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Research Paper

Investigation of the Factors Affecting the Unconfined Compressive Strength (UCS) of the Subgrade Soil Stabilized with Copolymers

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Abstract

Since transportation plays a crucial role in the economic and social development of a country and affects many aspects of life, it is considered as a vital artery there. Stabilizing the subgrade soil of roads improves their physical and mechanical properties and increases resistance to traffic load, moisture, and temperature changes. The goal is to extend the service life of roads, reduce maintenance costs, prevent premature failures, and enhance transportation. Most soils are stabilized with additives like cement, lime, and bitumen to improve their strength and durability, but these traditional stabilizers cause significant environmental pollution. Therefore, using environmentally friendly materials is important. This study examined the unconfined compressive strength (UCS) of the soil stabilized with styrene-acrylate and styrene-butadiene, as two eco-friendly emulsion copolymers, in dry and wet conditions and then in wet-dry and freeze-thaw cycles. The results were analyzed using the SPSS and Design-Expert software programs. It was indicated that increasing a pure polymer initially increases UCS, followed by a decrease. Also, moisture, wet-dry and freeze-thaw cycles reduce UCS. According to the independent t-test results, only the reduction of strength due to moisture was statistically significant. Using the equations proposed in this study, it is possible to estimate the UCS of the soil stabilized with the mentioned copolymers under different conditions and determine the optimal type and amount of polymers based on project requirements.

Keywords: Temperature and moisture variation cycles, Road subgrade soil, Sandy soil, Dry unconfined compressive strength, Wet unconfined compressive strength

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1. Introduction

One of the major challenges that engineers often face in the construction of civil infrastructures, such as road construction, is the poor quality of soil (Archibong et al., 2020; Dhakar & Jain, 2020). The first part in the structure of the road is the subgrade soil. Any weakness in its load-bearing capacity can lead to serious problems in the pavement (Buritatum et al., 2021; Lindh & Lemenkova, 2023). Therefore, improving the engineering properties of soil through stabilization is considered essential (Levy, 2023). In road construction, stabilization refers to improving the mechanical properties of the subgrade soil and increasing its strength, which is done to prevent premature failures and extend the service life of the road (Anburuvel, 2024; Kayumov et al., 2021). The unconfined compressive strength (UCS) of soil is a key parameter and the most commonly tested geotechnical feature. A UCS test serves as an important tool for geotechnical engineers and geologists, helping them understand soil behavior under various conditions and properly design their projects (Cao et al., 2018; Kormu et al., 2022). This is while various factors affect the uniaxial strength of stabilized soil. Therefore, the aim of this study is to investigate the factors affecting the uniaxial strength of the soil stabilized with emulsion copolymer, including moisture, polymer type, polymer amount, and temperature changes.

2. Literature Review

As mentioned, soil stabilization is a vital engineering process that significantly increases the strength and stability of the soil by improving its physical and mechanical properties. In the meantime, uniaxial strength serves as a fundamental indicator for measuring the success of this process. This parameter indicates the maximum axial compressive stress that a cylindrical soil sample, without applying any lateral stress, can withstand before failure. A significant increase in this strength after stabilization means the improved bearing capacity of the soil, reduced asymmetric settlements, and increased resistance to erosion. Therefore, measuring uniaxial strength is not only a direct measure for evaluating the effectiveness of stabilization methods but also a guarantee for the safety and durability of construction projects. So far, numerous studies have been conducted on the UCS of soils. For example, Rajabi and Hamrahi (2001) evaluated the UCS of clayey sand soil stabilized with metakaolin. In their study, UCS tests were performed on both unstabilized and stabilized soil samples with 5%, 10%, 15%, 20%, and 25% metakaolin contents cured for 7, 14, and 28 days. The aim was to investigate the effects of the stabilizer content and the curing time on UCS. It was shown that increasing the metakaolin content and curing time would lead to higher UCS values, with the highest strength observed at 25% metakaolin and in 28 days of curing. Additionally, the results indicated that, with an increase in the amount of metakaolin, the failure of the samples occurred more rapidly after they reached their peak strength (Rajabi & Hamrahi, 2019). Furthermore, Samimnia et al. (2020) emphasized that a suitable foundation would enhance the service life of structures. In this regard, they investigated the effects of pore water salinity and sandy soil content on the UCS and elastic modulus of clay soils. They found that increasing the content of sodium chloride reduced the strength properties of the soil, and the addition of sand had no significant effect on this decreasing trend. Kordi and Gohari (2017) also pointed out that the natural soil available in the environment is often not entirely suitable for structural loads in construction activities, and that the addition of stabilizing materials can improve its properties. They studied the UCS of a soil sample stabilized with cement and reinforced with polypropylene fibers. For this purpose, they performed UCS tests on soil samples stabilized with cement and reinforced with fibers at varying percentages, including 0%, 2%, and 4%

cement as well as 0%, 0.5%, and 1% polypropylene fiber, after the curing periods of 7, 14, and 28 days. As they found, the addition of both fibers and cement led to an increase in UCS. Moreover, the use of fibers changed the mode of failure from brittle to more ductile behavior.

As Ghanizadeh et al. (2018) pointed out, although the unconfined compressive strength (UCS) test is commonly used to determine the strength and control the quality of stabilized soils, it can become costly if the number of samples increases. Therefore, they focused on predicting the UCS of clay subgrade soil stabilized with Portland cement and lime using the Group Method of Data Handling (GMDH). In that study, some soil samples were stabilized with different percentages of cement and lime and three different moisture contents for various curing durations. Then, UCS tests were conducted on those samples. Based on the test results and the GMDH method, highly accurate equations were developed to estimate UCS values. Similarly, Yousefi et al. (2022) noted that stabilization with various additives can be a cost-effective method to improve the geotechnical properties of sandy soils. They evaluated the effect of adding zeolite and sawdust on the UCS of cement-stabilized sandy soil. The samples were stabilized with 4% cement by weight, varying amounts of sawdust powder and fibers (0%, 1%, 3%, and 5%), and different contents of zeolite (0%, 10%, 30%, and 50%). They were then cured for 7, 14, and 28 days. As the results indicated, the optimal level of zeolite replacement in sandy soil was 30%, and increasing the amounts of zeolite and sawdust led to higher strain at failure. Moreover, the UCS reached its maximum with the addition of 3% sawdust powder and 1% sawdust fiber. In another study, Masihpour et al. (2024) investigated the effect of adding nano-silica and cement on the UCS of soft clay. They evaluated the changes at three cement content levels (8%, 10%, and 12% by dry soil weight), nano-silica content (at eight levels ranging from 0 to 1.4% of dry soil weight), and in curing periods (7, 14, and 28 days) as the factors influencing UCS. The results showed that up to 1.2% nano-silica in combination with cement could improve the UCS compared to cement alone. Moreover, Kazemi and Davoodi (2015) conducted a study to examine the effect of calcium ions on the UCS of clay soil samples stabilized with a saturated lime solution. For this purpose, the soil samples were stabilized under identical conditions but in different curing durations. The calcium ion content was measured before and after stabilization to calculate the total calcium uptake. The results showed that the samples with longer curing times and higher calcium contents exhibited greater UCS and behaved similarly to rock.

In addition, the effect of polypropylene fibers and nano-silica colloid on soft stabilized soil under freeze-thaw cycles was investigated by Ardani and Sharafi (2023). In their research, a lime-based geopolymer and nanomaterials including nano-silica colloid and fibers were used to stabilize kaolinite soil. A key test to assess the impact of the geopolymer and nanomaterials on the mechanical behavior of the samples was the UCS test. The fiber- and nanomaterial-based geopolymer was indicated to be a suitable alternative to cement-based materials for soil stabilization, as the addition of fibers and nanomaterials led to an increase in the mechanical strength of the samples. Zandieh and Yasrebi (2010) also emphasized the widespread application of polymers in soil stabilization in geotechnical engineering. They studied the UCS of a soil sample stabilized with various polymer contents, considering different curing durations. They found that the polymers increased the compressive strength significantly. For instance, in a specific case, the use of polymers increased the UCS from 0.03 MPa to 5.2 MPa. Pham et al. (2022) noted that determining the UCS of stabilized soil is a key point in ground improvement. They conducted a study to develop a reliable predictive model for the UCS of clay soil stabilized with common cementitious additives. The Gene Expression Programming (GEP) technique was used for this purpose. Also, eleven parameters such as soil properties, types and contents of binders, mixing methods, and curing periods were taken into account as the independent variables in the model. The results showed that the selected GEP-based optimal model had acceptable correlation coefficients and low error rates, suggesting its good performance. Additionally, parametric analyses revealed that plasticity index**,** clay content, and moisture content had negative effects on the UCS of stabilized soil, while silt and sand contents, type and amount of the stabilizing material, and curing time had positive effects on the strength (Pham et al., 2022). Still in another study, Shahiri and Ghasemi (2017) evaluated UCS in order to examine the effect of copper slag on the mechanical properties of both cement-stabilized and unstabilized soils. To this end, dozens of samples were prepared using four different cement contents (i.e., 0%, 2%, 4%, and 6%) and five different copper slag contents (i.e., 0%, 5%, 10%, 15%, and 20%). The samples were then subjected to UCS testing. The results showed that, in the cement-stabilized samples, the improvement effects of copper slag on UCS were more noticeable than in the unstabilized samples.

As further research in the field, Umar and Lin (2024) investigated soil stabilization using waste marble powder. They focused on the effects of various factors such as curing time, moisture content, and amount of the stabilizing material on the UCS of soil. The UCS of the stabilized soil was found to increase from 170 kN/m^2 to 661 kN/m^2 after 28 days of curing with an optimal moisture content of 22.5% and 60% marble powder. In a similar context, Tabarsa et al. (2021) predicted the UCS of stabilized soils using artificial neural networks (ANNs). In this research, the soils were stabilized with various combinations of cement, lime, and rice husk ash. The results of the UCS tests conducted on these soils were predicted with a comprehensive laboratory dataset comprising 137 soil samples treated with different combinations of stabilizers. The proposed ANN models accurately predicted the UCS values, hence introduced as reliable predictive tools in geotechnical engineering.

Nowadays, with technological advancements, polymers have gained a prominent place in various aspects of human life, and the construction industry is no exception (Debbarma et al., 2023). One of the applications of different types of polymers, including geopolymers, biopolymers, and synthetic organic polymers, in civil engineering is soil improvement and stabilization. This is because polymers form polymeric bonds that connect adjacent, non-contacting particles, creating adhesion between them. As a result, surrounding soil particles are bound together to form a dense and strong matrix. In this regard, polymer-stabilized soils exhibit favorable engineering properties such as high strength, low permeability, minimal swelling and shrinkage, and good durability (Hasan et al., 2020; Huang et al., 2021). Numerous studies have, thus, been conducted on soil stabilization using polymers. For example, Bai et al. (2021) investigated the mechanical behavior of polyurethane-stabilized soil by conducting a series of unconfined compression and direct tension tests. They found that the addition of polyurethane binds adjacent soil particles together and improves the mechanical properties of the mixture. Similarly, Kumar et al. (2022) evaluated the effect of polymer emulsion on the properties of sandy soil used as a subgrade for highways and airport pavements. In that study, sand was stabilized with various amounts of polymer emulsion and cured for different durations. The results showed that stabilization with this polymer improves the compressive strength and elastic modulus of sandy soil. In addition, Bai et al. (2023) examined the stabilization of silty sand using synthetic polyurethane polymer. They found that adding polyurethane can significantly increase the compressive strength of that type of sand as well as its tensile and shear strength, particularly the first two, which increased from nearly zero to 952.61 and 211.47 kilopascals, respectively. In another study, Bozyigit et al. (2023) examined xanthan gum, guar gum, and anionic polyacrylamide, as three types of polymers, to improve the strength properties of kaolin clay. In their research, the samples were divided into two groups. The first group was subjected to unconfined compression testing after a specific curing period, and the second group was tested after undergoing freeze-thaw cycles. The results showed that using synthetic and biological polymers can lead to an increase in strength. Additionally, the findings indicated that curing time does not have a significant effect on strength improvement in samples containing anionic polyacrylamide. The study also revealed that freeze-thaw cycles drastically reduce strength by approximately 5% to 60%. Despite the reduction in strength, the anionic polymer was the most resistant to freeze-thaw conditions. In another study, Jianxin et al. (2025) investigated the stabilization of sandy soil using synthetic polymers. In that study, two polymers, polystyrene sulfonate (PSS) and (PDADMAC), were used at various concentrations ranging from 10% to 40%, and in different amounts of 2%, 4%, and 6% by dry soil weight. The strength of sandy soil was found improved after stabilization with PSS and PDADMAC, as the polymer solution concentration and the applied dosages increased.

As mentioned earlier, due to the particular importance of the unconfined compressive strength (UCS) parameter of soils, numerous studies have been conducted in this area. At the same time, owing to their unique properties, polymers are now widely used in soil stabilization. Therefore, the present research investigates the various factors affecting the UCS of the soil stabilized with a copolymer, including the amount and type of polymer, moisture content, freeze-thaw cycles, and wet-dry cycles. This is because the UCS of soil, especially for roads exposed to fluctuations in moisture and environmental conditions, reflects its durability, which is crucial for designing roads that are subjected to these changes over extended periods.

3. Materials and Methods

3.1. Materials

The soil used in this study was aeolian sand collected from a depth of half a meter in the deserts of Birjand, a city in South Khorasan Province, Iran. Its properties are presented in Table 1, and its grain size distribution curve is shown in Figure 1. To stabilize the soil, two types of copolymers were used, styrene-acrylate copolymer and styrene-butadiene copolymer. The specifications of these copolymers are provided in Table 2. This research investigates styrene-butyl acrylate terpolymers as a base for the polymers used in the construction industry. Since the performance and lifespan of materials depend on environmental conditions, the vital parameters of these terpolymers were introduced and evaluated in the present article. The molecular structure is designed to ensure long-term stability.

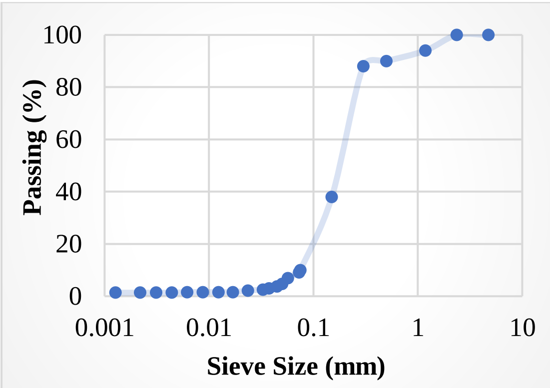


Figure 1. Grain size distribution of the soil used

3.2. Sample Preparation

As mentioned, the aim of this study is to investigate various environmental factors on the uniaxial strength of the soil stabilized with an environmentally friendly emulsion dicopolymer. It should be noted that the uniaxial strength test was used in this study due to being a simple, cheap and fast test serving as a direct indicator for measuring the success of soil stabilization. So, a significant increase in uniaxial strength directly indicates a successful reaction between the soil and the stabilizing materials. Also, since it is practically impossible to conduct a triaxial test in situ, uniaxial strength is used as a practical and applicable criterion for quickly assessing the quality of the stabilized soil in the project. Most technical specifications of civil engineering projects specify minimum values for uniaxial strength as a criterion for accepting the work. This has made uniaxial strength a standard contractual indicator. In the present study, to achieve the maximum dry density of windblown sand soil, the required amount of the emulsion copolymer at various concentrations (10%, 30%, and 50%) was first determined with a compaction test. According to the test results, the amounts of styrene acrylate copolymer at the concentrations of 10%, 30%, and 50% were 15%, 20.1%, and 24.11% (as percentages of dry soil weight), respectively. For the styrene-butadiene copolymer, the values were 12.6%, 13.1%, and 13.6%, respectively. Subsequently, to prepare unconfined compression test specimens, the copolymers were mixed with the soil and compacted in three layers into a mold with an internal diameter of 4.5 cm and a height of 9 cm (Table 3). It is to be noted that, with the addition of 15% of an emulsion polymer at a 10% concentration to the soil, the actual amount of the pure polymer was 1.5%. This is because an emulsion polymer at a 10% concentration contains 10 parts polymer and 90 parts water.

3.3. Research Methodology

This study was conducted with the aim of investigating the effects of various factors and conditions on the uniaxial compressive strength of some soil samples stabilized with copolymers. The evaluated factors included the amount and type of the polymer used, moisture, and freeze-thaw and wet-dry cycles. To this end, the sand soil samples were stabilized with two acrylate copolymers at different polymer doses. The stabilized samples for each polymer were divided into four groups. The first group was tested for uniaxial compressive strength after drying. The second group was fully dried, cured, and then submerged in water for 24 hours before undergoing uniaxial compressive strength testing. The third and fourth groups, after drying, were subjected to freeze-thaw cycles (ASTM D560) and wet-dry cycles (ASTM D559), respectively, and then tested for uniaxial compressive strength (Figure 2).

Furthermore, in order to evaluate the statistical significance of the uniaxial compressive strength under different conditions, statistical analyses were conducted using the SPSS software. The response surface methodology (RSM) and the Design-Expert software were also employed to estimate and predict the relationships between the uniaxial compressive strength test results under various conditions and the amount of the polymer used for stabilization.

Table 1. Properties of the soil used

Property	Standard	Value
Color	—	Light brown
Optimum moisture content (%)	ASTM D 2216	12
Maximum dry density (g/cm³)	ASTM D 698	1.73
Passing sieve No. 200 (%)	ASTM D 4318	10
Plasticity index	ASTM D 4318	0
Soil classification (USCS)	—	SP (Poorly graded sand)
Cohesion (kPa)	ASTM D 3080	5.19
Internal friction angle (°)	ASTM D 3080	37.9
Sand equivalent value	ASTM D 2419	4
Specific gravity	ASTM D 854	2.67

Table 2. Specifications of the copolymers used

Property	Type of copolymer	Value
Glass transition temperature (°C)	Styrene acrylate	20 to 40
	Styrene-butadiene	–50 to 20
Molecular weight (g/mol)	Styrene acrylate	100,000 to 300,000
	Styrene-butadiene	50,000 to 300,000
Solubility	Styrene acrylate	In water or organic solvents
	Styrene-butadiene	In water or organic solvents
pH	Styrene acrylate	6-7
	Styrene-butadiene	6-7

Table 3. Sample naming convention

Polymer type	Optimal emulsion dosage (%)	Pure polymer content (%)	Sample code
Styrene acrylate copolymer	15	1.5	A1
	20.1	6.03	A2
	24.11	12.055	A3
Styrene-butadiene copolymer	12.6	1.26	B1
	13.1	4.02	B2
	13.6	6.8	B3

4. Results

The results of the uniaxial compressive strength tests in dry and wet, after wet-dry cycles, and in a freeze-thaw cycle are presented in Table 4. In this study, three main aspects were examined, including the effects of the amount and type of polymers on uniaxial compressive strength, the effect of moisture on uniaxial strength, and the impact of wet-dry and freeze-thaw cycles on uniaxial strength. Also, the Kolmogorov-Smirnov test was performed to assess the normal distribution of the data and, thereby, select an appropriate statistical test for determining whether the differences in uniaxial compressive strength under various conditions, compared to a dry state, were significant. The significance value of 0.2 in this test, which is greater than 0.05, indicates that the data had a normal distribution. Therefore, independent t-tests were subsequently used for statistical analysis.

Table 4. UCS results under different conditions (kPa)

Sample	Dry	Wet	After a wet-dry cycle	After a freeze-thaw cycle
A1	1650.3	475.1	1097.5	767.4
A2	2824.6	1344.5	2443.3	1878.4
A3	1959.8	1648.4	1889.2	1752.0
B1	3048.5	376.19	1649.2	612.76
B2	4714.4	1668.9	3304.8	2201.6
B3	4059.4	2719.8	3675.4	3060.8

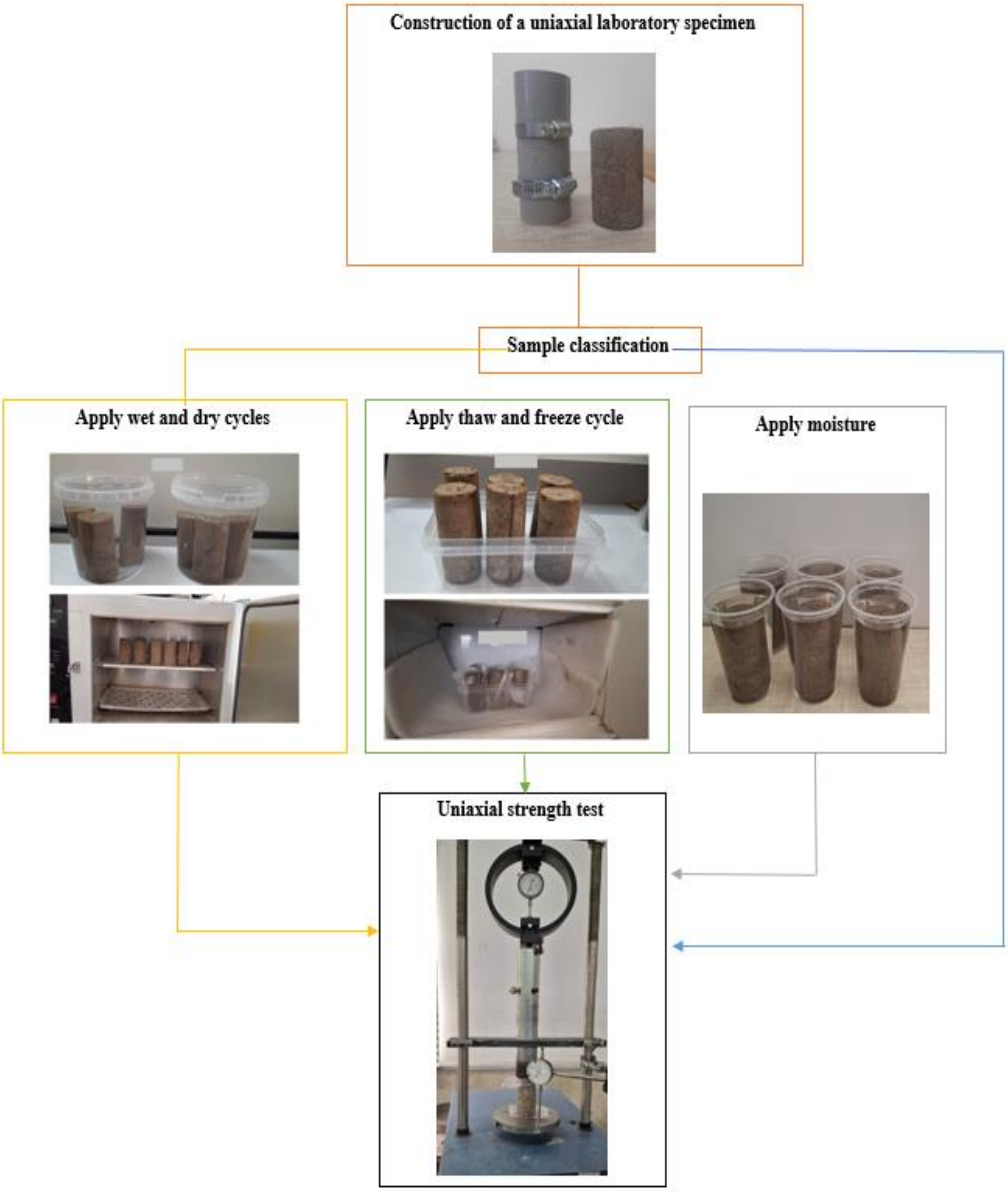


Figure 2. The research flowchart

4.1. Effect of the Polymer Content and Type

The According to Figure 3, as the concentration of the polymer and, consequently, the amount of the pure polymer were increased in the polymer emulsion used for soil stabilization, the unconfined compressive strength (UCS) of the soil initially rose and then decreased. Specifically, for the soil stabilized with the styrene-acrylate copolymer, a fourfold increase in the pure polymer content resulted in a 1.7-fold increase in the UCS, but further increase in the pure polymer content from 6.03% to 12.55% caused a 30% reduction in the UCS. Similarly, for the soil stabilized with the styrene-butadiene copolymer, a threefold increase in the pure polymer content initially led to a 1.5-fold increase in the UCS. However, as the pure polymer content rose from 4.02% to 8.6%, the UCS decreased by approximately 14%. As an explanation for what occurred in this process, the initial increase in the polymer content provided better lubrication, leading to better cohesion and adhesion as well as effective interaction of the soil particles. Beyond a certain concentration, however, excessive polymer particles were irregularly dispersed among the soil particles, disrupting the effective contact and interaction among the soil grains. Therefore, besides determining the optimum polymer amount at a specific concentration through compaction tests, it is essential to identify the optimum polymer concentration and the pure polymer percentage for soil stabilization to achieve maximum compressive strength through unconfined compressive strength testing. Furthermore, comparing the UCS values of the stabilized soils showed that samples A2 and B2 had the highest strength. From the perspective of maximum UCS, the optimum pure polymer percentages for the styrene-acrylate and styrene-butadiene copolymers were approximately 6.03% and 4.02%, respectively. The results of this study align with those of previous research. For example, Rajabi and Ghasemi (2025) investigated the soil stabilized with a polyester emulsion polymer and reported that the polymer improved the mechanical properties of the soil, including unconfined compressive strength. They emphasized that determining the optimum polymer quantity is necessary to achieve maximum strength. Similarly, Heravi and Cheshmi (2023) found that emulsion polymers such as vinyl acrylic create bonds between soil particles and thus significantly enhance the unconfined compressive strength of the soil after drying.

Furthermore, regarding the type of the stabilizing materials, the soil stabilized with the styrene-butadiene copolymer exhibited higher unconfined compressive strength. Specifically, the UCS of the optimal sample B2 was 1.7 times that of sample A2. Considering the amount of the pure polymer and the UCS values, it can be concluded that using a styrene-butadiene copolymer allows achieving higher compressive strength with a lower pure polymer percentage than a styrene-acrylate copolymer, which may also be more economical. To further examine the effect of the copolymer type on the UCS of the stabilized soil, an independent t-test was performed using the SPSS software. As shown in Table 5, the Sig. (2-tailed) value was less than 0.05; therefore, there was a statistically significant difference between the UCS of the soil stabilized with the styrene-acrylate copolymer and that stabilized with the styrene-butadiene copolymer.

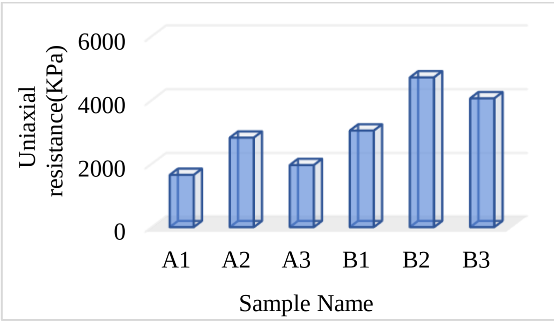


Figure 3. UCS results in dry conditions

Table 5. Independent t-test results for the polymer type

Test	t	df	Sig. (2-tailed)	Mean difference	Standard error
Equal variances assumed	2.7	10	0.019	1670.7	599.0
Equal variances not assumed	2.7	9.1	0.021	1670.7	599.0

4.2. Effect of Moisture on Unconfined Compressive Strength

Moisture is one of the key factors influencing soil strength; an increase in the moisture content can have a direct impact on the compressive strength of soil [18]. Therefore, to evaluate the unconfined compressive strength (UCS) of the copolymer-stabilized soil under wet conditions, the stabilized samples were submerged in water for 24 hours before undergoing UCS testing. According to the results presented in Table 4, the UCS in the wet state showed a significant decrease compared to that in the dry conditions. Specifically, the UCS of the optimal samples A2 and B2 dropped to half and one-third of their dry strength values, respectively, after wetting. Figure 4 illustrates the changes in the percentage of the UCS of the samples after wetting compared to the dry conditions. The negative percentage changes indicate a reduction of strength due to moisture, which decreased as the polymer content increased. Furthermore, according to Figure 4, increasing the polymer content reduced the uniaxial compressive strength loss due to a decrease in the porosity of the sample. Previous studies have also shown that an increase in stabilizing materials significantly reduces soil porosity and permeability, thereby enhancing resistance to moisture (Wang et al., 2024). The results of the present study also indicated that the wet strength of the soil stabilized with the styrene-acrylate copolymer was higher than that of the soil stabilized with the styrene-butadiene copolymer. This is because one of the properties of the styrene-acrylate copolymer is its high resistance to water and moisture. Therefore, for projects where the subgrade soil is frequently exposed to water and moisture is highly probable almost throughout the year, using the styrene-acrylate copolymer is preferable.

Table 6 presents the independent t-test results examining the significance of the difference in uniaxial compressive strength between the dry and wet states of the stabilized soil. The Sig. (2-tailed) value is less than 0.05, indicating a statistically significant difference between the UCS values of the copolymer-stabilized soil in dry and wet conditions.

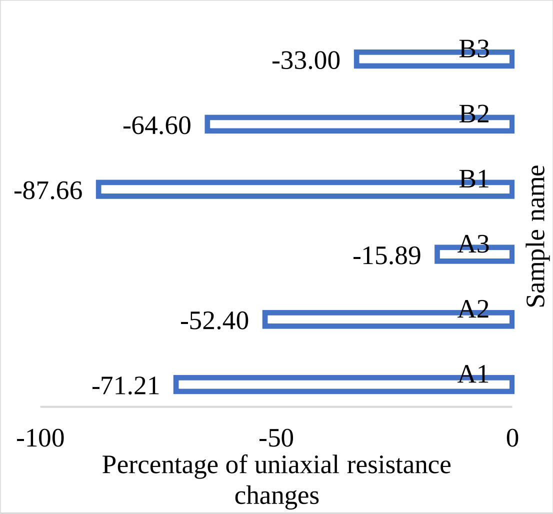


Figure 4. Change of the UCS percentage after soaking (wet vs. dry)

4.3. Effect of Wet-Dry and Freeze-Thaw Cycles

Climatic changes, such as wet-dry and freeze-thaw cycles, have significant impacts on the mechanical properties of stabilized soil (Li et al., 2018). In this study, to investigate the effect of wet-dry cycles on unconfined compressive strength (UCS), the samples were subjected to 12 wet-dry cycles, each consisting of 5-hour submersion in water (wet cycle) followed by 42 hours at 71°C (dry cycle), before undergoing UCS testing. Similarly, to evaluate the strength of the samples after freeze-thaw cycles, they underwent 12 cycles of freezing (5 hours at -23°C) and thawing (23 hours at 21°C) before UCS testing was performed. To provide a view of the changes in the UCS due to wet-dry and freeze-thaw cycles, the ratio of the UCS after these cycles to the initial dry UCS is presented in Figure 5.

According to Figure 5, as the amount of the pure polymer increased, the strength loss decreased. In other words, the ratio of the UCS after the wet-dry and freeze-thaw cycles to the initial dry UCS increased. This is because both styrene-acrylate and styrene-butadiene copolymers exhibit high resistance to temperature and moisture variations. Considering the two polymers comparatively, since one of the advantages of styrene-acrylate copolymer is its excellent performance against moisture and freezing, the UCS ratio of the soil stabilized with this polymer was higher than that of the soil stabilized with the styrene-butadiene copolymer. It can be concluded that, for soil stabilization in regions with severe climatic variations such as drastic temperature and moisture changes, the use of styrene-acrylate copolymer is preferable. It is noteworthy that the results of this study are consistent with the findings of previous research, which shows that soil stabilization improves soil durability against wet-dry and freeze-thaw cycles, and that the extent of this improvement depends on the type and amount of the stabilizing agent used (Pranshoo & Musharraf, 2014; Xia et al., 2023).

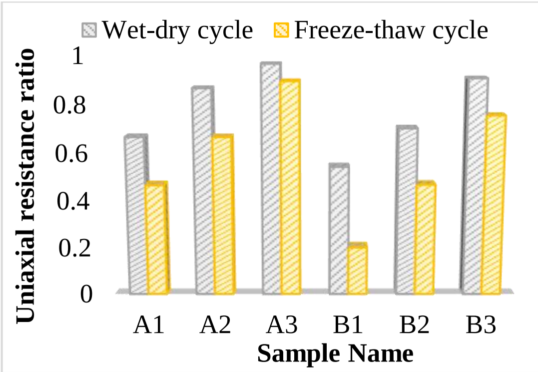


Figure 5. Ratio of the unconfined compressive strength (UCS) after wet-dry and freeze-thaw cycles to the initial dry UCS

Table 7 presents the results of the independent t-test, indicating that the UCS after the wet-dry and freeze-thaw cycles was not significantly different from the UCS in the dry conditions. This suggests the high resistance of the used copolymers to changes in moisture and temperature.

Table 6. Independent t-test results for dry vs. wet conditions

		t-test for equality of means				
		t	**df**	**Sig. (2-tailed)**	**Mean difference**	**Std. error difference**
UCS	Equal variances assumed	2.789	10	.019	1670.69882	599.02832
UCS	Equal variances not assumed	2.789	9.184	.021	1670.69882	599.02832

Table 7. Results of the independent t-test for evaluating the effect of wet-dry and freeze-thaw cycles

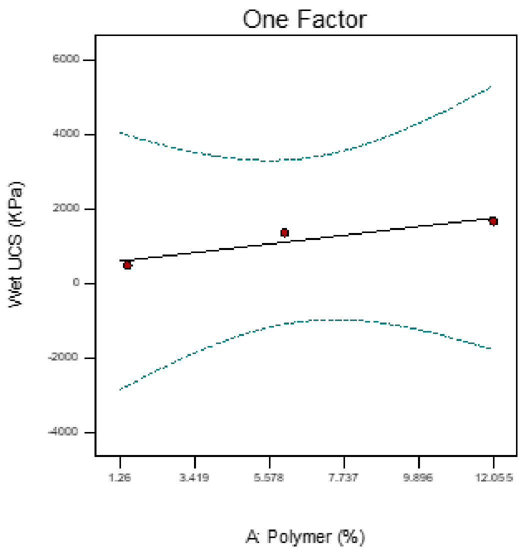
		t-test for equality of means				
		t	**df**	**Sig. (2-tailed)**	**Mean difference**	**Std. error difference**
Wet-dry cycle						
UCS	Equal variances assumed	1.109	10	0.293	699.61487	630.76716
UCS	Equal variances not assumed	1.109	9.717	0.294	699.61487	630.76716
Freeze-thaw cycle						
UCS	Equal variances assumed	2.180	10	0.054	1330.69643	610.35672
UCS	Equal variances not assumed	2.180	9.410	0.056	1330.69643	610.35672

4.4. Prediction of the Unconfined Compressive Strength of Soil under Various Conditions

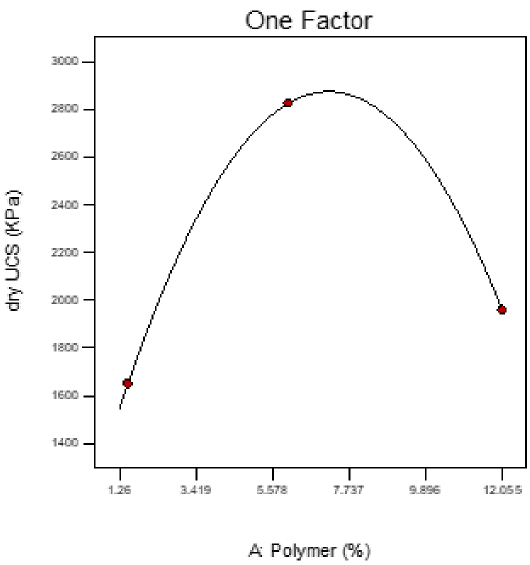
The Design-Expert software was used to estimate the unconfined compressive strength (UCS) of the soil stabilized with two copolymers, namely styrene-acrylate and styrene-butadiene. In this study, the amount of the pure polymer in the samples was considered as the independent variable, and the results of UCS tests under different conditions were the dependent variables. The statistical analysis results and the proposed equations are presented in Table 8. In this table, the "Polymer" parameter refers to the percentage of the pure polymer used. Also, since the R^2 values of the proposed equations were close to one, they provided accurate and reliable estimates of the UCS of the soil stabilized with the two examined copolymers under various conditions. An advantage of these models is that they allow for the estimation of dry, wet, and post-durability test UCS values without conducting experiments. In addition, they allow to determine the optimal type and amount of the polymer based on project requirements. The graphs of the equations presented in Table 8 are shown in Figures 6 and 7. As illustrated in Figures 6a and 7a and as previously mentioned, with an increase in the polymer content, the UCS initially increased and then decreased. Moreover, according to Figures 6b and 7b, the wet UCS increased with an increase in the polymer content, which is because the voids in the samples decreased as the polymer content increased. Finally, Figures 6c, 6d, 7c, and 7d indicate an increase in the resistance of the stabilized soil against wet-dry and freeze-thaw cycles as the polymer content increased.

Table 8. Relationships between the independent and dependent parameters

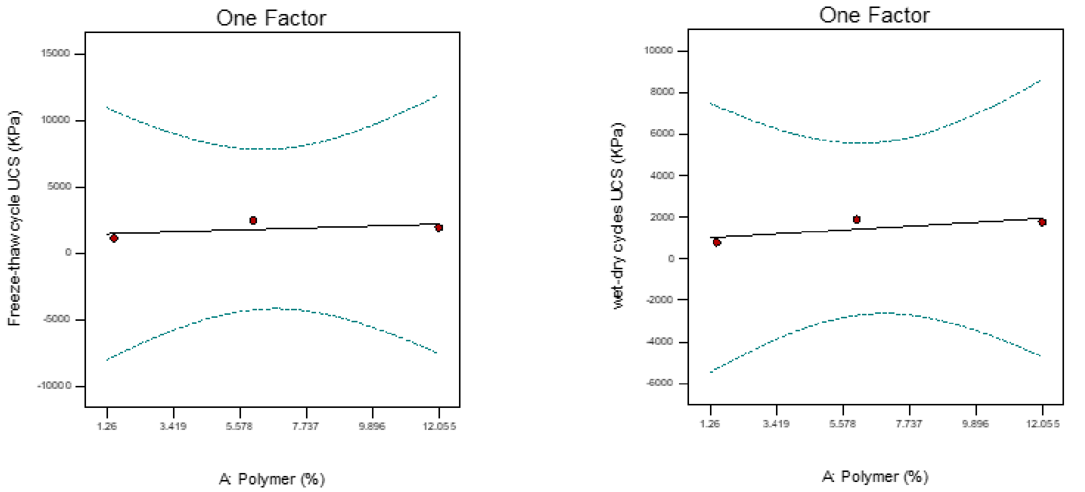
Relationships	R^2
Styrene acrylate copolymer	
Dry UCS = +916.39464++546.56828* Polymer-38.15940* Polymer2	0.999
Wet UCS = -+451.60725+107.90909* Polymer	0.880
Freeze-thaw cycle UCS +1378.69772+66.07380* Polymer	0.2675
wet-dry cycles UCS = -+896.89821+87.17127* Polymer	0.576
Styrene butadiene copolymer	
Dry UCS = +1520.83170+1403.33678* Polymer-151.47164* Polymer2	0.999
Wet UCS = -114.91912+422.98803* Polymer	0.996
Freeze-thaw cycle UCS = +1404.93894+365.45511* Polymer	0.880
wet-dry cycles UCS = +179.70354+441.73171* Polymer	0.970



(A)

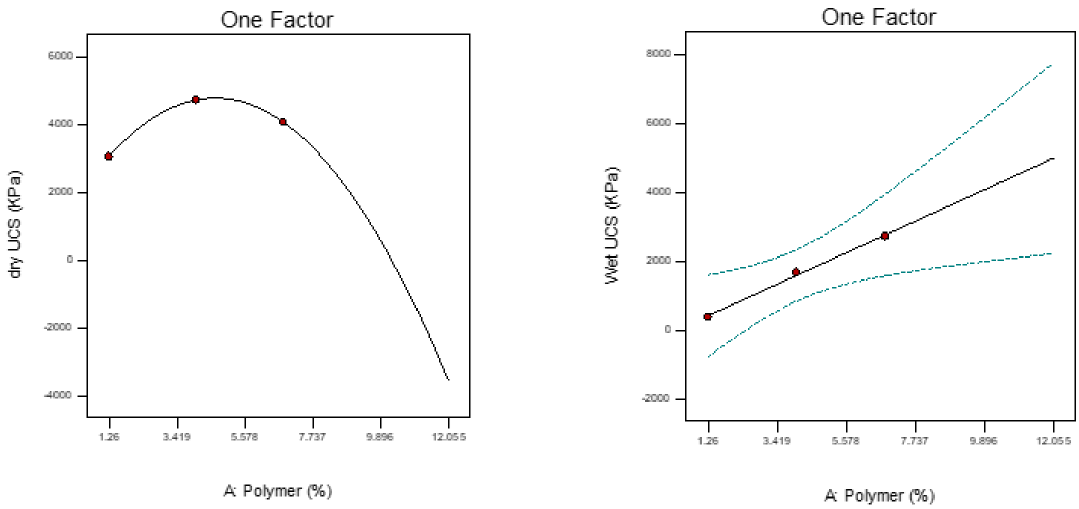


(B)

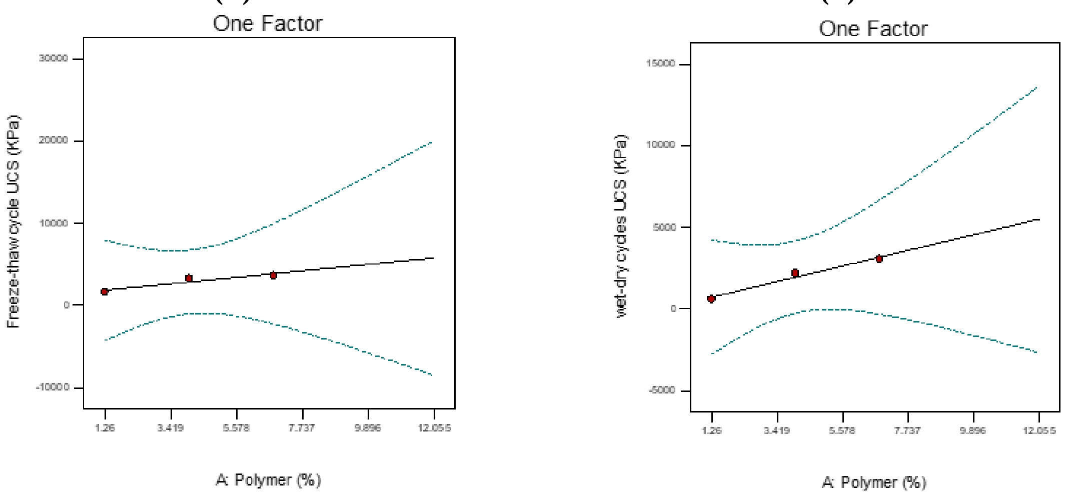


(C) **(D)**

Figure 6. Graphs of the relationships between the independent and dependent parameters for the styrene acrylate copolymer



(A) **(B)**



(C) **(D)**

Figure 7. Graphs of the relationships between the independent and dependent parameters for the styrene-butadiene copolymer

4.5. Comparison of Cement and Copolymer Stabilizers

As one of the most widely used and oldest materials in the geotechnical industry, cement plays an irreplaceable role in stabilizing and improving loose and problematic soils. The main purpose of stabilizing soil with cement is to improve the mechanical and physical properties of the soil, including increasing compressive and shear strength, reducing permeability, reducing shrinkage and expansion (in clay soils), and ultimately creating a stable base for construction projects such as road construction, foundation construction, and slopes. However, despite the numerous technical advantages of cement, its widespread use as a stabilizer has serious critics in the field of environment. Its disadvantages have led to a shift in attention to more sustainable alternatives. Hence, the use of stabilizing materials such as environmentally friendly polymers seems essential, which was addressed in this study. Figure 8 compares the soil samples stabilized with cement and emulsion copolymer. The two samples A2 and B2, as optimal samples with the highest uniaxial strength, contain 6% and 4% polymer, respectively. The wind-sand soil samples in the figure are stabilized with 4% and 6% cement. These data were extracted from the research by Mohammadzadeh Behrouz (2014). According to Figure 8, the uniaxial strength of sample A2 is about 1.5 times that of the soil stabilized with 6% cement, and the uniaxial strength of sample B2 is three times that of the soil stabilized with 4% cement. Generally, the test results indicate that the significant increase in uniaxial compressive strength, along with greater environmental compatibility, is a key advantage of polymer-stabilized soil compared to the traditional method of soil stabilization with cement. It should be noted that the uniaxial strength presented in the figure was achieved after 28 days of curing, while the one in the present study was acquired 14 days after the preparation of the sample. Both of the mentioned time periods are the final periods for the setting of samples and acquiring their strength.

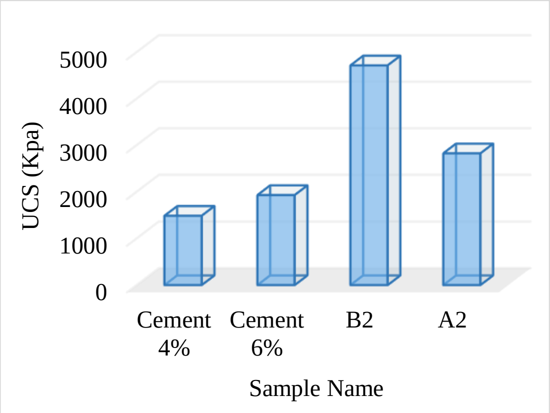


Figure 8. Comparison of wind-blown sand samples stabilized with cement and copolymer

5. Conclusion

This study was done to improve the physical and mechanical properties of soil, thereby creating a more stable and durable foundation. The process implemented in the present research can enhance pavement longevity, reduce maintenance costs, and prevent premature failures. Moreover, due to the environmental pollution caused by construction projects, soil stabilization with eco-friendly materials has become increasingly important. It is, thus, essential to evaluate the performance of stabilized soil under different climatic conditions, as in moisture exposure as well as wet-dry and freeze-thaw cycles. In this study, the unconfined compressive strength (UCS) of the soil samples stabilized with two environmentally friendly copolymers was investigated under various conditions, including dry and wet states as well as wet-dry and freeze-thaw cycles. The investigation yielded the following results:

- With an increase in the amount of the pure polymer, the uniaxial compressive strength of the stabilized soil initially increased and then decreased. Thus, the optimum percentage of the pure polymer for the styrene-acrylate copolymer and the styrene-butadiene copolymer was 6.03% and 4.02%, respectively.

- The soil stabilized with the styrene-butadiene copolymer exhibited higher uniaxial compressive strength. Specifically, the uniaxial strength of the optimal B2 sample was 1.7 times greater than that of the A2 sample.
- The uniaxial compressive strength in the wet state showed a significant drop compared to the dry state; however, with an increase in the polymer content, the reduction in the uniaxial strength decreased.
- The wet strength of the soil stabilized with the styrene-acrylate copolymer was greater than that of the soil stabilized with the styrene-butadiene copolymer.
- As the pure polymer content was increased, the strength loss reduced; in other words, the ratio of the uniaxial strength after wet-dry and freeze-thaw cycles to the initial dry strength increased.
- According to the results of the independent t-test, there was a significant difference between the uniaxial compressive strength values of the soil stabilized with the styrene-acrylate copolymer and that stabilized with the styrene-butadiene copolymer.
- The statistical test results also showed a significant difference between the dry and wet uniaxial compressive strengths of the polymer-stabilized soil. However, there was no significant difference between the uniaxial compressive strength after wet-dry and freeze-thaw cycles and the dry strength.
- Using the equations presented in Table 8, it was possible to estimate the uniaxial compressive strength of the soil stabilized with the two studied copolymers under different conditions and determine the optimal type and amount of the polymer according to the project requirements.

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