EFFECT OF LIME TREATMENT ON THE RESILIENT BEHAVIOR OF FINE-GRAINED SOILS

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Lime treatment of fine-grained subgrade soils has definite potential for beneficially altering subgrade softening due to high moisture contents and freeze-thaw action. The effects of high moisture content and freeze-thaw cycles on the resilient response of a number of untreated and lime-treated soils are examined. A finite element procedure is used to evaluate the structural response of a flexible pavement on untreated and lime-treated subgrades. The analysis reveals that high moisture contents and freeze-thaw action in the subgrade have a detrimental effect on the magnitude of pavement response parameters and that lime treatment of the upper layer of the subgrade causes a substantial improvement in pavement response.

•THE BEHAVIOR and performance of pavement systems are greatly affected by subgrade support conditions. In recent years, good correlation has been found between performance and the elastic or recoverable surface deflection of flexible pavements. Because typically 60 to 70 percent of the elastic or recoverable deflection observed at the surface of a flexible pavement is accumulated in the subgrade, it is obvious that the behavior of subgrade soils subjected to repeated loads of short duration is an important consideration in pavement design.

Early work by Seed, Chan, and Lee (1) on a very limited number of soils demonstrated the various factors that affect the recoverable or resilient deformation of laboratory-prepared and laboratory-tested samples of fine-grained cohesive soils. One of the significant factors was found to be compaction moisture content or degree of saturation. Recent studies (2) conducted at the University of Illinois with a large number of soils from the Midwest, Oklahoma, Georgia, and the Carolinas also demonstrated the dramatic influence of moisture content (degree of saturation) on the resilient behavior of soils.

Moisture content during field compaction is often difficult to control or in some cases is not controlled at all (density specification only). A variation in the resilient response of a given subgrade soil can therefore be expected immediately after construction. In addition, moisture content fluctuations due to climatic factors may contribute to seasonal variations in subgrade resilient response and pavement deflections.

Recent studies by Bergan and Fredlund (3), Culley (4), Chamberlain (5), Bergan and Monismith (6), and Bergan and Culley (7) have shown that the resilient behavior of fine-grained cohesive soils is also greatly affected by cyclic freeze-thaw action. The studies revealed that, for the soils studied, a small number of freeze-thaw cycles caused a substantial increase in resilient deformation even though no moisture changes were allowed (closed system freeze-thaw).

Consequently, it is obvious that moisture variations (during and subsequent to construction) and cyclic freeze-thaw action can greatly affect the resilient behavior of the subgrade and therefore the behavior and performance of the pavement system. The pavement engineer should be able not only to predict that such variable conditions may exist but also to design a pavement system that can accommodate these variable and unpredictable conditions or alternately to design a pavement system that is fairly insensitive to changes in soil support conditions due to moisture and freeze-thaw.

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PURPOSE AND SCOPE

The purpose of this paper is to evaluate the potential of lime treatment for altering the adverse effects of high moisture contents and freeze-thaw action on the resilient response of fine-grained soils. The effects of moisture and freeze-thaw action on the resilient response of untreated and lime-treated soils and the structural behavior of pavement systems containing lime-treated soil layers are considered.

RESILIENT BEHAVIOR OF SUBGRADE SOILS

A number of factors influence the resilient response of fine-grained soils. The effect of stress level on resilient modulus is shown in Figure 1 for a typical Illinois soil. Resilient modulus is defined as applied deviator stress divided by recoverable or resilient strain. Compaction moisture and density greatly affect resilient behavior as shown in Figure 2 for the AASHO Road Test subgrade soil. The effect of small moisture content increases on the wet side of optimum is quite pronounced. Figure 3 shows the substantial decrease effected in the resilient modulus as compaction moisture content is increased (compacted density remained constant) for three typical Illinois soils.

Recent studies (3, 4, 5, 6, 7) revealed the substantial influence of closed system freeze-thaw cycling (at constant moisture content) on the resilient behavior of cohesive soils. In the study by Bergan and Monismith (6) as few as one closed system freeze-thaw cycle drastically reduced the resilient moduli values of the Regina clay soil compared to the moduli values prior to freeze-thaw cycling.

Bergan and Fredlund (3) attribute this reduction in resilient modulus to a reorientation of moisture in the soil pores and to a change in soil suction. In Chamberlain's summary of freeze-thaw weakening of fine-grained soils (5), it was indicated that localized small moisture content increases on the surfaces of "nuggets of soil particles" were sufficient to reduce cohesion between the nuggets. Chamberlain concluded, "The literature review reveals that closed system freeze-thaw will induce weakening of clay soils with or without visible ice segregation. The compressive strength and the static and repetitive moduli are affected. The rate of strength reduction due to closed system freeze-thaw decreases with an increasing number of freeze-thaw cycles."

The study by Bergan and Fredlund (3) also showed that, when a large number (10,000) of loads were applied to the Regina clay sample that had previously been subjected to the freeze-thaw cycle, the sample gained strength and displayed a resilient response similar to the sample prior to the freeze-thaw cycle (Figure 4). This sequence of testing possibly approximates the spring softening and summer strengthening phenomenon that is commonly observed for flexible pavements in regions of seasonal freeze-thaw action.

EFFECT OF SUBGRADE RESILIENCE ON PAVEMENT STRUCTURAL RESPONSE

To demonstrate the influence of subgrade resilient behavior on pavement response, we considered the flexible pavement shown in Figure 5. Two Illinois subgrade soils, one high in silt content (Fayette C) and the other high in clay content (Tama B), displaying substantially different resilient responses (Figure 6) were used under the pavement. Pertinent properties of these soils are given in Table 1.

The structural response of the flexible pavement subjected to a 9-kip (40-kN) wheel load was analyzed by using a finite element computer program that considers the stress-dependent or nonlinear response of the subgrade soil and the granular base course material.

Table 2 gives the theoretical response data obtained from the analysis of the pavement on the two subgrades. It can be noted from the data presented in this table that substantial differences in pavement structural response can be effected by differences in subgrade resilient characteristics. Note for example that the surface deflection is

Figure 1. Resilient response of typical fine-grained Illinois soil.

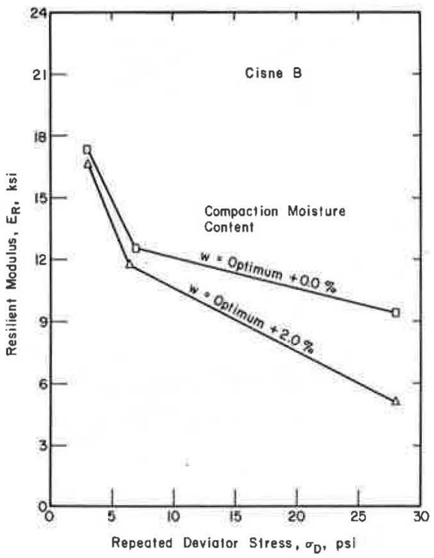


Figure 2. Effect of compaction moisture and density conditions on resilient axial strain of AASHO Road Test subgrade soil.

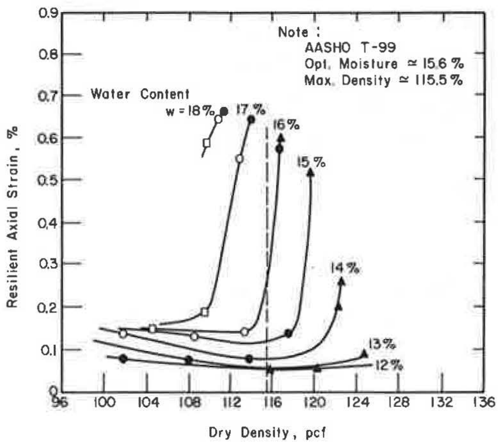


Figure 3. Effect of compaction moisture on resilient modulus.

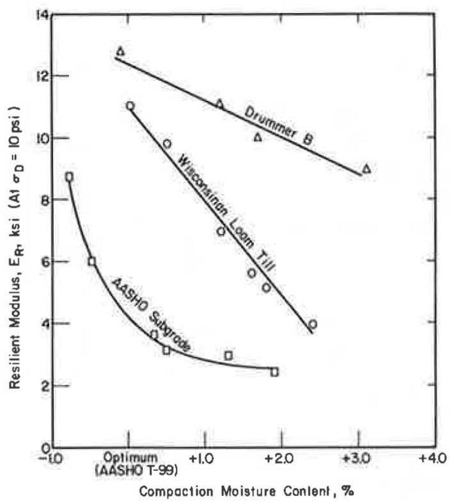


Figure 4. Resilient modulus test results before and after freeze-thaw for undisturbed Regina clay.

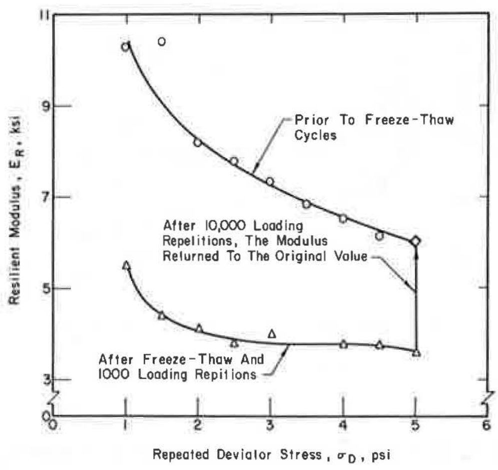


Figure 5. Dimensions and properties of flexible pavement used in study.

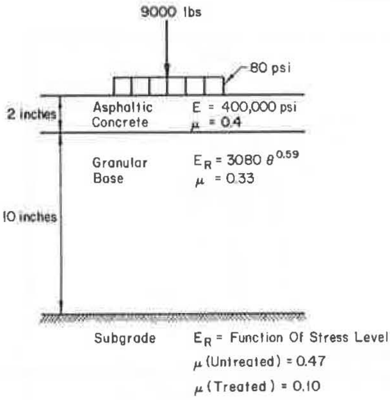


Figure 6. Resilient behavior of two subgrade soils.

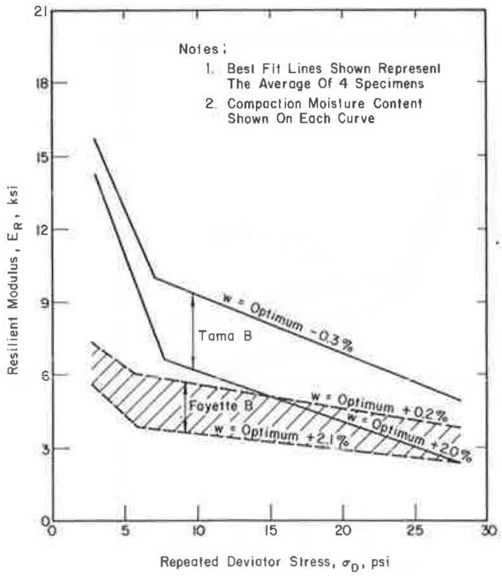


Figure 7. Effect of lime treatment and variable compaction moisture on resilient response of Flanagan B soil.

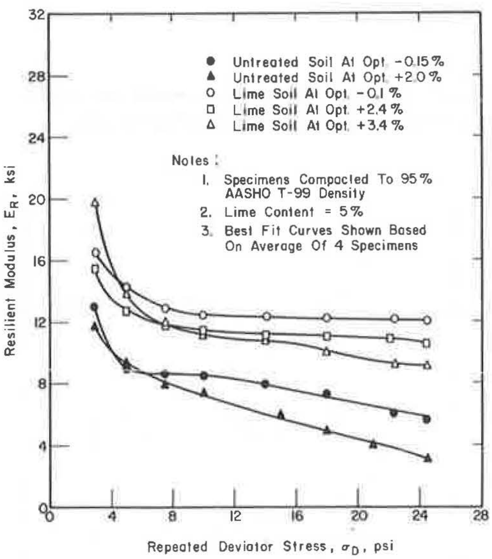


Table 1. Summary of pertinent soil properties.

Property	Fayette C	Tama B
Atterberg limits		
Liquid limit	32	46
Plasticity index	9	24
Grain size		
Percentage passing No. 200 sieve	98	100
Silt (0.002 to 0.050 mm), percent	75	67
Clay (<0.002 mm), percent	18	32
AASHO classification	A-4(9)	A-7-7(27)
Unified classification	ML	CL
Moisture-density (AASHO T-99)		
$\gamma_d$max, lb/ft^3	109.4	100.8
w_{opt}, percent	17.2	21.9
Soaked CBR	5.3	3.2
Compressive strength,[a] psi		
w = optimum	22	24
w = optimum + 2 percent	19	21

Note: 1 lb/ft^3 = 16 kg/m^3; 1 psi = 6.9 kPa.
[a]0 percent lime (95 percent AASHO T-99).

Table 2. Summary of results from analysis of pavement structural behavior.

	Surface Deflection (in.)		Radial Tensile Strain in Surface (in./in.)		Compressive Strain in Subgrade (in./in.)		Compressive Stress in Subgrade (psi)	
Subgrade Condition	Fayette C	Tama B	Fayette C	Tama B	Fayette C	Tama B	Fayette C	Tama B
Untreated								
Optimum moisture	0.060	0.041	0.00083	0.00065	0.00117	0.00076	10.9	13.1
Optimum + 2 percent	0.068	0.043	0.00087	0.00066	0.00161	0.00082	10.3	12.8
9-in. freeze-thaw layer[a]	0.073	0.055	0.00089	0.00082	0.00297	0.00186	9.9	11.6
18-in. freeze-thaw layer[a]	0.075	0.059	0.00089	0.00084	0.00271	0.00168	9.2	10.8
Lime treated								
9-in. treated layer[a]	0.050	0.040	0.00065	0.00063	0.00074	0.00037	5.3	6.9
18-in. treated layer[a]	0.045	0.039	0.00063	0.00061	0.00039	0.00021	2.8	3.8

Note: 1 in. = 2.5 cm; 1 psi = 6.9 kPa.
[a]For optimum + 2 percent compaction moisture condition.

about 60 percent greater for the pavement on the Fayette C subgrade than for the pavement on the Tama B subgrade. Similar trends are noted for the other pavement response factors. By comparing the relative magnitude of these response parameters and acknowledging that these response parameters are widely accepted as indicators of flexible pavement performance, it is obvious that substantially different potential performance would be expected from this flexible pavement on the two subgrades.

RESILIENT BEHAVIOR OF LIME-TREATED SOILS

Lime has been widely and successfully used as a stabilizing agent for fine-grained plastic soils. When lime is added to a fine-grained soil, several reactions are initiated. Cation exchange and agglomeration-flocculation reactions take place rapidly and produce immediate changes in soil plasticity, workability, and swell properties. Plasticity and swell are reduced and workability is substantially improved because of the low plasticity and the friable nature of the mixture.

Depending on the characteristics of the soil being stabilized, a soil-lime pozzolanic reaction may commence. The cementing agents formed as a result of the pozzolanic reaction increase mixture strength and durability. With some fine-grained soils, however, the pozzolanic reaction is inhibited, and extensive cementing agents are not formed. Thompson (8) has termed those soils that react with lime to produce substantial strength increases as reactive and those that display limited pozzolanic reactivity as nonreactive. For the nonreactive soils, plasticity, workability, and swell properties are beneficially altered, but strength increases are nominal. Both nonreactive and reactive soils display similar characteristics immediately after the lime and soil are mixed. It is only after the mixture is compacted and cured that substantial differences in strength are noted.

The strength properties of lime-treated soil mixtures at early ages are important in certain aspects of pavement design and construction. Neubauer and Thompson (9) reported immediate stability increases effected by lime treatment of fine-grained soils. Their study, however, was limited to a determination of static stability conditions such as shear strength, CBR, cone penetrometer value, and modulus of deformation.

From the standpoint of long-term pavement behavior and performance, it is desirable to have a knowledge and understanding of the resilient characteristics of lime-treated soil mixtures. A limited number of reactive and nonreactive soils were treated with lime, compacted into 2-in.-diameter by 4-in.-high (5- by 10-cm) specimens and immediately subjected to resilience testing (2). Complete study results may be found elsewhere (10).

Effect of Lime Treatment on Resilient Behavior

Results to date demonstrate that, without exception, the resilient response of uncured lime-treated soil is substantially different from the response of untreated soil. Figure 7 shows (a) the typical stress-dependent resilient behavior of untreated and lime-treated fine-grained soils, (b) the effect that compaction moisture content has on resilient behavior, and (c) the beneficial effect that lime treatment has on resilient behavior. The immediate effects of lime on the resilient behavior are evident. The resilient behavior is substantially improved (increased resilient modulus, reduced resilient deflection) when lime is added. Note also that, compared to the untreated soil at optimum moisture, lime treatment effects increased resilient moduli (higher resistance to repeated loads) at moisture contents as high as 3.4 percent above optimum. Other soils examined in this study (11) showed similar response trends upon lime treatment.

Freeze-Thaw Effects

As shown by previous studies (3, 4, 6, 7), a small number (as few as one) of freeze-thaw cycles apparently have an extreme softening effect on the resilient behavior of fine-grained soils. This effect was also evident in recent studies conducted at the University of Illinois (11, 12) as shown by the data in Figures 8 and 9. Based on only limited results, it appears that freeze-thaw more detrimentally affects the resilient behavior of the clayey Tama B soil than the more silty Fayette C soil. It also appears that, even though the clayey soil has substantially higher resilient moduli values after compaction than does the silty soil, a few freeze-thaw cycles cause the two soil types to display similar resilient behavior (Figures 8 and 9).

Shown in Figures 10 and 11 are the effects of additional repeated loading and 28 days of cure on the resilient behavior after initial freeze-thaw cycling. The 10,000 additional loadings appear to increase the resilient moduli of the silty soil but appear to have a minimal effect on the moduli of the clayey soil. The 28-day cure after the freeze-thaw cycling of the clayey soil also appears to have a minimal strengthening effect on resilient behavior (Figure 11).

When these two soils were treated with 5 percent commercially available high calcium hydrated lime, the detrimental effects of freeze-thaw cycling on resilient behavior appear to be minimized or eliminated. As shown in Figures 8 and 9 it can be seen that even as many as 10 freeze-thaw cycles do not significantly affect the resilient behavior. The resilient moduli of the untreated Fayette C and Tama B samples range from 3 to 6 ksi (20 to 41 MPa) after freeze-thaw cycling depending on the applied axial stress. However, when the soils are treated with lime (no cure), the resilient moduli range from 14 to 20 ksi (96 to 138 MPa) after 10 freeze-thaw cycles, showing the remarkable strengthening and desensitizing effected by the lime treatment. Note also that the resilient responses of these two lime-treated soils are very similar, although the pretreatment resilient responses were quite different.

Curing Effects

The Fayette C soil (which is considered lime reactive) was allowed to cure 20 days at 73 F (23 C) prior to freeze-thaw cycling. The resilient behavior was slightly improved compared to the uncured behavior (Figure 8). The range of resilient moduli is 18 to 24 ksi (124 to 165 MPa) depending on the magnitude of repeated deviator stress.

No additional strengthening is normally effected by curing for soils that are not lime reactive; therefore, the immediate and cured resilient responses of such materials are similar.

RESPONSE OF PAVEMENT SYSTEMS CONTAINING LIME-TREATED SOIL LAYERS

Based on previous discussion, the following facts are obvious:

1. High moisture contents and freeze-thaw action have a detrimental effect on the resilient behavior of fine-grained subgrade soils;
2. Lime treatment of fine-grained soils substantially improves the resilient moduli of the soils and reduces or eliminates the detrimental effects of freeze-thaw action; and
3. The resilient behavior of a subgrade has a profound effect on the behavior and potential performance of the flexible pavement examined.

The purpose of the following discussion is to evaluate the relative effect of a lime-treated layer of subgrade on the structural behavior and potential performance of typical flexible pavements.

The flexible pavement shown in Figure 5 was placed on the two subgrade soils, and the pavement structural behavior under a 9-kip (40-kN) wheel load was examined by

Figure 8. Effect of lime treatment, freeze-thaw, and curing on resilient response of Fayette C soil.

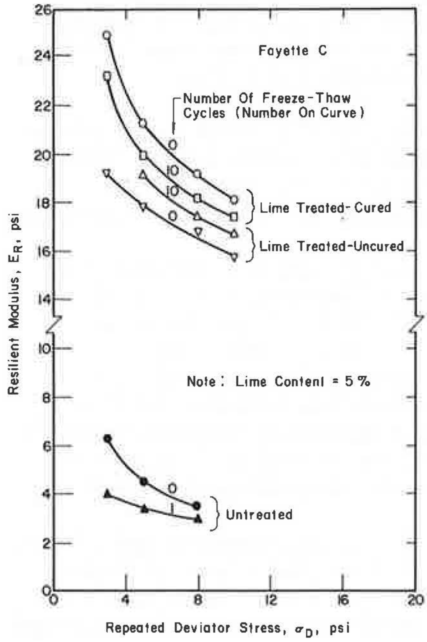


Figure 9. Effect of lime treatment, freeze-thaw, and curing on resilient response of Tama B soil.

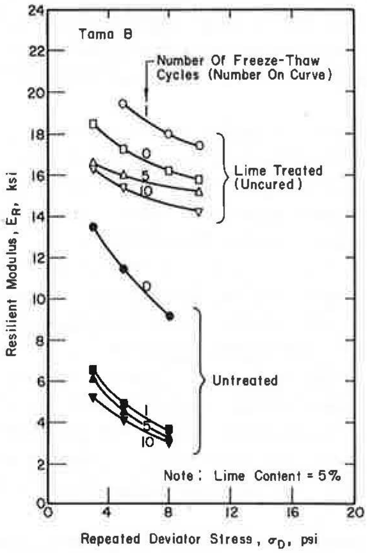


Figure 10. Effect of freeze-thaw and additional loading on resilient response of untreated Fayette C soil.

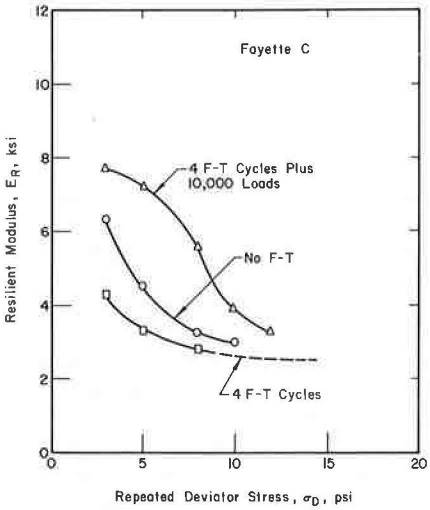
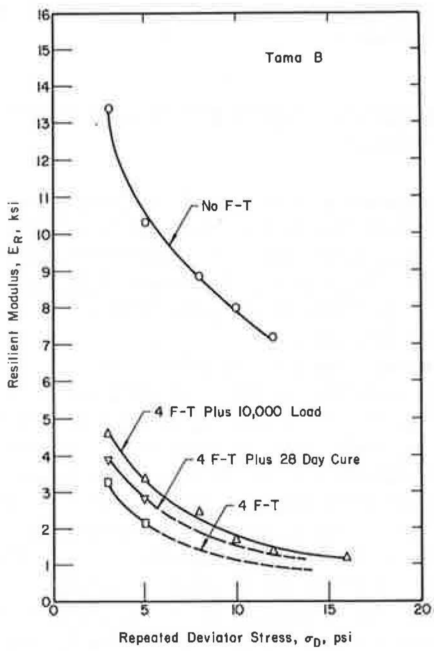


Figure 11. Effect of freeze-thaw, additional loading, and additional curing on resilient response of untreated Tama B soil.



using the finite element method previously discussed. Four variables were considered: soil type (silty and clayey), compaction moisture content (optimum and optimum +2 percent), thickness of subgrade layer subjected to the detrimental effect of freeze-thaw [9 and 18 in. (23 and 46 cm)], and thickness of lime-treated subgrade layer (9 and 18 in.).

Table 2 gives structural response data from the finite element computer analysis. By analyzing and comparing the relative magnitudes of the various response factors for the two subgrade soils, the following general observations can be made.

1. A moisture content increase from optimum to optimum +2 percent (constant dry density) leads to increases in surface deflection, surface layer radial tensile strain, compressive subgrade strain, and compressive subgrade stress. The greatest moisture-induced increases noted in the pavement response parameters are associated with the pavement on the Fayette C soil.
2. Subjecting a 9- or 18-in.-thick (23- or 46-cm) layer of subgrade soil to one or more freeze-thaw cycles, in general, causes a substantial increase in surface deflection, radial tensile strain, and compressive subgrade strain for the pavement on the clayey and silty subgrade soils compared to the condition of no freeze-thaw.
3. Treating the subgrade layer subjected to freeze-thaw with lime effects substantial reduction in the magnitude of the pavement response parameters examined. Reductions of (a) approximately 30 percent in surface deflection, (b) approximately 30 percent in radial tensile strain, (c) approximately 75 to 80 percent in compressive subgrade strain, and (d) approximately 50 to 70 percent in compressive subgrade stress are noted.
4. For the two thicknesses of lime-treated layer used in the analysis (9 and 18 in.), which coincide with the subgrade layer thickness affected by freeze-thaw, thickness appears to have only a slight effect on surface deflection and radial tensile strain but a rather substantial beneficial effect on compressive strain and stress in the untreated subgrade.

The data given in Table 2 also indicate that lime treatment of a 9- or 18-in.-thick (23- or 46-cm) layer of the subgrades that are 2 percent above optimum results in an improved pavement response compared to the pavement with a subgrade compacted at optimum moisture conditions. Thus, based on these data, lime treatment can be used to help eliminate poor subgrade resilient behavior associated with high moisture content subgrades.

DISCUSSION OF RESULTS AND SIGNIFICANCE OF FINDINGS

The phenomenon of subgrade softening or spring breakup is a very real problem associated with flexible pavements located in areas of seasonal frost. At the AASHO Road Test, substantial increases in surface deflection were noted following spring thaw (13). In an extensive study (14), the Canadian Good Roads Association found that spring Benkelman beam deflections for Canadian flexible pavements averaged 1.5 to 3 times the fall deflection values.

Numerous reasons including lower density and higher moisture content have been forwarded to explain the subgrade softening phenomenon that occurs during spring thaw. Based on the results presented here and previous studies (3, 4, 5, 6, 7), it appears that cyclic freeze-thaw even without changes in moisture conditions can cause detrimental alterations in flexible pavement behavior. These findings may at least partially serve to explain the observed spring softening of the AASHO Road Test flexible pavements, which occurred with no apparent subgrade moisture change.

Based on the limited results presented in this paper, it appears that treatment of the upper layer of the subgrade with lime will desensitize or protect the flexible pavement from the subgrade softening phenomenon associated either with freezing and thawing or moisture increase. For freeze-thaw protection, ideally, the subgrade should be treated to the maximum depth of frost penetration expected under the pavement.

Minimizing or eliminating the subgrade softening phenomenon through lime treatment will greatly enhance the pavement designer's capability for minimizing the uncertainties associated with future climatic factors (frost and moisture).

The following additional benefits may accrue from the use of lime treatment:

1. Possible reduction in pavement layer thicknesses and
2. Creation of a construction working table that will expedite construction operations and facilitate compaction of the overlying pavement layers.

One note of caution is warranted, however. Thompson (15) pointed out that, unless a certain level of strength is obtained with lime-treated fine-grained soils, frost heave may occur in the lime-treated layer under certain conditions. Based on limited results, a compressive strength of about 200 psi (1380 kPa) was needed to avoid frost heaving (15).

SUMMARY AND CONCLUSIONS

The potential of lime treatment for altering the adverse effects of high moisture contents and freeze-thaw action on the resilient behavior of fine-grained soils was examined. It was found that lime treatment greatly improves the resilient moduli of soils with high moisture contents and soils subjected to freeze-thaw cycling. It was also demonstrated that the inclusion of a lime-treated soil layer substantially improves the structural response and therefore the potential performance of a flexible pavement on a fine-grained subgrade that will be subjected to the softening effects of freeze-thaw action or moisture increase.

Other benefits may also accrue from lime treatment of the upper subgrade layer including possible reduced layer thicknesses and expedience and facilitation of construction operations.

Further research is needed, however, on the probable occurrence of frost heave in the lime-treated layer, especially for lower strength, nonreactive soils.

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