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Laboratory freeze–thaw assessment of cement, fly ash, and fiber stabilized pavement foundation materials

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ABSTRACT

Freeze–thaw cycles in pavement foundation layers can cause rapid accumulation of pavement damage. To reduce the effects of freeze–thaw cycles, there is a need to characterize and design low frost susceptible foundation layers. This paper focuses on the laboratory frost-heave and thaw-weakening performance of pavement foundation materials that were stabilized with combinations of self-cementing class C fly ash, Portland cement, and polymer fibers. Additions of fly ash (15% by weight), cement, and cement + fibers presented improvement on frost susceptibility of soils. Grain size distribution and curing time and compaction delay of chemical stabilization influenced soil freeze–thaw performance. The heave rate has to be controlled to less than 4 mm/day to achieve very low thaw-weakening susceptibility per ASTM D5918. A proposed classification for chemically stabilized soils identifies thaw-susceptibility as negligible for post-test CBR values ≥ 100.

1. Introduction

In seasonal frost regions, pavement foundation materials are subjected to cyclic freezing and thawing. In Iowa, where this study was undertaken, the upper 0.3 m of the pavement foundation materials can be subjected to approximately 10 to 50 freeze–thaw cycles annually (Fig. 1). Because cyclic freeze–thaw can significantly change the mechanical properties of the foundation layers, there is great interest in selecting durable materials and stabilizing poor materials. The mechanisms of frost heave have been studied extensively and can be generally described as the uptake of water during freezing (Brandl, 2008; Cassagrande et al., 1931; Lai et al., 2005; Taber, 1929) which is normally followed by weakening during and after thawing. Resilient modulus, California bearing ratio (CBR), and pre-consolidation pressure can be reduced by cyclic freeze–thaw action (Qi et al., 2008; Wang et al., 2007).

Capillary barriers and improved drainage can reduce the effects of freezing by stopping the uptake of water (Henry, 1990) while chemical stabilization of materials can improve freeze–thaw performance by modifying the soil structure (Becker et al., 2014; Dempsey and Thompson, 1973a; White et al., 2013). Generally, laboratory freeze–thaw tests are needed to verify performance of chemically or mechanically stabilized soils. Although research into the effects of freeze–thaw cycles has been conducted (Beskow, 1935, 1991; Cassagrande et al., 1931; Chamberlain, 1986; Johnson, 2012; Zhang, 2013), there is limited research about the effects of frost-heave and thaw-weakening on relationships between geomaterials and stabilizers used in pavement foundations. This study differs from previous research in that the laboratory freeze–thaw testing apparatus used in this study simulated a range of pavement foundation materials and stabilization methods subjected to typical frost penetration conditions in two ways. First, instead of controlling only air temperature during testing, the temperatures at the top and bottom of the specimens were controlled. Second, the test apparatus provided a continuous water supply.

In this study, laboratory freeze–thaw tests were conducted to determine the frost-heave and thaw-weakening performance of stabilized pavement foundation materials. Self-cementing Class C fly ash (per ASTM, 2003), type II portland cement, and two types of polymer fiber were selected as the stabilizers. To evaluate freeze–thaw performance, special laboratory equipment was fabricated to meet the requirements of ASTM, 2006. The test results are evaluated in terms of the frost-heave and thaw-weakening susceptibility rating as defined in ASTM, 2006. Because many of the post-test CBR measurements from this study were greater than 20, which is the upper limit in the test standard, an alternative frost susceptibility rating is proposed.

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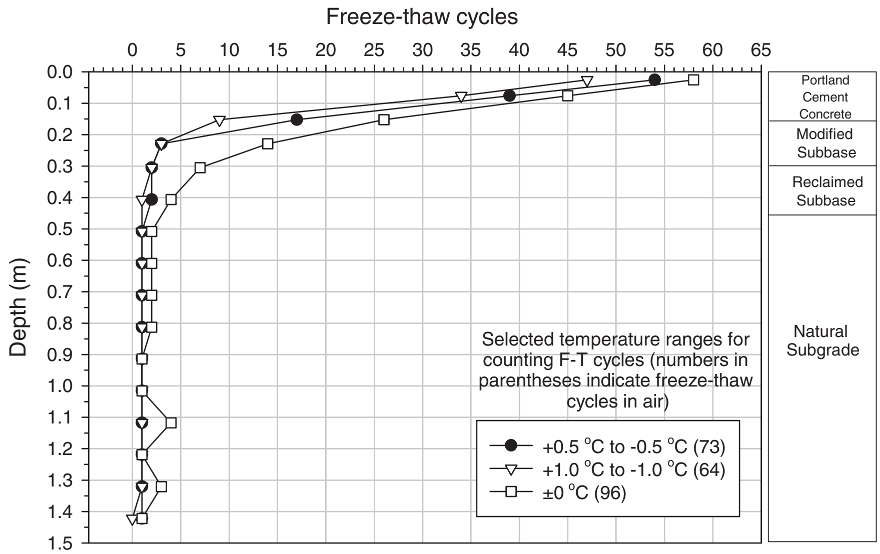

Fig. 1. Freeze–thaw profile of a typical Iowa pavement foundation (data collected in Boone County, IA Hwy 30, from Fall 2013 through Spring 2014).

2. Background

Testing freeze–thaw performance of stabilized soils requires special laboratory equipment. Chamberlain (1987) developed a five-day test that is the basis for the current ASTM, 2006. The Chamberlain test required two freeze–thaw cycles controlled by a top plate set to −4 °C (25 °F) and bottom plate set to 1 °C (33.8 °F). The resulting frost penetration rate was nominally 12.7 mm/day (0.5 in./day). Based on analysis of temperature gradient conditions, Svec (1989) suggested a modification to the D5918 protocol that better reflects in situ conditions while the freeze–thaw analysis should represent the largest heave potential. Accordingly, ASTM D5918 (2006) now presents 9 periods for conditioning, freezing, and thawing for one set of freeze–thaw testing. The temperatures vary from −12 °C to 3 °C at the specimen top plate and from 0 °C to 3 °C at the bottom plate. Zhou et al. (2014) reported a frost heave and ice lenses investigation utilizing a 1-D freezing laboratory testing. At the initial freezing stage, a small amount of pore water drained out and no frost heave was obtained. Consequently, external supplied water was attracted into soil specimens to fill the voids. Frost heave was observed until the amount of attracted water reached the amount of water drained out. Wang et al. (2015) conducted an experimental study focusing on effects of freeze–thaw cycles on silt. The freeze–thaw test apparatus utilized in that study was similar to the apparatus specified in ASTM, but the freeze–thaw cycles conditioning procedures were different. Wang et al. (2015) reported that in a total of seven freeze–thaw cycles, the first freezing period was 28 h including an initial 14-hour isothermal process, and consequently repeated 12-hour freezing and 12-hour thawing were subjected to the specimens. The temperatures of water bath plate at the top of specimens were set to −3.5 °C and 5 °C at freezing and thawing periods respectively. However, different temperatures were adopted in various studies. For example, Kang and Lee (2015) reported a freeze–thaw study on sand-silt mixtures and they used −13.5 °C for 18-hour freezing and then gradually increased to 20 °C for thawing.

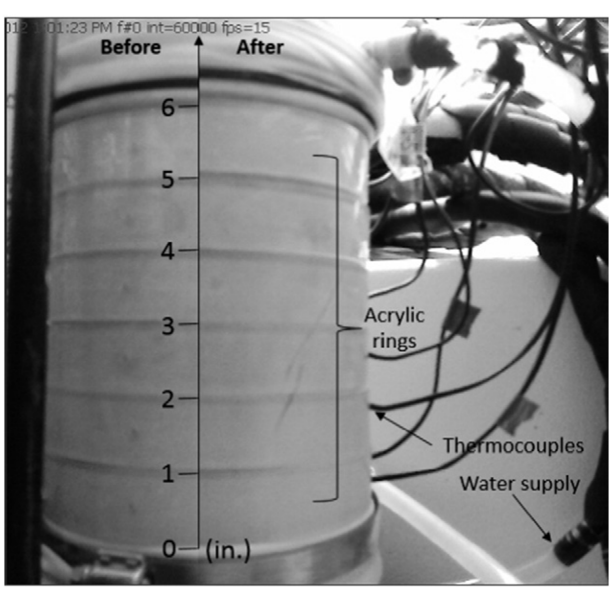

Fig. 2. Side by side specimen assembly before/after freeze0-thaw testing (1 in. = 25.4 mm).

Chemical stabilizers have long been studied to reduce the frost susceptibility of soils (Dempsey and Thompson, 1973b; Janoo et al., 1997). Janoo et al. (1997) obtained non-frost susceptible ratings using as little as 2% Portland cement for gravels. Guthrie et al. (2007) conducted laboratory freeze–thaw tests on silty soil and reported that the addition of 3.5% to 5.0% cement effectively reduced frost susceptibility; however, it was noted that excessive cement may lead to pavement damage from shrinkage cracking or insufficient cement may result in worse frost-heave behavior. Johnson (2012) reported that frost-heave of western Iowa loess (primarily silt size) can be effectively controlled with cement stabilization. Shibi and Kamei (2014) investigated the

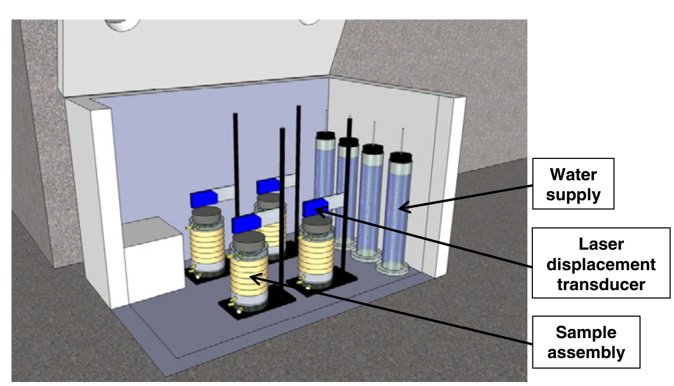

Fig. 3. Idealized view of the temperature control chamber (Johnson, 2012).

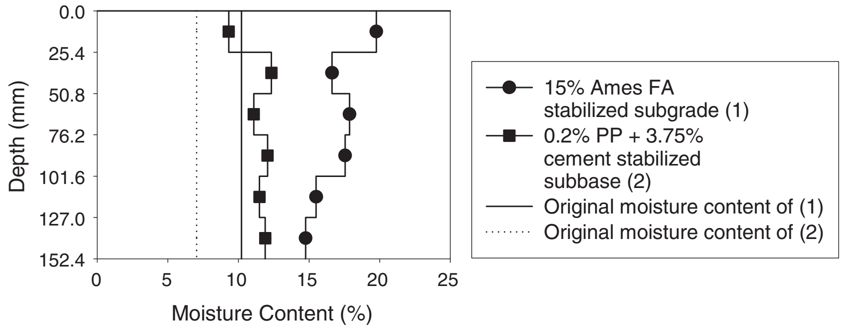

Fig. 4. Moisture content profiles of two different specimens.

changes in unconfined compressive strength (UCS) of cement stabilized soft clay under freeze–thaw cycles. Up to five freeze–thaw cycles were subjected to cement stabilized specimens mixed with and without recycled bassanite and fly ash, and 24-hour freezing at −10 °C and 24-hour thawing at room temperature were set for each cycle. The results indicated that the UCS of specimens with cement only decreased to 50% after testing compared to the specimens without freeze–thaw cycles. Interestingly, the addition of either recycled bassanite or fly ash improved this value to 55–65%. Further, around 65–85% post freeze–thaw testing UCS can be obtained if both recycled bassanite and fly ash were added. Eskisar et al. (2015) analyzed the soil property changes of cement stabilized fat and lean clay under freeze–thaw cycles. An important difference between this study and Shibi and Kamei (2014) was Eskisar et al. (2015) evaluated the Atterberg limits besides UCS. A key finding from this study was the liquid limit decreased and the plastic limit increased after freeze–thaw testing, which resulted in a decrease in plastic index.

Self-cementing fly ash is commonly used to dry out wet soils and to stabilize weak soil due to its calcium oxide content pozzolanic nature. Rosa (2006) and Cetin et al. (2010) reported that resilient modulus is reduced 20 to 70% for mixtures of fly ash and pavement foundation materials because of freeze–thaw cycles. Results from fly ash stabilized materials for the purpose of controlling freeze–thaw performance are variable in the literature and may be related to the variable chemical composition of fly ash and variations in curing times evaluated. Bin-Shafique et al. (2010), however, reported that fly ash stabilized soils experienced up to 40% strength loss due to freeze–thaw cycles. Johnson (2012) studied the frost-heave and thaw-weakening performance of self-cementing Class C fly ash stabilized loess and reported that improvement was not evident. Solanki et al. (2013) reported that Class C fly ash increased the freeze–thaw durability of silt and clay based on UCS and resilient modulus tests. Wei et al. (2015) designed and constructed laboratory apparatus to investigate the effect of freeze–thaw cycles on mechanical properties of silty clay. The apparatus and specimen assembly used in this study appropriately simulate the pavement structures and conditions including dynamic loading. Experimental moduli representing stiffness, which were defined as the maximum stress over maximum strain, were evaluated for unstabilized and fly ash and crumb rubber stabilized silty clay. The moduli of unstabilized specimens decreased 20.58%, 19.09%, and 17.75% under 32, 42, and 52 Hz dynamic load frequencies under freeze–thaw cycles. Interestingly, the moduli of stabilized specimens presented increases after freeze–thaw testing. The authors stated that fly ash and crumb rubber improved the cohesion of silty clay and strengthen the soil structures (Wei et al., 2015).

Allen et al. (1983) reported that fiber type based on hydrophobicity influences frost-heave in soils. The literature suggest that there is some benefit of using fibers, but the results are variable. Fiber reinforcement is still an emerging technology in soil stabilization. Under non-freeze–thaw conditions, compressive strength of fine-grained soils can be increased up to 25% with fibers (Freitag, 1986). Gray and Al-Refeal (1986) also found the addition of fibers into sand increased the ultimate strength and stiffness. They found the strength increased linearly up to a fiber weight content of 2%. For sandy silt, CBR increased from 65% to 133% by using monofilament fibers (Fletcher and Humphries, 1991). Hoover et al. (1982) reported that the addition of fibers reduced frost

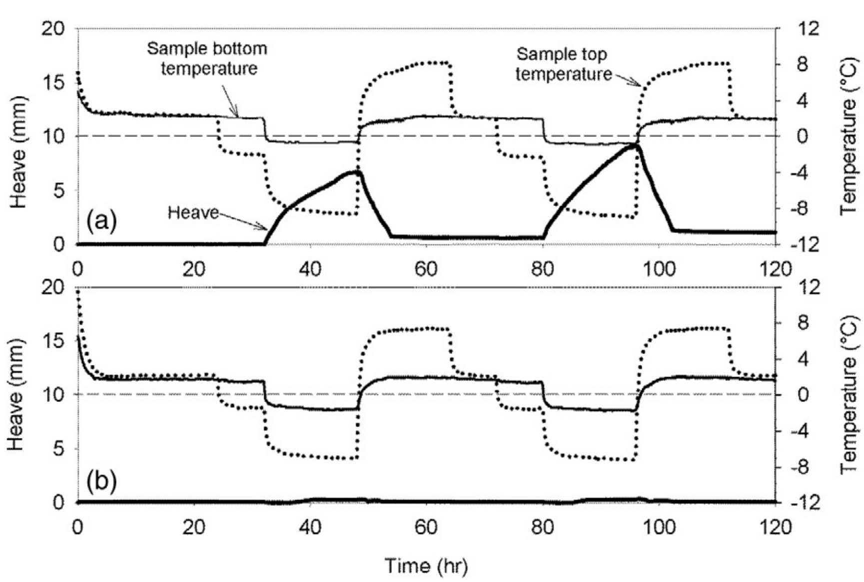

Fig. 5. Frost-heave time plots of (a) 0.2% PP fiber stabilized subbase and (b) 10% cement stabilized subgrade.

Table 1
ASTM D5918 frost susceptibility classification.

Frost susceptibility classification	2nd 8-h heave rate (mm/d)	CBR after thaw (%)
Negligible	<1	>20
Very low	1 to 2	20 to 15
Low	2 to 4	15 to 10
Medium	4 to 8	10 to 5
High	8 to 16	5 to 2
Very High	>16	<2

susceptibility of unstabilized loessial materials by 40%, and the stiffness increased up to 40% based on cyclic load tests following 10 freeze–thaw cycles. Viswanadham (2009) reported that fiber stabilization can decrease freeze–thaw volumetric changes on the order of 40% as compared with untreated soil. For saturated low-plastic fine-grained soils, 0.2% to 0.5% fibers effectively decreased the influence of freeze–thaw cycles on stiffness and reduced swelling potential (Hazirbaba and Gullu, 2010). Gullu and Khudir (2014) reported that though particular amounts of either jute fiber or steel fiber or lime alone improved the UCS of silty soils after freeze–thaw cycles, a combination of these three stabilizers better improved the post freeze–thaw testing UCS. Brittleness index (BI) was also measured after freeze–thaw testing for jute fiber, steel fiber, and lime stabilized soil specimens. Results indicated that the addition of lime contributed to a significant increase in post testing BI while jute fibers stabilized specimens presented BI towards zero, and specimens with steel fibers showed BI between jute fibers and lime stabilized specimens.

3. Methods

In the study reported herein, freeze–thaw tests were conducted according to ASTM, 2006 using the equipment setup shown in Fig. 2. Laser sensors with a range of 50 mm and a resolution of 0.75 μm were used to record vertical displacement, and thermocouples were placed at the top and bottom and in the middle of the acrylic rings at 25.4 mm (1 in.) intervals to record temperature changes (see Fig. 2 and Fig. 3). Displacement and temperature data were continuously recorded. Because ice lens theory and capillary effect mean that moisture is attracted upward and to attain ultimate frost heave, Mariotte tubes (Fig. 3) were used to supply water during the entire 120-hour testing period (Cassagrande et al., 1931). Fig. 4 showed the increase in moisture contents after freeze–thaw testing which indicated the necessity of water supplies during testing.

Table 2
Index properties of the soils.

Parameter	Recycled subbase	Subgrade	Western Iowa loess
Specific gravity	2.59	2.70	2.72
Gravel content (%) (>4.75 mm)	37.2	5.3	0
Sand content (%) (4.75–75 μm)	48.4	39.7	0
Silt content (%) (75 μm–2 μm)	6.3	21.4	82.0
Clay content (%) (<2 μm)	8.1	33.6	18.0
D_{10} (mm)	0.02	–	–
D_{30} (mm)	0.45	0.01	–
D_{60} (mm)	4	0.12	–
Coefficient of uniformity, C_u	160	–	–
Coefficient of curvature, C_c	2	–	–
Liquid limit, LL (%)	NP	33	29
Plasticity index, PI (%)		15	6
AASHTO	A-1-a	A-6(5)	A-4(0)
USCS group symbol	SM	CL	ML
USCS group name	Silty sand with gravel	Sandy lean clay	Silt
Maximum dry unit weight, $\gamma_{d,max}$ (kN/m^3)	19.62	18.15	16.2
Optimum moisture content, w_{opt} (%)	7.9	13.5	16.7

Note: – = not applicable.

Table 3
Chemical compositions of Class C fly ash materials.

Composition (%)	Port Neal FA	Ames FA	Muscatine FA
SiO_2	38.90	33.80	36.50
Al_2O_3	17.30	17.00	20.70
Fe_2O_3	5.03	5.36	7.08
SO_3	2.25	2.53	2.14
CaO	25.30	26.40	22.90
MgO	5.03	6.15	4.84
Na_2O	1.57	2.56	1.59
K_2O	0.58	0.62	0.40
P_2O_5	0.59	1.32	1.39
TiO_2	1.52	1.57	1.57
SrO	0.36	0.34	0.39
BaO	0.66	0.78	0.80

For each material, three to five replicate specimens of were prepared and compacted. CBR tests were conducted on one specimen (per ASTM, 2007), and the other specimens were subjected to two freeze–thaw cycles after which CBR tests were conducted for comparison with the pre-test CBR value. Penetration stress at 5 mm (0.2 in.) depth was used to calculate CBR values. Moisture content profiles for the freeze–thaw specimens were determined by dividing the specimen into six 25.4 mm (1.0 in.) thick layers. Moisture content profiles (Fig. 4) were analyzed to evaluate moisture content changes relative to the original compaction moisture contents.

Frost-heave time plots were developed to determine heave rates (Fig. 5). The larger heave rate of the two freeze cycles and the post-test CBR were used to determine frost-heave and thaw-weakening susceptibility in accordance with ASTM, 2006 (see Table 1).

Stabilized materials were cured for 7 days at 37.8 °C (100 °F). Specimens were sealed to prevent moisture loss during curing. Two groups of fly ash stabilized western Iowa loess specimens were cured for longer periods –– 90 days and 180 days at the same temperature to investigate the influence of longer-term pozzolanic reactions.

4. Materials

Three pavement foundation materials were tested. Soil index properties and chemical analysis for the stabilization materials are described in the following.

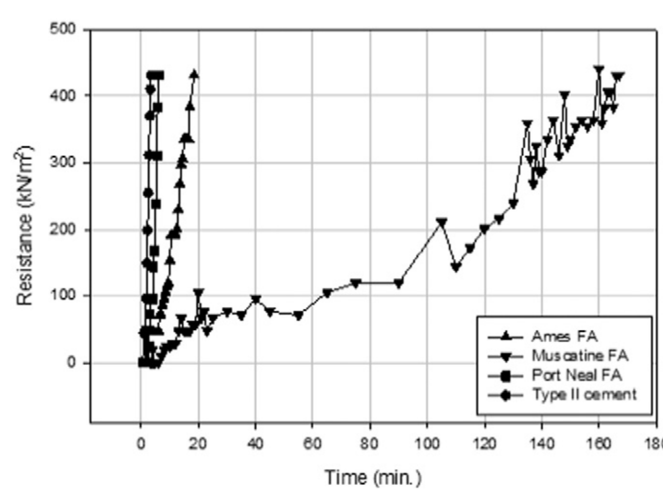

Fig. 6. Penetration resistance set time plots for fly ash and cement.

Fig. 7. White monofilament fibers (MF) (left) and black polypropylene fibers (PP) (right).

4.1. Pavement foundation materials

Recycled subbase (SM) and subgrade (CL) were collected from Boone County, Iowa. Loess (ML) was collected from Pottawattamie County, Iowa. Table 2 summarizes the index properties of the three soils.

4.2. Stabilizers

Self-cementing Class C fly ash and, type II Portland cement and fibers were selected for stabilizers. Three sources of Class C fly ash were collected from three power plants in Iowa: Port Neal, Ames, and Muscatine. Table 3 summarizes the x-ray fluorescence elemental compositions of the fly ashes.

Set time tests were conducted on the chemical stabilizers by preparing specimens at water to stabilizer ratio of 0.275 and then monitoring penetration resistance with time. The time recorded at the first non-zero resistance value was used as the initial set time and the final set time was recorded when 431 kN/m^2 (4.5 tsf) was reached (Fig. 6) using a pocket penetrometer (ASTM, 2008). For construction practice in Iowa, fly ash stabilization uses the set time test results as a guide

Table 4
Summary of frost-heave and thaw-weakening tests results.

Soil	Stabilizer	Heave rate (mm/d)	Post- test CBR (%)	Pre-test CBR (%)	Frost-heave susceptibility	Thaw-weakening susceptibility
Subgrade	No stabilizer	11.43	1.4	2.8	High	Very high
	5% Ames fly ash	8.40	6.6	15.5	High	Medium
	10% Ames fly ash	6.60	9.6	44.6	Medium	Medium
	15% Ames fly ash	6.87	20.1	73.2	Medium	Negligible
	20% Ames fly ash	7.85	10.2	18.2	Medium	Low
	5% Muscatine fly ash	9.88	2.9	–	High	High
	10% Muscatine fly ash	12.32	2.6	–	High	High
	5% Port Neal fly ash	6.61	5.7	–	Medium	Medium
	10% Port Neal fly ash	8.21	11.2	15.0	High	Low
	15% Port Neal fly ash	1.96	16.9	25.8	Very low	Very low
	20% Port Neal fly ash	3.16	17.9	–	Low	Very low
	5% cement	0.02	165.8	37.3	Negligible	Negligible
	10% cement	0.07	>200.0	94.5	Negligible	Negligible
Recycled subbase	No stabilizer	15.63	8.8	4.6	High	Medium
	2.5% cement	12.70	12.8	95.6	High	Low
	3.75% cement	2.09	35.1	127.0	Low	Negligible
	5.0% cement	3.35	56.7	208.9	Low	Negligible
	7.5% cement	1.64	43.4	>200.0	Very low	Negligible
	0.2% PP	12.11	11.4	4.6	High	Low
	0.4% PP	12.75	7.8	7.3	High	Medium
	0.6% PP	6.25	16.3	5.8	Medium	Very low
	0.2% MF	10.34	12.1	4.1	High	Low
	0.4% MF	9.90	14.8	7.9	High	Low
	0.6% MF	6.94	18.4	8.6	Medium	Very low
	0.2% PP + 3.75% cement	1.31	58.2	185.5	Very low	Negligible
	0.2% PP + 3.75% cement (12-h compaction delay)	3.83	20.3	–	Low	Negligible
	0.4% PP + 3.75% cement	0.18	127.4	>200.0	Negligible	Negligible
	0.4% PP + 3.75% cement (12-h compaction delay)	2.98	19.8	–	Low	Negligible
	0.6% PP + 3.75% cement	1.48	120.1	>200.0	Very low	Very low
	0.2% MF+ 3.75% cement	0.75	190.5	184.9	Negligible	Negligible
	0.4% MF+ 3.75% cement	1.43	203.2	143.1	Very low	Negligible
	0.6% MF+ 3.75% cement	1.00	177.0	158.7	Negligible	Negligible
Western Iowa loess	No stabilizer	19.1	0.5	–	Very high	Very high
	15% Ames fly ash 7 days curing	14.10	7.1	–	High	Medium
	15% Ames fly ash 90 days curing	11.83	8.7	–	High	Medium
	15% Ames fly ash 180 days curing	8.27	32.0	–	High	Negligible

Note: – = data not available.

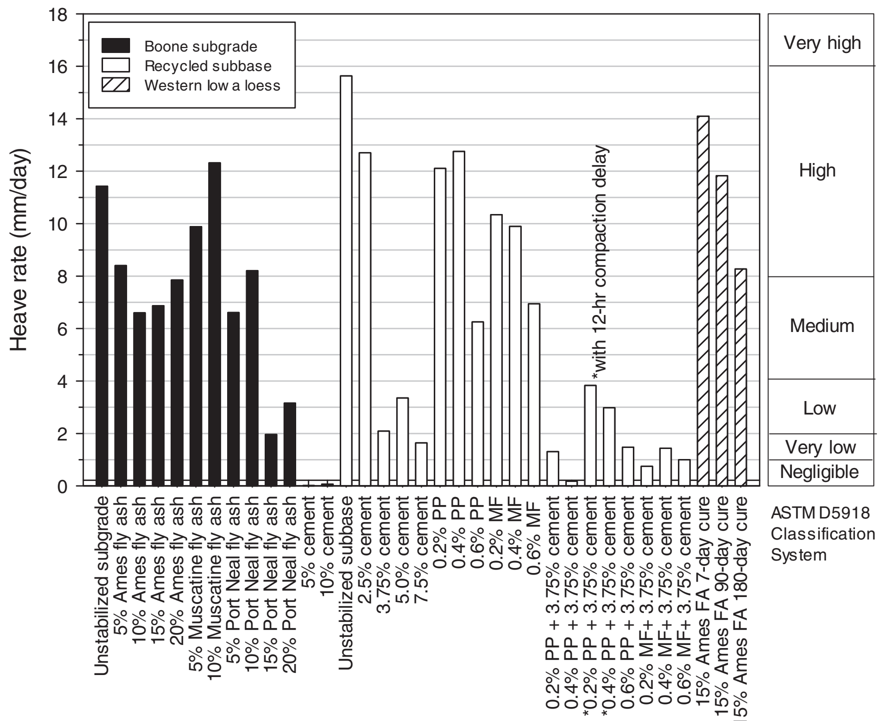

Fig. 8. Comparison of frost-heave rates of all tested materials.

for field construction operations, where the soil-fly ash mixture should be compacted before reaching the final set time.

Two types of fibers – polypropylene fibers (PP) and monofilament fibers (MF), (Fig. 7) – were tested. The black PP fibers are discrete fibrillated strands that are 25.4 mm (1 in.) long. The white MF micro-fibers are also discrete fibrillated strands, but are 19.1 mm (0.75 in.) long. Both fibers have a specific gravity of 0.91.

5. Results

Freeze–thaw and CBR tests were conducted on a total of 36 materials comprising unstabilized and stabilized materials. Table 4 provides a summary of the frost-heave and thaw-weakening susceptibility ratings for all materials. The unstabilized soils tested in this study (SM, CL, and ML) exhibited frost-heaves of 11.43 to 19.1 mm/day and post-test CBR

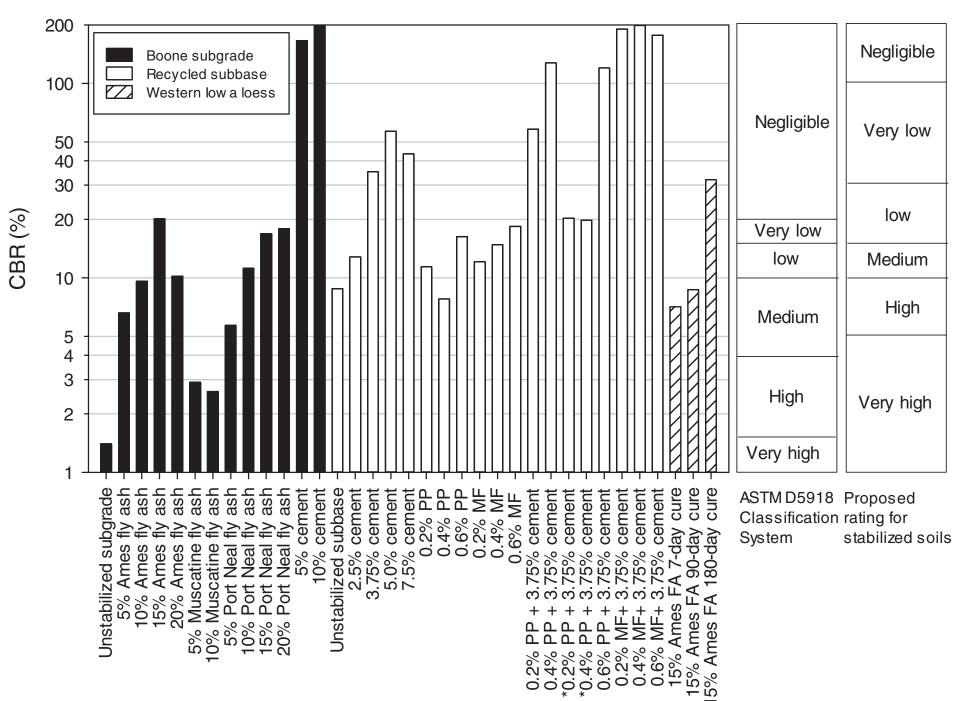

Fig. 9. Post-test CBR values and corresponding frost susceptibility ratings based on ASTM and the results from this study.

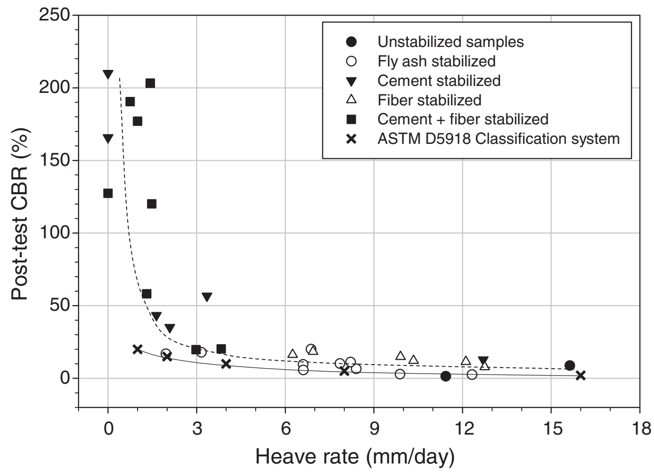

Fig. 10. Relationships between Post-test CBR and measured heave rates with comparison to the ASTM D5918 criteria.

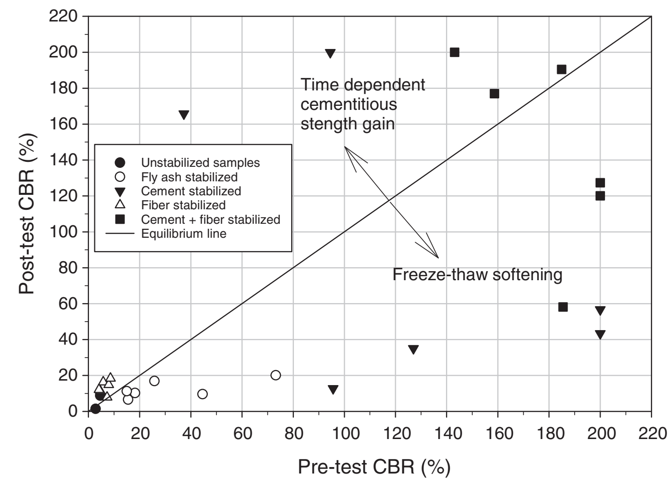

Fig. 11. Comparison between pre and post-test CBR values showing the influence of time dependent strength gain for cement and cement + fiber stabilized specimens.

of 0.5% to 8.8% resulting in high to very high frost susceptibility and medium to very high thaw-weakening susceptibility. The finding in grain size distribution indicated that the freeze–thaw susceptibility might be influenced by the fine contents of soils.

For all tests, the CBR pre-test values ranged from 2.8% to over 200%. The unstabilized subgrade is rated as very high thaw-weakening susceptibility based on the post-test CBR of 1.4%. The unstabilized recycled subbase resulted in a medium rating for thaw-weakening susceptibility with a post-test CBR of 8.8%.

Subgrade stabilized with fly ash yielded variable results, but generally showed improvement in post-test CBR and lower heave rates with increasing fly ash. Both the 15% Port Neal and Ames fly ash stabilized subgrade (based on dry weight of soil) reached the very low to negligible thaw-weakening susceptibility rating. Increasing the fly ash content to 20% resulted in slightly higher heave rates with medium to low frost-heave susceptibility for two fly ashes. The fly ash source was identified as a factor in the freeze–thaw susceptibility rating. Comparing the set time of the three fly ash specimens with the frost susceptibility rating shows that shorter set times resulted in reduced frost-heave and thaw-weakening for the 7-day curing duration. Tests performed on loess (ML) specimens stabilized with 15% Ames fly ash showed that curing up to 180 days before testing improved the freeze–thaw performance by both reducing the heave rate and increasing the post-test CBR.

For cement stabilized materials, heave rates for the subgrade specimens were close to 0 mm/day for both the 5% and 10% cement additional rates. For the recycled subbase, frost susceptibility decreased as the cement content increased; however, there was little improvement at 2.5% cement content. For all cement contents, the post-test CBR values were about four times lower than the pre-test CBR values.

Fibers were added to the recycled base (SM) at rates of 0.2%, 0.4%, and 0.6% (based on dry weight of soil). Results showed improvement in both reduced heave rate and increased CBR values. For this set of experiments, the post-test CBR values were all higher than the pre-test CBR values. This finding suggests that the freeze–thaw action and associated stress development in the fibers contributed to the increase in CBR values. The frost susceptibility ratings based on heave ranged from medium to high for all six combinations of fibers. At 0.6% fibers, the heave rate was reduced from about 15 mm/day to about 7 mm/day. The finding with respect to frost heave differs from Hoover's et al. (1982) conclusions, but the finding with respect to thaw-weakening matches to the conclusion reported by Gullu and Khudir (2014).

Adding cement to the recycled subbase-fiber mixtures significantly reduced the heave rates. The frost susceptibility classifications of all the cement + fiber stabilized recycled subbase (no compaction delay) ranged from very low to negligible levels. When the 0.2% PP + 3.75% cement and 0.4% PP + 3.75% cement stabilized recycled subbase specimens with a 12-hour compaction delay were tested, the frost susceptibility increased from very low or negligible to low. The addition of 3.75% cement into the fiber-soil mixtures reduced the thaw weakening susceptibility to negligible, even with the 12-h compaction delay. The possible reason to explain these results might be cement improved the compressive strength while fibers improved the tensile strength. This finding matches to the conclusion reported by Gullu and Khudir (2014), which was fibers plus chemical stabilization can provide better freeze–thaw performance than fibers alone.

Fig. 8 shows the heave rate values and ASTM, 2006 frost susceptibility classifications for all tests. Comparing 7-day and 90-day curing, thaw-weakening susceptibility of 15% fly ash stabilized loess decreased from medium to negligible. Based on these results, the improvements from longer curing times for fly ash stabilization was limited to strength improvement, and did not show significant improvement for controlling frost-heave. Fig. 9 shows the corresponding CBR values and thaw-weakening susceptibility ratings for all tests.

Relationships between frost-heave rates and CBR values are shown in Fig. 10. Very low thaw-weakening susceptibility is achieved when the heave rate is less than 4 mm/day. Frost susceptibility based on frost-heave cannot predict thaw-weakening susceptibility.

Based on the ASTM, 2006 frost susceptibility classification method and data from this research, an alternative thaw-weakening susceptibility classification rating is presented in Table 5. The boundary values were adjusted to reflect differences in post-CBR and heave rates for the stabilized materials. The current ASTM classification does not distinguish classifications with CBR values greater than 20. The alternative classification proposed herein identified thaw-susceptibility as negligible for post-test CBR values ≥ 100. Fig. 9 shows a side-by-side comparison of the ASTM rating and the rating proposed herein for stabilized soils. The advantage of the proposed rating criteria is that it allows for more refined classification of stabilized soils.

Table 5
Proposed frost-heave and thaw-weakening susceptibility classification for stabilized soils based on data from this study.

Frost/thaw-weakening susceptibility classification	2nd 8-h heave rate (mm/d)	CBR after thaw (%)
Negligible	<1	>100
Very low	1 to 2	100 to 30
Low	2 to 4	30 to 15
Medium	4 to 8	15 to 10
High	8 to 16	10 to 5
Very high	>16	<5

Fig. 11 shows yet another perspective of evaluating pre and post-test CBR values for stabilized soils. Five materials, the 5% and 10% cement stabilized subgrade and the 3.75% cement with 0.2%, 0.4%, and 0.6% MF fiber stabilized specimens, presented time dependent strength gain. Freeze–thaw softening or no stiffness changes occurred for the other tested materials. Plotting the results in terms of pre and post-test CBR values shows it is difficult to predict the post-test CBR values from the pre-test measurements and supports the need to perform the freeze–thaw tests and evaluate the influence of curing time for stabilized soils.

6. Summary and Conclusions

Frost-heave and thaw-weakening laboratory tests were conducted per ASTM, 2006 to determine freeze–thaw performance of stabilized sandy lean clay (CL) subgrade, silty sand with gravel (SM) recycled subbase, and loess silt (ML).

Subgrade stabilized with fly ash indicated some improvement in post-test CBR and lower heave rates with increasing fly ash content up to 15% with very low frost-heave and thaw-weakening susceptibility. Greater improvement was related to shorter fly ash set time. Subgrade and subbase stabilized with cement showed low to negligible frost susceptibility. For subbase, the addition of fibers increased the pre-test and post-test CBR values slightly. Comparatively, the addition of cement reduced the heave rates and increased the CBR values significantly. Results also indicated that curing time and compaction delay influence the freeze–thaw performance of chemically stabilized soils.

To achieve very low thaw-weakening susceptibility, the heave rate has to be controlled to less than 4 mm/day per ASTM, 2006. The current ASTM classification does not distinguish classifications with CBR values greater than 20. A proposed classification for chemically stabilized soils identifies thaw-susceptibility as negligible for post-test CBR values ≥ 100. The advantage of this rating is it provides additional criteria for rating freeze–thaw susceptibility for stabilized soils with post-test CBR values greater than 20. It is difficult to predict the post-tests CBR values from the pre-test measurements for chemically stabilized soils due to time-dependent strength gain and supports the need to perform the freeze–thaw tests and monitoring the influence of curing time for stabilized soils.

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