ABSTRACT
The purpose of this research was to evaluate the effects of reduced cement contents on the frost heave behavior of a silty subgrade soil treated with cement contents of 2.0, 3.5, and 5.0 percent. The laboratory testing procedures included soil characterization, compaction and strength testing, frost heave testing, suction testing, and permeability testing.

Treatment of the soil with cement proved to be effective in controlling frost heave when a sufficient amount of cement was added; however, when an insufficient amount of cement was applied, the frost heave exhibited was actually greater than that occurring in untreated samples. This unexpected behavior was clearly associated with the ingress of a substantial amount of water shown in further testing to be attributable to changes in suction and permeability properties. The measured soil properties were then successfully used in a computer simulation to match the observed frost heave behavior. Although cement treatment was effective in totally eliminating frost heave in specimens treated with higher cement contents, the laboratory results indicate that water ingress still occurs during freezing.

A primary implication of the results obtained in this study is that the amount of cement added to a given soil should not be selected arbitrarily. While too much cement may cause shrinkage cracking, too little cement may actually cause worse frost heave behavior than that observed in untreated specimens. The formation of more ice lenses in the soil would then lead to greater thaw weakening of the affected pavement layer during spring.
INTRODUCTION
Cement stabilization is a proven method for improving the strength and durability of frost-susceptible soils and aggregates (1, 2). When sufficient cement is added, the formation of cementitious products binds the soil or aggregate particles together, increasing the tensile strength of the matrix, and reduces the permeability of the matrix. However, the addition of excessive amounts of cement leads to shrinkage cracking, water ingress, structural deterioration, and pavement roughness (3, 4, 5).

Given these considerations and the results of research recently performed at the Texas Transportation Institute (6, 7), the Portland Cement Association (PCA) has suggested the use of reduced cement contents compared to historical values; present recommendations are primarily based on achieving a 7-day unconfined compressive strength (UCS) of 300 psi to 400 psi (8). In warm climates similar to Texas, the use of cement contents meeting this criterion has provided adequate performance and minimized shrinkage cracking. However, in cold climates, the ability of materials stabilized using reduced cement contents to resist damage due to frost action warranted investigation. Therefore, PCA funded a research project at Brigham Young University (BYU) to specifically evaluate the effects of reduced cement contents on the frost heave behavior of problematic soils typical of cold regions. The study included a silty subgrade soil sampled from Montana and incorporated cement contents associated with 7-day UCS values of 200 psi, 400 psi, and 600 psi at the request of PCA personnel.

The following sections provide background information about frost heave, explain the experimental methodology, describe the results of the study, present the numerical modeling, and offer conclusions and recommendations regarding the work.

FROST HEAVE
Frost heave is the vertical displacement of the ground surface caused by the ingress and freezing of subsurface water within the underlying soil strata in response to the penetration of freezing temperatures into the ground (9, 10, 11). The ability of water to move through the soil medium ultimately controls the growth of ice lenses in freezing soil. The transport of water from the warmer underlying soil towards the frost front is the result of three main mechanisms (12). First, the vapor pressure in warm, underlying soil is greater than in the cooler overlying soil; therefore, vapor flows toward the cold soil, where it condenses into liquid water and ultimately crystallizes into ice (13). The second mechanism of water transport is osmosis. As water crystallizes into ice at nucleation points within pore cavities, salts originally dissolved in the freezing water are expelled outwards into the adjacent, unfrozen water, thereby creating a region with higher ion concentrations and a depressed freezing temperature. In an effort to equalize ion concentrations with the pore water system, water migrates towards the frost front from below, where salt concentrations are lower (14, 15).

The third and usually controlling mechanism is capillary rise, or water flow in response to matric suction gradients within the freezing soil profile. Before the soil begins to freeze, water on the surfaces of the soil particles and in the pore spaces between soil particles forms a network of channels through which water is able to flow. As the freezing front passes through the soil, ice crystals nucleate in the pore water between soil particles. The formation of ice in the pores causes the unfrozen water films on the surfaces of the particles to become thinner so that the effective radius of the capillaries forming the unfrozen water network within the freezing soil decreases. With decreasing temperatures, increasing amounts of pore water change to ice, further reducing the liquid water content between soil particles. Although the reduced water
content causes a dramatic increase in capillary suction, the permeability of the soil rapidly diminishes as freezing progresses (16). Thus, as liquid water migrates from warmer to colder regions within the soil matrix, and especially as it approaches an active ice lens, its path becomes increasingly tortuous and narrow. At some point, the elevated matric suction levels may no longer able to overcome the reduced permeability caused by the formation of ice, in which case continuing water flow concentrates the occurrence of frost heave at or near the base of the most recently formed ice lens. As long as a sufficient water supply is maintained and the thermal gradient remains constant, the ice lens can continue to grow almost indefinitely.

As the pore ice grows to form an ice lens, particle-to-particle contact within the soil is disrupted. The weight of the overburden is subsequently transmitted from the soil matrix to the ice-water structure, leading to pressurization of the unfrozen water films along the soil-ice interfaces (15). Additional water can enter the film only when the suction at the interface is sufficient to overcome the counteracting overburden stresses. Because typical overburden pressures in a roadbed range from only 0.4 psi to 3.0 psi, and the pressure required to terminate heave in a silty soil is approximately 11.6 psi, frost heaving can readily occur in frost-susceptible soils given the presence of freezing temperatures and available moisture (17). A schematic of this process is shown in Figure 1.

![Schematic of a growing ice lens.](image)

**FIGURE 1** Schematic of a growing ice lens.

**EXPERIMENTAL METHODOLOGY**
The laboratory testing procedures included soil characterization, compaction and strength testing, frost heave testing, suction testing, and permeability testing, where the latter two were conducted primarily to investigate the observed frost heave behavior of the soil.

**Soil Characterization**
The Montana silt was first classified using two principal methods, the Unified Soil Classification System and the American Association of State Highway and Transportation Officials
(AASHTO) classification system. These methods are based on particle-size distributions and Atterberg limits, with the AASHTO method being the most common specification used in the United States for highway design. Soil preparation began with drying at 140°F for 24 hours and separation over several sieve sizes to facilitate construction of replicate specimens with identical gradations. A washed sieve analysis was performed according to the American Society for Testing and Materials (ASTM) standard D 2217, and a hydrometer test was conducted according to ASTM D 422. Atterberg limits tests were performed according to ASTM D 4318 to determine the plastic and liquid limits of the soil, and the apparent specific gravity of the material was measured using ASTM D 854.

The electrical conductivity of the soil was also assessed to give an indication of the salinity of the soil, which can have a direct impact on frost heave behavior as both the freezing temperature of the soil water and the magnitude of matric suction that develops upon freezing are dependent on salinity. For this test, 0.011 lb of air-dried soil was placed into a clean bottle with 0.220 lb of deionized water. The soil and water were thoroughly mixed, and a dual platinum-plate, contacting-type probe was used to measure the electrical conductivity of the solution. Measurements were taken at specified intervals until the electrical conductivity stabilized at a constant value.

**Soil Compaction and Strength Testing**

As the Montana silt tested in this research was a highway subgrade soil, the standard Proctor compaction effort was utilized in specimen preparation. Each specimen was prepared by weighing out exact amounts of each particle size as determined by the dry sieve analysis that had been conducted previously. The optimum moisture content (OMC) and maximum dry density were determined by compacting multiple specimens at various moisture contents.

State highway departments commonly specify UCS values for cement-treated soils used in road construction (18). In this research, cement contents corresponding to 7-day UCS values of 200 psi, 400 psi, and 600 psi were recommended by PCA personnel for evaluation. The specimens were prepared with various amounts of cement and tested for strength according to ASTM D 1633, except that the specimens were not soaked before testing. In order to provide water for cement hydration while still maintaining sufficient moisture for compaction, an additional amount of water equal to 20 percent of the cement weight was added to treated specimens. After curing for 7 days at 100 percent relative humidity, the specimens were capped with high-strength gypsum and tested in a compression machine at a strain rate of 0.05 in. per minute. The maximum loads sustained during testing were utilized to compute the specimen UCS values, which were in turn employed to determine the target cement contents for use in the research.

**Frost Heave Testing**

For frost heave testing, three replicate specimens were prepared in the untreated condition and at each of the three cement contents using proportions representative of the different particle sizes calculated from the dry sieve analysis initially conducted on the material. The samples were compacted to a height of 9 in. into 6-in.-diameter cylindrical molds pre-drilled with seven 0.125-in. diameter holes in the bottom to allow for water uptake. A filter paper was placed in the bottom of the mold prior to compaction in order to prevent the ejection of fines into the bath water during frost heave testing. The weight of the mold and specimen was measured just after
compaction, and four height measurements were taken to determine the initial height of each finished specimen.

Following a 28-day cure at 100 percent relative humidity, three specimens were instrumented with seven thermocouples inserted at 1-in. intervals beginning at the soil surface and extending down the sides of the specimens to a height of 3 in. from the specimen base. All of the specimens were then wrapped with lateral insulation and placed in the frost heave test apparatus shown in Figure 2. During frost heave testing, the height of the water table was set between 1.75 in. and 2.0 in., and linear variable differential transformers were utilized to measure changes in specimen heights. Ten-pound overburden weights were situated on the specimen surfaces to simulate the presence of overlying pavement layers. The air and bath water temperature in the freezing chamber were maintained at 19.4°F and 36.5°F, respectively, and temperature and frost heave data were both automatically recorded on 10-minute intervals throughout the duration of the 10-day test using a computerized data acquisition system. The specimens were all oven-dried at 230°F following the testing to facilitate computation of water contents and dry densities.

**FIGURE 2 Frost heave testing apparatus.**

**Suction Testing**

Next, soil samples representative of those subjected to frost heave testing were subjected to suction testing in order to produce soil-water characteristic curves for the soil treated with different levels of cement. The specimens were approximately 1.5 in. in diameter and about 0.25 in. in height. Because of this size restriction, only particles finer than the No. 4 sieve were used to fabricate these specimens, which were compacted into plastic molds and allowed to cure for
28 days at 100 percent relative humidity. A minimum of four specimens were prepared at each cement content.

The cured specimens were then tested individually in a dewpoint potentiometer to determine the suction at no fewer than three moisture contents each, yielding at least 12 data points for each cement content. The specimens were allowed to dry for approximately 45 minutes between readings, at which time the specimen container was sealed for a 24-hour moisture-equilibration period. Figure 3 shows a prepared specimen ready to be tested.

![Prepared suction specimen ready to be tested.](image)

**FIGURE 3** Prepared suction specimen ready to be tested.

**Permeability Testing**
For the purpose of measuring the hydraulic conductivity, or coefficient of permeability, of the soil treated at each of the cement contents, additional specimens were prepared. These specimens were 4 in. in diameter and 4.5 in. in height and were also cured for 28 days at 100 percent relative humidity. Following curing, the specimens were soaked under water for 4 hours and then placed in an 11-in. length of plastic pipe having an inner diameter of 5 in. Heated paraffin wax was then poured around each specimen to seal the void between the specimen sides and the pipe. The upper part of the pipe was then filled with water for the constant-head permeability testing, and the unit was enclosed in a compression fitting that allowed constant application of 10 psi air pressure to the top of the water reservoir. The apparatus used for this testing is shown in Figure 4. The steady-state flow rate was the measured for each specimen to facilitate computation of the hydraulic conductivity. Three specimens of each cement treatment were evaluated, and three measurements were taken on each specimen.
RESULTS
The test results address soil characterization, compaction and strength testing, frost heave testing, suction testing, and permeability testing.

Soil Characterization
The particle-size distribution for the tested soil is shown in Figure 5. Both the liquid and plastic limits of the soil were 25.8, and the apparent specific gravity of the soil was determined to be 2.67. Based on these data, the Unified soil classification is ML, and the AASHTO soil classification is A-4 (0). According to the frost susceptibility classification system developed by the United States Army Corps of Engineers, this soil meets the requirements for an F-4 rating, the most frost-susceptible classification possible.

The electrical conductivity of the soil stabilized at approximately 432 micro-Siemens per in. after 26 days of equilibration. This comparatively low salt concentration was expected, as the soil was obtained from a borrow pit and had never been exposed to deicing salts.

FIGURE 4 Permeability testing apparatus.
Soil Compaction and Strength Testing

From the moisture-density curve prepared from the initial compaction tests, the optimum moisture content and maximum dry density were determined to be 20 percent and 101 lb/ft³, respectively. The UCS testing revealed that the desired compressive strengths of 200 psi, 400 psi, and 600 psi were approximately obtained when the soil was mixed with, 2.0, 3.5, and 5.0 percent cement, respectively.

Frost Heave Testing

Figure 6 reports the change in specimen height, weight gained, and final moisture content of the specimens subjected to the frost heave test. The bar in the figures represents the average value, while the upper and lower ends of the lines denote the high and low data points, respectively. Treatment of the soil with cement proved to be effective in controlling frost heave when a sufficient amount of cement was added; however, when an insufficient amount of cement was applied, the frost heave exhibited was actually greater than that occurring in untreated samples. This unexpected behavior was clearly associated with the ingress of a substantial amount of water as indicated in Figure 6, which also shows that the final water content was 14 percentage points higher than the OMC for the soil. This behavior is likely caused by changes in suction and/or permeability characteristics uniquely associated with the addition of 2 percent cement. The data collected for specimens treated with 3.5 percent and 5.0 percent cement suggest that once a sufficient amount of cement required to prevent frost heave is reached, the addition of more cement only marginally increases resistance to frost heave. The slight decrease in length exhibited by the specimens with 3.5, and 5.0 percent cement was likely caused by thermal contraction as the specimens cooled.
(a) Frost heave at end of test.

(b) Weight gained by end of test.

FIGURE 6 Results of frost heave testing.
The specimens with 5.0 percent cement imbibed 73 percent as much water as did the untreated control specimens and yet exhibited negative heave, whereas the control group heaved an average of 1.19 in. This result shows that although the cement treatment is effective in totally eliminating frost heave, significant water ingress may still occur.

Figure 7 shows the typical temperature profile of a specimen throughout the duration of the test. The coldest temperature occurs at the surface (bottom part of the figure) and increases at a constant rate with increasing specimen depth. The temperature difference between the top and bottom of the specimens was 10.80°F, which corresponds to a thermal gradient of 1.20°F/in.
Suction Testing
The results of the suction testing are displayed in Figure 8. This figure displays the soil-water characteristic curves for each of the cement contents evaluated in the research. The data displayed in the figure were subjected to logarithmic transformations, and the slopes, or pore size distribution constants, were computed for use as inputs in the numerical modeling of the frost heave process.

FIGURE 7 Temperature readings at various heights within a specimen.
Permeability Testing
The results of the permeability testing are displayed with the inputs for the numerical modeling in Table 1. Similar to the results of the frost heave testing, specimens treated with 2 percent cement exhibit the capacity for greater water flow rates compared to untreated specimens; however, at higher cement contents, a significant reduction in permeability results.

NUMERICAL MODELING
After all of the data were collected, numerical modeling was performed to simulate the results of the laboratory testing. In particular, the ability to utilize suction and permeability parameters to explain the unexpected behavior of the specimens treated with 2 percent cement was of interest. The computer model ICE-1 was selected for this purpose because of its ability to analyze heat, water, and solute transport in unsaturated, partially frozen soils together with frost heave effects. The program output gives temperature, total water content, liquid water content, and osmotic suction in each layer of a simulated soil column, as well as the total amount of heave, as these values change with time.

Table 1 gives the inputs used in the computer simulation. The distance to the lower boundary was given to be the same as the height of the tested specimen, and the pore size distribution constant was the slope of the linearized soil-water characteristic curve developed from the suction testing. The initial osmotic suction was estimated from the electrical conductivity test results performed on the untreated soil, and successively higher values were used for higher cement contents due to the expectation of higher concentrations of calcium ions in the pore water. The temperature gradient was set equal to the value measured during frost heave testing.
### TABLE 1 Model Inputs

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>0% Cement</th>
<th>2.0% Cement</th>
<th>3.5% Cement</th>
<th>5.0% Cement</th>
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<tr>
<td>Distance to Lower Boundary (cm)</td>
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<td>23.3</td>
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<tr>
<td>Pore Size Distribution Constant</td>
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<td>8</td>
<td>9</td>
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<td>Initial Osmotic Pressure of Soil Solution (cm of H₂O)</td>
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<td>650</td>
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<td>Temperature Gradient (°C/cm)</td>
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<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Saturated Hydraulic Conductivity (cm/hr)</td>
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<tr>
<td>Load on Surface (cm of H₂O)</td>
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<td>0.17</td>
<td>0.17</td>
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<tr>
<td>Saturated Water Content (cm³/cm³)</td>
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<td>0.40</td>
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<td>Initial Water Content of the Soil (cm³/cm³)</td>
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<td>Initial Soil Temperature (°C)</td>
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<td>24</td>
<td>24</td>
<td>24</td>
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<tr>
<td>Time Increment (hr)</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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<tr>
<td>Total Simulation Time (hr)</td>
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<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Air Entry Pressure (cm of H₂O)</td>
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<td>190</td>
<td>400</td>
<td>600</td>
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<tr>
<td>Lower Temperature Limit of Soil Surface (°C)</td>
<td>-3</td>
<td>-3</td>
<td>-3</td>
<td>-3</td>
</tr>
</tbody>
</table>

The saturated hydraulic conductivity was calculated from the permeability tests performed in this study, and the given load on the surface reflects the application of the 10-lb overburden weight on the specimens during frost heave testing. The saturated water content was given to be the same as the average porosity computed from the specific gravity of the soil and the dry densities of the tested specimens. The initial water contents of the specimens were measured before the frost heave tests were performed, and the initial soil temperature was input to be the same as the initial bath water temperature to satisfy the program’s assumption of a uniform initial soil temperature. The time increment was the default value, and the total simulation time was set equal to the duration of the actual frost heave tests. The air-entry pressure was used in the modeling as a fitting parameter, and the lower limit of the soil surface temperature was determined from Figure 7. An open lower boundary condition was utilized in all of the simulations to match the actual frost heave testing conditions.

Based on these inputs, the computer simulation produced satisfactory matches of the measured frost heave data, including proper simulation of the unexpected effects of 2 percent cement, as shown in Figure 9; for convenience, the measured and simulated frost heave data are both shown in the figure for visual comparison. Given these results, one may conclude that the effect of stabilization with reduced cement contents was to alter both the suction characteristics and the permeability of the soil matrix. Specifically, the application of 2 percent cement altered both the slope of the soil-water characteristic curve and the permeability of the treated soil compared to the untreated soil, and the effects of these changes in soil properties were successfully simulated in the computer software.
CONCLUSION
The purpose of this research was to evaluate the effects of reduced cement contents on the frost heave behavior of problematic soils typical of cold regions. The study included a silty subgrade soil sampled from Montana and incorporated cement contents associated with 7-day UCS values of 200 psi, 400 psi, and 600 psi. Based on the soil characterizations, the Unified soil classification for the soil was ML, the AASHTO soil classification was A-4 (0), and the United States Army Corps of Engineers frost group classification was F-4. The optimum moisture content and maximum dry density were determined to be 20 percent and 101 lb/ft³, respectively. The UCS testing revealed that the desired compressive strengths were approximately obtained when the soil was mixed with, 2.0, 3.5, and 5.0 percent cement.

Treatment of the soil with cement proved to be effective in controlling frost heave when a sufficient amount of cement was added; cement contents corresponding to 7-day UCS values of 400 psi and 600 psi did not exhibit frost heave. However, when an insufficient amount of cement was applied, the frost heave exhibited was actually greater than that occurring in untreated samples. This unexpected behavior was clearly associated with the ingress of a substantial amount of water shown in further testing to be attributable to changes in suction and permeability properties. The measured soil properties were then successfully used in a computer simulation to match the observed frost heave behavior. Although cement treatment was effective in totally eliminating frost heave in specimens treated with higher cement contents, the laboratory results indicate that water ingress occurs during freezing.

A primary implication of the results obtained in this study is that the amount of cement added to a given soil should not be selected arbitrarily. While too much cement may cause shrinkage cracking, too little cement may actually cause worse frost heave behavior than that
observed in untreated specimens. The formation of more ice lenses in the soil would then lead to greater thaw weakening of the affected pavement layer during spring. Further research is needed to investigate the relationship between UCS and frost heave behavior.

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