Study of Resilient Characteristics of Tropical Soils for Use in Low-Volume Pavement Design

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The resilient modulus is a necessary factor for the mechanistic analysis of pavement structures, but it is also relatively expensive to measure. Material characterization is, however, a routine operation during the design and construction of a road. The aim of this study was to develop prediction models for estimating the resilient modulus from standard laboratory test results. Data collected during a research project conducted in Brazil by the Brazilian government and the United Nations Development Program were used as a primary source. The models were tested and extended on data collected by Austin Research Engineers in the United States, and the revised models were evaluated by using published data from different parts of the world. Resilient moduli measured on the Brazilian samples (lateritic materials) were very much higher than those measured on samples (clays) from the United States. Even among the Brazilian samples, sandy materials, thought to indicate an advanced degree of laterization, had a higher modulus than clayey materials. Moisture content was not found to influence the modulus of the Brazilian materials, but it had a significant effect on the U.S. samples. Comparison of values predicted from the models with measured values obtained in the United States suggests that although the models were developed on undisturbed materials, the results may also be applicable to laboratory-compacted samples. The moisture content should, however, be below optimum, since a high moisture content can have an unpredictable influence on the results. Comparison of the predicted resilient modulus with untrafficked and trafficked undisturbed roadbed materials used in the road test conducted by the American Association of State Highway Officials (AASHO) showed that there may be a traffic influence.

Pavements were traditionally designed by empirical methods derived from road test results and local experience. Severe problems are encountered when these methods are transferred to different environments or when materials fall outside the range of experience. These problems, together with developments in electronic computations, have led to mechanistic pavement analysis procedures that use elastic-layer theory. Inputs to these programs include, among others, the elastic properties of the different pavement layers.

The resilient modulus (M_R) for the elastic properties of pavement materials was originally used by Hveem (1). He preferred resilience to such terms as elasticity, since movements much greater than those that can occur in many elastic solids such as glass, concrete, and steel must be considered in pavement layers. For widespread application of elastic-layer theory programs in pavement design, it is essential that the resilient properties of the pavement layers, in particular the roadbed material, be readily obtainable.

It is common practice virtually everywhere in the world to carry out a soil survey along the route of a new road. Further material testing is also done at the completion of each layer, e.g., subgrade, subbase, and base. Standard material classification test results are then routinely available for each of the layers. Resilience testing, on the other hand, is a sophisticated procedure and relatively expensive. It would therefore be of considerable value if the resilient modulus could be estimated from standard laboratory test results.

This study was aimed at developing models for predicting the resilient modulus of undisturbed roadbed samples obtained in tropical regions from standard laboratory test results. The samples were collected and tested in a research project conducted in Brazil under the auspices of the Brazilian Government and the United Nations Development Program. The applicability of the models to other environments and materials was extended by using unpublished data made available by Austin Research Engineers (ARE).

This paper first gives a review of existing methods for predicting the resilient modulus. Then a brief description of the procedure for obtaining the samples and the test procedure is given. Prediction models are developed from a statistical analysis, and the implications of the models are discussed. Finally, the applicability of the models is extended to data collected in the United States, and the models are compared with other data sources.

CURRENT PROCEDURES FOR ESTIMATING RESILIENT MODULUS

Probably the most common method for predicting the resilient modulus is to use the California bearing ratio (CBR). Heukelom and Klomp (2) proposed a relation between the dynamic subgrade resilient modulus (MR) and the CBR value, developed on clays and sandy soils, as follows:

MR (MPa) = constant x CBR.

Normally, a value of 10.4 is taken as the constant, although Barksdale and Hicks (3) showed that this can vary from 4.8 to 79.0. Kirnan and Glynn (4) studied two boulder clays and found the value of the constant to be 1.7. The tremendous variations in the value of the constant clearly indicate the great extent to which the estimate can be incorrect when the above relationship is used. This point is further supported by the plot of resilient modulus versus CBR shown in Figure 1 for the Brazil data evaluated in this paper. The values of the constant of the envelope lines are 0.7 and 106.0. It is clearly not advisable to use CBR for estimating the resilient modulus.

Monismith (5) developed the relation given in Figure 2, which shows isolines of resilient modulus for different combinations of density and moisture content from the study of a pavement section in California. However, evaluation of the data showed tremendous scatter in the data points. Seed, Chan, and Lee (6) showed large variations in resilient modulus for above-optimum moisture content. Moisture content and density have thus been shown to influence the resilient modulus.

A detailed study to identify and quantify those soil properties that control the behavior of Illinois soils was conducted by Thompson and Robnett (7). Kneading-compacted samples were used. They found no single soil property that was highly correlated with resilience properties. Low plasticity, low group index, high silt content, low clay content, low specific gravity, and high carbon content contribute to low resilient moduli. For moisture content at and above optimum, the soaked CBR was negatively correlated with the resilient modulus, which is contrary to engineering experience. They also found a fair correspondence between the resilient modulus and the static modulus of elasticity, the unconfined compressive strength, and the degree of saturation.

SAMPLE COLLECTION AND RESILIENT-MODULUS DETERMINATION

Samples of undisturbed roadbed were collected from a number of paved road sections in the central region of Brazil in the states of Goias, Minas Gerais, and Sao Paulo. By using a 75-mm diameter Shelby tube, an undisturbed-roadbed sample some 500 mm long was taken from a depth of 900 mm below the road surface. A loaded truck was used as a counterweight for the pneumatic jack for sinking the Shelby tube, and the tube with the sample was extracted manually. Both ends of the tube were sealed with paraffin wax immediately after the sample was taken.

When the sample was tested in the laboratory, the wax seals were removed and the sample was extracted from the Shelby tube with a sample extractor. The moisture content and density of the undisturbed samples were compared with those obtained from the in situ measurements, and close agreement was found. This indicated that the wax seal was effective, that no moisture was lost, and that no densification had occurred during the taking and extraction of the sample. After extraction, the sample was trimmed to a height-to-diameter ratio of about 2. The sample was then placed in a rubber membrane and fitted in the triaxial cell. The sample was tested at deviator stresses ranging from 14 to 70 kPa at a confining pressure of 14 kPa. The range of deviator stresses used depended on the stiffness of the material. At each stress level, the sample was tested for 10 000 repetitions at 1 Hz with a load-on time of 0.1 s and a load-off time of 0.9 s. Resilient deformation readings were taken after 100, 200, 500, 1000, 2000, 5000, and 10 000 load applications. Reasonably constant deformations were usually found after some 2000 load repetitions, but in those cases where the resilient deformation was not constant, the result at 10 000 repetitions was used to compute the resilient modulus.

The undisturbed sample taken in the field had a length of about 500 mm. It was therefore sometimes possible to obtain more than one sample for repeated triaxial testing from one Shelby tube sample. The measured resilient moduli provided information for determining the repeatability of the tests.

Figure 1. Comparison of CBR and resilient modulus of Brazil data for deviator stress of 14 kPa.

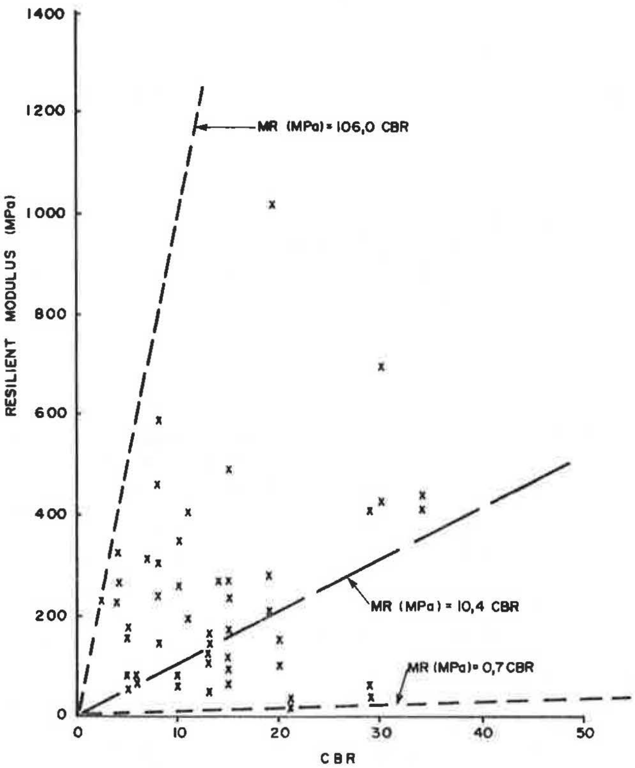
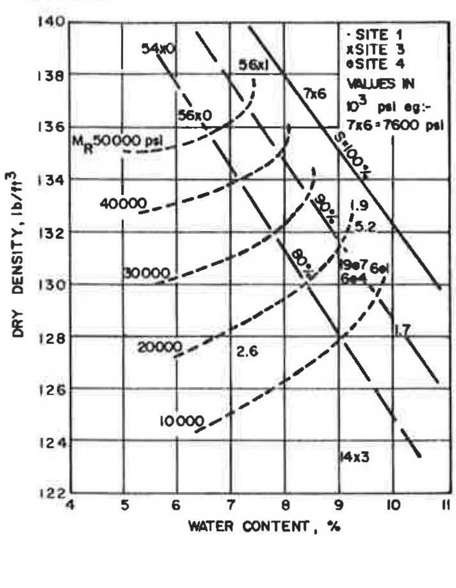


Figure 2. Relation among water content, dry density, and resilient modulus for subgrade soil.



ANALYSIS OF RESULTS

For each sample the resilient modulus, deviator stress, in situ moisture content, density and CBR, grading analysis, standard Proctor density and moisture content, liquid limit, plasticity index, and American Association of State Highway and Transportation Officials (AASHTO) soil classifications were available. Table 1 gives the mean, standard deviation, and range of the dependent variables used in the analysis. The discussion and models are only applicable within the ranges of the different variables. Extrapolation of the models, or the discussions below, beyond the limits of the data range should be approached with caution.

It is interesting to note the very high resilient-modulus values found on some sections. The maximum value of 1710 MPa is greater than the value generally used in pavement design for high-quality unstabilized base materials. Another surprising aspect is the very large range of the degree of saturation and the relatively low mean value. This observation contrasts with the general experience in the United States, where roadbed materials are considered to be highly saturated. The very low degrees of saturation found in Brazil may explain the very high modulus values obtained.

The results of the literature survey suggested a number of possible explanatory variables. The first was CBR, which was shown to be correlated with the resilient modulus by Heukelom and Klomp (2). The work by Monismith (5) suggested that dry density and moisture content could be used to predict the resilient modulus. Seed, Chan, and Lee (6) also showed the importance of a moisture content above or below the AASHTO test optimum value. In their study of Illinois soils, Thompson and Robnett (7) found that the degree of saturation was an important prediction variable.

In the regression analysis, the resilient modulus was used as a dependent variable, and the other

Table 1. Mean, SD, and range of dependent and independent variables of Brazil data analyzed.

Variable	No. of Observations	Mean	SD	Minimum	Maximum
In situ moisture content (%)	75	20.8	5.6	8.6	31.2
In situ density (kg/m³)	75	1519	215	1051	1978
In situ CBR (%)	75	14.2	8.3	2	34
Liquid limit (%)	75	46.4	11.2	21	67
Plasticity index (%)	75	22.1	7.0	7	36
Material passing 0.074-mm sieve (%)	75	63	17	18	90
Degree of saturation (%)	75	49.6	11.4	28.4	83.2
Relative density	75	0.90	0.11	0.63	1.25
Resilient modulus (kPa)					
at deviator stress = 14 kPa	50	235.3	193.6	13.4	1019
at deviator stress = 28 kPa	74	340.1	364.6	12.4	1480
at deviator stress = 42 kPa	75	278.2	313.2	11.6	1600
at deviator stress = 56 kPa	75	246.5	297.3	11.0	1700
at deviator stress = 70 kPa	25	476.4	375.8	28.1	1710

available variables were investigated as independent variables. Two-factor interactions of these independent variables were also considered. In addition, the degree of saturation was computed; a specific gravity of 2.65 was assumed for the grains. Certain other independent variables were also investigated, such as the ratio of field density to laboratory density and plastic limit. Because of the large number of independent variables thus generated, groups of variables had to be evaluated and the insignificant variables eliminated.

A stepwise regression program (STEP01), which is based on the BMDO2R program, was used in the least-squares regression analysis. After the first set of runs, it was decided to eliminate the following:

1. The percentage of material passing the 0.074-mm sieve, which was the grading analysis variable analyzed, since although it had a high simple correlation with the resilient modulus, it was also very highly correlated with the liquid limit, the plasticity index, the moisture content, and combinations of these variables;
2. The optimum moisture content and laboratory density, since the simple correlation coefficient with the resilient modulus was low and because no plausible explanation could be found why the laboratory test results would predict the in situ resilient modulus; and
3. The relative density, i.e., the ratio of field density to laboratory density, because of the insignificantly low simple correlation coefficient with the resilient modulus.

After the above simplifications, the models investigated were in a more manageable form.

Model Employing Atterberg Limits

As a first step in the development of suitable models, a simplified model was evaluated that uses as predictor variables Atterberg limits and moisture content besides a material type classification and the deviator stress for a constant confining pressure of 14 kPa. In the preliminary runs it was found that the moisture content entered into the regression, but it had a positive sign. This means that the resilient modulus increases as the water content increases, all other factors being constant. This result is contrary to engineering experience. Inspection of the results showed that the water content was highly correlated with the Atterberg limits. Substitution of water content by one of the Atterberg limits resulted in an equation that was equally good, in terms of standard error, and considerably more logical.

During the analysis runs, it was noted that when visual classification of materials indicated the presence of sandy particles, these materials had a higher resilient modulus than samples that did not contain sandy particles, all other conditions being equal. The clay materials usually had an AASHTO A-7 classification, whereas the materials containing sandy particles were classified as A-2-4, A-2-6, A-6, and sometimes A-7. It was suspected from visual observations that sandy particles indicated laterization, which is a cementing process, in various stages of cementing. This would also explain the very high resilient moduli measured. Since a hydrometer analysis had not been done on the finer fractions, the visual classification was adopted. It is strongly recommended that in future work the proportion of clay, silt, and sand fractions be taken into account.

The model employing the Atterberg limits, which is also termed the short model, is the following:

$$\mathrm{LMR} = 2.041 + 0.0328\mathrm{LL} + 0.749\mathrm{DV} - 0.0060\mathrm{LL} \times \mathrm{DV} - 0.0573\mathrm{PL} - 0.000\,159\mathrm{PL} \times \mathrm{SD} \quad (1)$$

where

LMR = log to base 10 of resilient modulus (MPa);
LL = liquid limit (%);
DV = material-type dummy variable, 0 for clay materials and 1 for sandy materials;
PL = plastic limit (%); and
SD = deviator stress (kPa).

A total of 299 observations was used to derive this model. The model has an R^2 of 0.57 and a standard error for residuals (in log terms) of 0.317. Consequently, the 95 percent confidence interval of a predicted value is LMR ± 0.62. This means that if model 1 predicts a resilient modulus of 100 MPa, the confidence interval is 24-417 MPa.

Model 1 predicts a decrease in the resilient modulus when PL and deviator stress increase. The predicted resilient modulus of sandy-type materials is greater than that of clayey materials for LL within the range studied. In fact, this applies up to a value of 124.8 for LL. For the clay material (DV = 0) the term containing LL has a positive sign. However, there is usually a strong interdependence between LL and PL. Therefore as LL increases, so generally does PL. As long as the ratio of LL to PL is less than 1.81, an increasing LL will result in a decrease in the resilient modulus for the lowest deviator stress (14 kPa) evaluation. This ratio will increase for larger deviator stresses to a value of 2.09 for a deviator stress of 70 kPa. Examination of the data showed that in general the ratio of LL to PL lies in the range from 1.8 to 2.1.

The fact that the in situ moisture content did not enter into the regression equation in a logical manner was cause for concern. When two variables are highly correlated, one variable may enter into the regression in a manner that is unacceptable in an engineering sense. Ridge regression (8), which is a relatively recent development in statistics, overcomes problems related to correlations between variables. However, a ridge regression showed the influence of moisture content (9) to be small for clayey materials and illogical for sandy materials, which suggests that the data set was probably deficient in its ability to predict moisture content influences or that moisture content does not affect the lateritic materials.

Model Employing Atterberg Limits, in Situ Density, and CBR

More information than the Atterberg limits is often available, and a better estimate of the resilient modulus is expected. As the next step in the analysis procedure, several additional predictor variables were investigated. The independent variables studied were the Atterberg limits; in situ moisture content, density, and CBR; a material type classification; and the deviator stress for a constant confining pressure of 14 kPa. The following variables, shown in the long model, were found to be significant:

$$\begin{aligned} LMR = {} & 1.824 + 0.0423LL + 0.289DV + 0.000\,010\,3DI \times CBR \\ & - 0.000\,607CBR \times LL + 0.0143CBR \times DV - 0.0604PL \\ & - 0.000\,166PL \times SD \end{aligned} \tag{2}$$

where DI is the in situ dry density in kilograms per cubic meter and CBR is the California bearing ratio in percent. In the derivation of this model, 299 observations were used. The model has an R^2 of 0.61 and a standard error for residuals (in log terms) of 0.304. The 95 percent confidence interval of a predicted value is LMR ± 0.60. This means that if model 2 predicts a resilient modulus of 100 MPa, the confidence interval is 25-398 MPa.

If the confidence intervals of models 1 and 2 are compared, it is obvious that there is little meaningful difference between the predictive precision of the two models. However, statistically, the long model is significantly better at the 0.01 level of significance than the short model. Because of the small difference in the predicted accuracy and the fewer predictor variables that are required for the short model, it is recommended that this model be used in practice. Evaluation of other sources will thus be restricted to the short model.

Because of the larger number of variables in the long model, it is more difficult to evaluate the influence of each predictor variable than in the short model. It is not possible to isolate the effect of LL because it is related to PL and it has an interaction with CBR. For increasing PL there is a decrease in the resilient modulus and for increasing CBR the resilient modulus increases. The general trend of the predicted resilient modulus is as would be expected from practical experience.

Evaluation of Errors

In this paper, errors are considered to be deviations from predicted values or variations between observed resilient moduli rather than something done in error. Two types of variations, or errors, are identified. These are the variations in the measured resilient modulus of samples extracted from the same Shelby tube and the variations in measured resilient moduli between tubes when the material characteristics of the tubes were essentially identical.

The first type of error represents an estimate of the repeatability of the test procedure. Since all the analyses were performed on the logarithmic transformation of the resilient modulus, an estimate of the measurement error was also calculated on the logarithm of resilient modulus. The computation is essentially a calculation of the variance for each set of measurements from the same tube at the same deviator stress and a sum of the variances of all the tubes and deviator stresses. The degrees of freedom for each variance calculation were one less than the number of samples. The total sum of squares, or variance, was 4.381, and there were 128 degrees of freedom. The SD of the logarithm of the resilient modulus is thus 0.185. Therefore, the 95 percent confidence interval is LMR ± 0.36. This means that if a value of 100 MPa is measured, the true value lies between 47.9 and 229.1 MPa with 95 percent confidence. As would be expected, the SD of measurements on the same sample is smaller than the standard error of the models (0.185 versus 0.31 for the short model). Since the SD does not consider the inherent variability in materials when their properties are essentially similar, the SD should not be used to evaluate the adequacy of the model. For this purpose the variability between materials when their properties are essentially similar was evaluated. Ideally, the properties should be equal in all respects, but in samples taken in the field the calculations were performed on samples the properties of which were essentially the same.

The calculation of the variance between measurements of essentially similar materials leads to the pure error, or error due to replicate or repeated measurements. In each case the average resilient modulus per tube was used, and the computation was done as described above. There were 32 degrees of freedom, and the sum of the variances was 6.01. The SD of replicate measurements was 0.433, which is greater than the standard error of residuals. A statistical test comparing the lack-of-fit error (sum squares of residuals minus replicate sum of squares) to the replicate error showed that there was no reason to doubt the adequacy of both short and long models at the 0.01 level of significance.

Verification of Short Model

The data were collected by ARE on undisturbed fine-grained subgrade samples, which had an AASHTO classification of A-7. For each sample, LL, PL, gradation, in situ moisture content and density, confining pressure, and deviator stress at which the resilient moduli were measured were known. Measurements were made at two different confining pressures, 18 and 32 kPa. Since the short model was valid for a confining pressure of 14 kPa, only the ARE data at a confining pressure of 18 kPa were used, and it was assumed that the small difference in confining pressure would not affect the results. The test procedure was essentially as described for the Brazil study. For each ARE data point, the resilient modulus predicted by the short model was computed. Plots of the difference between the logarithms of the measured and predicted resilient moduli, i.e., the residuals, against the various independent variables showed that there was a considerable difference in the resilient modulus of the two samples. A plot of the residuals against moisture content (7) showed that the resilient modulus predicted for the Brazil materials was greater than that of the ARE sample. There was also a decrease in the resilient modulus with increasing moisture content, as expected.

It was thus shown that the short model derived from the Brazil data was not applicable to samples obtained in the United States.

Revision of Short Model

It was hypothesized that the basic short model was applicable to the ARE data and that additional terms could help to explain the difference between actual and predicted values. Both data sets were therefore pooled, each identified by a dummy variable, and analyzed together.

The stepwise least-squares regression technique was again employed. The same independent variables that were found to be significant in the development of the short model were again significant for the Brazil data, and some additional independent variables were entered in the model for the ARE data. Although the following three models were derived together in the same analysis, they are presented for each material type for easier understanding.

Brazil data, clayey materials:

$$LMR = 2.050 + 0.0326LL - 0.0573PL - 0.000\,158PL \times SD \quad (3)$$

Brazil data, sandy materials:

$$LMR = 2.790 + 0.0268LL - 0.0573PL - 0.000\,158PL \times SD \quad (4)$$

ARE data, A-7 materials:

$$LMR = 2.050 + 0.0326LL - 0.0661W + 0.000\,626W \times SD - 0.000\,434LL \times SD - 0.0030PL - 0.000\,158PL \times SD \quad (5)$$

where W is the percentage of moisture content. A total of 368 observations was used to derive these models. The overall R^2 is 0.64, and the standard error for residual (in log terms) is 0.314.

When models 3 and 4 are compared with the short model, i.e., model 1, it can be seen that the same terms are significant but that the values of the coefficients are slightly different. This is attributed to the inclusion of the ARE data in the analysis.

For the ARE data an increase in moisture content results in a decrease in the predicted resilient modulus for a deviator stress less than 106 kPa. All the data were collected at a deviator stress below this value, and therefore the model predicts logically. It is conceivable that the model predicts an increase in resilient modulus at low deviator stresses when there is an increase in LL, but it is difficult to isolate this effect because of correlation between LL and PL and moisture content.

Many researchers have shown (10) that log resilient modulus and log deviator stress are linearly related. For this reason an additional analysis was performed by using log deviator stress instead of deviator stress as an independent variable. The resulting models are as follows:

Brazil data, clayey materials:

$$LMR = 2.518 + 0.0348LL - 0.293 \log SD - 0.0683PL \quad (6)$$

Brazil data, sandy materials:

$$LMR = 2.646 + 0.0243LL - 0.101 \log SD - 0.287PL - 0.0198PL \times \log SD \quad (7)$$

ARE data, A-7 materials:

$$LMR = 2.518 + 0.0266LL - 0.293 \log SD - 0.0433W - 0.006\,59LL \times \log SD - 0.0097PL \quad (8)$$

The predictive capability of these models is the same as for models 3 to 5, since the overall R^2 is 0.64 and the standard error for residuals (in log terms) is 0.313. Both sets of models represent the data equally well, and within the range of the independent variables investigated, either set may be used.

This revised analysis supports the previous finding that the Brazil data are inadequate for evaluating moisture-content influences. However, moisture content is an important variable for predicting the resilient modulus. Model 5, derived from the ARE data, will be used to evaluate other data sources, mostly samples taken in the United States.

Verification of Revised Short Model

Several sources of data were available to verify the revised short model (model 5). These were studies by Monismith (5); Seed, Chan, and Lee (6); Hsia and Padgett (11); Thompson and Robnett (7); and data collected in South Africa (12).

The subgrade soils studied by Monismith (5) were described as a combination of weathered slate, lava conglomerate, and silty clay or dredger tailings, red silty clay, and cemented cobbles. The samples for laboratory resilience testing were compacted by kneading compaction into specimens 100 mm in diameter by 200 mm in height. Repeated-load tests were conducted with a constant cell pressure of 20 kPa and deviator stresses of 7, 14, and 20 kPa applied at a frequency of 20 repetitions per minute and a load duration of 0.1 s. Resilient moduli were ascertained from recoverable deformations measured over the center 100 mm of the specimens after 1000 stress repetitions.

Although the samples were laboratory compacted, were not A-7 type materials, and were tested at a confining pressure of 20 kPa instead of the 14 kPa for which model 5 was derived, the measured and the predicted resilient moduli were compared. This is shown in Figure 3. The measured resilient modulus was within the 95 percent confidence interval of prediction for sites 3 and 4, whereas the measured resilient modulus was considerably lower (by a factor greater than 10) than the predicted value at site 1. Comparison of the density, moisture content, LL, and PL of the materials at sites 1 and 3 shows that these are similar, and one would not expect the large difference in the measured resilient modulus that was reported. It thus appears that some factor that was not reported influenced the measured resilient modulus of site 1 and consequently the correlation between the predicted and measured resilient moduli. This requires further study.

Seed, Chan, and Lee (6) investigated the resilient characteristics of the AASHO road test subgrade soil. Undisturbed subgrade samples were repeatedly loaded with a deviator stress of 7 kPa, and the confining pressure was held at 24 kPa. The frequency of stress application was 20/min and the duration of stress application was 0.25 s. The resilient modulus was computed after 60 000 load repetitions.

Samples taken from the untrafficked and trafficked loops were investigated. Figures 4 and 5 show the plots of resilient modulus versus moisture content for these two conditions. Again the test conditions differed from the conditions for which the predictor model was developed. However, the frequency of stress applications and the different confining pressures were assumed not to influence the comparison. Average values for LL and PL of 29 and 16 measured at the AASHO road test (13) were used in the prediction. The predicted values and the lower bound of the 95 percent confidence inter-

Figure 3. Comparison of Monismith resilient moduli with those predicted by revised short model 5.

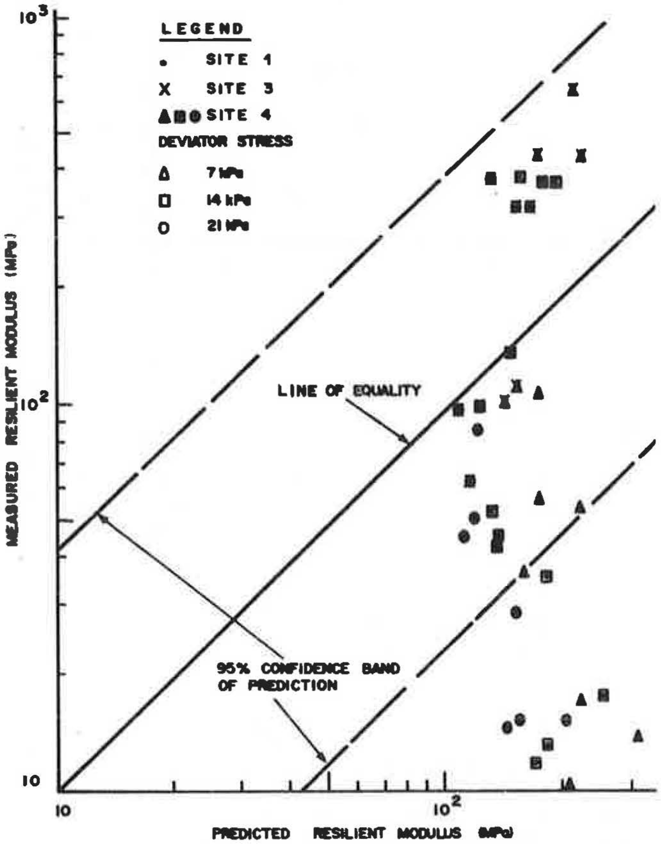


Figure 4. Resilient characteristics of undisturbed samples from untrafficked loop of AASHO test road.

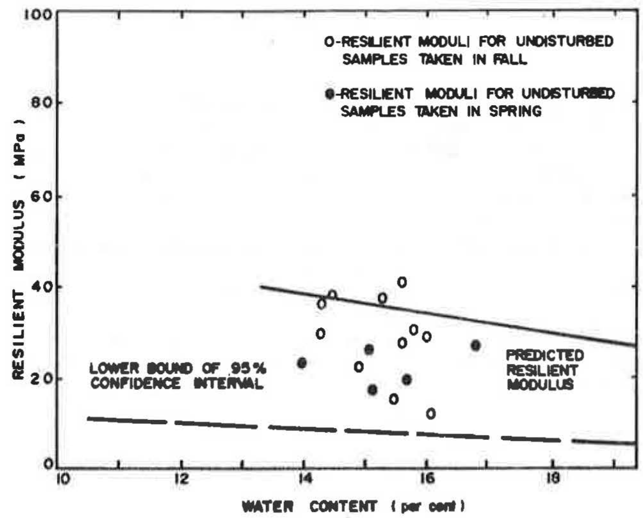
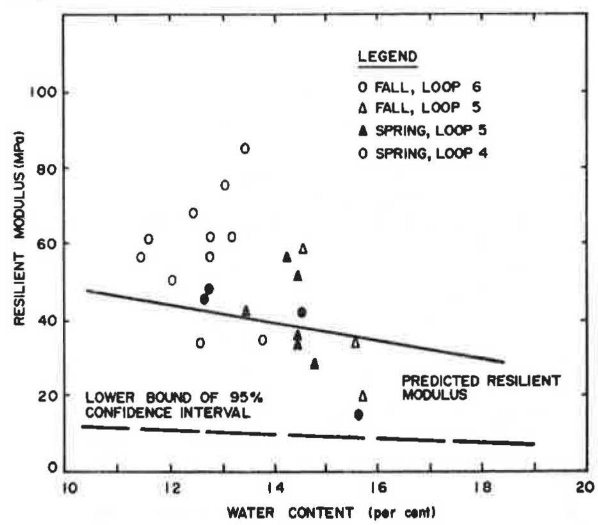


Figure 5. Resilient characteristics of undisturbed samples from trafficked loops of AASHO test road.



val are also shown in Figures 4 and 5. The upper bound lies outside the figures because it is a logarithmic relationship. Very good agreement between the measured and predicted resilient moduli is obvious. It is interesting to note that most of the data points lie below the predicted modulus line on the untrafficked loop, whereas most of the data points lie above the predicted line on the trafficked loop. This may be random scatter, but it is also possible that trafficking increases the resilient modulus. This is another aspect that requires further study.

Resilient moduli of laboratory-compacted roadbed materials were also presented in a Forest Service report (11). Tests were conducted at optimum moisture content and higher. A comparison of the measured resilient modulus with values predicted by model 5 showed that for some samples the values were underpredicted by as much as a factor of 10, and on other samples the prediction was very close.

The study by Thompson and Robnett (14) also gives measured resilient moduli of samples compacted in the laboratory at or above optimum moisture content. Model 5 generally predicted a resilient modulus greater than that measured. Both the Forest Service and the Illinois studies were conducted on samples compacted in the laboratory at very high moisture contents, and the comparisons suggest that model 5 is not applicable to these conditions. This conclusion is not unexpected, since Seed, Chan, and Lee (6) showed that the resilient modulus is extremely sensitive to a moisture content above the optimum.

As a pilot study of a project to characterize the resilience characteristics of roadbed materials in South Africa, a sandy clay material (LL = 37 percent, PL = 21 percent) was studied in detail. These limited data are, however, valuable for evaluating the acceptability of model 5. The samples were prepared in the laboratory by static compaction methods and tested without confining pressure. One set of tests was done on samples compacted at optimum standard AASHTO moisture content (13.6 percent) to 90 percent relative standard AASHTO density. Measured resilient moduli varied from 362 MPa at 50 kPa repeated deviator stress to 150 MPa at 200 kPa deviator stress after 10 000 load repetitions. By using model 5, the predicted resilient modulus ranged between 56 and 1.3 MPa, so the measured values lie outside the 95 percent confidence band. Model 3 gave a higher predicted value, which ranged from 77 to 19 MPa. The measured values lie at the upper bound of the 95 percent interval. Model 4 would give even higher predicted values, but it is unlikely that any cementation would occur in the short time that elapses between molding the sample and testing. A sample was also saturated in a triaxial cell by cell pressure. The measured resilient modulus was 65 MPa at a repeated deviator stress of 40 kPa and zero confining stress. The predicted resilient modulus by using model 3 was 83 MPa. For a moisture content of 20 percent, model 5 predicts a value of 40 MPa. There is thus good agreement, but compared with the first set of tests there are certain moisture-content influences that appear to be undefined. This requires further investigation.

DISCUSSION OF RESULTS

Analysis of the Brazil data showed that sandy-type materials exhibited a higher resilient modulus than clayey-type materials. The predictor equations, models 1 and 2, reflect this situation. It was hypothesized that the presence of sand grains reflects a state of laterization that is more advanced than in the absence of sand grains, i.e., clayey materials. The greater degree of laterization could then account for the higher resilient modulus. Laterization, or cementation, could also account for the fact that water content was entering into the model in an illogical manner in the least-squares regression technique and had little influence on the model from the ridge regression. It is thus possible that these materials from the central plateau regions of Brazil, where most materials are lateritic, have a resilient modulus that is insensitive to moisture content.

Comparison of model 1 derived from the Brazil data and data collected in the United States showed that the clayey Brazilian materials exhibited a resilient modulus considerably greater than that of the U.S. materials. This difference is again attributed to laterization, albeit weak. In the predictor model based on the U.S. data, moisture content has a meaningful influence, which substantiates experience.

Verification of the U.S. model against other data sets gave very promising correspondence. Good agreement was found between the predicted and measured resilient moduli of undisturbed AASHO roadbed samples. There may be a trafficking influence, since on the untrafficked samples the measured values were lower than the predicted values, whereas on the trafficked samples the opposite was true. Trafficking may thus alter the soil structure or strengthen the soil by reorienting the particles, since in situ density was not found to be a significant factor.

There was also good agreement between the predicted and measured resilient moduli at two of the three sites studied by Monismith (5). According to the data from the third site, a considerably higher resilient modulus should have been obtained, so it appears that some factor that was not reported influenced the results of this site. It may be tentatively stated that model 5 is applicable to laboratory-compacted samples, but further data are required to prove this beyond doubt.

Comparisons of model 5 with resilient moduli measured on laboratory samples from the United States compacted at or above optimum moisture content revealed large discrepancies, and it appears that the model is not applicable to these high-moisture conditions. In a limited study on a South African sandy clay, models 3 and 5 agreed closely with the measured resilient modulus of a saturated sample, but there was a great difference between value of the resilient modulus measured on samples at optimum moisture content and the predicted value. There may therefore be another effect besides moisture content that influences the results.

CONCLUSIONS AND RECOMMENDATIONS

In the development of models for predicting the resilient modulus of undisturbed Brazilian roadbed soils, it was found that certain materials of a sandy nature had a considerably higher resilient modulus than clayey material types. There are two possible explanations, which need to be investigated. The more likely explanation is that when a visual examination shows that the material is of a sandy type, there is a more advanced stage of laterization than in the clayey type. Some method of determining the degree of laterization, perhaps the silica/sesquioxide ratio, may help to distinguish between the materials. The second possible explanation is that in fact the finer fractions influence the resilient modulus, and hydrometer analysis of the finer fraction may provide sufficient discrimination.

The resilient moduli measured on the Brazilian samples were very much higher than those of samples obtained in the United States. However, the addition of other explanatory variables to the basic Brazil model gave a good prediction model for U.S. conditions, as shown by its verification against two other data sets. It appears that the predictor equation, model 5, is valid for laboratory-compacted samples, as shown by the agreements with the Monismith data, but further verification is necessary to prove this beyond doubt. Work by Seed, Chan, and Lee (6) showed that there was close agreement between the resilient modulus obtained on undisturbed and laboratory-compacted samples of the AASHO roadbed material. We would therefore expect the predictor model to be applicable to laboratory-compacted samples as well.

Comparison of the predicted resilient modulus with untrafficked and trafficked AASHO road test roadbed materials showed that there may be a traffic influence. This phenomenon can be studied by obtaining samples from different roads of different ages built on the same geological roadbed material and by considering, e.g., cumulative equivalent axles or the number of applications above some load as an additional independent variable.

Further investigation is required into the influence of the moisture content, both below and above optimum. This should be investigated in both in situ and laboratory-compacted samples.

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Aggregate Pavement Design: A Comparison of Two Models

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The U.S. Army Engineer Waterways Experiment Station (WES) model for Thickness Requirements for Unsurfaced Roads and Airfields is compared with the model developed from the Interim Guide for the Design of Flexible Pavement Structures of the American Association of State Highway and Transportation Officials (AASHTO). The WES model extends an earlier model for a single unsurfaced soil to include a more competent surfacing material overlying a subgrade soil. The AASHTO model for flexible pavements with a bituminous surface course is based primarily on the AASHO Road Test and associated studies. The paper demonstrates the adaptation of the WES model into the same parameters as the AASHTO model. These models, on three-dimensional drawings, show continuous curved surfaces from a minimum required pavement strength at low traffic and high subgrade strength, to progressively higher required pavement strengths at higher traffic and weaker subgrades. Of particular significance is the dramatic similarity of the two models, although one was developed for soil surfaces and the other for asphalt surfaces. The WES (soil surface) model indicates a required pavement strength 10-50 percent lower than the AASHTO (asphalt surface) model for the same traffic and subgrade strength. From this comparison, it is concluded that the WES model provides cost-effective aggregate pavement designs.

This paper compares the U.S. Army Engineer Waterways Experiment Station (WES) model for Thickness Requirements for Unsurfaced Roads and Airfields: Bare Base Support (1) with the model developed from the Interim Guide for the Design of Flexible Pavement Structures of the American Association of State Highway and Transportation Officials (AASHTO) (2). The procedure used here compares the models on a common-parameter basis for purposes of evaluation and discussion. The comparison gives an added perspective to both models and substantiates the application of the WES model in the design of aggregate-surfaced pavements for low-volume roads.

The WES model extends an earlier model for a single unsurfaced soil to include a more competent surfacing material overlying a subgrade soil. The model determines the thickness and minimum California bearing ratio (CBR) of surfacing material for a given number of coverages of a design wheel load and tire pressure in order to prevent failure of the subgrade soil. Failure was defined as a 3-in rut or elastic deformation of 1.5 in of the surface. The model is based on load tests of a variety of surfacing material strengths and depths over a variety of subgrade strengths by a variety of wheel loads and tire pressures to represent both truck and aircraft traffic.

The AASHTO model for flexible pavements with a bituminous surface course is based primarily on the AASHO Road Test and associated studies. The failure criterion on the AASHO Road Test was a terminal serviceability index (TSI) of 1.5 on a serviceability scale of zero (very bad) to 5 (very good). The AASHTO model relates the number of equivalent 18-kip axle loads (EALs) to subgrade strength (soil support) to determine pavement strength [structural number (SN)]. This SN may be adjusted by a regional factor. Pavement alternatives are developed by summing layer thicknesses times layer strength coefficients to total the required SN. The procedure relates a variety of strength measures, such as CBR and R-value, to soil support and layer coefficients. The resulting pavement model considered here is designed to reach a TSI of 2.0 (complete resurfacing needed) at the end of its design traffic volume. A similar model for TSI = 2.5 is included in the AASHTO Interim Guide (2).

PROCEDURE

It was first necessary to convert the WES model to the same parameters as the AASHTO model--that is, soil support, number of 18-kip EALs, and SN. Then the models could be compared on three-dimensional and two-dimensional graphical plots.

Correlation charts for CBR and soil support and layer coefficients are used here to compare the models. As the AASHTO Interim Guide (2) cautions, correlations will vary with local soils and test methods.

To calculate plotting points for the WES model, a 9000-lb wheel load with pressure of 80 lb/in^2 was assumed. "Coverage" was assumed to be equivalent to the number of passes. Soil support of the subgrade was determined from the correlation chart, static CBR, shown in Figure 1 (2). Surfacing thickness was determined by using the WES equation (1):

$$t = (0.176 \log C + 0.12) \sqrt{[P/8.1\,(CBR)] - (A/\Pi)} \quad (1)$$