Examining Freeze/Thaw Cycling and its Impact on the Hydraulic Performance of a Cement-Treated Silty Sand

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ABSTRACT

Cement-based solidification/stabilization (s/s) is a remediation technology that has been widely used for treatment of a range of contaminants. Currently there is limited published data on changes in hydraulic performance of cement-treated materials subjected to cycles of freezing/thawing (f/t). Fourteen sets of tests were performed to examine the influence of factors such as number of f/t cycles, freezing temperature, curing time, and mix design on hydraulic conductivity and unconfined compressive strength (UCS) of a cement-treated silty sand. Results showed an increase of up to three orders of magnitude in hydraulic conductivity as well as decreases in UCS values after exposure to four to twelve f/t cycles. Analysis of variance (ANOVA) performed on the results of a factorial experiment considering the effect of freezing temperature, curing time, and number of f/t cycles showed that all of these factors are significant in affecting the measured changes in the hydraulic conductivity and UCS values. Monitoring of damage using the impact resonance method showed that changes in the resonant frequency of specimens was consistent with changes in hydraulic conductivity and UCS after f/t exposure and also allowed monitoring of damage for intermediate cycles with minimal effort.

Keywords: cement, soil, freeze, thaw, hydraulic conductivity, resonant frequency, compressive strength.

1. INTRODUCTION

A wide range of contaminants have successfully been treated using cement-based solidification/stabilization (s/s) technique (Bone et al. (2004); Batchelor (2006); Paria and Yuet (2006)). Depending on the desired treatment of these systems, the resulting material may be "soil-like" or in a monolithic physical form (i.e. compacted and plastic soil-cement). Monolithic s/s materials are usually designed to have a significantly lower hydraulic conductivity compared to surrounding environment to ensure the contaminant release mechanism is a slower, diffusion-controlled process (ITRC (2011)). Hydraulic conductivity is also a measure of the connectivity of the pore structure and is an important factor in the durability of cementitious materials (Hearn (1998); Hearn et al. (2006); Antemir et al. (2010)).

Although considerable research has been performed to investigate the effectiveness of cement-based s/s for treatment of different types of contaminants and matrixes (see Bone et al. (2004) for a review), current knowledge on the possible changes in the performance of these treated soils under environmental stresses is limited. In northern regions of the world (e.g. Canada and parts of USA) the long term physical performance of a cement-treated monolith after freeze/thaw (f/t) conditions is an important factor governing the success of this technology. Damage due to freeze/thaw exposure may occur shortly after placement of the material (before installation of a cover system) under immature conditions, or later in the service life of the material when it reaches the final form of the structure due to the completion of cement hydration processes. The latter type of damage was observed by Klich et al. (1999) who used microscopic techniques on field samples to show how weathering processes such as f/t can cause damage to cement-treated materials.

Despite the lack of information on the long-term performance of monolithic cement-treated soils used in cement-based s/s projects (especially for materials prepared at higher water contents) subjected to f/t cycles, there is considerable research related to the f/t effects on the performance of soils and other types of cement-based systems. This includes examination of the formation of ice lenses and subsequent increase in the hydraulic conductivity of compacted clays for landfill applications (e.g. Othman and Benson (1992); Othman and Benson (1993); ASTM-D6035, (2002)); degradation of mechanical performance (i.e. modulus of elasticity, compressive strength, etc.) in compacted soil-cement for pavement applications (e.g. Dempsey & Thompson (1973); Kettle (1986); Shihata and Baghdadi (2001)), and changes in the physical performance (i.e. dynamic modulus of elasticity) of concrete (e.g. Penttala (2006); Micah Hale et al. (2009)).

Current engineering practice for evaluating f/t resistance of s/s materials often considers percent mass loss as a performance indicator (Stegman and Coté (1996); Paria and Yuet (2006); ITRC (2011)). However, mass loss does not necessarily correspond to changes in the internal structure of a solidified soil which controls the hydraulic conductivity and inherently, the leaching potential of a cement-treated material (El-Korchi et al. (1989)). Any potential change in hydraulic conductivity under f/t exposure becomes an important consideration for the long term performance of monolithic cement-treated materials where solidification is the primary mitigation mechanism for the contaminant migration. Based on evaluation of limited number of samples, Pamukcu et al. (1994) previously showed the hydraulic conductivity of cement-treated materials can undergo up to two orders of magnitude increase under exposure to f/t cycles.

The primary objective of the current paper is to investigate the influence of various f/t testing conditions on hydraulic and mechanical performance of a cement-treated monolithic silty sand. A laboratory-based testing program was developed to assess the impact of freezing temperature, number of f/t cycles, and curing time on the hydraulic conductivity and unconfined compressive strength (UCS) of individual specimens. Influence of modifications in the mix design in improving f/t resistance of cement-treated systems is discussed. In addition, impact resonance (IR) testing was used as a non-destructive method to monitor the changes in the structure of specimens at different f/t cycles.

2. MATERIALS AND METHODS

2.1 General

The majority of testing conducted in this paper was used for a “three factor”-“two level” factorial study (Brown and Berthouex (2002)). The factorial approach was used to examine the influence of freezing temperature (-10°C vs. -2°C), number of freeze/thaw cycles (4 vs. 12 cycles), and curing time (“immature” vs. “mature”) on the hydraulic conductivity and unconfined compressive strength (UCS) of the cement-treated soil. In this paper a curing time of 16 days prior to f/t exposure is referred to as “immature” and a curing time of over 35 days prior to f/t exposure is referred to as “mature”. A summary of the different factors used in the factorial experiments and their levels is presented in Table 1. Test results obtained as part of the factorial experiments were analyzed using the Statistical Package for Social Science (SPSS) 18 software (SPSS Inc., Chicago, IL, USA) to quantify the significance of each factor. In addition to the factorial experiments, six additional tests (referred as complementary tests in this paper), were performed to further quantify the effect of lower freezing temperatures and changes in the mix design on the performance of “immature” and “mature” cement-treated soil.

A summary of exposure conditions and mix designs for all tests is provided in Table 2. In the names provided for each test series in this table, “I” refers to immature, “M” refers to mature, “04” and “12” refer to number of f/t cycles, and “-2”, “-10”, and “-20” refer to freezing temperature. Also “20%” and “LWS” refer to 20% cement content (by mass of dry soil) and “lower water to solids ratio” conditions, for the complementary tests.

2.2 Soil Characterization and Specimen Preparation

This study used a soil that classified as silty sand (SM) by the Unified Soil Classification System (USCS). The non-plastic soil had a maximum particle size of 10 mm, a coefficient of uniformity (C_u) of 17, a specific gravity of 2.7, and 30 percent passing the 75 μm sieve. General use Portland cement (ASTM Type I) was used as the binding agent for the soil-cement samples. A drill mounted paddle was utilized for mixing of the sample constituents. To prepare the test specimens, dry cement and water were first proportioned and then mixed to form a slurry in a 20 liter bucket. The soil was then incrementally added to the cement slurry and mixed to uniformity. Soil-cement mixtures were placed in three layers into cylindrical plastic molds, of 101 mm diameter by 118 mm height. Each layer was subjected to 20 strokes using a standard concrete slump testing rod to provide consistent consolidation. Molds were placed in a sealed plastic bag for 5 days before extrusion, after which the specimens were kept in a 100% humidity moist curing room prior to further testing.

2.3 F/t conditioning for exposed specimens

All of the specimens to be tested under exposed conditions (described in the following sections) were saturated under a minimum back-pressure of 524 kPa in a triaxial cell (ASTM-D5084 (2010) saturation phase). Each f/t cycle consisted of 24 hours of freezing at the required temperature (see Table 2), followed by thawing in a 100% humidity room at ambient temperature (22±1^{o}C). Complete freezing and thawing of specimens in a typical f/t cycle was confirmed by monitoring the temperature in a dummy sample with a similar mix design to the specimens being tested. Specimens were allowed to absorb ambient moisture during the thawing phase and were exposed to three dimensional freezing conditions. Such conditions (i.e. open system and three-dimensional f/t exposure) are typical of those currently used in industrial practices for compacted soil-cement and cement-based s/s materials (i.e.

ASTM-D560 (2003) and withdrawn ASTM-D4842 (2001)). Studies by Othman and Benson (1993) showed that freezing dimensionality has little effect on the changes in the hydraulic performance of compacted clays. The authors are currently undertaking work to examine the influence of one-dimensional freezing exposure on cement-treated soils.

2.4 Performance Evaluation of Specimens

2.4.1. Hydraulic conductivity testing

Hydraulic conductivity measurements were performed in general accordance of Method A of ASTM-D5084 (2010) (i.e. flexible-wall method). Permeation stage was conducted using de-aired water under a hydraulic gradient of approximately 30. Specimens for the I12-10 and M12-10 tests that experienced higher degradation after the f/t exposure were subjected to a lower hydraulic gradient of approximately 6 due to the higher hydraulic conductivity of these samples. The tests were generally terminated according to the criteria of ASTM-D5084 (2010) (i.e. outflow to inflow ratio and steady hydraulic conductivity criteria). However, in some of the complementary tests where the hydraulic conductivity values were lower than 10^{-10} m/s, acceptable outflow to inflow rates were difficult to achieve in the time span of the tests, as a result those tests were terminated when consecutive measurements resulted in a steady hydraulic conductivity value.

Two replicates of each hydraulic conductivity test were performed to consider specimen variability. Hydraulic conductivity measurements were performed before (i.e. control) and after (i.e. exposed) f/t conditioning of each specimen. The average hydraulic conductivity ratio, defined as the average for hydraulic conductivity values of exposed specimens ($K_{exposed}$) divided by the values obtained prior to exposure (K_0) is utilized to compare different scenarios.

2.4.2. Compressive strength

Unconfined compressive strength (UCS) testing was also performed on two replicates for each of exposed and control conditions. With respect to curing times, it was assumed that no curing took place during freezing of the exposed specimens. Hence, specimens (control and exposed) were tested for UCS after at least 35 days of curing in the moist room (i.e. excluding freezing time). To ensure consistency, control and exposed specimens were tested on the same day. A total of four specimens (i.e. two as control and two exposed) were used for UCS measurements of factorial experiments. For the complementary tests, only one set of specimens were used to measure control values for immature and mature f/t exposure, thus a total of six specimens (i.e. two as control and four exposed (two for each of immature and mature exposure conditions)) were tested.

All specimens were sulfur-capped prior to testing to ensure that the specimens were tested under non-eccentric axial loading. UCS values were obtained using a vertical deformation rate of 0.5 mm/min. Changes in the UCS ratio, defined as the average UCS for exposed specimens divided by the average UCS for control specimens, are reported in the results section.

2.4.3. Impact resonance (IR) testing

To further characterize the development of damage during the f/t process (i.e. intermediate cycles in addition to the 4th and 12th cycles), longitudinal resonant frequency (RF) measurements were performed using the IR method for selected tests (I12-02, I12-10, M12-02, M12-10, I12-10(LWS), and I12-10(20%) as specified in Table 2) to cover a wide range of observed f/t degradation. IR is a non-destructive test that is routinely used to predict the dynamic properties of cementitious materials (ASTM-C215 (2008)). A similar technique is suggested by ASTM-C666 (1997) to evaluate changes in the dynamic modulus of elasticity of concrete beams after exposure to rapid cycles of f/t.

In order to perform the IR testing, specimens were placed on a rectangular sponge measuring 23 by 9 by 7 cm to permit relatively unrestrained resonance under the impact load. A steel ball (9.5 mm in diameter) attached to a plastic band was used to excite the specimens on their axial centerline. A square tab of steel sheet metal (10×10×1 mm) glued on the specimen provided the base for the application of the impact. The hardness of the steel tab ensured that a consistent frequency content was created for each impact event, while impact on the damaged specimen surface could result in relatively plastic and longer duration contact. Longer contact duration may reduce and limit the available bandwidth of the forcing function and possibly influence the ability to detect the RF of the sample (Sansalone (1997)). An accelerometer (PCB model 353B02) magnetically coupled to the specimen was used to acquire the resulting signal and to transfer it to a Freedom NDT Data PC Platform (Olson Instruments Inc.) for further processing. A fast Fourier transformation (FFT) was applied to the signal in the computer's software to calculate the longitudinal RF of each specimen. Data were sampled using a 500 kHz data acquisition card with a period of 2 μs and a record size of 8192 in order to provide a frequency resolution of 61 Hz. Five replicates of the RF were measured and averaged for each of two different specimens at different f/t cycles.

The normalized changes in the longitudinal RF at the mth f/t cycle (β_m), were calculated based on Equation 1, as follows:

$$\beta_m = \frac{RF_m}{RF_0} \qquad [1]$$

Where RF_m and RF_0 are resonant frequencies at the mth and initial cycle of f/t, respectively. The average values for the normalized RF values of duplicate specimens are reported in the results section.

3. RESULTS

Of the fourteen sets of tests performed, the highest level of physical damage to the specimens was visually observed for the I12-10 and M12-10 test series. A high degree of surface degradation was observed for these tests and resulted in problems with handling and testing of the specimens, especially at higher f/t cycles. As a result of the damage to these specimens, the method of measurement for the hydraulic conductivity and strength properties did not meet the requirements of available standard methods. Hence, the residual hydraulic conductivity and compressive strength of these specimens are presented in this paper only for the sake of a rough estimate for comparison between the scenarios and completion of the factorial experiment analysis.

A summary of hydraulic conductivity and compressive strength test results are presented in Figure 1 and Figure 2, respectively. Comparing the results for control and exposed conditions show that f/t cycles can greatly influence the expected performance of solidified soils. Increases of up to three orders of magnitude in hydraulic conductivity and decreases of up to 95% in UCS values were observed. In the following sections, the changes in the ratios of hydraulic conductivity and UCS values are separately discussed for each studied factor.

3.1 Influence of f/t cycles, curing time, and freezing temperature on hydraulic conductivity and UCS

3.1.1 Number of f/t cycles

The extent of f/t cycles expected in any exposed system depends on the local climate and depth of freezing (Benson and Othman (1993); Othman et al. (1994)). Previous studies on compacted clays show that a significant portion of total damage (in terms of increase in hydraulic conductivities) can occur at exposure to initial f/t cycles (Othman and Benson (1992)). In the current study, the performance of the cement-treated soils at 4 and 12 f/t cycles was investigated. Impact resonance testing was performed on selected specimens at intermediate cycles between 0, 4, and 12 cycles.

Figure 3 presents changes in the values of the hydraulic conductivity ratio ($K_{exposed}/K_0$) with respect to the number of f/t cycles performed. It can be observed that for both immature and mature specimens exposed to -10°C, a considerable increase in hydraulic conductivity (approximately 30 to 70 fold) occurs in the first 4 f/t cycles. The damage continues as the number of f/t cycles is increased to 12, resulting in hydraulic conductivity values of up to three orders of magnitudes higher than initial conditions. Mature specimens exposed to -2°C also see a continued increase in the hydraulic conductivity from 0 to 4 to 12 cycles (approximately 10 and 500 fold, respectively). This constant increase in the hydraulic conductivity at higher f/t cycles is in agreement to reported observations in the literature on soil-cement (Guney et al. (2006)).

For immature specimens exposed to -2°C the approximately six-fold increase after 4 f/t cycles is followed by a slight decrease in hydraulic conductivity from 4th to 12th cycle, resulting in hydraulic conductivity values comparable to initial conditions. This reduction in hydraulic conductivity is likely a result of interaction between the self-healing processes and the damage development in the solidified soil. A detailed explanation of these processes is presented by Hearn (1998).

Figure 4 shows the changes in UCS ratio at different f/t cycles based on the factorial experiments. A general trend of decreasing strength can be observed for specimens exposed to -10°C as the number of f/t cycles increases from 0 to 4 to 12 (up to approximately 40 and 95% reduction, respectively). For the specimens exposed to -2°C, at 4 cycles of f/t, the changes seem to be negligible, which is in contrast to the results of hydraulic conductivity ratios (approximately 6 times increase). This might imply the unsuitability of strength indicators for predicting the hydraulic performance of solidified soils subjected to f/t cycles at early stages of damage development. As the number of f/t cycles increases from 4 cycles to 12 cycles, a contrasting response is observed for immature and mature specimens. While mature specimens exposed to 12 cycles of f/t at -2^{o}C show a decrease of over 20% in the UCS values, immature specimens seem to reach higher strengths compared to control conditions (approximately 10%). This strength gain is consistent with the trends observed for hydraulic conductivity results described above (i.e. I12-02 series). The higher compressive strength values for f/t exposed specimens compared to control conditions may also be due to the conditioning (i.e. saturation) of the specimens prior to f/t exposure.

IR results shown in Figure 5 provide some further insight on the damage occurring during the successive f/t cycles. Shifts in the RF of specimens can represent changes in their structure which may be a result of mechanical damage or section loss (reduction in the frequency) or due to curing (increase in the frequency) as the RF is proportional to the dynamic modulus of elasticity of the material (ASTM-C215 (2008)). Based on the RF ratios at the end of the first f/t cycle, two distinct types of behavior were observed at further f/t exposures. For the exposed specimens in which the frequency reduction was less than 30% of the initial value, the specimens seem to self-heal at further f/t cycles resulting in an increase in the RF ratio (I12-02, I12-10(LWS), and I12-10(20%) in Figure 5). These specimens showed a better performance in terms of hydraulic conductivity (less than an order of magnitude increase) and unconfined compressive strength (less than 10 percent decrease) changes. However, for the cases in Figure 5 where the decrease in the frequency at the end of the first cycle were more than 30%, the propagation of damage continues resulting in a considerable change in the performance of the specimens measured at the end of the 12th cycle (I12-10, M12-10, and M12-02 in Figure 5). Previous studies (e.g. Yang et al. (2009)) have shown that autogenous healing can happen at a certain crack width, which may explain the recovery in resonant frequency of certain specimens. Results imply that resistance of a solidified soil to the first cycle of f/t action may have the potential to be considered as a predictive tool for the performance of the samples at higher exposure levels. However, this conclusion needs to be examined on a larger database of experimental results.

3.1.2 Curing time

Curing time is a factor that greatly influences the length of time required to perform experiments related to cement-based materials. Current practices for the examination of soil-cement under f/t cycles suggest short curing periods prior to f/t exposure (as low as seven days in ASTM-D560 (2003) for instance). This approach overlooks the differences in the structure of the soil-cement as a result of hydration progress and also neglects the possible interference of damage formation mechanisms during f/t exposure with the hydration of cement. In this paper, the effect of curing time before f/t exposure was evaluated on specimens cured for 16 (i.e. immature) and over 35 days (i.e. mature). Visual observations showed that, in general, mature specimens undergo a higher degree of surface damage compared to immature specimens.

In Figure 6, changes in hydraulic conductivity values due to different f/t conditions are compared for exposure of immature and mature specimens. In general, a higher degree of change in the hydraulic conductivity (up to 410 times) was observed for mature specimens as compared to immature specimens. The results might suggest that immature specimens may have a higher capacity for self-healing compared to mature specimens. The exception to this was the case of exposure to 12 cycles at -10°C (factorial experiments: I12-10 and M12-10). This slightly higher increase in immature specimens is likely due to the high degradation of specimens in both cases. Comparison of compressive strength test results for different scenarios of immature and mature f/t exposure (Figure 2), however, do not suggest any notable trend.

3.1.3 Freezing temperature

One of the main concerns in the design of a testing procedure for examining the performance of cement-treated soils under f/t exposure is to estimate the conditions expected in the field and attempt to replicate these conditions in the laboratory. Freezing temperature is an important factor with this regard as it controls the rate of freezing (Newton's law of cooling) and amount of freezable water (Nmai (2006)) within a material's structure. Choosing a freezing temperature for this purpose would greatly depend on the scenario that is investigated. For cases where exposure of the s/s material during the construction phase is concerned, freezing temperatures closer to 0^oC might present a more realistic scenario. On the other hand, if the exposure in the service life of the product is of concern, harsher scenarios (lower freezing temperatures) could be preferable. Previous study by Othman and Benson (1992) on compacted clays show a slight increase in the hydraulic conductivity of exposed specimens as the freezing temperature is reduced from -1^oC to -23^oC.

In the current study, specimens were examined at three freezing temperatures (-2, -10, and -20^oC). As shown in Figure 6, for mature specimens exposed to 4 f/t cycles, it was observed that the hydraulic conductivity ratio increased as the freezing temperature decreased from -2^oC to -10^oC and -20^oC (approximately 8 and 35 times, respectively). For immature specimens exposed to 4 f/t cycles, although a six times increase in hydraulic conductivity ratio is observed for exposure to -10^oC compared to -2^oC, these values show no significant change as the freezing temperature is further reduced to -20^oC.

An increase in the hydraulic conductivity ratio (approximately 3 orders of magnitudes) with the decrease in the freezing temperature (from -2^oC to -10^oC) was also observed for immature specimens exposed to 12 f/t cycles. However, as presented in the case of the mature specimens (12 cycles), relatively similar hydraulic conductivity ratios were observed at these freezing temperatures. The reason is likely the high degree of damage at these exposure conditions that could influence the expected trends for the results.

Exposed compressive strength values (Figure 2) also show a noticeable reduction when the freezing temperature drops from -2^{o}C to -10^{o}C for most of the cases studied. However, as the freezing temperature changes from -10^{o}C to -20^{o}C (for exposure to 4 f/t cycles) contradictory results were observed. For these cases, while immature specimens showed a reduction in the UCS values, changes in the UCS values for mature specimens were negligible (See Figure 2). Therefore, the data currently available is not sufficient to suggest any trends at temperatures below -10^{o}C.

3.2 Statistical analysis of investigated factors (Factorial experiments)

A "three factor"-"two level" factorial experiment was performed to identify the effect of freezing temperature, curing time, and number of f/t cycles on the performance of solidified soils exposed to f/t cycles. Values for unconfined compressive strength ratio and logarithm of hydraulic conductivity ratio were chosen as the dependent variables in the analysis. For the hydraulic conductivity study, due to the high variability of the results in different test conditions, the logarithm of the hydraulic conductivity ratios was preferable as it helped to provide constant variance under the assumed normality of the data (Brown and Berthouex (2002)). As a result, the response, $\widehat{K}$, for each hydraulic conductivity test was calculated by:

$$\widehat{K} = \log(\frac{K_{exposed}}{K_0}) \qquad [2]$$

A summary of the testing conditions for different experiments and observed values for changes in the performance of replicate specimens (denoted as Trial 1 and Trial 2) are presented in Table 3. Analysis of Variance (ANOVA) was performed using the SPSS 18 software (SPSS Inc., Chicago, IL, USA), to examine the significance of each factor on changes in the hydraulic conductivity and UCS ratios, for which the results are presented in Table 4. The influence of a factor is usually considered significant when the corresponding p-value is less than 0.05 which means it can be claimed, with 95% confidence, that observed changes are a result of the different levels in the investigated factor (and not only due to the random error occurring between the tests). Based on the results, all of the studied factors are significant (with p-values less than 0.01) in observed changes for hydraulic conductivity and compressive strength. This is consistent with discussions presented in the previous sections. These results further emphasize the requirement for developing case specific f/t studies for cement-based s/s projects, based on the environmental conditions and specific project objectives.

3.3 Discussion

The previous sections have focused on evaluating the influence of various testing factors on the resulting damage (i.e. hydraulic conductivity and UCS) of soil-cement samples. For the majority of the tests performed, differing degrees of damage were observed for both immature and mature specimens. From a practical perspective, this does not necessarily mean that all cement-based s/s materials undergoing f/t exposure are at risk to damage, but more so that it is important to evaluate a given mixture design for risk of f/t damage using some of the techniques outlined in this paper. The mixture design used throughout the factorial tests was held constant and had a high water content, hence explaining some of the excessive damage observed from the f/t exposure. Also, the possible interaction of contaminants in cement-based s/s systems with f/t exposure degradation processes was not considered.

To demonstrate how the damage observed for this silty soil can be mitigated in a mix design for this particular soil, the complementary tests with higher cement content and reduced water to cement ratio (i.e. I12-10(20%) and M12-10(20%)) and lower water to solids ratio with 10 percent cement content (i.e. I12-10(LWS) and M12-10(LWS)) were performed. As is shown in Figure 1 and

Figure 2, by increasing the cement content and decreasing the water content, both mix design modifications may partially improve the performance of solidified soil under the f/t exposure conditions adopted. When examining the absolute hydraulic conductivity values of both these mix designs in Figure 1, it can be seen that for both immature and mature specimens, the specimens all achieved a hydraulic conductivity of less than 10^{-9} m/s, which is often the lower limit of specification set for s/s projects. Similarly, high strengths are maintained after f/t, as shown in Figure 2. As shown in Figure 6, this does not mean that damage is prevented in the specimens, but rather that damage can be mitigated by increasing cement content or lowering water to solids ratio. Lowering the water content (while keeping the cement content constant) seems to be an effective tool to improve the overall performance of solidified soil as it reduces the porosity, and consequently the amount of freezable water in the porous structure, and increases the strength of the soil-cement mixture. Currently additional testing is being performed to further evaluate the effect of water content in the mix design on the performance of soil-cement exposed to cycles of f/t.

4. CONCLUSIONS

In this study, physical performance of a cement-treated silty sand was evaluated under exposure to different f/t scenarios. A total of fourteen sets of tests were performed. The results of hydraulic conductivity and unconfined compressive strength testing show that depending on the f/t exposure scenario, a considerable change was observed for the solidified soil tested. This included changes as high as three orders of magnitude increase in the hydraulic conductivity results and strength loss of up to 95 percent based on the residual UCS values. Based on the results of statistical analysis using ANOVA, the number of f/t cycles, freezing temperature, and curing time all are significant factors in observed changes in hydraulic performance and strength of the cement-treated soil examined. Monitoring of the RF changes in the specimens show that, changes in the structure can be expected as early as one f/t cycle exposure. Changes in hydraulic conductivity and compressive strength of specimens were studied after 4 and 12 f/t cycles in factorial experiments. Results show that for most cases higher damage happens at the end of 12th cycle. This is with the exception of immature specimens exposed to -2°C which (due to the hydration process) specimens seem to “self-heal” resulting in better performance compared to results of exposure at 4 cycles of f/t.

Specimens exposed to -10°C were shown to be considerably more damaged compared to specimens exposed to -2°C. However, observations due to further reduction of freezing temperature to -20°C (as discussed based on the results of complementary tests) were inconclusive.

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Table 1: Factors and levels used in the factorial experiment.

Factors	Levels	
	Lower level	Upper level
Curing time	“Mature” (> 35 days)	“Immature” (16 days)
Freezing temperature	-10°C	-2°C
Number of cycles	12	4

Table 2: Summary of mix designs and exposure conditions for the different tests performed

		Mix design			Exposure scenario		
Test group	Test series	W/C[1]	W/S[2]	Cement content[3], %	Curing	Freezing temperature, °C	Number of f/t cycles
Factorial tests	I04-10	2.7	0.25	10	“Immature”	-10	4
	I12-10				“Immature”	-10	12
	I04-02				“Immature”	-2	4
	I12-02				“Immature”	-2	12
	M04-10				“Mature”	-10	4
	M12-10				“Mature”	-10	12
	M04-02				“Mature”	-2	4
	M12-02				“Mature”	-2	12
Complementary tests	M04-20	2.7	0.25	10	“Mature”	-20	4
	I04-20				“Immature”	-20	4
	M12-10(20%)	1.2	0.20	20	“Mature”	-10	12
	I12-10(20%)				“Immature”	-10	12
	M12-10(LWS)	1.6	0.15	10	“Mature”	-10	12
	I12-10(LWS)				“Immature”	-10	12

Note:

1. W/C: water to cement ratio.
2. W/S: water to solids ratio.
3. Cement content expressed per dry mass of soil.

Table 3: Testing program and results for the factorial experiments

Testing conditions			Log($K_{exposed}/K_0$)				UCS ratio			
curing time	f/t cycles	Freezing temperature, °C	Trial1, $\widehat{K_1}$	Trial2, $\widehat{K_2}$	Average	Variance	Trial 1	Trial 2	Average	Variance
“Immature”	4	-2	0.82	0.77	0.80	1.6E-03	0.95	1.01	0.98	1.8E-03
“Mature”	4	-2	1.19	0.78	0.98	8.3E-02	0.96	1.02	0.99	1.8E-03
“Immature”	12	-2	0.06	0.20	0.13	9.3E-03	1.09	1.10	1.10	5.0E-05
“Mature”	12	-2	2.95	2.61	2.78	5.7E-02	0.77	0.74	0.75	4.5E-04
“Immature”	4	-10	1.34	1.68	1.51	5.5E-02	0.85	0.97	0.91	7.2E-03
“Mature”	4	-10	1.94	1.76	1.85	1.7E-02	0.62	0.50	0.56	7.9E-02
“Immature”	12	-10	3.50	2.34	2.92	6.7E-01	0.27	0.15	0.21	7.2E-03
“Mature”	12	-10	2.42	3.10	2.76	2.3E-01	0.02	0.09	0.05	2.5E-03

Table 4: P-values based on the results of ANOVA test on hydraulic conductivity and UCS changes

Factor	P-value	
	$\mathrm{Log}(K_{exposed}/K_0)$	UCS ratio
Curing time	3.9×10^{-3}	1.1×10^{-4}
Number of f/t cycles	1.7×10^{-3}	3.7×10^{-6}
Freezing temperature	4.1×10^{-4}	1.1×10^{-7}

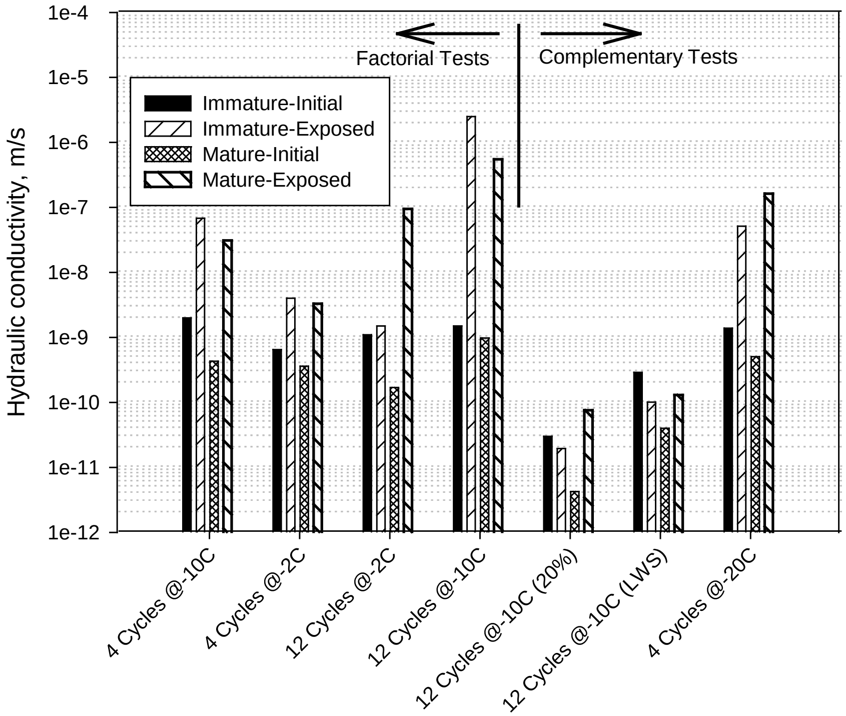

Figure 1: Summary of hydraulic conductivity results for different exposure scenarios and mix designs.

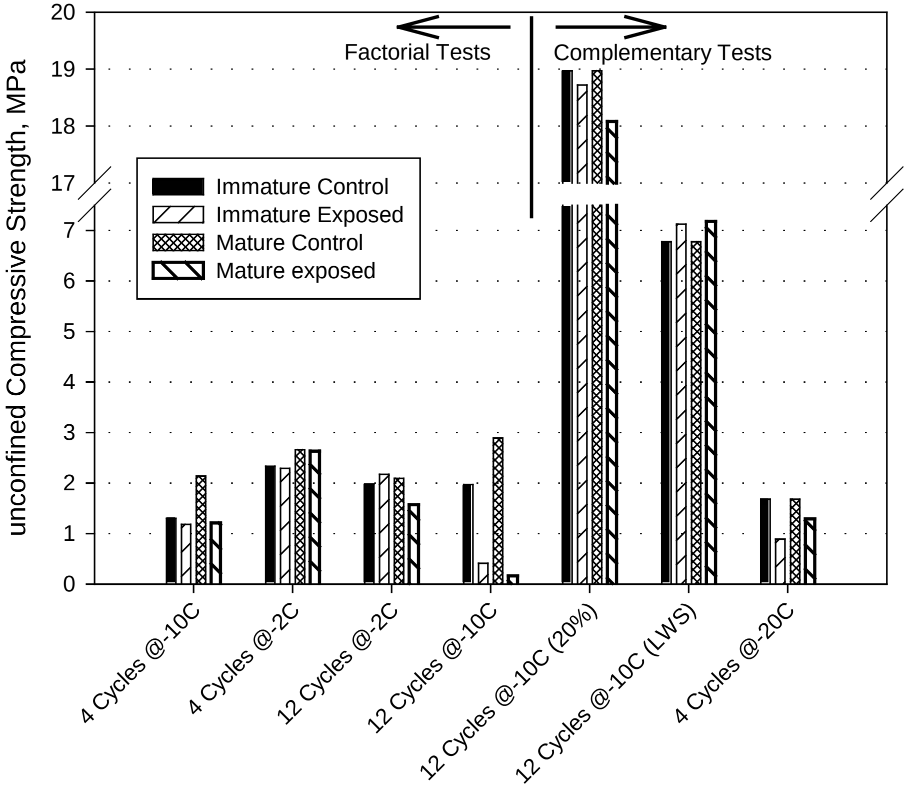

Figure 2: Summary of UCS test results for different exposure scenarios and mix designs.

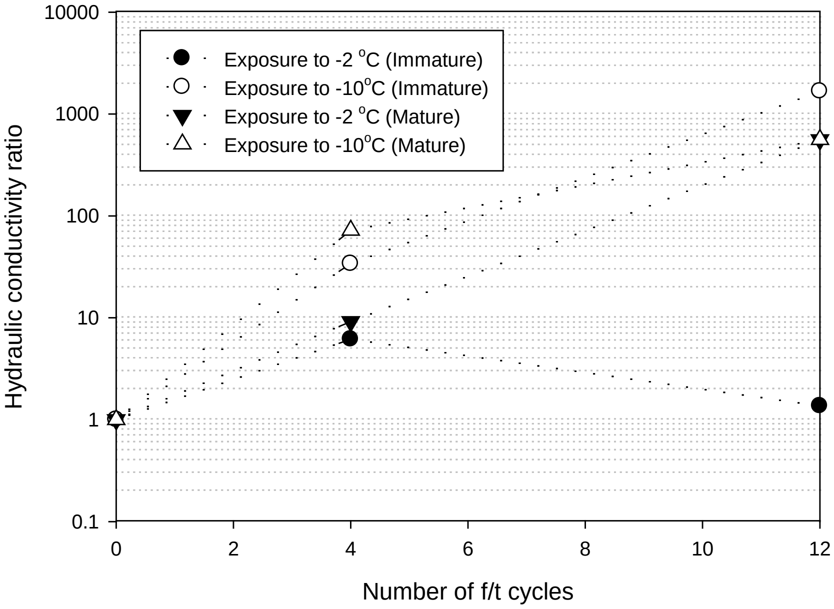

Figure 3: Changes in hydraulic conductivity ratios at different f/t cycles.

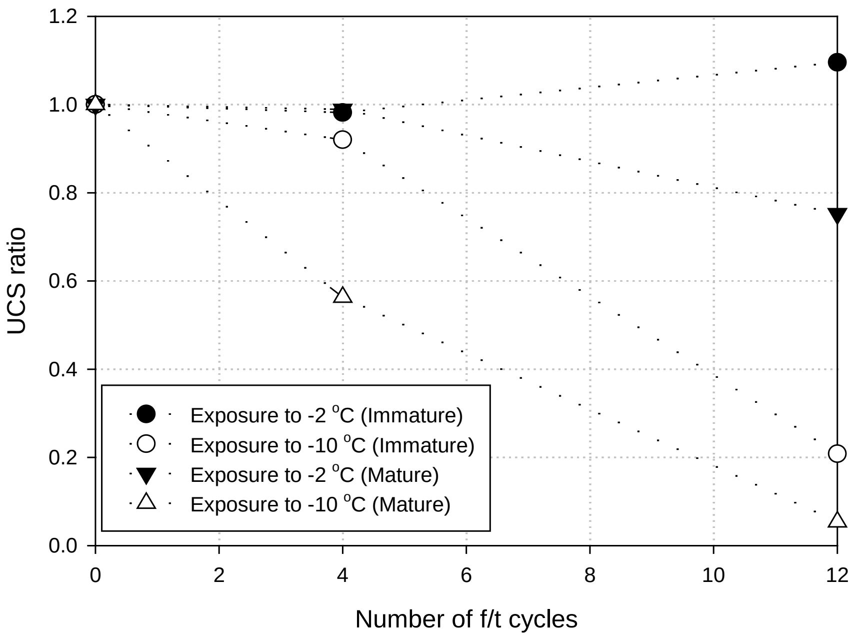

Figure 4: Changes in the UCS ratios due to exposure to different number of f/t cycles.

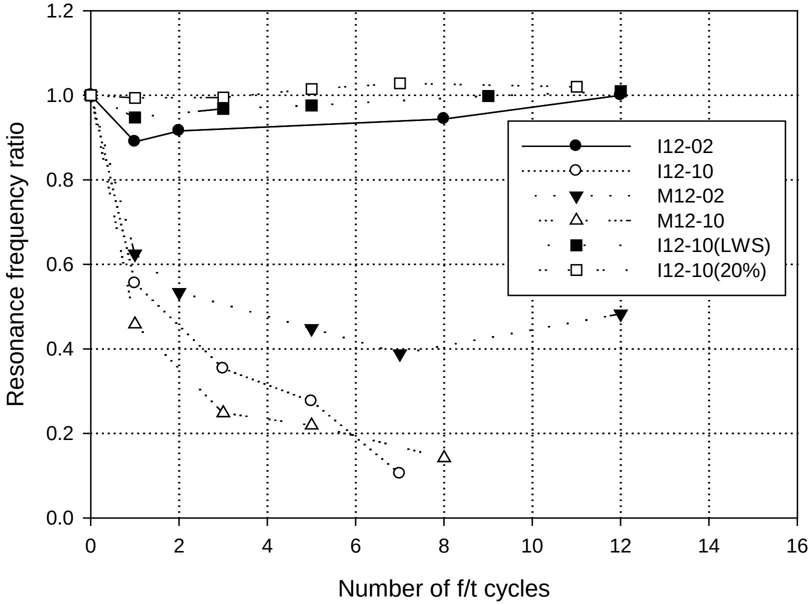

Figure 5: Changes in the resonant frequency ratio after exposure to different f/t scenarios.

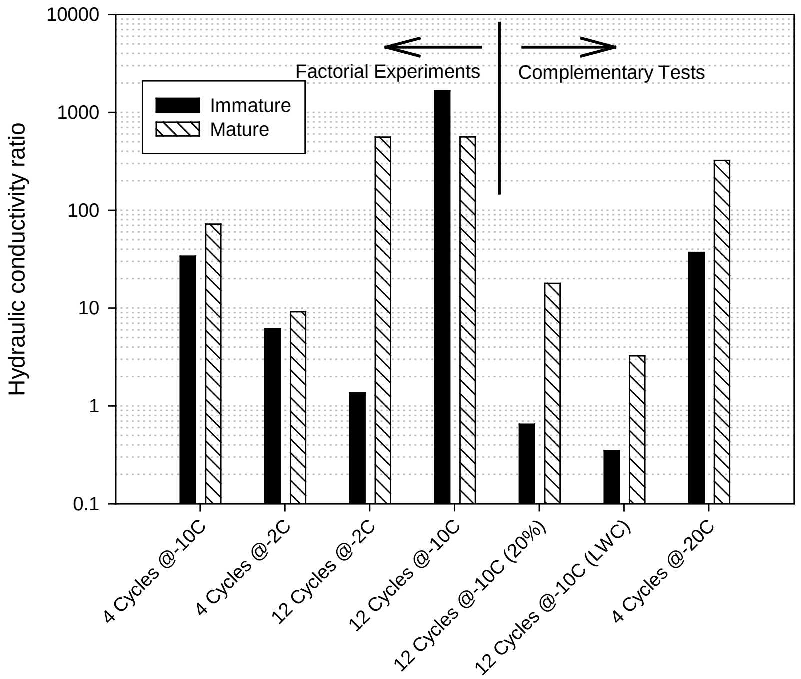

Figure 6: Comparison of the hydraulic conductivity changes for different scenarios of mature and immature conditions.