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Treatments Technology and Mechanisms of East Africa Black Cotton Soil

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ABSTRACT

The East Africa black cotton soil (BCS) cannot be used as embankment filling directly, because it is high in clay content, liquid limit, plasticity index, and low in CBR strength (CBR < 3%). Therefore, this paper uses tests and analysis on the indicators, such as basic physical properties, swelling characteristics and mechanical properties of the East Africa BCS modified by the lime and volcanic ash, in order to explore the influence of the different blending amounts of lime, volcanic ash on expansion and contraction deformation strength and the law of change. So that the economical and feasible chemical treatments of the East Africa BCS which meet the requirements of specifications can be found. In addition, the chemical treatment mechanism of the East Africa BCS will be analyzed.

Keywords:

Road engineering, Black cotton soil, Base, Lime, Volcanic ash.

1. Introduction

In recent years, China's highway and railway construction technology has made considerable progress in outward export. China's construction engineering group often encounters engineering problems caused by the local BCS in the road and railway construction projects undertaken by East African countries. BCS is a high expansive soil and major deposits of India where cotton is grown in large quantities, and it will cause serious diseases in the base project, including uneven settlement, landslide, slope collapse and etc. So it has to adopt a replacement program, which increases the amount of earthwork and project cost. The in-depth study of the expansion characteristics and treatment technology of BCS in East Africa can increase the safety of the project, reduce the project cost, and enhance the environmental benefits. Due to the relatively backward research conditions in East Africa, there is little research on the expansion characteristics of BCS in this area. Most of the achievements came from Chinese road and railway industry technicians, due to Chinese engineering companies encountered a large number of engineering diseases caused by BCS in the process of construction in Africa and Southeast Africa. Investigate the survey of black soil distribution and the characteristics of macro-geological features. Through geological mapping, geophysical prospecting combined with laboratory tests, in-situ tests, etc., a set of exploration methods suited to the national conditions of the country was established [1]. X-ray diffraction and thermal analysis were used to analyze the composition and porosity of the soil [2,3]. Based on the above analysis, the composition of BCS in African is similar with the expansive soil in Yunnan, Tibet, and other provinces in China is basically similar. However, the color of expansive soils in Africa is deeper and the self-expansion rate is very high [4,5]. The content of clay montmorillonite distributed in southern Iran reached 83% [6] . The expansive soil roadbed should be improved from two aspects of building structure and additives. In terms of structure, the subgrade drainage system shall be reinforced; the subgrade bed for the weak medium expansive soil shall be replaced by not less than 0.5 m, and the subgrade bed for middle and strong expansive soil shall be replaced by not less than 1 m [7,8]. The compaction of expansive soil should adopt the heavy-duty compaction standard, and the water content should be 3% more than the optimum moisture content [9]. When piles are used to lift the bearing capacity of the subgrade, the length of the pile should be increased, and special piles such as bamboo piles should be used [10]. In terms of additives, a certain amount of lime can improve the soil structure[11]. The use of slag composites can also increase the strength of the soil, allow construction to be carried out as quickly as possible, and reduce costs [12, 13]. India uses coconut fiber, banana fiber, and sisal fiber to reinforce the expansive soil subgrade, and concluded that the maximum load-carrying capacity was obtained at 0.5% of the 2.5 cm long fiber [14]. Microscopically, SEM images were used to create a map of the clay microstructure and explain the engineering properties of the clay [15, 16].

In this paper, through the free expansion rate test, limiting moisture content, compaction test and CBR test, the treatment effect of different lime and volcanic ash content on the BCS in East Africa was studied. It was found that the lime + volcanic ash conformation scheme is better than the single use of lime or volcanic ash. It is recommended that the 3% lime + 15% volcanic ash treatment plan meets the specification requirements and reduces the construction cost. At the same time, using computer molecular modeling to explain the modified mechanism of black soil in East Africa from the microscopic and mesoscopic levels.

2. Treatment Technology

2.1. Materials

The BCS used in the experiment was taken from the South Link K2+130, Nairobi, Kenya. The BCS in East Africa was mainly composed of hydrophilic clay minerals with high percentage of fine clay particles. The free expansion of BCS was determined between 40% and 140%, and was categorized as expansive soil with medium strength in according to TB 10077-2001 [17]. So it is a kind of high liquid limit clays with strong expansion potential and low strength. The volcanic ash used in this paper was produced during volcanic activities. Generally, it is dark gray, yellow or white in color. The volcanic ash was tiny debris and becomes tuff after compaction. There were a certain amount of activated silica (SiO_2) and activated alumina (〖Al〗_2 O_3) in the mixture. Thus, the volcanic ash could bond the clay together and reduce the water absorbing capacity of clay particles.

Table 1.Chemical composition of volcanic ash (unit: %).

Ash sample number	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2	K_2O	Na_2O	SO_3	P_2O_5	MnO	TiO_2	LOI
Sample 1	10.69	11.69	12.43	13.35	43.26	1.29	2.76	0.065	0.54	0.17	2.85	0.32
Sample 2	10.88	12.18	12.41	13.07	43.08	1.26	2.75	0.061	0.54	0.17	2.81	0.22

The milled volcanic ash and BCS were mixed together manually, and then the appropriate amount of volcanic ash was determined by relevant tests. The hydrated lime provided by a local company was adopted with effective calcium hydroxide (Ca(OH)2) content of 96.2%. The 80 μm pass rate of the lime was 100%.

2.2. Test Plan

The BCS specimens were prepared. Then free expansion rate test, limiting moisture content test, compaction test, and CBR test were conducted to test the engineering properties of the modified soil. Finally, the results of lime, volcanic ash and mixture of lime and volcanic ash were analyzed, and the optimum proportion of additives was recommended to modify BCS.

2.2.1. Specimen Preparation

The dried BCS was crushed into particles with 0.5mm and 2mm in diameter, and was sieved for the preparation of further experimental tests. The volcanic ash was crushed and sieved through 75 μm sieve. All row materials were dried in an oven with temperature range from 100°C to 105°C for 24 hours in accordance with JTG E40-2007 [18]. The effect of additives on BCS performance, consisting of volcanic ash, lime, and a combination of volcanic ash and lime, were analyzed. Four contents of volcanic ash (10%, 15%, 20%, and 25%), and four contents of lime (1%, 3%, 6%, and 9%) were utilized. The contents of the combined volcanic ash and lime were 1 % lime + 15 % volcanic ash, 1 % lime + 20 % volcanic ash, 3 % lime + 15 % volcanic ash, as well as 3 % lime + 20 % volcanic ash. After the additive content was determined, the raw material were measured accurately and mixed together in an enamel pan or iron pot. Then the soils were poured and mixed in a small mixer with appropriate amount of water for at least 10 minutes. Finally, the mixture was poured into a plastic bag, shake manually and conditioned for 24 hours.

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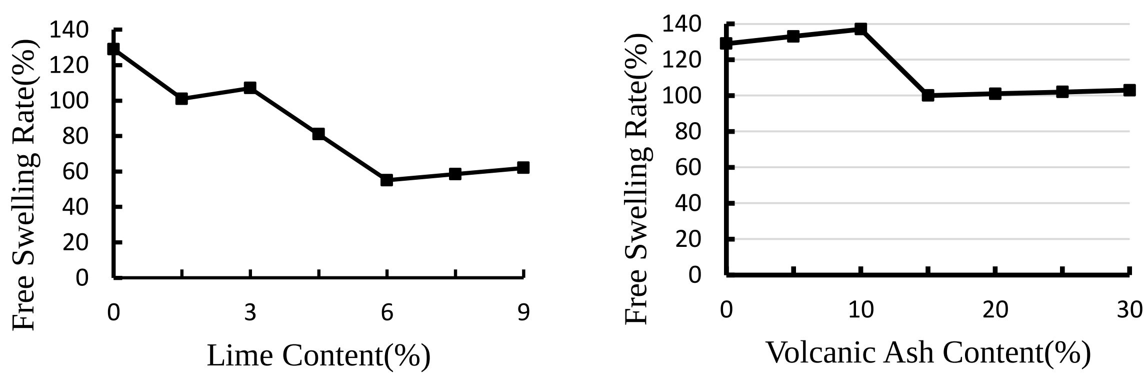
2.2.2. Test Program

Four tests were carried out according to JTG E40-2007 and ASTM D4318, including free expansion rate test, compaction test, limiting moisture content test, and California Bearing Ratio test (CBR test). Prior to the experiment, BCS samples with different additives were prepared and were kept under wet condition for 24hours. For the free expansion test, the soil particles should be smaller than 0.5mm in diameter. Then 10mL soil sample was taken through the sample device placing the 50mL measuring cylinder on the test bench. Finally, 30mL distilled water and 5mL of 5% analytical pure sodium chloride solution were injected into samples, and the soil sample was poured into the measuring cylinder. When the soil sample was stable, the free expansion rate should be calculated. Heavy-duty compaction was adopted for compaction test, where the hammer was 4.5kg with 45cm drop height. In order to obtain optimum moisture content, the soil sample was compacted using the same method as the heavy-duty compaction method. The test specimens were prepared and emerged into water for a continuous 96 hours, and then were tested using the CBR value and CBR expansion set up.

2.2.3. Testing Results

The BCS in East Africa was modified with different proportions of lime, volcanic ash, and a combination of lime and volcanic ash. The results of free swelling rate are shown in Figures. 1 and 2. Figure 1(a) shows that the maximum free expansion rate of BCS was 129% without modification, and such value could drop up to 55% when 6% of lime was used. The free swelling rate kept increased slight if higher percentage of lime was added. Figure 1(b) shows that the maximum drop of free expansion rate of BCS was 29% when mixed with 15% volcanic ash, whereas it did not drop further with additional volcanic ash. The free swelling rate of BCS with 3% lime or 15% volcanic ash alone is 105% or 100%, respectively. While adding 3% lime and 15% volcanic ash at the same time, free swelling rate fell to 71%. Thus the mixture of lime and volcanic ash can obtain preferably modification effect.



(a) (b)

Figure 1. Free swelling rate of BCS with different blending amounts of (a) lime, and (b) volcanic ash.

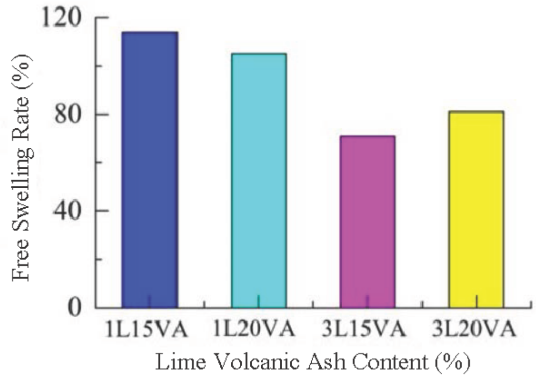
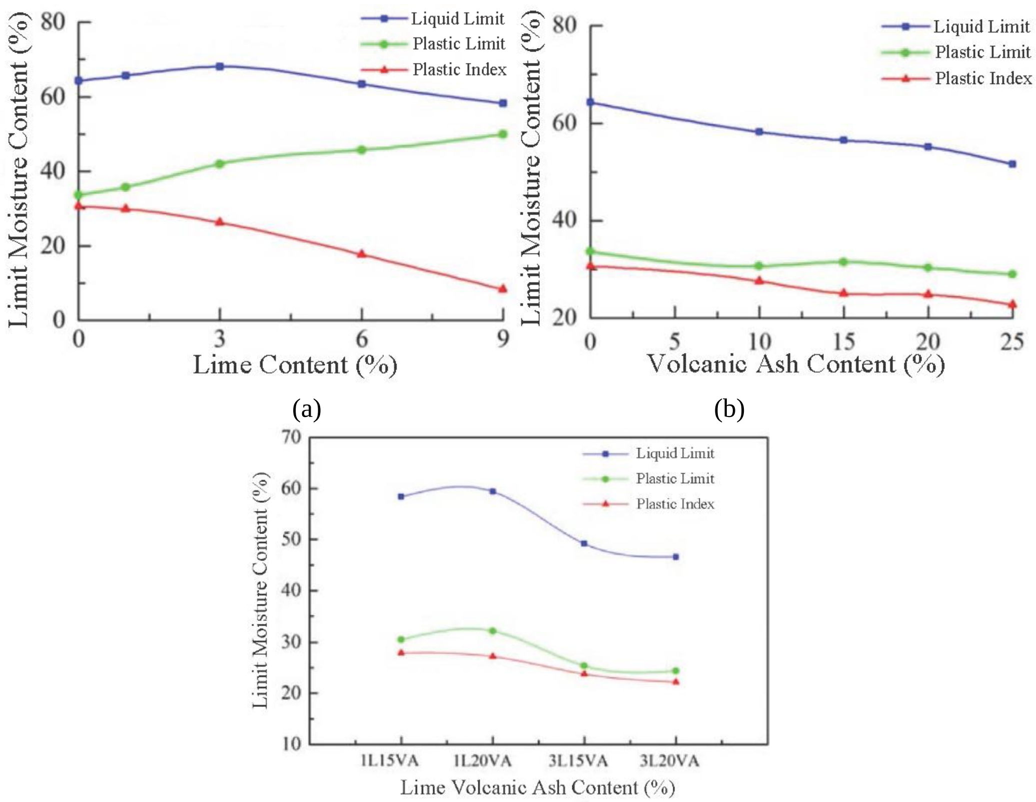


Figure 2. Free swelling rate of BCS with different blending amounts of lime and volcanic ash
(Note: L indicates lime, VA is volcanic ash, 1 is 1% content, 15 is 15% content, and the rest of paper is the same)

The greater liquid limit and plasticity index of the expansive soil, the stronger water storage capacity and expansibility would be. On the contrary, reducing the boundary moisture content would increase the water stability and soil strength of the expansive soil. Therefore, liquid-plastic limit tests were conducted on plain and modified BCS and results were shown in Figure 3. If the lime content is about 9%, the plastic index significantly reduced and the plasticity index is approaching non-expansive soil. It is worth noting that the liquid limit increases at beginning. Because the lime particle size was very small and did not completely react with the BCS which leaded to absorb a large amount of water and increased the liquid limit index. Liquid limit dropped slightly with lime content increasing. When volcanic ash was added increasingly, the liquid limit decreases significantly and the plasticity index decreases slightly. The modification effect of the mixture of lime and volcanic ash was much better than that of lime or volcanic ash. The liquid limit and plasticity index of black cotton were 68.1 and 26.2, when 3% lime was added. The liquid limit and plasticity index of black cotton were 56.5% and 25 using 15% volcanic ash. However, the liquid limit and plasticity index decreased to 49.2% and 23.8 with the mixture of 3% lime and 15% volcanic ash. According to JTG D30-2015, liquid limit and plastic index of fine-grained subgrade filling should be less than 50% and 26. The additive of 3% lime and 15% volcanic ash could not only meet the requirements of the standard, but also minimize project cost.



(a) (b)

(c)

Figure 3. Limit moisture content of BCS with different blending amounts of (a) lime, (b) volcanic ash ,(c) lime volcanic ash.

The maximum dry density and optimum moisture content of BCS was obtained in order to control the subgrade filling quality. The compaction curves of BCS with different additive was tested and presented in Figure 5. It is seen in the figure, with the increase of lime, the optimum moisture content increase, varies the maximum dry density. With the volcanic ash content increasing the optimum moisture content of the mixture decreased, while the maximum dry density increased. Figure 4 c shows that if lime and volcanic ash were used jointly together, lime and volcanic ash exert the opposite effect on the compaction characteristics. CBR test and CBR expansion test were conducted to evaluate the effect of additives on strength properties, as well as to recommend an optimum content of additive. Testing results are presented in Figure 5. As noted, the CBR value increased steadily with the increase of lime content or volcanic ash, with an increased growth rate. In contrast, the CBR expansion capacity decreased gradually at beginning and tends to plateau. It is also observed that CBR value was more sensitive if lime was utilized compared to the volcanic ash. It was also noted that if the mixture of lime and volcanic ash were both added, the CBR value was significantly increased and CBR expansion rate was greatly reduced, compared to solely adding lime or volcanic ash. This provides an option to utilize more volcanic ash since the price of lime in local East Africa was at a high level.

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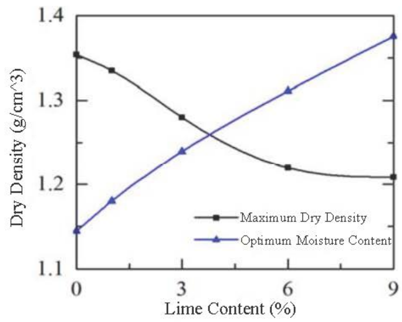
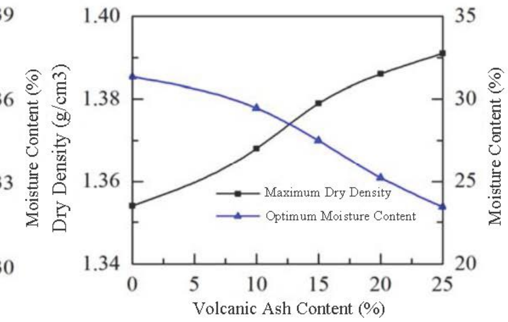


(a)



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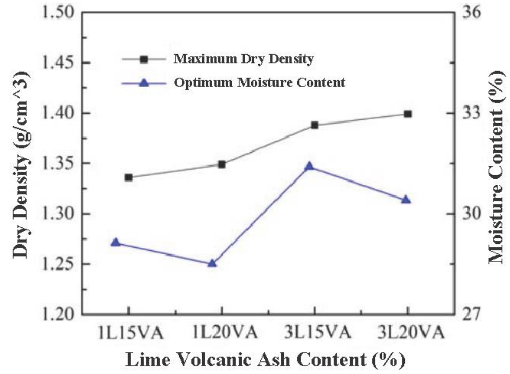
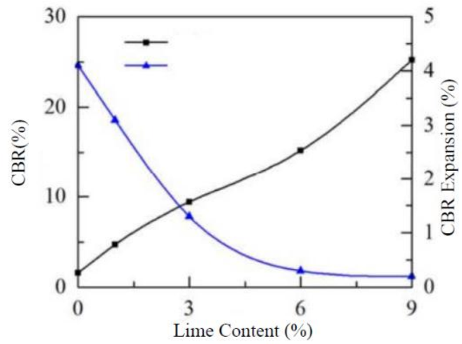


(c)

Figure 4. Optimal moisture content and maximum dry density of BCS with additive of (a) lime, (b) volcanic ash and (c) lime volcanic ash.



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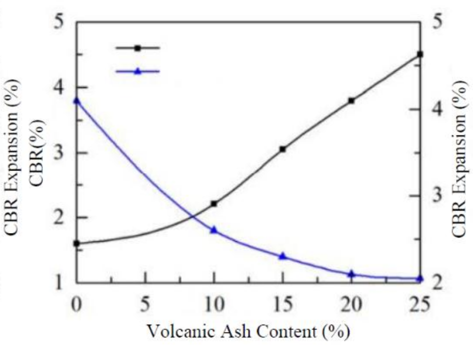
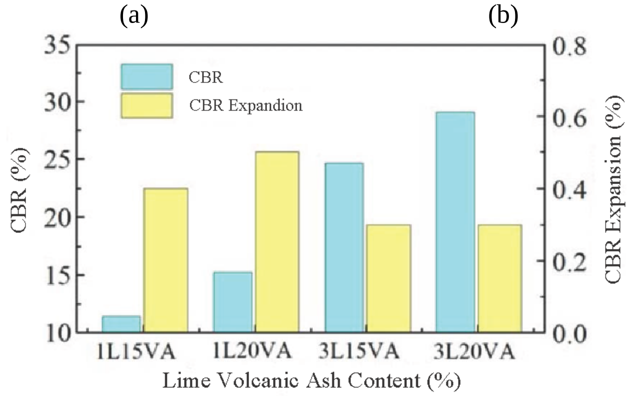


(b)



(c)

Figure 5. CBR value and CBR swelling capacity of BCS with blending amounts of (a) lime, (b) volcanic ash and (c) lime volcanic ash.

3. Microscopic Treatment Mechanism

This section conducted a research and analysis on the treatment mechanism of lime and volcanic ash.

3.1. Hydration Exothermic Reaction

The Ca (OH) $_2$When was generated if quick lime or slaked lime was added into high liquid limit BCS. On the one hand, the reaction could reduce the moisture content by hydration and evaporation process. On the other hand, the reaction generated Ca^{2+}, OH^- and Ca (OH) $_2$ which provided necessary conditions for carbonation reaction and $Ca(OH)_2$ crystallization. The addictive was carbonated by absorbing CO_2 and H_2O in the air and result in dense calcium carbonate. $CaCO_3$ and $Ca(OH)_2$ could combine with each other which made soil particles form an integral structure. Meanwhile, the Ca^{2+} adsorbed around clay minerals produced flocculate and bonded mineral particles, and changed the pore structure of the entire soil particles. With the increase of lime dosage, the chemical bond forces was rapidly decreased expansion volume and force, which resulted in a continuous decrease in hydrophilicity and an increase in water stability and strength stability. This is one of the most important reasons of lime-modified soil strength improvement.

3.2. Volcanic Ash Reaction

The OH ionized by $Ca(OH)_2$ makes the soil alkaline. Under alkaline conditions, $Ca(OH)_2$ reacts with active SiO_2 and Al_2O_3 in volcanic ash and BCS producing hydrated calcium silicate (CSH), hydrated calcium aluminate (CAH) or hydrated calcium sulphoaluminate. Partial chemical reaction formulas are shown in the following formula 1 and 2.

$$5\mathrm{Ca}(OH)_2 + 6SiO_2 + nH_2\mathrm{O} \xrightarrow{\text{alkaline}} Ca_5Si_6O_{16}(OH)_2 \cdot (4+n)H_2\mathrm{O} \quad (1)$$

$$\mathrm{Ca}(OH)_2 + Al_2O_3 + nH_2\mathrm{O} \xrightarrow{\text{alkaline}} \mathrm{CaO} \cdot Al_2O_3 \cdot (1+n)H_2\mathrm{O} \quad (2)$$

This reaction was similar to the hydration of volcanic ash cement to get strength known as the volcanic ash reaction. From Table 1, it can be seen that the oxide composition of all volcanic ash is very similar in East Africa. Among the oxide, the content of SiO_2 was over 40%, and the content of Al_2O_3 reached 13%, which provided raw materials for volcanic ash reaction. The hydrated calcium silicate produced by the reaction between SiO_2 and $Ca(OH)_2$ is the most important hydration product of Portland cement hydration and the most important strength source of cement-based composite materials. Therefore, the main reason for high strength of BCS mixed with lime and volcanic ash is that there was a large amount of volcanic ash reactions in soil. In addition, hydrated calcium silicate (C-S-H) and hydrated calcium aluminate (C-A-H) were gelling materials with cementation effect. The gelling materials accumulate on the surface of the soil particles forming a solidification layer through hardening and crystallization, which prevented the diffusion of particles' moisture and reduced the expansion potential and liquid limit of the soil.

3.3. Semipermeable Membrane Effect

Due to the high moisture content of the BCS, the montmorillonite crystals are surrounded by the pore solution, as shown in Figure 6. In order to study the interaction between the solution in montmorillonite layer and the pore solution, the P point in Figure 8 was enlarged to Figure 9.

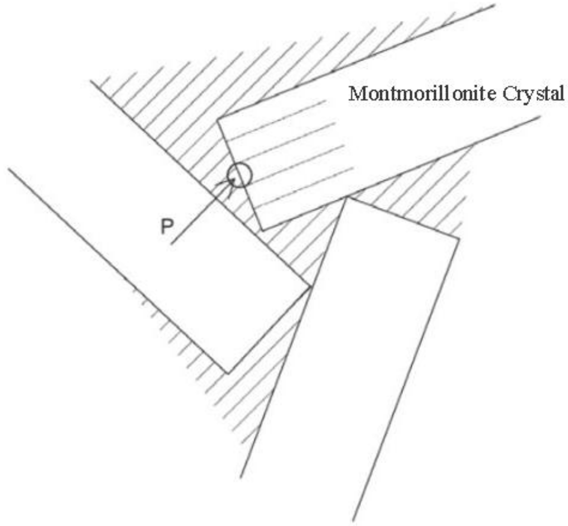


Figure 6. Montmorillonite crystal schematic diagram.

As shown in Figure 6, there was an imaginary interface between the montmorillonite layer and the pore solution, which was a dotted line MN. Zheng (2013) believes that under certain conditions, MN could be equal to a semipermeable membrane, which means only water could pass freely [19]. There were various electrolyte molecules and ions in pore solutions, and the solution between montmorillonite layers also contained a certain concentration of cationic. It could be used to explain the treatment technology of East Africa BCS from the microscopic level:
After a certain amount of water was added to BCS, the montmorillonite minerals are shown as Figure 7(a). According to the diffusion theory and the semipermeable membrane principle, the osmotic pressure makes the water molecules continuously enter the crystal layer from the pore solution (Figure 7(a) arrow direction), until the osmotic pressures achieved a balance. In the continuous flow of water molecules, montmorillonite in BCS would appear significant expansion. After treating by mixture of lime and volcanic ash, a large number of cations flowed into pore solution. The concentration of ions in the pore solution increased significantly, and the solutions in the pores and between the montmorillonite layers were shown as Figure 7(b). The ion concentration between the layers was smaller than pore solution, thus the osmotic pressure difference caused water molecules to enter the pore solution from the intercrystallite layer (as shown in Figure 7(b). The spacing of montmorillonite decreases and contracts, which would reduce the expansion potential of BCS.

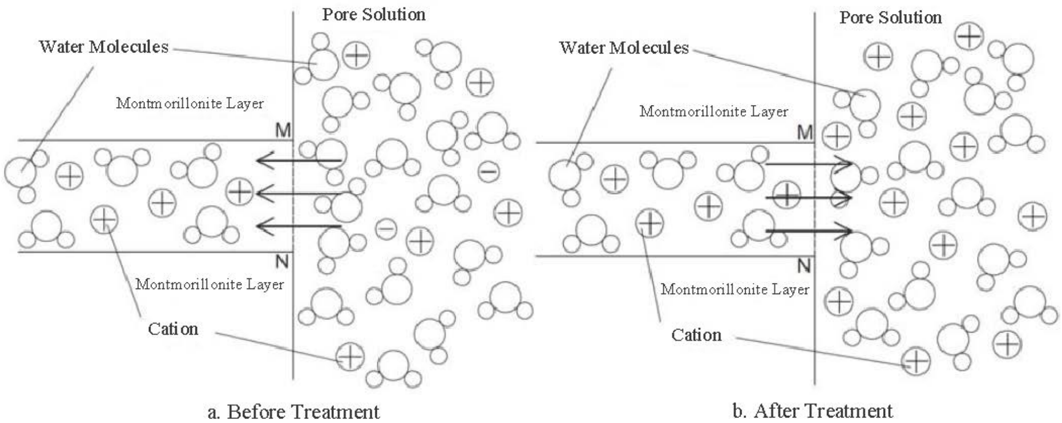


Figure 7. Schematic diagram of semipermeable membrane.

4. Conclusions

In this paper, the BCS in East Africa was treated by lime, volcanic ash, and mixture of lime and volcanic ash. And its engineering properties were obtained by four experiments. The results showed that the addition of lime reduced the free swelling rate, improved limit moisture content, increased optimum moisture content increase, decreased the maximum dry density, and increased CBR value. Adding volcanic ash could also improve the performance of BCS but the effect was not as good as that of lime. The compound treatment of lime and volcanic ash was much better than lime or volcanic ash. Generally, the mixture of lime and volcanic ash in the BCS could greatly reduce the expansion potential and significantly increase the strength. The compound treatment of 3% lime and 15% volcanic ash could improve the liquid limit, plasticity index and CBR value to be 49.2%、23.8 and 24.7% respectively, which could meet with the requirements of JTG D30-2015 and reduce the constructing cost. Considering molecular simulations, phase composition and engineering properties, the treatment mechanism of BCS were put forward: hydration exothermic reaction, volcanic ash reaction, semipermeable membrane effect. Hydration exothermic reaction provided the basis conditions for the other reactions. Semipermeable membrane effect and ion exchange could reduce the layer spacing of montmorillonite cell, weak water absorbing ability and water film thickness in soil particle surface, which resulted in expansion potential reducing. Carbonation reaction, $Ca(OH)_2$ crystallization and volcanic ash reaction could produce dense high-strength calcium carbonate, hydrated calcium silicate (C-S-H), hydrated calcium aluminate (C-A-H) or hydrated calcium sulphoaluminate those could significantly enhance strength of treatment soil.

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