

# Compressive Strength of Acrylic Polymer-Stabilized Kaolinite Clay Modified with Different Additives

Hasan Ghasemzadeh, Aida Mehrpajouh, and Malihe Pishvaei\*



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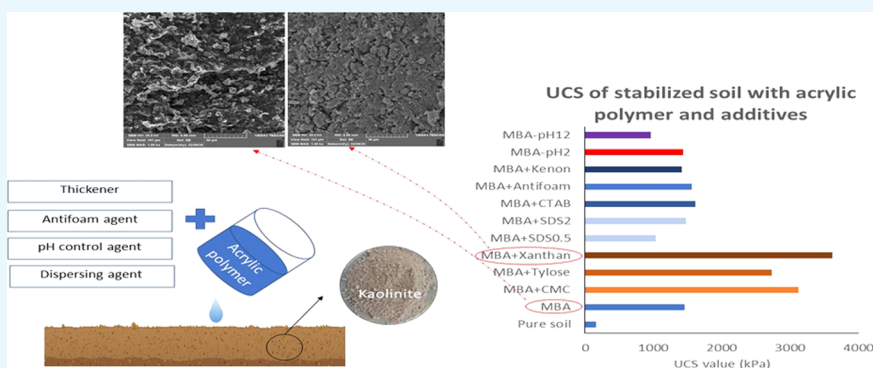


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**ABSTRACT:** Although numerous studies have shown the successful use of acrylic-based polymers as one of the chemical substances to improve soil mechanical behavior, their basic ingredients in commercial products are not revealed due to the manufacturers' confidential policy. Among them, additives including pH control agents, thickeners, antifoams, and wetting agents are widely well-known owing to their enhancement effects on different properties of polymers. However, the effect of additives on the soil–polymer mixture is not completely investigated. Therefore, in this study, some of the frequently used additives in acrylic polymers were selected to investigate the effects of each one on the compressive strength of clayey soil. These additives include xanthan gum, Tylose, and carboxymethyl cellulose (CMC) as thickeners, sodium dodecyl sulfate (SDS), cetyltrimethylammonium bromide (CTAB), and Kenon 10 as wetting agents, an ether-based antifoaming agent, and ammonia solution as a pH control agent. A combination of each additive (between 0 and 5% by weight) and polymethyl methacrylate-*co*-butyl acrylate (with 5% by weight) was added to kaolinite soil to measure the variation of unconfined compressive strength (UCS) and the stress–strain behavior of the soil–polymer–additive mixture. The results indicated that thickeners significantly affected the unconfined compressive strength up to 248% and increased the ductility of the stabilized samples. Acidic pH of the emulsion led to higher unconfined compressive strength of the stabilized soil up to 2.33 times that with alkaline. It is also demonstrated that the use of a higher amount of anionic wetting agent resulted in higher failure strain and lower unconfined compressive strength.

## INTRODUCTION

Most challenging and costly civil engineering projects require adequate soil conditions due to problems such as in situ bearing weakness, liquefaction, high swelling, and excessive settlements. A large number of exerted successful techniques increase the bearing capacity and reduce the subsequent settlements. The use of chemical binders is one of the recent attractive methods for improvement of soil properties such as strength,<sup>1–3</sup> erosion control,<sup>4</sup> and settlement reduction.<sup>5–7</sup> Materials such as lime,<sup>8,9</sup> cement,<sup>10,11</sup> and fly ash<sup>12–14</sup> are some of the traditional additives with environmental drawbacks, including CO<sub>2</sub> emission, leading geo-engineers to search for innovative substances.<sup>9,15–19</sup>

Polymers are one of the well-documented nontraditional materials to unravel problems of various constructional materials such as soil and concrete under short-term and long-term conditions.<sup>20–25</sup> In addition, waterborne polymers have been

considered less polluting, easily applicable, and cost-effective nontraditional binders.<sup>26–29</sup> However, some ingredients of manufactured polymeric soil additives are not utterly disclosed owing to their patent policy. Wetting agents, plasticizers, antifoams, pH control agents, and rheology control agents such as thickeners are examples of numerous additives used in industries during the production process or application of acrylic latexes.<sup>30,31</sup>

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Among the polymer additives, a surface-active agent (surfactant), also called a wetting agent, is defined as a diffuser for merging materials in a host fluid with the capability of lowering the surface tension between two liquids.<sup>32,33</sup> Wetting agents can be divided into cationic, anionic, and nonionic based on their charge. Some wetting agents such as sodium dodecyl sulfonate (SDS) and cetyltrimethylammonium bromide (CTAB) have been used in the literature as soil remediation materials to protect from contamination, including oil derivatives.<sup>34–40</sup> Pei et al. investigated the effect of two different surfactants on the mechanical behavior of styrene copolymer-modified mortar.<sup>40</sup> They stated that the polymeric surfactant with a higher molecular weight performed more effectively than sodium dodecyl sulfonate (SDS) did in terms of enhancing strength. Chavez et al. studied the impact of three surfactants on the geotechnical properties of loamy soil.<sup>41</sup> They found that addition of surfactants resulted in a higher liquid limit, while the plastic index was decreased using a cationic surfactant. This limited amount of research has not entirely investigated the effect of different types and dosages of wetting agents on the soil–polymer mixture.

Rheological additives (e.g., thickeners) are the other groups of polymer additives commonly used to enhance the viscosity, typically through the interaction with water.<sup>42,43</sup> There are two kinds of organic-based thickeners associated with waterborne polymers: the first group, like cellulose or starch derivatives, thickens the aqueous phase, and the second group interacts with other ingredients.<sup>44</sup> Cellulose ethers like carboxymethylcellulose (CMC) are among the most common thickeners used in the waterborne coating industry. The function of cellulose-based thickeners relies primarily on their high molecular weight. In addition, the chain entanglements decrease the mobility of water molecules due to the hydrogen bonds between dissolved thickener molecules. Cellulosic thickeners including xanthan gum have been successfully used as soil additives.<sup>45,46</sup> It has also been ascertained that some cellulosic biopolymers including xanthan have positive influences on the soil strength.<sup>21,47</sup> Qingwen<sup>48</sup> reported the salient improvement of the cohesion value of silt soil using a composite of polyacrylamide and carboxymethyl cellulose (CMC) owing to a dense soil aggregate cementation effect. Sujatha et al.<sup>49</sup> investigated different geotechnical properties of clayey sand stabilized with xanthan gum. They found that the use of this biopolymer led to an increase in the plastic index and unconfined compressive strength (UCS), while a higher amount of xanthan resulted in a lower maximum dry unit weight. However, a stiffer matrix is structured with xanthan gum after curing. Adhikari et al.<sup>50</sup> also examined viscosity modifiers on the performance of a polyurethane-based sprayable polymer as a soil additive. They used four thickeners, including alginate, xanthan gum, gelatin, and polyacrylamide, to investigate the physical and mechanical properties of soil. Their results revealed significant improvements in membrane formation and water retaining of polymer-stabilized soil due to addition of thickeners. They also concluded that addition of xanthan gum resulted in the highest outcome in terms of minimal wicking, defined as water absorption by capillary forces, and prevention of water evaporation. Since cellulosic thickeners are widely known as biopolymers, their appropriate effect on enhancing soil properties is successfully observed. However, the mechanical behavior of the combination of polymer, different thickeners, and soil is still unclear and needs to be investigated to understand their efficiency on the properties of the soil–polymer mixture.

Antifoaming agents are another common group of polymer additives, lessening an induced bubble formation of surfactants.<sup>51</sup> It provides a less-void structure for a treated material with polymers if it is well-matched with the polymer structure.<sup>52</sup> Bahranifard et al.<sup>53</sup> in one study conducted in the polymer-stabilized concrete modified with silicon-based antifoam and superplasticizer agents indicated that adding 16% antifoam improved the mechanical properties of concrete considerably due to the reduction of the air content. Lee et al.<sup>81</sup> also found that addition of a defoamer with 0.1 wt % of binding material resulted in over a 20% increase in the compressive and tensile strength of the alkali-activated cementless composite. They also obtained a denser composite by an increase in the amount of defoamer. The antifoaming agent can positively influence the geomaterial matrix by reducing voids. However, the percentage and compatibility of the additives with other materials' chemical structure have not been fully investigated in terms of geotechnical applications.

The value of pH also affects the mechanical properties of soil.<sup>54–56</sup> Yang et al.<sup>57</sup> investigated the effect of water's pH on the shear strength of silty clay soil. Their finding depicted that saturation with distilled water with pH = 7 resulted in the lowest cohesion value. Furthermore, the cohesion value is increased with time as the sample is immersed in an acidic solution. Rahman and Nahar<sup>58</sup> also found that the direct shear strength increased with an increase in pH using the ammonia solution for granular soils. Hassanlourad et al.<sup>59</sup> studied the effect of sulfuric acid with a different concentration on the shear strength of the sand–bentonite mixture. They found that although the shear strength of sandy soil decreased in acidic pH, the addition of sulfuric acid led to the higher strength of the sand–bentonite mixture at a pH of 3. Hence, the variation of pH can affect the material properties depending on the structure and chemical interactions. Nevertheless, few studies focused on the effect of pH on the mechanical behavior of fine-grained soils, and this is essential to consider due to different in situ conditions of construction projects.

Despite the valuable information that can be obtained from the previous studies, there is still a lack of comprehensive investigation of the effect of the combination of polymer and additives on soil properties and the effect of the final mixture on the strength parameters of the stabilized soil. Hence, this study attempts to understand the effect of mixing different additives with a polymer on the mechanical properties of stabilized fine-grained soil. To reach that, some polymer additives including thickeners (xanthan, Tylose, and carboxymethyl cellulose), antifoaming agent, wetting agents (sodium dodecyl sulfate (SDS), cetrimonium bromide (CTAB), and Kenon 10), and ammonia solution as a pH control agent were used to investigate the effect of each additive on the unconfined compressive strength of polymer-stabilized clayey soil. The final objective of this paper is to help find the optimum values of ingredients to be used to improve the mechanical properties of clayey soil.

## ■ MATERIALS AND SAMPLE PREPARATION

**Soil.** The soil used in this study was a commercial kaolinite clay, represented as cohesive, purchased from a local company, Iran China Clay Company. This soil was chosen to investigate the effect of these materials on the charged clay mineral surfaces. Therefore, the commercial kaolinite was selected for the properties to be controlled. Figure 1 shows the particle size distribution curve of the studied soil obtained from the grading test.<sup>60,61</sup> According to the UCSC classification system, it is

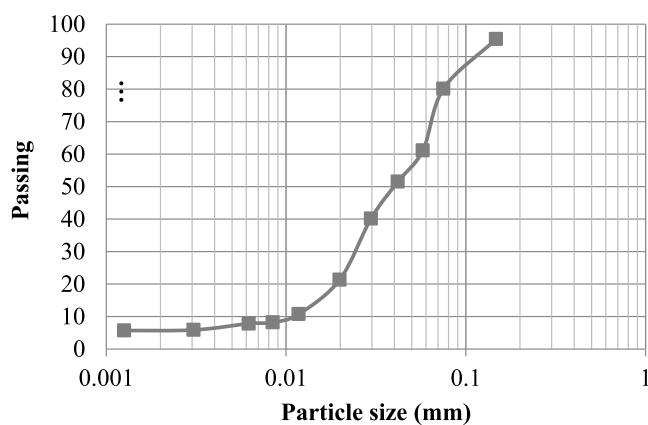


Figure 1. Grain size distribution of the kaolinite clay.

classified as CL with a liquid limit, plasticity index, specific gravity, and unconfined compressive strength of 44.0%, 25.7%, 2.69, and 161.0 kPa, respectively, based on ASTM standards.<sup>62–64</sup>

**Polymer.** The copolymer of methyl methacrylate and butyl acrylate, namely MBA, which is used in this study, has been recently synthesized *via* chain growth emulsion polymerization by Ghasemzadeh et al.<sup>65</sup> The polymerization was performed with 0.5, 2, and 4% SDS. The solid content and conversion percent of the final product obtained were approximately 38 and 97%, respectively, guaranteeing the polymerization completion, and the percent of remaining toxic materials was negligible. Table 1 depicts some properties of the synthesized amorphous copolymer.

Table 1. Some Properties of the Synthesized Copolymer (MBA)

properties	value	test method
form	liquid	
color	white	
pH	2–3	pH meter
solid content	38%	solid content test
average particle size	76 nm	DLS (with Horiba sz-100)
glass transition temperature ( $T_g$ )	33 °C	DSC (with Mastersizer 2000, Malvern Instruments Ltd., U.K., and model: 11029)

**Rheology control agents (thickeners).** Carboxymethyl cellulose (CMC), sodium carboxymethyl cellulose (Tylose), and xanthan gum were used as cellulosic thickening agents to

increase viscosity. It is of note that the studied Tylose was the derivative salt of CMC with higher solubility. Figure 2 depicts the chemical structures of the thickeners used in this study.

**Wetting Agents.** Wetting agents were applied to reduce the surface tension so that the polymer can easily penetrate the soil structure. Sodium dodecyl sulfate (SDS) as an anionic surfactant, cetrimonium bromide (CTAB) as a cationic surfactant, both purchased from Merck Company, and nonylphenol poly(ethylene glycol ether) (Kenon 10) as a nonionic one, purchased from Rayan Shimi Sanat (Iran), were added to the polymer. In a series of tests, the copolymer was synthesized with different dosages (i.e., 0.5, 2, and 4%) of SDS to compare with the results obtained from using it as an additive. Table 2 illustrates the properties of different surfactants used in this study. It is worth mentioning that ionic surfactants are mostly hydrophilic. This depends on the capacity balance between the hydrophilic group to attract water and the hydrophobic group (lipophilic) to attract the oil phase. This is denoted via an hydrophilic–lipophilic balance (HLB) indicator quantifying the balance of hydrophilic and lipophilic capacity. Nonionic surfactants have HLB numbers from 0 to 20, while the ionic surfactants tend to have HLB values up to 50.<sup>37</sup> An HLB of higher than 10 indicates that the surfactant is water-soluble, which can be used as an emulsifier, wetting agent, and detergent. The HLB value as a measure to choose a suitable surfactant is determined for each surfactant in Table 2, indicating that all the studied surfactants are hydrophilic.

**pH Control Agent.** Based on the microfabric investigations in the literature, pH affects the distribution of ionic charges on the surface and edge of clay minerals.<sup>66</sup> The ammonia solution was used to vary the pH value of the polymer emulsion from acidic (2–3) to alkaline (over 12) to investigate the variation of the UCS of stabilized samples.

**Antifoaming Agent.** Antifoaming agents are used to eliminate the formation of foam caused by surfactants used in polymerization. This is also predicted to reduce the consequent voids through the soil sample preparation. The antifoam used in this study is a white emulsion used in the industrial water treatment, paper industry, and auxiliary coating agents. Table 3 presents the properties of the antifoam.

**Sample Preparation and Experimental Investigation.** According to the sample preparation of acrylic latexes proposed by Ghasemzadeh et al.,<sup>23</sup> the liquid polymer was diluted with distilled water to prepare the optimum polymer concentration of 5%. The compaction parameters of soil were determined using the proctor test.<sup>67</sup> The values of the optimum moisture content and the maximum dry density were found to be 15.4 kN/m<sup>3</sup> and 25% for unstabilized soil and 15.3 kN/m<sup>3</sup> and 26% for stabilized

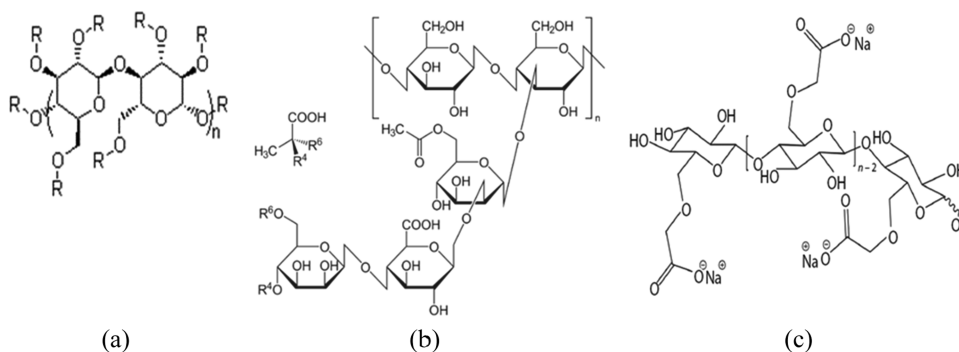


Figure 2. Schematic chemical structure of different rheological agents (a) CMC: R is H or CH<sub>2</sub>CO<sub>2</sub>H, (b) xanthan, and (c) Tylose.



**Table 2. Some Properties of the Studied Wetting Agents**

material	charge	form	molecular weight (g/mol)	HLB	chemical formula
SDS	anionic	solid	288.38	40	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>11</sub> OSO <sub>3</sub> Na
CTAB	cationic	solid	364.45	10	CH <sub>3</sub> (CH <sub>2</sub> ) <sub>15</sub> N(Br)(CH <sub>3</sub> ) <sub>3</sub>
Kenon10	nonionic	liquid	220.35	12	C <sub>9</sub> H <sub>19</sub> C <sub>6</sub> H <sub>4</sub> (OCH <sub>2</sub> CH <sub>2</sub> ) <sub>n</sub> OH

**Table 3. Properties of the Studied Antifoaming Agent**

properties	value
pH value	6–8
solid content	≥98%
viscosity (25 °C)	1000–1500 mPa·s

soil with the desired polymer content, respectively. The soil–polymer mixture was statically compacted in the UCS mold with a diameter of 380 mm and a height of 800 mm at the optimum moisture content and maximum dry density.<sup>68,70</sup> For static compaction, two molds were locked together and filled with the amount of mixture needed to be compacted at one layer. The hydraulic jack with a specific fixed displacement rate<sup>69</sup> was used for compaction to ensure that soil was compacted without creating excessive pore water pressure. Afterward, the sample was brought out from the mold using an extruder jack. Then, the samples were allowed to dry at ambient temperature for seven days. It should be noted that for each sample, the void ratio was calculated from the dry density after sample preparation.

Additives were mixed into an emulsion by the physical mixing method. To assess the effect of the additives, Table 4 illustrates

**Table 4. Percentage of the Additives Used in a Series of Stabilized Samples**

series	additive	percent
1	SDS	0.5, 2, 4
2	CTAB	0.5, 2, 4
3	Kenon	0.5, 2, 4
4	xanthan	1, 2, 3, 5
5	Tylose	1, 2, 3, 5
6	CMC	1, 2, 3, 5
7	pH	2, 6.5, 9, 11, 12
8	antifoam	0.5, 1, 2, 3, 4

the amount of each additive in the prepared samples. It should be noted that the percentage of antifoam was considered the ratio of antifoam weight to polymer weight. On the contrary, others were calculated based on their proportion to soil weight. Meanwhile, the combination of emulsion and additives can be considered a mixture that will develop as a commercial soil conditioner.

Powder-form additives with determined proportions were added to the diluted polymer emulsion of 5% concentration and then mixed with soil. All samples were statically compacted in a 38 mm × 80 mm mold at an optimum moisture content and maximum dry density and then air-dried. The sample was then tested.<sup>63</sup>

To understand the effect of wetting agents on the polymer behavior and subsequent interactions with soil, a series of surface tension tests were conducted. The surface tension measurements were performed using a Kruss K100 tensiometer based on ASTM-D1331.<sup>70</sup> Moreover, rheological tests were run on treated polymers with different thickeners to identify the effect of each additive on the final product. Shear viscosity curves were attained at ambient temperatures (23–25 °C) using a

controlled-stress Couette rheometer (Anton-Paar, MCR300). The microscale structure was also investigated using the scanning electron microscopy (SEM) technique via a VEGA3 TESCAN microscope.

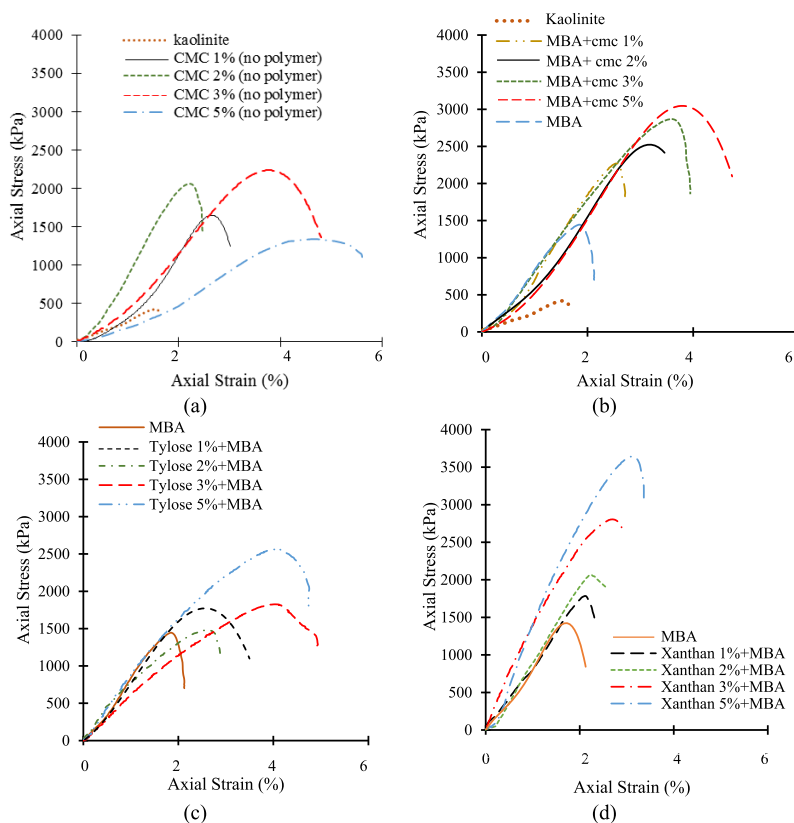
## RESULTS AND DISCUSSION

**Effect of Rheological Agents on the UCS of Stabilized Clay.** Figure 3 shows the variation of the stress–strain curves of unstabilized and polymer-stabilized samples with different percentages of CMC, Tylose, and xanthan gum. The UCS values of the pure kaolinite at an optimum moisture content and after drying were obtained to be 161 and 406 kPa, respectively. It should be noted that the moisture content before drying was in the range between 25.0 and 26.8%, and after being allowed to dry, the moisture content reached below 0.2%. It is observed that regardless of the type and the amount of thickener agent, there are significant improvements in the failure stress value compared to that of the unstabilized soil. The UCS value increased sharply to 2283 kPa when only 3% of CMC was added to pure kaolinite. The UCS and ductility of samples stabilized with CMC were increased, according to the results obtained by Ma and Ma.<sup>71</sup> As the CMC concentration reached over 3%, the rate of strength gain was reduced, while the failure strain was increased. However, by increasing the percentage of CMC to 5%, the final strength of the stabilized sample was reduced to 1335 kPa. This can be attributed to the negative charge of CMC molecules in alkaline media repelled by negatively charged clayey soils.<sup>72</sup> Hence, high CMC concentration in clayey soil led to repulsion forces between the clay surface and CMC molecules, resulting in lower strength.

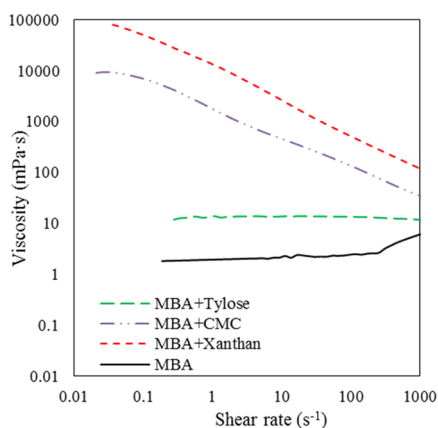
Moreover, the UCS value and the corresponding strain of stabilized samples with the mixture of synthetic polymer (MBA) and thickener (CMC) increased dramatically. The UCS value and failure strain were obtained to be 1462 kPa and 0.027 for the MBA-stabilized sample and over 3094 kPa and 0.047 for the sample stabilized with the combination of MBA and 5% CMC, respectively. As can be observed, the samples stabilized with the thickener and polymer exhibited a more ductile behavior than those stabilized only with a polymer. Soil particles could be coated, and the inter- and intra-aggregate pores were filled with the gel-like structure of thickener (i.e., CMC) and polymer chains. Hence, the interparticle bonding and cohesion rapidly increase with addition of CMC. It should be noted that after drying, the gel system is turned to a flexible network between soil particles. This can also be attributed to cellulosic thickeners (as biopolymers) since they change the osmotic pressure between the polymer chains and water. Their main function as a thickener leads to higher viscosity, causing a denser soil–polymer structure. This outcome was also achieved with other thickeners, such as xanthan and Tylose. The samples stabilized with the addition of 5% Tylose and xanthan to MBA exhibited significant improvements in the UCS values (1.8 and 2.5 times more than stabilized samples with only MBA, respectively).

However, the effect of Tylose as a rheological additive on the UCS is less than that of its peers. This can be explained by the results of rheological tests. Figure 4 depicts the shear viscosity–





**Figure 3.** Stress–strain curves of the stabilized clay with different rheological agents: (a) CMC, (b) with CMC and MBA, (c) Tylose and MBA, and (d) xanthan and MBA.



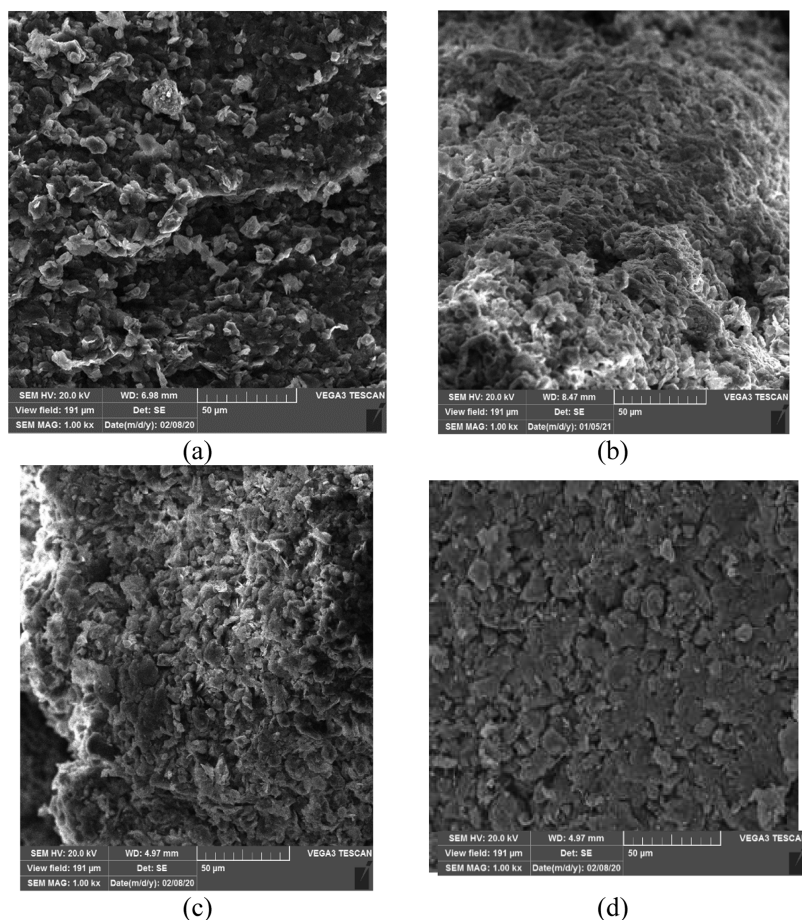
**Figure 4.** Shear viscosity curves of the polymer latex and different thickeners.

shear rate curves for the polymer treated with different additives at 5% concentration (regarding the polymer weight). It is observed that the viscosity differs between the studied additives. The viscosity of xanthan gum and CMC-treated polymer is the highest, while it is near that of the pure polymer for the one treated with Tylose. The higher viscosity indicates the higher interaction between the molecules of polymer with water and thickener. Hence, their interaction would be increased through mixing with the soil minerals. It is noteworthy that the studied Tylose was completely water-soluble among other thickeners owing to its salt-based chemical structure. However, it can be deduced that lower viscosity leads to the lower compressive strength of the polymer-stabilized soil treated with a thickener.

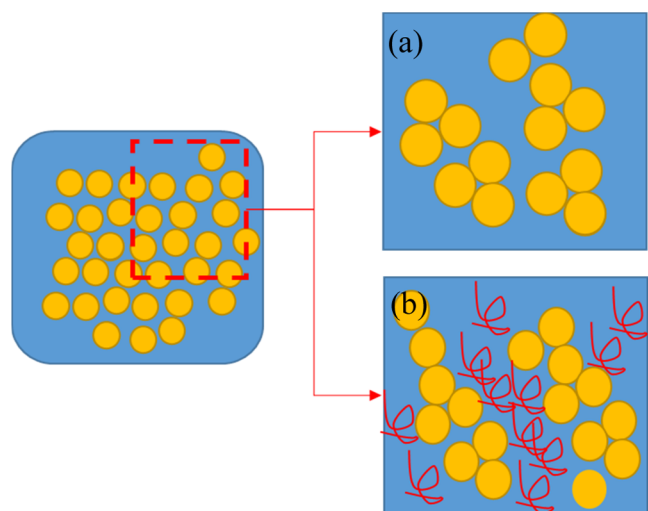
**Figure 5** displays the microfabric of the clay stabilized with different thickeners. The sample treated with xanthan exhibits a more uniform structure than its peers do. The boundaries between minerals are faded, and a coherent structure is formed due to the physical interaction of thickeners with polymer chains in water medium. Indeed, the interaction between cellulosic thickeners and acrylic polymers is physical as they are recognized as conventional thickeners. Conventional thickeners primarily increase the thickness by hydrodynamic and flocculation mechanisms. By dissolving in water, the polymer chains of conventional thickeners dominate a large hydrodynamic volume and retain considerable water through the coils of their backbones. This increases the viscosity of the solution considerably.

As **Figure 6** shows, due to the hydrogen bonds occurring between water molecules and thickener chains, the thickener molecules pose between polymer particles in a water media, increasing the viscosity. As a polymer emulsion is added to the soil, this system replaces water in the inter- and intra-aggregate pores. As **Figure 5** depicts, after water evaporation, the thickener's molecules remain and fill the pores.

**Effect of the Wetting Agent on the UCS of Stabilized Clay.** Two series of samples were prepared using SDS as a surfactant and additive. In the first group, defined as SS, 0.5, 2, and 4% SDS participated in the polymerization as a part of the main ingredients. In the second group, samples were prepared using the prepared polymers, with 0.5, 2, 4, and 10% SDS as the additive after synthesis. **Figure 7** presents the UCS and strain value of polymer-stabilized soil with different SDS amounts in synthesis (SS) or as an additive (SA). It can be observed that increasing the concentration of SDS, whether in the synthesis



**Figure 5.** SEM images of the polymer-stabilized clay mixed with different thickeners: (a) pure, (b) with CMC, (c) with Tylose, and (d) with xanthan gum.

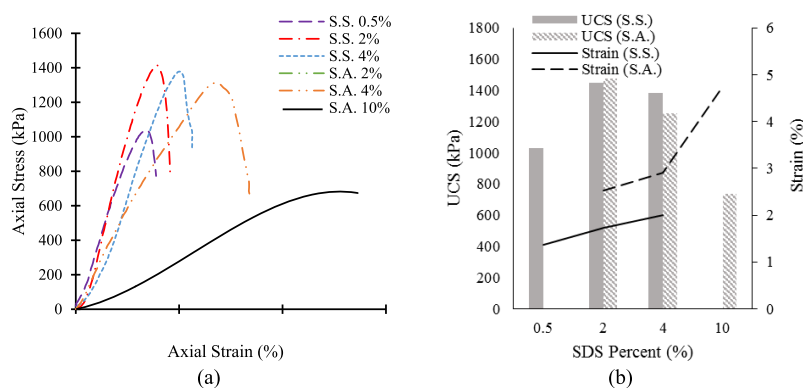


**Figure 6.** Schematic of the polymer emulsion (a) without the thickener and (b) with cellulosic thickeners.

process or as an additive after the polymerization process, led to an increase in the failure strain and, consequently, the ductility of the stabilized soil with the acrylic polymer. However, the final unconfined compressive strength is in the most significant value as the SDS concentration was 2%, and then, it gradually decreased with further SDS concentration. It appears that 2% SDS helps suspend the polymer molecules in water media.

Hence, the polymer chains contribute homogeneously to filling the pores between soil particles to bind them. Furthermore, by increasing the SDS concentration, its molecules dispersed in soil media lead to higher repulsion due to negative charges. Therefore, the maximum bearable stress is significantly reduced from 1474 kPa for SA 2% to 722 kPa for SA 10%. From a surface tension viewpoint, the use of a lower percentage of surfactant leads to a higher surface tension. This causes the higher capillary increase and higher matric suction in the unsaturated soil.<sup>73</sup> Higher matric suction leads to higher shear strength, and this can explain the higher UCS of samples containing lower surfactant values. Table 5 presents the results of surface tension. As previously mentioned, although the use of 0.5% SDS in synthesis led to higher surface tension (i.e., 68.321 mN/m), the UCS value for the soil stabilized with that was less than that stabilized with the polymer synthesized with 2% SDS. This is due to the polymer nonhomogeneous distribution in the soil microfabric. Polymer particles adhere together at lower surfactant concentrations, and the matrix is not dispersed well in water media. However, at 2% SDS, the surface tension is almost too high (i.e., 47.401 mN/m), where the matric suction is increased, and the highest UCS is achieved. The higher surfactant value led to lower surface tension, and the lubricant effect resulted in a lower UCS value.

Figure 8 presents the results of UCS tests on the polymer-stabilized samples having three different dosages of two other surfactants (CTAB and Kenon). In small percentages (0.5%), the wetting agent with a positive charge (CTAB) increased the



**Figure 7.** Stress–strain behavior of the clay stabilized with the polymer and different amounts of SDS (a) stress–strain curves, (b) UCS, and the corresponding strain value.

**Table 5. Surface Tension Value for Different Surfactant Types and Dosages**

surfactant name/percent	surface tension (mN/m)		
	0.5	2	4
CTAB	59.243	41.074	34.323
SDS	68.321	47.401	32.676
Kenon	40.253	37.652	33.089

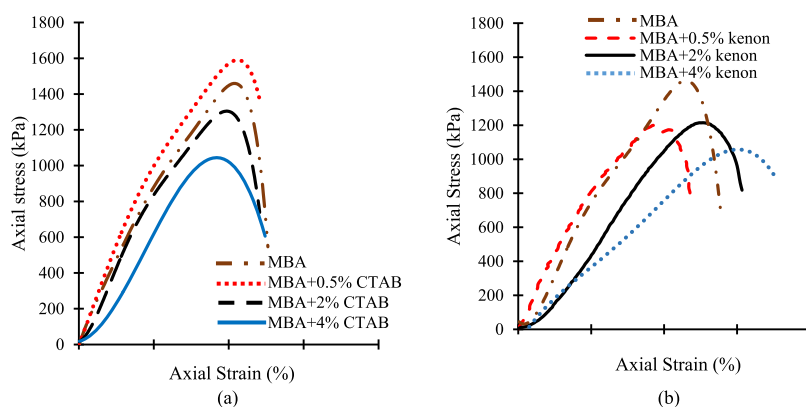
UCS value from 1446 to 1588 kPa. The higher amount of CTAB resulted in a decreasing trend as the UCS is reduced to 1077 kPa for 4% CTAB concentration. As Table 5 shows, the value of surface tension varies between 59.423 mN/m for the treated sample and 0.5% CTAB to 32.676 mN/m for the sample with 4% CTAB. This can be attributed to the competition of electrical charges in absorbing each other or the clay surface. By losing the moisture content, the positively charged CTAB molecules are placed in the vicinity of negative SDS charges (as one of the ingredients in the synthesis process) and the surface of kaolinite. Moreover, the edges of clay platelets possessed a positive charge. The winning system of this complex interaction is strongly dependent on the charge density. It appears that at lower CTAB concentrations, the SDS molecules are neutralized, and the polymer molecules have the opportunity to be adsorbed on the clay particles. However, the higher amount of CTAB yields higher absorption to the clay surface, and the main polymer molecules are less adsorbed onto soil particles.

Figure 8b depicts the effect of adding Kenon in different dosages on the stress–strain behavior of the clay soil stabilized

with MBA. It can be observed that Kenon caused a decrease in the final UCS from 1446 kPa for the control sample to 958 kPa for that prepared with 4% Kenon. A constant decreasing trend is observed with increasing the Kenon concentration, unlike the other surfactants. Furthermore, a higher amount of Kenon yields a higher axial strain at the failure point. This is because the use of Kenon as a wetting agent, like other peers, leads to lower surface tension,<sup>74</sup> resulting in decreased aggregation. According to the results obtained by Mohammadi et al.,<sup>74</sup> 2004, and Table 5, the addition of nonionic surfactant leads to lower surface tension among its peers. This is in accordance with the findings obtained by Bera et al.,<sup>75</sup> who stated that the use of a combination of anionic and nonionic surfactants would lead to higher foamability, and this could be the reason for a higher porosity in the structure of the soil treated with Kenon (Figure 9).

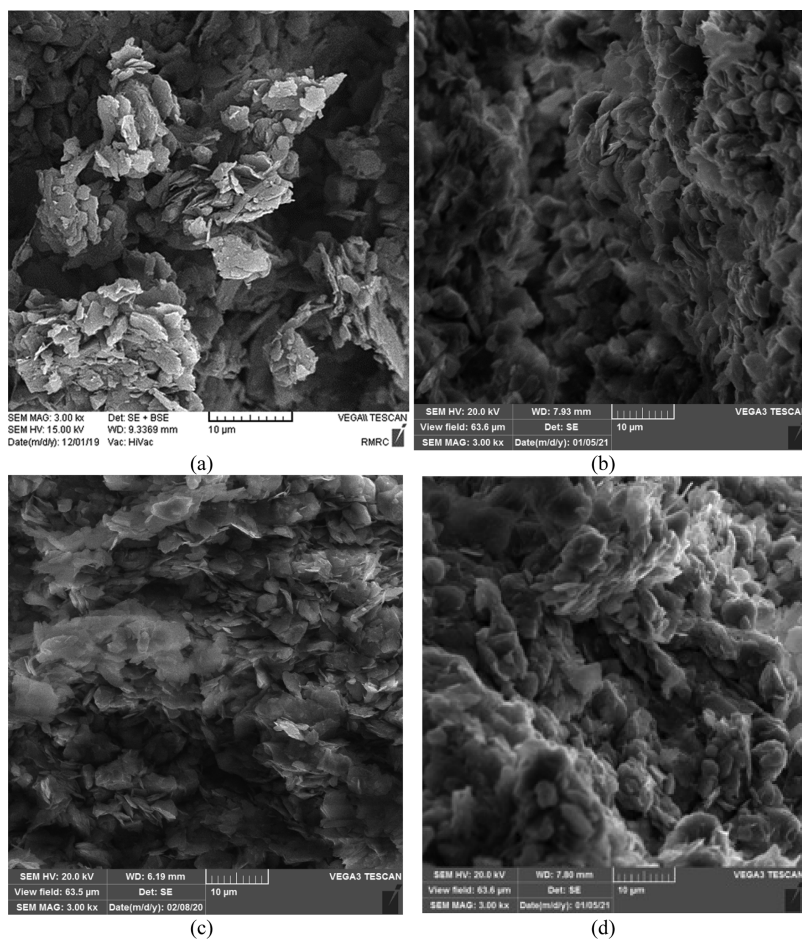
Figure 9 shows the microstructure of the polymer-stabilized clay with different wetting agents. The lower aggregation was induced by wetting agents. This leads to a lower UCS value, while the particles slip through the failure surface, leading to a higher failure strain. This is in accordance with the results of one study conducted by Jones et al.,<sup>76</sup> indicating that the use of surfactant leads to higher plasticity and consequently yields higher plasticity, and this led to a higher strain value.

**Effect of the pH Control Agent on the UCS of Stabilized Soil.** Figure 10 depicts the UCS variation and stress–strain curves of the polymer-stabilized clay with different pH values (using ammonia to vary the pH of the polymer emulsion) from acidic (2, 6) to alkaline (9, 10, and 12). The UCS value was decreased as the pH was increased by adding

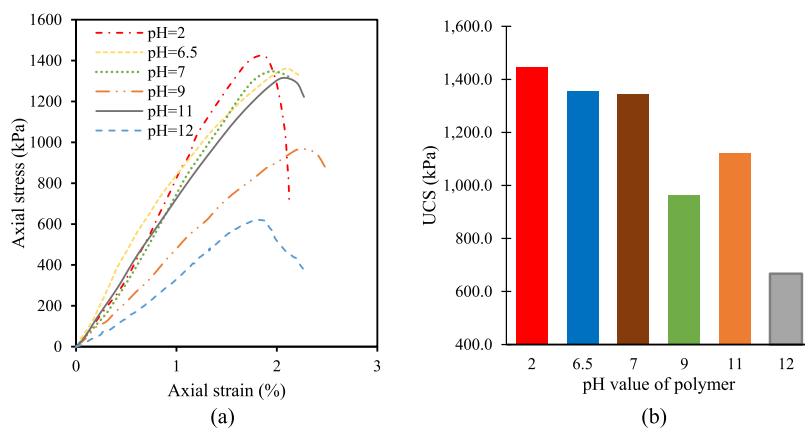


**Figure 8.** Stress–strain behavior of the clay stabilized with the polymer and different amounts of wetting agents: (a) CTAB and (b) Kenon.





**Figure 9.** SEM images of the polymer-stabilized soil with different wetting agents: (a) unstabilized soil, (b) 0.5% CTAB, (c) 10% SDS, and (d) 0.5% Kenon.

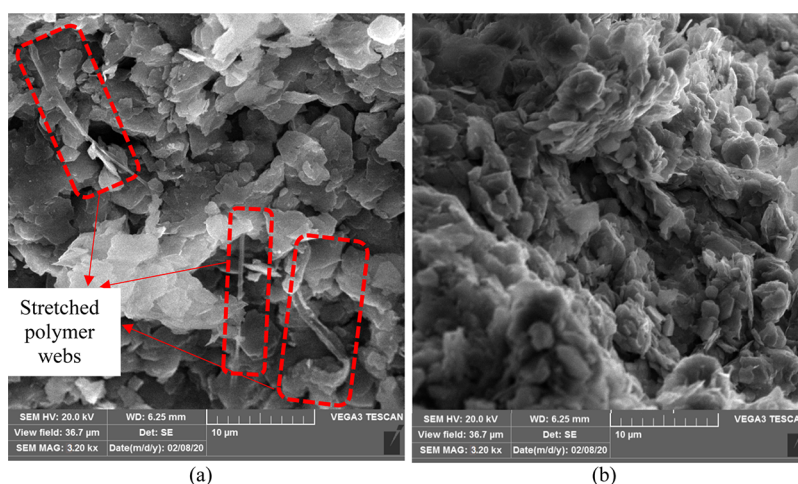


**Figure 10.** Results of the unconfined compressive strength of the polymer-stabilized clay with different pH values: (a) stress–strain curves and (b) UCS value.

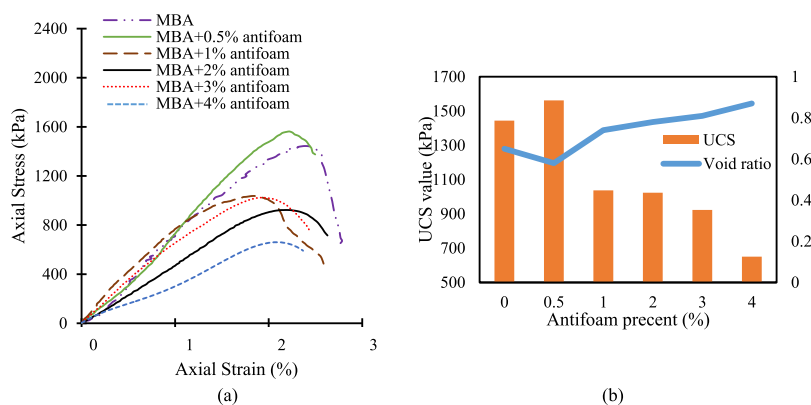
ammonia. Theng<sup>66</sup> previously implied that in low-pH medium, polar polymers (e.g., methyl methacrylate-*co*-butyl acrylate) have a stretched geometry bridging the soil particles. This can lead to higher binding between the soil surface and the polymer, resulting in the higher strength of the soil–polymer mixture. Moreover, polymer chains are also absorbed by the anion exchange reaction to clay due to the induced positive charge of clay minerals' edges through acidic pH, as it has been reported by Sommerfeldt and Schaik.<sup>77</sup>

It should be noted that although the pH of the emulsion varies with introducing ammonia, the total pH of the soil–polymer composite has not been changed due to the insignificant amount of the solution.

In alkaline media, the polymer molecules shaped like coils tend not to bind with the negatively charged surfaces of clay minerals. This phenomenon can also be observed in the microfabric of the polymer-stabilized soil, which is indicated in Figure 11. As Figure 11a shows, there are some stretched polymer webs through the clay structure at pH = 2, which bind



**Figure 11.** SEM images of the polymer-stabilized clay in different pH values: (a) pH = 2 and (b) pH = 12.



**Figure 12.** UCS behavior of the MBA-stabilized clay with different amounts of antifoaming agent: (a) stress–strain curves and (b) void ratio and UCS value.

particles, creating a more resilient fabric against the pressure. Furthermore, no chain is observed between the clay surfaces as pH is increased to 12 (Figure 11b). It should be noted that the samples were analyzed right after 7 days of curing, and the differences between the image date were owing to the preparation of the samples at different times.

**Effect of the Antifoam Agent on the UCS of Stabilized Soil.** Figure 12 shows the stress–strain behavior, UCS value, and strain energy (corresponding to the peak stress value) of the polymer-stabilized clay with different antifoaming agent dosages. The UCS value is increased from 1446 kPa for the MBA-stabilized clay to 1562 kPa for the MBA-stabilized clay with 0.5% antifoam. This can be explained by the fact that a sufficient amount of antifoaming agent helps destruct the foam induced by surfactants. Thus, the total void ratio is reduced, leading to gained strength. This is in accordance with the results obtained by Łaźniewska-Piekarczyk,<sup>78,79</sup> where an antifoaming agent led to a higher UCS value and a decrease in the void content. As Figure 12b depicts, the value of the void ratio for the sample treated with 0.5% void ratio is 0.58, which is the smallest value among other samples, and this can explain its highest UCS value.

However, there is a general declining trend induced by the addition of antifoam with higher concentrations, as the UCS is reduced to 650 kPa for the sample with 4% antifoam. This finding complies with the result obtained by Łaźniewska-Piekarczyk,<sup>78</sup> where the high amount of antifoam affected the

UCS of the concrete mortar negatively. Moreover, a high concentration of antifoaming agent can reversely affect the foaming process by stabilizing the generated foam.<sup>80</sup> Therefore, the foam structure that remained in the soil–polymer mixture leads to a higher void content and lower UCS.

## CONCLUSIONS

Water-based acrylic polymers have been used for geotechnical purposes owing to their easy application, low threat to the environment, and low cost among peers. However, the effect of additives for acrylic latex is not thoroughly evaluated on soil improvement since the details of the manufactured additive ingredients are not disclosed. This paper disclosed the effects of a series of common industrial additives to polymer emulsions on the unconfined compressive strength of clay under air-dried conditions. According to the significant effect of some of these additives, the final product provided by solving them into an emulsion can be sprayed on the surface or mixed with soil in the field. The results of the tests demonstrated the following facts:

1. Thickeners such xanthan gum, Tylose, and CMC have a profound positive effect on the stress–strain behavior of the clay stabilized with acrylic polymer. Using 5% of these agents yields a 272% increase in UCS of the stabilized sample. Moreover, the ductility of the samples is increased by these additives.

- An increase in the value of SDS resulted in UCS reduction and higher failure strain. The use of Kenon as a neutral surfactant also resulted in the same trend.
- Although addition of CTAB as a cationic wetting agent in low dosage can lead to a higher UCS value for the polymer-stabilized soil, higher dosage causes lower strength.
- The value of pH for the emulsion also influences the UCS and stress–strain behavior of the final clay–polymer mixture. Since at lower pH, the polymer chain is formed with a stretch geometry, it bridges through inter- and intra-aggregate pores, leading to higher strength.
- At low concentrations (below 0.5%), the addition of an antifoaming agent leads to higher UCS, while for higher concentrations, the value of the stabilized soil treated with the polymer decreases significantly.

## AUTHOR INFORMATION

### Corresponding Author

Malihe Pishvaei – Department of Resin and Additives, Institute for Color Science and Technology, Tehran 1668836471, Iran;  
 orcid.org/0000-0001-7148-0919; Email: pishvaei@icrc.ac.ir

### Authors

Hasan Ghasemzadeh – Department of Civil engineering, K.N. Toosi University of Technology, Tehran 19967-15433, Iran  
 Aida Mehrpajouh – Hochschule für Technik und Wirtschaft Dresden, 01069 Dresden, Germany

Complete contact information is available at:

<https://pubs.acs.org/10.1021/acsomega.2c00236>

### Notes

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## REFERENCES

- Geiman, C. M.; Brandon, T. L.; Plaut, R. H. *Stabilization of Soft Clay Subgrades in Virginia Phase I Laboratory Study*; Virginia Polytechnic Institute and State University, 2005.
- Ghasemzadeh, H.; Modiri, F. Application of novel Persian gum hydrocolloid in soil stabilization. *Carbohydr. Polym.* **2020**, *246*, No. 116639.
- Pham, V.-N.; Oh, E.; Ong, D. E. L. Effects of binder types and other significant variables on the unconfined compressive strength of chemical-stabilized clayey soil using gene-expression programming. *Neural. Comput. Appl.* **2022**, *38*, 1–19.
- Liu, J.; Shi, B.; Jiang, H.; Huang, H.; Wang, G.; Kamai, T. Research on the stabilization treatment of clay slope topsoil by organic polymer soil stabilizer. *Eng. Geol.* **2011**, *117*, 114–120.
- Chen, Q.; Abu-Farsakh, M. Ultimate bearing capacity analysis of strip footings on reinforced soil foundation. *Soils Found.* **2015**, *55*, 74–85.
- Kiliç, R.; Küçükali, Ö.; Ulaş, K. Stabilization of high plasticity clay with lime and gypsum (Ankara, Turkey). *Bull. Eng. Geol. Environ.* **2016**, *75*, 735–744.
- Mehrpazhouh, A.; Moghadas Tafreshi, S. N.; Mirzababaei, M. Impact of repeated loading on mechanical response of a reinforced sand. *J. Rock Mech. Geotech. Eng.* **2019**, *11*, 804–814.
- Dumpa, V.; Vipparthy, R.; Mantripragada, A. K.; Raju, G. V. R. P. Evaluating the strength characteristics of lime and metakaolin stabilized expansive soil. In *Lecture Notes in Civil Engineering*; Springer, 2019; Vol. 14, pp 239–248.
- Kumar, B. S.; Preethi, T. V. Behavior of Clayey Soil Stabilized with Rice Husk Ash & Lime. *Int. J. Eng. Trends Technol.* **2014**, *11*, 44–48.
- Lemaire, K.; Deneele, D.; Bonnet, S.; Legret, M. Effects of lime and cement treatment on the physicochemical, microstructural and mechanical characteristics of a plastic silt. *Eng. Geol.* **2013**, *166*, 255–261.
- Lepakshi, R.; Reddy, B. V. V. Shear Strength Parameters and Mohr–Coulomb Failure Envelopes for Cement-Stabilized Rammed Earth. *Constr. Build. Mater.* **2020**, *249*, No. 118708.
- Hoy, M.; Rachan, R.; Horpibulsuk, S.; Arulrajah, A.; Mirzababaei, M. Effect of wetting–drying cycles on compressive strength and microstructure of recycled asphalt pavement – Fly ash geopolymer. *Constr. Build. Mater.* **2017**, *144*, 624–634.
- Rajak, T. K.; Yadu, L.; Pal, S. K. Analysis of Slope Stability of Fly Ash Stabilized Soil Slope. In *Lecture Notes in Civil Engineering*; Springer, 2019; Vol. 13, pp 119–126.
- Sharp, K. D. In *Fly Ash for Soil Improvement*, Proceedings of Sessions Sponsored by Committees on Soil Improvement and Geosynthetics of the Geotechnical Engineering Division of the American Society of Civil Engineers in Conjunction with the ASCE Convention in Dallas, Texas; American Society of Civil Engineers, 1993.
- Bekhiti, M.; Trouzine, H.; Rabehi, M. Influence of waste tire rubber fibers on swelling behavior, unconfined compressive strength and ductility of cement stabilized bentonite clay soil. *Constr. Build. Mater.* **2019**, *208*, 304–313.
- Safehian, H.; Rajabi, A. M.; Ghasemzadeh, H. Effect of diesel-contamination on geotechnical properties of illite soil. *Eng. Geol.* **2018**, *241*, 55–63.
- Majeed, Z. H.; Taha, M. R. A Review of Stabilization of Soils by using Nanomaterials. *Aust. J. Basic Appl. Sci.* **2013**, *7*, 576–581.
- Saha, A.; Sekharan, S.; Manna, U. Hysteresis Model for Water Retention Characteristics of Water-Absorbing Polymer-Amended Soils. *J. Geotech. Geoenviron. Eng.* **2022**, *148*, No. 04022008.
- Mirzababaei, M.; Arulrajah, A.; Horpibulsuk, S.; Aldava, M. Shear strength of a fiber-reinforced clay at large shear displacement when subjected to different stress histories. *Geotext. Geomembr.* **2017**, *45*, 422–429.
- Baghini, M. S.; Ismail, A.; Naseralavi, S. S.; Firoozi, A. A. Performance evaluation of road base stabilized with styrene–butadiene copolymer latex and Portland cement Performance evaluation of road base. *Int. J. Pavement Res. Technol.* **2016**, *9*, 321–336.
- Chen, C.; Wu, L.; Perdjon, M.; Huang, X.; Peng, Y. The drying effect on xanthan gum biopolymer treated sandy soil shear strength. *Constr. Build. Mater.* **2019**, *197*, 271–279.
- Georgees, R. N.; Hassan, R. A.; Evans, R. P. A potential use of a hydrophilic polymeric material to enhance durability properties of pavement materials. *Constr. Build. Mater.* **2017**, *148*, 686–695.
- Ghasemzadeh, H.; Mehrpajouh, A.; Pishvaei, M.; Mirzababaei, M. Effects of Curing Method and Glass Transition Temperature on the Unconfined Compressive Strength of Acrylic Liquid Polymer–Stabilized Kaolinite. *J. Mater. Civ. Eng.* **2020**, *32*, No. 04020212.
- Marto, A.; Latifi, N.; Eisazadeh, A. Effect of Non-Traditional Additives on Engineering and Microstructural Characteristics of Laterite Soil. *Arabian J. Sci. Eng.* **2014**, *39*, 6949–6958.
- Yaowarat, T.; Horpibulsuk, S.; Arulrajah, A.; Mirzababaei, M.; Rashid, A. S. A. Compressive and flexural strength of polyvinyl alcohol-modified pavement concrete using recycled concrete aggregates. *J. Mater. Civ. Eng.* **2018**, *30*, No. 04018046.
- Abidin, A. Z.; Nuriman, R. B. E. T.; Pradipto, N. A.; Putra, R. P. Emulsion Polymers of Carboxymethyl Cellulose and Methyl Methacrylate with Sodium Dodecyl Sulfate Surfactant as Soil Stabilizer. *Indones. J. Chem. Res.* **2022**, *9*, 163–170.



- (27) Mamedov, A. I.; Wagner, L. E.; Huang, C.; Norton, L. D.; Levy, G. J. Polyacrylamide effects on aggregate and structure stability of soils with different clay mineralogy. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1720–1732.
- (28) Rezaeimalek, S.; Nasouri, A.; Huang, J.; Bin-Shafique, S.; Gilazghi, S. T. Comparison of short-term and long-term performances for polymer-stabilized sand and clay. *J. Traffic Transp. Eng.* **2017**, *4*, 145–155.
- (29) Zandieh, A. R.; Yasrobi, S. S. Study of factors affecting the compressive strength of sandy soil stabilized with polymer. *Geotech. Eng. J.* **2010**, *28*, 139–145.
- (30) Mascia, L.; Xanthos, M. An overview of additives and modifiers for polymer blends: Facts, deductions, and uncertainties. *Adv. Polym. Technol.* **1992**, *11*, 237–248.
- (31) Grossman, R. F.; Lutz, J. T. *Polymer Modifiers and Additives*, 1st ed.; CRC Press, 2000.
- (32) Kalam, S.; Abu-Khamsin, S. A.; Kamal, M. S.; Patil, S. Surfactant Adsorption Isotherms: A Review. *ACS Omega* **2021**, *6*, 32342–32348.
- (33) Sulfate, S. D.; Sur, C.; Surfactant, N.; Williams, J. J. Anionic Surfactants Learn more about Anionic Surfactants Formulation of Carpet Cleaners Hair Cosmeceuticals ENVIRONMENTAL APPLICATIONS | Pressurized Fluid Extraction 2007.
- (34) Ali, N.; Bilal, M.; Khan, A.; Ali, F.; Iqbal, H. M. N. Effective exploitation of anionic, nonionic, and nanoparticle-stabilized surfactant foams for petroleum hydrocarbon contaminated soil remediation. *Sci. Total Environ.* **2020**, *704*, No. 135391.
- (35) Ghaith, E. I.; Rizvi, S.; Namasivayam, C.; Rahman, P. K. S. M. In *Removal of Cd<sup>++</sup> from Contaminated Water Using Bio-surfactant Modified Ground Grass as a Bio-sorbent*, 2019 Advances in Science and Engineering Technology International Conferences (ASET); IEEE, 2019.
- (36) Harendra, S.; Vipulanandan, C. Sorption and transport studies of cetyl trimethylammonium bromide (CTAB) and Triton X-100 in clayey soil. *J. Environ. Sci.* **2013**, *25*, 576–584.
- (37) Karthick, A.; Roy, B.; Chattopadhyay, P. A review on the application of chemical surfactant and surfactant foam for remediation of petroleum oil contaminated soil. *J. Environ. Manage.* **2019**, *243*, 187–205.
- (38) Lee, G.-W.; Park, M.; Kim, J.; Lee, J. I.; Yoon, H. G. Enhanced thermal conductivity of polymer composites filled with hybrid filler. *Composites, Part A* **2006**, *37*, 727–734.
- (39) Qiu, Y.; Xu, M.; Sun, Z.; Li, H. Remediation of PAH-Contaminated Soil by Combining Surfactant Enhanced Soil Washing and Iron-Activated Persulfate Oxidation Process. *Int. J. Environ. Res. Public Health* **2019**, *16*, 441.
- (40) Pei, M.; Kim, W.; Hyung, W.; Ango, A. J.; Soh, Y. Effects of emulsifiers on properties of poly(styrene-butyl acrylate) latex-modified mortars. *Cem. Concr. Res.* **2002**, *32*, 837–841.
- (41) Chavez, R. A. *Surfactant Impacts on Soil Properties and Feasibility for In-Situ Remediation of Heavy Metals*; Oklahoma State University, 2000.
- (42) Bhavsar, R. A.; Nehete, K. M. Rheological approach to select most suitable associative thickener for water-based polymer dispersions and paints. *J. Coat. Technol. Res.* **2019**, *16*, 1089–1098.
- (43) Lochhead, R. Y.; Davidson, J. A.; Thomas, G. M. *Poly(acrylic acid) Thickeners*; ACS Publications, 1989; pp 113–147.
- (44) Bieleman, J. H. Organic thickeners for water-borne paints. *Chimia* **2002**, *56*, 163–169.
- (45) Dehghan, H.; Tabarsa, A.; Latifi, N.; Bagheri, Y. Use of xanthan and guar gums in soil strengthening. *Clean Technol. Environ. Policy* **2019**, *21*, 155–165.
- (46) Lee, S.; Im, J.; Cho, G. C.; Chang, I. Laboratory triaxial test behavior of xanthan gum biopolymer-treated sands. *Geomech. Geoeng.* **2019**, *17*, 445–452.
- (47) Cabalar, A. F.; Wiszniewski, M.; Skutnik, Z. Effects of Xanthan Gum Biopolymer on the Permeability, Odometer, Unconfined Compressive and Triaxial Shear Behavior of a Sand. *Soil Mech. Found. Eng.* **2017**, *54*, 356–361.
- (48) Yang, Q.; Xiang-jun, P.; Run-qiu, H. Impact of polymer mixtures on the stabilization and erosion control of silty sand slope. *J. Mt. Sci.* **2019**, *16*, 470–485.
- (49) Sujatha, E. R.; Atchaya, S.; Sivasaran, A.; Keerdthe, R. S. Enhancing the geotechnical properties of soil using xanthan gum—an eco-friendly alternative to traditional stabilizers. *Bull. Eng. Geol. Environ.* **2021**, *80*, 1157–1167.
- (50) Adhikari, R.; et al. Effect of viscosity modifiers on soil wicking and physico-mechanical properties of a polyurethane based sprayable biodegradable polymer membrane. *Agric. Water Manage.* **2019**, *222*, 346–353.
- (51) Karakashev, S. I.; Grozdanova, M. V. Foams and antifoams. *Adv. Colloid Interface Sci.* **2012**, *176–177*, 1–17.
- (52) Łażniewska-Piekarczyk, B. Influence of Antifoaming Admixture Type on Several Properties of High-Performance Self-Compacting Concrete. *J. Mater. Civ. Eng.* **2015**, *27*, No. 04014247.
- (53) Bahranifard, Z.; Farshchi, F.; Reza, A. An investigation on the effect of styrene-butyl acrylate copolymer latex to improve the properties of polymer modified concrete. *Constr. Build. Mater.* **2019**, *205*, 175–185.
- (54) Bakhshipour, Z.; Asadi, A.; Huat, B. B. K.; Sridharan, A.; Kawasaki, S. Effect of acid rain on geotechnical properties of residual soils. *Soils Found.* **2016**, *56*, 1008–1020.
- (55) Haling, R. E.; Simpson, R. J.; Culvenor, R. A.; Lambers, H.; Richardson, A. E. Effect of soil acidity, soil strength and macropores on root growth and morphology of perennial grass species differing in acid-soil resistance. *Plant, Cell Environ.* **2011**, *34*, 444–456.
- (56) Tombácz, E.; Dobos, Á.; Szekeres, M.; Narres, H. D.; Klumpp, E.; Dékány, I. Effect of pH and ionic strength on the interaction of humic acid with aluminum oxide. *Colloid Polym. Sci.* **2000**, *278*, 337–345.
- (57) Yang, X. J.; Fan, H. H.; Chen, C.; Yan, Y. J.; Liu, R. M. Effects of the pore water's pH value on the shear strength of the Loess. *Indian J. Geo-Mar. Sci.* **2018**, *47*, 2008–2012.
- (58) Rahman, M.; Nahar, T. T. Effect of pH on Shear Strength Behavior of Granular Soil. *Global J. Res. Eng.* **2015**, *15* (1).
- (59) Hassanlourad, M.; Khatami, M. H.; Ahmadi, M. M. Effects of sulphuric acid pollutant on the shear behavior and strength of sandy soil and sand mixed with bentonite clay. *Int. J. Geotech. Eng.* **2017**, *11*, 114–119.
- (60) ASTM-D6913-17, *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*; ASTM International: West Conshohocken, PA, 2017.
- (61) ASTM-D7928, *Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis*; ASTM International: West Conshohocken, PA, 2017.
- (62) ASTM D854, *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*; ASTM International: West Conshohocken, PA, 2014.
- (63) ASTM D2166, *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*; ASTM International: West Conshohocken, PA, 2016.
- (64) ASTM D4318, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*; ASTM International: West Conshohocken, PA, 2017.
- (65) Ghasemzadeh, H.; Mehrpajouh, A.; Pishvaei, M. Laboratory analyses of Kaolinite stabilized by vinyl polymers with different monomer types. *Eng. Geol.* **2021**, *280*, No. 105938.
- (66) Theng, B. K. G. Clay-polymer interactions: summary and perspectives. *Clays Clay Miner.* **1982**, *30*, 1–10.
- (67) ASTM D698, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft<sup>3</sup> (600 kN-m/m<sup>3</sup>))*; ASTM International: West Conshohocken, PA, 2012.
- (68) Estabragh, A.; et al. Effect of Resin on the Strength of Soil-Cement Mixture. *J. Mater. Civ. Eng.* **2011**, *23*, 969–976.
- (69) Wheeler; Sivakumar. An elasto plastic critical state framework for unsaturated soil. *Geotechnique* **1995**, *45*, 35–53.
- (70) ASTM-D1331, *Standard Test Methods for Surface and Interfacial Tension of Solutions of Paints, Solvents, Solutions of Surface-Active Agents,*

and Related Materials; ASTM International: West Conshohocken, PA, 2013.

(71) Ma, H.; Ma, Q. Experimental Studies on the Mechanical Properties of Loess Stabilized with Sodium Carboxymethyl Cellulose. *Adv. Mater. Sci. Eng.* **2019**, *2019*, No. 9375685.

(72) Pensini, E.; Yip, C. M.; O'Carroll, D.; Sleep, B. E. Carboxymethyl cellulose binding to mineral substrates: Characterization by atomic force microscopy-based Force spectroscopy and quartz-crystal microbalance with dissipation monitoring. *J. Colloid Interface Sci.* **2013**, *402*, 58–67.

(73) Lu, N.; Kim, T.-H.; Sture, S.; Likos, W. J. Tensile Strength of Unsaturated Sand. *J. Eng. Mech.* **2009**, *135*, 1410–1419.

(74) Mohammadi, R.; Wassink, J.; Amirfazli, A. Effect of surfactants on wetting of super-hydrophobic surfaces. *Langmuir* **2004**, *20*, 9657–9662.

(75) Bera, A.; Ojha, K.; Mandal, A. Synergistic effect of mixed surfactant systems on foam behavior and surface tension. *J. Surfactants Deterg.* **2013**, *16*, 621–630.

(76) Jones, N.; Lourenço, S. D. N.; Paul, A. Testing surfactants as additives for clay improvement: Compaction and suction effects. *E3S Web Conf.* **2016**, *9*, No. 13006.

(77) Sommerfeldt, T. G.; Van Schaik, J. C. Influence of soil pH on surface charge and water transmission. *Can. J. Soil Sci.* **1971**, *51*, 277–282.

(78) Łaźniewska-Piekarczyk, B. Examining the possibility to estimate the influence of admixtures on pore structure of self-compacting concrete using the air void analyzer. *Constr. Build. Mater.* **2013**, *41*, 374–387.

(79) Łaźniewska-Piekarczyk, B. The Interactions Between Anti-Foaming and Superplasticizing Admixtures and Their Consequence for Properties of Self-Compacting Mortar and Concrete. *Archit., Civ. Eng., Environ.* **2019**, *12*, 61–71.

(80) Denkov, N. D.; Marinova, K. G.; Tcholakova, S. S. Mechanistic understanding of the modes of action of foam control agents. *Adv. Colloid Interface Sci.* **2014**, *206*, 57–67.

(81) Lee, Y.; Choi, J.-I.; Kim, H.-K.; Lee, B. Y. Effects of a defoamer on the compressive strength and tensile behavior of alkali-activated slag-based cementless composite reinforced by polyethylene fiber. *Compos. Struct.* **2017**, *172*, 166–172.