Research on pavement performance of mixed filler with alkaline residue-expansive soil

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Abstract. The expansive soil, a special clay, can cause crack, bulge, landslides and other accidents in the highway subgrade. To reduce the harm of expansive soil and realize the resource utilization of alkaline residue which is industrial solid waste, different ratio of alkaline residue and expansive soil with medium expansive potential are mixed as subgrade filling. A series of experiments are carried out for the pavement performance of the mixture. The results show that the swelling ratio of the mixture decreases significantly with the mixing rate. The longer the curing time is, the lower the swelling ratio will be. And the expansibility is completely eliminated in 28 days. The unconfined compressive strength(UCS) heightens with the growth of mixing rate, and when the mixing rate reaches 30%, the increasing level gradually stabilizes. Similarly, the curing time has an obvious effect on the unconfined compressive strength. After cured for 14 days, the UCS of samples is twice of that not cured. And the cohesion goes up in first stage, then decreases, and peaked as the mixing rate reaches to 30%. However, the internal friction angle changes little. The CBR increases with the increase of mixture ratio and the curing time. In addition, the mechanism of alkali residue modifying curing expansive soil is mainly based on the substitution effect of alkali residue, coagulation reaction and ion exchange of alkali residue - expansive soil.

1. Introduction

As we know, large areas of expansive soil have distributed in China, at least in 25 provinces. Expansive soil is rich in strong hydrophilic mineral like montmorillonite and illite, with especial engineering properties such as fissure, shrinkage and superconsolidability [1]. If water content in expansive soil changes, its volume will change, and then expansion or contraction cracks appear, causing damage in roads, railways and other engineering. Meanwhile the hazards caused by expansive soil are repetitive and laten in long-term. Expansive soil is known as "The cancer of engineering "[2]. Therefore, if the project is to be built in the expansive soil area, the expansive soil should be treated through a certain technology, then used as filler.

Modified measures of expansive soil are numerous, for instance, soil replacement, humidity controlling, physical modification and chemical improvement. Of course, different modified methods have different principles and characteristics. In recent years, since environment protection attracts more and more people's attention, scholars began to use a variety of solid waste as expansive soil
improver, such as fly ash, blast furnace slag, cement kiln dust, rice husk sh [3]. Mohanty M K(2016) has studied systematically the effects of different blending fly ash on the liquid limit, plastic limit, swelling rate, grain gradation, unconfined compressive strength and CBR of Indian black cotton soil. It was confirmed that fly ash was an effective improver for expansive soil [4]. Sharma A K(2012) used blast furnace slag to modify the expansive soil, and got that the effect of curing time and blast furnace slag content on the unconfined compressive strength is not particularly obvious, but the shear modulus increased sharply with the blast furnace slag content [5]. In addition, Sharma A K(2016) mixed fly ash and blast furnace slag particles as gelling material and found the optimum mixing rate of fly ash and blast furnaces is about 20%. Then the mixture gelling material has adopted for improving expansive soils, and it showed that the liquid limit and plasticity index of modified expansive soils were significantly reduced, unconfined compressive strength increased quickly [6]. Salahudeen A B(2014) added 0 ~ 10% cement kiln dust to Indian black cotton soil. The conclusion can been reached that the maximum dry density and the optimum water content of the modified soil were the maximum when the mixing content of cement kiln was 6%. The compressive strength and CBR increase with the coagulation rate, meantime, the mechanical properties of the modified soil are improved [7]. Gupta S's research has also obtained similar results[8]. Satyanarayana P V V(2016)analyzed the feasibility of modifying expansive soil by rice husk ash. The results showed that rice husk ash can significantly reduce the plasticity of the expansive soil and improve the soil strength. When adding 30% rice husk ash, the plastic index of expansive soil decreases to 0, the swelling rate reaches to 0 and CBR falls to 8% [9]. In addition, Liu Yuyi(2017)used waste foam particles to improve the expansion and contraction of expansive soil, and achieved good performance [10].

Alkali residue is waste residue discharged by alkali production factory. Annual alkali residue generated by ammonia-soda process is up to 500 million tons in China. So it becomes a serious problem, which should been solved urgently for production factory[11]. Alkali residue is composed of calcium carbonate, calcium sulfate, calcium chloride and other calcium salts, so it can be used as soil curing materials. Sun Shulin(2012) has used alkali residue as an additive to improve the weak expansive soil, and confirmed that alkali residue had a conspicuous improvement effect[12]. Regrettably, alkali residue improvement effect influenced by curing period has not yet reported. As is well-known, which with large destructive effect in nature is generally medium or strong expansive soil. However, at home and abroad few researchers pay close attention to this aspect.

In this paper, for expansive soil with medium expansion potential, the swelling rate, compressive strength, shear strength and California bearing ratio of mixed filler with alkali residue and expansive soil under different curing period and different mixture ratio were analyzed. As thus, the results of the study will provide some reference for future engineering practice.

2. Materials

2.1. Alkali residue
The alkali residue for test is collected from a soda plant in Huai'an, Jiangsu Province, China. In the natural state, alkali residue is gray and very pungen when approaching. After drying at 105℃, and over 10 mesh sieve, it looks like white powder, as shown in Figure 1(a), while pungent odor disappeared. The basic physical properties of alkali residue are shown in Table 1. It can be seen that the natural moisture content, liquid limit, plastic limit of alkali residue are relatively high, but plasticity index is low and expansion does not exist. The chemical composition of alkali residue is analyzed by polycrystalline X-ray fluorescence spectrometer, as illustrated in Table 2. The main cation is Ca$^{2+}$, Na$^{+}$, Mg$^{2+}$, and the main component is CaO. Its pH value is 8.9, which is weakly alkaline.

2.2. Expansive soil
The expansive soil for test is collected from construction site in Huai'an, Jiangsu Province, China. Expansive soil is crushed into fine particles after air-dried, as shown in Figure 1 (b).
According to the standard of "Test Methods of Soil for Highway Engineering" (JTG E40-2007, China) [13], grain composition, limit moisture content, compaction characteristic and free expansion ratio were carried out. Then it can be concluded that expansive soil has moderate expansion potential.

The chemical composition of expansive soil was also tested by XRF, as list in table 2. Its main components are SiO$_2$ and Al$_2$O$_3$.

![Test material](image1)

**Figure 1.** Test material

**Table 1.** The physical properties of alkali residue

| Chemical composition | alkali residue | expansive soil |
|---------------------|---------------|---------------|
| CaO                 | 52.25         | 5.78          |
| SO$_3$              | 16.97         | —             |
| Cl$^-$              | 18.39         | —             |
| SiO$_2$             | 4.06          | 60.45         |
| Na$_2$O             | 2.46          | 2.20          |
| MgO                 | 2.33          | 1.86          |
| Al$_2$O$_3$         | 1.76          | 19.34         |
| Fe$_2$O$_3$         | 1.17          | 3.42          |
| K$_2$O              | 0.15          | 3.13          |
| LOI                 | 0.46          | 3.82          |

LOI: Loss on Ignition

**Table 2.** Chemical components of alkaliresidue and expansive soil

**Table 3.** The physical properties of expansive soil
3. Test

3.1. Mixing rate
The mixing rate in this paper is the dry mass ratio between alkali residue and expansive soil. On account of the feasibility and convenience of sample operation, the mixing rate is designed to be 0%, 10%, 20%, 30%, 40% and 50%.

3.2. Test methods
In order to acquire the pavement performance of mixed filler with alkali residue and expansive soil, the swelling test, the unconfined compressive strength test, the direct shear test and the CBR test were carried out. All test methods refer to the standard of "Test Methods of Soil for Highway Engineering".

3.3. Test procedure
(a) After dried and sieved, alkali residue and expansive soil mixed evenly according to the design ratio. Then the mixture is stirred while adding water, and placed in a sealed bag stew for 24 h.

(b) Through the homemade sample preparation device [14], a certain amount of mixture can be compact for standard samples using static pressure method. The sample surface roughness and height should be checked if it is in line with the requirements. The compactness was selected as 95%.

(c) The samples are placed in the standard curing box with temperature 20±3℃, humidity more than 95%. And the setting time were set as 0, 7, 14, 28 days.

(d) When reaches a specific curing time the sample is taken out, and the experiment are carried out, including swelling test, unconfined compressive strength test, direct shear test and CBR test. Two sets of parallel test are performed for all samples.

4. Results and discussion

4.1. Swelling ratio
The swelling ratio of expansive soil is the key index of swelling and deformation. The swelling ratio without pressure of expansive soil after incorporating with alkali residue is shown in Fig.2. The results show that swelling ratio without pressure is significantly decreased with the mixing rate decreasing. When mixing rate reaches to 20%, the swelling ratio without pressure has decreased from 15.7% to 3.2%. In addition, through observing swelling process of the mixture, it is found that when saturated with water, expansion increased rapidly in the fore 10 hours, and then became slow, and basically completed after 50 hours.

![Figure 2. Variation of swelling ratio without pressure with mixing rate](image1)

![Figure 3. Variation of swelling ratio without pressure with setting time](image2)
Samples with mixing rate of 20% were selected to carry out swelling test with curing time of 0, 7, 14 and 28 days respectively, and the results illustrated in Fig. 3. It can be concluded that with the increase of setting time, the swelling rate decreased significantly. Curing for 7 days, the swelling ratio without pressure has dropped to 0.9%, while maintenance to 28 days, the mixture has completely eliminated expansion.

4.2. Unconfined compressive strength
The effects of adding alkali residue on the unconfined compressive strength (UCS) of mixed filler are described in Fig. 4. A general pattern is observed in which the alkali residue has a obvious effect on the UCS. With the raise of the mixing rate, the UCS increases gradually, but the increase rate tends to be stable after the mixing rate reaches 30%. This reveals that the more alkali residue content, not necessarily the higher UCS. When the mixing rate exceeds 30%, too much alkali residue is equivalent to increase its own non-cohesive ingredient.

It is illustrated in Figure 5 that the UCS of samples with mixing rate of 20% at setting time of 0, 7, 14 and 28 days respectively. Clearly, the longer setting time is, the higher UCS will reach. After 7 days, UCS has increased to 817.5kPa, and after 14 days, it’s 940.5kPa, which is double of original state. However, the UCS did not promote significantly with the change of setting time beyond 14 days, which indicated that with the increase of curing age, alkali residue had little contribution to the upper strength of stabilized soil. The strength increased slightly because of the transformation of aragonite to calcite inside alkali residue.

“Code for design of highway subgrades” (JTG D30-2015, China) [15] pointed out that the unconfined compressive strength of the expansive soil is to meet the requirement of 800kPa as subgrade. The above studies show that the mixture of alkali residue-expansive is not satisfied if not cured, but it will be able to achieve the required strength, after curing for 7 days. The result has a great significance for subgrade design and construction.

![Figure 4. Variation of unconfined compressive strength with mixing rate](image1)

![Figure 5. Variation of unconfined compressive strength with setting time](image2)

4.3. Shear strength
The shear strength index tested by the direct shear test is shown in Fig.6 It can be found that the cohesion (C) increases first and then decreases with the increase of alkali residue content, and reaches its peak at 30%. The cohesion of untreated soil is 30.19 kPa, and maximum cohesion is 104.73 kPa, which is increased by 235.7%. The main reason is that the alkali residue and the expansive soil reacted chemically and produced new complex which improve the density of the soil.

The internal friction angle (φ) varies little with the increase of the mixing rate, which has been stable between 25 and 29°. This is due to the friction of the expansive soil particles and modified soil particles are roughly equal.
Figure 6. Variation of shear strength with mixing rate

4.4. California bearing ratio (CBR)
CBR is used to assess the subgrade material carrying capacity and resistance to deformation. In subgrade construction it is a very important index. Fig.7 shows the variation of mixing filler’s CBR value with alkali residue. It can be obtained from the figure that the CBR of the original expansive soil is less than 8%, so original expansive soil can not be directly used for highway subgrade. After the improvement of alkali residue, the CBR value is greatly improved, which fully satisfies the embankment filling requirements of the highway subgrade. For example, when mixing rate is 30%, CBR value reaches to 33.6%. In addition, CBR values of mixing filler is significantly affect by setting times. The longer setting time is, the higher CBR will be. After 14 days of curing, CBR increased by 125.6% compared with untreated samples, and 28 days increased by 162.3%.

Figure 7. Variation of CBR with mixing rate
Figure 8. Variation of CBR with setting time

5. Curing mechanism
The swelling ratio, unconfined compressive strength, shear strength and CBR of mixture with alkali residue - expansive soil show that alkali residue has significant improvement on expansive soil, and the curing mechanism mainly lies in:

5.1. Replacement of alkali residue
Added to expansive soil, alkali residue played a certain degree of replacement effect. Due to the low plasticity and nonexpansion of alkali residue, the replacement efficiency is more and more obvious with the increase of alkali residue content.
5.2. Coagulation reaction of alkali residue - expansive soil
Hydrated calcium silicate (CaO·SiO$_2$·nH$_2$O) and hydrated calcium aluminate (CaO·Al$_2$O$_3$·mH$_2$O) can be generated with CaO from alkali residue and SiO$_2$, Al$_2$O$_3$ from expansive soil under the water environment. The chemical product are ideal cementitious materials in the internal structure of the soil. Along with these cementitious materials gradually transforming from gel state to crystalline state, the particle size of mixture (alkali residue-expansive soil) increase, so that the strength and rigidity increase and the water stability is improved.

5.3. Ion exchange of alkali residue - expansive soil
Expansion and shrink of expansive soil is mainly due to water absorption of expansive mineral in soil. Once absorbing water, the thickness of water film will change. The thinner the thickness, the greater the cohesive force between the particles, the higher the shear strength of the soil, the smaller the swell-shrinking property. After added to the expansive soil and assisted by water, alkali residue is dissociated into Ca$^{2+}$ and OH$^-$ ions. Ca$^{2+}$ is replaced by Na$^+$ and K$^+$ in the clay particles by ion exchange, so that the colloidal adsorption layer is thinned. As a result, the thickness of water film becomes thinner and the swelling potential of the soil reduces. In addition, alkaline environment accelerates ion exchange. As the pH of alkali residue is about 8.9, the pH value of expansive soil increases with the addition of alkali residue. Generally speaking, the more alkali residue, the more ion exchange.

6. Conclusion
Through a series of indoor experiment, the pavement performance of mixed filler with industrial alkali residue - expansive soil were studied comprehensively. The research conclusions are as follows:

1. The swelling ratio without pressure of alkali-residue-expansive soil mixture decreases significantly with the increase of the mixing rate. Nevertheless, the mixing rate exceeds 20%, the swelling ratio has a little change. There is a negative exponential relationship between the swelling rate and the mixing rate. Meanwhile, the swelling ratio is effected obviously by setting time. Curing for 7 days, the swelling ratio without pressure has dropped to 0.9%, while maintenance to 28 days, the mixture has completely eliminated expansion.

2. The unconfined compressive strength of mixture with alkali residue-expansive soil increases with the growth of mixing rate. However, when the mixing rate exceeds 30%, the change of unconfined compressive strength is minor. Besides, the curing time had a significant effect on the unconfined compressive strength, for instance, the unconfined compressive strength of sample after cured for 14 days is double of non-cured one. Obviously, the longer curing time, the higher unconfined compressive strength.

3. The cohesion of alkali residue-expansive soil mixture increased first and then decreased with the raise of mixing rate. When the mixing rate was 30%, the cohesion reached the peak, and triple of untreated expansive soil. The internal friction angle varies little with the increase of the mixing rate and has been stable between 25 and 29°.

4. CBR value of alkali residue-expansive soil mixture increases with mixing rate and setting time. After 14 days of curing, CBR increases by 125.6% compared with untreated samples, and after 28 days increases by 162.3%.

5. It is shown that Alkali residue can improve expansibility of expansive soil. The main reasons for resisting expansion, enhancing strength and promoting bearing capacity are: substitution efficiency of alkali residue, coagulation reaction and ion exchange of alkali slag - expansive soil.

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