The reinforcement mechanism and effect of potassium silicate solutions in an unsaturated loess soil subjected to saturation

Le mécanisme de renfort et l'effet des solutions de silicate de potassium dans un loess soumise à saturation

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ABSTRACT
Solutions of potassium silicate (PS) have been applied to reinforce ancient unsaturated earthen structures in arid regions in northwest China in recent years. Some technical challenges in this reinforcement method still require further study. The performance of PS-reinforced loess soil after rainfall is of great concern. This study investigates the permeability and shear strength of PS-reinforced loess soil from the ancient city of Jiaohe upon saturation. Saturated loess specimens reinforced by 3% PS and 7% PS show higher peak shear strength by 90% and 360%, respectively, as compared with unreinforced specimens. The addition of 3% PS and 7% PS reinforcement also results in higher residual shear strength by about 50% and 250%, respectively. These results suggest that PS reinforcement should be effective under saturation conditions due to rainfall. SEM and TEM analysis reveals that the effectiveness of PS reinforcement is related to reticular and dense structures in PS-reinforced soil. The structure of PS-reinforced soil results from non-crystalline and crystalline mixtures produced t from the interaction between PS and clay minerals.

RÉSUMÉ

Texte du résumé： Utilisé largement dans les régions sèches du Nord-Ouest de la Chine,le PS (un Materiel de renforcement)a connu un grand succes aux travaux de sauvegarde des ruines historiques par son effet de renforcement du sol. Mais certains problemes concernées sont a etudier plus profondement, dont un urgent est de connaitre son effet apres la saturation de pluie sur la terre de site. Dans cet article, nous exposons l’essai au site de JiaoHe de la Province Xinjiang comme une exemple pour chercher la reponse. Premièrement, nous testons des echantillons de sol-melanges de PS de purete différente et puis on les seche pour une période de temps,de sorte qu’ on obtient des sols de l’humidite initiale diffenrente, et ensuite, on les trempe dans l’eau pour qu’ils soient satures d’eau, et sans sechage ni consolidation on mesure leur résistance au cisaillement. Les résultats ont montré que les echantillons a 3% de PS et a 7% de PS ont tous pu elever la force de résistance du terrain au pic de cisaillement , respectivement, a 90% et a 360% aux valeurs originales; meme leur résidus ont également augmenté la résistance au cisaillement a 50% et a 250%. Cela dit que, même si saturés par la pluie,le sol renforcé de PS ,est encore très solide avec l'effet evident de renforcement. D’ailleurs, des analyses de SEM et TEM ont aussi ete faites pour trouver le mécanisme de ce renforcement PS. Les résultats d’analyse ont montré que une fois utilise dans le sol des ruines,le PS en a change la structure en s’y integrant pour former une nouvelle structure plus densee; en même temps, le sol connait une réaction chimique avec PS, augmentant ainsi la force de collage. Cette structure a augmenté la capacité d’ anti-érosion du sol dont la résistance organique pourrait protéger les sites des ruites historiques.

Keywords : PS; reinforcement; unsaturated, loess; saturation

1 INTRODUCTION

China has many ancient cities like the 2300-year-old Jiaohe, which was a major city along the “Silk Road” in northwest China. Many of the earthen structures in this ancient city were made of unsaturated loess soil and these earthen structures are now subject to severe threat due to climate change. Apart from surface erosion due to wind, severe temperature and rainfall conditions have led to an increase in mechanical and chemical weathering of the ancient structures in Jiaohe, mainly because of rainfall infiltration into the unsaturated loess structures and extreme temperature ranges (i.e., freeezing and thawing) leading to seasonal expansions and contractions of the unsaturated loess soil. Cracks in the unsaturated loess city walls have been growing substantially wider and the stability of some of the unsaturated earthen structures is decreasing. It is clear that swift action must be taken to protect this historical city from the hostile natural environment. However, any preservation action taken and any technology used must be environmentally friendly and essentially non-visible to the public. In addition, the knowledge of unsaturated soil mechanics (Ng & Menzies, 2007) is essential in understanding the behavior of these unsaturated earthen structures and devising protective solutions.

Potassium silicate (PS) solution, originally invented at Dunhuang Academy in China, is an inorganic cementing-consolidating material in an aqueous solution (Li 2003). It can be used as a chemical material for protecting earthen structures from weathering. In recent years, this material has been widely applied to reinforce ancient earthen structures in arid regions located in northwest China. Years of experimental studies and applications have proved that PS is a suitable and effective material for the conservation of ancient earthen structure sites. Based on laboratory and field experiments, it has been found that PS reinforcement in a soil largely increases the shear strength of the soil and greatly enhances the soil’s resistance to erosion from wind and rain and freeze-thaw cycles (Su et al. 2000; Wang 2003; Zhao et al. 2006; Li et al. 2007). However, many questions related to PS reinforcement in loess soil remain unanswered and the mechanism of the interaction between PS and loess soil is not yet fully understood. One important question is if PS reinforcement is effective when it is subjected to rainfall. Another important question is related to the permeability of the loess soil reinforced by PS. Loess soil reinforced by PS should remain permeable to water in order to prevent a layer of impervious dense crust forming on the surface of the soil. A crust can cause exfoliation of the loess soil and

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then produce secondary destruction to earthen structures. However, little research has been carried out to study changes in the permeability of loess soil after it is reinforced with PS. In this study, these two questions are answered by carrying out permeability and unconsolidated undrained (UU) shear tests on a loess soil reinforced by PS. The mechanism of the interaction between PS and loess soil is also discussed.

2 PERMEABILIYT AND SHEAR STRENGTH OF AN INITIALLY UNSATURATED LOESS SOIL REIFORCED BY PS UPON SATURATION

2.1 *Specimen preparation*

The soil from the ancient city of Jiaohe is typical loess in the west of China. It has an extremely low water content of less than 3%. It is mostly yellow in color and mottled with gray and black. The soil has a relatively large void ratio and relatively high permeability. Its basic physical properties are summarized in Table 1. As determined from X-ray diffractometry, the predominant minerals in the soil are chlorite and illite. The clay minerals are laminar aluminium silicate.

To produce specimens reinforced by PS, each soil specimen was firstly mixed with different PS solutions (including water, 3% PS and 7% PS) to reasch a liquid content of 15% to 21%, as summarized in Table 2. After equalization in a sealed plastic bag for 48 hours, the soil was compacted to cylindrical specimens with 70 mm diameters and 150 mm heights in a mould. The compaction resulted in a dry density of 1.38 to 1.45 g/cm^3, as summarized in Table 2.

2.2 *Testing procedures*

After specimen compaction, each specimen was subjected to a drying process by exposing it to the ambient air in the laboratory for some time. This drying process with different durations resulted in different liquid contents, as summarized in Table 2. To simulate rainfall effects, each specimen after drying was subjected to a saturation process in a triaxial cell. Water was forced to flow into each specimen by applying a constant water pressure of 10 kPa at the bottom of the specimen while maintaining the air pressure on top of the specimen at atmospheric pressure. The amount of water flowing into and out of specimen was monitored. When the rates of inflow and outflow were equal, the saturation process was terminated and the coefficient of permeability under saturated conditions was measured. After saturation, UU shear tests were carried out on each specimen with an axial displacement rate of 1 mm/min. A proving ring with a capacity of 3 kN was used to measure the axial force on the specimen. The estimated accuracy of the deviatoric stress was 2 kPa.

2.3 *Results from the permeability tests*

Figure 1 show the coefficients of the permeability of unreinforced specimens and specimens reinforced by 3% and 7% PS. The coefficient of permeability of the unreinforced specimens ranged from 4.7×10^{-7} to 1.8×10^{-6} m/s. After 3% PS reinforcement, the coefficient of permeability ranged from 9.8×10^{-7} to 2.0×10^{-6} m/s. The specimens reinforced by 7% PS had coefficient of permeability ranging from 4.8×10^{-7} to 7.0×10^{-7} m/s. These data indicate that PS reinforcement produces negligible influences on the permeability of loess soil under saturated conditions. Therefore, PS reinforcement does not influence the transfer of vapor between the atmosphere and the soil. An impervious crust will not be formed and exfoliation will be prevented with PS reinforcement.

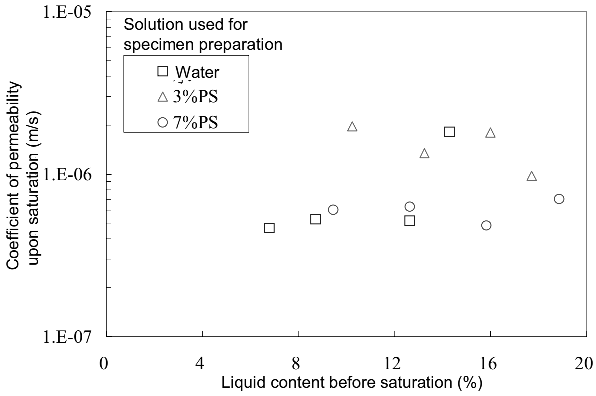


Figure 1. Coefficients of permeability of unreinforced and PS reinforced specimens upon saturation.

2.4 *Results from UU shear tests*

In terms of stress-strain relationships, specimens reinforced by PS exhibit strain-softening behavior, whereas unreinforced specimens exhibit strain-hardening behavior. This means that PS reinforcement increases the brittleness of loess soil. A detailed discussion of the effects of PS reinforcement on stress-strain relationships has been presented by Li et al. (2008). In this paper,on the focus is on the shear strength.

Figure 2 shows the relationships between shear strength and liquid content before saturation in unreinforced specimens and in specimens reinforced by 3% PS and 7% PS. Figure 2a shows the results of peak shear strength tests. This figure clearly shows that the relationship between the shear strength and the liquid content before saturation in specimens reinforced by 7% PS varied more than that in unreinforced and 3% PS-reinforced specimens. The average peak shear strengths for unreinforced specimens and specimens reinforced by 3% PS and 7% PS were 5 kPa, 9.5 kPa and 23 kPa, respectively. The addition of 3% PS and 7% PS reinforcement resulted in a higher peak shear strength by 90% and 360%, respectively, when specimens were subjected to saturation after PS reinforcement. This means that PS reinforcement remains effective even under saturation conditions due to rainfall. This finding is consistent with the observed increase in resistance to rain erosion with PS reinforcement as reported by Wang (2003) and Zhao et al. (2006).

Figure 2b shows results of residual shear strength tests. The relationship between the residual shear strength and the liquid content before saturation varied less as compared with the peak shear strength. The average residual shear strengths for unreinforced specimens and specimens reinforced by 3% PS and 7% PS were 4.5 kPa, 7 kPa and 16 kPa, respectively. The addition of 3% PS and 7% PS reinforcement resulted in higher residual shear strength by about 50% and 250%, respectively, when specimens were subjected to saturation after PS reinforcement. This means that PS reinforcement increases the shear strength even when there is shearing to large deformations.

3 THE MECHANISM OF PS REINFORCEMENT

The results of UU shear tests suggested that PS reinforcement is effective under rainfall conditions. To understand the mechanism of PS reinforcement in loess soil, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to analyze the microscopic characteristics of loess soil reinforced by PS.

Table 1 Basic soil properties of loess soil from the ancient city of Jiaohe (He et al. 2007)

Sample type	Water content (%)	Natural density ($g{\cdot}cm^{-3}$)	Dry density ($g{\cdot}cm^{-3}$)	Specific gravity	Void ratio	Liquid limit (%)	Plastic limit (%)	Plasticity index
Raw soil	1.0-3.0	1.51-1.77	1.47-1.73	2.7	0.6-0.9	24.9-31.7	16.0-19.9	8-13
Rammed soil	1.5-2.6	1.56-1.72	1.54-1.70	2.7	0.6-0.8	27.5-30	16.0-18.5	9-13
Buttress soil	1.3-2.2	1.50-1.70	1.55-1.68	2.7	0.7-0.9	27.0-32.0	17.2-18.5	9-14

Table 2 Specimens prepared with various solutions and dried to different liquid contents

Test identity	Solution used for specimen preparation	Dry density at compaction ($g{\cdot}cm^{-3}$)	Liquid content at compaction (%)	Liquid content after drying (%)
W-1	Water	1.43	17	7
W-2		1.44	15	9
W-3		1.42	17	13
W-4		1.45	15	14
3% PS-1	3% PS	1.38	21	10
3% PS-2		1.38	20	13
3% PS-3		1.39	20	16
3% PS-4		1.40	18	18
7% PS-1	7% PS	1.39	20	9
7% PS-2		1.39	20	13
7% PS-3		1.39	20	16
7% PS-4		1.39	20	19

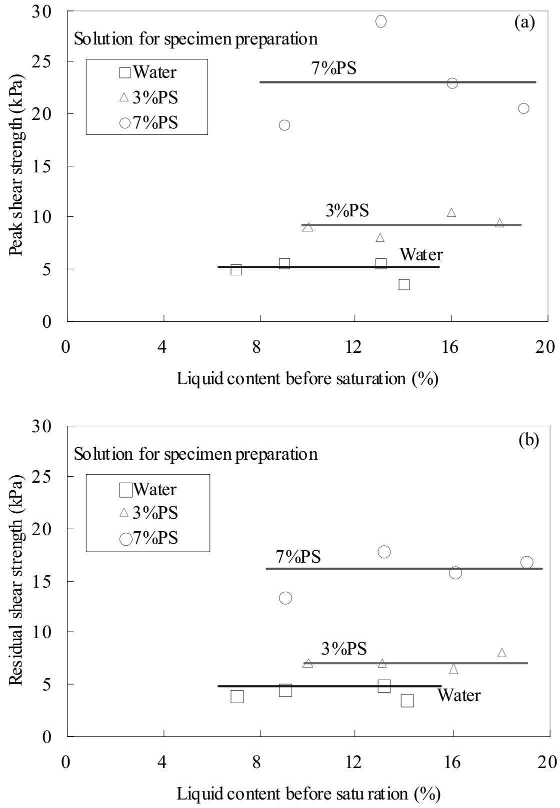
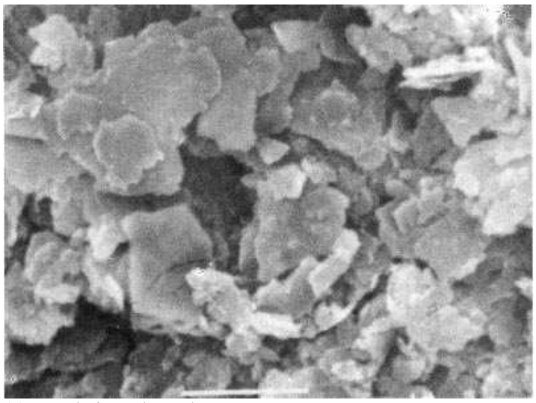


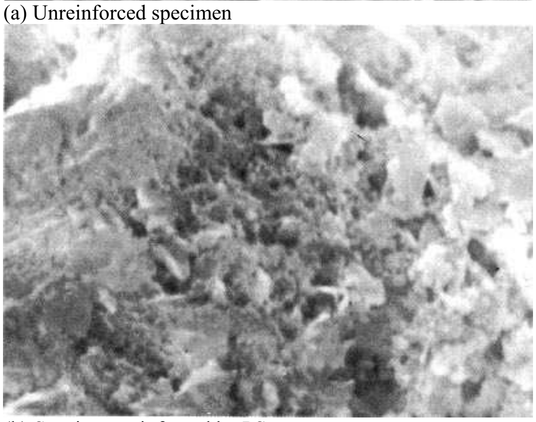
Figure 2. Relationships between shear strength and liquid content before saturation in unreinforced specimens and specimens reinforced by 3% and 7% PS.

3.1 *SEM analysis*

Figure 3 compares microscopic images of an unreinforced specimen and a specimen reinforced with PS. A JSM-5600LV SEM was used. As shown in Figure 3a, the soil structure of the unreinforced soil was laminar and loose. This soil structure had a relatively low shear strength and weak resistance to erosion from wind and rain. As shown in Figure 3b, when the soil was reinforced with PS, the soil structure became reticular and dense, due to the occurrence of non-crystalline and crystalline mixtures (discussed below) as a product from the interaction between PS and the clay minerals. The reticular and dense soil structure increased the shear strength and improved the soils' resistance to erosion from wind and rain.



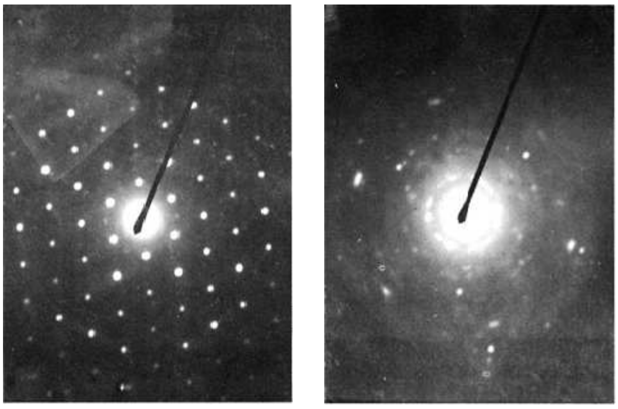
(a) Unreinforced specimen



(b) Specimen reinforced by PS
Figure 3. SEM results (×5000).

3.2 *TEM analysis*

Figure 4 shows electronic diffraction diagrams of an unreinforced specimen and a specimen reinforced by PS. These two diagrams were obtained by using a JEM-1200EX TEM. As shown in Figure 4a, the crystalline diffraction pattern if the unreinforced specimen is regular and hexagonal. This means that monocrystalline structures of the clay minerals in the unreinforced specimen were perfect and laminar. After PS reinforcement, as shown in Figure 4b, the crystalline diffraction pattern changed, indicating that the clay minerals were decrystallized and became mixtures of crystalline and non-crystalline structures. This type of mixture can result in a reticular and dense soil structure (see Figure 3b), which improves the shear strength and increases the resistance to erosion from wind and rain.



(a) Unreinforced specimen (b) Specimen reinforced by PS
Figure 4. TEM results.

3.3 *The performance of PS reinforcement with rainfall*

The UU tests on specimens subjected to saturation (Figure 2) revealed that PS reinforcement is effective after saturation. This suggests that the reticular and dense soil structure created by the interaction between PS and the clay minerals (see Figure 3b) is not destroyed by saturation. Large amounts of water seem not to dilute the PS or affect the interaction between PS and the clay minerals. The non-crystalline mixture (see Figure 4b) resulting from the interaction between PS and the clay minerals is resistant to water infiltration. Therefore, PS reinforcement is effective under rainfall conditions.

4 CONCLUSIONS

PS reinforcement has a negligible influence on the permeability of loess soil under saturated conditions. Therefore, PS reinforcement does not influence the transfer of vapor between the atmosphere and the soil. Hence, an impervious crust will not form and exfoliation will be prevented with PS reinforcement.

As compared with unreinforced specimens, specimens reinforced by 3% PS and 7% PS have higher peak shear strengths by 90% and 360%, respectively. The addition of 3% PS and 7% PS reinforcement also results in higher residual shear strengths by about 50% and 250%, respectively. These results demonstrate that PS reinforcement should be effective under saturation conditions due to rainfall.

The SEM and TEM analyses indicate that the effectiveness of PS reinforcement is related to the reticular and dense structure of PS-reinforced soil. This soil structure results from the occurrence of non-crystalline and crystalline structures produced by the interaction between PS and the clay mineral. Rainfall has a negligible influence on the interaction between PS and the clay minerals.

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REFERENCES

He, F.G, Chen, W..W., Zhang, J.K., Ren, F.F. & Cui, K. 2007. Reinforcement experiment to soil at the Ancient City of Jiaohe by PS binding material, Dunhuang Research, Vol.105, No.5, pp.: 32-35 (in Chinese).

Li, L., Chen, R., Ng, C.W.W., Wang, S.J. & Li, Z.X. 2008. Shear strength of an unsaturated loess soil reinforced by potassium silicate upon saturation. Proc. International Symposium on Conservation of Ancient Sites 2008, 22-24 Sept., Dunhuang, pp. 291-295.

Li, L., Sun, M.L.,Zhao, H.Y., Li, Z.X. & Wang, S.J. 2007. Conservation study on earthen sites of ancient architecture in China Northwest, Proceedings of 10th Chinese Conference of Soil Mechanics and Foundation Engineering. pp.103-106 (in Chinese).

Li, Z.X. 2003. Conservation of ancient sites on the silk road, Beijing: Science Press (in Chinese).

Ng, C.W.W. & Menzies, B. 2007. *Advanced Unsaturated Soil Mechanics and Engineering.* Publisher: Taylor & Francis. 687p.

Su, B.M., Li, Z.X. & Hu, Z.D. 2000. Preliminary study on mechanism of interaction between PS and soil, Dunhuang Research, Vol.63, No.1, pp.3-35 (in Chinese).

Wang, Y.M. 2003. A brief of reinforcement of earth structure sites in the arid areas of northwest china, Journal of Engineering Geology, Vol. 11, No..2, pp.189-192 (in Chinese).

Zhao, H.Y., Wang, X.D, Li, Z.X., Han, W.F., Guo, Q.L., Chen, W.W. & Wang, S.X. 2006. Impact of modulus and concentration of potassium silicate material on consolidating earthen architecture sites in arid region, Chinese Journal of Rock Mechanics and Engineering, Vol.25, No.3, pp. 557-562 (in Chinese).