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Improvement of Shear Strength of Clay Shale Soil using Polymer-Calcite Precipitation (PCP) as Soil Stabilization Technique

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Abstract

Clay shale is an expansive soil owing to its shrinkage and expansion, leading to geotechnical issues, such as loss of strength. This study explored the effectiveness of the Polymer–Calcite Precipitation (PCP) method in improving clay shale's shear strength. This study evaluated the optimum Polyvinyl Alcohol (PVA) concentration for enhancing the shear strength and identifying the residual shear strength of the treated soil. Various tests were conducted to determine the soil properties and assess soil improvement using direct shear tests. The results indicate that adding PVA increases the cohesion value of saturated clay shale and maintains its residual strength close to its peak strength value, with the optimum concentration of 4% PVA boosting cohesion from 4.47 kPa to 32.83 kPa. In conclusion, the PCP method effectively enhances the shear strength of clay shale and offers a potential solution for soil stabilization.

INTRODUCTION

Infrastructure development in Indonesia often occurs in soils that are inadequate to support the structural loads. Expansive soils can cause land subsidence, especially non-uniform subsidence, and soil development, such that buildings are uplifted, and the bearing capacity of the soil is reduced, which results in the collapse of the structure above it [1,2]. Expansive soils, such as clay shale, are prevalent in the West Java, Central Java, and Kalimantan regions. Clay shale, composed of clay and shale, exhibits unique physical and chemical properties. Expansive soils have a high plastic index and pose significant geotechnical challenges [3,4]. Under dry conditions, clay shale appears rock-like, gray, and cohesive; however, it becomes soft and loses strength when exposed to air or water [5,6]. XRD testing shows that clay shale contains montmorillonite, *illite*, kaolinite, quartz, and albite, making it highly susceptible to water interactions, swelling, and weakening of soil bonds [7,8]. The weathering of clay shale, particularly from repeated exposure to water, reduces its durability and bearing capacity. This reduction in shear strength can lead to potential disasters, such as landslides on the Cipularang toll road in West Java and the Salatiga Toll Road in Central Java [9,10]. Consequently, improving the shear strength of clay shale is essential for reducing the risk of landslides.

Some stabilization methods used to overcome these problems in clay shale include stabilization using lime [11], liquid $CaCO_3$ [12], and cement [13,14]. Using 2M $CaCO_3$ substitution, as much as 80% of the OMC value increased the cohesion value from 0.171 kg/cm2 to 0.289 kg/cm^2 and the internal friction angle from 8° to 11.13°. Adding 10% cement increased the CBR value by 38.4% and decreased its development by 0.6%. Hambalang clay shale compacted and stabilized with 15% Portland cement increased the slake durability index by 68%. However, using cement as a

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stabilization material impacts soil drainage owing to the impenetrable nature of the soil, which can cause environmental problems. This impenetrable nature of the soil can cause waterlogging, affecting plant growth and leading to potential flooding in the surrounding areas [15]. Additionally, lime stabilization can lead to environmental concerns due to the leaching of heavy metals [16,17]. Therefore, an alternative method that is more environmentally friendly and does not significantly change soil characteristics is needed.

Soybean Crude Urease Calcite Precipitation (SCU-CP) is an emerging environmentally friendly soil improvement method. The SCU-CP method uses the urease enzyme in soybeans to replace the pure urease enzyme. This enzyme acts as a catalyst to accelerate the formation of calcium carbonate minerals by mixing urea and chloride [18]. The SCU-CP method is used as a soil improvement method because it can improve soil properties through calcite precipitation, which binds particles and fills gaps in the soil [18]. The SCU-CP method applied to sand soil types by [19] and [20] was able to increase the UCS value to 623.18 kPa. Meanwhile, research [21] reported that the soil strength can increase to a UCS value of 859 kPa. The application of the SCU-CP method is still limited to expansive soils, especially clay shale. Based on research by Khairunnisa *et al*. [22], applying the SCU-CP method to expansive clay soils can reduce the potential for soil development by 2-3% so that the degree of development drops from high to medium. However, the SCU-CP method has challenges in expansive soils, such as clay shale; namely, the dilute SCU-CP solution tends to form a sticky soil consistency owing to the plastic nature of fine-grained soils. In addition, water is a challenge for clay shale; therefore, additional materials are required to overcome these problems. Hence, the SCU-CP method must be modified to ensure its effectiveness when applied to expansive soils, such as clay shale.

The low viscosity of the cementing solution in SCU-CP presents a challenge, as it restricts the solution's retention and distribution of calcium carbonate within the intended treatment zone [23]. Modifying the SCU-CP method for practical use in clay soils involves thickening the SCU-CP solution to increase its viscosity. This thickening aims to maintain the SCU-CP solution at the same concentration during dissolution but with a smaller solution volume during curing. With this thicker solution, it is expected that there will be no significant changes in the physical characteristics of the clay shale owing to the pouring of the SCU-CP solution, and the amount of calcium carbonate formed will be more optimal. One of the materials that has the characteristics of being able to thicken and related to soil improvement is polymer. Yan et al. [24] used a polyacrylic acid (PAA) polymer to assist the Enzyme Induced Calcite Precipitation (EICP) process in soil stabilization. Another study [25] used a polymer-modified Microbially Induced Calcite Precipitation (MICP) approach to condense the loose sand. In addition, using Polyvinyl Alcohol (PVA) and silica fume in coarse-grained soils can increase the Unconfined Compressive Strength (UCS) by adding a PVA solution and curing time [26]. Combining PVA with EICP significantly improved the strength of beach and river sands, with compressive strengths reaching 11.07 MPa and 8.96 MPa, respectively [27]. Using PVA in soft clays can increase the UCS value from 10 kPa to 116 kPa [28]. PVA was selected because of its water solubility, stability at various temperatures, and excellent cohesive properties. When PVA is dissolved in water, PVA polymer chains are formed, which increases the solution viscosity [29,30]. Therefore, there is potential for using PVA in the SCU-CP method to overcome the weaknesses of SCU-CP application in clay soils.

Clay shale soil is an expansive soil that is highly sensitive to changes in moisture content. The SCU-CP method promises potential stabilization and soil improvement; however, the excessively dilute nature of the SCU-CP solution may affect the shrinkage expansion condition of the clay shale. Therefore, the addition of the PVA polymer to the SCU-CP solution is expected to stabilize the clay shale while optimizing soil improvement through calcite precipitation. This study aims to identify the effect of PVA addition in SCU-CP method on the shear strength of clay shale soil by increasing the cohesion value and internal friction angle. The optimum PVA concentration was evaluated based on the highest increase in strength. In addition, this study aims to identify the residual shear strength to understand the changes in the mechanical characteristics of clay shale after PVA addition.

METHODS

Material

A mixed solution of reagents composed of urea ($CO(NH_2)_2$), calcium chloride ($CaCl_2.H_2O$) lab grade with 99% purity, polyvinyl alcohol (PVA) grade A, and soybean powder as urease were used as premixing materials in this study. The clay shale soil used in this study was obtained from Sentul, Bogor Regency, West Java, with a specific gravity of GS 2.35, liquid limit of 41.60%, plastic limit of 21.97%, and plasticity index of 19.62%. Based on the USCS system, it was classified in the CL group, namely, organic clays with low-to-medium plasticity. The soybean powder was obtained from dried soybeans, which were ground and passed through a No. 40 sieve. The clay shale soil used was a fine-grained soil that passed sieve No. 200 and was oven-dried to completely reduce the soil moisture content. Sample preparation was based on field density, which was remolded using the specific gravity of the soil with the volume following the shear mold. The solution requirements were based on 100% saturated sample conditions (SR = 100%) with values between LL and PL so that the soil could be molded without becoming fully liquid.

Polymer-Calcite Precipitation Solution

The polymer-calcite precipitation solution was prepared based on a modified SCU-CP preparation procedure [31]. The volume ratios of Urea, $CaCl_2$, and soybean solution were 1:1:2, and the soybean concentration was 20 g/L. This volume ratio was chosen because it produced the most optimum calcium carbonate precipitate according to [31]. The polymer-calcite precipitation solution was prepared based on the concentrations listed in Table 1 and illustrated in Figure 1. The solution was prepared by dissolving soybean with distilled water, and the soybean solution was filtered through a No. 400 sieve. Urea and $CaCl_2$ were mixed with distilled water, and PVA was mixed in different glasses for 5 min. The rapid dissolution of urea and $CaCl_2$ is due to their high solubility in aqueous solutions, and only a short mixing time is required. The reagent solution (Urea, $CaCl_2$, and PVA) was mixed, added to the filtered soybean solution, and stirred for 5 min. The amounts of reagents and soybeans required were calculated using Equations (1) and (2), where MR is the relative atomic mass of $CaCl_2$ or Urea (g/mol), and v is the volume of water (mL).

Table 1. Experiment Condition Variation of PVA Concentration

Treated Sample	Concentration			
	Urea (mol/L)	$CaCl_2$ (mol/L)	PVA (%)	Soybean (g/L)
PCP0	1	1	0	20
PCP1	1	1	1	20
PCP2	1	1	2	20
PCP3	1	1	3	20
PCP4	1	1	4	20
PCP5	1	1	5	20
PCP6	1	1	6	20
PCP7	1	1	7	20

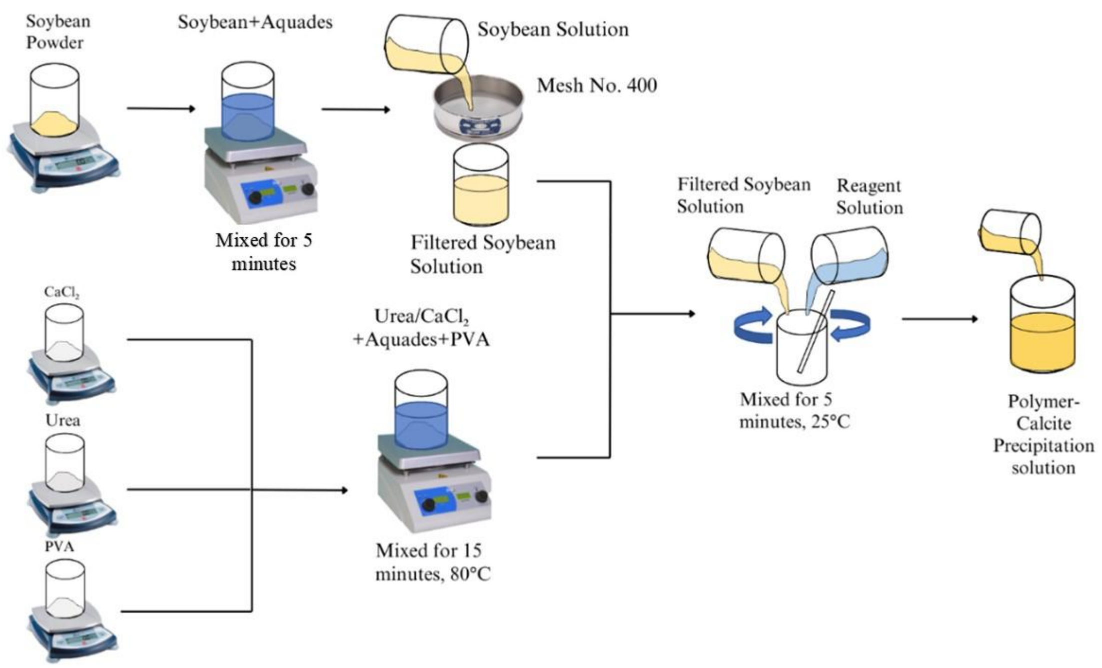

Figure 1. Schematic of PCP Solution Preparation

$$\text{Reagent mass} = \frac{reagent\ mol \times Mr \times v}{1000\ mL} \tag{1}$$

$$\text{Soybean mass} = \frac{soybean\ concentration \times v}{1000\ mL} \tag{2}$$

Direct Shear Test

Direct shear testing aims to identify the cohesion and internal friction angle between soil grains. This test was based on the BSN standard [32]. Direct shear is used because of its ability to accommodate drained conditions effectively and allow direct observation of shear failure along a predefined plane. For clay soils, failures often occur along naturally weak planes owing to anisotropy or pre-existing fissures [33].

The test samples were untreated (UT) and treated (TE). The direct shear test also yielded residual shear strength and cohesion (c_{res}) values. The direct shear test used three normal stress variations of 50, 150, and 330 kPa, respectively. Based on the results of the pre-study, the use of this combination of normal loads resulted in a more consistent failure trend than that of the smaller normal load variations. In addition, a statistical analysis using regression was conducted to ensure that the tests and results had reliable values. Equation (3) shows the relationship between the normal and shear stresses in the soil plane, where τ is the shear stress (kPa), c is the cohesion (kPa), σ is the normal stress (kPa), and φ is the friction angle (°).

$$\tau = c + \sigma \tan \varphi \tag{3}$$

RESULTS AND DISCUSSION

Application of Polymer-Calcite Precipitation

The addition of PVA to the SCU-CP solution affected its viscosity. The most striking difference between the solutions with and without PVA was the ease of compaction of the soil samples. The solution without PVA (PCP0) was difficult to compact because the soil became soft and sticky. This is because clay shale has a high clay content (70%), and therefore, it has a stickier consistency and tends to stick when wet. The clay content of the soil affects its plasticity, and the plasticity index increases with the percentage of clay content; the more plastic the soil condition, the better the adhesion [34]. However, clay shale treated with the PCP solution cannot be tested for the plasticity index because the soil becomes stiff.

In contrast, the solution with added PVA was more straightforward to compact because it tended to be drier, even though it had the same volume of solution, as shown in Figure 2. When PVA was added at concentrations of 1–4%, the soil sample was more manageable for compaction. However, at 5–7% concentration, the soil sample was easy to mold but difficult to compact because the soil tended to be sticky owing to the hydrogel formed from the PVA molecules. The PVA hydrogel provides resistance during compaction; therefore, the density formed is not maximized during compaction.

(a) (b)

Figure 2. Consistency of Clay Shale with a Mixture of a) SCU-CP Solution, b) PCP Solution

The addition of PVA to the SCU-CP solution influenced the soil moisture content of the samples. After curing for 7 days, the soil moisture content decreased owing to physicochemical processes in the soil, characterized by the drying of the soil surface and the formation of gels on the soil surface. In addition, the soil moisture content test showed that the degree of saturation of the samples decreased as the PVA concentration increased. Samples treated with only the SCU-CP solution without PVA had the highest degree of saturation. Samples treated with the PCP solution at PVA concentrations of 1–4% had a degree of saturation value that tended to be stable, ranging from 77 to 82%. The sample then experienced a significant decrease in the degree of saturation at PVA concentrations of 6–7 %.

This occurs because PVA molecules absorb water from the soil during hydrogel formation. The hydrogel is formed through the chemical crosslinking of PVA polymer chains, creating a three-dimensional network capable of retaining water. The ability of the hydrogel to absorb water increases as the concentration of PVA increases; therefore, the degree of soil saturation decreases because of the groundwater absorbed by the hydrogel [35]. The relationship between the results of the water content testing and direct shear testing is consistent with the characteristics of clay shale, which has greater strength under dry conditions than under water-saturated conditions [34]. However, with the addition of PVA at a concentration of 7%, the lowest water content produced the lowest cohesion among all the treatments. The hydrogels were formed to resist compaction; therefore, the resulting density was not maximum. In addition, the amount of hydrogel formed binds more to the soil than the cohesion bond between soil particles. This result is also in line with the research of Mirzababei et al. [28], who showed that adding PVA can result in unnecessary bonding owing to excessive lubrication.

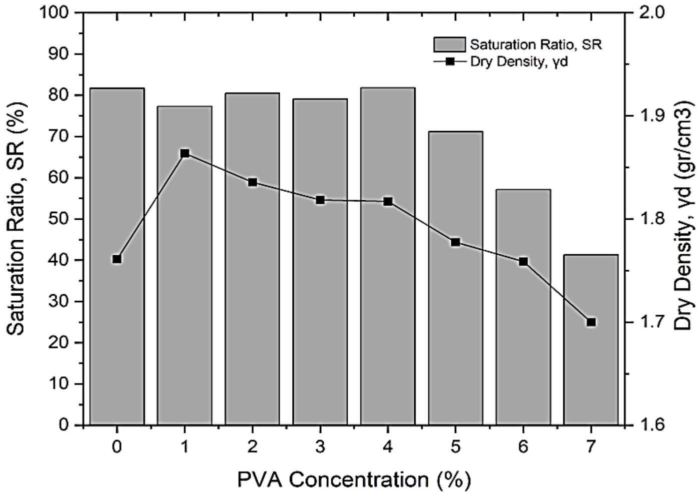

Figure 3. Degree of Saturation and Dry Density of Treated Samples

The addition of PVA also affected the density of the soil samples. Samples without PVA had a density that tended to be smaller than that of samples with the addition of PVA. This occurs because the soil tends to be sticky and liquid during sample compaction, making it difficult to compact. The soil density decreased as the concentration of PVA increased. The soil density tended to decrease because the height of the sample increased with a similar sample area, resulting in a larger sample volume. The decrease in soil density was significant at 5-7% PVA concentration. Hydrogels that fill soil pores increase the sample volume and provide resistance during sample compaction. While the hydrogel infiltrates the pore structure, it expands upon water absorption. This can lead to slight swelling of the soil matrix, influencing its compressibility. At higher concentrations, more hydrogels are formed and absorb more water, resulting in the enlargement of the hydrogel volume, which is greater than the size of the soil pores, so that the soil expands, and its density decreases [36].

Shear Strength Parameter

In Figure 4, the intersection of the shear stress trend line with the ordinate (y-axis) is the cohesion (c) value, and the slope of the trend line is the internal friction angle (φ). The untreated clay shale sample exhibited a low shear strength value of cohesion (c) of 4.47 kPa and an internal friction angle (φ) of 0.56°. In addition, a residual shear strength with a cohesion (c_{res}) of 4.1 kPa and a residual internal friction angle (φ_{res}) of 0.54° were generated. Under untreated conditions, the small cohesion value is due to the characteristics of clay shale, which is easily weathered when exposed to water and thus loses its strength [37]. Therefore, an improvement in soil shear strength using the PCP method was investigated in this study.

After curing for 7 d, the treated samples were subjected to direct shear tests, and the results are presented in Figure 5. Applying the SCU-CP solution without PVA (PCP0) increased the cohesion value to 7.09 kPa and the internal friction angle to 2.62°. This increase was caused by the formation of calcium carbonate from urea and CaCl2 precipitation, which bound the soil grains and filled the soil pores [38]. The addition of PVA to the SCU-CP solution increased the shear strength of the clay shale. The shear test results showed a significant increase in the cohesion value of the PCP sample at concentrations of 1–5%. At 4% PVA concentration, the maximum increase in cohesion was obtained, which amounted to 32.83 kPa. However, with the addition of PVA at 6% and 7% PVA concentrations, the increase in clay shale cohesion was no longer effective because it only increased the cohesion value to 8.83 kPa and 6.53 kPa, respectively. All test results of the samples using the PCP solution showed an increase in the cohesion value of clay shale compared to the untreated condition. The results indicated that modifying the SCU-CP solution by adding PVA effectively improved the shear strength of the clay shale.

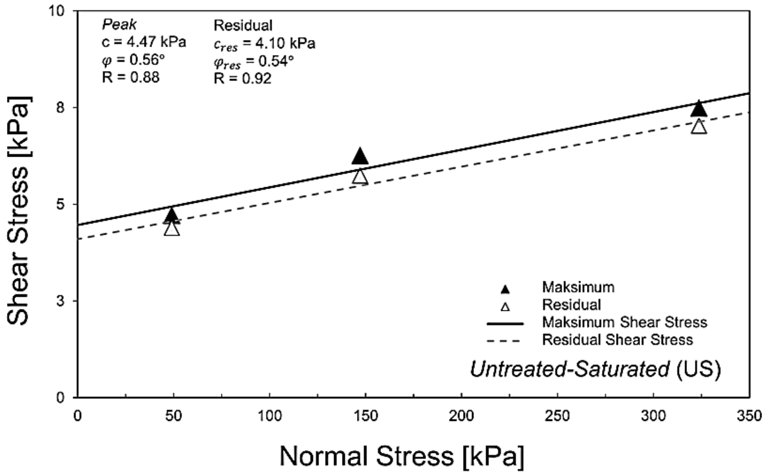

Figure 4. Cohesion and Friction Angle of Untreated Sample

The treated clay shale samples showed an increasing trend in shear strength, characterized by increasing cohesion values, as shown in Figure 5. The cohesion value increased by adding up to a concentration of 4 %, and then the cohesion value decreased to 5%. The cohesion value was significantly reduced to almost the same value at higher concentrations without the PVA addition treatment (PCP0). At higher concentrations (6 – 7 %), the hydrogel fills more soil pores and binds more soil particles; however, the bond is weaker than cohesion, and the water-filled hydrogel creates a slippery bond. Therefore, the overall cohesion of the soil decreases. However, the test results indicated an insignificant increase in the internal-friction angle. The internal friction angle increased with the addition of PVA, ranging from 2.64°to 5.70°, as shown in Figure 5. The internal friction angle did not significantly influence the shear strength. The slight internal friction angle was due to the characteristics of clay soil, which has a slight friction angle. According to [39], the greater the percentage of clay, the smaller the internal friction angle.

The direct shear test results also produced residual shear strength values for the residual cohesion (c_{res}) and residual internal friction angle ($φ_{res}$). These results showed an increasing trend, which was similar to that of the maximum shear strength. However, the resulting cohesion values were smaller, with differences ranging from 0.25–1.1 kPa, while the internal friction angle values varied, with larger angles between 0.02°–0.09° and smaller 0.07°–0.13°. After reaching its peak value, the residual shear strength value was obtained from the static shear dial reading so that the sample did not collapse to the deformation limit of the tool (17 mm). The residual shear strength value indicates the shear strength remaining in the soil after it has undergone large deformations and reached stability, even though shear forces continue to occur without further increases in stress [40].

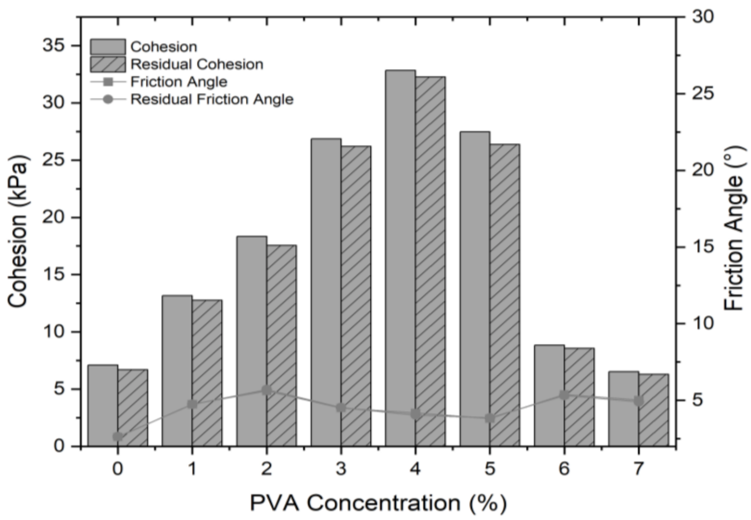

Figure 5. Cohesion and Friction Angle of PCP Treated Sample

Residual shear strength is an important parameter that distinguishes clay soils from sandy soils. Unlike sandy soils, which collapse shortly after reaching the maximum shear stress, clay soils have the remaining strength to withstand further shear stress with more significant deformation. This is due to the plastic nature of clay, which solidifies when pressure is applied and does not crack or break, whereas sandy soil has a more brittle nature. The shear strength of clay soil is influenced by the soil mineral composition, moisture content, degree of saturation, over consolidation ratio (OCR), loading conditions, and weathering [41]. Residual shear strength is a reference for the design of geotechnical structures because its value is lower than the maximum shear strength. In expansive soils, the peak and residual shear strengths should ideally be significantly different, as these soils tend to experience strength degradation owing to cyclic swelling and shrinkage. This study showed that the residual shear strength results were not significantly different from the peak shear strength, indicating that the soil could still withstand large loads after deformation.

The addition of Polyvinyl Alcohol (PVA) aims to improve the weakness of the SCU-CP method, which has a solution that is too dilute; therefore, it needs to be adjusted when used to strengthen expansive soils. The soil improvement mechanism with the addition of PVA involves water absorption through the formation of hydrogels using PVA molecules [42]. The formed gels also increased the strength of the soil, similar to the mechanism of other polymers. Water absorption by PVA molecules also results in less hydrated clay shale; therefore, the soil samples tend to dry out during curing. According to Souhila et al. [42], adding PVA and curing increased the soil ductility. However, higher concentrations resulted in excessive particle lubrication, which led to the formation of unnecessary bonds. Adding PVA to the SCU-CP solution increased the cohesion of the clay shale by 363%, from 7.09 kPa to 32.83 kPa. Additionally, the addition of PVA can maintain the shear strength of clay shale close to its peak value, but at high concentrations, it can result in a significant decrease in strength and density. This significant increase indicates that modifying the SCU-CP method by adding a PVA polymer can improve its applicability in expansive soils. The addition of PVA to the PCP method has the advantage of being able to absorb soil water by forming a hydrogel that can also bind soil particles. With the hydrogel, the soil is not completely impermeable, and PVA is a biodegradable material that does not cause environmental problems, such as the use of cement. However, the hydrogel may be able to absorb more water and make the soil drier and denser; therefore, further research needs to be conducted with a longer curing time.

CONCLUSIONS

The addition of PVA to the SCU-CP solution significantly increased the cohesion of the clay shale. The cohesion value of the soil increased as the PVA concentration increased until it reached the maximum value at a concentration of 4% but decreased at higher concentrations. In addition, the addition of PVA had no significant effect on the internal friction angle of the clay shale. The residual shear strength of the Untreated Sample (UTR) was 4.10 kPa, and those of the samples treated with 0–7% PVA were 6.69, 12.76, 17.55, 26.21, 32.26, 26.37, 8.56, and 6.28 kPa, respectively. Increasing the concentration of PVA can increase the cohesion value of clay shale; however, at a concentration of 6%-7% it is no longer effective, and the addition of PVA to PCP does not significantly increase the friction angle. The addition of the PCP solution to clay shale decreased the soil moisture content during curing. At PVA concentrations of 5–7%, the soil moisture content decreased dramatically, and the soil became drier. The decrease in soil moisture content was caused by the absorption of water by the PVA to form hydrogels. The effect of PVA addition to the SCU-CP solution on water retention and longer curing time in clay shale needs to be investigated further. In addition, the application of PCP using PVA on other soil types or on a field scale is required to strengthen its effectiveness.

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