

EFFECT OF PARTICLE SHAPE ON THE BEHAVIOR OF POLYMER-IMPROVED SANDY SOIL USED IN PAVEMENTS DUE TO FREEZE-THAW CYCLES

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Abstract. Freeze-thaw cycles have a significant negative effect on the engineering behaviour of soil in cold regions. In this study, the compressive strength of stabilized, poorly graded sandy soil used in road pavement that was subjected to different freeze-thaw cycles was studied. Samples with three different particle shapes were stabilized with a binder developed by mixing polyvinyl acetate (PVAc) and ethylene glycol monobutyl ether (EGBE). The PVAc/EGBE weight ratio was 2:1, and PVAc was added at 1%, 2%, and 3% of the dry weight of the soil, with the effect of up to ten freeze-thaw cycles evaluated. Results showed that the addition of binder decreased optimum moisture content and increased compressive strength. An increase in particle roundness results in a decrease in the magnitude of compressive strength but increases the soil composite ductility. Changing particle shape from angular to rounded resulted in a more significant decrease in compressive strength than changing from rounded to well-rounded. The decrease in compressive strength is most significant between the first and fourth freezing-thawing cycles and marginal between the fourth and tenth. The negative effect of increasing the roundness of particles is compensated by increasing binder percentages.

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Keywords: ethylene glycol monobutyl ether, freezing thawing, particle shape, polyvinyl acetate, sandy soil, soil stabilization.

Introduction

In wet and cold climates, soils and aggregates are exposed to freeze-thaw cycles. During the freezing period, the volume of water and the void ratio of soil increase, and during the thawing period, the void ratio also fluctuates and often negatively impacts the soil mechanical properties such as ultimate compressive strength, shear strength, compressibility, and permeability (Graham & Au, 1985). During freezing the ice induces particle segregation and changes in soil properties in both micro and macro scales. Different civil engineering infrastructures, such as roads, rail roads, and pipelines, as well as different building foundations, can be affected by freezing and thawing. Freezing and thawing can affect the behaviour of both sandy and clayey soils. Both laboratory and large-scale field studies have been documented (Hohmann-Porebska, 2002). De Guzman et al. (2018) investigated the effect of freeze–thaw cycles on the large-scale response of embankments. They conducted large-scale direct shear tests on remolded frozen samples of soil at different transitional, frozen, and freezing-thawing conditions. Results of their study showed that the most critical condition was during the onset of the thawing period, when the volume of ice was bonding in the soil matrix dwindles. Different additives and stabilized materials can provide additional resistance to the disintegrating effect of stress induced by freeze-thaw cycles (Qi et al., 2008). Typically, increasing the durability of soil in frozen areas can have a positive effect (Hohmann-Porebska, 2002). In the study of Lu et al. (2018), they investigated the deformation induced by freezing-thawing cycles on samples of silty clays. The result showed that freezing-thawing cycle-induced deformation was divided into five different stages: cold shrink, fast frost heave, slow frost heave, thermal bulge, and finally thaw settlements.

Uzer (2016) worked on the effects of different freezing-thawing cycles on stabilized soil used as the foundation of buildings and infrastructure. He noted that lignin-based biofuel co-products (BCPs) binders increased soil durability and reduced compressive strength degradation due to freezing-thawing cycles. Others, like Güllü & Fedakar (2017), investigated the unconfined compressive strength (UCS) of marginal sands. Sludge ash and polypropylene fibre (PF) were used as additives for stabilizing sand. 0%, 0.5%, and 1% of polypropylene fibre and 10%, 15%, 20%, and 30% of sludge ash by total dry weight of the sand and sludge ash mixture were used, and the freezing-thawing

resistance of samples was investigated. It was observed that both the UCS and durability were greatly improved by the addition of the binder mix.

In a study reported by Krainiukov et al. (2020), the effect of freezing-thawing on silty sand reinforced by polyvinyl alcohol (PVA) was studied. A series of unconsolidated undrained (UU) triaxial compression tests were conducted on samples to determine their physical properties. Different PVA concentrations of 5%, 7.5%, and 10% of water weight were added to silty sand. Samples were tested after 0, 5, 10, 15, and 20 cycles of freezing and thawing. Results showed that stabilizing soil with PVA had a significant positive effect on the resistance of samples at different freezing-thawing cycles. The study by Fard et al. (2020) showed that using polyvinyl acetate had a positive effect on soil mechanical properties at different freeze-thaw cycles. There are different factors that influence the design of pavement. The factors may be those of the materials used, vehicle speed, loading, environment, etc. In evaluating subgrade materials, the type of material and engineering properties such as shear and compressive strengths should be considered. At the same time, the Poisson ratio and elastic moduli of each component layer must be specified. Resilient modulus is one of important factor in the pavement design. The parameter decreases significantly even with a few freezing-thawing cycles. The decrease is more pronounced in fine-grained aggregates than in coarse-grained soils (Simonsen & Isacson, 2001). Hemmati & Arab (2020) proposed a model of stress-strain behaviour of fly ash concrete at different freezing-thawing cycles. Lai et al. (2017) worked on crystallization deformation in saline soils during freezing-thawing cycles on soil mixed with sewage sludge and fly ash. Adding sewage sludge or fly ash reduced the negative effect of freezing-thawing effect on some properties like bulk density and permeability of wet aggregate. Size and shape of particles can affect the soil behaviour at different conditions. Ghalehjough et al. (2017, 2018) reported that the bearing capacity of granular soil was affected by particle shapes. In their study different samples with different size, particle shapes and relative densities were prepared, tested and bearing capacity and failure mechanism of soil under loading were studied. Zhou et al. (2020) combined statistical methods with mesoscopic and macroscopic methods to quantitatively analyse the damage degree of intact rocks under freezing-thawing cycles and loads.

The current study is focused on the effect of freezing and thawing on the mechanical properties of poorly graded sandy soil stabilized with a polyvinyl acetate (PVAc) and ethylene glycol monobutyl ether (EGBE) mixture. Stabilized samples were prepared in three different particle shapes (angular, rounded, and well-rounded) and subjected to different

cycles of freezing and thawing. The study provided the basis for the evaluation of the effect of particle shapes and additives on the stability of samples at different freezing-thawing cycles.

1. Materials and method

1.1. Soil

The soil that was investigated in the current study was collected in Erzurum Province, Turkey. It was moved to a laboratory, dried, and sieved. The grain size distribution of soil selected due to Turkish Highway Standards has upper and lower limits, so a grain size distribution between these limits reported in the study of Yarbasi et al. (2007) was used for better comparison. The grain size distribution of soil is shown in Figure 1. Due to ASTM D2487-17e1, the specific gravity was calculated 2.85 and classified as poorly graded sandy soil (SP).

Samples were prepared in three different particle shapes. The calculation method and roundness values of the soil particles were explained and classified by the Cox equation and Power chart (Cox, 1927; Powers, 1953). This value was used for the classification of soil into angular, rounded, and well-rounded groups, as shown in Table 1. Based on the roundness values, the collected soil was classified as soil with angular particle shape. Particle shape of angular soil was changed to a rounded and well-rounded shape by the Los Angeles Rattler machine without using balls. By subjecting the angular soil in the Los Angeles machine to 50 000 revolutions and calculating the roundness value,

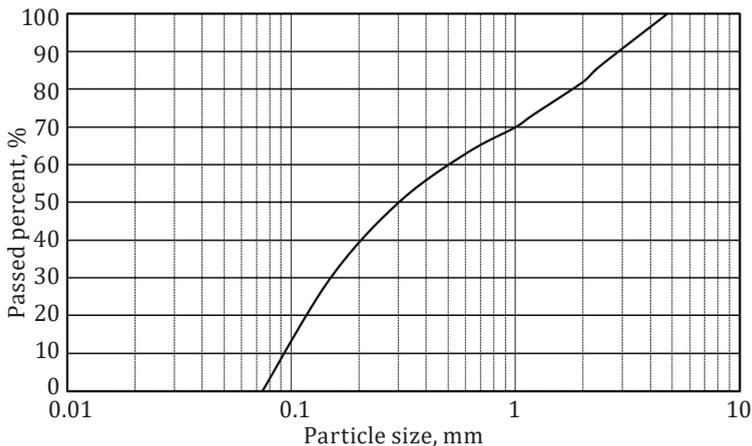


Figure 1. Grain size distribution of soil

it found that the particle shape changed to a rounded particle shape. Similar to it, 100 000 revolutions were used on the Los Angeles machine to change angular particles into well-rounded shapes. The numbers of 50 000 and 100 000 revolutions were gained by different tests, and the roundness value was calculated after each test (Arasan, 2011). After changing the shape of the particles, the soil was sieved again to get the grain size distribution.

Table 1. Roundness properties of materials

Sample	Roundness Value	Roundness Class
Angular Soil	0.693–0.744	Angular – Sub-angular
Rounded Soil	0.786–0.803	Rounded – Well Rounded
Well-Rounded Soil	0.834–0.854	Well Rounded

1.2. Additives

– Ethylene Glycol Monobutyl Ether (EGBE)

Ethylene glycol monobutyl ether, with the formula $C_6H_{14}O_2$, is an organic solvent. It is used as a processing aid and sanitizer in food processing. EGBE is a colourless liquid that can be used in cleaning products, paints, links, and as a solvent in surface coating. Other products that contain EGBE include asphalt release agents, firefighting foams, oil spill dispersants, leather protectors, bowling pins, and lane degreasers. It is also a primary component of liquid soaps, dry cleaning solutions, cosmetics, whiteboard cleaners, varnishes, latex paints, and herbicides. Table 2 shows some properties of EGBE.

Table 2. Properties of ethylene glycol monobutyl ether

Parameter	Value	Unit
Molecular Weight	118.2	g/mol
Physical State	Colourless Liquid	–
Melting Point	–74.8	°C
Boiling Point	168.4	°C
Relative Density	0.9	g/cm ³
Vapour Pressure (at 20 °C)	<1	mmHg

– Polyvinyl Acetate (PVAc)

Polyvinyl acetate (PVAc) is a thermoplastic resin prepared by the polymerization of vinyl acetate. The properties of PVAc are shown in Table 3. It is widely used as a water-dispersed resin. Setting is accomplished by the removal of water due to evaporation or absorption

into a substrate. PVAc resins produce clear and hard films that withstand water, grease, and oil. It is an emulsion and not a true water solution, softening at 30–45 °C and having high initial adhesion. It is largely used in reinforced plastics for improving antishrink and stress properties. At the same time, it can be added to concrete to improve its water-resistance properties.

Table 3. Properties of PVAc

Parameter	Value
Shape	White and Wet
Density at 25 °C	1.19, g/cm ³
pH	4–6
Special volume at 28 °C, L/kg	0.84, mmHg

PVAc shows hydrophobic properties. Low cost, nontoxic properties, weather resistance, and the ability to withstand water (Kaborani & Riedl, 2015) are some reasons for selecting PVAc as an additive. The picture of additives used in this study is shown in Figure 2.

1.3. Method

This study involved a series of laboratory tests. Pre-tests were done with different percentage of PVAc and EGBE binders (CAE) to determine the best mix design for the soil and additives. The percentage of additives selected for stabilization depend on different parameters such as the cost of stabilization and feasibility. At the same time, results should satisfy the purpose of stabilization. According to pre-test results, the final mix design was selected by considering the mentioned parameters and the behaviour of stabilized samples. Finally, for each of the three angular, rounded, and well-rounded groups of soils, 1%,

a) Polyvinyl acetate



b) Ethylene glycol monobutyl ether



Figure 2. Picture of additives

2%, and 3% of the dry soil weight was used as polyvinyl acetate (PVAc) weight. For each percentage of PVAc, half of its weight was used as EGBE weight and, finally, PVAc+EGBE binder was mixed with soil to prepare the samples. Thus, for 1% of polyvinyl acetate, 0.5% of ethylene glycol monobutyl ether (CAE-1.5), for 2% of polyvinyl acetate, 1% of ethylene glycol monobutyl ether (CAE-3), and for 3% of polyvinyl acetate, 1.5% of ethylene glycol monobutyl ether (CAE-4.5) were used to prepare the samples. Additive mixtures were respectively added to soil samples of three different shapes: angular, rounded, and well-rounded. Tests program is shown in Table 4.

The effect of stabilization on samples with three particle shape groups that were subjected to different freezing-thawing cycles was investigated. The parameter of compressive strength was based on the testing of at least three identical samples, and the average was reported. By considering the pre-tests, samples with different particle shapes and different additives, freezing-thawing cycles, and a minimum number of three tests for each type of sample, about 350 different samples were prepared and tested.

Optimum moisture contents and maximum dry densities of normal and stabilized samples with different percentage of additives in three

Table 4. Additives and tests program

Group	Additives	Type of Soil	Weight of PVAc	Weight of EGBE
Angular Group	CAE-0	Angular Soil	0% of Dry Soil Weight	0.0% of Dry Soil Weight
	CAE-1.5	Angular Soil	1% of Dry Soil Weight	0.5% of Dry Soil Weight
	CAE-3	Angular Soil	2% of Dry Soil Weight	1.0% of Dry Soil Weight
	CAE-4.5	Angular Soil	3% of Dry Soil Weight	1.5% of Dry Soil Weight
Rounded Group	CAE-0	Rounded Soil	0% of Dry Soil Weight	0.0% of Dry Soil Weight
	CAE-1.5	Rounded Soil	1% of Dry Soil Weight	0.5% of Dry Soil Weight
	CAE-3	Rounded Soil	2% of Dry Soil Weight	1.0% of Dry Soil Weight
	CAE-4.5	Rounded Soil	3% of Dry Soil Weight	1.5% of Dry Soil Weight
Well-Rounded Group	CAE-0	Well-Rounded Soil	0% of Dry Soil Weight	0.0% of Dry Soil Weight
	CAE-1.5	Well-Rounded Soil	1% of Dry Soil Weight	0.5% of Dry Soil Weight
	CAE-3	Well-Rounded Soil	2% of Dry Soil Weight	1.0% of Dry Soil Weight
	CAE-4.5	Well-Rounded Soil	3% of Dry Soil Weight	1.5% of Dry Soil Weight

particle shape groups were determined by the standard proctor test method ASTM D698-12e2. Cylindrical moulds of 5 cm in diameter and 10 cm in height were used to prepare samples. All samples were compacted and prepared at optimum moisture content to obtain the maximum unit weight. Pre-tests showed that the soil-additives mixture reached its maximum compressive strength in 7 curing days. Prepared samples in the moulds were placed inside aluminium foil and plastic bags to prevent moisture loss and left at ambient temperature in the laboratory to cure and harden for 7 days. Prepared samples were subjected to different freezing-thawing cycles due to ASTM D560/D560M-16 and previous scientific publications. In alignment with documented literature on freezing-thawing cycle, the samples were placed in freezing-thawing apparatus at temperature of $-20\text{ }^{\circ}\text{C}$ for 12 hours to freeze and then at temperature of $18\text{ }^{\circ}\text{C}$ for 12 hours to thaw (Yarbasi et al., 2007; Ghazavi & Roustaei, 2010; Akbulut & Zaimoglu, 2019). Unconfined compressive strength of samples was tested before and as well as after 1, 4, 7 and 10 cycles of freezing-thawing. Results showed that after 10 freezing-thawing cycles, most samples lost a significant percentage of their strength, so the tests were limited to 10 cycles. Freezing-thawing machine and samples are shown in Figure 3.



Figure 3. Prepared samples and freezing-thawing machine

2. Results

2.1. Optimum moisture content and maximum dry density

Optimum moisture content (W_{opt}) of samples with three different particle shapes were determined by standard proctor test ASTM D698-12e2 2012. Graph of Optimum Moisture-Maximum Dry Density of angular, rounded and well-rounded samples is shown in Figure 4. Figure 4(a) indicates that adding of CAE leads to a decrease at optimum moisture content. For the samples with angular particle shape, W_{opt} was 13% but decreased to 12.6%, 11.1%, and 10.75% with the addition of CAE-1.5, CAE-3, and CAE-4.5 binder contents, respectively. For samples with the rounded particle shape shown in Figure 4(b), the W_{opt} of normal soil was 11%; however, by adding CAE binder contents, the W_{opt} decreased to 10%, 8.5%, and 7.3% for samples with CAE-1.5, CAE-3, and CAE-4.5, respectively.

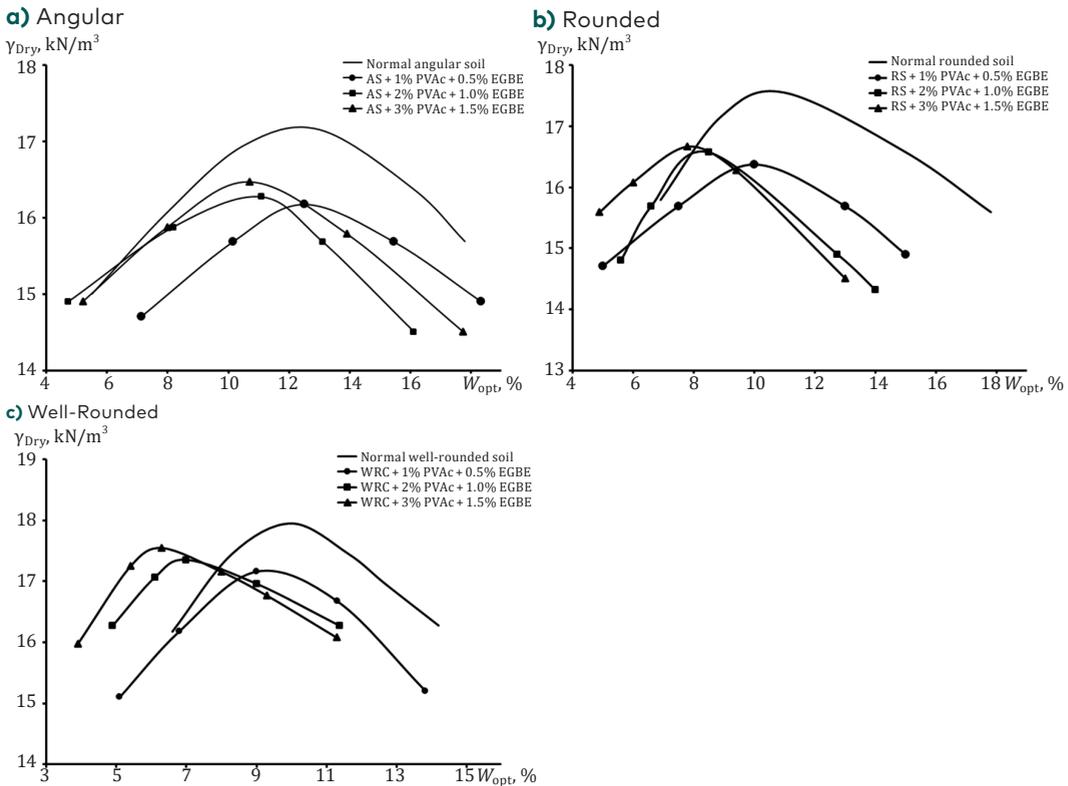


Figure 4. Optimum moisture content of samples with different percentages of additives

Optimum moisture content of well-rounded samples without any additives was 10% (Figure 4(c)). By adding CAE 1.5, CAE-3, and CAE-4.5 binders, it decreased to 9%, 7%, and 6.3%, respectively. Results showed marginal differences in the optimum moisture content from 13% to 10%, with changes in particle shape from angular to well-rounded because particle shape, quite unlike particle size, had minimum effect

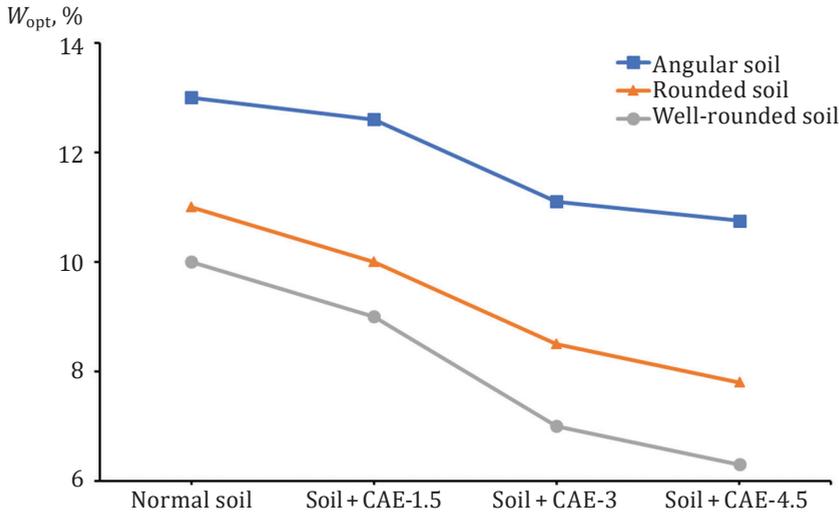


Figure 5. Optimum moisture content of samples affected by particle shapes

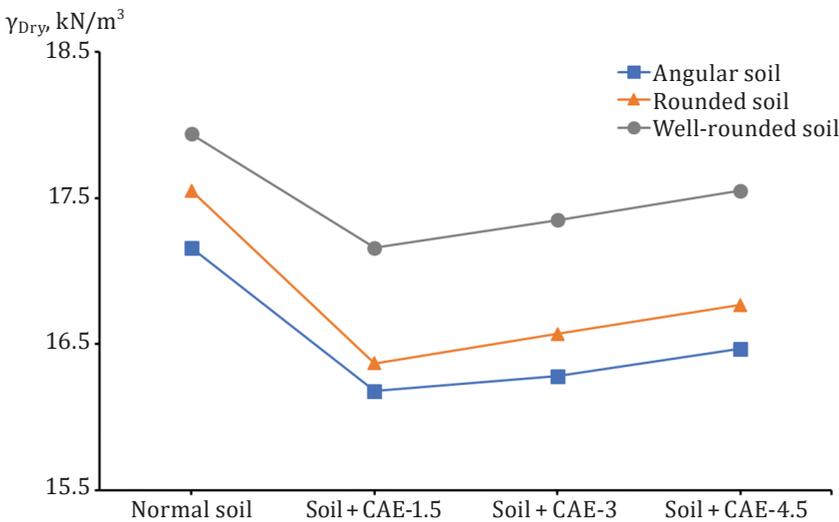


Figure 6. Maximum dry density of soils with different percentage of additives and particle shapes

on particle-specific surfaces. In addition, by increasing the amount of CAE binder added as an additive to the soil, the optimum moisture content decreased in all samples. Because of the chemical properties of the binder, such as the thermoplastic properties of PVAc and the lower density of EGBE in comparison with water, that with less weight of water, the soil can be compacted in the best way. The optimum moisture content of samples depends on both particle shape and additive content. As shown in Figure 5, the optimum moisture content of samples was decreased by increasing the roundness of particles from an angular to a rounded and well-rounded shape. The difference in optimum moisture content between angular and rounded particle shapes was greater than the difference between rounded and well-rounded particle shapes.

In addition, the addition of 1% of PVAc+0.5%EGBE (CAE-1.5) decreased the maximum dry density of the samples. The magnitude of the decrease was more significant in angular and rounded samples compared to well-rounded samples. Subsequent increases in the percentage of the additive resulted in a linear increase in the maximum dry density of samples (Figure 6). The change in particle shapes from angular to rounded was more significant for both maximum dry density and optimum moisture content than the change from rounded to well-rounded.

2.2. Unconfined compressive strength (UCS)

Unconfined compressive strength of soil is one the most used property in earthwork application for determining the geotechnical behaviour of soil (Xiu et al., 2021). After applying 0, 1, 4, 7, and 10 freezing-thawing cycles to all samples of normal and stabilized samples with different particle shapes, the UCS tests were done in accordance with ASTM D2166, and stress-strain graphs were drawn for different particle shapes at different freezing-thawing cycles.

Results showed that adding CAE binder to soil improved the compressive strength of samples during different freezing-thawing cycles. Figure 7 shows stress-strain graphs and the maximum compressive strength of angular soil with and without additives during different freezing and thawing cycles. As the soil that was used for preparing samples was not washed, there was a little amount of clay and silt in normal soil that led to a small amount of cohesion and low compressive strength in normal soil. Maximum unconfined compressive strength was seen in samples with angular soil stabilized with CAE-4.5. By decreasing the percentage of CAE binder and moving from angular particles toward well-rounded shape, the UCS of samples was decreased. Maximum compressive strength in samples with angular particle

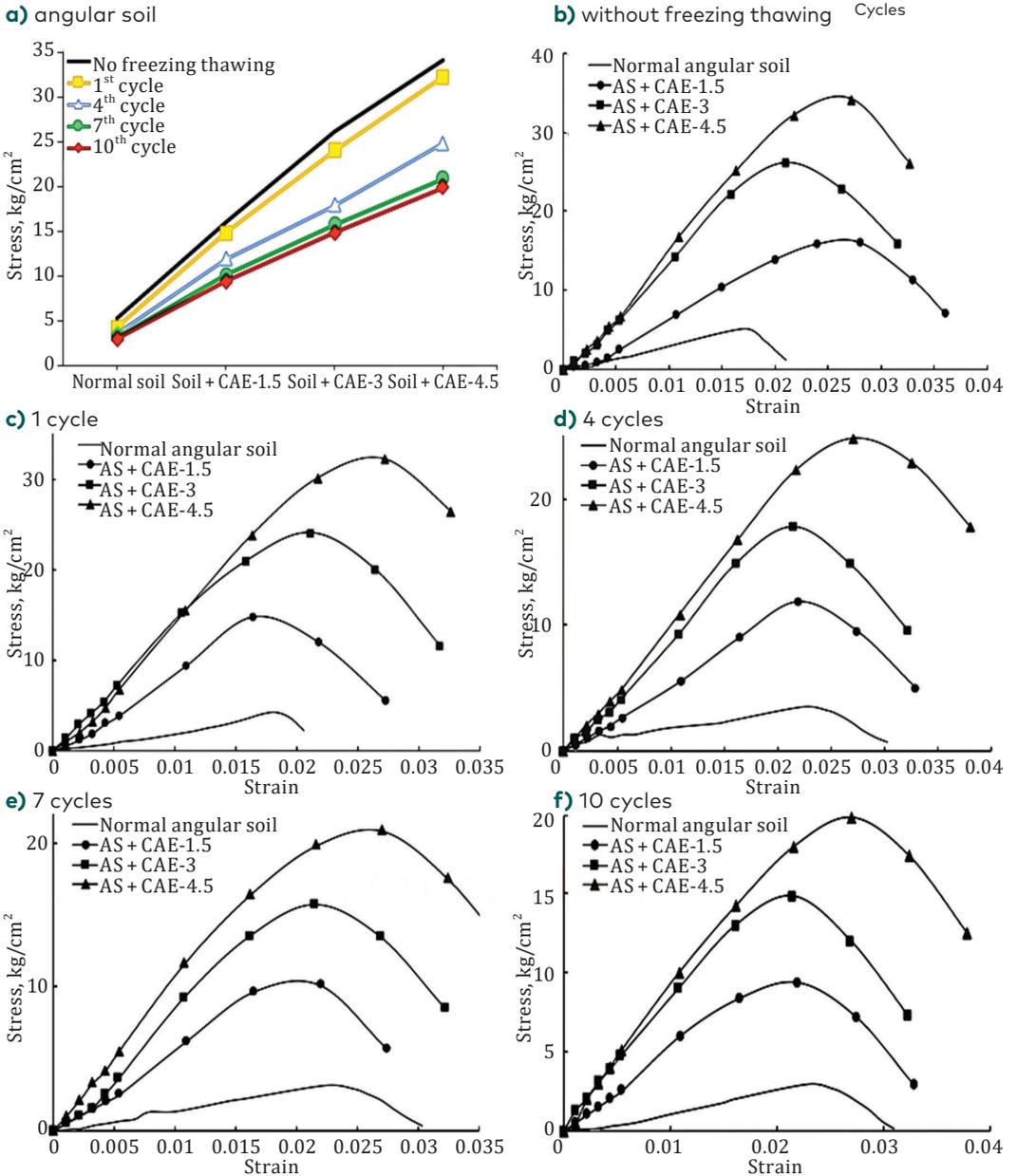


Figure 7. Maximum compressive strength and stress-strain graphs of samples with angular particle shape during different freezing thawing cycles

shape stabilized with CAE-4.5 without applying any freezing thawing was 34.2 kg/cm². It was 26.13 kg/cm², 16.02 kg/cm² and 5.20 kg/cm² in samples with CAE-3, CAE-1.5 and normal soil, respectively. The 1st freezing-thawing cycle was applied to a set of samples and also for each cycle stage, a minimum of three samples for different additive contents was tested and the average value was considered as the UCS.

It was observed that by applying the first cycle of freezing-thawing the compressive strength of samples decreased. The UCS of samples with angular particle shapes is shown in Table 5.

Figure 8 shows the stress-strain graphs and maximum compressive strength of rounded particle shape soil with and without additives during different freezing and thawing cycles.

In the rounded particle shape, without applying any freezing thawing, the maximum strength values were 23.12 kg/cm², 19.60 kg/cm², 13.13 kg/cm² and 3.87 kg/cm² for samples with CAE-4.5, CAE-3, CAE-1.5 and normal soil, respectively.

The UCS of samples with rounded particle shapes is presented in Table 6. Results show that increasing the roundness value and freezing and thawing cycles led to a decrease in the UCS value.

Table 5. UCS of samples with angular particle shape

UCS of Samples with Angular Particle Shape, kg/cm ²				
	Normal Soil	Soil+CAE-1.5	Soil+CAE-3	Soil+CAE-4.5
No Freeze Thaw	5.2	16.02	26.13	34.2
1st Cycle	4.2	14.18	24.05	32.25
4th Cycles	3.5	11.85	17.84	24.84
7th Cycles	3.15	9.64	15.73	20.86
10th Cycles	2.94	9.35	14.83	19.84

Table 6. UCS of samples with rounded particle shape

UCS of Samples with Rounded Particle Shape, kg/cm ²				
	Normal Soil	Soil+CAE-1.5	Soil+CAE-3	Soil+CAE-4.5
No Freeze Thaw	3.87	13.1	19.6	23.32
1st Cycle	2.34	11.35	18.21	20.83
4th Cycles	1.85	6.45	9.88	11.32
7th Cycles	1.76	5.11	7.35	8.46
10th Cycles	1.55	4.54	6.23	7.21

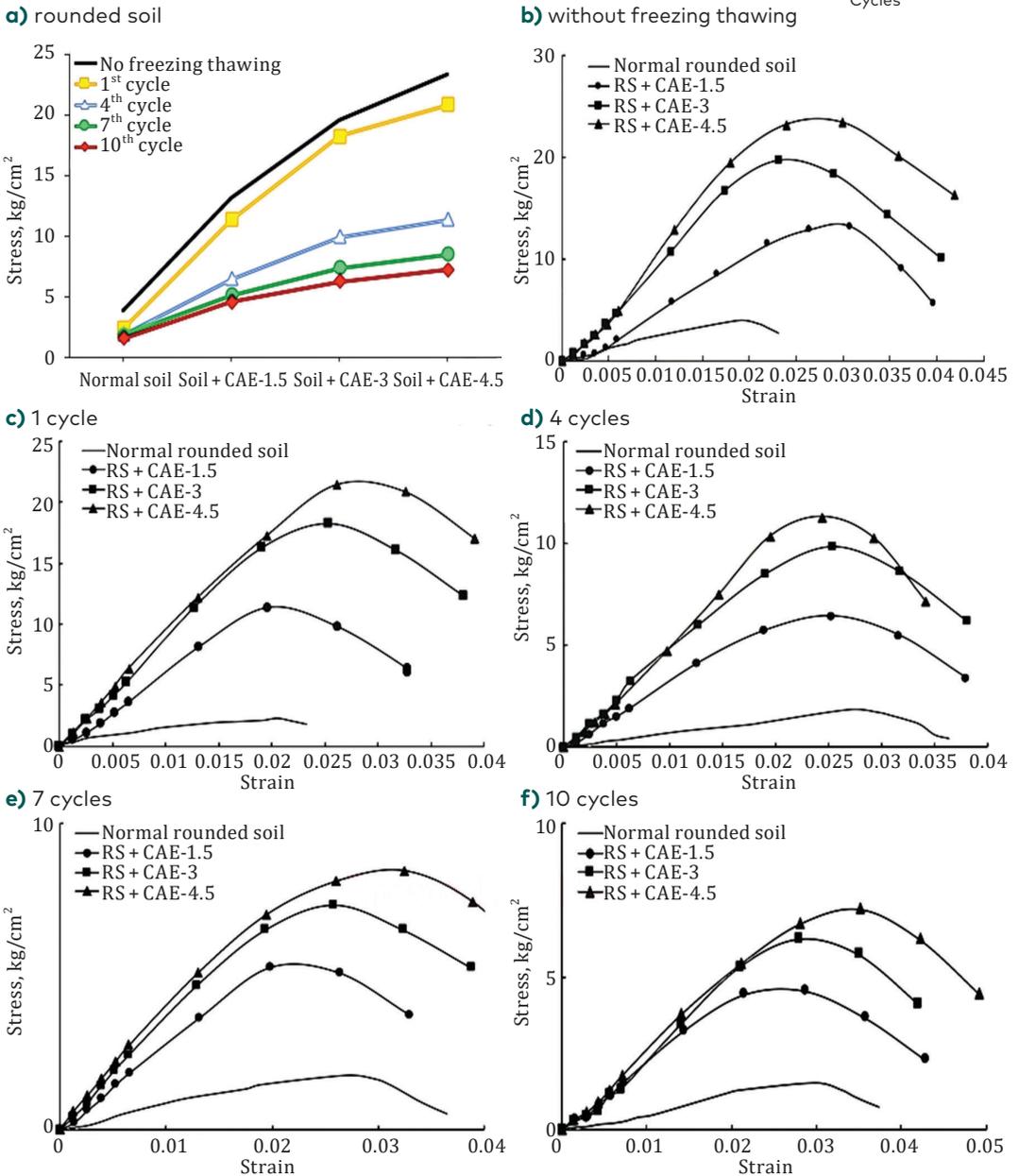


Figure 8. Maximum compressive strength and stress-strain graphs of samples with rounded particle shape during different freezing thawing cycles

Figure 9 shows the stress-strain graphs and maximum compressive strength of well-rounded particle shape soil with and without additives during different freezing thawing cycles. Maximum compressive strength of normal soil with well-rounded particle shape after the first freezing thawing period was 1.41 kg/cm². For samples with CAE-4.5, CAE-3 and CAE-1.5 this strength was 15.95 kg/cm², 12.83 kg/cm² and 7.85 kg/cm², respectively.

The UCS of samples with well-rounded particle shapes is presented in Table 7.

The amount of decrease in this strength after 1 freezing-thawing cycle was between 7% and 10% in most of samples. In other words, the first freezing-thawing cycle causes the soil to lose 7% to 10% of its strength. By considering all results, it was found that in all samples, the maximum compressive strength of samples increased with the increasing percentage of CAE. At the same time, by increasing the roundness of particles, this strength decreased in all samples.

Another considerable result was that, by changing the shape of particles and increasing the roundness value or freezing-thawing cycles, the samples failed with more settlements. Increasing the percentage of additives made the samples fail in less strain. For example, in angular soil with CAE-4.5, during the first freezing-thawing cycle, the samples failed at a strain of 0.022; for the same samples, after applying 10 freezing-thawing cycles, the strain was 0.027 at the failing point. As another example for a better understanding of the effect of roundness on particles, the strain of samples at failure point for angular soil with CAE-4.5 after 4 freezing-thawing cycles was 0.026; in the same sample with the same condition but well-rounded particle shape, the strain was 0.038. Results showed that differences in strength of samples was more considerable between the first and fourth cycles. This difference was more considerable when the roundness of the particle increased. Results showed that samples could keep their resistance and strength

Table 7. UCS of samples with well-rounded particle shape

	UCS of Samples with Well-Rounded Particle Shape, kg/cm ²			
	Normal Soil	Soil+CAE-1.5	Soil+CAE-3	Soil+CAE-4.5
No Freeze Thaw	2.53	9.59	14.13	18.83
1st Cycle	1.4	7.85	12.83	15.95
4th Cycles	1.1	4.23	7.21	8.85
7th Cycles	0.95	3.75	5.05	7.21
10th Cycles	0.78	2.69	4	5.83

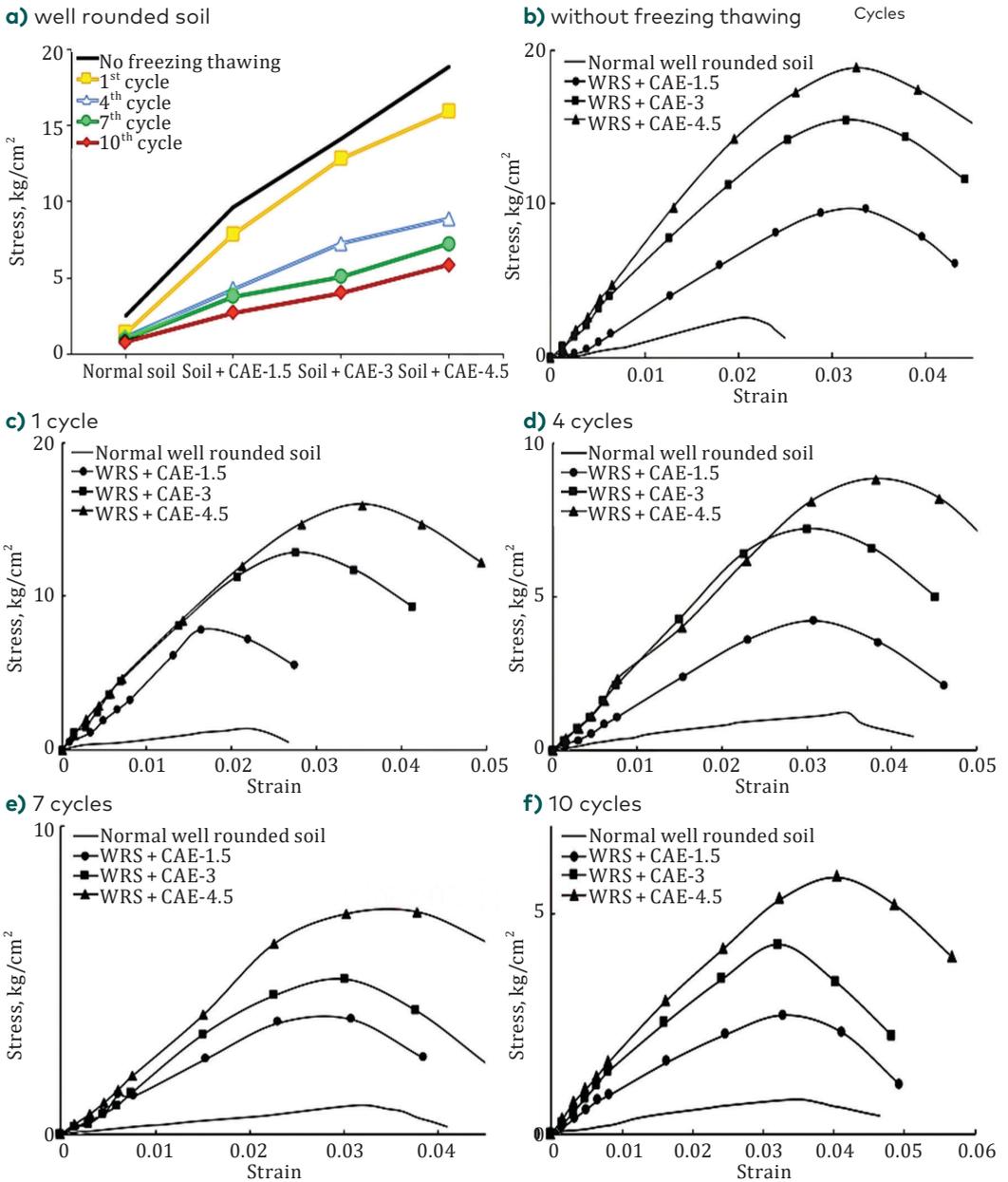


Figure 9. Maximum compressive strength and stress-strain graphs of samples with well-rounded particle shape during different freezing thawing cycles

up to the first cycle. After the first cycle of freezing-thawing, samples lost a large amount of their compressive strength up to the fourth cycle, but after the 4th cycle of freezing-thawing, the decreasing ratio of this strength reduced. As discussed previously, the UCS of samples with angular particle shape were more than rounded shape, and UCS of rounded soil was more than well-rounded. Increasing the percentage of CAE resulted in an increase in the UCS of the samples. Increased particle roundness had a negative effect on the compressive strength of samples. By increasing the percentage of additives from CAE-0 to CAE-4.5, the compressive strength of samples increased, which led to a decrease in the negative effect of increasing particle roundness. It thus indicated that the maximum compressive strength of samples with rounded particle shapes with CAE-4.5 and CAE-3 was greater than the strength mobilized by samples with angular particle shapes with CAE-1.5. Also, for well-rounded particle shapes with CAE-4.5, the maximum compressive strength was higher than for samples with angular particle shapes with CAE-1.5. Thus, it means that increasing percentage of additive can compensate the negative effect of increasing roundness. In samples with an angular particle shape, the decreasing ratio of compressive strength was considerable up to the 7th freezing-thawing cycle, especially in samples with CAE-4.5 and CAE-3. It was because the structure and angularity of particles in the samples showed better behaviour up to 7 freezing-thawing cycles. However, in rounded and well-rounded particle shape after 4 cycles of freezing-thawing, the decreasing ratio in maximum compressive strength was less than in angular soil.

2.3. Secant Modulus (E_s)

Secant modulus of soil is defined in Equation (1):

$$E_s = \frac{50\% \text{ of Peak Stress}}{\text{Corresponding Strain}}. \quad (1)$$

By considering the results, it was found that E_s decreased by applying more freezing and thawing cycles to the samples. The most significant decrease was up to the 4th cycle, and with further increase in freezing and thawing cycles, the rate of decrease in the secant modulus diminished significantly.

Figure 10 shows the changes in secant modulus of samples versus percentage of additives at different particle shapes. Results showed that increasing the amount of CAE led to an increase in E_s . The values of E_s depend on stress history, water content, and density of soil. The water content and percentage of additives have a significant influence on the behaviour of samples. A comparison with the values of E_s from a series of tests presented by Ranjan & Rao (2007) shows that the normal soil without any additives behaves like loose sand under compressive loads. Adding CAE to the soil changes the behaviour of samples in hard and dense soils.

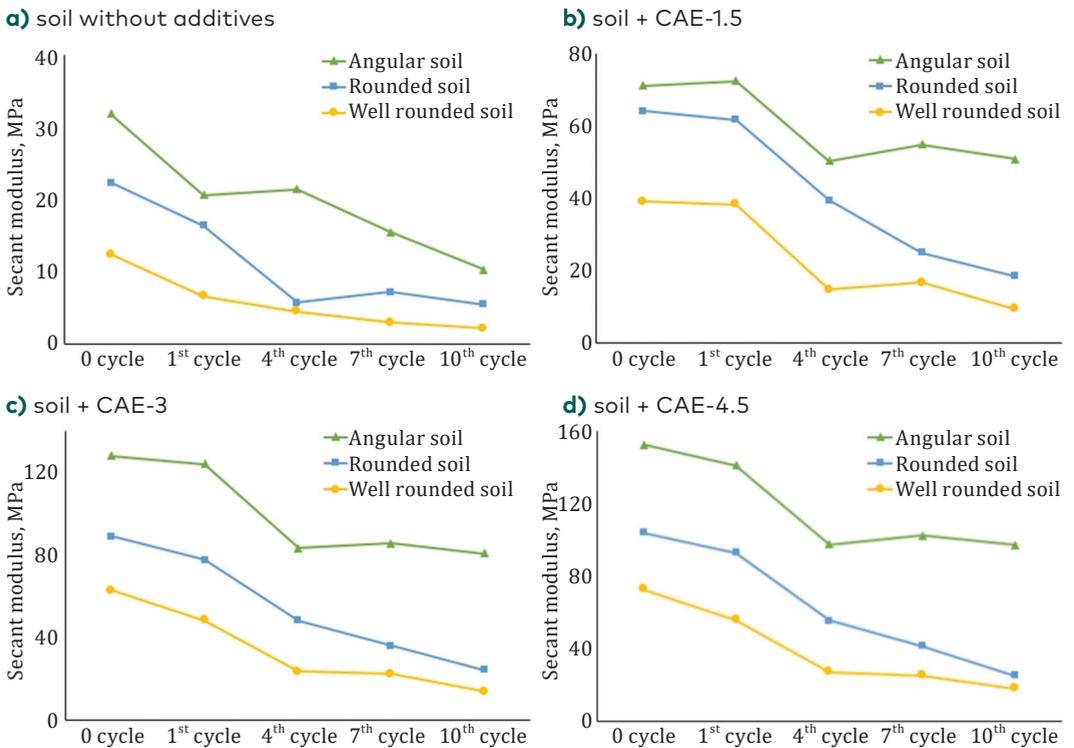


Figure 10. Secant modulus of samples versus percentages of additives at different particle shapes

2.4. Effect of binder-sand particle shape ratio on mobilized shear strength and modulus

The effect of binder-particle shape ratio on mobilized shear strength and secant modulus of specimens that were subjected to 0 and 10 cycles of freeze-thaw is presented in Figure 11. It is noted the mobilized shear strength and secant modulus increased exponentially with the binder–shape ratio. However, the degree of determination is greater for the samples that were not degraded by freeze-thaw. It should be noted that for a binder-particle ratio of 0, the mobilized shear strength and secant modulus decreased with an increase in particle roundness. Figure 11 further reveals that the binder content is the dominant determinant of the mobilized mechanical properties.

2.5. Deformability index

Another parameter that reflects the volume change behaviour of soil is the deformability index (Jahandari et al., 2020). This parameter is defined as Equation (2):

$$I_D = \frac{\epsilon_{ct}}{\epsilon_{ut}}, \quad (2)$$

where I_D is the deformability index of soil, ϵ_{ct} is axial strain at peak strength in stabilized samples, and ϵ_{ut} is axial strain at peak strength in unstabilized samples.

The deformability index is useful when residual stress or peak stress is not clearly observed. Application of I_D is limited to stabilized samples made of cement or additives with similar behaviour that have the same percentage of additives. The values of I_D were calculated for different

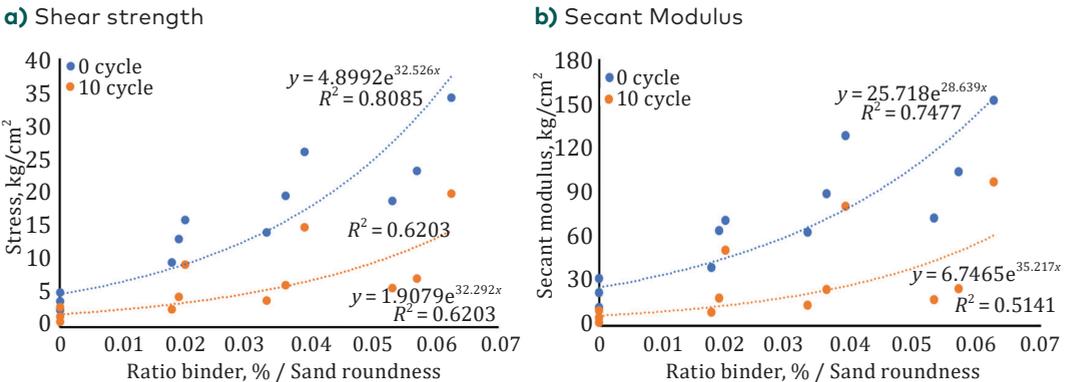


Figure 11. Effect of binder-aggregate shape ratio on mobilized shear strength and secant modulus

particle shapes and additives during different freezing and thawing cycles. The ratio of the deformability index to the binder-particle roundness ratio is shown in Figure 12.

The maximum ID value was reflected by the well-rounded particle shape stabilized with CAE-4.5 and an ID of 1.6. By applying freezing and thawing cycles to samples, ID decreased, and at the same sample it became 1.17. The minimum value of ID was evident for an angular shape with CAE-1.5. A deformability index can be applied for the evaluation of the deformability or ductility of stabilized sandy samples with different percentage of additives (Kustov & Ruppeneit, 1985; Randhawa et al., 2022). At the same time, this index can be used for selecting the suitable percentage of additives for different conditions.

The ratio of the deformability index to the binder-particle roundness ratio is presented in Figure 12. For non-degraded, i.e., intact specimens, the deformability index decreased exponentially with an increase in the binder-particle shape ratio. The degree of correlation is very weak because the deformability index is a measure of structural degradation and ductility, and this specimen stiffness increased with an increase in the binder-particle shape ratio. For fresh, intact specimens, although an increase in roundness resulted in an increase in ductility due to reduced particle interlocking, the associated increase in binder content resulted in a net increase in specimen stiffness, i.e., a reduced deformability index.

For specimens that were degraded by 10 cycles of freeze and thaw, the deformability index increased with the binder-particle roundness ratio with a medium degree of correlation. It is thus noted that for

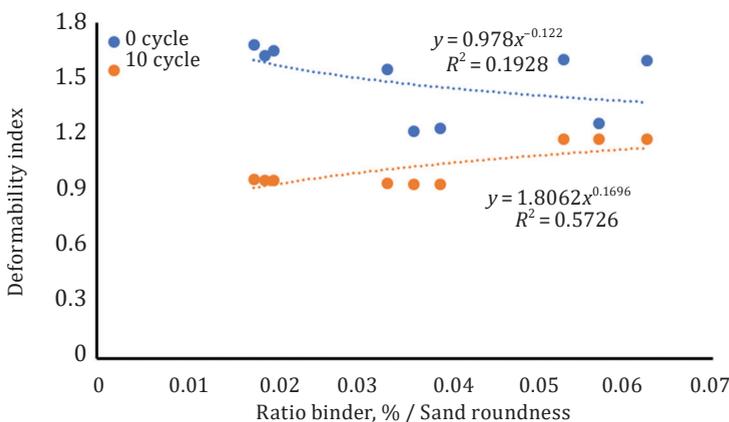


Figure 12. The ratio of deformability index to the binder-particle roundness ratio

degraded specimens, an increase in roundness resulted in an increase in ductility due to reduced particle interlocking. Janoo (1998) reported that for road base course materials that were degraded by loading for 5000 cycles, the cyclic creep strain (ϵ , %) increased from 1.5% to 2.5% due to changes in particle shape from rounded (1.0) to sub-angular (0.6).

Discussion and Conclusion

Considering the properties of the PVAc+EGBE mixture, this additive mixture increased the compressive strength of samples. It gave enough strength to the samples for up to 10 freezing-thawing cycles. By considering the results, using 3% of PVAc as an additive showed better results for improving the settlement of samples, while adding 2% of PVAc was more suitable when the final goal was both improving compressive strength and settlement. By increasing the roundness of particles, the compressive strength of samples decreased. Using the PVAc+EGBE additive could compensate for the observed negative effect of increasing roundness of particles.

Criteria for highway fill material: According to the Turkish General Directorate of Highways, backfills compacted to a dry density less than 14.22 kN/m^3 are good candidates for domestic infrastructure development. Thus, all the well-rounded soils and the unstabilized rounded soils and well-rounded soils met the requirement for construction backfill for domestic infrastructure applications. For the development of low traffic volume roads or domestic grade roads, the unconfined compression strength is in the range of 0.75 MPa to 1.5 MPa. Only well-rounded stabilized materials with binder content greater than CAE-1.5 were exposed to a maximum of 1 cycle of freezing and thawing, and rounded materials with minimum of CAE-3 were exposed to a maximum of 4 cycles of freezing and thawing; and all angular soil composites with a minimum of CAE-1.5 were exposed to a maximum of 10 cycles. Although the CAE-4.5 stabilized angular sand composite is stable to extreme cycles of freezing and thawing, it fell short of the BS 8500 ST1 minimum compression strength of 7.5 MPa for application to concrete works like concrete blinding, kerb bedding, drainage works, and similar domestic applications.

Finally, PVAc+EGBE binder can be selected as a useful additive for improving the compressive strength and durability of soil during different freezing-thawing cycles and particle shapes. By considering all above, using 2% or 3% of PVAc can be applied in practical engineering with different particle shapes.

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