essentially a trial-and-error process, since a universally acceptable design procedure is still not available.

2. Curing is not as important a consideration in open-graded mixes as in dense mixes, although it will be slower in the cooler climates.

3. Aggregates used in open-graded mixes must be clean, of good quality, uniform in size, and rough in texture. Dirty aggregate causes coating problems, and unsound aggregate causes performance problems.

4. Open-graded emulsion mixes, though they possess little if any unconfined strength, can support gross loads as heavy as 890 kN (200 000 lbf) without significant rutting.

5. Open-graded mixes should not be placed in heavy rain, for this may result in washoff of emulsion from the aggregate. The emulsion must break to be safe from washoff.

Although a number of designs for open-graded emulsion mixes are available, the results in terms of design emulsion and water content are similar. It would be desirable to establish one of the methods discussed in this paper as a standard for others to use.

However, design strength criteria are badly needed. Values used to date have been chosen based on limited experience and engineering judgment. A means of better predicting the effects of curing is needed in the design process. Whatever is done should ensure that laboratory curing conditions compare as much as possible with curing conditions in the field.

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Mechanistic Thickness-Design Procedure for Soil-Lime Layers

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A mechanistic thickness-design procedure for soil-lime pavement layers is presented. The procedure, which is based on a stress-dependent finite-element computer model called ILLI-PAVE, is limited to pavements constructed of a cured soil-lime layer and a nonstructural surface course (surface treatment or thin asphalt concrete). Design input data are soil-lime strength and modulus, subgrade resilient modulus, and estimated traffic. The procedure assumes that the soil-lime mixture is capable of developing significant increase in strength (relative to the strength of the natural soil) and that quality field construction and control are achieved.

Thompson (1) has considered the use of soil-lime mixtures for the construction of low-volume roads. The topics reviewed by Thompson include mixture properties and characteristics, soil-lime pavement layers (load-deflection behavior and field performance) and thickness-design concepts. Thompson concluded that "a more mechanistic and rational design procedure would be appropriate for designing pavements containing lime-treated soils" (1).

A repeated-loading study of soil-lime layers by Suddath and Thompson (2) indicated that a stress-dependent finite-element computer model called ILLI-PAVE adequately predicted load-deflection behavior. The study demonstrated that high load-carrying capacities can be developed by a soil-lime structural paving layer.

A simple thickness-design procedure for soil-lime layers has been developed based on the ILLI-PAVE model. The procedure is limited to pavements constructed of a cured soil-lime layer and a nonstructural surface course (surface treatment or thin asphalt concrete).

DEVELOPMENT OF DESIGN PROCEDURE

General Observations

Normally, only soil-lime mixtures that develop significant strength increases—mixtures that Thompson has called "lime reactive" (3)—are used in constructing structural paving layers. These mixtures have compressive and shear strength, and the factor that controls layer thickness is the flexural stress at the bottom of the soil-lime layer. The design procedure is based on the concept of a limiting stress ratio (S = flexural stress/flexural strength), which accounts for mixture fatigue behavior.

Description of ILLI-PAVE

ILLI-PAVE, a stress-dependent finite-element computer program, is described elsewhere (4). The program was developed based on the early work of Duncan, Monismith,

and Wilson (5). Several University of Illinois modifications concerning input-output routines and material-failure models have been incorporated into ILLI-PAVE.

Material Properties

Soil-lime mixtures were considered to be linear-elastic materials. Cured reactive soil-lime mixtures develop significant flexural strengths and flexural moduli of elasticity (1,6). Typical ranges of flexural moduli are given below (compressive strength = 4 x flexural strength; 1 Pa = 0.000 145 lbf/in²):

Flexural Strength (kPa)	Estimated Compressive Strength (kPa)	Estimated Flexural Modulus (MPa)
210	840	175
285	1140	345
350	1400	690
500	2000	1380
650	2600	2050
950	3800	3500

Moduli values of 172, 345, 690, and 3445 MPa (25 000, 50 000, 100 000, and 500 000 lbf/in²) were considered.

A stress-dependent resilient-modulus behavior model was used to characterize the fine-grained subgrades. Thompson and Robnett (7) have developed a comprehensive data base and procedures for predicting the resilient behavior of Illinois soils. Stiff, medium, and soft subgrades were included in the study. Figure 1 shows the relations between resilient modulus and stress level for the various subgrades.

Thickness Levels

Soil-lime layer thicknesses of 15, 23, and 30 cm (6, 9, and 12 in) were included. For high-quality soil-lime mixtures, applications to low-volume roads, and typical highway loadings, layer thicknesses greater than 30 cm (12 in) are not common.

Loading

A wheel load of 40 kN (9000 lbf), half of the 80-kN [18 000-lbf (18-kip)] single-axle load commonly considered for design, was used in the study. A uniform tire pressure of 550 kPa (80 lbf/in²), distributed over a circular area, was applied in 138-kPa (20-lbf/in²) increments.

ILLI-PAVE Data

A summary of ILLI-PAVE soil-lime pavement responses is given in Table 1 for the range of soil-lime moduli, layer thicknesses, and subgrades considered. Figures 2-4 show relations among moduli, thickness, and flexural stress for stiff, medium, and soft subgrades, respectively. Relations between flexural strength and moduli, based on data given in the above text table, are also shown in the figures.

Development of Regression Equations

Because of computer capability requirements and cost considerations, ILLI-PAVE will not generally be available for use on a widespread basis. Even though Figures 2-4 can be used to approximate flexural stress for various conditions, it was considered essential to develop an algorithm for estimating soil-lime flexural stress for general use.

Several regression equations were developed to predict soil-lime flexural stress as a function of layer thickness, soil-lime modulus of elasticity, and subgrade resilient modulus. The best equation (based on the smallest standard error of estimate) is

$$\sigma_r = 23.22 - 4.66t + 42.36 \log E_B - 29.11 \log E_{Ri} \quad (1)$$

where

σ_r = flexural stress at the bottom of the soil-lime layer (lbf/in²),
t = thickness of soil-lime layer (in),
E_B = modulus of elasticity of the soil-lime layer (kip/in²),
E_{Ri} = resilient modulus of the subgrade (kip/in²) (Figure 1),
R = correlation coefficient = 0.95, and
$S_{\bar{x}}$ = standard error of estimate = 8.3 lbf/in².

A nomogram for solving Equation 1 is shown in Figure 5. Equation 1 should not be extrapolated beyond the range of parameters considered in this study.

Design Criteria

The shear and compressive strengths of cured soil-lime mixtures are not the limiting factors in their use as structural layers in the construction of low-volume roads. Soil-lime layers experience repeated flexural stresses, and therefore flexural strength and fatigue response are important considerations.

A typical fatigue-response relation for Illinois soils, obtained by averaging fatigue test results from previous studies (8), is shown in Figure 6 and can be expressed by the following equation:

$$S = 0.923 - 0.058 \log N \quad (2)$$

where S = stress ratio = repeated flexural stress/ flexural strength and N = number of load applications to failure.

Thompson (1) has emphasized that for many soil-lime mixtures the effect of continued strength development with increased curing tends to negate the effect of repeated loading. Many agencies use a "designated curing period" (fixed time and temperature conditions) for design of soil-lime mixtures (6). Quality criteria are based on mixture characteristics achieved by the soil-lime mixture cured in the specified manner. It is suggested that flexural strength and moduli should be determined in a like manner. Subsequent strength and modulus adjustments may be appropriate in some situations.

The design criteria for the soil-lime layer provide for adequate performance of that layer. Consideration of subgrade stresses should also be included in a comprehensive pavement design approach. The effects of soil-lime thickness, soil-lime-mixture modulus, and subgrade support are evident in Table 1.

USE OF DESIGN PROCEDURE

Required design inputs are soil-lime strength and modulus [the text table given earlier provides a general guide, and additional information is available elsewhere (6)], subgrade resilient modulus [information on testing procedures, estimating techniques, and other factors of influence is given elsewhere (7,9,10)], and traffic data (many procedures are available for calculating 80-kN equivalent single-axle loads). Flexural stress can be determined for a given thickness by using Equation 1, Figures 2-4, or the nomogram shown in Figure 5.

Calculate the stress ratio S, and predict the fatigue life based on Equation 2 or Figure 6 (8). Compare the predicted fatigue life with the estimated traffic to determine the adequacy of the design.

If significant soil-lime-mixture strength development (in excess of that assumed in design) is expected, a higher stress ratio may be acceptable. Factors such as freeze-thaw durability and curing conditions (time and temperature) should be considered in establishing a final thickness.

The design procedure is based on the concept of "flexural fatigue cracking". However, Suddath and Thompson (2) have demonstrated that the ultimate load-carrying capacity of

Figure 1. Resilient modulus versus repeated deviator stress for ILLI-PAVE analyses.

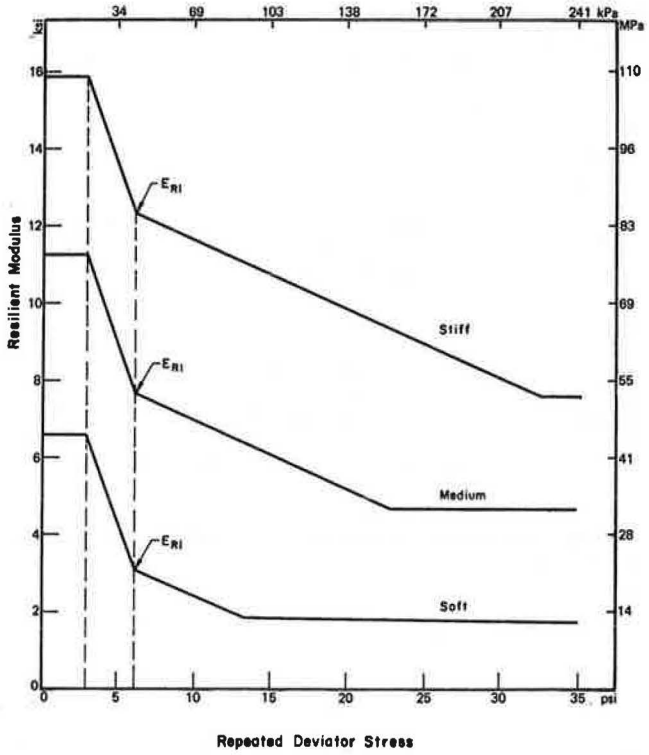


Figure 2. Relations among moduli, thickness, and flexural stress for stiff subgrade.

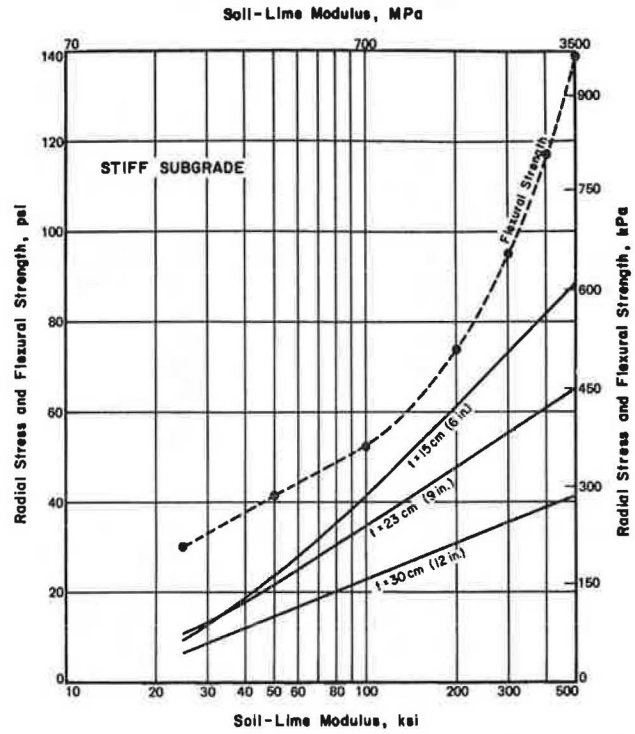


Table 1. Summary of ILLI-PAVE data for soil-lime layers.

Type of Subgrade	Thickness (cm)	Modulus (MPa)	Surface Deflection (mm)	Radial Strain[a]	Radial Stress (kPa)	Subgrade Vertical Stress (kPa)
Stiff	15	172	0.78	993	68	252
		345	0.69	814	165	206
		690	0.58	607	287	161
		3445	0.33	229	611	79
	23	172	0.58	678	74	167
		345	0.48	538	149	132
		690	0.41	388	238	101
		3445	0.23	135	452	46
	30	172	0.46	458	50	116
		345	0.38	358	99	92
		690	0.30	254	154	70
		3445	0.18	85	281	32
Medium	15	172	1.09	1389	129	220
		345	0.91	1051	238	176
		690	0.74	734	365	136
		3445	0.41	252	681	65
	23	172	0.79	906	116	145
		345	0.64	669	198	113
		690	0.51	455	287	85
		3445	0.28	146	486	38
	30	172	0.58	597	76	102
		345	0.48	436	127	79
		690	0.38	293	183	59
		3445	0.20	91	302	26
Soft	15	172	1.75	2210	255	166
		345	1.37	1468	365	132
		690	1.07	934	486	101
		3445	0.56	285	779	48
	23	172	1.17	1329	196	112
		345	0.91	879	276	86
		690	0.71	554	361	65
		3445	0.38	162	548	28
	30	172	0.86	837	120	81
		345	0.69	557	172	61
		690	0.53	352	227	45
		3445	0.28	98	329	20

Note: 1 mm = 0.039 in; 1 kPa = 0.145 lbf/in².

[a] μ strain.

Figure 3. Relations among moduli, thickness, and flexural stress for medium subgrade.

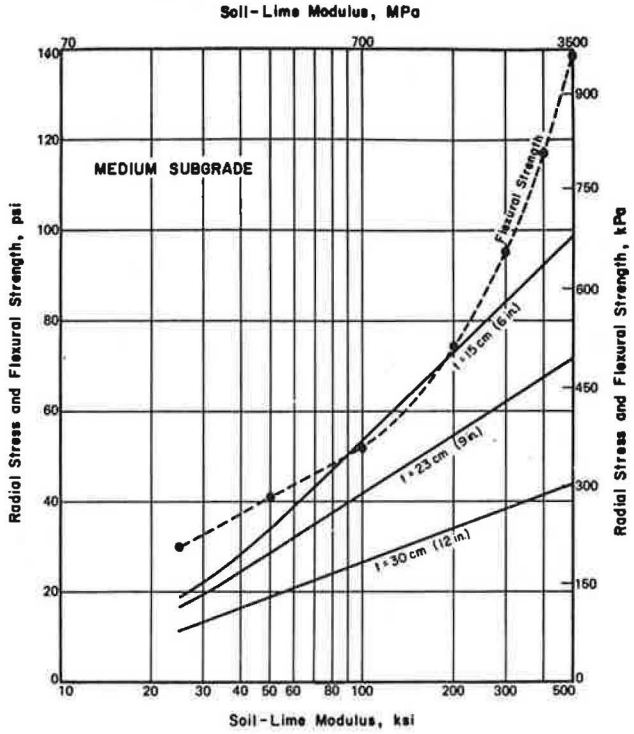


Figure 4. Relations among moduli, thickness, and flexural stress for soft subgrade.

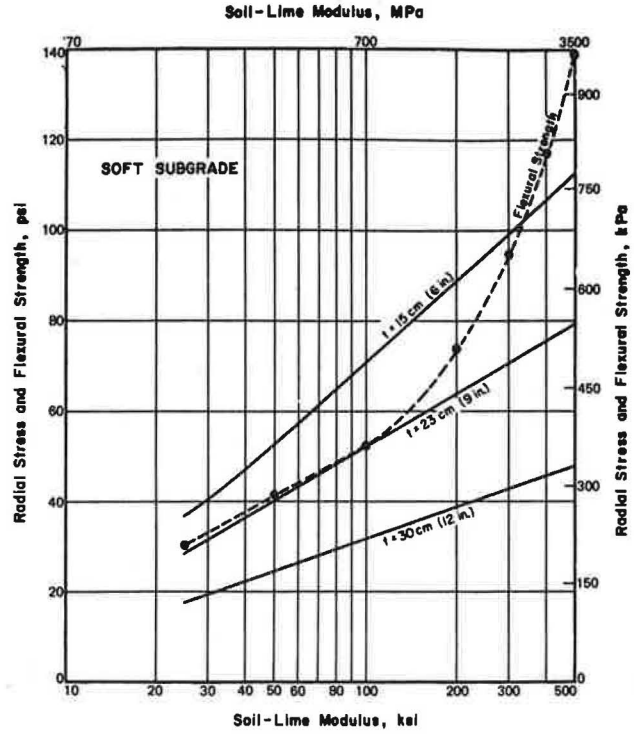


Figure 5. Nomogram for soil-lime flexural stress.

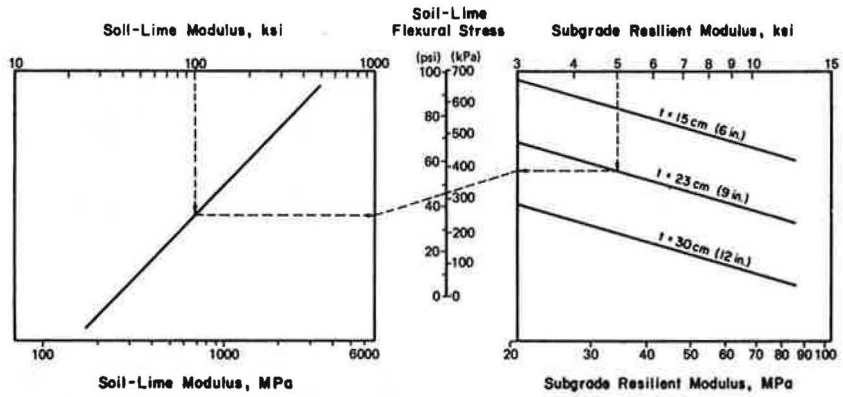


Figure 6. Fatigue response for cured soil-lime mixtures.

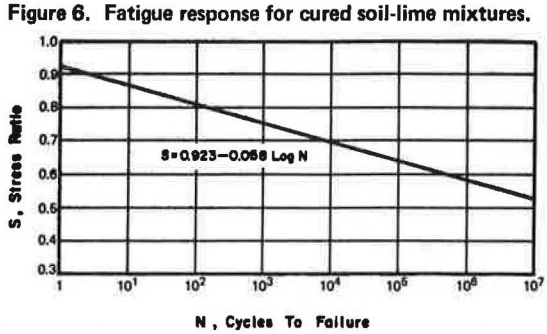
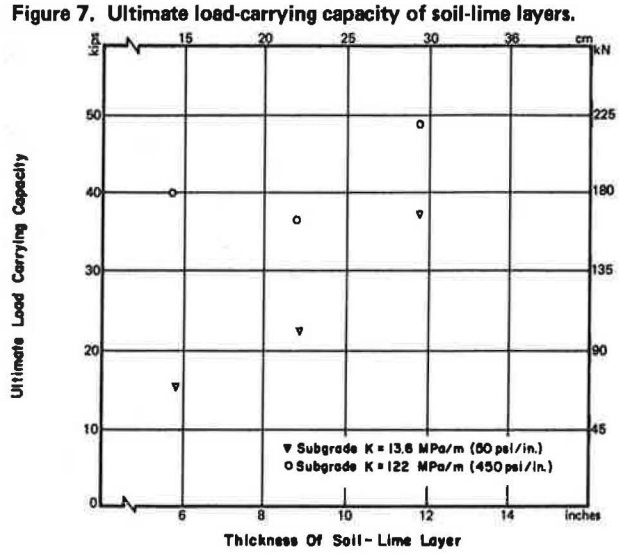


Figure 7. Ultimate load-carrying capacity of soil-lime layers.



soil-lime layers of normal thickness is considerably larger than the 40-kN (9000-lbf) wheel loading assumed in the development of the proposed design procedure (see Figure 7). Thus, the pavement does not fail in a catastrophic manner, even though a so-called flexural fatigue crack develops.

SUMMARY

A mechanistic thickness-design procedure for cured soil-lime structural paving layers is presented. Design input data are soil-lime strength and modulus, subgrade resilient modulus, and estimated traffic. The procedure assumes that the soil-lime mixture is capable of developing significant strength increase (relative to the strength of the natural soil) and that quality field construction and control are achieved.

It is emphasized that careful consideration must be directed to the proper selection of design input data, particularly soil-lime properties and subgrade resilient modulus. Additional factors, particularly freeze-thaw durability, may also need to be considered in some applications.

The procedure considers the thickness of the soil-lime layer only. Additional consideration of subgrade stress is required in a comprehensive approach to pavement design.

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Use of Cement-Kiln Dust and Fly Ash in Pozzolanic Concrete Base Courses

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The results of a study to determine the usefulness, as stabilized base, of pozzolanic concrete that contains cement-kiln dust (CKD) and fly ash are reported. Test strips of six different mixes of pozzolanic concrete that contained CKD and fly ash as the cementitious ingredients and crushed limestone as the aggregate were constructed on a concrete plant drive at Silica, Ohio. Deflection measurements, monitoring of axle-load accumulations, and periodic compression tests of field samples were performed. Laboratory test cylinders were also prepared and tested. After 25 820 equivalent 80-kN (18 000-lbf) single-axle loads over six months, no cracking or surface damage was visible except in a localized area. Deflection was found to decrease as curing time for the test strips increased. A set of regression equations was developed for predicting laboratory compressive strengths as a function of CKD content, curing temperature, and curing time in weeks. Application of these equations to field conditions resulted in reasonable predicted, as compared with observed, field strengths in most cases. Pozzolanic concrete containing CKD and fly ash as cementitious ingredients was found to have the property of autogenous healing. Anomalies were found in mixes that contained admixtures of portland cement. More study of the behavior of such mixes is needed. It is concluded that pozzolanic concrete that contains CKD and fly ash is potentially useful as stabilized base and merits further development.

Stabilized pavement bases are considered by many engineers to offer advantages with respect to load-carrying capacity and resistance to climate-induced deterioration. Various materials have been used as binders in stabilized bases, including asphalt, portland cement, and lime-fly ash mixtures.

Lime-fly ash mixtures, which are well known in Illinois, Ohio, Pennsylvania, and other states, use a waste product as one of two dry ingredients that react in the presence of water to form a "pozzolanic cement". This waste product is fly ash collected from the stacks of coal-burning utilities. In addition to the structural advantages of a stabilized pavement base, use of a waste product as part of the cementitious binder of such a base can produce other beneficial results, including

1. Lower construction cost because of the lower prices for ingredients developed from waste products,
2. Energy savings as a result of the elimination of the necessity for environmentally sound waste-disposal procedures, and
3. Reduced energy consumption for the construction of pavements, since relatively little energy is required in the preparation of paving ingredients made from waste products.

Potential energy-related benefits can be expected to become increasingly important if the cost of energy continues to rise or if petroleum shortages persist. Thus, from the standpoint of energy conservation, it would be useful if a pozzolanic concrete could be developed that would use some waste product in place of lime, a material that requires a rather energy-intensive manufacturing process. Such a pozzolanic material would thus be formed of two waste products. It is, of course, essential that the