

Research Article

Effect of Polyvinyl Acetate Stabilization on the Swelling-Shrinkage Properties of Expansive Soil

Jin Liu,¹ Yong Wang,¹ Yi Lu,² Qiao Feng,¹ Faming Zhang,¹ Changqing Qi,¹ Jihong Wei,¹ and Debi Prasanna Kanungo³

¹School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China

²Key Laboratory of Earth Fissures Geological Disaster, Ministry of Land and Resource, Geological Survey of Jiangsu Province, Nanjing 210049, China

³CSIR-Central Building Research Institute (CBRI), Roorkee 247667, India

Correspondence should be addressed to Jin Liu; jinliu920@163.com

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Polyvinyl acetate constitutes a class of polymers that can entirely dissolve in water to form a solution. In this study, polyvinyl acetate as a nontraditional chemical stabilizer was used in soil improvement. Laboratory tests were carried out to evaluate the effect of polyvinyl acetate on swelling-shrinkage properties of expansive soil. A series of shrink/swell tests were performed with adding polyvinyl acetate as amendment at a concentration 3 g/cm^3 to four aggregate sizes in the range of 0–0.5 mm, 0.5–1 mm, 1–2 mm, and 2–5 mm and five concentrations 1.5 g/cm^3 , 3 g/cm^3 , 4.5 g/cm^3 , 6 g/cm^3 , and 9 g/cm^3 to soils with aggregate size in the range of 0.5–1 mm for comparison of results with those of untreated soils. The results show that all the linear swelling ratio (LSWR) and linear shrinkage ratio (LSHR) values of the treated specimens decrease. SEM images and the test results indicate the achieved reduction in volume change of the soil tested using soil pore filling and particle encapsulation.

1. Introduction

Swelling-shrinkage of clayey soils due to the water moisture is a problem in many climatic and pedological zones that are characterized by alternate wet and dry seasons [1, 2]. Normally, the mineralogical composition, the volume fraction of such soils, the dimensions of soil aggregates, and the soil physicochemical environment are the main factors that affect the shrinkage-swelling potential of soil. The hydration characteristics of clay minerals in the soils and the surface force interactions including interparticle attractive and repulsive forces at the colloidal level influence volume change in clays. The presence of the more inert soil particles such as sand and silt in real soil is acknowledged but it is the clay function that undergoes volumes change reactions. Clayey soil stabilization methods must address the interactions among clay particles. The fundamental target of swelling soil stabilization measures is to change the balance between the interaction forces through

the introduction of ions/molecules of the soil stabilization agent or alteration of the environmental conditions. Theng [3] introduced a clay swelling theory that recognizes the existence of a diffuse double layer of ions around the clay particles in an aqueous condition. Another feature is the access of liquids and substances to the interlayer spaces in clay during crystalline swelling. This theory often is used as the basis for phenomenological and quantitative interpretations [4–7]. Thus, soil stabilization substances should be able to inhibit clay swelling and shrinkage by reducing the expansion and shrinkage of the interlayer space through bonding the clay particles together on their external surfaces.

Recently, aqueous polymers which can provide these functions under the suitable physicochemical conditions have been analyzed as stabilizers for the control of the swelling-shrinkage of clayey soils [8–11]. Various kinds of polymers in aqueous solutions have been investigated [12–19]. These analyses often assess polymer potential for use as dust suppressants, antierosion agents, and crack inhibitors

TABLE 1: Important physicochemical properties of polyvinyl acetate.

Physical state	Solvability in water	Boiling point	pH	Viscosity (Mpa·s)	Density (g/cm ³)	Solid content (%)
Liquid-white colour	Solution	100°	6~7	400	1.05	41

in waste containment barrier materials. The sorption and interaction between aqueous molecules and clay surfaces have also been studied. The interaction between surfactant and surface active polymer was analogous to mix micelle formation. Jonsson et al. [20] explained that polymer sorption on solids was mostly irreversible owing to the high energy level required to debond the molecules from solids. Bae and Inyang [21] explained the effects of aqueous polymers on clay desiccation where polyethylenimine solution can retard liquid loss from montmorillonite with possible desirable effects on dust generation from exposed clayey soils. Liu et al. [22] found that the water stability of clay aggregates was improved by bonding the clay surfaces with aqueous polymers, and the ability of the polymer soil stabilizer depended on the membrane structure of the soil aggregate surface. Azzam [23] used a polymer nanocomposite material as a partial soil stabilizer to reduce the shrinkage-swelling potential of expansive soil by modifying the microstructure of soil and altering the texture of clay. Mousavi et al. [24] found that soil samples treated with RPP showed significantly lower swelling potential and swelling pressure in comparison with control samples. Based on the above stated advances, it is well known that aqueous polymers have a good potential for use as soil stabilizers in the control of the swelling-shrinkage of expansive clayey soils.

A new aqueous polymer soil stabilizer, named as polyvinyl acetate (PVA), is introduced in this research paper. In order to evaluate the effect of the use of PVA as a soil stabilizer in controlling the swelling-shrinkage of expansive clayey soils, the swelling test and shrinkage test on the untreated and treated expansive clayey soil with different aggregates were performed. Also, the soil structure modification mechanism is herein analyzed.

2. Experimental

2.1. Materials. PVA is a type of organic aqueous polymer soil stabilizer. Its main component is acetic-ethylene-ester polymer. It contains a large number of $-OOCCH_3$ functional groups. Important physicochemical properties of polyvinyl acetate are given in Table 1. It has a pH of 6-7, a solid content of 41%, a specific gravity of 1.05 g/cm^3 , and a viscosity of $400 \text{ Mpa}\cdot\text{s}$. As a new kind of soil stabilization material used in controlling the swelling-shrinkage of clayey soil, PVA has the following primary advantages: (i) it is a water-soluble material which can be diluted to different concentrations; (ii) the presence of PVA soil stabilizer can form an elastic and viscous membrane on soil surface at the natural situation; and (iii) it is an environment-friendly product and easy to be produced at low cost.

Expansive clayey soils used in this study were obtained from Nanjing area, China. The soil sample has a liquid

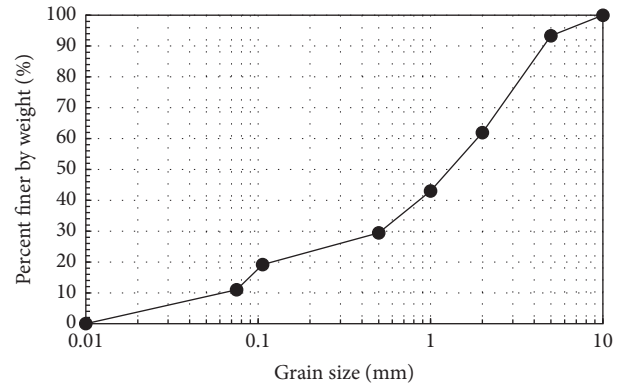


FIGURE 1: The grain size distribution curve of the expansive soil.

limit of 52.6%, a plasticity index of 19.7, a specific gravity of 2.73, an optimum moisture content of 15.4% by weight, and a maximum dry density of 1.71 g/cm^3 . The grain size distribution curve of the expansive soil is shown in Figure 1. The mineralogical compositions of the soil samples were tested by the X-ray diffraction (XRD) and the percentages of montmorillonite, kaolinite, and illite were 75.4, 13.5, and 10%, respectively. It has a specific surface of $41.66 \text{ m}^2/\text{g}$ for the aggregate size smaller than 0.5 mm. Its free swelling ratio is 53% and is considered as a low expansive soil. The free swelling ratio of expansive soil was measured with the free swelling test. The aggregate size in this test is smaller than 0.5 mm. The ratio of the increased volume and original volume of sample was defined as the free swelling ratio.

2.2. Preparation of Soil Samples. Soil samples were first oven-dried and four groups of aggregates were obtained through four different sieves. The room temperature was about 25°C in the test process. The four aggregate sizes were as follows: (i) less than 0.5 mm; (ii) 0.5–1 mm; (iii) 1–2 mm; and (iv) 2–5 mm. PVA solutions were prepared in concentrations of 1.5 g/cm^3 , 3 g/cm^3 , 4.5 g/cm^3 , 6 g/cm^3 , and 9 g/cm^3 by dissolving the appropriate quantity in the distilled water completely. Subsequently, the PVA solution with concentration 3 g/cm^3 was selected to study the soil aggregate size effect on swelling and shrinkage behavior. Each group of aggregates was mixed with the 16.7% by weight of the parent soil to prepare different soil aggregate samples. The aggregate with grain sizes between 0.5 and 1 mm was selected to study the effect of polymer concentrations on the soil swelling-shrinkage. The soil (0.5–1 mm) was mixed with each solution in a proportion of 16.7% of the weight of soil to make the different admixtures for the swelling and shrinkage tests. The soil mixed with the same weight of water was used as the control for all test groups.



FIGURE 2: WZ-2 dilatometer used in swelling test.



FIGURE 3: SS-1 contractometer used in shrinkage test.

The samples were prepared with the static compaction method. The tests complied with the national criterion for geotechnical tests in China which was set based on ASTM standards. The dry density is 1.3 g/cm^3 . It should be pointed out that the two-layered compaction was adopted to keep the soil density relatively uniform within the diameter of 61.8 mm and height of 20 mm. Thereafter, specimens were air-dried at about 25°C for 24 hours for use in the swelling and shrinkage tests.

2.3. Swelling and Shrinkage Test. The equipment types used in the swelling and shrinkage tests in this study were WZ-2 dilatometer (Figure 2) and SS-1 contractometer (Figure 3), respectively. WZ-2 dilatometer is used to determine the expansion of clay during soaking and moisture content after expansion and stability. It is mainly composed of ring knife, regulating adjusting screw and inflation proof guide ring. SS-1 contractometer is used to determine the shrinkage limit moisture content, shrinkage, and body contraction coefficient of determination of clay in the dehydration process. It consists of the main body and bulldozing part. The main body is composed of bottom plate, watch rod, table clamp, and perforated plate. Bulldozing part is composed of guide ring, ring knife, positioning ring, and push head.

In the swelling test, each prepared specimen was filled to the rim in the sample box of 61.8 mm inner diameter and 20 mm height. Then, the dilatometer was immersed in the water, and the water level was kept 5 mm higher than the soil specimen. During immersing in the water,

the specimen continued to expand for several days and the swelling height was recorded by the height indicator at specific time intervals. When there was no further change in height of the soil specimen, a final reading was taken. Then, the ratio of the final swelling height to the initial height 20 mm was calculated for each specimen. The average time to attain maximum swelling was about 7 days. Soil swelling is evaluated using linear swelling ratio (δ_{sw}), which is calculated according to the following formula:

$$\delta_{\text{sw}} = \left(\frac{Z_t - Z_0}{Z_0} \right) \times 100. \quad (1)$$

δ_{sw} is defined as linear swelling ratio (LSWR) at an immersion time (%), Z_t is the reading of indicator at the immersion time of T (mm), and Z_0 is the initial reading of indicator (mm).

In the shrinkage test, after specimen setting, the contractometer was subjected to a temperature around 25°C . The height of the specimen was observed to decrease with the water evaporation and the magnitude of this decrease was recorded by the height indicator at specific time intervals. The final reading with no further change in height was recorded to calculate the linear shrinkage ratio, δ_{sh} , using

$$\delta_{\text{sh}} = \left(\frac{Z_i - Z_f}{Z_i} \right) \times 100. \quad (2)$$

δ_{sh} is defined as linear shrinkage ratio (LSHR), Z_i is the initial height reading of indicator (mm), and Z_f is the final height reading (mm).

3. Results and Discussion

3.1. Effect of Aggregate Size on Swelling-Shrinkage Properties. The results of the swelling and shrinkage tests performed on expansive soils containing different aggregate sizes are presented in Tables 2 and 3 and Figures 4–7. Swelling and shrinkage are expressed in terms of the linear swelling ratio (LSWR) and the linear shrinkage ratio (LSHR), respectively, as previously defined. LSWR is the ratio of the increment of specimen height to the initial height and LSHR is the ratio of the decrement height to the initial height. The variation of LSWR with immersion time is shown in Table 2 and Figure 4. As seen in Table 2, all the LSWR values of specimens treated with concentration 3 g/cm^3 of polymer are smaller than the untreated specimens with the same time. It is clearly shown in Figure 4 that, in all cases, the greatest jump in LSWR occurs within the first 30 min and the LSWR values show a relative stable value after 5 hours. The LSWR at 7 days is selected as the final value to analyze the effect of aggregate size on swelling ratio.

Figures 5 and 6 illustrate the effect of aggregate size on LSWR and LSHR, respectively. As observed in Figure 5, LSWR of the treated and untreated soils increases with increase of the aggregate sizes beyond 1 mm. LSHR data exhibits the opposite trend with respect to aggregate size. For the results of shrinkage tests shown in Table 3, the LSHR of PVA treated specimens are smaller than the untreated ones. The LSHR of treated specimens with aggregate sizes 0–0.5 mm, 0.5–1 mm, 1–2 mm, and 2–5 mm are 56.48%,

TABLE 2: The linear swelling ratio of specimens with different aggregate sizes.

Time	3 (g/cm ³)				Untreated			
	0–0.5 mm	0.5–1 mm	1–2 mm	2–5 mm	0–0.5 mm	0.5–1 mm	1–2 mm	2–5 mm
0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5 min	2.06%	1.46%	3.00%	3.11%	4.00%	3.90%	4.90%	5.10%
10 min	3.23%	2.53%	5.09%	5.19%	6.53%	6.30%	8.50%	9.00%
15 min	4.05%	3.35%	5.88%	6.00%	7.90%	7.80%	10.90%	11.30%
20 min	4.98%	4.22%	6.72%	6.85%	9.50%	9.30%	12.90%	13.30%
30 min	5.47%	4.71%	7.27%	7.40%	11.07%	11.01%	14.50%	14.90%
1 hour	5.95%	4.96%	7.50%	7.93%	11.91%	11.86%	14.60%	15.10%
3 hours	6.40%	5.12%	7.67%	8.32%	12.60%	12.35%	14.65%	15.24%
5 hours	6.53%	5.45%	7.75%	8.45%	12.81%	12.43%	14.68%	15.28%
7 hours	6.60%	5.50%	7.77%	8.54%	12.94%	12.46%	14.69%	15.31%
9 hours	6.65%	5.54%	7.80%	8.60%	13.04%	12.50%	14.71%	15.33%
12 hours	6.70%	5.58%	7.83%	8.64%	13.07%	12.53%	14.75%	15.42%
1 day	6.78%	5.63%	7.86%	8.68%	13.10%	12.56%	14.80%	15.55%
2 days	6.83%	5.64%	7.88%	8.70%	13.12%	12.57%	14.82%	15.59%
3 days	6.87%	5.65%	7.89%	8.71%	13.14%	12.58%	14.85%	15.62%
4 days	6.88%	5.65%	7.90%	8.72%	13.15%	12.59%	14.87%	15.65%
5 days	6.89%	5.66%	7.91%	8.73%	13.16%	12.60%	14.88%	15.68%
6 days	6.90%	5.66%	7.92%	8.74%	13.17%	12.60%	14.90%	15.74%
7 days	6.92%	5.66%	7.92%	8.74%	13.17%	12.61%	14.91%	15.75%

TABLE 3: The linear shrinkage ratio of specimens with different aggregate sizes.

Aggregate sizes (mm)	Linear shrinkage ratio (%)	
	Untreated	PVA (3 g/cm ³)
0–0.5 mm	3.187	1.800
0.5–1 mm	2.895	1.279
1–2 mm	2.316	1.150
2–5 mm	2.044	0.930

44.18%, 49.65%, and 45.50% of the untreated ones. As seen in Figure 6, the LSHR of both untreated and treated specimens decreased with increase of aggregate size. Additionally, the relative decreases of LSWR and LSHR of the different aggregate size specimens are presented in Figure 7. It is observed that the relative decreases of both LSWR and LSHR are larger than 40% in all soils. Their respective maximum values (55.11% for LSWR and 55.82% for LSHR) are observed in soil specimens that have the aggregate sizes in the range of 0.5–1 mm.

3.2. Effect of Polymer Concentration on Swelling-Shrinkage Properties. The effects of polymer concentration on swelling and shrinkage properties of soils with aggregate size 0.5–1 mm are given in Tables 4 and 5 and Figures 8–10. As shown, with an increase in polymer concentration, the values of both LSWR and LSHR decrease. The variations of LSWR and LSHR with polymer concentration are presented in Figures 8 and 9. They show that polymer concentration plays an important role in controlling the swelling-shrinkage properties of soils. Compared with the values between the

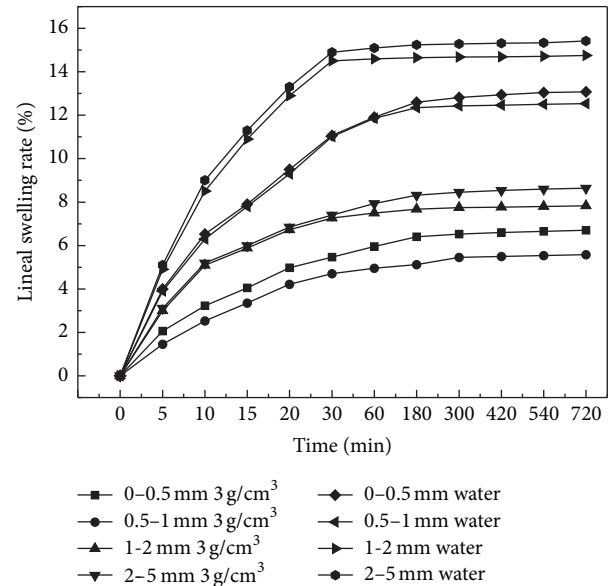


FIGURE 4: Variation of linear swelling ratio with immersed time.

untreated and treated specimens with concentration 9 g/cm³, LSWR decreases from 12.61% to 1.85% and LSHR decreases from 2.9% to 0.87%, respectively.

Figure 10 shows the relative decrease of LSWR and LSHR of specimens with the different polymer concentrations. It is clearly seen that LSWR and LSHR of all tested specimens decrease; the relative decrease ratios of both LSWR and LSHR increase with the increasing of polymer concentration. The relative decrease of LSWR of specimens treated with

TABLE 4: The linear swelling ratio of specimens with different concentration of PVA.

Concentration (g/cm^3)	0	1.5	3	4.5	6	9
Aggregate sizes	0.5–1 mm	0.5–1 mm	0.5–1 mm	0.5–1 mm	0.5–1 mm	0.5–1 mm
Swelling ratio of 7 d (%)	12.61	7.81	5.66	3.65	2.33	1.85

TABLE 5: The linear shrinkage ratio of specimens with different concentration of PVA.

Concentration (g/cm^3)	0	1.5	3	4.5	6	9
Aggregate sizes	0.5–1 mm	0.5–1 mm	0.5–1 mm	0.5–1 mm	0.5–1 mm	0.5–1 mm
Linear shrinkage ratio (%)	2.895	1.697	1.279	1.067	0.913	0.872

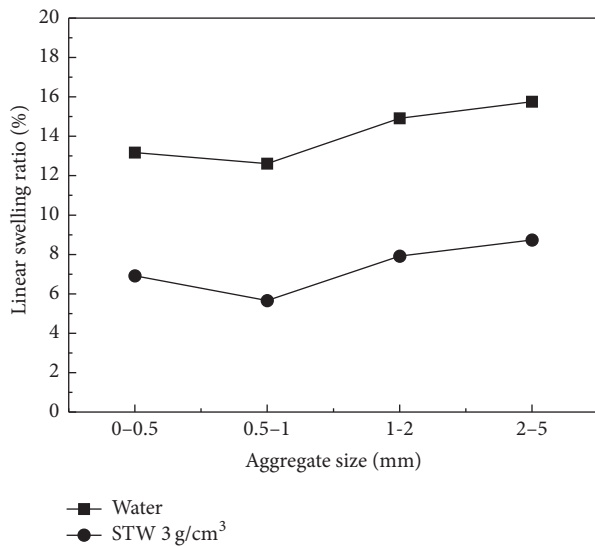


FIGURE 5: Effect of aggregate size on linear swelling ratio of soils.

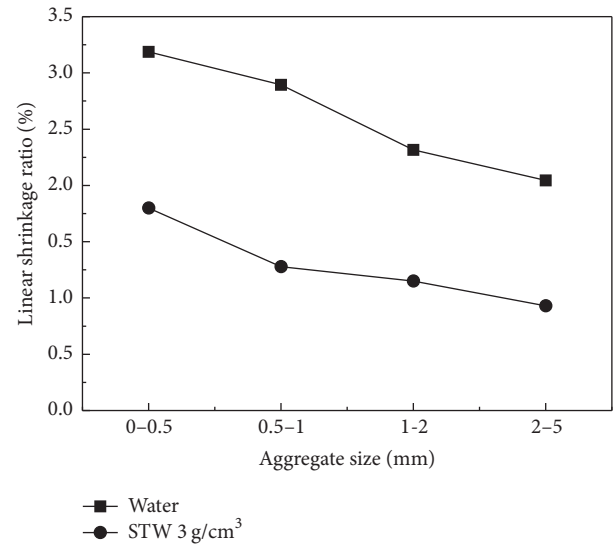


FIGURE 6: Effect of aggregate size on linear shrinkage ratio of soils.

the polymer concentrations $1.5 \text{ g}/\text{cm}^3$, $3 \text{ g}/\text{cm}^3$, $4.5 \text{ g}/\text{cm}^3$, $6 \text{ g}/\text{cm}^3$, and $9 \text{ g}/\text{cm}^3$ reaches 38.07%, 55.11%, 71.05%, 81.52%, and 85.33%, respectively. The relative decreases of LSHR of specimens with the different concentrations reach 41.38%, 55.82%, 63.14%, 68.46%, and 69.88%, respectively. These results indicate that PVA can effectively suppress the swelling and shrinkage of expansive soils.

4. Mechanism Analysis

The results of this investigation show that both the soil aggregate and polymer concentration influence swelling and shrinkage of soils to different extents. The aqueous polymer stabilization mechanism can be described as pore filling, physicochemical reaction, and enwrapping. The SEM photograph of the untreated soil at $\times 450$ magnification is shown in Figure 11. It shows the presence of many voids and aggregates in the untreated soils. When PVA solution is applied to clayey soil, a part of the polymeric material fills up the voids of soil as shown in Figure 12, and part is sorted onto soil aggregate surface as shown in Figure 13. The hydrophilic groups ($-\text{OOCCH}_3$) in its molecular structure react chemically with the adsorbed ions of clay particles and create physicochemical bonds between polymer molecules

and soil aggregates. The bonds are of the ionic, hydrogen, or Van der Waals varieties. Through these bonds, long-chain macromolecules of polymers encapsulate the aggregate surfaces and interlink around them to form elastic and viscous membrane structures that decrease the swelling-shrinkage capacity of soil.

Photographs that enable the comparison of untreated and treated soil aggregates are shown in Figure 14. As shown, when the soil aggregate is immersed in water, the untreated soil aggregate collapses, but the treated soil maintains the structure reasonably well. For a soil that collapses, expansion occurs because of the diffuse double layer of ions of inner clay mineral and the access of liquids and substances to interlayer spaces in clay. With higher polymer concentration, the soil has a greater bonding and stability to keep the structure relatively intact as more polymer molecules penetrate the intra-aggregate pores and encapsulate the soil surface. Thus, aqueous PVA polymer decreases the clayey soil swelling potential. The decrease in swelling ratio increases with the increase of polymer concentration.

As evident in the test results for soils of different aggregate sizes, the soil swelling decrease may not depend on the polymer effect alone but on the existing soil skeleton. When the soil aggregate size is smaller than 1 mm, the soil swelling

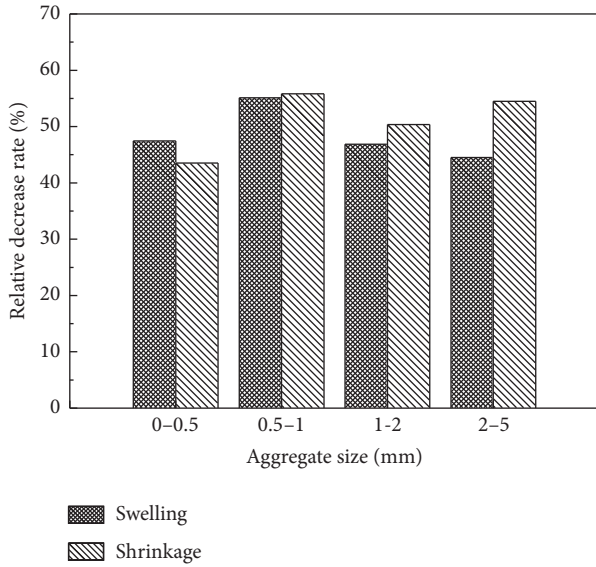


FIGURE 7: Relative decrease of LSWR and LSHR of different aggregate size specimens.

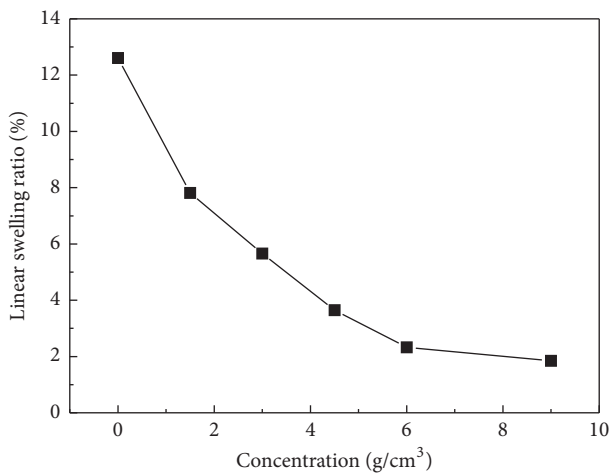


FIGURE 8: Effect of aqueous polymer concentration on linear swelling ratio of soils.

is mainly due to the diffuse double layer of ions. In this case, the larger the specific surface area of the smaller aggregate, the greater the effect of double layer of ions. Conversely, the result of the soil aggregate that is larger than 1 mm in average particle size has the opposite trend. The structure of the soil skeleton affects the swelling of soil with the larger aggregate. The liquids and other substances that gain access into large voids and interlayer spaces in clay during swelling may lead to an expansion of the whole soil skeleton. This effect should become more significant with the increase in aggregate size, so that swelling increases with increase in aggregate size in both untreated and treated soils.

With the decrease in moisture content of soils, the double layer of ions becomes thinner, resulting in dry shrinkage of soil. The presence of polymer creates a reticular membrane

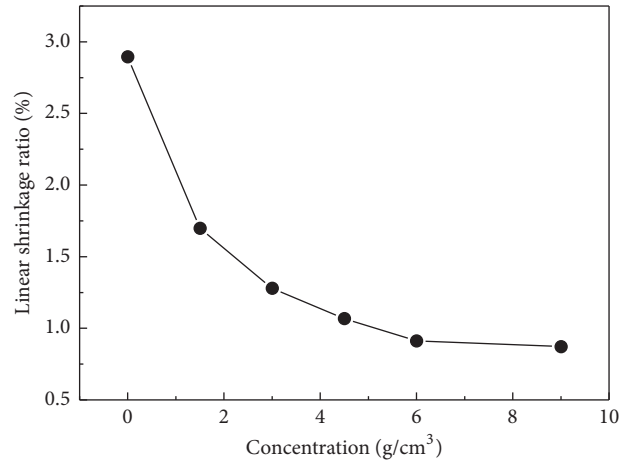


FIGURE 9: Effect of aqueous polymer concentration on linear shrinkage ratio of soils.

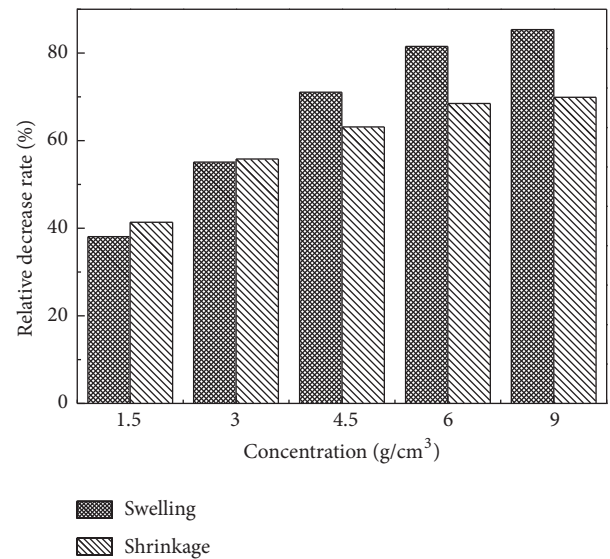


FIGURE 10: Relative decrease of LSWR and LSHR in different polymer concentration specimens.

structure among soil particles. This structure inhibits the movement of soil particles. Meanwhile, since the PVA concentration is increasing, the probability of winding and bonding during the interaction of polymer molecules with soil aggregates also increases, aiding the formation of a more complete membrane structure in soil. So, the soil shrinkage decreases because of the presence of PVA, and the shrinkage ratio also decreases with increase in PVA concentration. Furthermore, considering that the specific surface area decreases with increase in aggregate size, the already thin or negligible double layer of ions becomes thinner with increase in aggregate size. This is the reason why the shrinkage ratios of both untreated and treated soils decrease with increase in aggregate size.

It should be noted that this paper is only limited to select PVA 3 g/cm³ to evaluate the effect of soil aggregate size and

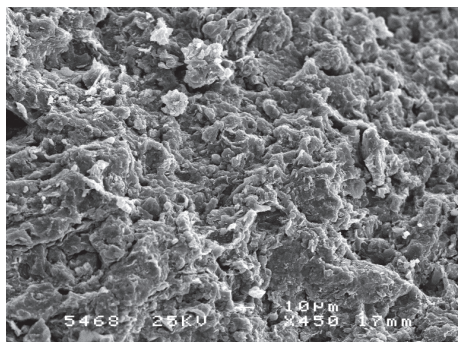


FIGURE 11: SEM image of untreated soil at $\times 450$.

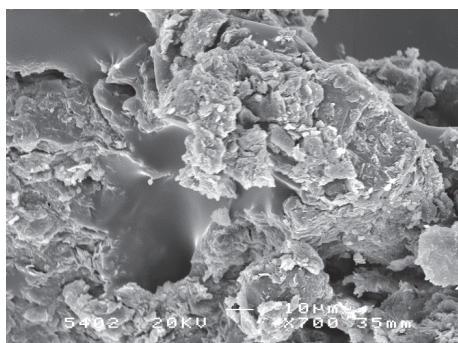


FIGURE 12: SEM image of soil void filled by STW at $\times 700$ magnification.

the soil aggregate size 0.5–1 mm to evaluate the effect of PVA concentration. Furthermore, the PVA concentration should be adjusted to meet the different engineering requirements in practical application.

5. Conclusions

The results of this investigation indicate that PVA is effective in controlling the swelling and shrinkage of soils with size smaller than 5 mm. Both soil aggregate classes and PVA concentration play important roles in determining the magnitude of the effect on the swelling-shrinkage characteristics of the clayey soil investigated.

It is observed from swelling and shrinkage tests that soil swelling mainly occurs at after 5 hours of immersion in water. For aggregate size smaller than 1 mm, the linear swelling ratios (LSWR) of both untreated and treated soil decrease with the increase of aggregate size. However, when the aggregate size is greater than 1 mm, the trend is reversed. The values of both LSWR and LSHR increase with increase in PVA concentration. SEM photos indicate that PVA produces a reticular membrane structure as soil through pore through filling, physicochemical reaction, and encapsulation to inhibit the swelling and shrinkage of soil.

The findings of this research indicate that it is possible to use PVA as soil stabilizer to control volume change of expansive soil in practical soil stabilization projects.

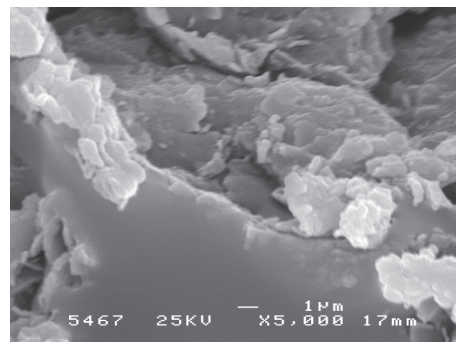


FIGURE 13: SEM image of treated soil surface at $\times 5,000$ magnification.

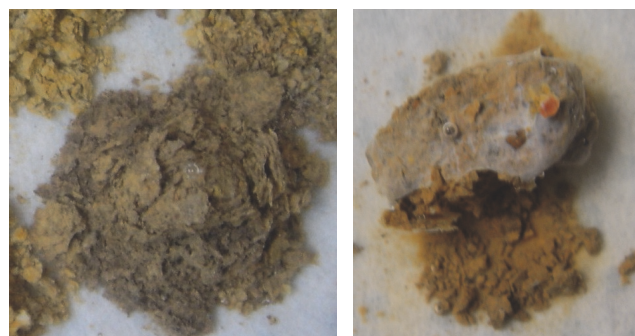


FIGURE 14: The photo of comparison between untreated and treated soil aggregate.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

- [1] S. M. Rao, B. V. V. Reddy, and M. Muttharam, "The impact of cyclic wetting and drying on the swelling behaviour of stabilized expansive soils," *Engineering Geology*, vol. 60, no. 1–4, pp. 223–233, 2001.
- [2] H. I. Inyang, S. Bae, G. Mbamalu, and S.-W. Park, "Aqueous polymer effects on volumetric swelling of Na-montmorillonite," *Journal of Materials in Civil Engineering*, vol. 19, no. 1, pp. 84–90, 2007.
- [3] B. K. G. Theng, *Formation and Properties of Clay-Polymer Complexes*, Elsevier Scientific, Amsterdam, The Netherlands, 1979.
- [4] A. C. D. Newman, "The specific surface of soils determined by water sorption," *European Journal of Soil Science*, vol. 34, no. 1, pp. 23–32, 1983.

- [5] D. E. Ulberg, N. V. Churaev, V. V. Ilyin, and G. L. Malashenko, "Molecular dynamics simulation of the aggregation of colloidal particles," *Colloids & Surfaces A: Physicochemical & Engineering Aspects*, vol. 80, no. 2-3, pp. 93-102, 1993.
- [6] D. A. Laird, "Layer charge influences on the hydration of expandable 2:1 phyllosilicates," *Clays and Clay Minerals*, vol. 47, no. 5, pp. 630-636, 1999.
- [7] J. Chen, A. Anandarajah, and H. I. Inyang, "Pore fluid properties and compressibility of kaolinite," *Journal of Geotechnical & Geoenvironmental Engineering*, vol. 126, no. 9, pp. 798-807, 2000.
- [8] F. Yazdandoust and S. S. Yasrobi, "Effect of cyclic wetting and drying on swelling behavior of polymer-stabilized expansive clays," *Applied Clay Science*, vol. 50, no. 4, pp. 461-468, 2010.
- [9] A. S. Mohammed and C. Vipulanandan, *Behavior of Polymer Modified Expansive CH Soil*, CIGMAT, Houston, Tex, USA, 2012.
- [10] W. R. Azzam, "Durability of expansive soil using advanced nanocomposite stabilization," *International Journal of Geomate*, vol. 7, no. 1, pp. 927-937, 2014.
- [11] S. R. Bekkouche and G. Boukhatem, "Experimental characterization of clay soils behavior stabilized by polymers," *Journal of Fundamental and Applied Sciences*, vol. 8, no. 3, pp. 1193-1205, 2016.
- [12] P. V. Barry, D. E. Stott, R. F. Turco, and J. M. Bradford, "Organic polymers' effect on soil shear strength and detachment by single raindrops," *Soil Science Society of America Journal*, vol. 55, no. 3, pp. 799-804, 1991.
- [13] F. G. Bell, "An assessment of cement-PFA and lime-PFA used to stabilize clay-size materials," *Bulletin of Engineering Geology and the Environment*, vol. 49, no. 1, pp. 25-32, 1994.
- [14] A. Nadler, E. Perfect, and B. D. Kay, "Effect of polyacrylamide application on the stability of dry and wet aggregates," *Soil Science Society of America Journal*, vol. 60, no. 2, pp. 555-561, 1996.
- [15] K. N. Nwankwo, "Polyacrylamide as a soil stabilizer for erosion control," Tech. Rep., Wisconsin Department of Transportation, Madison, Wis, USA, 2001.
- [16] H. I. Inyang and S. Bae, "Polyacrylamide sorption opportunity on interlayer and external pore surfaces of contaminant barrier clays," *Chemosphere*, vol. 58, no. 1, pp. 19-31, 2005.
- [17] J. L. Daniels and H. I. Inyang, "Contaminant barrier material textural response to interaction with aqueous polymers," *Journal of Materials in Civil Engineering*, vol. 16, no. 3, pp. 265-275, 2004.
- [18] S. Bae and H. I. Inyang, "Confirmation of aqueous polymer sorption on contaminant barrier clay using TGA," *Journal of Materials in Civil Engineering*, vol. 18, no. 2, pp. 307-311, 2006.
- [19] M. A. Mohsin and N. F. Attia, "Inverse emulsion polymerization for the synthesis of high molecular weight polyacrylamide and its application as sand stabilizer," *International Journal of Polymer Science*, vol. 2015, Article ID 436583, 10 pages, 2015.
- [20] B. Jonsson, B. Lindman, K. Holmberg, and B. Kronberg, *Surfactants and Polymers in Aqueous Solution*, Wiley, New York, NY, USA, 1998.
- [21] S. Bae and H. I. Inyang, "Effects of various polyethylenimine solutions on desiccation of Na-montmorillonite," *Soil and Sediment Contamination*, vol. 10, no. 6, pp. 675-685, 2001.
- [22] J. Liu, B. Shi, H. Jiang, S. Bae, and H. Huang, "Improvement of water-stability of clay aggregates admixed with aqueous polymer soil stabilizers," *Catena*, vol. 77, no. 3, pp. 175-179, 2009.
- [23] W. R. Azzam, "Reduction of the shrinkage-swelling potential with polymer nanocomposite stabilization," *Journal of Applied Polymer Science*, vol. 123, no. 1, pp. 299-306, 2012.
- [24] F. Mousavi, E. Abdi, and H. Rahimi, "Effect of polymer stabilizer on swelling potential and CBR of forest road material," *KSCE Journal of Civil Engineering*, vol. 18, no. 7, pp. 2064-2071, 2014.



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