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The effects of polymers and fly ash on unconfined compressive strength and freeze-thaw behavior of loose saturated sand

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Abstract. Constructions over soft and loose soils are one of the most frequent problems in many parts of the world. Cement and cement-lime mixture have been widely used for decades to improve the strength of these soils with the deep soil mixing method. In this study, to investigate the freeze-thaw effect of sand improved by polymers (i.e., styrene-acrylic-copolymer-SACP, polyvinyl acetate-PVAc and xanthan gum) and fly ash, unconfined compression tests were performed on specimens which were exposed to freeze-thaw cycles and on specimens which were not exposed to freeze-thaw cycles. The laboratory test results concluded that the unconfined compressive strength increased with the increase of polymer ratio and curing time, whereas, the changes on unconfined compressive strength with increase of freeze-thaw cycles were insignificant. The overall evaluation of results has revealed that polymers containing fly ash is a good promise and potential as a candidate for deep soil mixing application.

Keywords: deep soil mixing; polymer; unconfined compressive strength; sand, freeze-thaw

1. Introduction

Deep soil mixing involves the in-situ mixing of soil and additives (i.e., cement and lime) with special apparatus, frequently using rigs with counter rotating augers (Taki and Yang 1991, O'Rourke and O'Donnell 1997). Cement and lime have been widely used in deep soil mixing as the main binder since the 1970s. Techniques commonly utilized include column installation and slurry pressure injection. These decrease soil moisture contents; thereby reducing their likelihood of swelling /shrinkage and increasing shear strength and compaction properties (Glendinning and Rogers 1996, Threadgold 1996, Rogers *et al*. 2000, Ahnberg *et al*. 2003, Bruce *et al*. 1998, Bruce and Bruce 2003, Sargent *et al*. 2013).

In 1970s, many studies were applied on the deep mixing method to marine clays with lime in the form of quick lime, whereas today a mixture of cement and lime is the clearly dominating binder in deep mixing application on clayey and sandy soils. Nowadays, deep mixing applications are used at hydraulic cut-off walls, excavation support walls, liquefaction mitigation, environmental remediation, in situ reinforcement and large volume ground treatment (Bruce *et al*. 1998, Bruce and Bruce 2003). A great number of experimental studies dealing with the effects of

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binder type and ratio on deep mixing method are available in the literature. Some of these studies focused on water/cement-lime (*w*/*c*) ratio (Okumura and Terashi 1975, Terashi and Tanaka 1981, Ahnberg 1996, Porbaha *et al*. 1998, Bahner and Naguib 2000, Jacobson 2002, Miura *et al*. 2002, Lorenzo and Bergado 2004, Ratherford 2004, Horpibulsuk *et al*. 2005, Pathivada 2005, Lorenzo and Bergado 2006, Maher *et al*. 2007, Lewsley 2008, Shrestha 2008, Şengör 2011, Tang *et al*. 2011, Dias *et al*. 2012) and curing period (Hartlen and Holm 1995, Andromalos and Bahner 2004). Most of the researchers pointed out that the unconfined compressive strength (UCS) increased when the w/c ratio and curing time were increased.

In comparison with cement or lime, there are a limited number of studies in the literature on the utilization of waste materials in improvement of soils using the deep mixing method (Ahnberg and Holm 1996, Ahnberg 2006, Ajorloo 2010). It was indicated that silica fume, fly ash and slag were used with or without cement in deep mixing applications. A fly ash based mixture represents a cost effective alternative to conventional cement based mixture commonly in use. However, some previous experimental studies in this area have demonstrated that many soil additives have little or no benefit for silty, sandy soil types. Sandy soils are problematic for stabilization and often require cement and/or asphalt emulsion to bind the soil particles into a cohesive unit (Santoni *et al*. 2003, Newman and Tingle 2004). Therefore, some researchers focused on improvement methods with polymers (Ahmed 1995, Bishop *et al*. 1998, Al-Khanbashi and Abdalla 2006, Gallagher *et al*. 2007, Gupta *et al*. 2009, Naeini and Ghorbanalizadeh 2010, Cabalar and Canakci 2011). Polymers are widely used in the industry although they are rarely applied in soil stabilization. Some of non-traditional soil stabilization binders such as acids, asphalt emulsions, lignin derivatives, enzymes, tree resins, biopolymers and silicates are available from the commercial sector. These additives may be in liquid or solid form and are touted to be applicable for most soils (Newman and Tingle 2004). However, deep mixing of sand with polymers is a new research subject.

Soils are exposed to at least one freeze-thaw cycle every year in environments prevailed by cold climate and seasonally frozen areas. It has thus a significant effect on many civil engineering applications such as highway, railway, pipeline, retaining structures and building constructions. Most of the engineering properties of soils (i.e., unconfined compressive strength, permeability, etc.) are significantly affected by freeze-thaw period and cycle (Yarbasi *et al*. 2007, Zaimoglu 2010, Shibi and Kamei 2014). A great number of studies about the effects of freeze-thaw behavior of soils and stabilized soils are available in the literature (Guney *et al*. 2006, Qi *et al*. 2006, Yarbasi *et al*. 2007, Altun *et al*. 2009, Gullu and Hazirbaba 2010, Zaimoglu 2010, Olgun 2013, Shibi and Kamei 2014). However, very limited information has been reported on the freeze–thaw behavior of the deep mixed soils (De Silva *et al*. 2001) and stabilized soil with polymers (Welling 2012). Some researchers also pointed out that the usage of fly ash (Yarbasi *et al*. 2007) and polymers (Welling 2012) as an additive in soils generally improve the freeze-thaw behavior.

Loose saturated sandy soils have great potential of liquefaction and some researchers have indicated that liquefaction potential of saturated sand can be greatly reduced if the sand can be slightly unsaturated (He *et al*. 2013). Polymers, especially biopolymers (xanthan gum, guar gum, etc.), can reduce the degree of saturation and liquefaction potential of sand. Consequently, the present study was undertaken to investigate the effects of fly ash, styrene-acrylic-copolymer (SACP) and Polyvinyl acetate (PVAc) on unconfined compressive strength (7, 14 and 28 days curing period) and freeze-thaw properties (5 and 10 cycles) on the loose saturated sand with deep soil mixing method. In the experimental study, saturated sand was mixed with fly ash (10%, 20% and 30% by total weight of sand and water) and polymer mixtures (5%, 10% and 20% by total weight of sand and water). For eliminating the negative effect of water, a biopolymer such as xanthan gum (0.25% by total weight of sand and water) was used in the study. Some of the tests were repeated as many as three times to assure the reliability of the results. Test results were compared with those in the literature and discussed.

2. Materials and methods

2.1 Materials

Natural sand was collected from a sandy area near Erzincan (Turkey) and sieved between 0.3 mm-0.6 mm for experiments. Saturated sand was then prepared at 30% relative density for tests by mixing the required amount of water. The geotechnical properties of sand are given in Table 1. Class C (ASTM C618) fly ash (FA) supplied from Afsin-Elbistan thermal power station was used in experiments. This fly ash is a predominantly silt-sized uniform material and its specific gravity is 2.51. The chemical composition of fly ash is presented in Table 2. In the experiments, two different polymers (styrene-acrylic-copolymer (SACP), polyvinyl acetate (PVAc) produced by KEMPRO Factory (Turkey) and xanthan gum as biopolymer were used. Some physical and chemical properties of mentioned polymers obtained from manufacturer are given in Table 3.

Table 1 Some geotechnical properties of sand

Properties	Sand loess
Soil classification (USCS)	SP
Specific gravity, G_S	2.66
Max void ratio,	1.00
Min void ratio,	0.80
D_{10}, mm	0.34
D_{30}, mm	0.40
D_{60}, mm	0.47
C_u	1.38
C_c	1.00

Table 2 Chemical composition of fly ash (Turker *et al*. 2009)

Constituent	Fly ash (%)
SiO_2	18.27
Al_2O_3	9.16
Fe_2O_3	3.26
CaO	53.44
MgO	1.75
Na_2O	0.19
SO_3	11.41
K_2O	0.38
Loss on ignition	2.12

Table 3 Some properties of SACP and PVAc

Properties	SACP	PVAc
Name	Styrene-acrylic-copolymer	Polyvinyl acetate
Formula	$(C_{10}H_{10}.C_8H_8.C_7H_{12}0_2)_n$	$(C_4H_6O_2)_n$
Viscosity 25°C (cps)	1000-5000	1700-3000
Particle size (μm)	0.01 to 0.05	-
pH	8.5-9.5	-
Specific gravity	0.93	1.18
Minimum film forming temperature	4-5°C	2-8°C

Table 4 Quantity and percentages of additives of soil specimens

Specimen name	Quantity	Dry sand *(**)	Water content *(**)	PM1 *(**)	PM2 *(**)	Xanthan gum *(**)	Fly ash *(**)
S1	5%PM1+10%FA	74 (*100*)	26 (*35*)	5 (*7*)		0.25 (*0.34*)	10 (*13*)
S2	5%PM1+20%FA	74 (*100*)	26 (*35*)	5 (*7*)		0.25 (*0.34*)	20 (*27*)
S3	5%PM1+30%FA	74 (*100*)	26 (*35*)	5 (*7*)		0.25 (*0.34*)	30 (*40*)
S4	10%PM1+10%FA	74 (*100*)	26 (*35*)	10 (*13*)		0.25 (*0.34*)	10 (*13*)
S5	10%PM1+20%FA	74 (*100*)	26 (*35*)	10 (*13*)		0.25 (*0.34*)	20 (*27*)
S6	10%PM1+30%FA	74 (*100*)	26 (*35*)	10 (*13*)		0.25 (*0.34*)	30 (*40*)
S7	20%PM1+10%FA	74 (*100*)	26 (*35*)	20 (*27*)		0.25 (*0.34*)	10 (*13*)
S8	20%PM1+20%FA	74 (*100*)	26 (*35*)	20 (*27*)		0.25 (*0.34*)	20 (*27*)
S9	20%PM1+30%FA	74 (*100*)	26 (*35*)	20 (*27*)		0.25 (*0.34*)	30 (*40*)
S10	5%PM2+10%FA	74 (*100*)	26 (*35*)		5 (*7*)	0.25 (*0.34*)	10 (*13*)
S11	5%PM2+20%FA	74 (*100*)	26 (*35*)		5 (*7*)	0.25 (*0.34*)	20 (*27*)
S12	5%PM2+30%FA	74 (*100*)	26 (*35*)		5 (*7*)	0.25 (*0.34*)	30 (*40*)
S13	10%PM2+10%FA	74 (*100*)	26 (*35*)		10(*13*)	0.25 (*0.34*)	10 (*13*)
S14	10%PM2+20%FA	74 (*100*)	26 (*35*)		10(*13*)	0.25 (*0.34*)	20 (*27*)
S15	10%PM2+30%FA	74 (*100*)	26 (*35*)		10(*13*)	0.25 (*0.34*)	30 (*40*)
S16	20%PM2+10%FA	74 (*100*)	26 (*35*)		20(*27*)	0.25 (*0.34*)	10 (*13*)
S17	20%PM2+20%FA	74 (*100*)	26 (*35*)		20(*27*)	0.25 (*0.34*)	20 (*27*)
S18	20%PM2+30%FA	74 (*100*)	26 (*35*)		20(*27*)	0.25 (*0.34*)	30 (*40*)

* percent proportions (%) in relation to total mass of sand and water
** percent proportions (%) in relation to dry mass of the sand

2.2 Specimen preparation and testing

In order to determine the polymer type to be used in this study, many preliminary tests were conducted (Nasirpur 2014). According to these tests results, two different polymers were chosen (i.e., PM1 and PM2). PM1 is composed of 100% SACP and PM2 is a mixture of 75% of SACP and 25% of PVAc. Also, the percentages of additives (i.e., polymer, fly ash and xanthan gum) were determined from Nasirpur (2014). The percentage of polymer mixtures were determined as

5%, 10% and 20%. On the other hand, 10%, 20% and 30% of fly ash and 0.25% xanthan gum were chosen for experiments. The percentages of additives were determined as the total weight of saturated sand (i.e., sand and water). The quantity and percentages of each additive of soil specimens are summarized in Table 4. It should be mentioned that the numbers given in bold font illustrate the percentages of specimens determined according to the total mass of sand and water. Additionally, the numbers given in the parentheses demonstrate the percentages of specimens calculated by using dry mass of the sand.

The procedures described by JGS 0821 (2000) and Euro Soil Stab (2001) were used for the preparation of specimens. Firstly, sandy soil was mixed with enough water to obtain saturated sand specimens. Then, xanthan gum, fly ash and polymer mixture were added into saturated sand and mixed for 5 minutes in 150 rpm with a mechanical mixer. The prepared specimens were then placed into metal cylinder molds (i.e., each 38 mm in diameter and 76 mm in height) in three layers. It should be noted that inside of the molds were lubricated to make extrusion of the specimen easier. In order to remove air bubbles, molds were slightly vibrated. The prepared specimens were cured in the moisture room where the temperature was kept at 20 ± 3°C and relative humidity was 90%. The curing periods were determined as 7, 14 and 28 days for this study to determine the curing period effect on strength. After curing, the specimens were removed from the molds and subjected to unconfined compression strength (UCS) test. UCS tests were conducted in accordance with ASTM D 2166. The testing load was applied at a rate of 0.5 mm/minute.

On the other side, the freeze-thaw tests were performed by a programmable cabinet. The specimens were placed in the freeze-thaw cabinet and conditioned at −20°C for 6 hours. Then, they were thawed at + 25°C for 6 hours (Zaimoglu 2010). This process was named as “one cycle”. All specimens were exposed to 5 and 10 freeze-thaw cycles.

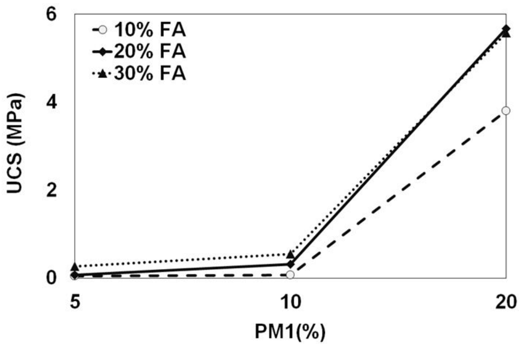
3. Results and discussion

In the following passages, the effects of polymers, fly ash, curing period and freeze-thaw cycles on the unconfined compressive strength for sand specimens are presented at varying values. Additionally, the findings from the experimental tests are compared with those from other studies in the literature and discussed.

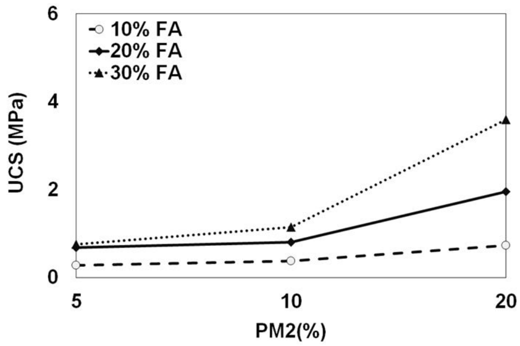
3.1 The effect of polymer mixture, fly ash and curing period on UCS

The relationship between polymer percentage and UCS of PM1 and PM2 specimens cured for 7 days are given in Figs. 1(a) and (b), respectively. It can be seen from Fig. 1, while the UCS values of specimens added with 5% and 10% PM1 are very small, the UCS value in the additive percentage of 20% PM1 increases up to 5 MPa. When PM1 and PM2 are compared, the UCS values of PM2 are higher than PM1 at the range of 5% and 10%. Additionally, the UCS values of PM2 at 20% additive percentage are between 1 MPa and 4 MPa, which are lower than PM1 values. An increase on percentage of fly ash causes increase on UCS values (Fig. 1). The maximum values in the specimens of S7, S8, S9 and S18 are obtained as 3.80, 5.67, 5.58 and 3.59 MPa, respectively.

The effect of the curing period on the UCS is given in Fig. 2. It can be clearly seen from Fig. 2 that the curing period has no significant effect on the UCS of the specimens with an exception of



(a)



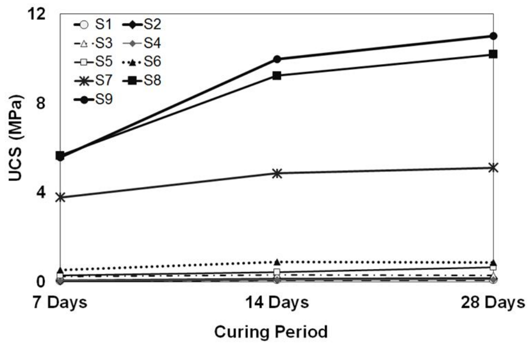
(b)

Fig. 1 UCS versus polimer mixture ratio for 7 days cured specimens

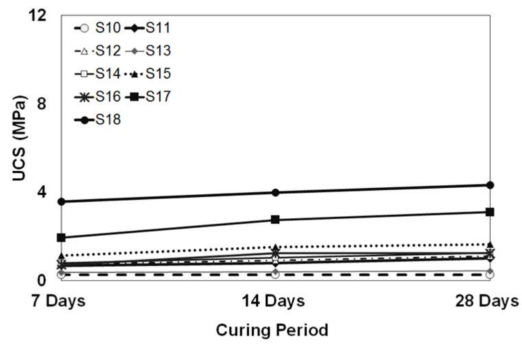
S8 and S9 specimens. The increment ratio of UCS values between 7 days and 14 days is more than that the same ratio between 14 days and 28 days (Fig. 2). The UCS values of S8 specimen are determined at 7, 14 and 28 days curing as 5.67 MPa, 9.24 MPa and 10.19 MPa, respectively. Similarly, the UCS values of S9 specimen at same curing periods are obtained as 5.58 MPa, 9.97 MPa and 11.01 MPa, respectively (Fig. 2). It is also seen that the UCS values of PM1 polymer mixture (Fig. 2(a)) are approximately 2.5 times higher than that of the UCS values of PM2 polymer mixture (Fig. 2(b)).

These remarkable and rapid increases on UCS are attributed to rapid cure and adhesion properties of polymers. Similar to the findings of this study, Al-Khanbashi and Abdalla (2006), Naeini and Mahdavi (2009) and Ates (2013), based on their experimental studies on silty sand and sandy soils, pointed out that the polymers increased unconfined compressive strength at shorter curing periods (i.e., 7 days). Ates (2013) attributed this behavior to the formation of cross-linking structures by means of polymers between soil particles.

In the literature, unconfined compressive strengths of soils improved by deep soil mixing method should be between 0.5 and 5 MPa for the granular soils (Bruce *et al.* 1998, Bruce and Bruce 2003). It is observed in this study that the UCS values of 7 day-cured specimens were higher than that of the lower UCS limit (i.e., 0.5 MPa) of deep soil mixing method reported by Bruce *et al.* (1998) and Bruce and Bruce (2003). As a result, it can be said that polymer mixtures (especially PM1 at 20% percentage) and fly ash are used for deep soil mixing applications and for rapid stabilization of soils.



(a)



(b)

Fig. 2 UCS versus curing period for all mixtures

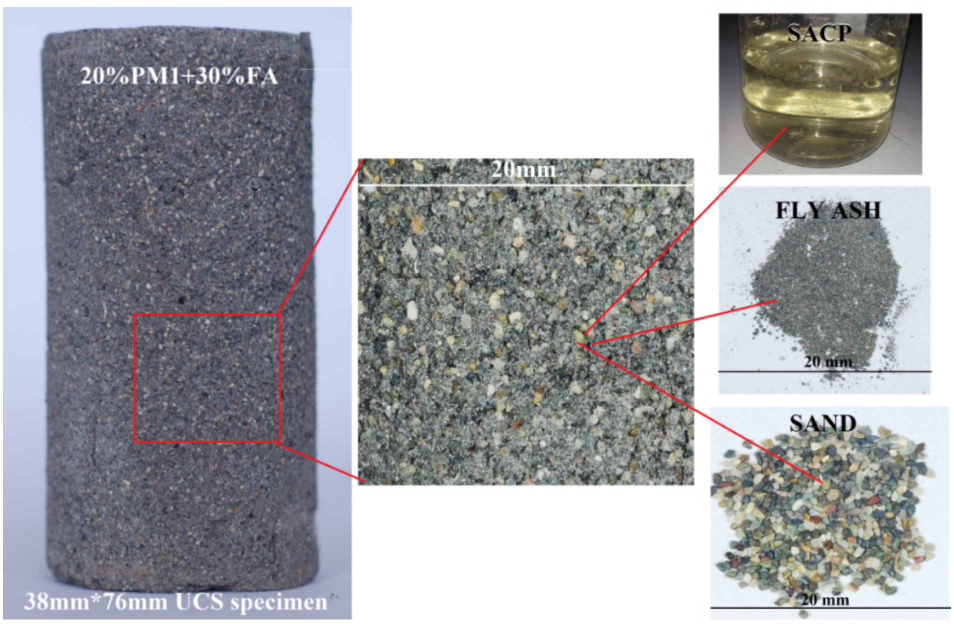


Fig. 3 Cured specimen S9 (20%PM1 + 30%FA), materials and magnified view of the specimen

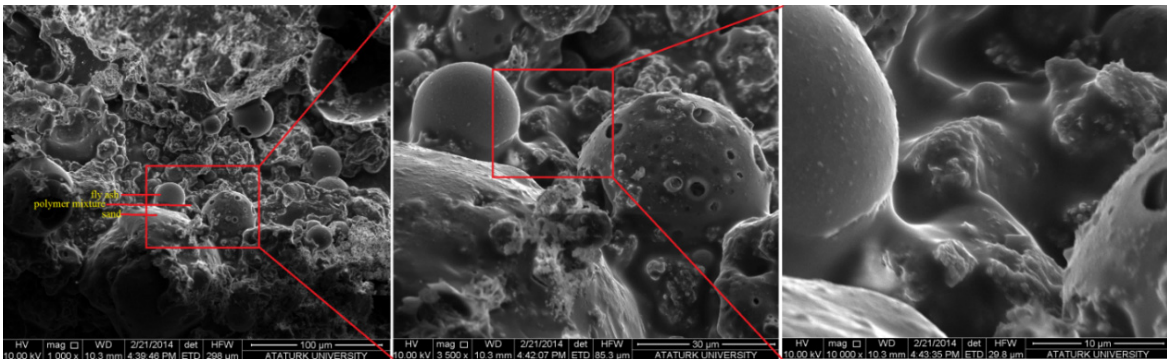


Fig. 4 SEM micrographs of S9 (20%PM1 + 30%FA)

On the other hand, the polymer and fly ash mixtures affect the durability of loose saturated sand specimens positively. The reason for this fact is considered to be that polymers are durable to ambient conditions. In conclusion, it is considered that the biopolymer (i.e., xanthan gum) reduces saturation degree of sand as similarly observed by Gupta *et al*. (2009). Due to the voids of specimens filled with fly ash and polymer mixtures, the UCS values of specimens were obtained higher than the limit values of UCS mentioned by Bruce and Bruce (2003). Additionally, Fig. 3 (i.e., shows the image of cured specimen) and Fig. 4 (i.e., shows SEM micrographs of cured specimen) support this comment. It is clearly seen from Figs. 3 and 4 that the voids among the sands are filled with fly ash and these materials are adhered by polymer mixtures. Similarly, Al-Khanbashi and Abdalla (2006) indicated that polymers alter the properties of sand by structural changes. They also observed three structural changes: the covering of the sand particles with a thin polymer film; the formation of polymer ties connecting neighboring sand particles that are not in direct contact; and the development of adhesion between neighboring sand particles that are in contact. Additionally, SACP and PVAc are also components of widely used glue types (wood glue, carpenter's glue, school glue). Therefore, the behavior of polymer mixtures could be attributed to the adhesive property of SACP and PVAc.

3.2 The effect of freeze-thaw

In order to determine freeze-thaw on specimens, a serious experimental study was conducted on 7, 14 and 28 days cured specimens. The specimens were subjected to 5 and 10 freeze-thaw cycles. The UCS values of specimens subjected (i.e., 5 and 10 cycles) and not subjected (i.e., 0 "zero" cycle) to freeze-thaw cycles are given for 7, 14 and 28 days curing periods in Fig. 5, Fig. 6 and Fig. 7, respectively. It can be seen in Fig. 5 that the decrement ratio of UCS value of S9 specimen are 2.87% and 3.40% after 5 and 10 freeze-thaw cycles, respectively. The UCS value of S9 decreases step by step from 5.58 MPa at 0 cycles to 5.42 MPa at 5 cycles and then 5.39 MPa at 10 cycles. It can be seen in Fig. 6 that the decrement ratio of UCS value of S9 specimen are 5.72% and 13.64% after 5 and 10 freeze-thaw cycles, respectively. The UCS value of S9 decreases step by step from 9.97 MPa at 0 cycles to 9.40 MPa at 5 cycles and then 8.61 MPa at 10 cycles. A similar trend occurred at 28 days curing specimens. The decrement ratio of UCS value of S9 specimen are 8.90% and 5.00% after 5 and 10 freeze-thaw cycles, respectively (Fig. 7). The UCS value of S9 decreases step by step from 11.01 MPa at 0 cycles to 10.03 MPa at 5 cycles and then

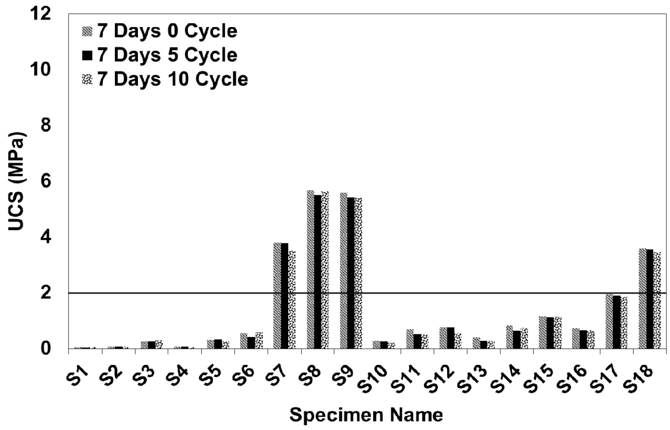


Fig. 5 The effect of freeze-thaw cycles of 7 days cured specimens on UCS

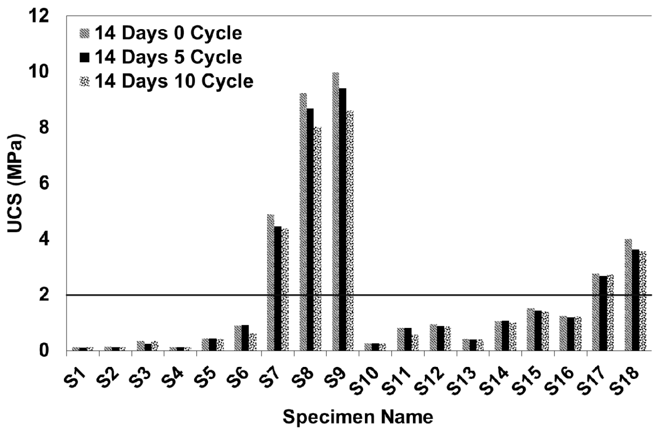


Fig. 6 The effect of freeze-thaw cycles of 14 days cured specimens on UCS

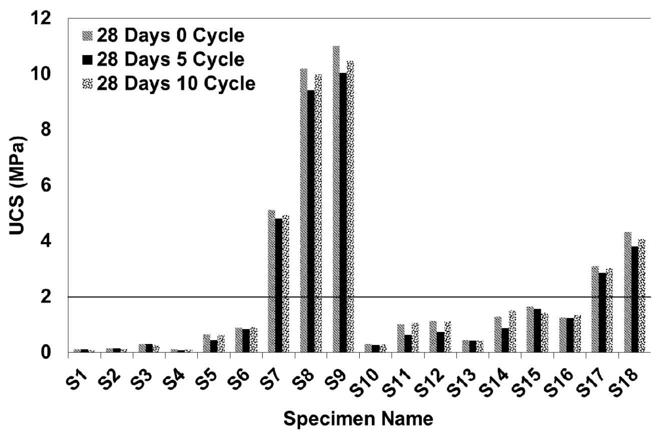


Fig. 7 The effect of freeze-thaw cycles of 28 days cured specimens on UCS

10.47 MPa at 10 cycles (Fig. 7). Similar behavior is also obtained for other specimens (Figs. 5, 6 and 7). Having similar findings of this study, Welling (2012) reported that the durability of stabilized sand specimens increased with the addition of polymer. This improvement could be explained by the ability of the polymer to adhere to the sand particles.

Figs. 5, 6 and 7 show that the specimens which have 2 MPa and over UCS values are S7, S8, S9, S17 and S18. Surface graphs in three dimensions were drawn to enable investigation of the

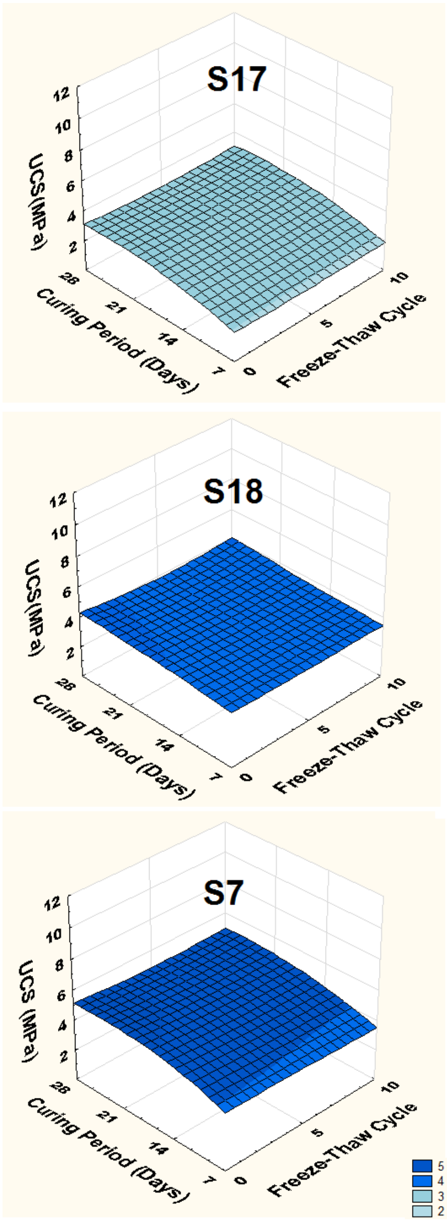


Fig. 8 3D response surface graphs with specimens (S7, S17 and S18) for combined effects of the curing period and freeze-thaw cycle on UCS

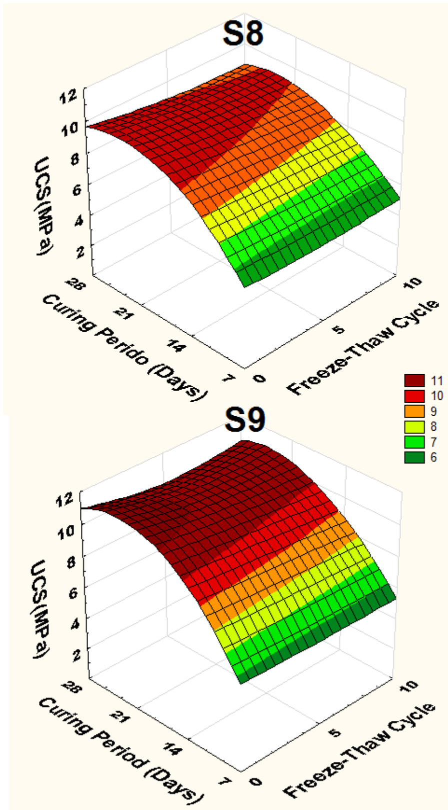


Fig. 9 3D response surface graphs with specimens (S8 and S9) for combined effects of the curing period and freeze-thaw cycle on UCS

combined effect of curing periods and freeze-thaw cycle numbers of those five specimens on UCS values. The graphs related to S7, S17 and S18 are given in Fig. 8. The graphs regarding S8 and S9 are given in Fig. 9. According to Fig. 8, the specimens of S7, S17 and S18 were not affected seriously by the curing period and freeze-thaw cycles. It can be said that those kind of specimens, which have higher strength than the suggested UCS value for deep soil mixing method and not affected by freeze-thaw cycles, may be used in the field applications which need rapid soil stabilization such as slopes that are about to slide. Furthermore, it is observed that the UCS values of 28 days cured S8 and S9 specimens reach up to 10-11 MPa (Fig. 9). There is not a serious decrease on UCS values at each curing period when specimens subjected to freeze-thaw cycles. In this sense, it could be said that in order to improve the mechanical behavior of loose saturated sands, which are exposed to freeze-thaw cycles and/or presented in liquefiable sites, mixture of SACP and fly ash can be used as binder material at those sandy soils.

4. Conclusions

In this study, to investigate the freeze-thaw effect of loose saturated sand (at 30% relative density) improved by polymers (i.e., styrene-acrylic-copolymer-SACP, polyvinyl acetate-PVAc and xanthan gum) and fly ash, unconfined compression tests were performed on specimens exposed to freeze-thaw cycles and on specimens which were not exposed to freeze-thaw cycles. The following conclusions are made, based on the test results and on the discussion presented in this study.

- The highest UCS values were obtained from S9 (20%SACP+30%FA) specimen. The UCS values of this specimen for 7, 14 and 28 days curing periods were determined as 5.58 MPa, 9.97 and 11.01 MPa, respectively.
- The curing period did not seriously affect the other specimens except for S8 (20%SACP + 20%FA) and S9 (20%SACP + 30%FA) specimens.
- PM1 (SACP) polymer mixture gave approximately 2.5 times higher UCS values than those of the PM2 (75%SACP + 25%PVAc) polymer mixture.
- The UCS values of 7 days cured specimens were higher than those of the suggested lower UCS limit (i.e., 0.5 MPa) of deep soil mixing. For this reason, polymer mixtures and fly ash can be used for deep soil mixing applications and for rapid stabilization of soils.
- Based on the experimental results, it could be said that biopolymer (xanthan gum) reduced saturation degree of saturated sand. The voids of loose sand was filled by fly ash particles. Polymer mixtures also strengthened the specimen by its feature of glue and in this way higher UCS values were obtained.
- In this study, higher UCS values up to 11 MPa were obtained by adding SACP, PVAc, fly ash and xanthan gum to loose saturated sands by using deep soil mixing method. Additionally, there was no significant effect of freeze-thaw cycles on specimens.

In this sense, it could be said that soil stabilizations to be performed by using additives used in this study can also be used as an alternative to cement and lime in the environments prevailed by cold climate and in fields where freeze-thaw is effective. It is recommended that a detailed cost analysis should be made by considering the cheapness of cement and lime according to the polymers.

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