

Research Article

Effect of Curing Condition on the Compressive Mechanical Behavior of Clayey Soil Stabilized with Liquid Polymer

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This study investigates the potential use of polyvinyl acetate emulsion in soil strengthening with emphasis on curing condition. Molded clay specimens treated with three polymer contents of 1%, 2%, and 3% (by the weight of dry soil) are cured in dry and humid environment, respectively. Unconfined compression tests are performed on the specimens after 1, 3, and 9 days of curing, and the results are compared with that for the untreated clay specimens. This comparison shows that polyvinyl acetate polymer can enhance soil mechanical properties. It was found that the compressive strength of soil-polymer composite increases significantly with the increase of polymer content and curing time in air-drying condition, which is 24% higher than that of plain soil after 9-day curing. The role of polymer treatment is to provide soil interparticle binding, which becomes particularly important in humid environments. In curing environments of high moisture, polymer-treated soils always have greater strength, but the effectiveness of polymer treatment decreases with polymer content. The scanning electron microscopies indicate that soil structure is reinforced mostly by three-dimensional interparticle polymeric bridges. The tension in polymeric threads and textiles provides the interparticle bonding that prevents the development of cracks.

1. Introduction

The mechanical performance of natural soil is complicated and changes with the environment such as desiccation and precipitation. Soil stabilization is therefore used to improve its engineering characteristics. The most common methods of soil stabilization can be categorized into mechanical, chemical, and biological [1–3]. In the past decade, the emergence of new materials and technologies make soil stabilization practical in engineering projects. The concept of reinforcing soil with short fibers has attracted growing attention because of its advantages of simple procedure, effectiveness in soil strength promotion, and reasonable cost. Various types of fibers have been employed for soil reinforcement, including synthetic and natural fibers [4]. Although the incorporation of fibers effectively enhances the strength of fiber-soil composite, some shortcomings

may be encountered in fiber-soil mixture: potential microplastic pollution of synthetic fiber due to its poor degradability and unsatisfactory durability of natural fiber [5, 6]. Biological methods have also shown to be an effective means of improving soil strength and load-bearing capacity [7–11]. Examples of biological methods are microbial-induced carbonate precipitation (MICP) and biopolymer treatment which exhibit a fine prospect, but nevertheless have few practical applications and need further study and improvement. This is because they are very affected by factors like environmental condition and soil type (e.g., microbe infiltration problem in fine-grained soils). In addition, some other investigations discussed the feasibility of the utilization of recycled materials for reinforcement of clays [12, 13] and indicated their benefits in soil strength and deformation properties. Also, soil stabilization using chemical additives has a long history and is still being employed in many

geotechnical practices. Considerable efforts have been made to understand the mechanisms of chemical additives in soil improvement, not only through the laboratory and field experiments [14–19] but also based on numerical analysis [20, 21], artificial models [22], and theoretical models [23].

The incorporation of chemical additives to soil is expected to contribute to the internal structure and stability of soil mass by conferring additional cohesion to the adjacent soil particles and providing interparticle cementation. Conventional materials for chemical stabilization, such as lime, cement, fly ash, and bituminous emulsion [24–27], can lead to the significant development of the compressive and tensile strength of soils. However, soil treated with these conventional materials usually shows brittle nature, especially under dynamic loading, which brings to the decrease of yield strain and ductility and could in turn result in a sudden instability of the structures [28]. From an environmental perspective, another critical issue for the conventional materials is the huge amount of energy consumption for production, numerous greenhouse gas emissions (particularly carbon dioxide, CO₂), and particulate air suspensions in their production process. For example, the cement industry is one of the major contributors of greenhouse gases, as cement production is an energy-intensive process and each ton of Portland cement produced releases about 1 ton of CO₂ [29]. Moreover, several studies also point out that there is a possibility of creating an alkaline soil environment and hence affecting the normal growth of vegetation and groundwater quality due to the presence of the cement within the soil [30, 31]. Therefore, it is desirable to seek sustainable and environmental-friendly alternatives to conventional soil stabilizers, which has become an important research interest in the aspect of civil and geotechnical engineering.

In the past decades, a number of studies about the chemical stabilization of soil have been performed with nonconventional additives, such as resins, acids, enzymes, and lignin derivatives [32–34]. Liquid polymers, as newly emerging soil additives, have been introduced in the recent years and attracted much interest in engineering applications due to their relatively easy use, low curing time, and promising outcomes. The published literature has shown the significant effect of liquid polymers on soil physical properties [35, 36]. It was reported that the incorporation of liquid polymers could affect the liquid and plastic limits (LL and PL) of soils. Zumrawi and Mohammed [37] studied the effect of polymer treatment on Atterberg's limits and observed an increase of PL and slightly decrease of LL with the increase of polymer content, while some other researches found no significant change in the LL and PL value [38, 39]. It is clear that the effectiveness of polymer treatment in soil stabilization is not only associated with soil composition and mineralogy but also dependent on the structure and physical properties of the polymer used. Authors like Tingle et al. [14] and Rezaeimalek et al. [40] also mentioned that some stabilizers may work well in specific soil types and curing environment, but possibly have significantly different results following different curing methods and environment. The dosage and usage of polymers could be different in terms of polymer type and soil properties.

Meanwhile, various types of liquid polymers have currently been used for the stabilization of sandy and clayey soils [41–43]. Rezaeimalek et al. [44] used a methylene diphenyl diisocyanate-based liquid polymer to stabilize poorly graded sand and obtained well effect on soil strengthening. The strengthening mechanism could be related to the formation of the bonds between sand particles and polymers. Mousavi et al. [42] introduced a liquid cationic-exchanger polymer to mitigate the swelling of expansive soil and found a reduction in swelling potential and swelling pressure. Liu et al. [45] found similar phenomena when used polyvinyl acetate emulsion in expansive soil treatment and deduced that the reduction in volume change is ascribed to the pore filling and particle encapsulation induced by polymers. In general, liquid polymers are applicable for the stabilization of most soils. The mechanical properties of liquid polymer stabilized soil have been discussed by many experimental studies through laboratory tests, such as triaxial compression test, unconfined compression test, direct shear test, and California Bearing Ratio test [42, 44, 46–48]. Also, several authors have investigated the utilization of liquid polymers on erosion control and desertification prevention in view of its promotional effect on soil cohesion and water retention capacity [15, 49, 50].

In the present study, polyvinyl acetate emulsion as a nonconventional additive was used. This polymer has been increasingly used in slope protection, permeation grouting, and expansive soil mitigation due to its low cost, safe operating condition, and environmental-friendly features [15, 46–49]. However, most of the soil-polymer reinforcement experiments are conducted in favourable laboratory environments while in geotechnical engineering projects such as slope protection and foundation treatment, polymers might suffer from moisture after precipitation, especially at the early stage of curing. In particular, the effects of curing environment and time on the interparticle relations and mechanical performance of polyvinyl acetate treated soil have not been extensively discussed in the current literature. For this reason, the purpose of this study is to identify the influence of polymer content, curing environment, and time on the strength behavior of polyvinyl acetate-treated clayey soil. A series of unconfined compression tests were conducted to determine the stress-strain properties of soil-polymer composite cured at room and optimum water content conditions. Scanning electronic microscopy (SEM) tests are performed to investigate the interactions between soil particles and polymers.

2. Materials and Methods

2.1. Soil Characteristics. Natural clayey soil sampled from Nanjing, China, is used for this study. The testing soil was oven-dried, crushed to pass through no. 4 (4.75 mm) sieve as to remove the gravel fraction. Hydrometer and sieve analysis were conducted based on the ASTM D7928 [51] to obtain the particle size distribution curve of the soil (Figure 1).

The Atterberg plastic and liquid limits of the soil were evaluated based on the ASTM D4318 [52] equal to 21 and

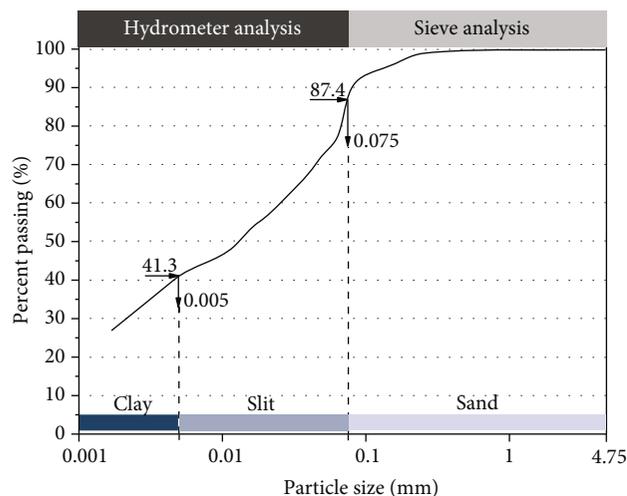


FIGURE 1: Particle size distribution curve of the soil used.

TABLE 1: Physical properties of soil.

Soil properties	Values
Specific gravity	2.71
Consistency limit	
Liquid limit (%)	38
Plastic limit (%)	21
Plasticity index (%)	17
USCS classification	CL
Grain fractions	
Sand (%)	12.6
Slit (%)	46.1
Clay (%)	41.3
Compaction study	
Optimum water content (%)	18
Maximum dry density (kg/m^3)	1,700

38, respectively. The compaction curve of the soil was determined by the standard Proctor test (ASTM D698) [53]. The optimum water content of 18% and maximum dry density of $1,700 \text{ kg/m}^3$ were therefore used in the later experiments. Considering the results obtained from the above tests, the soil used in this investigation is classified as low plastic clay (CL) according to the Unified Soil Classification System (ASTM D2487) [54]. Its physical properties are summarized in Table 1.

2.2. Liquid Polymer. The liquid polymer used in this study is polyvinyl acetate (PVAc) emulsion. It is produced by the emulsion polymerization of vinyl acetate (VAc) monomers, in which polyvinyl alcohol (PVA) is used as protective colloid, sodium dodecyl sulfate (SDS) is adopted as emulsifier, and persulfate solution is incorporated as initiator. Physical properties of the polyvinyl acetate used are presented in Table 2.

As a common adhesive, polyvinyl acetate emulsions are widely used for the bonding of porous materials such as wood, paper, leather, ceramics, and so on. Attempt in appli-

TABLE 2: Physical properties of liquid polymer.

Physical properties	Values
Specific gravity	1.05
Solid content (%)	41
Viscosity (cP)	2500-3000
pH	6-7

cations of cement modification and permeation grouting has also been reported in recent years [55–60]. Considering the low glass transition temperature of PVAc, polymers generally show brittle nature in room condition, in which case they could be more responsive to soil crack expanding. The feasible use of PVAc in geotechnical engineering fields, however, are still worthy of consideration because of the temperature change with seasons in real situation. The thermoplastic of polymer matrix has the possibility to cause the worse strength performance of the soil-polymer composite in the condition of hot summer, especially for the applications in pavement layers and railway embankments. In this regard, using PVAc as a supplement or alternative reinforcement material for slope protection would be more practical when combined with vegetation protection or other engineering countermeasures such as geotextiles and slope anchorage net. With respect to its applications in soil stabilization, polyvinyl acetate polymer is introduced to provide an improvement in the bonding between soil particles in order to develop the engineering characteristics such as shear strength and compressibility.

2.3. Specimen Preparation. In the purpose of contrast and analysis, pure and polymer-treated soil specimens were prepared. Same amount of water based on the optimum water content (i.e., 18%) was applied for both. The polymer-treated specimens were made by hand mixing the soil, polymer, and water. With regard to the mixing procedure, the researches on this matter have not reached a clear conclusion yet whether using polymer dilutions or mixing dried soil with polymer first is more popular [15, 30, 36]. The mixing procedure to be adopted seems to depend more on the physical properties of the polymer and soil used. In our study, due to the high viscosity of liquid polymer, the polymer was first mixed with water to form polymer dilutions, which is easy and feasible for the final uniform mixing. As there was few information available about the optimal polymer-water ratio, 1%, 2%, and 3% polymers by the weight of dried soil (i.e., polymer content) were used in this study for investigating the effect of polymer on soil reinforcement.

Afterwards, the treated soils were obtained by manually mixing pure soils with polymer solution until a uniform polymer-soil mixture was achieved. The well-mixed mixture was then placed into the mold and compacted to cylindrical specimen with 39.1 mm in diameter and 80 mm in height. The dry density of $1,700 \text{ kg/m}^3$ corresponded to the maximum dry density of the soil, and it was selected for specimen preparation. Compaction method can be an important factor influencing gravimetric and volumetric properties of

remolded specimen (e.g., mass density and porosity) by which soil mechanical performance could be differed with respect to these structural differences [61]. The compaction in this study was performed in three layers by static pressure, each of which has equal thickness and weight so as to ensure the similarity of density between each layer after demolding. Prior to the curing process, all specimens were conserved in sealed plastic bags for 24 hours for homogeneous water distribution.

Considering that water content plays a very important role in soil strength performance, there were two curing methods proposed. The specimens were carefully transported to different environments for curing: (i) one group of specimens was cured as common at the room condition with a temperature of $25 \pm 2^\circ\text{C}$ and relative humidity (RH) of $40 \pm 2\%$; (ii) another group of specimens was cured at the optimum water content condition, in which the specimens were wrapped with thin plastic film and placed in the curing box ($25 \pm 2^\circ\text{C}$, $90 \pm 2\%$ RH). The optimum water content condition is assumed to be relevant to high moisture and sufficient water supply in an environment where short-term precipitation occurs after treatment, while the room condition is related to great water evaporation induced by continuous fine weather.

When 1, 3, and 9 days of curing were done, the specimens cured at these two conditions were used for strength testing. The reason that the curing time was limited to 9 days is because the water content of the specimens in dry condition was observed to be a low value (i.e., about 1-2%). In this case, the further increase of curing time will more focus on the durability of polymer reinforcement effect. In addition, the compressive strength of 2% polymer-treated soil cured for 9 days and 28 days in room condition was compared, and a slight increase (about 10%) with curing time was found.

2.4. Test Procedure. The unconfined compressive strength (UCS) of specimens was measured using a conventional unconfined compression apparatus as per the experimental procedures in the ASTM D2166 [62]. The axial load was applied by moving up the platform below to produce an axial strain at a rate of 1%/min (i.e., 0.8 mm/min). The loading and displacement transducers were employed to provide a continuous measurement of stress and strain. During compression, the loading continued until the calculated stress value decreased to 70% of the peak, or until 20% strain was reached. Upon the completion of tests, the water contents of specimens were determined by drying in an oven of 110°C . The water contents were measured before and after testing, and only very slightly variation was observed ($< 0.2\%$). As for the UCS value, three measurements from one case were averaged as a data point; the deviation of which was controlled at 10% less from the average.

In addition, SEM tests were performed on the treated soil specimens to further understand the interparticle relations under the effect of polymer treatment. Results from the pure and 3% polymer-treated specimen were compared. The interparticle structure and morphology were analyzed through SEM images.

3. Results and Discussion

3.1. Unconfined Compressive Strength. The compressive strength values of the specimens with different polymer contents, cured in room and optimum water content condition at 1, 3, and 9 days are shown in Figures 2 and 3, respectively. The water content of the specimen in each case are also plotted for better analyzing the reasons that lead to such variation in compressive strength.

For the specimens cured in room condition, the polymer-treated ones demonstrated higher compressive strength compared to the untreated ones at the same curing time regardless of polymer content (Figure 2(a)), which proves the potential use of PVAc polymer for soil strengthening. It can also be observed that polymer treatment showed similar patterns in soil strength enhancement where the compressive strength of specimens increased with polymer content. It is expected that soil particle aggregation and cementation are induced due to the bridging effect of polymer matrix among soil particles by which greater interparticle relations are provided. The increase in compressive strength with polymer content can therefore be simply considered as a result of the accumulation and wide distribution of polymer matrix in soils that forms more interparticle connections. In this regard, the filling degree of polymers in soil pore space turns to be an important factor controlling the polymer treatment effectiveness. Thus, there always has a threshold value for polymer usage that provides the most soil stabilization outcome since porosity is almost fixed when the same soil dry density and compaction are applied. At high polymer content, the bond strength between particles will likely tend to be saturated, in which case the subsequent gains in compressive strength become harder to get when further increasing polymer content. The results obtained by Ghasemzadeh et al. [63] who investigated the effects of curing method and acrylic polymer concentration on soil stabilization showed that polymer treatment with higher concentration in turn led to an unexpected reduction in UCS. In addition, Latifi et al. [36] explained this variation as a decrease in the strength of soil skeleton induced by the overincorporation of polymers, which acts as lubricative materials so as to encourage the relative slip behavior between soil particles. However, polymer treatment has influence on particle size and morphology to a lesser extent [15, 63], and such lubrication induced by polymers may only exist locally. Within our test range, the increasing tendency of compressive strength had not a clear plateau or fading showing with polymer content. It can be anticipated that there is still room for the amount of polymer used to pursue higher strengthening benefits.

It was also observed in Figure 2(a) that when curing at room condition, the effect of curing time on compressive strength is significant, as also shown by Gilazghi et al. [35] and Rezaeimalek et al. [40]. The variation in compressive strength with curing time is mainly attributed to the water loss during curing as the water content decreased to less than 8% on the 1st day and to about 1% on the 9th day for the treated specimens (Figure 2(b)). On the whole, the compressive strength of polymer-treated specimens is related to two

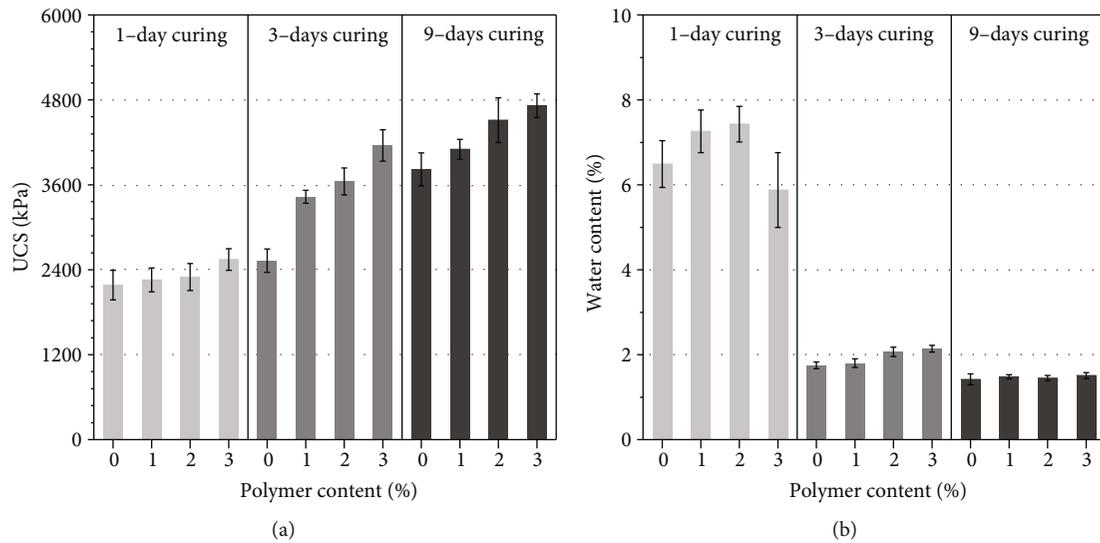


FIGURE 2: Results of the polymer treated specimens cured in room condition. Variations of (a) compressive strength and (b) water content of the specimens after 1, 3, and 9 days of curing. Results of the nontreated specimens are also plotted for comparison.

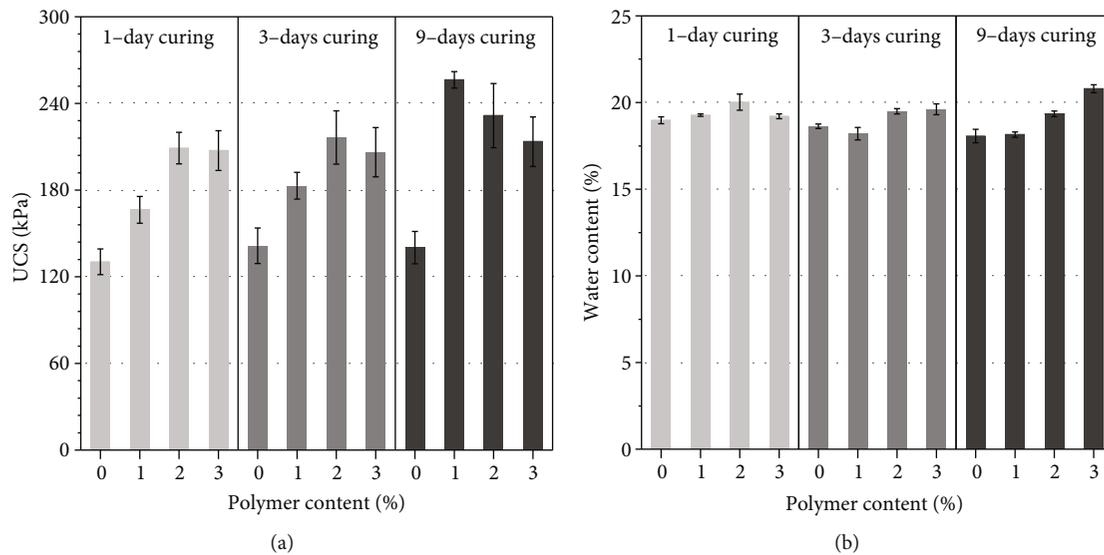


FIGURE 3: Results of the polymer-treated specimens cured in optimum water content condition. Variations of (a) compressive strength and (b) water content of the specimens after 1, 3, and 9 days of curing.

sources: the compressive strength of soils and the additional strength conferred by polymers. For the former, it generally increases with decreasing water content due to high soil suction and strong liquid bridges between soil particles; and for the latter, it is very dependent on the strength of polymeric threads and textiles between particles. At low water content, the polymer matrix is prone to contract via dehydration, and hence, strong soil-polymer interactions are provided. This results in high bond strength between particles which greatly contributes to the compressive strength.

In our observation, polymer treatment has more contributions to the early compressive strength when curing at room condition. The compressive strength of the specimens with 3% polymer content was risen by 63% when the curing time increased from 1 day to 3 days and by only 13% from 3

days to 9 days. The strength variation with curing time is similar to the results presented in the work of certain studies [15, 35]. For polyvinyl acetate emulsion, the most important part at the early stage of curing is the emulsion breaking and subsequent water loss by evaporation [43]. This results in the rapid development of particle coating and interfacial bonding. If adopting a higher initial water content, a longer curing (e.g., 14 or 28 days) could be helpful to further soil strengthening. The polymer matrix inside soil-polymer composite reaches an optimum in enhancing interparticle interactions via the evaporation of water. Considering that a very low water content (i.e., less than 2%) was measured after 9 days of curing, the compressive strength would level off with further increase of curing time. The optimum curing time here is therefore relevant to the water retention capacity of

not only the soils themselves but also the polymers used. Based on our results, curing time of 3 to 4 days could be the most economical and effective.

The variation in compressive strength induced by polymer content and curing time at optimum water content condition is showed in Figure 3(a). As observed, a higher compressive strength was rendered by polymer treatment compared to the pure clay. Although polymer treatment still shows the potential in soil strengthening, the compressive strength variation induced by polymer content shows different development in different curing periods. In shorter period (i.e., 1-3 days), the compressive strength gradually increased due to polymer treatment and tended to stability when beyond 2% polymer content; instead, a gradual decrease in compressive strength with polymer content (i.e., from 256 kPa to 213 kPa) was observed in longer period. As the water content was almost constant through the course of time (Figure 3(b)), the explanation for such dramatic changes may lie in the formation process of polymer film inside the polymer-soil composite.

The evolution of compressive strength can be described according to the formation process of polymer film affected by polymer content and curing time. The gelation occurs because of the water distribution change, by which the polymer particles coalesce and turn into a special semisolid gel. Even if at the very early stage of curing (1-day curing), particle coats and interparticle bridges inside the soil are formed, in view of the fact that the specimen with 1% polymer content exhibited 36 kPa higher compressive strength than the untreated one. However, according to Rezaeimalek et al. [40], water bathing the treated specimens immediately after compaction resulted in the collapse of the specimens. This phenomenon suggests that the interparticle cohesion enhancement caused by polymer treatment could be less marked in short period. Considering almost no water evaporation during curing, the polymer colloids do not show an obvious film forming trend in the early days of curing, and this state is likely to last for quite some time due to the moisture. Thus, at higher polymer content, the polymer matrix in semisolid state has more possibility to act as a lubricating layer between soil particles when loading is applied, resulting in a stable or even decreased compressive strength (Figure 3(a)).

In addition, as also showed in Figure 3(a), it is found that compressive strength monotonically decreased with polymer content after 9 days of curing. The reason for this could be attributed to the poor water resistance of PVAc material, which causes the weakness of interparticle bonding due to the softening of polymeric material under the influence of moisture. But if that is the main reason, it is unlikely to observe such differences in strength growth over curing time with regard to the specimens with 1% and 3% polymer content. It is clear that film formation exists in curing process since the specimen treated by 1% polymer yielded a compressive strength up to 256 kPa. The results suggest therefore that the strength variation with polymer content at 9-day curing is because the degradation of bond strength between soil particles outweigh the benefits conferred by polymer bonds. Due to the strong hydrophilic property of polymer

material, the specimen with high polymer content is more affected by water, in which case more water is expected to be absorbed by polymer matrix and retained within it.

It is not obvious yet whether this strength degradation induced by water is reversible after dehydrated or not. In our observations, the use of PVAc has some advantages in improving the water absorption and retention of soil, but it is not clear whether these advantages are sufficient for field applications. Therefore, further study on the water retention capacity of the PVAc-treated soil and its mechanical performance after drying-wetting cycles is of interest. Concerned with soil mechanical performance improvement purpose, we suggest that polymer content less than 2% is more suitable in high moisture environment.

3.2. Stress-Strain Properties. With regard to the room condition, the typical compressive curves and elastic moduli of specimens with different polymer contents and curing times are presented in Figure 4, which shows the changes of axial stress with axial strain. As observed, sharp and well-defined peak occurred in the stress-strain curve for both untreated and treated specimens. An increase in peak value was found as polymer content increased, but more importantly, the presence of polymers had not significantly modified the mechanical responses prior to cracking. It is expected that short strain is insufficient to mobilize the full tensile strength of polymer bonds due to their low elastic stiffness. Soil particles can only bear short strains (i.e., less than 2%), as shown by the stress-strain curve of untreated specimens, while the polymer films between particles are yet in the process of stretching within the same strain level, resulting the compressive forces are directly applied on soil skeleton.

It is also showed in Figure 4 that the effect of polymer treatment on axial stress after the peak is not significant. The decreasing trend of curves was observed to be almost consistent regardless of polymer content, possibly because most of the polymer films along the failure plane are broken. It is worth noting that previous studies on fiber reinforced soil showed a gentler decrease in axial stress after the peak, especially when combined use with cement or lime [64, 65]. If the polymeric material used has relatively high tensile strength and elastic modulus, it is possible to mimic the effect of fiber incorporation on postpeak behavior, thus obtaining a broader and flatter peaked stress-strain curve. This is in agreement with the results of Liu et al. [66] which showed that the sand specimens treated by hydrophilic polyurethane can bear much longer strains (about 10%) before reaching the peak, contributed by the good flexibility of polyurethane due to its soft-hard segments in molecular structure.

In room condition, the effect of polymer content on stress-strain properties is mainly presented in the enhancement of peak stress and strain values. As observed in Figures 4(a)–4(c), axial strain at the peak was enhanced to a great extent with the increase of polymer content. On the one hand, longer strains are required for crack generation, which directly indicates that soil specimens underwent a transition from a brittle to ductile manner because of polymer treatment (Figure 4(d)). On the other, to be more

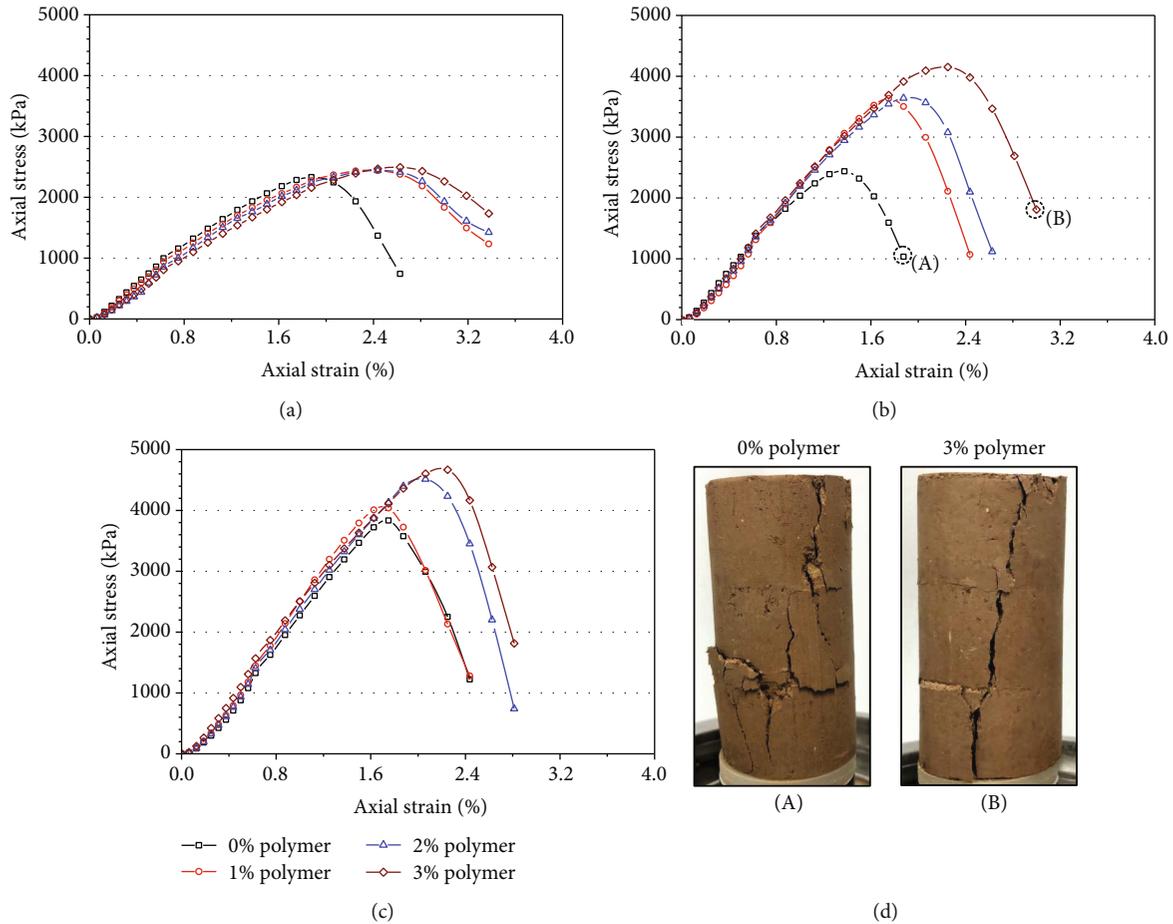


FIGURE 4: Typical stress-strain curves of the specimens in room condition after (a) 1-day curing, (b) 3-day curing, and (c) 9-day curing. And (d) failure patterns of the specimens treated by 0% and 3% polymer after 3 days of curing.

ductile implies to bear larger plastic deformation, meaning polymer matrix prevents crack propagation via provision of enhanced interparticle relations while particle rearrangement. In this scenario, these polymeric threads and textiles would continuously confer resistance to compressive shear, either because their breakages occur gradually instead of simultaneously, considering the inhomogeneous microdistribution of polymers between particles, or because they still provide friction even if they are broken.

Moreover, in the condition of same curing time, the stiffness of polymer-treated specimens remained nearly constant to that of pure ones. Similar variations were also found in the other groups of tests. Due to the presence of water, the curves at short curing time tended to be flatter, exhibiting greater peak strains and lower stiffness. However, the compressive strength had a notable increase with time, which may also prove the state change of polymers that becomes firm and hard from soft state due to dehydration.

Figure 5 shows the stress-strain responses and elastic moduli of specimens cured at optimum water content condition. As observed in Figure 5(a), even if only 1 day, curing the clay with polymer treatment in high moisture environment still increased the compressive strength and stiffness of specimens compared to the pure clay. The most differences are that, with the curing process going on, the speci-

mens with lower polymer content had a more significant increase in peak value and stiffness, while those with higher content general showed better ductility where the peak strains were enhanced to a great extent and wider curves were conferred (Figure 5(d)).

The change of the stress-strain response occurred after 3 days of curing but showed good consistency before this timing (Figures 5(b) and 5(c)). At low polymer content, the formation and mechanical performance of polymer film seems to be less affected by moisture because of relatively less water absorption amount. The question is whether the water-induced reduction in polymer treatment effectiveness is permanent or temporary, i.e., it is possible for the specimens cured at optimum water content condition to be competitive with those cured at room condition if drying in air subsequently. Considering the strong moisture susceptibility of the specimens due to the hydrophilic groups, the debonding at the soil-polymer interface may occur. The tests on polymer-treated specimens at combined curing environments would enable us to better evaluate the influence of moisture on soil strengthening.

3.3. *Elastic Modulus and Energy Absorption.* As shown previously in the stress-strain curves (Figures 4 and 6), the deformation of the specimen was generally very small until the

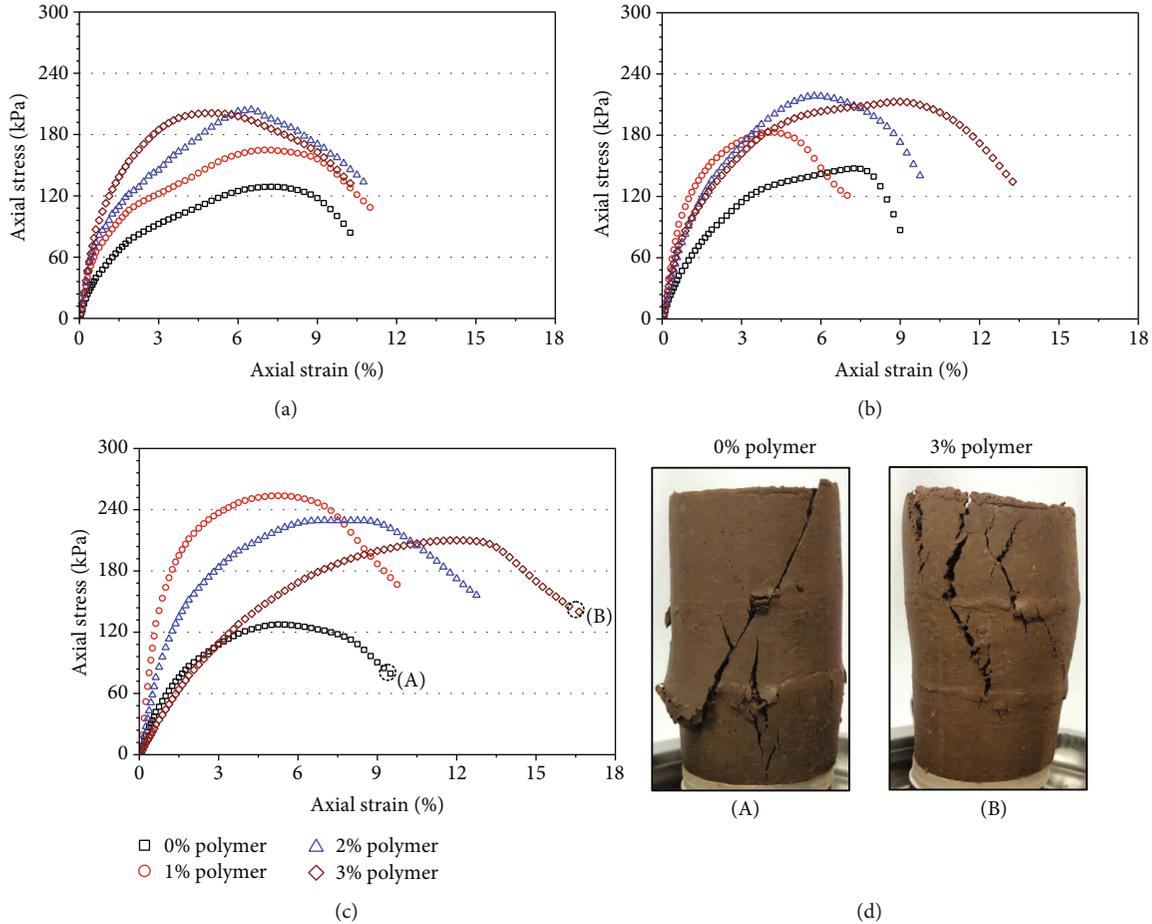


FIGURE 5: Typical stress-strain curves of the specimens in optimum water content condition after (a) 1-day curing, (b) 3-day curing, and (c) 9-day curing. And (d) failure patterns of the specimens treated by 0% and 3% polymer after 9 days of curing.

cracking failure, especially for those cured at room condition (between 2 and 3% strain in most cases). For this reason, the elastic modulus was represented by the secant modulus which was estimated by calculating the slope of the line between the origin and the point corresponding to 50% compressive strength in the stress-strain curve. Also, as an important indicator of the overall mechanical performance during compression, the energy absorption capacity was computed as the strain energy (i.e., the area under the stress-strain curve) at the peak using the method of calculus. The results above were based on the average of three measurements in one case.

In general, the results show that the incorporation of polymers to soil has the potential to improve the elastic modulus of specimen, but there are stages and differences in terms of polymer content (Figures 6(a) and 6(b)). After 1 day of curing, the elastic modulus decreased with polymer content at room condition, instead increased at optimum water content condition. It is expected that, the soft texture of polymer film leads to the fact that it is more tolerant than soils to deformation (i.e., better flexibility), by which the relatively high elastic modulus exhibited by natural soils would be balanced and more develop to an intermediate value with more polymers incorporated. The value of elastic modulus is

more dependent on soil mechanical and rheological properties at early stage of curing. According to Nugent et al. [67], the liquid limit of kaolinite clay generally increases with polymer concentration because of the increased pore fluid viscosity. This could explain the increase of elastic modulus with polymer content after 1 day of curing in optimum water content condition (Figure 6(c)). Up to 9 days of curing, polymer treatment is more effective in elastic modulus enhancement in room condition due to the soil consolidation and hardening of polymer film induced by dehydration, showing the highest value (251 MPa) at 3% polymer content. In contrast, with a constant water content, high polymer content is not favorable in the purpose of elastic modulus improvement. This could be attributed to the strong hydrophilicity of polyvinyl acetate, which enhances the water absorption of the film, and correspondingly leads to poor water resistance (i.e., reduction in bond strength and failure in surface coating and interparticle connection). This phenomenon is likely to be magnified with longer exposure to moisture, especially at high polymer content.

Both in room and optimum water content condition, it is observed that the increased polymer content has positive effect on strain energy (Figures 7(a) and 7(b)). As an indicator that combines overall consequence of peak stress and

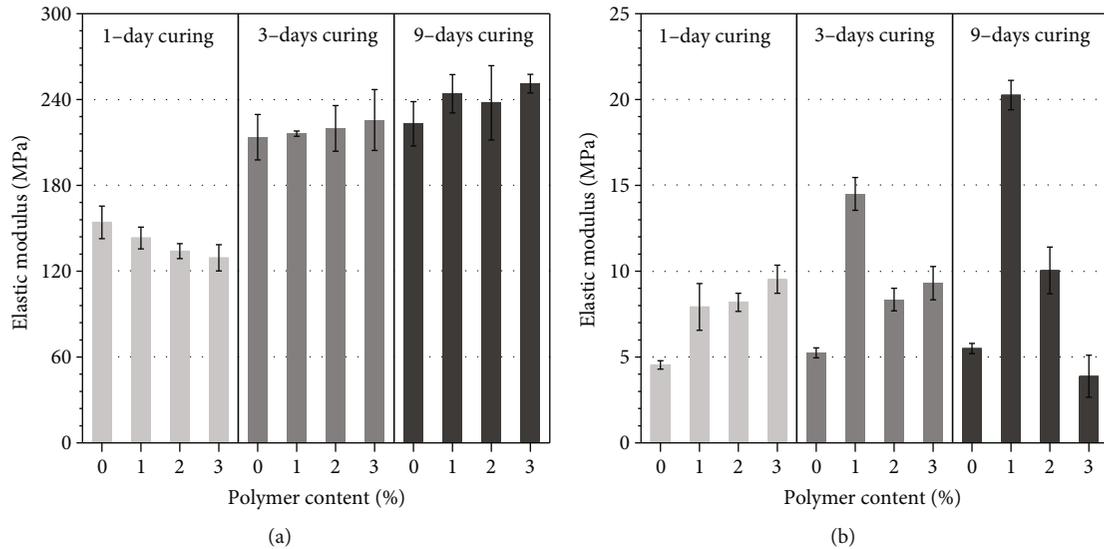


FIGURE 6: Variation of elastic modulus with polymer content and curing time. (a) Specimens cured in room condition and (b) specimens cured in optimum water content condition.

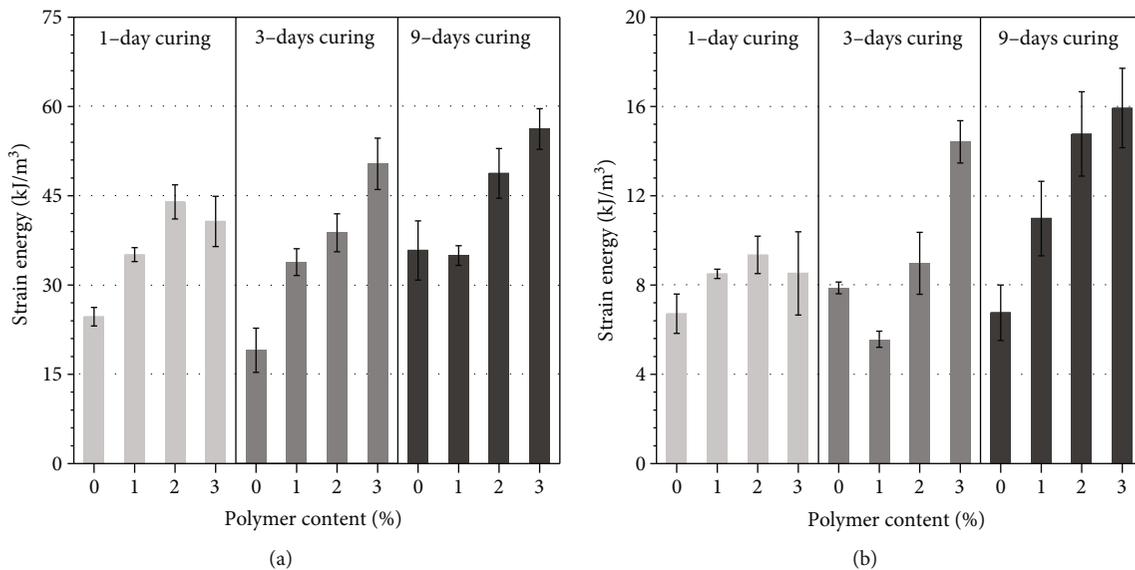


FIGURE 7: Variation of energy absorption with polymer content and curing time. (a) Specimens cured in room condition and (b) specimens cured in optimum water content condition.

strain, the strain energy better demonstrates the effect of polymer treatment on soil deformation resistance. The increase in strain energy implies the promotional effect on crack resistance. One explanation for this result is the enhanced interparticle and interfacial interactions provided by polymer treatment. It is also found in the research of Qi et al. [68] that polymer treatment using polyacrylamide prevents soil shrinkage cracking triggered by desiccation to a certain extent.

3.4. Strengthening Mechanism. Our experimental study showed promising results that the use of PVAc polymer in soil reinforcement effectively provides an improvement in the mechanical behavior of the soil composite under both dry and humid environments. Figure 8 shows the SEM

images of untreated and PVAc-treated clay. As observed, polymer treatment for clayey soil coated the particle surface and increased the interfacial contacts among the clay particles, which also bonded soil particles together with polymer fabrics and textiles and formed larger aggregates (Figures 8(a) and 8(b)). Thus, the improvement in soil strength is closely related to the development of particle coats and interparticle bonds, as well as the formed three-dimensional membrane structure. The enhanced interactions between soil particles and polymer matrix are generally realized by surface coating, pore filling, and subsequently close particle arrangement.

In the case of curing in drying environment, viscous polymers adhere to the surfaces of soil particles, accumulating and forming the interparticle bridges. Due to the

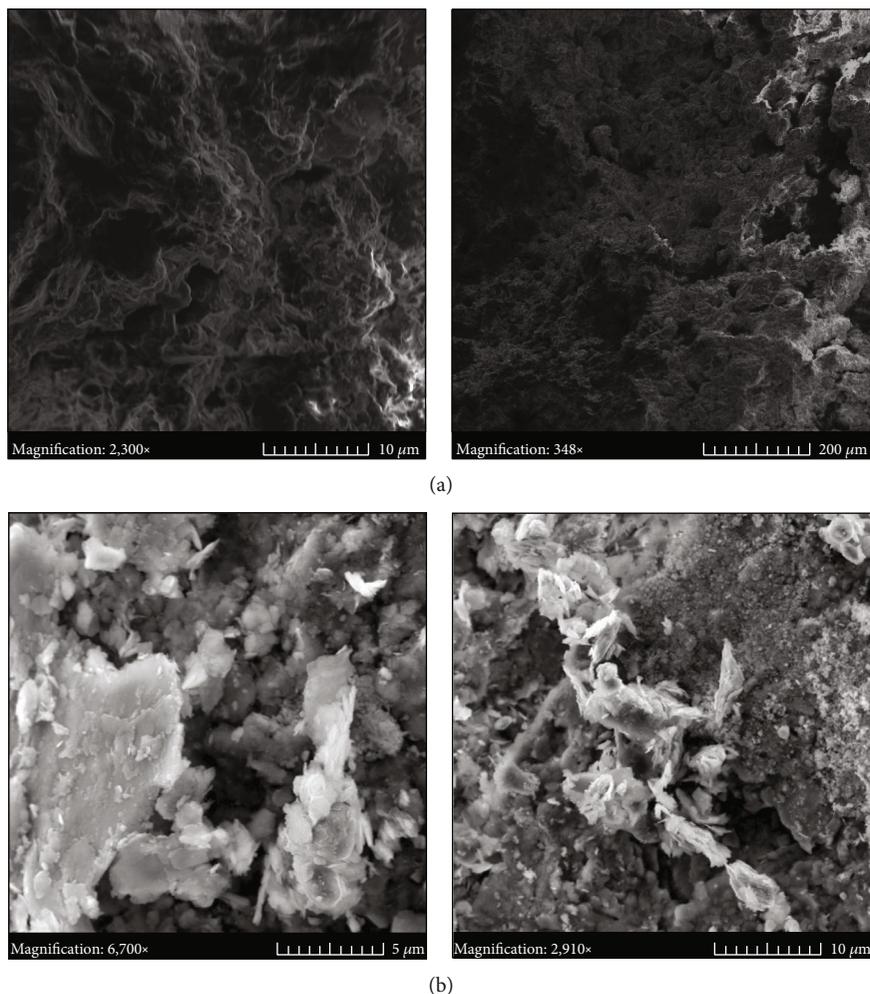


FIGURE 8: SEM images of (a) pure clay and (b) 3% polymer-treated clay. Both are conserved in room condition for 9 days.

presence of the hydrophilic groups on the polymer chain (e.g., carboxyl and hydroxyl), a close connection between soil particles and polymer matrices forms through hydrogen bonds and cation exchange. The interactions between the polymers and soil contribute to better particle interlock and increased agglomeration of the clay through the membrane structure characterized by particle coats, fine particle-PVAc matrices, and interparticle bridges (Figure 8(b)). The polymers effectively enhance the interparticle structure of soil as a result of the increased contact areas among the soil particles and additional support to soil skeleton from the membrane structure. As water evaporates during curing, the dehydrated polymer matrices turn to be firm and strong enough to maintain the connection between two particles not in direct contact, thereby limiting their relative movement under stress. The shrinkage of polymer matrix due to dehydration would also pose tensions among particles that offset the external load stress in part. In some respects (macroscopic view), PVAc polymer strengthens the soil through enhanced interparticle interactions, which depends on the physical and mechanical properties of the polymeric threads and fabrics. Polymer-treated soil could be considered as a composite material in which the polymers with relatively high strength performance

and flexible texture distribute inside. Stresses in the soil are shared by polymer matrix, mobilizing its tensile resistance through either stretching or bending, which confers additional cohesion to the soil through the bridge system as a result.

In particular, the soil-polymer interaction characteristics are supposed to be different in view of the differences in mineral composition, particle morphology, and size. A previous study also mentioned that the increase in clay (fine particle) content reduces polymer treatment effectiveness as the stronger attraction of fine particles to polymers leads to its uneven distribution in the soil matrix [43]. It is emphasized that the interactions of polymers with clay particles could be greater than that with sand particles. Polymers are absorbed on the fine particle surfaces due to the hydrogen and ionic bonding, gathering, and enwrapping particles to promote soil aggregation.

In the case of curing in humid environment, the effectiveness of polymer treatment is greatly affected due to the hydrophilic properties of polymer matrix, which leads to a reduction in the strength of the formed interparticle bridges [17]. This is ascribed as the presence of polyvinyl alcohol (i.e., protective colloid) which contains considerable hydroxyl groups that confer strong water absorption capacity to the polymer matrix.

In the short term, the membrane structure is not dramatically changed and still provides sufficient reinforcement effect since the treated soil generally yields higher compressive strength than natural soil. The competition between polymers and soils for moisture may also contribute to soil strength. However, in the long term, the swelling behavior would be intensified with the gradual diffusion of water into polymer matrices, possibly resulting in the increase of soil particle spacing and further decrease in bond strength.

4. Conclusions

Unconfined compression tests on the polymer treated soil were conducted in this research to evaluate the influence of curing environment and curing time on the contribution of polymer treatment to soil strength. The role of polyvinyl acetate in enhancing interparticle interactions at dry and humid environment was analyzed through experimental results and SEM images. The following conclusions can be drawn:

- (1) The incorporation of polyvinyl acetate generally leads to higher compressive strength. In room condition, the compressive strength monotonously increased with polymer content and curing time, reaching up to 4.7 MPa at 3% polymer content as soil water content reduced to less than 2%. For curing in humid environment, a soil water content of about 18%, the increase in compressive strength of treated soil with curing time was also observed, but the strengthening effect provided by high polymer content could fade in long-term curing because of the degradation of bond strength induced by water absorption of polymers
- (2) The presence of polymers has no significant effect on the pre- and postpeak behavior of the soil because short strains are insufficient to fully mobilize the tensile strength of polymers, whereas long strains would cause the breakage of polymer matrix between soil particles. Wide and flat peaked stress-strain curves often occur in the treated soil with high water content as a result of the flexibility of polymer matrix
- (3) The incorporation of polymers to soil has the potential to improve the elastic modulus and strain energy, even in a high moisture environment. The interparticle interactions induced by polymer treatment contribute to crack resistance and hence lead to a more ductile behavior of soil. However, in terms of longer curing time, the elastic modulus of the soil with high polymer content is much less than the one with low polymer content because of the poor water resistance of polymers
- (4) SEM analysis indicates that polyvinyl acetate could act as a binder to enhance the bond of soil particles via bridging effect. The formation of particle surface coats due to the hydrogen and ionic bonding imparts greater aggregation to soil. The improvement in soil

mechanical properties could be attributed to the tensile strength of polymeric threads and textiles that maintain the integrity of soil structure

Our experimental results show that polyvinyl acetate emulsion can be potentially used for soil stabilization. Within our test range, 1-2% polymer content and at least 3-4 days of dry curing are suggested to be economical and effective for reinforcement purpose. Further studies on the mechanical properties of soil-polymer composite in the complex environment and experienced drying-wetting cycles are particularly of interest in order to evaluate its long-term performance and durability, and make reasonable use and design of polyvinyl acetate in soil stabilization.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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