Effect of cyclic freezing-thawing on strength and durability of sand stabilized with CSA cement

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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 changes in climatic conditions, which are referred to as freeze-thaw cycles. This damage can be mitigated by exploiting soil stabilization techniques that improve the engineering properties of the soils. Generally, ordinary Portland Cement (OPC) is the most commonly used binding material as extensive researches have been studied for the behavior of the cementing agent. However, due to the issue of OPC producing a significant amount of carbon dioxide emission, calcium sulfoaluminate (CSA) cement which has a lesser carbon footprint can be used as one of the eco-sustainable alternatives. Although several studies have been conducted on the strength development of CSA treated sand for replacing OPC in ground improvement, no research has been concerned about CSA cement-stabilized sand affected by cyclic freeze and thaw. This study aims to fill such a research gap by conducting 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) was 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 when CSA content increases from 3% to 10%. The early freeze-thaw cycles (1 and 3) have a higher negative influence on the durability index compared to later freeze-thaw cycles (5 and 7). Overall, the use of CSA as a stabilizer for sandy soils would be useful to achieve sufficient strength and durability against the freeze-thaw action in cold regions.

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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). 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.

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 applied 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 (Kamei et al. 2012; Hotineanu et al. 2015; Liu et al. 2016; Zhang et al. 2019). Therefore, this study aims 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, unconfined compressive strength (UCS) testing was 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.

2. EXPERIMENTAL

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 in Fig. 1. According to Unified Soil Classification System (USCS), the tested soil can be classified as poorly graded sand “SP”.

Table 1. Physical properties of the sand used in this study.

Properties	Value
Effective diameter (D_{10}) (mm)	0.39
Mean diameter (D_{60}) (mm)	0.75
Coefficient of uniformity C_u	1.92
Coefficient of curvature C_c	1.00

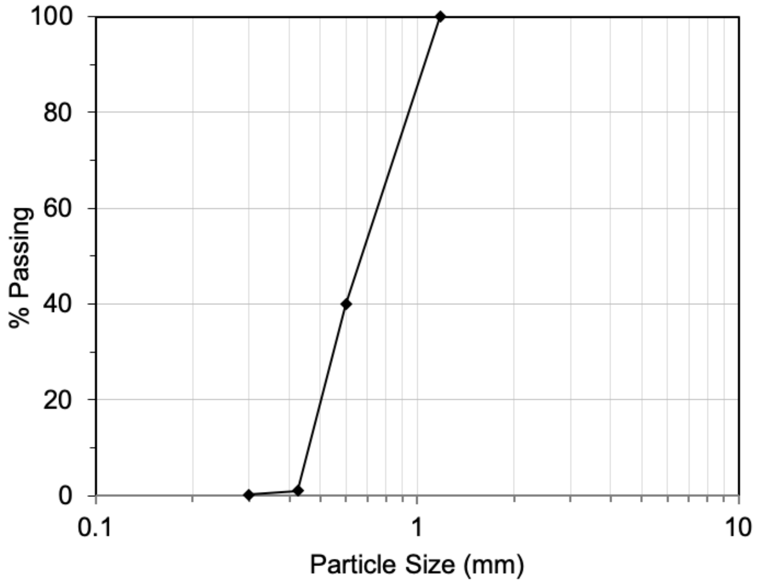

Fig. 1 Particle size distribution curve for the sand used in this study.

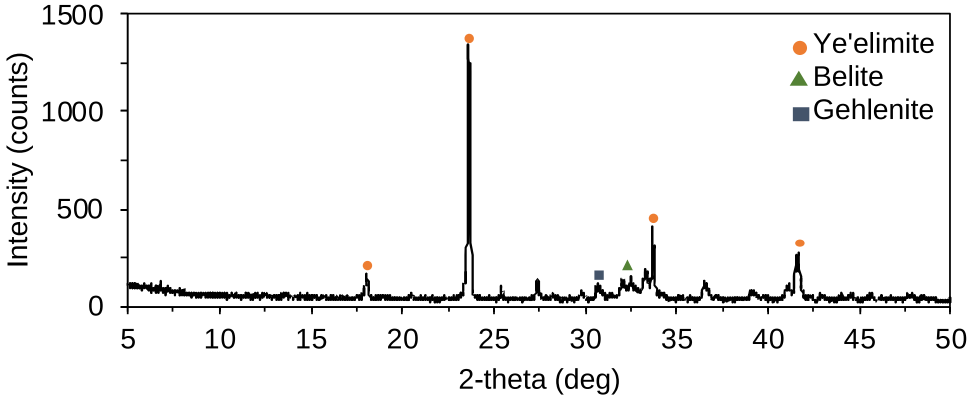

Fig. 2 X-ray diffraction analysis of CSA cement used in this study.

Fig. 2 shows the composition of CSA cement that was obtained by X-ray diffraction (XRD) analysis. CSA cement used in this study is mainly composed of ye'elimite, belite, and gehlinite, and gypsum is not present in the cement. In previous study, the high initial strength gain was detected 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.

2.2 Sample preparation

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

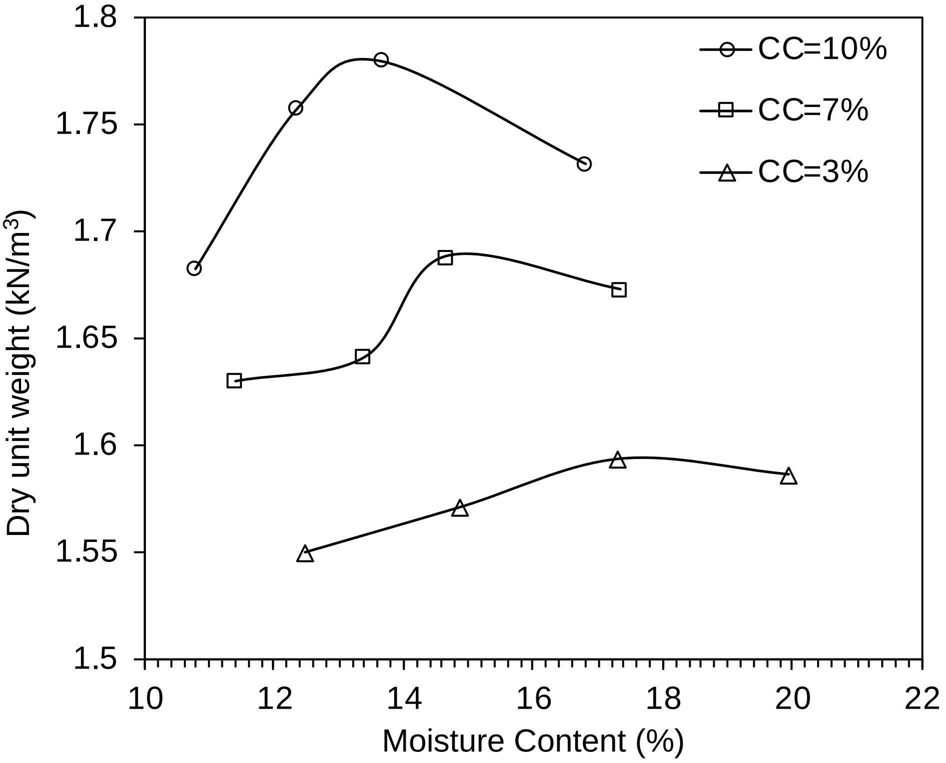

Fig. 3 Standard Proctor Compaction curves of the CSA-stabilized sand.

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 (ASTM 1996; 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 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 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). After the completion of each freeze-thaw cycle, unconfined compressive tests were performed with a constant displacement rate of 1 mm per minute.

3. RESULTS AND DISCUSSIONS

Fig. 4, Fig. 5Fig. 6 show the stress-strain relationships for the CSA-treated samples with varying cement content subjected to 0, 3, 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 performance of stress-strain relationships decreases in comparison with that of the specimens without exposure. Also, it is clear that the initial slope related to elastic modulus considerably reduced, and the peak compressive strength decreased with an increasing number of freeze-thaw cycles. 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 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 0^{o}C, the ice crystals melt and the volume of the specimen shrinks. It causes the formation of internal cracks and consequent soil weakening. This result is in agreement with 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. 4, Fig. 5Fig. 6, for the specimens without freeze-thaw exposure, the compressive strength increased from 92 kPa to 3,825 kPa for 7 curing days, and from 164 kPa to 4,596 kPa for 14 curing days, when the CSA cement content increased from 3% to 10%. This considerable strength development in the CSA cement-treated samples is a result of the cementation between soil particles. The hydration of belite contained in the CSA cement and gypsum leads to the formation of hydration products which are either ettringite or monosulphate (Glasser and Zhang 2001). After 3 freeze-thaw cycles, the UCS of 7 days cured specimens with cement content of 3%, 7% and 10% decreased from 92 kPa to 78 kPa (15% reduction), from 1,565 kPa to 1,399 kPa (11% reduction), and from 3,825 kPa to 3,543 kPa (7% reduction), and after 7 freeze-thaw cycles, reduced to 74 kPa (20% reduction), 1,388 kPa (11% reduction), and 3,503 kPa (9% reduction), respectively. A similar trend was observed for 14 days cured specimens as shown in Fig. 4, Fig. 5Fig. 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.

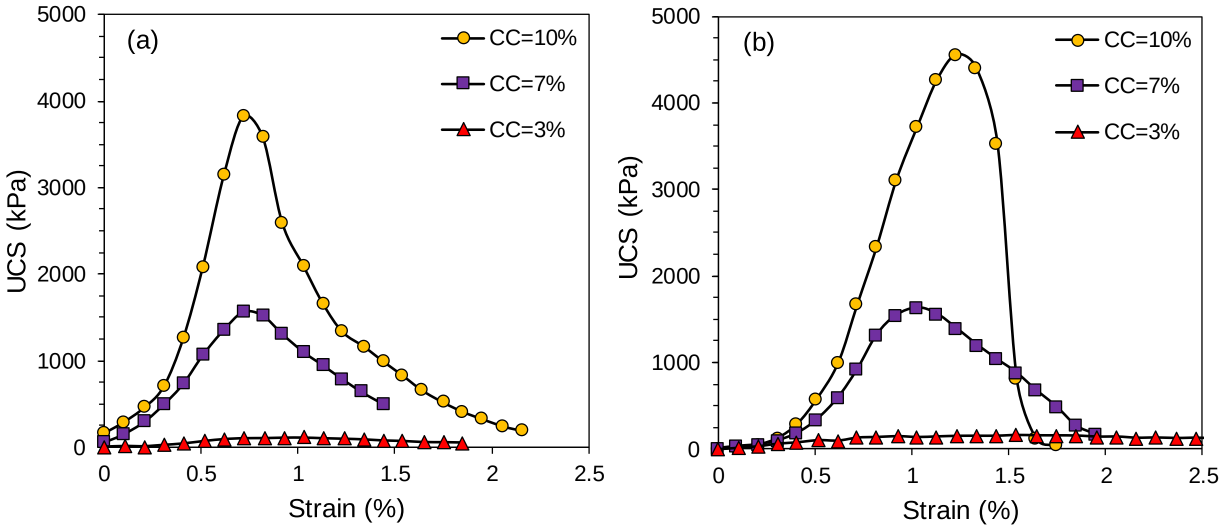

Fig. 4 Stress-strain relationship in the case of 0 freeze-thaw cycle for (a) 7 curing days and (b) 14 curing days.

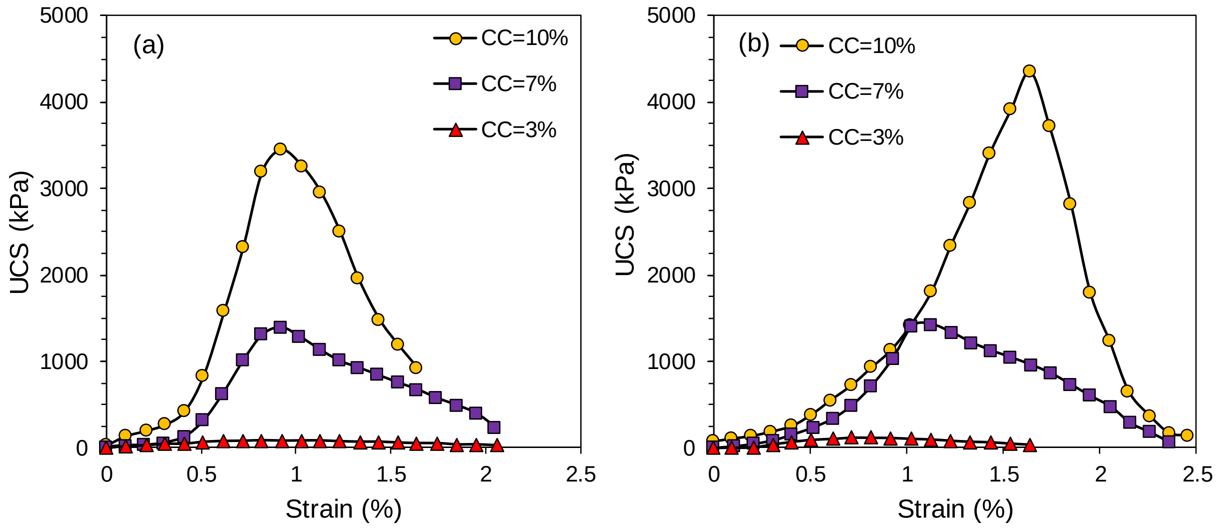

Fig. 5 Stress-strain relationship in the case of 3 freeze-thaw cycles for (a) 7 curing days and (b) 14 curing days.

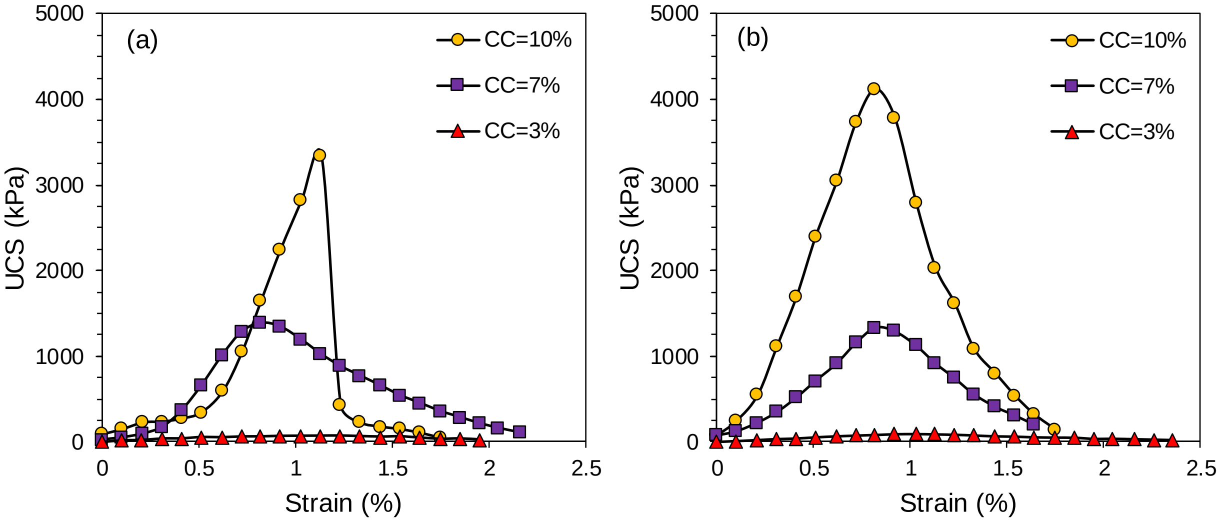

Fig. 6 Stress-strain relationship in the case of 7 freeze-thaw cycles for (a) 7 curing days and (b) 14 curing days.

To assess the effect of freeze-thaw on the durability of the sand treated with the CSA cement, the durability index was computed using Eq. (1) below:

$$\text{Durability index} = \frac{\text{UCS}_{\text{n cycle}}}{\text{UCS}_0} \times 100\% \tag{1}$$

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. 7 presents the correlation between durability index, CSA content, and a number of freeze-thaw cycles. 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%, 7% and 10% decreased to 0.8, 0.89 and 0.92 for 7 curing days, and to 0.58, 0.83 and 0.91 for 14 curing days, respectively. Hence, it can be concluded that the CSA content has a significant effect on the improvement of both strength and durability. In addition, the increase in the numbers of the freeze-thaw cycles negatively affects the durability index, as shown in Fig. 7. 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 of it, micro-cracks will 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 micro-cracks 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. 7 shows that the durability index reduces significantly after the first freeze-thaw cycle, and 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) have a higher 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.

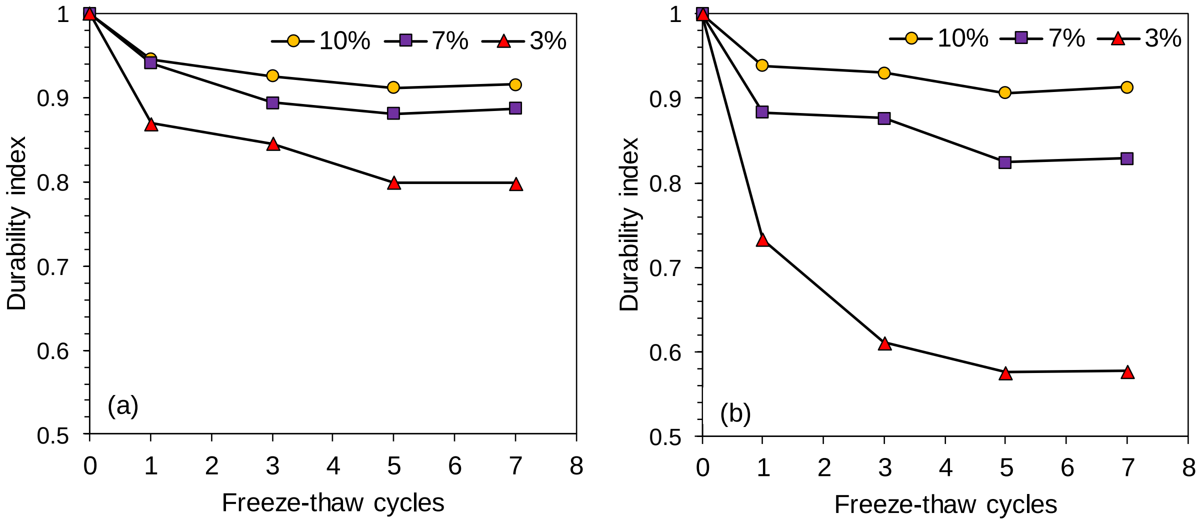

Fig. 7 Effect of freeze-thaw cycles on the durability index of the CSA-treated sand specimens cured for (a) 7 curing days and (b) 14 curing days.

3. 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:

1. The increase of the CSA amount in the soil mixture reduces the negative effect of the freezing-thawing. It should be noted that the soil samples with 10% CSA content after 7 and 14 days of curing lost only around 10% of their strength and durability index.
2. 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. The same results can be observed for the durability index of the specimens.
3. The early freeze-thaw cycles (1 and 3) have a higher negative influence on the durability index compared to the later freeze-thaw cycles (5 and 7).
4. The minimum values of durability index was obtained after the first, third and fifth freeze-thaw cycles. Then, it stabilized after the fifth freeze-thaw cycle. It is recommended to use the UCS and durability index of CSA cement-stabilized soil

experienced five freeze-thaw cycles for the engineering design in the seasonally cold regions.

In the future, the effect of water on durability should be examined by performing wet-curing cycles.

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