Frost Resistance of Lime-Stabilized Clay Soil

M. Arabi, S. Wild, and G. O. Rowlands

A frost-susceptible soil (red marl) was treated with various amounts of lime (calcium hydroxide) and cured for up to 24 weeks at different temperatures. Frost resistance of the cylindrical specimens was determined by measuring the frost heave in a controlled freezing environment. Soil-lime specimens with 2 wt% lime were more susceptible to frost action than soil alone—regardless of curing time and curing temperature. However, cured specimens with relatively high lime contents (>2 wt%) showed significant improvement in frost resistance. From previous studies by the authors, it was found that cementitious gel forms and develops in these specimens during curing—increasing the degree of interparticle bonding and producing greater strength. It is suggested that this restricts ice segregation and prevents heave and that frost resistance is dependent on the extent of the formation and growth of the cementitious gel within the cured soil-lime composites.

Strength development and improvement in durability of clay soils by the addition of lime is widely recognized. The pH value of clay soil increases sharply when lime and water are mixed with the soil. Workability improves and plasticity decreases (*1*). These changes occur quite rapidly and are attributed to the adsorption of calcium ions onto the clay particle surfaces, thus causing modification of the electrical double layer and the characteristic flocculation of the fine clay particles to form a workable material.

The particles within each floc are thought to be weakly bonded together by the formation of small amounts of cementitious material at the contact points. Long-term reaction is complex and, according to Diamond and Kinter (*2*), is due to pozzolanic activity between the lime and clay minerals. Cementitious materials comprising calcium silicate hydrate gel and calcium aluminate hydrate are formed during the curing stage.

REVIEW OF PREVIOUS WORK

Wild et al. (*3*) analyzed the cementitious materials formed when a lime clay mixture was cured at different temperatures using techniques of X-ray diffraction, transmission and scanning electron microscopy (TEM and SEM), energy dispersive analysis by X-ray (EDAX), and thermogravimetry (TG). No evidence of the formation of calcium aluminate hydrate was detected in this investigation.

The reaction products were found to be poorly crystalline, even at high curing temperatures [75°C (167°F)] and longer curing periods (1 year). The amorphous products were found to comprise coarse platelets in the early stages of curing, but at later stages they formed fine foils and filaments of an aluminum-containing calcium silicate hydrate gel. This gel was found to bind the soil particles together, resulting in an increase in compressive strength. The increase in compressive strength was found [see work by Arabi and Wild (*4*)] to be directly related to the amount of gel formed.

The formation and growth of the cementitious products were also found to affect the porosity and pore size distribution, which in turn affected the permeability of the reacted soil. These changes in strength, porosity, and permeability, due to the gel formation, are also likely to affect the frost susceptibility of the soil significantly.

Wild et al. (*5*) observed that gel formation leads to an increase in the proportion of pores in the size range of 4 to 40 nm. In a relatively open-textured material, this is likely to lead to a reduction in pore sizes greater than 40 nm as the gel forms. However, the development of the gel does not seem to influence the overall porosity significantly. In fact, the porosity of compacted material was found to increase slightly as the material cured.

The permeability of the soil-lime mixture also changed as curing proceeded. The addition of a small quantity of lime (2 wt%) resulted in a sharp increase in permeability compared with that of compacted lime-free material. This was found to be independent of the amount of gel formed and was probably due to the coarsening of the pore structure and the opening of capillary channels as a consequence of flocculation or soil modification.

At low curing temperatures only a limited amount of gel formation was observed and both porosity and permeability were found to increase with increase in curing time, implying a gradual coarsening of the pore structure with age. At elevated curing temperatures and particularly with higher lime contents and longer curing periods, substantial gel formation was observed. This was associated with a decrease in permeability, but the porosity continued to increase slightly as the gel developed. The population of pores also moved toward the 4- to 40-nm size range. The effect of the growth and development of the microporous gel was, therefore, to shift the pore size distribution toward the finer pore sizes and to block some pores and channels.

It is apparent from this discussion that lime stabilization is likely to affect the frost susceptibility of clay soils by modifying the pore structure and, hence, the permeability and tensile strength of the soil. The mechanism of frost heave is complex, but it is widely recognized that the governing factors are the particle size distribution, the permeability of the soil, the

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availability of water, and the duration of the freezing period. In weakly cemented soils, the tensile strength is also likely to be an influencing factor. Croney and Coleman (*6*) indicated that the addition of a small quantity of portland cement to frost-susceptible granular materials can render them less prone to frost damage without materially affecting their permeability in the unfrozen state.

These materials develop frost resistance because the small level of tensile strength developed is adequate to restrict ice segregation (i.e., it is sufficient to resist the suction forces on the ice phase alone as it tries to expand). Townsend and Klym (*7*) have shown that the frost resistance of cured soil-lime specimens is directly related to their tensile strength, but they contend that the compressive strength may also be used to give an indirect indication. Thompson (*8*) suggested a minimum compressive strength value of 1.4 N/mm^2 (200 lb/in^2) for a saturated soil-lime specimen in order to restrict heave to 2 percent.

In relation to lime content, Brandl (*9*) found that the frost heave in a highly plastic clay (PI = 32.2 percent) and a silty clay (PI = 15.5 percent) increased with the addition of 1 percent lime but decreased with the addition of 5 percent lime and with the curing period. He also noted that the compressive strength of cured specimens decreased after freezing and thawing.

Other researchers [e.g., Allen et al. (*10*), Rosen and Marks (*11*), and Dempsey et al. (*12*)] have shown that the strength of cured specimens decreases with increasing number of freeze-thaw cycles. No doubt, this is due to the rupturing of the bonds between particles as a consequence of ice formation in the freezing zone. It is now also recognized that actual measurement of heave yields a more realistic criterion of assessing frost susceptibility than compressive strength.

Although Dempsey and Thompson (*13*) have shown a linear relationship between heave of test specimens and the number of freeze-thaw cycles (for up to 12 cycles), a simple continuous freezing test is preferred, because this is likely to yield results more quickly. This is the basis on which Croney and Jacobs (*14*) developed the Transport and Road Research Laboratory (TRRL) freezing test to assess the frost susceptibility of road materials. In this test, a limiting heave of 12.5 mm (½ in.) is accepted for compacted cylindrical specimens [100 mm (4 in.) in diameter by 150 mm (6 in.) high] subjected to continuous freezing at −17°C (1.4°F) for 10 days. Through the work of Roe and Webster (*15*), this time has now been reduced to 4 days.

The current work is intended to accomplish the following:

1. To determine the effect that different additions of lime and different curing conditions have on the frost heave of a particular clay soil (Devonian red marl), and
2. To relate the changes in frost behavior of the cured lime-treated soil to changes [previously reported by the authors (*3–5*)] in its porosity, permeability, and strength.

MATERIALS AND TESTING

A local silty clay of the Devonian series (a red marl) was chosen as a test material. Its engineering properties were as follows:

Property	*Amount*
Liquid limit	32–33 percent
Plasticity index	11–12 percent
pH value	6.4
Specific gravity	2.73
Optimum moisture content	12.5 percent
Maximum dry density	1.89 $g{\cdot}cm^{-3}$ (118.4 $lb{\cdot}ft^{-3}$)

Its mineralogical components were quartz, feldspar, and illite with traces of chlorite and hematite. The particle size distribution of the soil was determined using a combination of sieve analysis for the coarse fraction (>63 μm) and a hydrometer method for the fine fraction in compliance with British Standard (BS) 1377 (1975). The clay fraction (particles <2 μm) was found to be 12 percent by weight. The lime used was commercially available, high-calcium hydrated lime conforming to BS 890 (1972).

Standard 50-mm (2-in.) diameter by 100-mm (4-in.) long cylinders were prepared with moisture contents of 12 wt% (expressed as a percentage of the total dry weight) and with lime contents of 2, 6, and 10 wt% (expressed as a percentage of the dry weight of the soil), in accordance with BS 1924 (1975). All cylinders were compacted to a constant dry density of 1.89 $g{\cdot}cm^{-3}$ (118.4 $lb{\cdot}ft^{-3}$). Samples were sealed in polyethylene containers, cured at temperatures of 25, 50, and 75°C (77, 122, and 167°F) for periods of 1, 6, 12, and 24 weeks, and then subjected to the freezing test.

The TRRL freezing test equipment was modified to accommodate six standard stabilized soil specimens 50 mm (2 in.) in diameter by 100 mm (4 in.) long as shown in Figure 1. The specimens were first saturated with water in the following manner. The assembled specimens, supported in a polystyrene block, were placed on a metal tray in a vacuum chamber, and their lower ends were immersed to a depth of 15 mm (0.6 in.) in distilled water. They were left in this condition until they showed no further gain in weight. The period of time required for saturation was found to be up to a maximum of 48 hr. Fully saturated specimens were placed in the freezing cabinet with the lower 10 mm (0.4 in.) immersed in water maintained at a constant temperature of 4°C (39.2°F). The cabinet was then placed in a freezing chamber and maintained at a temperature of −10°C (14°F).

Figure 2 gives a detailed illustration of the immediate specimen environment. The temperature directly above the specimen was −10°C (14°F). Vertical movement of the specimens was monitored at regular intervals for seven days, and the heave at this time was taken as an indication of the frost susceptibility of the specimen. Measurements were made relative to a fixed reference point, using a traveling microscope.

Only one frost heave determination was made for each composition and for each curing condition. In addition, two specimens were prepared for each strength test and one specimen for each permeability test. This relatively small number of specimens per test was chosen because of the practical problems associated with preparing, processing, and testing very large numbers of specimens. This was, however, compensated for by careful control of materials, mixing, pressing, curing, and testing. Details of the porosity, permeability, and strength tests performed on these specimens have been reported elsewhere (*3–5*).

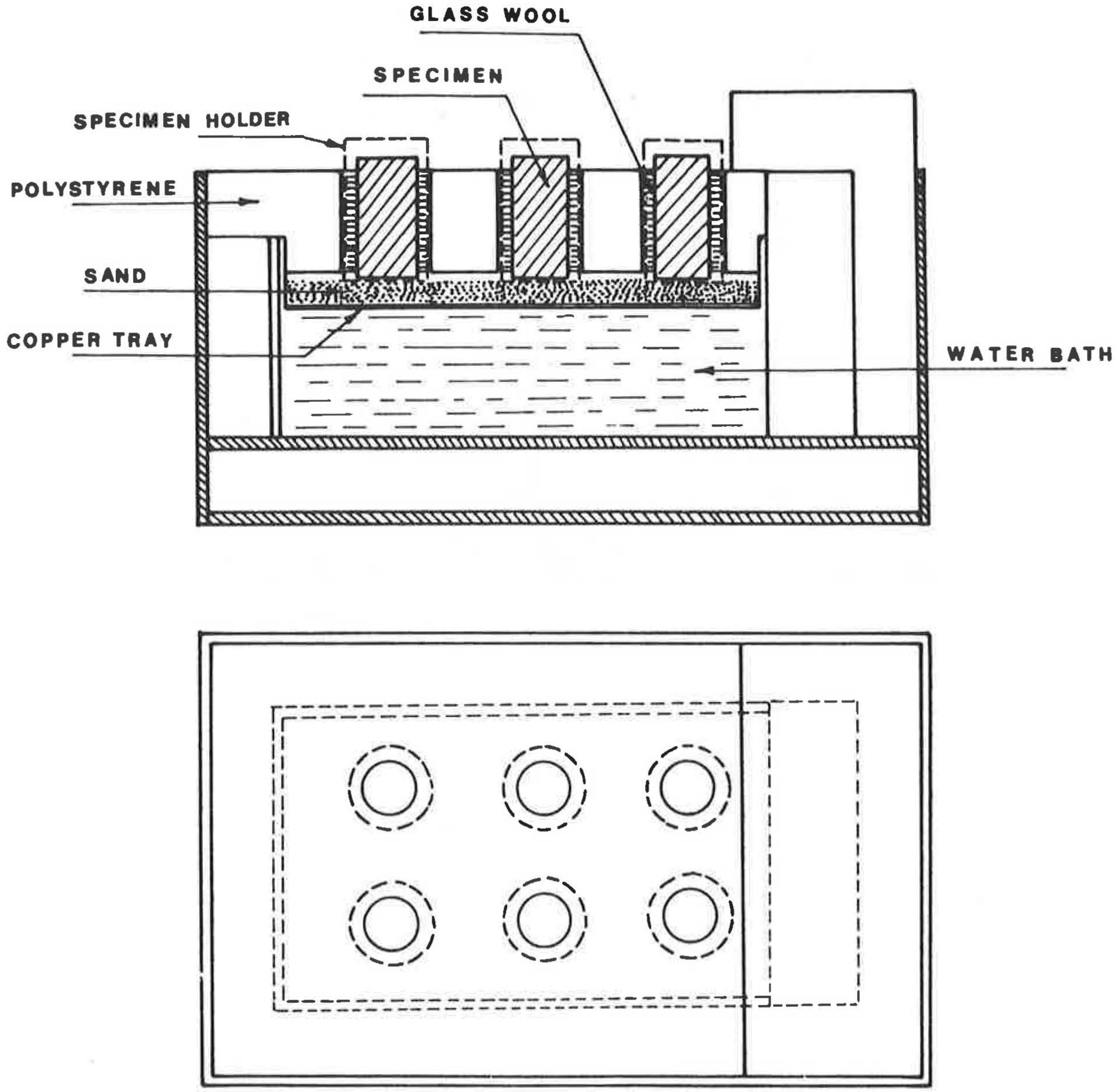

FIGURE 1 Apparatus used to measure frost heave.

DISCUSSION OF TEST RESULTS

Figure 3 shows the heave developed after seven days of continuous freezing versus curing time for samples cured at 25°C (77°F). The heave with 2 percent lime was almost twice the amount that developed for untreated soil and decreased slightly with longer curing times. With 6 percent lime, however, the heave increased slightly after 1 week of curing, but it decreased with longer curing times to a low value after 12 weeks and to zero after 24 weeks. With 10 percent lime, the heave after 1 week of curing was less than that of the untreated soil and decreased to an insignificant value after 12 weeks.

Figure 4 shows the development of heave versus curing time for specimens cured at 50°C (122°F) with the same lime contents as used previously. In this case, the heave developed with 2 percent lime was again about twice the amount developed for the untreated soil after 1 week of curing, but it decreased to less than 80 mm (3.15 in.) after 12 weeks, and to about 70 mm (2.76 in.) after 24 weeks. The material with 6 and 10 percent lime, however, showed a heave of about 20 mm (0.8 in.) after 1 week of curing, and thereafter the heave decreased to zero after 12 weeks.

The results for the material cured at 75°C (167°F) are shown in Figure 5. Here again, the heave that developed with 2 percent lime after 1 week of curing was more than twice the amount that developed with untreated soil, but it decreased thereafter to approximately 40 mm (1.57 in.) after 24 weeks. With 6 percent lime content, however, only a slight heave was observed in specimens cured for 1 week, and heave decreased to an insignificant value in specimens cured for 6 weeks. No heave was observed even after 1 week with 10 percent lime content.

As outlined above, previous studies by Wild et al. (*5*) on the porosity and permeability of these specimens showed a

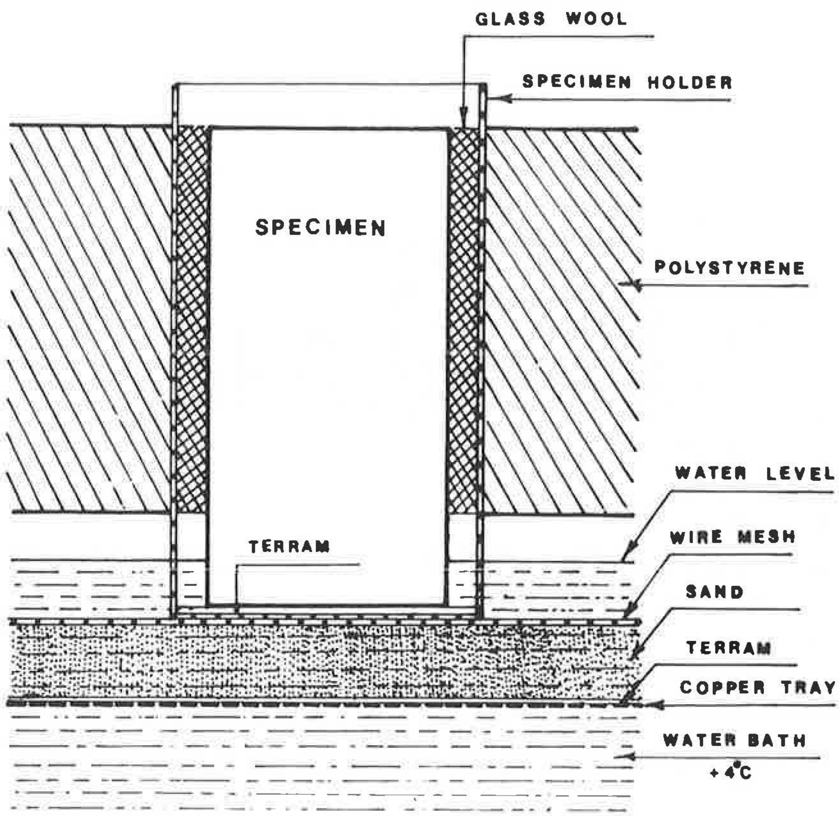

FIGURE 2 Immediate specimen environment during frost heave testing.

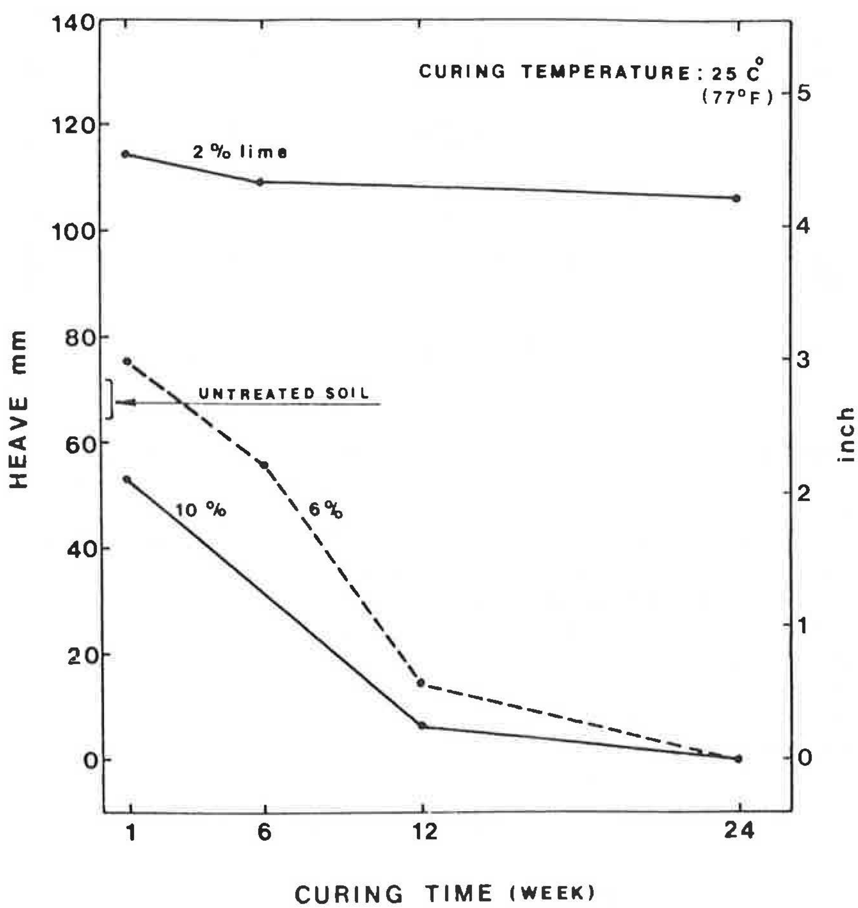

FIGURE 3 Frost heave after 7 days of freezing versus curing time for specimens cured at 25°C (77°F).

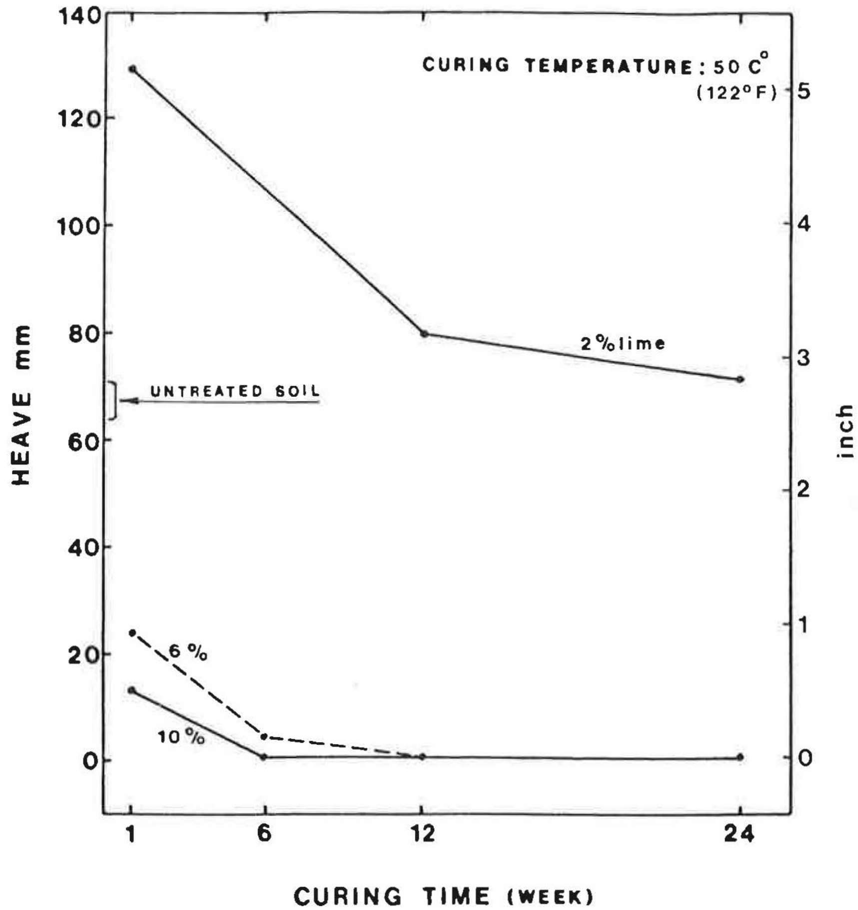

FIGURE 4 Frost heave after 7 days of freezing versus curing time for specimens cured at 50°C (122°F).

general decrease both in porosity and permeability with increasing lime content for lime contents greater than 2 percent by weight. These changes therefore appear to correlate with the observed changes in frost heave behavior.

However, the change in frost heave behavior with curing time did not, in the same way, reflect the changes in porosity and permeability. For example, at 25°C (77°F) curing, permeability actually increased with increased curing time (Figure 6). For higher curing temperatures, permeability was found to decrease only slightly with curing time at 50°C (122°F) (Figure 7), although at 75°C (167°F) curing (Figure 8), the decrease in permeability with curing time was more substantial. Porosity was found to increase with curing time at all curing temperatures.

Evidently, the improvement in frost resistance with curing time for the specimens tested in this study is not principally a function of changes in porosity and permeability. However, continuous development of interparticle bonding occurs with increase in curing time for these specimens, particularly at high lime contents and high curing temperatures. This is apparent from observations of microstructural changes (*3,4*) and compressive strength increases (*3*) previously reported by the authors.

Figures 9–11 show the changes in compressive strength with curing time for specimens with different lime contents cured at different temperatures. The strength developed at low lime content (2 wt%) is very small even at high curing temperatures [75°C (167°F)], whereas strength increases significantly with curing time at the higher lime contents, particularly as curing temperature is increased.

Typical photographs of heaved specimens are shown in Figure 12. The nature of the surface cracking shows a characteristic variation in relation to the degree of interparticle bonding that has developed. For short curing times and low lime contents, only limited interparticle bonding occurs even at 75°C (167°F). The surface (Figure 12a) shows particle agglomerates that are coarse and widely separated close to the unfrozen zone (lower part) and much finer and less widely separated toward the frozen zone (upper part). The spaces between the particle agglomerates are created by the development and growth of ice lenses.

At longer curing times and higher lime contents, even at 25°C (77°F), some interparticle bonding occurs, and the surface (Figure 12b) shows a network of large cracks separating areas that are still essentially coherent. At even higher lime contents (10 wt%) and increased curing temperature [50°C (122°F)], specimens exhibit very limited cracking and retain their original shape and dimensions (Figure 12c).

CONCLUSIONS

From the work reported in this paper, it appears that the addition of a small amount of lime (up to 2 wt%) is likely to

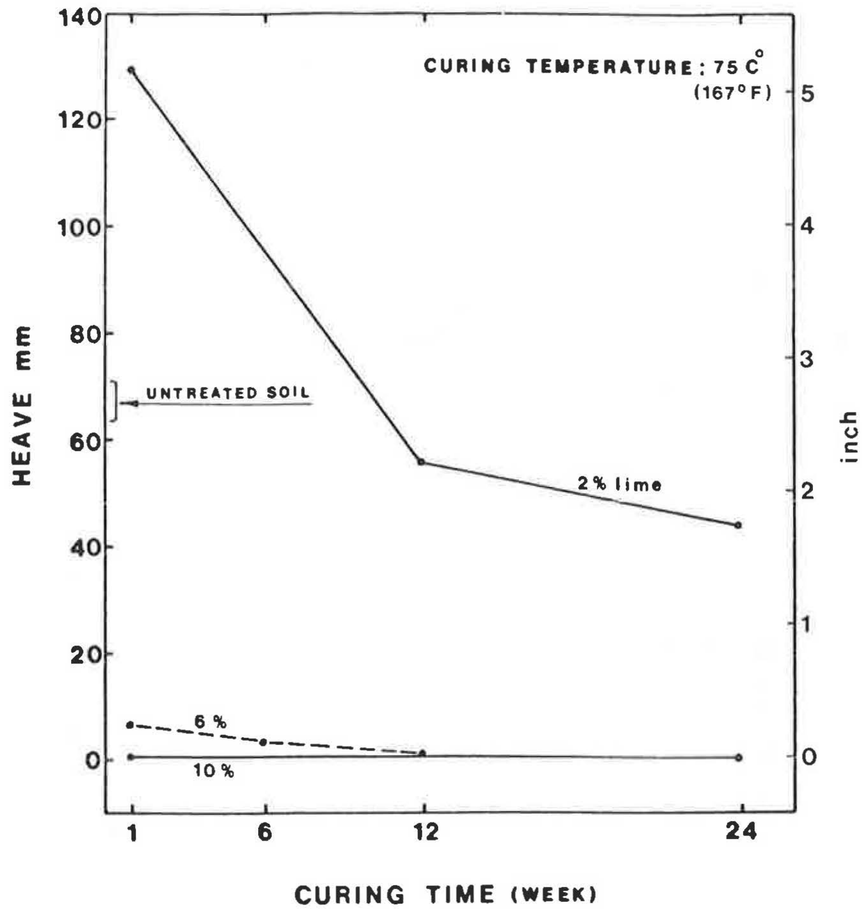

FIGURE 5 Frost heave after 7 days of freezing versus curing time for specimens cured at 75°C (167°F).

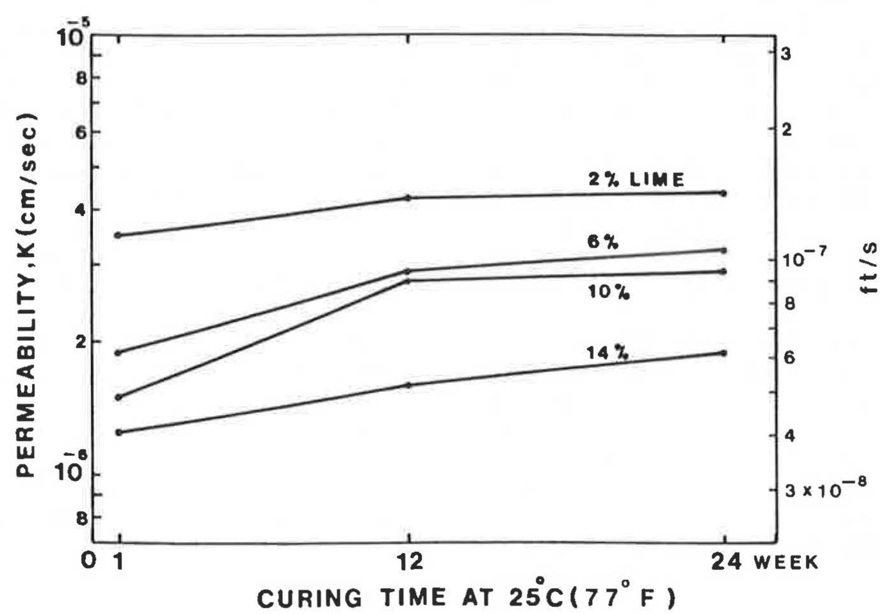

FIGURE 6 Permeability versus curing time for specimens cured at 25°C (77°F).

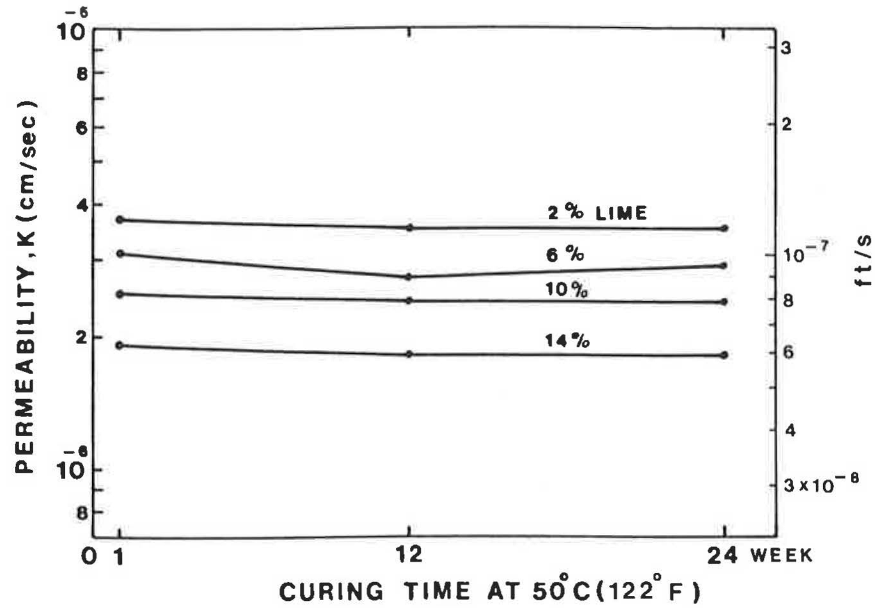

FIGURE 7 Permeability versus curing time for specimens cured at 50°C (122°F).

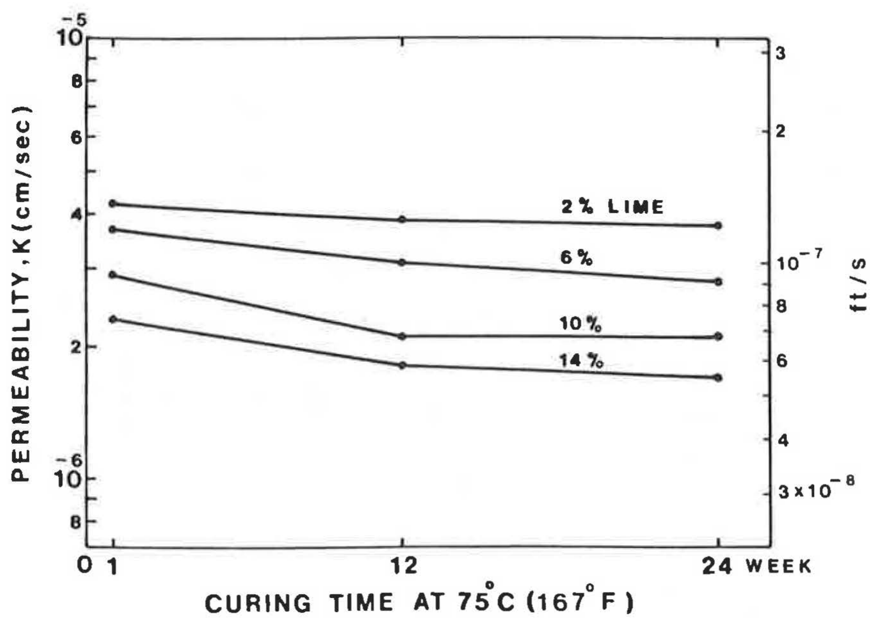

FIGURE 8 Permeability versus curing time for specimens cured at 75°C (167°F).

increase the frost susceptibility of the soil, even after long curing periods and high curing temperatures. It is suggested that this initial sharp increase in the observed frost heave (relative to the heave observed for the untreated soil compacted to the same initial dry density) is a result of the substantial increase in permeability on addition of lime to the soil. The permeabilities of 1-week cured soil cylinders containing 2 wt% lime (see Figures 6–8) are between 4 and 5 times that for untreated soil [0.83×10^{-6} cm·s^{-1} (2.72×10^{-8} ft·s^{-1})]. This increase in permeability following the addition of lime is attributed to the effect of flocculation of the clay particles, which produces a more open and permeable soil structure. Brandl (*9*) observed a similar effect.

The addition of 6 percent or more lime reduces the frost susceptibility of the soil significantly, even at short curing times (1 week) and low curing temperatures [25°C (77°F)] (see Figure 3). Under these conditions, there is negligible cementitious gel formation and only limited interparticle bonding. The reduction in frost heave with increased lime content for specimens cured for these very short periods at low curing temperatures is attributed mainly to the reduction in the permeability of the compacted soil as the lime content is increased above the 2 wt% level (see Figure 6).

It is suggested that the observed improvement in frost resistance with curing time is due predominantly to the development of interparticle bonding, even at the low curing tem-

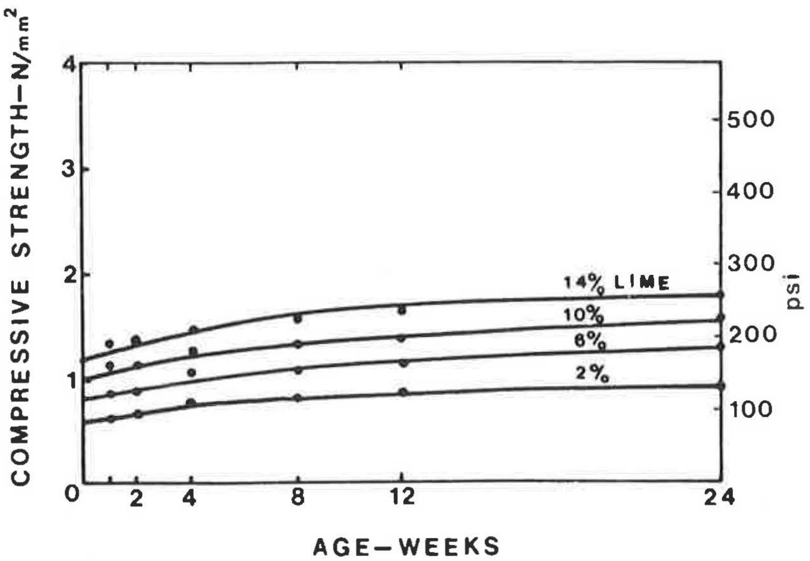

FIGURE 9 Compressive strength versus curing time for specimens cured at 25°C (77°F).

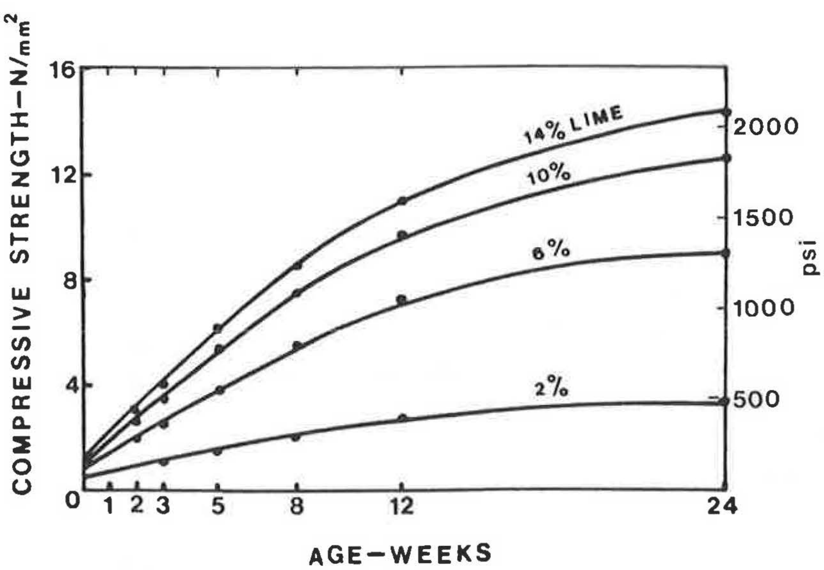

FIGURE 10 Compressive strength versus curing time for specimens cured at 50°C (122°F).

perature of 25°C (77°F), where formation of cementitious material is limited and strength gains are small (see Figure 12). At high curing temperatures (Figure 5) the amount of heave falls off rapidly with curing time. A 75°C (167°F) cured 10 wt% lime-soil cylinder is fully frost resistant within one week, and a 2 wt% lime-soil cylinder experiences less heave than the untreated soil after 12 weeks at 75°C (167°F), even though it is more permeable than the soil alone. This reflects the rapid rate of strength development and interparticle bonding at high curing temperatures (see Figures 10 and 11).

Both permeability and interparticle bonding play a role in determining the frost resistance of soil-lime composites. The development of interparticle bonding during curing improves the mechanical properties, including tensile strength, which restricts ice segregation and reduces heave. The small changes in permeability that occur during curing have a negligible effect on frost heave behavior. This is in contrast to unbonded materials (e.g., soil-lime composites cured for short times at low temperatures), in which frost resistance is dictated mainly by the permeability of the materials.

It would appear from this investigation that, under conditions of high ambient temperatures often met in the summer in arid regions, only relatively short periods of curing are required to protect clay soils from the problems of heave often experienced in winter—as long as the lime added to the soil is above an optimum level (6 wt% in the present work). Hence, whenever an improvement in the frost resistance of

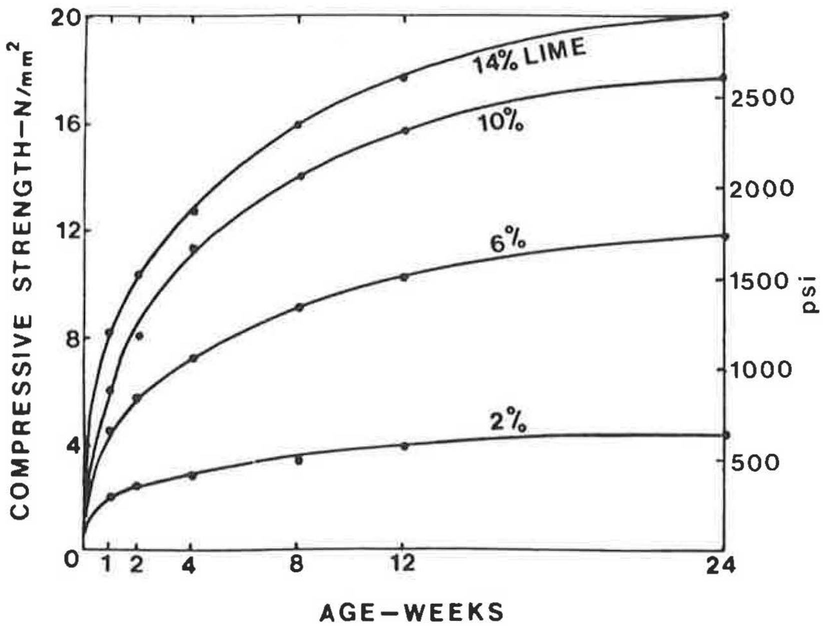

FIGURE 11 **Compressive strength versus curing time for specimens cured at 75°C (167°F).**

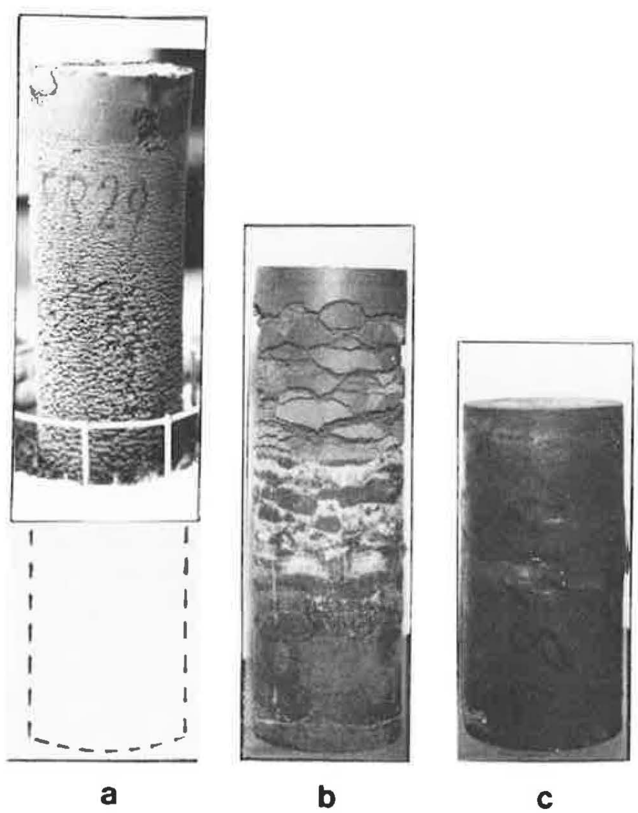

FIGURE 12 **Frost heave and cracking of soil-lime cylinders: (a) 2% lime cured for one week at 75°C, (b) 6% lime cured for 6 weeks at 25°C, and (c) 10% lime cured for 6 weeks at 50°C.**

road materials such as the subgrade is required, lime stabilization should be considered as an appropriate solution, particularly if the work can be carried out in warm weather.

REFERENCES

1. G. O. Rowlands, M. Arabi, and R. Delpak. Lime and the Plasticity of Clays. *Journal of the Institution of Highways and Transportation*, Vol. 34, No. 5, 1987, pp. 21–24.
2. S. Diamond and E. B. Kinter. Mechanisms of Soil-Lime Stabilization. In *Highway Research Record 92*, HRB, National Research Council, Washington, D.C., 1965, pp. 83–102.
3. S. Wild, M. Arabi, and G. Leng-Ward. Soil-Lime Reaction and Microstructural Development at Elevated Temperatures. *Clay Minerals*, Vol. 21, 1986, pp. 279–292.
4. M. Arabi and S. Wild. Microstructural Development in Cured Soil-Lime Composites. *Journal of Materials Science*, Vol. 21, 1986, pp. 497–503.
5. S. Wild, M. Arabi, and G. O. Rowlands. Relation between Pore Size Distribution, Permeability and Cementitious Gel Formation in Cured Clay-Lime Systems. *Materials Science and Technology*, Vol. 3, Dec. 1987, pp. 1005–1011.
6. D. Croney and J. D. Coleman. Pore Pressure and Suction in Soil. *Proc., Conference on Pore Pressure and Suction in Soils*, London, 1960, pp. 31–37.
7. D. L. Townsend and T. W. Klym. Durability of Lime-Stabilized Soils. In *Highway Research Record 139*, HRB, National Research Council, Washington, D.C., 1966, pp. 25–41.
8. M. R. Thompson. Lime Stabilization of Frost-Susceptible Soils. *Frost I Jord*, 1973, pp. 45–52.
9. H. Brandl. Alteration of Soil Parameters by Stabilization with Lime. *Proc., 10th International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, Vol. 3, 1981, pp. 587–594.
10. J. J. Allen, D. D. Currin, and D. N. Little. Mix Design, Durability, and Strength Requirements for Lime-Stabilized Layers in

Airfield Pavements. In *Transportation Research Record 641*, TRB, National Research Council, Washington, D.C., 1977, pp. 34–41.
11. W. J. Rosen and B. D. Marks. Cold Weather Lime Stabilization. In *Transportation Research Record 501*, TRB, National Research Council, Washington, D.C., 1974, pp. 35–41.
12. B. J. Dempsey and M. R. Thompson. Vacuum Saturation Method for Predicting Freeze-Thaw Durability of Stabilized Materials. In *Highway Research Record 442*, HRB, National Research Council, Washington, D.C., 1973, pp. 44–57.
13. B. J. Dempsey and M. R. Thompson. Durability Properties of Lime-Soil Mixtures. In *Highway Research Record 235*, HRB, National Research Council, Washington, D.C., 1968, pp. 61–75.
14. D. Croney and J. C. Jacobs. *The Frost Susceptibility of Soils and Road Materials*. Report No. 90. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1967, pp. 1–68.
15. P. G. Roe and D. C. Webster. *Specification for the TRRL Frost-Heave Test*. Supplementary Report 829. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1984, pp. 1–17.

Publication of this paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization.