chain polymer can increase the viscosity of liquid, and adsorb on the surface of bentonite particles by forming hydrogen bonds. The ionization and hydration of the carboxylic sodium group (–COONa) in Na-CMC can increase the absolute value of zeta potential and thicken the hydration shell on the surface of bentonite particles, which can keep the dispersion of bentonite and reduce the filtration loss (Li, 1989). The slurry with m_1 = 1:8 and c = 0.06% meets the construction requirements, and is used to condition the sand in this study.

Table 2. *The changes in the properties of slurry after adding 0.06% Na-CMC*

Composition content of agents	Funnel viscosity (s)	API filtration loss (mL)	Slurry cake thickness (mm)
m_1 = 1:8	29.5	45.5	3.5
m_1 = 1:8, c = 0.06%	33.0	13.3	1.5

2.2.2 Foam agent solution

The foaming properties of foam agent solution are generally evaluated by foam expansion ratio (FER) and half-life. FER is the volume ratio of the foam formed by full foaming of foam agent solution to the initial solution. Half-life is the time from the completion of foaming to the time when the solution formed by foam breaking is half of the volume of the initial solution. In the shield construction, it is generally required that FER is 10 – 20, and half-life is more than 5 min (Huang et al., 2019). The foaming test was carried out for the foam agent solution with m_2 = 3% and the foam agent solution with m_2 = 3% and c = 0.06%. During the foaming process, compressed air was injected into the foam agent solution under continuous stirring. After foaming, FER and half-life of foam were measured. The test was repeated three times to take the average value. The test results are shown in Table 3. The half-life of foam agent solution with m_2 = 3% is more than 5min, but its FER is slightly larger. The half-life of foam agent solution with m_2 = 3% and c = 0.06% is significantly increased, and the stability of foam is enhanced. Na-CMC can improve the viscosity of liquid membranes of foam, and attract water to thicken the liquid membranes due to its hydrophily, which can improve the stability of foam. However, thick liquid membranes are not conducive to the formation of foam, and reduces the FER. The foam agent solution with m_2 = 3% and c = 0.06% meets the engineering requirements, and is used to condition the sand in this study.

Table 3. *The changes in the properties of foam agent solution after adding 0.06% Na-CMC*

Composition content of agents	FER	Half-life (min)
m_2 = 3%	22	6.3
m_2 = 3%, c = 0.06%	19	8.3

3 TEST METHODS

Slump test is a simple, fast and empirical test used to evaluate the workability of conditioned sand. Referring to the evaluation method proposed by Wu et al. (2022), the study measured the slump state of conditioned sand to evaluate its flow plasticity. The workability is adequate when the slumped soil has no crack, the slump is 180 – 210 mm, the slump shape is pear shape, and the slump angle is less than 90°. According to the slump tests of sands conditioned by three agent combinations, the test analyzed the influence of different agent combinations on the slump state of sands, and obtained the conditioned sands with adequate workability and their conditioning schemes. The three agent combinations are listed in Table 4. According to the property test results of the agents, the slurry with m_1 = 1:8, c = 0.06% was used as the Combination 1, and the foam agent solution with m_2 = 3%, c = 0.06% was used as the Combination 2. The Combination 3 consisted of Combination 1 and Combination 2. The mass percentage of slurry added in sand is recorded as n. The addition of foam is expressed by the foam injection ratio (FIR).

The rheology of conditioned sands with adequate workability obtained from the slump test was measured when shearing under atmospheric pressure. According to the results of slump test and shear test under atmospheric pressure, the conditioned sand with more workable rheology was selected. Its mechanical properties were measured under different pressures.

During the test, a pressurized vane shear apparatus was used to measure the rheology and mechanical properties of conditioned sands. The pressurized vane shear apparatus can continuously shear sands under different shear rates and vertical pressures. The rotating speed range of the vane is 0 – 10 r/min, the vertical pressure range is 0 – 500 kPa, the torque range is 0 – 100 N·m, and the shear step is 0.5°. In the shield construction, the conditioned sand cannot be drained in time during the excavation process. Therefore, the sands were not drained during shearing.

Table 4. *Three conditioning agent combinations*

Combination series number	Combination 1	Combination 2	Combination 3
Composition	Bentonite slurry and Na-CMC	Foam and Na-CMC	Bentonite slurry, foam and Na-CMC

4 TEST RESULTS AND ANALYSIS

4.1 Workability

The slump test results of sand conditioned by the Combination 1 and Combination 2 are shown in Table 5. According to Table 5, the unconditioned sand is stacked loosely in a cone shape after slumping, as shown in Figure 1 (left). When the agent Combination 1 is used, with the increase of slurry addition, the workability of the conditioned sand is gradually improved. When n = 27.5%, the workability of the conditioned sand is adequate, as shown in Figure 1 (right). Considering the construction cost, the slurry addition in the actual project generally does not exceed 10%. Therefore, the slurry formed by the t Combination 1 to improve the sand does not meet the requirement. When the Combination 2 is used, with the increase of FIR, the cohesion of the conditioned sand is improved, and the flowability is workable when FIR is relatively lower or higher. When FIR = 130%, the slump shape, slump and slump angle of the conditioned sand meet the requirements of workability, and only part of its surface has some cracks, as shown in Figure 2 (left). Therefore, it is considered that it basically has adequate workability. If foam is added continuously, the slump of the conditioned sand will be too high and its flowability will be too high. Considering the limitation of two agent combinations, the sand is improved by the Combination 3. Since the slurry addition in the project is generally not more than 10%, the slurry addition is controlled at 10% in the test. During the test, the workability of sand is changed by controlling the FIR. When the conditioned sand has adequate workability, FIR is the minimum addition under the combination 3. The test results are listed in Table 5. When n = 10% and FIR = 28%, the workability of the conditioned sand is adequate, as shown in Figure 2 (right).

Table 5. *Slump test results of conditioned sand*

Agent addition	Cracking	Slump shape	Slump (mm)	θ (°)	Workability
No agents	Loose particle	Cone shape	195		Poor cohesion
n = 10%	Cracking	Cone shape	5	97	Poor workability
n = 20%	Cracking	Cone shape	5	97	Poor workability
n = 25%	Uncracked	Pear shape	85	65	Poor flowability
n = 26%	Uncracked	Pear shape	125	55	Poor flowability
n = 27%	Uncracked	Pear shape	170	45	Poor flowability
n = 27.5%	Uncracked	Pear shape	185	40	Adequate
FIR = 40%	Loose particle	Cone shape	185		Poor cohesion
FIR = 80%	Loose particle	Cone shape	150		Poor workability
FIR = 120%	Cracking	Pear shape	170	45	Poor workability
FIR = 130%	Slight cracking	Pear shape	195	35	Adequate
n = 10%, FIR = 5%	Cracking	Cone shape	5	97	Poor workability
n = 10%, FIR = 10%	Cracking	Cone shape	5	97	Poor workability
n = 10%, FIR = 20%	Slight cracking	Pear shape	95	40	Poor flowability
n = 10%, FIR = 25%	Slight cracking	Pear shape	160	35	Poor flowability
n = 10%, FIR = 28%	Uncracked	Pear shape	190	30	Adequate

Figure 1. *Unconditioned sand (left). Conditioned sand when n = 27.5% (right)*

Figure 2. *Conditioned sand when FIR = 130% (left). Conditioned sand when n = 10%, FIR = 28% (right)*

According to the slump test results, the Combination 1 can effectively prevent the cracking of slumped sand to improve its cohesion. The Combination 2 can effectively increase the slump of sand to improve its flowability. Compared with Combination 1 and Combination 2, Combination 3 can effectively improve the slump state of sand to have adequate workability, and significantly reduce the addition of bentonite slurry and foam.

4.2 Rheology

The conditioned sands with adequate workability are recorded as A, B and C, as shown in Table 6. The rheology of conditioned sand A, B and C was measured by the pressurized vane shear apparatus under atmospheric pressure. In the process of shearing, the strain softening occurs in the conditioned sands. The conditioned sands have obvious peak strengths and residual strengths. The peak strength can be used to evaluate the difficulty of shearing sand when the cutter head and screw conveyor start operation. The residual strength can be used to evaluate the difficulty of shearing sand when the cutter head and screw conveyor are working stably. Taking the test at the shear rate of 0.0181 s^{-1} as an example, the study compares the peak strength and residual strength of unconditioned sand and conditioned sands under atmospheric pressure, as shown in Figure 3 (left). After conditioning, the peak strength and residual strength of the sands decrease significantly. The conditioned sands with adequate workability have low shear strengths to be easily sheared in the tunnel face, excavation chamber and screw conveyor.

Table 6. *Three kinds of conditioned sands with workable flow plasticity*

Conditioned sand	**A**	**B**	**C**
Agent addition	n = 27.5%	FIR = 130%	n = 10%, FIR = 28%

The relationship curve between shear strength of conditioned sands and shear rate is shown in Figure 3 (right) and Figure 4 (left). With the increase of shear rate, the shear strength of conditioned sands increases gradually. There is an obvious linear relationship between shear strength and shear rate. The conditioned sand A has low residual strength and is easily sheared when the cutter head and screw conveyor are working stably, but its peak strength is high. The conditioned sand B has high peak strength and residual strength. The conditioned sand C has low peak strength and is easily sheared when the cutter head and screw conveyor start operation, but its residual strength is high. The peak strength reflects the strength of the structure formed by the friction and cohesion between sand particles before the shear failure. The residual strength reflects the strength of the structure formed by the rearrangement of sand particle after the shear failure. When the shear stress reaches the peak strength, the conditioned sand appears the shear failure. In order to ensure that the conditioned sand has good flow continuity after the shear failure, the structure of the conditioned sand should be able to recover quickly after the shear failure. This requires a small difference between the peak strength and residual strength. The difference between the peak strength P and residual strength R of conditioned sands is recorded as P-R. The change of P-R with shear rate is shown in Figure 4 (right). The higher the shear rate, the larger the P-R. It shows that the higher the shear rate is, the more obvious the strain softening property of the conditioned sand is. Therefore, the peak strength increases with the increase of the shear rate. Compared with other conditioned sands, the conditioned sand C has the smallest P-R. With the decrease of the P-R of the conditioned sand, the strength recovery ability of the sand structure increases after the shear failure. Therefore, the conditioned sand C has a stronger strength recovery ability of its structure and good flow continuity after the shear failure, and is more like a fluid from the macro behavior.

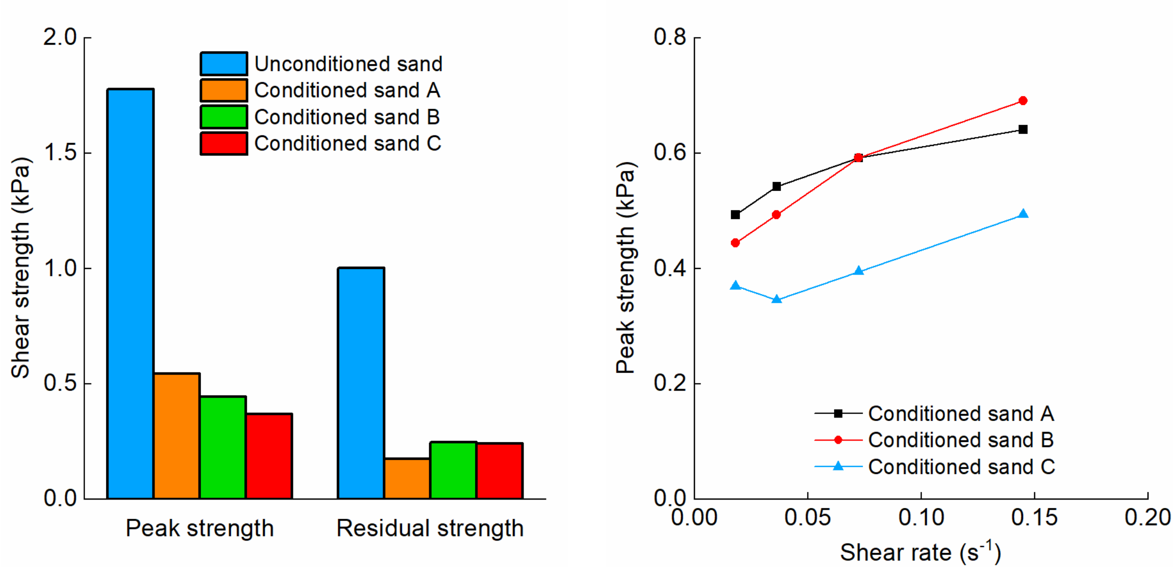

Figure 3. *Comparison of shear strength between unconditioned sand and conditioned sand (left). Peak strength of conditioned sands under different shear rates (right)*

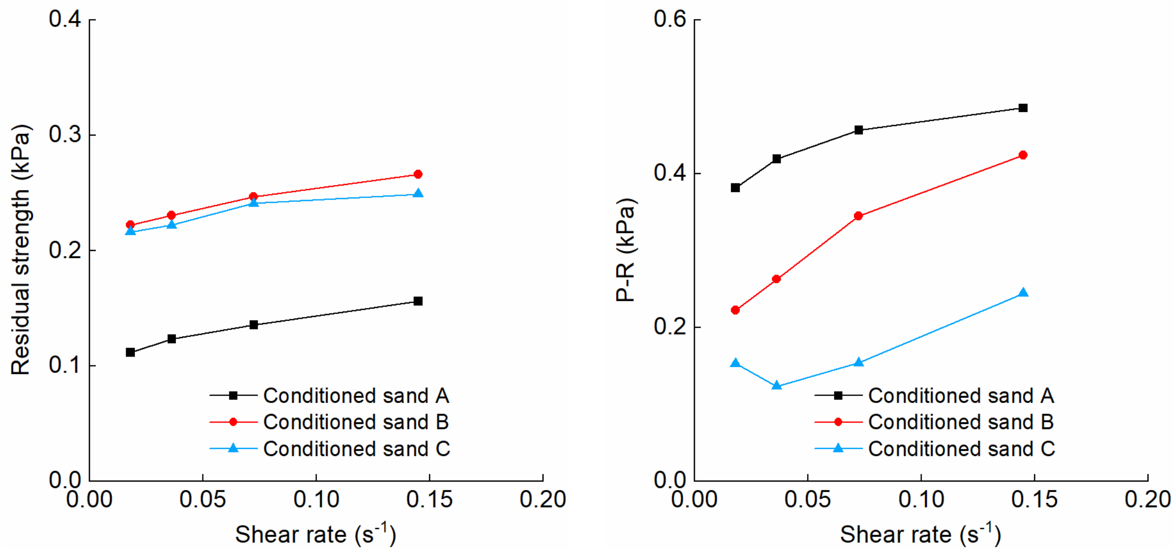

Figure 4. *Residual strength of conditioned sands under different shear rates (left). Difference between peak strength and residual strength of conditioned sands under different shear rates (right)*

Bingham model is a linear model commonly used to describe the relationship between shear strength and shear rate. The equations of Bingham model are as follows:

$$\gamma = 0, |\tau| \leq b \quad (1)$$

$$\tau = a\gamma + b, |\tau| > b \quad (2)$$

where τ is the shear strength, γ is the shear rate, a is the plastic viscosity, and b is the yield stress. Meng et al. (2011) and Chen (2016) showed that the rheology of conditioned sands with adequate workability usually conforms to Bingham model. In this study, Bingham model was used to fit the change of shear strength of conditioned sands with shear rate. The fitting curve and parameter results are shown in Figure 5 and Table 7, and the fitting results are good. A_p in Table 7 represents the peak strength of conditioned sand A, and other symbols are similar. The yield stress obtained from the peak strength can reflect the strength of the conditioned sand without shear, and reflect the difficulty of the sand from static to flowing. The plastic viscosity obtained from the residual strength can reflect the total internal friction resistance of the conditioned sand during stable shear. It reflects the difficulty of flow when the sand is in the flow state. According to Table 7, the rheological parameters of different conditioned sands are different. For conditioned sand A and B, the yield stress obtained from the peak strength and plastic viscosity obtained from the residual strength are high, and it is difficult to flow when they are sheared. However, for conditioned sand C, the yield stress obtained from the peak strength and plastic viscosity obtained from the residual strength are low, and the P-R is small. It is easy to flow like a fluid when it is sheared. Therefore, the rheology of conditioned sand C is optimal.

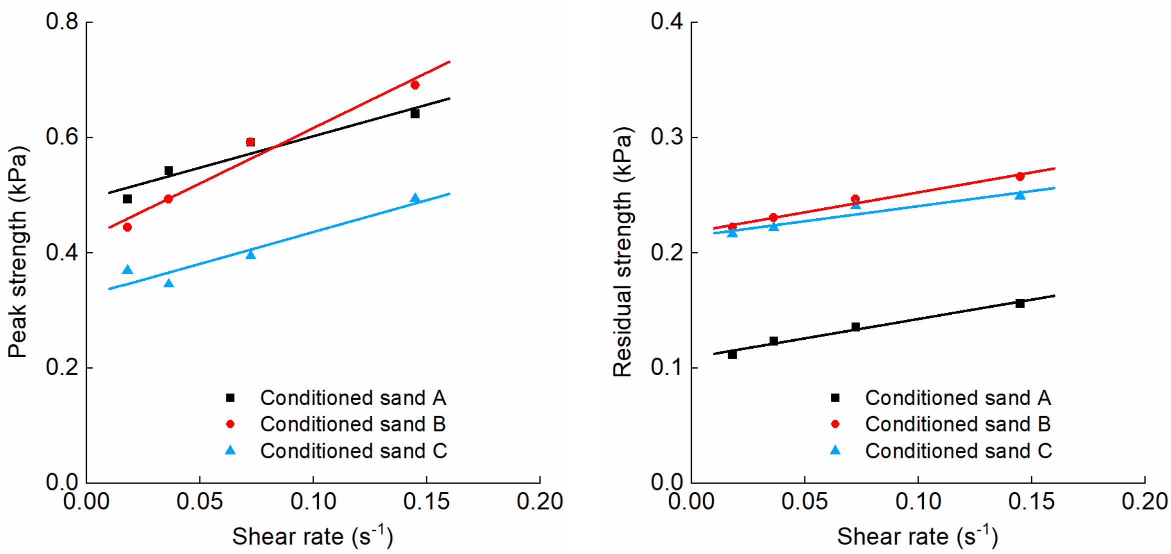

Figure 5. *Fitting results of peak strength (left). Fitting results of residual strength (right)*

Table 7. *Fitting results of Bingham model parameters*

Conditioned sand	Yield stress (kPa)	Plastic viscosity (kPa·s)	R^2
A_p	0.493	1.090	0.92
B_p	0.425	1.919	0.97
C_p	0.326	1.103	0.91
A_r	0.109	0.335	0.97
B_r	0.218	0.345	0.98
C_r	0.214	0.261	0.89

4.3 Mechanical properties

The shear strength of conditioned sand C was measured under different pressures. During shearing, the shear rate was set as 0.0181 s^{-1}. The test results were fitted with polynomial function, as shown in Figure 6 (left). In Figure 6 (left), P is the peak strength, R is the residual strength, and p is the pressure. With the increase of pressure, the peak strength and residual strength of conditioned sand C increase gradually. The relationship between shear strength and pressure of conditioned sand C conforms to the quadratic equation, and the determination coefficient R^2 reaches 0.99. Mori et al. (2018) showed that the shear strength of the conditioned sand is 0 – 40 kPa under the vertical pressure of 0 – 200 kPa. Therefore, the shear strength of conditioned sand C under 0 – 200 kPa is small and workable.

The conditioned sand C had vertical displacement under pressure, and its void ratio decreased. The semi logarithmic coordinate curve was used to plot the change process of void ratio of conditioned sand C with pressure, as shown in Figure 6 (right). With the increase of pressure, the void ratio of conditioned sand C decreases logarithmically. The increase of the compressibility of conditioned sand can reduce pressure fluctuations caused by the change of the sand volume in the excavation chamber, so as to maintain the stability of the tunnel face. According to Budach and Thewes (2015), the compression index of conditioned sand in EPB shield construction should not be less than 0.04. The compression index of conditioned sand C is 0.102, and its compressibility is workable.

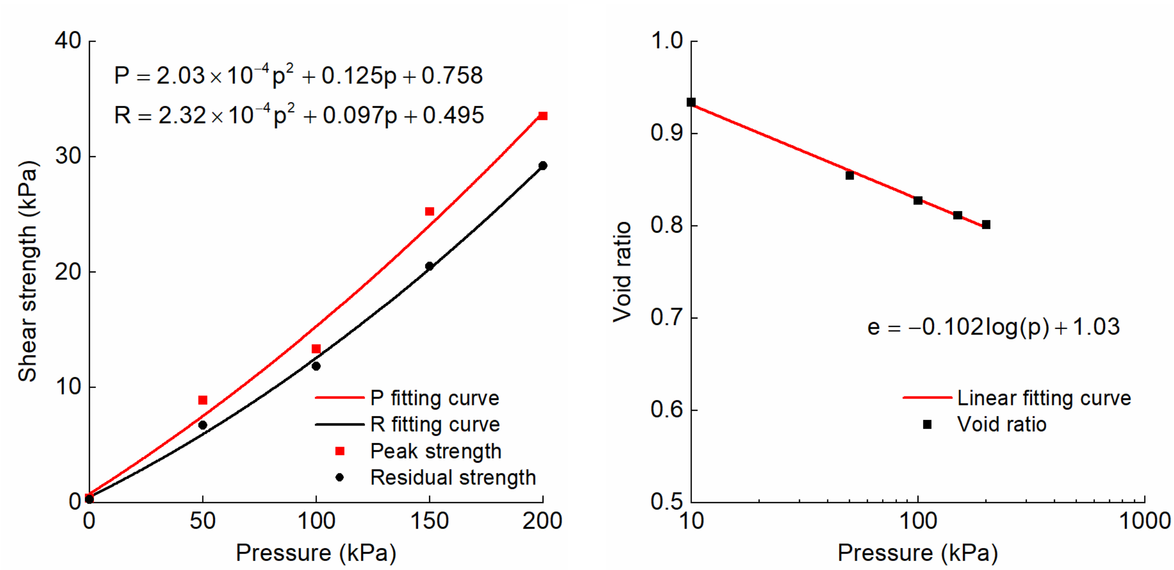

Figure 6. *Shear strength of conditioned sand C under different pressures (left). Void ratio of conditioned sand C under different pressures (right)*

5 CONCLUSIONS

In this study, the influence of workable agent combinations on the workability and mechanical properties of sand was analyzed. The following conclusions are drawn:

(1) Na-CMC can improve the properties of bentonite slurry and foam agent solution to meet engineering requirements. Na-CMC can significantly increase the funnel viscosity of bentonite slurry and reduce its API filtration loss. Na-CMC can enhance the stability of foam.

(2) The combination of bentonite slurry, foam and Na-CMC can effectively improve the workability of sand. The combination of bentonite slurry and Na-CMC can effectively improve the cohesion of sand. The combination of foam and Na-CMC can effectively improve the flowability of sand. If the bentonite slurry and foam are used to condition the sand, a large amount of bentonite slurry or foam should be added to achieve the workability, which causes high costs and difficulty in sand recycling. The combination of bentonite slurry, foam and Na-CMC can effectively improve the workability of sand, and significantly reduce the addition of bentonite slurry and foam.

(3) The combination of bentonite slurry, foam and Na-CMC can effectively condition sand to have workable rheology and mechanical properties. The rheological curves of conditioned sands with adequate workability meet the Bingham model. The sand conditioned by combination of bentonite slurry, foam and Na-CMC has low yield stress and plastic viscosity, low shear strength and workable compressibility. When it is sheared in the excavation chamber and the screw conveyor, the conditioned sand is easy to flow and deform, and can effectively stabilize the tunnel face.

6 ACKNOWLEDGEMENTS

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