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Performance of cement-stabilized sand subjected to freeze-thaw cycles

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Abstract. In cold regions, the integrity of the infrastructures built on weak soils can be extensively damaged by weathering actions due to the cyclic freezing and thawing. This damage can be mitigated by exploiting soil stabilization techniques. Generally, ordinary Portland cement (OPC) is the most commonly used binding material for investigating the chemo-hydro-mechanical behavior. However, due to the environmental issue of OPC producing a significant amount of carbon dioxide emission, calcium sulfoaluminate (CSA) cement can be used as one of the eco-sustainable alternatives. Although recently several studies have examined the strength development of CSA treated sand, no research has been concerned about CSA cement-stabilized sand affected by cyclic freeze and thaw. This study aims to conduct a comprehensive laboratory work to assess the effect of the cyclic freeze-thaw action on strength and durability of CSA cement-treated sand. For this purpose, unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV) tests were performed on the stabilized soil specimens cured for 7 and 14 days which are subjected to 0, 1, 3, 5, and 7 freeze-thaw cycles. The test results show that the strength and durability index of the samples decrease with the increase of the freeze-thaw cycles. The loss of the strength and durability considerably decreases for all soil samples subjected to the freeze-thaw cycles. Overall, the use of CSA as a stabilizer for sandy soils would be an eco-friendly option to achieve sufficient strength and durability against the freeze-thaw action in cold regions.

Keywords: freeze-thaw; cement-treated sand; calcium sulfoaluminate; unconfined compressive strength; durability

1. Introduction

Frost heave, thaw settlement and soil weakening induced by changes in temperature can trigger the damage mechanism in problematic soils and even subsequent collapse of infrastructure constructed on them. Such consequences of the freeze-thaw action can be prevented by exploiting soil stabilization techniques (e.g., physical, and chemical methods) (Arasan and Nasirpur 2015, Güllü and Fedakar 2017, Yilmaz and Fidan 2018). Among all of the existing soil treatment technologies, chemical stabilization with cement has proven to be the most effective method to enhance engineering behavior of the soils to achieve satisfying strength, bearing capacity, durability, compressibility, permeability, resistance to water, favorable deformation characteristics and stability (Kamei *et al.* 2012, Shooshpasha and Shirvani 2015, Zhang *et al.* 2016, Vinoth *et al.* 2018).

So far, several studies have examined the applicability of several additives (e.g., ordinary Portland cement (OPC), lime, and fly ash) for ground improvement by assessing the mechanical and physical properties of stabilized soil subjected to cyclic freezing-thawing (Parsons and Milburn 2003, Zhang *et al.* 2016). In terms of the cost and environmental characteristics, the use of OPC for geotechnical applications is less attractive, despite its easy adaptability and robustness. Hence, many studies have focused on the use of alternative binders to replace OPC. For example, calcium sulfoaluminate (CSA) cement which is an environmentally friendly binder has been investigated for ground improvement based on several laboratory testing with various conditions such as curing time, curing method, and cement/water content, without consideration of seasonal effects (Subramanian *et al.* 2018, Vinoth *et al.* 2018, Subramanian *et al.* 2019, Moon *et al.* 2020).

In concrete industry, CSA cement has been used mainly as a binder in concrete for the structures where quick repair or frost damage prevention is needed in cold regions. The degree of damage induced by freeze-thaw cycles can be controlled by different variables such as the number and duration of cycles, curing time and type, the initial density of cement, moisture and cement content, and cement type (ASTM/2166 2003, Liu *et al.* 2010, Kamei *et al.* 2012, Hotineanu *et al.* 2015, Zhang *et al.* 2016, Zhang *et al.* 2019, Jumasultan *et al.* 2020). In this study, we aim to investigate the applicability of CSA cement for soil stabilization in cold regions by assessing the effect of cyclic freeze-thaw on strength and durability. For this purpose, ultrasonic pulse velocity (UPV) and unconfined compressive strength (UCS) testing were performed on the stabilized soil specimens, which are subjected to increasing numbers of freeze-thaw cycles. The stress-strain behavior and freeze-thaw durability were analyzed in terms of the freeze-thaw cycles and CSA cement contents.

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2. Experimental work

2.1 Materials

The materials used for this research are quartz sand, CSA cement and gypsum. The physical properties of the sand are shown in Table 1, and the particle-size distribution curve of the soil is shown in Fig. 1. According to Unified Soil Classification System (USCS), the tested soil can be classified as poorly graded sand "SP".

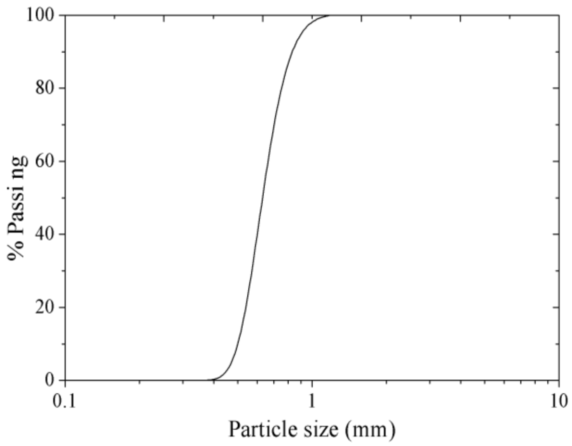


Fig. 1 Particle size distribution curve for the sand used in this study

Table 1 Physical properties of the sand used in this study

Properties	Value
Effective diameter (D_{10}) (mm)	0.39
Median diameter (D_{50}) (mm)	0.75
Coefficient of uniformity C_u	1.92
Coefficient of curvature C_c	1.00
Specific Gravity G_S	2.64

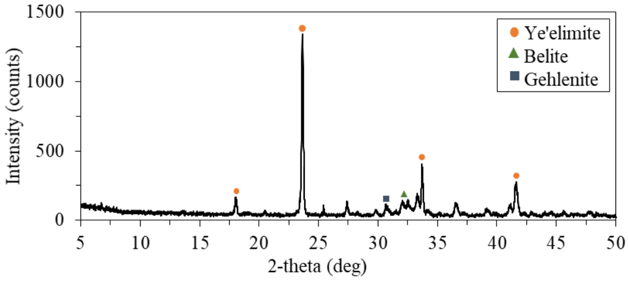


Fig. 2 X-ray diffraction analysis of CSA cement used in this study

Table 2 Standard Proctor Test results of CSA treated soil

CSA content (%)	Optimum moisture content (%)	Maximum dry unit weight (kN/m³)
3	0.39	1.59
5	0.75	1.65
7	1.92	1.69
10	1.00	1.78

The CSA cement mainly consists of ye'elimite (C_4A_3S or $4CaO{\cdot}3Al_2O_3$) that allows to make the manufacturing process ecologically friendly, whereas the alite in ordinary Portland cement produce almost 2.7 times more carbon dioxide than the ye'elimite (Gartner 2004). Fig. 2 shows the composition of CSA cement that was obtained by X-ray diffraction (XRD) analysis. CSA cement used in this study is composed mainly of ye'elimite, belite, and gehlinite, and gypsum is not present in the cement. In a recent study, the high initial strength gain and sustainable strength development were found in the soil sample when 30% of CSA cement content was replaced by gypsum (Subramanian *et al.* 2019). Therefore, in this study, the optimum gypsum content of 30% was used to replace a partial fraction of CSA content. The following reaction (Eq. 1) shows the hydration of ye'elimite in the presence of gypsum (Ukrainczyk *et al.* 2013). The final product of hydration is ettringite with the chemical formula $6CaO{\cdot}Al_2O_3{\cdot}3SO_3{\cdot}32H_2O$ or $C_3A{\cdot}3CS{\cdot}32H$.

$$\begin{gathered}4\mathrm{CaO}\cdot3\mathrm{Al_2O_3}\cdot\mathrm{SO_3}+2\mathrm{CaSO_4}\cdot2\mathrm{H_2O}\\+32\mathrm{H_2O}\rightarrow\\6\mathrm{CaO}\cdot\mathrm{Al_2O_3}\cdot3\mathrm{SO_3}\cdot32\mathrm{H_2O}+4\mathrm{Al(OH)_3}\end{gathered}\tag{1}$$

2.2 Sample preparation

The cement-sand mixtures were prepared at an optimum moisture content that was determined from the Standard Proctor Test (ASTM/D698 2007). Table 2 shows the optimum moisture contents (OMCs) for the sand samples with 3%, 5%, 7%, and 10% cement that are 17.5%, 15.8%, 14.8%, and 13.5%, respectively.

Sample preparation was carried out in three stages. Firstly, half the water was added to the dry soil and mixed by an automatic mixer for 5 minutes. Secondly, for the next 5 minutes, the cement and gypsum were mixed thoroughly with the soil. Thirdly, the remaining water was added to the mix, and blended for the last 5 minutes. Once the mixing was completed, the prepared soil samples were placed into the molds in three layers. The inner walls of the cylindrical steel molds were lubricated by oil to provide easy extrusion of the specimens. Each layer was compacted 25 times by a hand rammer, and the tops of the first and second layers were scarified to eliminate the problem of smooth compaction planes and to ensure sufficient surface-to-surface contact before placing and compacting the succeeding layer (Ding *et al.* 2018).

All specimens were prepared with a diameter of 50 mm and a height of 100 mm. Then, the prepared soil specimens were sealed with a plastic membrane to avoid a moisture loss and were put into a room with standard temperature (23 ± 2 °C) and moisture conditions. The curing periods were selected as 7 and 14 days due to early strength development of the CSA-stabilized soils.

2.3 Freeze-thaw test

In this study, a closed system was adopted to perform freeze-thaw tests, and the stabilized samples were not supplied with water during freeze-thaw cycling. The closed

Fig. 3 Schematic of experimental setup

system is appropriate for the case when there is no considerable change in the in-situ water content between winter and summer seasons. In addition, a reasonably close approximation of the field conditions can be obtained by simulating the water transport process in the closed system (Wong and Haug 1991; Hazirbaba and Gullu 2010). After each curing period, the specimens were placed into a freezing-thawing chamber (Fig. 3) where temperature and humidity are controlled. Because the lowest temperature in surface subgrade is around –20°C in Nur-Sultan, Kazakhstan (Askar and Zhanbolat 2015) and typical thawing temperature in previous studies (Ding *et al.* 2018) is +23°C, the temperature was kept at –20°C for 12 hours for freezing, and at +23°C for 12 hours for thawing. This represents one complete freeze-thaw cycle with duration of 24 hours. The freeze-thaw process was repeated for 1, 3, 5, and 7 times. The maximum number of the freeze-thaw cycle was taken as 7, as many previous studies have demonstrated insignificant changes in mechanical and physical properties of the treated soils after 5 to 7 cycles (Wang *et al.* 2007, Ding *et al.* 2018, Li *et al.* 2018).

2.4 Pulse velocity measurement

Ultrasonic pulse velocity (UPV) tests were performed to evaluate the development of stiffness of the samples treated with CSA cement. The UPV test is considered non-destructive because the test can be repeated several times for a same sample at different times, which can be particularly useful for testing soils with easily deformable structures (Sayers and Grenfell 1993, Reinhardt and Grosse 2004). There are several factors that can influence the wave velocity of granular materials, such as the number of contacts per particle, the cement percentage, the degree of saturation, and the elastic constants (Cascante and Santamarina 1996). For this study, the UPV test is applied using a portable ultrasonic non-destructive digital indicator tester (PUNDIT). Fig. 3 shows an experimental test setup with two transducers attached to the surface of samples. The diameter of the transducers are same with the diameter of the soil samples. For testing, the method of direct transmission along the longitudinal length of soil samples is used. After calibrating the device, the transducers were placed on the circular sample surfaces. The UPV value is determined from a pulse travelled along the length of sample. The transit time and pulse velocity values are directly monitored from the PUNDIT device. The UPV test was carried out after each freeze-thaw cycle according to ASTM/597-09 (2009).

2.5 Unconfined compression test

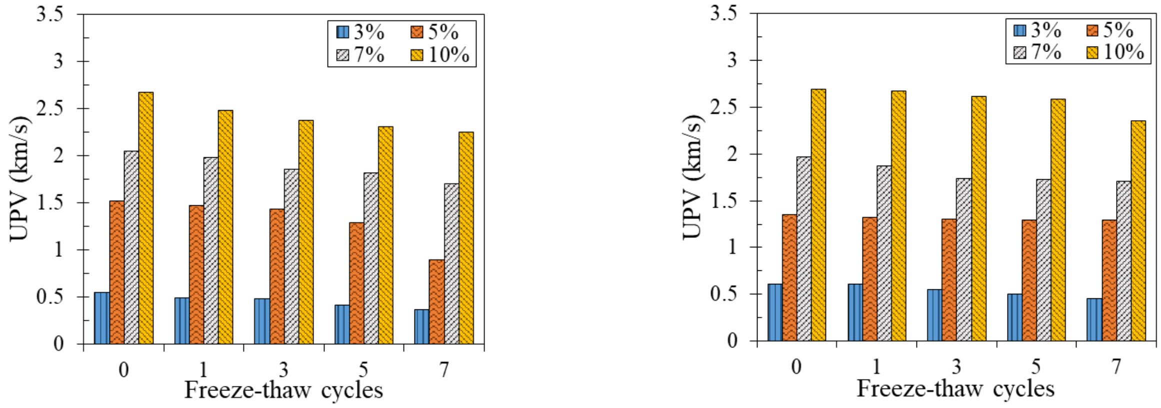
After the completion of each freeze-thaw cycle, the UPV and then the unconfined compression strength (UCS) tests were applied. The UCS test was performed with a constant displacement rate of 1 mm per minute (ASTM/2166 2003). Fig. 3 illustrates a schematic of an experimental setup where soil samples are tested first at UPV and then at UCS. In order to obtain average value of unconfined compressive strength, three samples were prepared for each combination to minimize uncertainties in the testing results.

3. Results and discussions

Fig. 4 shows the results of ultrasonic pulse velocity test for CSA cement treated sand over 7 and 14 days curing conditions. From the Fig. 4, it is clearly seen that the ultrasonic pulse velocity (UPV) value is equivalent or higher for 14 day cured specimen than 7 day cured specimens. The values of UPV increased from 547 to 2,674 m/s at 7 curing days, and from 612 to 2,695 m/s at 14 curing days, when the cement content increased from 3% to 10%. Moreover, with the increase of freeze-thaw cycles the UPV values reduced. After 7 freeze-thaw cycles the UPV values of 7 day cured specimens with 3%, 5%, 7% and 10% cement content, were decreased from 547 m/s to 366 m/s (33% reduction), from 1,517 m/s to 894 m/s (41% reduction), from 2,045 m/s to 1,701m/s (17% reduction), and from 2,674 m/s to 2,247 m/s (16% reduction), respectively. The same trend was observed for the 14 days cured specimens. The decrease of UPV with the increase of freeze thaw cycle can be explained with the increase in soil volume and micro crack formation in the transition zone (Eigenbrod 1996, Abo-Qudais 2005).

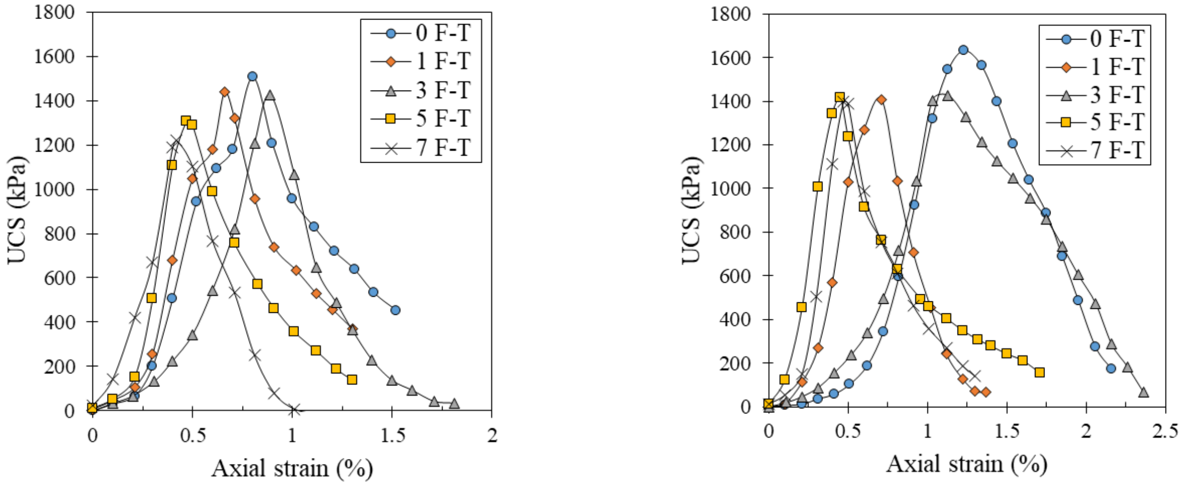
Fig. 5 presents the stress-strain relationships for the CSA-treated samples with 7% cement content subjected to 0, 1, 3, 5 and 7 freeze-thaw cycles. The results show that the freeze-thaw cycling has a significant impact on the stress-strain relationships. When the number of freeze-thaw cycles increases, the strength decreases in comparison with that of the specimens without exposure. In addition, it is clear that the peak compressive strength decreased with an increasing number of freeze-thaw cycles.

Fig. 6 shows the UCS test results for CSA cement treated sand over 7 and 14 curing days conditions. For both curing periods, the effect of freezing-thawing on strength reduction of 3% CSA cement stabilized specimens is much more pronounced compared to the specimens composed of 5%, 7% and 10% CSA content. It is attributed to the structural damage of modified soil specimens due to the formation of ice crystals between soil particles during freezing. During thawing, when the temperature is above 0ºC, the ice crystals melt and the volume of the specimen shrinks. It causes the formation of internal cracks and



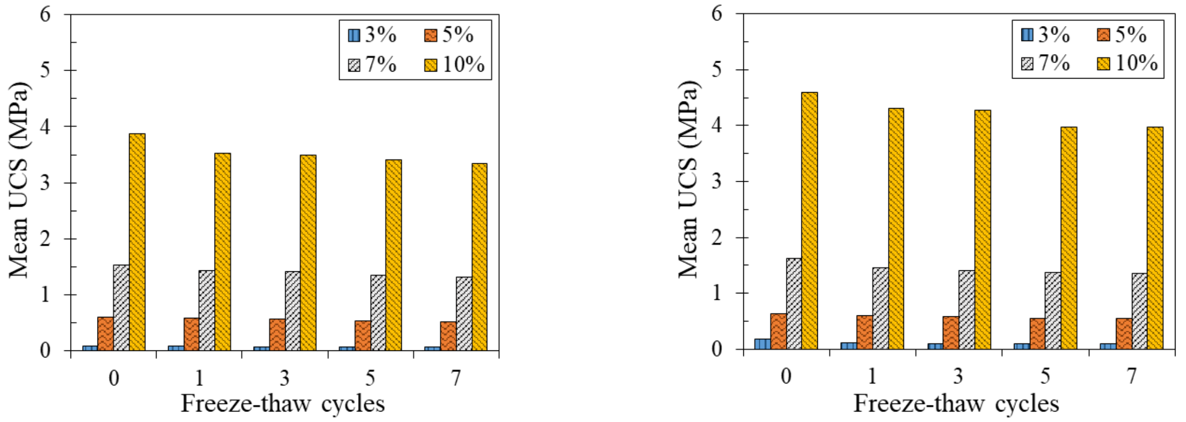
(a) 7 curing days (b) 14 curing days

Fig. 4 The UPV test results for CSA cement treated sand



(a) 7 curing days (b) 14 curing days

Fig. 5 The UCS values for the CSA cement treated sand with 7% cement content



(a) 7 curing days (b) 14 curing days

Fig. 6 The UCS test results for CSA cement treated sand

consequent soil weakening. This result is in agreement with the findings from previous researches that have studied the effect of freezing thawing on the strength of the cement stabilized soil (Liu *et al.* 2010, Shibi and Kamei 2014, Zhang *et al.* 2016, Ding *et al.* 2018). Furthermore, as presented in Fig. 6, for the specimens without freeze-thaw exposure, the compressive strength increased from 83 kPa to 3,882 kPa for 7 curing days and from 172 kPa to 4,596 kPa for 14 curing days, when the CSA cement content increased from 3% to 10%. This considerable strength

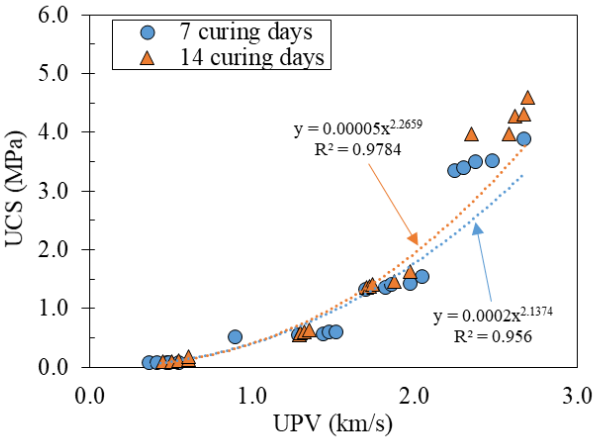
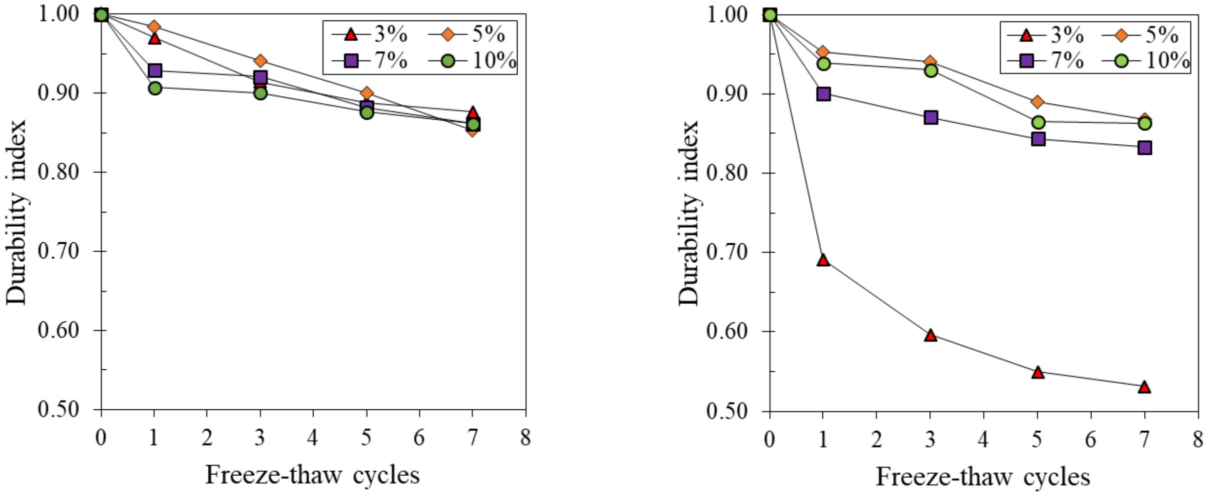


Fig. 7 Relationship between UPV and UCS



(a) 7 curing days (b) 14 curing days

Fig. 8 Effect of freeze-thaw cycles on the durability index of the CSA-treated sand specimens

development in the CSA cement-treated samples is a result of the cementation between soil particles.

The hydration of ye'elimite for short-term strength development and belite for mainly long-term strength development (after 7 days curing) contained in the CSA cement and gypsum leads to the formation of hydration products, which are either ettringite or monosulphate (Glasser and Zhang 2001, Subramanian *et al.* 2019). After 3 freeze-thaw cycles, the UCS of 7 days cured specimens with cement content of 3%, 5%, 7% and 10% decreased from 83 kPa to 75.9 kPa (8.5% reduction), from 600 kPa to 565 kPa (6% reduction), from 1,535 kPa to 1,413 kPa (8% reduction), and from 3,882 kPa to 3,495 kPa (11% reduction) and after 7 freeze-thaw cycles, reduced to 72.7 kPa (12% reduction), 512.6 kPa (15% reduction), 1,322.6 kPa (14% reduction), and 3,346 kPa (14% reduction), respectively. A similar trend was observed for 14 days cured specimens as shown in Fig. 6. It can be noted, that the amount of CSA cement in the soil mixture plays a significant role in the strength enhancement behavior, and eventually minimize the effect of freeze-thaw cycling.

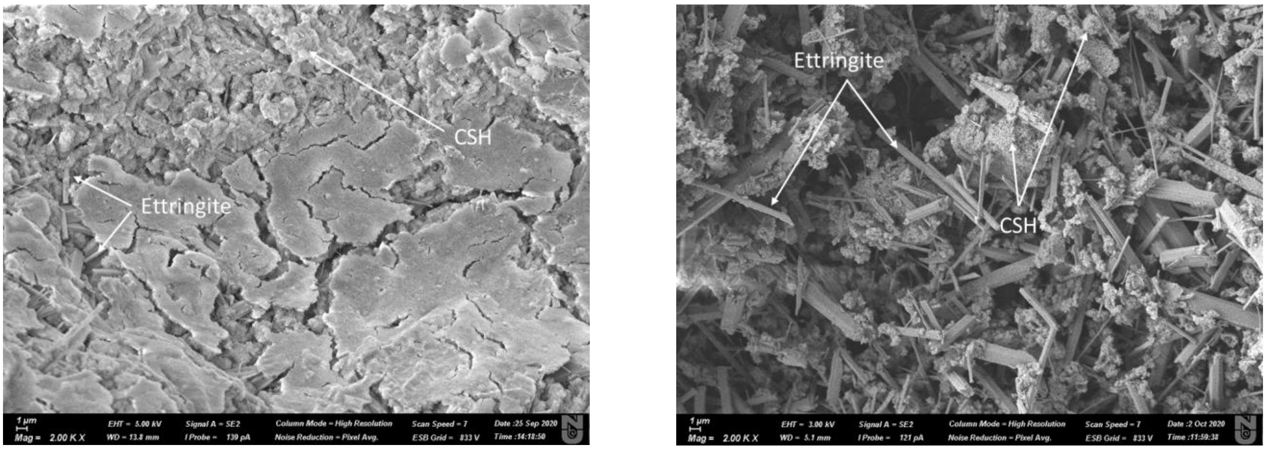
Fig. 7 illustrates the correlation between the UCS and UPV test results for 7 and 14 days cured specimens. Better correlation between the UPV and UCS tests can be observed without consideration of freeze-thaw test, as internal cracks in the soil samples formed after freeze-thaw test can distort the signals in UPV test. Therefore, the UPV test should be taken several times on the same specimen. It can be seen that with the increase of strength the pulse velocity value also increased (Fig. 7). For the evaluation of UPV and UCS tests correlation, the power relationship was established for 7 and 14 day cured specimens. From Fig. 7, it can be seen that power relationship fit with the experimental data.

To assess the effect of freeze-thaw on the durability of the treated sand with the CSA cement, the durability index was computed using Eq. (2) below:

$$\text{Durability index} = \frac{\text{UCS}_{\text{n cycle}}}{\text{UCS}_0} \times 100\% \qquad (2)$$

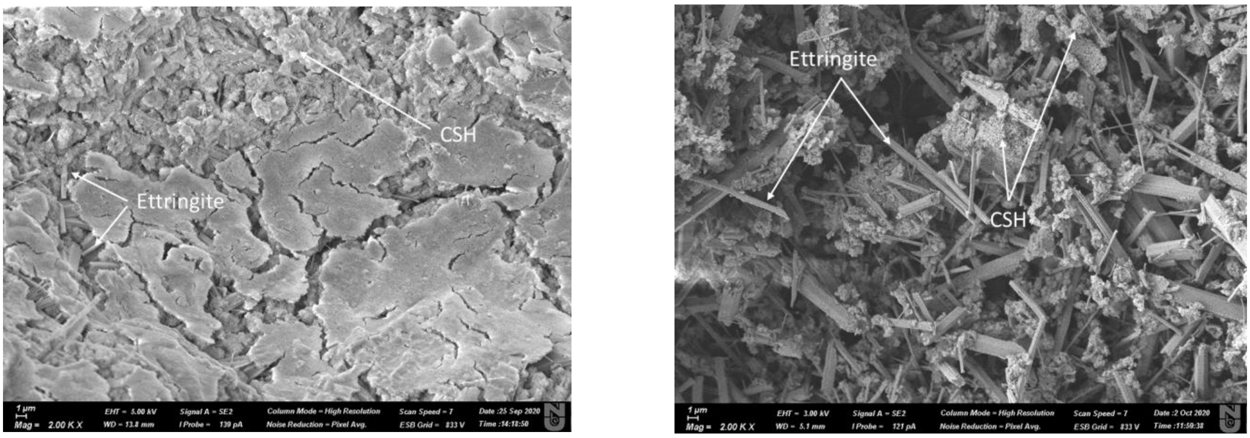
where $\text{UCS}_{\text{n cycle}}$ is the unconfined compressive strength (UCS) after the required freeze-thaw cycle, UCS_0 is the UCS of an identical specimen without exposure to the freeze-thaw cycle.

Fig. 8 presents the relation between durability index and

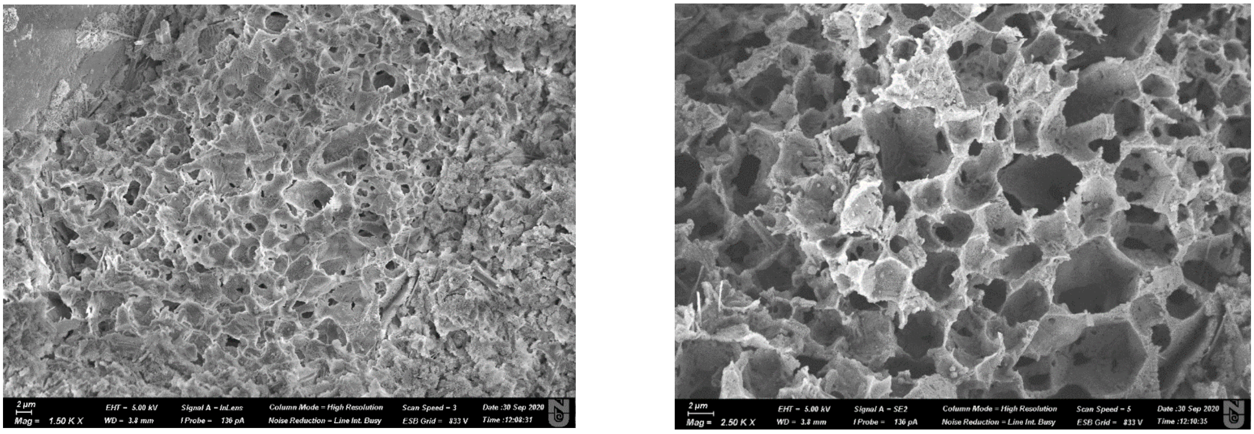


(a) 0 F-T (b) 7 F-T

Fig. 9 Microstructure of CSA cement treated soil samples



(a) 0 F-T (b) 7 F-T



(c) 0 F-T (d) 7 F-T

Fig. 10 Formation of cracks (a, b) and pores (c, d) after freeze-thaw (F-T) cycles

a number of freeze-thaw cycles with consideration of CSA content. The same trend as for UCS was observed for durability as well. After 1, 3, 5 and 7 freeze-thaw cycles, the durability index of specimens with CSA cement content of 3%, 5%, 7% and 10% decreased to 0.88, 0.85, 0.86 and 0.86 for 7 curing days, and to 0.53, 0.87, 0.83 and 0.86 for 14 curing days, respectively. Hence, it can be concluded that the CSA content has a significant effect on the improvement of strength. In addition, the increase in the numbers of the freeze-thaw cycles negatively affects the durability index, as shown in Fig. 8. This result is attributed to the development and augmentation of micro-cracks as discussed above. Shang *et al.* (2008) described that the water inside the soil particles expands in volume due to the negative temperature during freezing and tensile stresses are generated around the soil particles when the water turns to ice crystals. As a result, micro-cracks would be developed within the soil structure. The increase in the number of freeze-thaw cycles determines the number of micro-cracks since the amount of water in the cracks increases during thawing (Wang *et al.* 2007, Kamei *et al.* 2012, Ding *et al.* 2018).

More microcracks are formed, more bonds within the soil structure are damaged, and the specimens cannot sustain the required loads consequently. The subsequent loss of stiffness and deformation decreases the durability of the stabilized soils. In addition, Fig. 8 shows that the durability index reduces significantly after the first freeze-thaw cycle, and in most cases, the durability loss is inconsiderably small after the 5 freeze-thaw cycle. It can be concluded that the early freeze-thaw cycles (1 and 3 cycles) generally have a greater negative impact on the CSA-stabilized specimens than the latter freeze-thaw cycles (5 and 7 cycles). It is understandable since the water absorption through capillary rise is higher in the early cycles in contrast to the latter cycles.

Hence, the degree of saturation in the pores is not changed after 5 freeze-thaw cycles, and no more micro-cracks are formed between the soil particles. To observe changes in the microstructure of soil specimens, scanning electronic microscopic (SEM) pictures were taken before and after freeze-thaw test. Fig. 9 illustrates the microstructure of soil samples at 0 and 7 freeze-thaw cycles. The needle shaped ettringite is the product from hydration of ye'elimite that contributes to the early strength formation. Also, the hydration of belite forms CSH that has dense and fibrous structure (Subramanian *et al.* 2019). Moreover, Fig. 10 shows the presence of cracks and pores after cyclic freezing and thawing. After freezing and thawing testing, the total porosity of soil increased and large pores were formed, due to the formation of ice crystals. The changes in pore size can be explained with the dissolution of gypsum and ettringite formation.

4. Conclusions

This study illustrated the laboratory-based experimental results to investigate the impact of cyclic freeze-thaw on the strength and durability of quartz sand stabilized with CSA cement. The major findings of this study can be summarized as follows:

- Freeze-thaw cycling significantly affects the strength and durability of the soils. A considerable loss of strength was detected for 3% cement-treated sand specimens cured for 14 days. The same results can be observed for the durability index of the specimens.
- The results of ultrasonic pulse velocity have shown a same trend with the UCS test results. The stiffness of 3 and 5 percent cement treated soil specimens considerably decreased with the increase of freeze-thaw cycle.
- The early freeze-thaw cycles (1 and 3) have a greater negative influence on the durability index compared to the later freeze-thaw cycles (5 and 7).
- The minimum values of durability index were obtained after the first, third and fifth freeze-thaw cycles. However, it is not fully stabilized yet after the fifth freeze-thaw cycle. Thus, the long-term effect of freeze-thaw cycles should be examined for engineering design in seasonally cold regions in the future. In addition, the effect of water on durability should be examined by performing wet-curing cycles.

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References

Abo-Qudais, S.A. (2005), "Effect of concrete mixing parameters on propagation of ultrasonic waves", *Constr. Build. Mater.*, **19**(4), 257-263. https://doi.org/10.1016/j.conbuildmat.2004.07.022.

Arasan, S. and Nasirpur, O. (2015), "The effects of polymers and fly ash on unconfined compressive strength and freeze-thaw behavior of loose saturated sand", *Geomech. Eng.*, **8**(3), 361-375. https://doi.org/10.12989/gae.2015.8.3.361.

Askar, Z. and Zhanbolat, S. (2015), "Experimental investigations of freezing soils at ground conditions of Astana, Kazakhstan", *Sci. Cold Arid Reg.*, **7**(4), 399-406.

ASTM/597-09 (2009), Standard Test Method for Pulse Velocity through Concrete, American Society for Testing and Materials, U.S.A.

ASTM/2166 (2003), Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, American Society for Testing and Materials, Philadelphia, Pennsylvania, U.S.A.

ASTM/D698 (2007), Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort, American Society for Testing and Materials, Philadelphia, Pennsylvania, U.S.A.

Cascante, G. and Santamarina, J.C. (1996), "Interparticle contact behavior and wave propagation", *J. Geotech. Eng.*, **122**(10), 831-839. https://doi.org/10.1061/(ASCE)0733-9410(1996)122:10(831).

Ding, M., Zhang, F., Ling, X. and Lin, B. (2018), "Effects of freeze-thaw cycles on mechanical properties of polypropylene fiber and cement stabilized clay", *Cold Reg. Sci. Technol.*, **154** 155-165. https://doi.org/10.1016/j.coldregions.2018.07.004.

Eigenbrod, K. (1996), "Effects of cyclic freezing and thawing on volume changes and permeabilities of soft fine-gained soils", *Can. Geotech. J.*, **33**(4), 529-537. https://doi.org/10.1139/t96-079-301.

Gartner, E. (2004), "Industrially interesting approaches to "low-CO2" cements", *Cement Concrete Res.*, **34**(9), 1489-1498. https://doi.org/10.1016/j.cemconres.2004.01.021.

Glasser, F.P. and Zhang, L. (2001), "High-performance cement matrices based on calcium sulfoaluminat-belite compositions", *Cement Concrete Res.*, **31**(12), 1881-1886. https://doi.org/10.1016/S0008-8846(01)00649-4.

Güllü, H. and Fedakar, H.I. (2017), "Unconfined compressive strength and freeze-thaw resistance of sand modified with sludge ash and polypropylene fiber", *Geomech. Eng.*, **13**(1), 25-41. https://doi.org/10.12989/gae.2017.13.1.025.

Hazirbaba, K. and Gullu, H. (2010), "California bearing ratio improvement and freeze-thaw performance of fine-grained soils treated with geofiber and synthetic fluid", *Cold Reg. Sci. Technol.*, **63**(1-2), 50-60. https://doi.org/10.1016/j.coldregions.2010.05.006.

Hotineanu, A., Bouasker, M., Aldaood, A. and Al-Mukhtar, M. (2015), "Effect of freeze-thaw cycling on the mechanical properties of lime-stabilized expansive clays", *Cold Reg. Sci. Technol.*, **119**, 151-157. https://doi.org/10.1016/j.coldregions.2015.08.008.

Jumasultan, A., Sagidullina, N., Kim, J. and Moon, S.W. (2020), "Effect of cyclic freezing-thawing on strength and durability of sand stabilized with CSA cement", *Proceedings of the 2020 World Congress on Advances in Civil, Environmental, & Materials Research*, Seoul, Korea, August.

Kamei, T., Ahmed, A. and Shibi, T. (2012), "Effect of freeze-thaw cycles on durability and strength of very soft clay soil stabilised with recycled Bassanite", *Cold Reg. Sci. Technol.*, **82**, 124-129. https://doi.org/10.1016/j.coldregions.2012.05.016.

Li, Y., Ling, X., Su, L., An, L., Li, P. and Zhao, Y. (2018), "Tensile strength of fiber reinforced soil under freeze-thaw condition", *Cold Reg. Sci. Technol.*, **146**, 53-59. https://doi.org/10.1016/j.coldregions.2017.11.010.

Liu, J., Wang, T. and Tian, Y. (2010), "Experimental study of the dynamic properties of cement- and lime-modified clay soils subjected to freeze-thaw cycles", *Cold Reg. Sci. Technol.*, **61**(1), 29-33. https://doi.org/10.1016/j.coldregions.2010.01.002.

Moon, S.-W., Vinoth, G., Subramanian, S., Kim, J. and Ku, T. (2020), "Effect of fine particles on strength and stiffness of cement treated sand", *Granul. Matter*, **22**(1), 9. https://doi.org/10.1007/s10035-019-0975-6.

Parsons, R.L. and Milburn, J.P. (2003), "Engineering behavior of stabilized soils", *Transport. Res. Rec.*, **1837**(1), 20-29. https://doi.org/10.3141/1837-03.

Reinhardt, H. and Grosse, C. (2004), "Continuous monitoring of setting and hardening of mortar and concrete", *Constr. Build. Mater.*, **18**(3), 145-154. https://doi.org/10.1016/j.conbuildmat.2003.10.002.

Sayers, C. and Grenfell, R. (1993), "Ultrasonic propagation through hydrating cements", *Ultrasonics*, **31**(3), 147-153. https://doi.org/10.1016/0041-624X(93)90001-G.

Shang, H.S., Song, Y.P. and Qin, L.K. (2008), "Experimental study on strength and deformation of plain concrete under triaxial compression after freeze-thaw cycles", *Build. Environ.*, **43**(7), 1197-1204. https://doi.org/10.1016/j.buildenv.2006.08.027.

Shibi, T. and Kamei, T. (2014), "Effect of freeze-thaw cycles on the strength and physical properties of cement-stabilised soil containing recycled bassanite and coal ash", *Cold Reg. Sci. Technol.*, **106-107**, 36-45. https://doi.org/10.1016/j.coldregions.2014.06.005.

Shooshpasha, I. and Shirvani, R.A. (2015), "Effect of cement stabilization on geotechnical properties of sandy soils", *Geomech. Eng.*, **8**(1), 17-31. http://doi.org/10.12989/gae.2015.8.1.017.

Subramanian, S., Khan, Q. and Ku, T. (2019), "Strength development and prediction of calcium sulfoaluminate treated sand with optimized gypsum for replacing OPC in ground improvement", *Constr. Build. Mater.*, **202**, 308-318. https://doi.org/10.1016/j.conbuildmat.2018.12.121.

Subramanian, S., Moon, S.W. and Ku, T. (2019), "Effect of Gypsum on the strength of CSA treated sand", *Proceedings of the 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*, Taipei, Taiwan, October.

Subramanian, S., Moon, S.W., Moon, J. and Ku, T. (2018), "CSA-treated sand for geotechnical application: Microstructure analysis and rapid strength development", *J. Mater. Civ. Eng.*, **30**(12), 04018313. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002523.

Ukrainczyk, N., Frankoviæ Mihelj, N. and Šipušić, J. (2013), "Calcium sulfoaluminate eco-cement from industrial waste", *Chem. Biochem. Eng. Quart.*, **27**(1), 83-93.

Vinoth, G., Moon, S.W., Kim, J. and Ku, T. (2018), "Effect of fine particles on cement treated sand", *Proceedings of the China-Europe Conference on Geotechnical Engineering*, Vienna, Austria, August.

Vinoth, G., Moon, S.W., Moon, J. and Ku, T. (2018), "Early strength development in cement-treated sand using low-carbon rapid-hardening cements", *Soils Found.*, **58**(5), 1200-1211. https://doi.org/10.1016/j.sandf.2018.07.001.

Wang, D.Y., Ma, W., Niu, Y.H., Chang, X.X. and Wen, Z. (2007), "Effects of cyclic freezing and thawing on mechanical properties of Qinghai-Tibet clay", *Cold Reg. Sci. Technol.*, **48**(1), 34-43. https://doi.org/10.1016/j.coldregions.2006.09.008.

Wong, L.C. and Haug, M.D. (1991), "Cyclical closed-system freeze-thaw permeability testing of soil liner and cover materials", *Can. Geotech. J.*, **28**(6), 784-793. https://doi.org/10.1139/t91-095.

Yilmaz, F. and Fidan, D. (2018), "Influence of freeze-thaw on strength of clayey soil stabilized with lime and perlite", *Geomech. Eng.*, **14**(3), 301-306. https://doi.org/10.12989/gae.2018.14.3.301.

Zhang, W., Guo, A. and Lin, C. (2019), "Effects of cyclic freeze and thaw on engineering properties of compacted loess and lime-stabilized loess", *J. Mater. Civ. Eng.*, **31**(9), 04019205. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002858.

Zhang, Y., Johnson, A.E. and White, D.J. (2016), "Laboratory freeze-thaw assessment of cement, fly ash, and fiber stabilized pavement foundation materials", *Cold Reg. Sci. Technol.*, **122,** 50-57. https://doi.org/10.1016/j.coldregions.2015.11.005.

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