Experiment study on mechanical properties of sand-doped bentonite

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Abstract. Bentonite is a special soil with water expansion and water loss shrinkage properties, which is widely used as backfill material. In order to explore the effect of sand content on the properties of bentonite, compaction test, \( w_L \) (liquid limit) and \( w_P \) (plastic limit) test, direct shear test and permeability test were taken to analyse the compaction, hydrophilic, shear characteristics and permeability of sand-doped bentonite. The results show that as the amount of bentonite increases, \( w_{op} \) (the optimal water content), \( w_L \), \( w_P \) and \( I_P \) (plastic index) of sand-doped bentonite increase, the \( \rho_{dmax} \) (the maximum dry density) and cohesion increase first and then decrease, the angle of internal friction decreases gradually. When bentonite content is less than 20\%, increasing the content of bentonite has significant effect on reducing coefficient of permeability.

1. Introduction

Bentonite is a non-metallic clay mineral with montmorillonite as the main mineral component. It has the characteristics of low permeability and is an ideal buffer backfill material [1-3]. In practical application, the cost of using pure bentonite is high, and the construction performance is poor due to its high plasticity. It is found that the construction performance of bentonite mixed with sand is better than that of pure bentonite, and the permeability and mechanical strength of bentonite will not be significantly reduced [4-8]. Therefore, the research on the mechanical nature of sand-doped bentonite has become the main research direction in various countries.

There is a large amount of sandy soil in the strata of Yancheng city, Jiangsu province in China, whose mechanical properties and permeability cannot meet the requirements of buffer/rebound material, and it is necessary to modify sandy soil. As a good buffer/rebound material, sand-doped bentonite is widely used in landfill sites [9-11]. Its anti-seepage and deformation stability play a key role in the stability of landfill sites.

In this paper, the sand-bentonite mixture with different bentonite contents were taken as the research object to comprehensively evaluate the properties of sand-bentonite from four aspects: compaction characteristics, consistency limit, shear strength and permeability. The influence of bentonite content on compaction property, limit water content, shear strength and permeability coefficient of the mixture was analysed. It provides experimental basis for engineering practice.
2. Test materials and methods

The bentonite samples were taken from Jiangsu province, with montmorillonite as the main component and a small amount of illite, calcite and other ore components. The test sand was taken from Yancheng. Table 1 lists the properties of these two materials.

Before test, bentonite and sand were stirred and mixed according to different bentonite contents to prepare groups of sand-blended bentonites with mass ratios of 5%, 10%, 20%, 30%, 40% and 50%, respectively. Pure bentonite and pure sandy soil were prepared at the same time to serve as comparative test materials. Compaction test, $w_L$ and $w_P$ test, direct shear test and permeability test were carried out for each sample. The test methods and steps strictly followed the reference [12].

| Table 1. Properties of materials |
|----------------------------------|
| Grain size | $G_s$ | $w_L$ | $w_P$ | Grain size | $G_s$ |
| <2μm | 2.69 | 274.09% | 52.71% | 0.5~1mm | 2.66 |

3. physical and mechanical properties of sand-doped bentonite

3.1. compaction characteristics

Figure 1 shows the changing law of dry density $\rho_d$ with water content $w$ under different bentonite contents. When bentonite contents are at 10-50%, the $\rho_d$ of sand-doped bentonite increase at the early stage and then decrease along with the increase of $w$, and the sand-doped bentonite with different content of bentonite has $w_{op}$ and $\rho_{dmax}$. The $w_{op}$ increases as the amount of bentonite increases, showing a good linear relationship between the two, as shown in Figure 2. As the content of clay minerals increase, the water absorption capacity of soil increases. Therefore, when the mass ratio of clay mineral bentonite increases, the water absorption capacity of sand-doped bentonite will increase and $w_{op}$ of soil to reach the $\rho_{dmax}$ will increase.

![Figure 1. $w$ and $\rho_d$ at different bentonite contents](image)

Figure 2 also shows the change law of $\rho_{dmax}$ of sand-doped bentonite with different bentonite contents. We can find out that following the increase of bentonite content, $\rho_{dmax}$ of sand-doped bentonite first increases and then decreases, and the optimal bentonite content is 30%. There are many pores in the pure sandy soil, which can be filled properly by adding a small amount of bentonite. The more bentonite, the more filling will be done, thus increasing the $\rho_{dmax}$ of soil. However, as the mass ratio of bentonite increases, the density of bentonite is smaller than that of sandy soil, so the $\rho_{dmax}$ will gradually decrease after reaching the maximum value.
3.2. Consistency limit

The $w_L$ and $w_P$ reflect the deformability of the soil. Bentonite contains a large amount of clay minerals, such as montmorillonite, which has good hydrophilic ability. It is a highly plastic soil, and is easy to form agglomeration when it encounters water. Therefore, it is difficult to reconcile evenly when adding water in the construction. The properties bring many inconveniences in engineering, while the addition of sandy materials can change the plasticity characteristics of bentonite. The $w_L$ and $w_P$ of 7 kinds of sand-bentonite mixtures with different amounts of bentonite were measured. Figure 3 shows the relations among limit water content $w$ and bentonite content. The $w_L$ and $w_P$ of the mixture increase linearly as the amount of bentonite increases. The category of the mixture changes from low $w_L$ clay to high $w_L$ clay, indicating that the plasticity of sand-doped bentonite increases with the decrease of sand content. This is mainly because the added sand has weak water absorption capacity, and the main component of bentonite is malleable mineral montmorillonite.

Figure 3 also shows that as the amount of bentonite increases, the increase of the $w_L$ of sand-doped bentonite is much larger than that of the $w_P$, which is mainly caused by the change of the skeleton action of sand particles. When sand-doped bentonite is in fluid-plastic state, sand plays a small role in the skeleton. As the amount of bentonite increases, the relative content of montmorillonite increases significantly, so that the $w_L$ of soil increases significantly. When the soil is in a plastic state, the sand plays an obvious role as a skeleton. When the state of sand-doped bentonite changes from plastic to semi-solid, limit-water-content will increase with the relative content of montmorillonite. However, due to the skeleton effect of sand, the increase range of $w_P$ is much smaller than that of $w_L$. 

![Figure 2. $\rho_{d max}$ and $w_{op}$ with different bentonite contents](image2)

![Figure 3. Relationship between limit water content and bentonite content](image3)
3.3. The shear strength

Figure 4 shows the relations among the shear strength and vertical pressure of 5 groups of sand-doped bentonite. We can see that the shear strength increases with the increase of vertical stress. The strength property is in line with the Mohr-Coulomb destruction criterion. When the applied vertical stress more than 200 kPa, the smaller the mass ratio of bentonite, the larger the shear strength, and the shear strength mainly depends on the friction strength between sand particles. When the applied vertical stress is less than 200 kPa, and the bentonite content is 30%, the shear strength is the highest, and the shear strength is determined by both sand and bentonite.

![Figure 4. Relations between shear strength and vertical pressure](image1)

Figure 5 shows that when the mass ratio of bentonite is less than 50%, the cohesive force of sand-doped bentonite increases at the early stage and then decrease as the amount of bentonite increases, and reaches the peak value of 100.65 kPa when the content of bentonite is 30%. When the bentonite content is between 10%-30%, due to the low bentonite content, the bentonite particles fail to form a complete skeleton structure with sand, and the cohesive force increases as the amount of bentonite increases. When the content of bentonite is between 30%-50%, the cohesive force is mainly provided by soil particles, and the cohesive force between sand and soil is weakened. As the amount of bentonite increases, the angle of internal friction shows a decreasing trend, which is mainly due to the thickening of the bonded water film between the soil particles, and the formation of "lubricant" between bentonite and water.

![Figure 5. Relationship of bentonite content with c and φ](image2)
4. Permeability

Figure 6 shows the relationship between permeability coefficient and bentonite content when the void ratio is 0.8. The permeability coefficient data is chosen from Fan et al. [13, 14] for the properties of raw materials are the same. When the bentonite content is less than 40%, the permeability coefficient decreases as the amount of bentonite increases. This is mainly because bentonite expands with water, and the water passage in the soil is more tortuous, leading to the decrease of permeability coefficient. When the content of bentonite increases from 10% to 20%, the permeability coefficient decreases by an order of magnitude. This is due to the increase of bentonite content, the pores between sand grains are filled with bentonite, and the mixture’s void ratio decreases. When the content of bentonite increases from 20% to 40%, the permeability coefficient only decreases by about three times. When the content of bentonite is 20%, the pores in sand-doped bentonite are basically filled up. Therefore, increasing the content of bentonite has a limited effect on reducing the coefficient of permeability.

![Figure 6. The relationship between permeability coefficient and bentonite content](image)

5. Conclusions

1. When the mass ratio of bentonite is less than 50%, $w_{op}$, $w_L$, $w_P$ and $I_P$ of sand-blended bentonite increases as the amount of bentonite increases, but the increase of $w_P$ was less than that of $w_L$. The $\rho_{dmax}$ increases at the early stage and then decrease as the amount of bentonite increases.

2. The cohesive force of sand-doped bentonite increases at the early stage and then decrease with increase of bentonite mass ratio, but the angle of internal friction decreases as the amount of bentonite increases.

3. The permeability coefficient of sand-doped bentonite decreases as the amount of bentonite increases. Increasing the content of bentonite can effectively reduce the coefficient of permeability, however, when the content of bentonite is reaching at 20%, increasing the amount of bentonite on the decrease of permeability was not very effective.

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