Serviceability Loss Due to Roughness Caused by Volume Change in Expansive Clay Subgrades

BRENT RAUHUT and ROBERT L. LYTTON

ABSTRACT

It is common knowledge that pavements built on expansive clay subgrades will become rough whether heavily trafficked or not. Therefore it is obvious that much of the roughness that occurs on such roadways is caused by differential volume change in the subgrade, but this has been largely ignored in both analysis and design. Relatively little research effort has been expended to study this source of serviceability loss. Velasco and Lytton recently developed a multiple regression model to predict loss of serviceability with time caused by differential volume change in expansive clay subgrades. This model was developed from a limited data base that included present serviceability indices and various characteristics of the subgrade soils indicative of volume change potential. Applications of this model to four test sections in Texas and four in Colorado indicated that the effects of the independent variables on the loss of serviceability caused by expansive clay predicted by the model appeared to be reasonable. The predicted results for each test section are discussed with relation to known 18-kip equivalent single-axle loads and the characteristics of the subgrade clays. The assignment of responsibility for loss of serviceability between axle loads and differential volume change in the subgrade is explored and is discussed in detail.

A recent research effort (1) had as one of its goals the identification and application of predictive distress models for distresses significant to the generation of repair or rehabilitation of flexible pavements. Roughness caused by differential volume change in subgrades was identified as a significant distress and was studied during that project.

There are three known causes of volume change in subgrades. One is consolidation of subgrade materials in embankments or of natural subgrade materials in marshes or swamps. A second is the roughness induced by freezing of moisture in subgrade materials and subsequent thawing in the spring. The third is roughness due to differential volume change caused by seasonal or other moisture changes in expansive clay subgrades. There are no known models for predicting roughness caused by the first two and only one for predicting roughness caused by the third; therefore this third cause of roughness is the subject of this paper and is discussed in detail herein.

DIFFERENTIAL VOLUME CHANGE IN EXPANSIVE CLAY SUBGRADES

The mechanism involved relates to the relative ability of various clay soils to imbibe or relinquish moisture. The moisture migration from or to the clay depends directly on environmental conditions such as temperature, rainfall, and humidity, but the relative volume change depends on characteristics of the clay and soil mixture such as clay mineral type, the fraction of the soil mixture that is composed of clay minerals, and whether it was initially formed in freshwater or saltwater. A network of cracks in the subgrade is usually well established before construction of any roadway over clay soils, and these cracks apparently continue to offer convenient paths for moisture migration after the pavement is in place.

Because volume change in expansive clays has damaged structures worth billions of dollars worldwide, geotechnical engineers have studied this phenomenon for decades and much progress has been made in understanding it. Measurements have also been made of pavement surfaces over expansive clays, and a number of methods such as subgrade stabilization with lime or cement have been applied to limit the volume change. These studies have not directly contributed much to the prediction of the roughness that may be expected to occur in a specific environment and for a specific clay subgrade, but they did identify those parameters that should be considered as potential independent variables for empirical models to predict the occurrence of such roughness.

PREDICTING ROUGHNESS CAUSED BY DIFFERENTIAL VOLUME CHANGE IN EXPANSIVE CLAY SUBGRADES

Velasco and Lytton (2,3) recognized the need for models that would predict the reduction in present serviceability index (PSI) caused by expansive clay subgrades in pavements and developed an empirical model based on a limited data base in Texas. This equation was developed empirically by using regression techniques, with change in PSI as the dependent variable, and a range of independent variables intended to represent pavement structure, the effects of environment, and the nature of clay subgrades. Serviceability was obtained from 12 flexible and 5 rigid pavements in Texas through calculations based on measurements with a GM surface profilometer. Samples of the clay subgrades were obtained, and the required properties were derived from laboratory testing. The form of this equation was as follows:

$$\Delta SI = Ac^{B}n^{D} \qquad (1)$$

Because the initial values of serviceability when the roadways were opened were unavailable, it was necessary to estimate initial values to calculate the difference considered to be the change in serviceability index (SI). The initial serviceability index was assumed to be 5.0, and the resulting regression coefficients A, B, and D were 2,675, 1.09, and 7.62, respectively. The values of c and n were also obtained through regressions as follows (2,3):

$$c = 0.0004\ \mathrm{Depth}^{-0.81}\,\mathrm{Time}^{0.49}\,\mathrm{AC}^{-1.20}\,\mathrm{ESP}^{0.12} \qquad (R^2 = 0.77) \qquad (2)$$

$$n = 0.79\ \mathrm{Depth}^{0.09}\,\mathrm{CEC}^{-0.16}\,\mathrm{Clay}^{0.40}\,\mathrm{Range}^{-0.16} \qquad (R^2 = 0.83) \qquad (3)$$

where

Depth = effective depth of pavement (in.) based on a moment of inertia I for the pavement section above the subgrade with its layer thicknesses weighted by layer stiffness relative to that of the surface layer (1,2), i.e.,

$$\text{Depth} = \sqrt[3]{12I/1}\ \text{in.}$$

Range = range of values of Thornthwaite moisture index for a 20-year period (range is usually 50 to 90), smaller values generally apply in drier areas and vice versa;

Time = time since construction, or since last rehabilitation before the roughness was measured (years);

Clay = percentage of clay (grain size less than 0.002 mm), which is obtained from hydrometer grain size testing;

AC = activity [i.e., (Plasticity index/% clay)];

CEC = cation exchange capacity, where meg/100 gm ≈ (plastic limit)$^{1.17}$; and

ESP = exchange sodium percentage (approximately 2 for lacustrine deposits and 16 for saltwater deposits).

The test sections used for the development of this empirical relationship were specifically selected because they were essentially free of any load-induced distresses and because the only important observable distress was long wavelength unevenness. Further, the analyses made with the Fast Fourier transform method were for wavelengths of 10 ft or greater to essentially eliminate most of the effects of any load-induced damage. Therefore, it appears reasonable to assume that virtually all of the measured roughness remaining after the "filtering" previously described was caused by the expansive clay subgrades.

Although the data base for the development of this relationship was limited, it appeared to be reasonably well-founded, except that (a) the assumption of an initial PSI of 5.0 appeared to be much too optimistic for the known capabilities of the highway construction industry, and (b) the data base included measurements from five rigid pavements. It was decided to rerun the regressions using the more probable value of 4.2 for initial serviceability index and omitting the rigid pavements from the regression.

IMPROVEMENT OF THE MODEL

As discussed previously, it was decided to conduct a new regression analysis using only data from flexible test sections and using revised reductions in PSI based on an assumed initial PSI value of 4.2. This was done, and the result using the original equation form given in the previous section was as follows:

$$\Delta SI = 39{,}396\ c^{1.544} n^{9.59} \quad (R^2 = 0.66) \tag{4}$$

The values for c and n may be obtained as described in Equations 2 and 3; their substitution into Equation 4 results in

$$\Delta SI = 0.02323\ \text{Depth}^{-0.387}\text{Time}^{0.757}\text{AC}^{-1.85}\text{ESP}^{0.185}\text{CEC}^{-1.53}\ \text{Clay}^{3.84}\text{Range}^{-1.53} \tag{5}$$

EVALUATION OF MODEL

To check the reasonableness of this model, predicted changes in SI were made for four Texas test sections and four Colorado test sections for which measured data were available. Data needed for the calculations are given in Tables 1 and 2. As most of the data needed was not available from records, estimates were made by using Equations 2 and 3.

Equation 4 was used for the calculations, and it calculated values of the independent variables. The resulting predictions of ΔSI due to expansive clay are given in Tables 3 and 4. Note that the measured changes in SI are also shown, and the difference shown is caused by traffic (although it could be due partially to other causes such as differential embankment settlement and so forth). Where the calculated predictions for change in SI due to expansive clay exceeded the measured changes, no change because of traffic is assumed.

The results in Tables 3 and 4 are plotted in Figures 1 and 2. The approximate 18-kip equivalent single-axle loads (ESALs) experienced by the test sections at an appropriate point in time are also shown. Note that the measured values of PSI (shown as filled circles) are somewhat erratic, and that the total changes are drawn in smoothly to represent the most probable values. Total changes have been extrapolated in some cases with dashed lines to allow approximate comparisons to predicted changes caused by expansive clays.

The predicted changes in SI caused by expansive clays are discussed by individual test sections.

TABLE 1 Available Data Collected for Texas and Colorado Test Sections

Test Section	Plastic Limit	Plasticity Index	% Passing No. 200	Thicknesses Surface	Base	Subbase	Year of Last Const. or Rehab.
TX-25-82(2971)	20	26	78	3.5	13.0	----	Oct 1961
TX-25-82(2853)	10	24	50-70	9.5	5.0	6.0	Oct 1970
TX-25-62(2895)	20	7	40-65	9.5	5.0	----	Nov 1972
TX-5-87(2675)	20	28	60-80	2.3	10.0	5.0	Mar 1967
CO-1-70(4-59)	22	31	95	9.0	24.0	----	Jun 1975
CO-3-70(114-19)	19	24	65	9.0	17.0	----	May 1965
CO-3-40(5-1-1)	23	21	95	9.5	----	----	Aug 1969
CO-96(1)	20	28	80	2.8	4.5	11.4	Jun 1965

TABLE 2 Approximate Values of Independent Variables for Calculating c and n

Test Section	Range	AC	ESP	% CLAY	DEPTH	CEC
TX-25-82(2971)	50	.80	16	33	7.7	33.3
TX-25-82(2853)		1.0	16	24	11.4	14.8
TX-25-62(2895)		.80	16	9	10.0	33.3
TX-5-87(2675)		.80	16	35	9.5	33.3
CO-1-70(4-59)		.80	16	39	15.6	37.2
CO-3-70(114-19)		.80	2	30	12.6	31.3
CO-3-40(5-1-1)		.80	2	26	9.5	39.2
CO-96(1)		.80	16	35	9.7	33.3

TABLE 3 Measured Changes in SI and Calculated Changes Caused by Expansive Clays for Texas Sections

Test Section	Time (Years)	c	$c^{1.544}$	n	$\|n\|^{9.59}$	Δ SI		
						Total Measured	Due To Expansive Clay	Due to Traffic
TX-25-82(2971)	4	2.753×10^{-4}	3.18×10^{-6}	-1.173	4.634		0.58	
	8	3.866×10^{-4}	5.38×10^{-6}	-1.173	4.634		0.98	
	13	4.905×10^{-4}	7.77×10^{-6}	-1.173	4.634	0.7	1.42	
	16	5.430×10^{-4}	9.01×10^{-6}	-1.173	4.634	1.3	1.66	
	19	5.907×10^{-4}	1.04×10^{-5}	-1.173	4.634		1.89	
TX-25-82(2853)	2	1.091×10^{-4}	7.63×10^{-7}	-1.218	6.647	0.20	0.20	
	4	1.532×10^{-4}	1.29×10^{-6}	-1.218	6.647	0.10	0.33	
	6	1.869×10^{-4}	1.75×10^{-6}	-1.218	6.647	1.40	0.46	0.94
	8	2.152×10^{-4}	2.18×10^{-6}	-1.218	6.647		0.57	
	10	2.401×10^{-4}	2.6×10^{-6}	-1.218	6.647		0.68	
TX-25-62(2895)	2	1.395×10^{-4}	1.1×10^{-6}	-0.7144	0.0397	0.10	0.002	0.10
	4	1.959×10^{-4}	1.9×10^{-6}	-0.7144	0.0397		0.003	
	6	2.389×10^{-4}	2.6×10^{-6}	-0.7144	0.0397	0.20	0.004	0.20
	8	2.751×10^{-4}	3.2×10^{-6}	-0.7144	0.0397		0.005	
	10	3.069×10^{-4}	3.8×10^{-6}	-0.7144	0.0397		0.006	
	13	3.490×10^{-4}	4.6×10^{-6}	-0.7144	0.0397		0.007	
TX-5-87(2675)	2	1.653×10^{-4}	1.45×10^{-6}	-1.224	6.958		0.40	
	4	2.322×10^{-4}	2.45×10^{-6}	-1.224	6.958		0.67	
	6	2.832×10^{-4}	3.32×10^{-6}	-1.224	6.958	1.3	0.91	0.39
	8	3.261×10^{-4}	4.14×10^{-6}	-1.224	6.958	1.6	1.13	0.44
	10	3.638×10^{-4}	4.90×10^{-6}	-1.224	6.958	1.7	1.34	0.36
	13	4.137×10^{-4}	6.0×10^{-6}	-1.224	6.958		1.65	

TABLE 4 Measured Changes in SI and Calculated Changes Caused by Expansive Clays for Colorado Sections

Test Section	Time (Years)	c	$c^{1.544}$	n	$\lvert n\rvert^{9.59}$	Δ SI Total Measured	Δ SI Due To Expansive Clay	Δ SI Due to Traffic
CO-1-70(4-59)	2	1.106×10^{-4}	7.79×10^{-7}	-1.313	13.64	0.4	0.42	--
	3	1.349×10^{-4}	1.06×10^{-6}	-1.313	13.64	0.5	0.57	--
	5	1.733×10^{-4}	1.6×10^{-6}	-1.313	13.64	0.7	0.86	--
CO-3-70(114-19)	2	1.024×10^{-4}	6.92×10^{-7}	-1.192	5.40	0.5	0.15	0.35
	4	1.438×10^{-4}	1.17×10^{-6}	-1.192	5.40	1.1	0.25	0.85
	6	1.754×10^{-4}	1.59×10^{-6}	-1.192	5.40	1.2	0.38	0.82
	8	2.02×10^{-4}	2.0×10^{-6}	-1.192	5.40	1.4	0.43	0.97
CO-3-40(5-1-1)	2	1.288×10^{-4}	9.86×10^{-7}	-1.059	1.73		0.07	
	4	1.809×10^{-4}	1.67×10^{-6}	-1.059	1.73	0.0	0.11	--
	6	2.207×10^{-4}	2.26×10^{-6}	-1.059	1.73	1.5	0.15	1.35
CO-96(1)	2	1.627×10^{-4}	1.41×10^{-6}	-1.226	7.084	0.1	0.39	--
	4	2.286×10^{-4}	2.39×10^{-6}	-1.226	7.084		0.67	
	6	2.788×10^{-4}	3.25×10^{-6}	-1.226	7.084		0.91	
	8	3.21×10^{-4}	4.03×10^{-6}	-1.226	7.084		1.12	
	10	3.58×10^{-4}	4.78×10^{-6}	-1.226	7.084	0.7	1.33	--
	13	4.07×10^{-4}	5.82×10^{-6}	-1.226	7.084	1.9	1.63	0.27

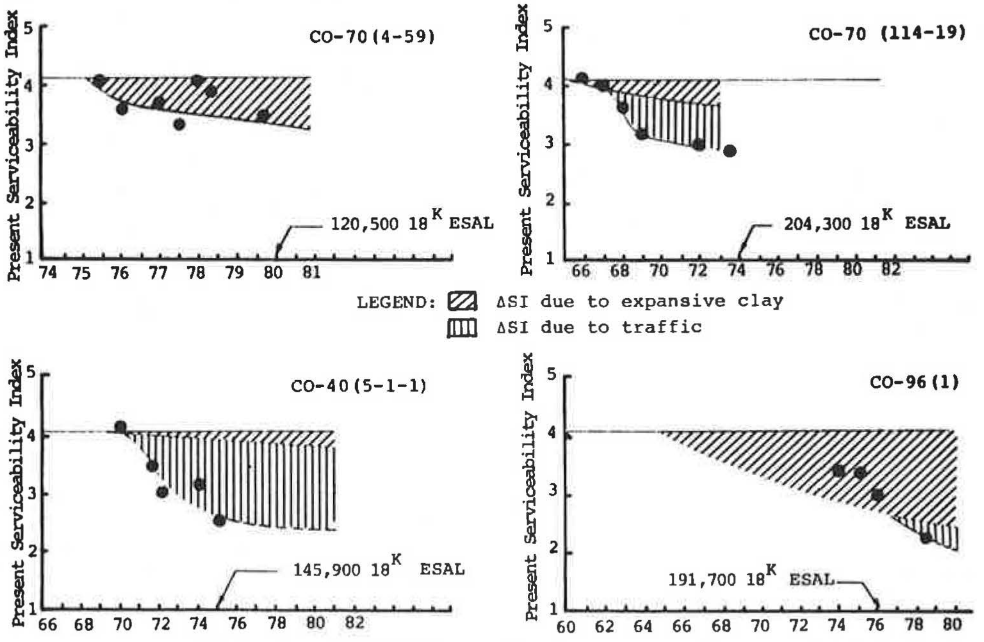

FIGURE 1 Measured changes in SI divided into predicted changes caused by expansive clay and traffic, Colorado test sections.

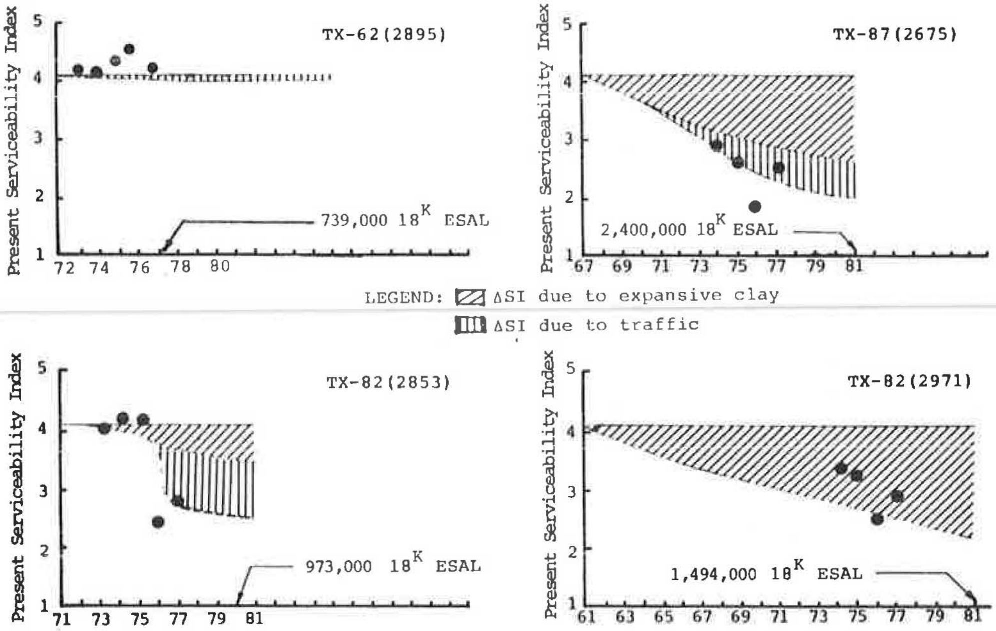

FIGURE 2 Measured changes in SI divided into predicted changes caused by expansive clay and traffic, Texas test sections.

1. TX-62(2895): There was virtually no measured change in PSI between 1972 and 1977, nor was there any measurable change predicted. The plasticity index of the subgrade was quite low, so no roughness caused by differential volume change in the subgrade would be expected.
2. TX-87(2675): Most of the measured change in PSI was attributed to the moderately expansive clay, but traffic loadings appear to have contributed to the measured changes after a few years.
3. TX-82(2853): The moderately expansive clay subgrade contributed to the loss of serviceability, but it appears that the majority of the loss was caused by traffic.
4. TX-82(2971): This pavement experienced relatively minor serviceability loss during the first 14 years after rehabilitation, but the rate increased after that. The model appears to have overpredicted the change in serviceability because of the moderately expansive clay subgrade in this case. It appears more likely that virtually all of the change was caused by differential volume change in the clay for the first 14 years, but that the increase in the rate of serviceability loss around that point was likely caused by traffic.
5. CO-70(4-59): The expansive clay subgrade is credited by the model for all of the serviceability loss. This appears logical, considering the changes in PSI with time and the relatively light traffic on the pavement.
6. CO-70(114-19): The moderately expansive clay appears to have contributed to the loss of serviceability, but the primary cause was considered to be traffic. The moderate prediction in this case is caused primarily by a relatively low estimated clay content.
7. CO-40(5-1-1): The clay subgrade was predicted to have caused little of the loss of serviceability. Most of the loss was believed to have been due to traffic or other causes.
8. CO-96(1): The model appears to have overpredicted the loss in serviceability because of the moderately expansive subgrade. It appears that the clay was the primary cause of roughness for the first 10 years after the pavement was overlaid, but the sudden increase in serviceability loss at that point was caused by traffic.

The effects of the independent variables on the loss of serviceability because of expansive clay, as predicted by the model, appear to be reasonable. The predictions appear reasonable, but they also appear to trend somewhat toward overpredictions where the clay content was relatively high.

It is recognized that the assignment of responsibility for relatively high changes in serviceability to differential volume change in expansive clay or shale subgrades will meet with strong opposition from many relatively knowledgeable researchers, especially those with close ties to the AASHO Road Test, who tend to ascribe virtually all pavement roughness to the effects of axle loads. This will be partly because there has been little effort to quantify roughness caused by expansive clay subgrades before the recent work of Velasco and Lytton. However, it is well-known by researchers who practice in areas that have expansive clays that pavements on expansive clays become rough fairly rapidly, even if traffic is nominal. It appears logical that early roughness is caused by the seasonal shrinkage and swelling of the expansive clays, which will never be uniform. The magnitudes of such movements are generally greater than those attributable to material variations and consequent differential compaction caused by repetitive wheel loadings. Also, it is becoming increasingly apparent from data collection on test sections around the country that rutting is often relatively nominal; thus differential rutting is not likely to induce much roughness. The primary effects of axle loads on increasing roughness in typical pavement structures appear to generally begin when surface cracking occurs and excess moisture infiltrates base and subgrade materials. If an unstable asphalt cement (AC) mix is used or other inadequate design or construction practices are applied, however, it is possible to experience roughness because of shoving, corrugations, differential consolidation of base, and so forth.

In limited support of the previous discussion, Florida test sections also studied during the project reported by Rauhut et al. (1) reveal virtually no change in serviceability, even under heavy traffic (see Figure 3). This is partially due to the stiffness of the limerock base, but it is strongly believed that serviceability loss could be expected if these pavements were on expansive clay instead of on sand subgrades. It should also be noted that Texas test section TX-62(2895), the only one of the eight from Texas and Colorado with a subgrade having low plasticity, experienced almost no change in serviceability during the first 10 years after reconstruction.

New York test sections also had relatively nonexpansive subgrades, but they are silty and they undergo freezing and thawing that also cause important changes of serviceability (see Figure 4). Note that the cumulative 18-kip ESALs for these test sections were not especially high.

It is not the intent of this discussion to suggest that heavy axle loads do not cause roughness in pavements (as they certainly did at the AASHO Road Test), but there are strong reasons to believe that the results of the AASHO Road Test would have been quite different if conducted at lower traffic rates over a longer period in a no-freeze area with an expansive clay subgrade. Of course, they would also have been considerably different for flexible pavements if either conducted in a southern climate or as a long-term test with lower traffic rates.

SUMMARY

The model described herein for predicting changes in serviceability caused by differential volume changes in expansive clays is the only one known to exist.

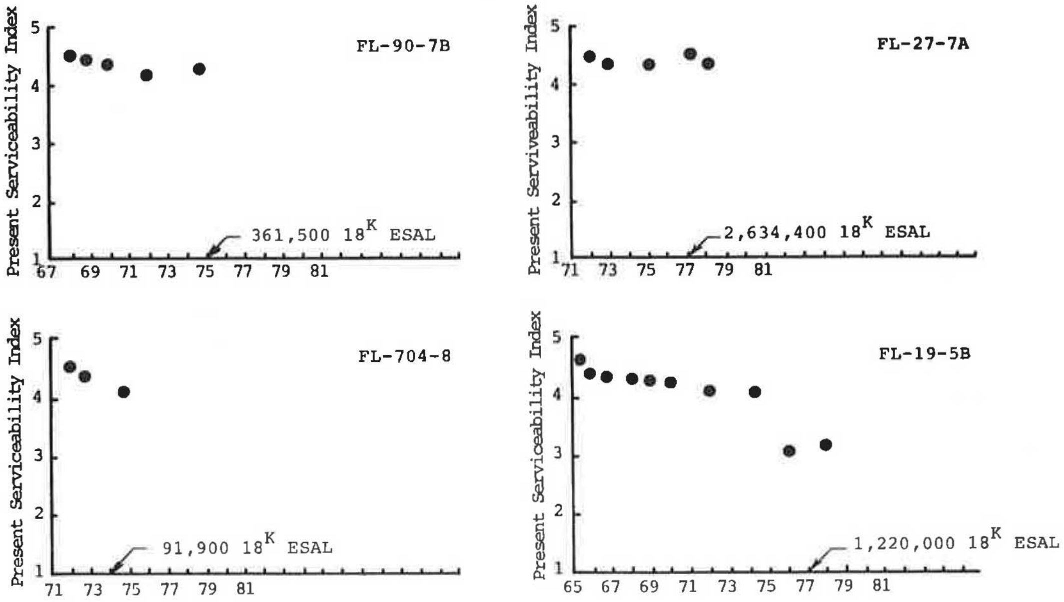

FIGURE 3 Measured PSI, Florida test sections.

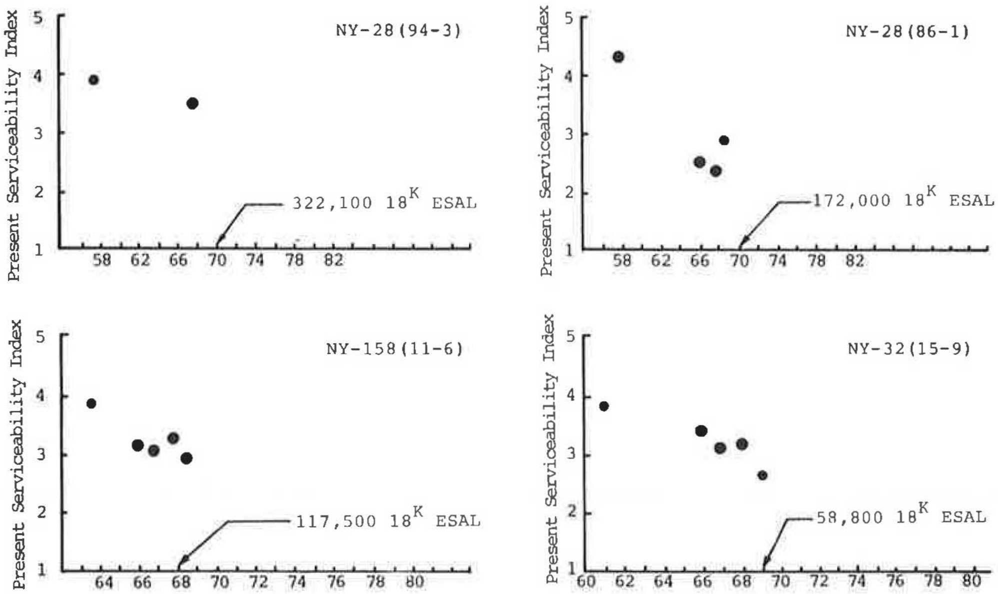

FIGURE 4 Measured PSI, New York test sections.

Its development is believed to have been well-founded but based on a limited data base, and it requires input data that are frequently not available and thus must be developed on the basis of approximate relationships. Even with these approximations, the model appears to generally provide reasonable predictions of serviceability loss. It is not clear whether the two overpredictions out of the eight examples studied were caused by a tendency toward overprediction by the models or caused by high estimates of clay content. It should be noted, however, that use of a clay content of 30 percent in lieu of 35 percent for test section CO-96(1) would have reduced the predicted ΔSI by 45 percent and resulted in a reasonable prediction. Similarly, a reduction of 5 percent in clay content from 33 to 28 percent for test section TX-82(2971) would have reduced the predicted SI by 47 percent and would also have resulted in reasonable predictions.

The overall evaluation of the proposed model is that it is likely as reliable as the other models available for predicting change in PSI, including the AASHO equation and those developed during the "cost allocations" project (1,4) for total change in PSI.

The approach to differentiating between load-induced serviceability loss and that caused by differential volume change because of expansive clay subgrades was to assume that the predicted change in serviceability from the VESYS III-B regression equations is the total predicted change in PSI (as it should be). That assignable to load-induced effects will be the total predicted change in PSI using the flexible pavement models, less that calculated by the expansive clay model. Where the serviceability loss caused by the expansive clay exceeds that predicted for the axle loads, the serviceability loss is assumed to be caused by the environment. As the serviceability loss caused by traffic increases with axle load applications and begins to exceed that attributable to the clay subgrade, the difference is attributed to the axle loads.

The approach adopted does not deal directly with combined roughness, but it is believed to be an advancement of the state of the art in understanding roughness in pavements and the consequent reduction in serviceability. The ability to divide sources of roughness more accurately between the environment and axle loads must await substantial future research.

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