sign of Asphalt Pavements, Ann Arbor, Mich., Vol. 1, 1977.
14. D.L. De Jong, M.G.F. Peutz, and A.R. Korswagen. Computer Program BISAR, Layered Systems under Normal and Tangential Surface Loads. External Report AMSR.0006.73. Koninklijke Shell Laboratorium, Brussels, Belgium, 1973.
15. A.F. Bissada, S.K. Hamdani, and H.R. Guirguis. Design Criteria of Asphalt Pavement Structures at High Service Temperatures. Proc., Fifth International Conference on the Structural Design of Asphalt Pavements, Delft, The Netherlands, Vol. 1, 1982.
16. R.J. Schmidt. A Practical Method for Measuring the Resilient Modulus of Asphalt Treated Mixes. In Highway Research Record 404, HRB, National Research Council, Washington, D.C., 1972, pp. 22-32.
17. Test Procedures for Characterizing Dynamic Stress-Strain Properties of Pavement Materials. TRB Special Report 162. TRB, National Research Council, Washington, D.C., 1975.
18. A.F. Bissada. Asphalt Pavement Temperatures Related to Kuwait Climate. In Highway Research Record 404, HRB, National Research Council, Washington, D.C., 1972, pp. 71-85.
19. A.F. Bissada and A. Al-Abdulla. Asphalt Pavement Response to Excessive Axle-Loads in Kuwait. Presented at the International Road Federation Conference for the Middle East and North Africa, Cairo, Egypt, April 1978.
20. F.F. Saccomanno and A.O. Abdel Halim. Economic Analysis of Axle-Load Limits in Less-Developed Countries. In Transportation Research Record 898, TRB, National Research Council, Washington, D.C., 1983, pp. 357-364.

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Abridgment

Predicting Resilient Modulus: A Study to Determine the Mechanical Properties of Subgrade Soils

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ABSTRACT

Extensive literature review, detailed regression studies, and limited laboratory testing were used to develop models for predicting subgrade resilient modulus. General models are proposed for cohesive soils and nonplastic or granular-type soils. These two models are provided in the new Forest Service Surfacing Handbook (FSH 7709.56a) to provide the practicing engineer with guidance in the absence of test results. More than 250 different soils, representing more than 3,300 modulus test points, were placed in a computerized data base for regression studies. Although these data come from a literature search and testing variations definitely existed, the final models provide a useful first estimate. However, it was strongly recommended that resilient modulus laboratory tests be obtained whenever feasible. The effect of an error in subgrade modulus estimation on the thickness obtained from the design procedure was also studied. Some laboratory tests were made for use in model verification.

Since 1972 the U.S.D.A. Forest Service has been developing a program to provide systematic pavement management for the design of Forest Service roads. As initially developed, this project-level design system uses the AASHO Interim Design Guides as the basic structural and performance model (1-3) for paved roads and a rut depth model developed by the U.S. Army Corps of Engineers for the design of aggregate-surfaced roads.

Recently the structural models in the Surfacing Design and Management System (SDMS) were modified to use the mechanistic approach for determining the thickness of the structural roadway section components (4). This work was basically a revision of Chapter 50 of the Forest Service Transportation Engineering Handbook (5). At this time, the Forest Service has decided to place the information in Chapter 50 in a separate handbook. The Surfacing Handbook, Forest Service publication FSH 7709.56a, will be the new equivalent to the existing Chapter

50 design procedure. The new mechanistic approach is based on elastic-layered theory and requires that the resilient modulus of the subgrade soil be input into the design procedure. Although this input can be determined with repetitive load triaxial testing of subgrade soil samples, such testing is not currently widely available to Forest Service field engineers. The need exists to develop a quick method for determining the resilient modulus from correlations with established or newly developed tests or procedures (6).

STUDY OBJECTIVE

The overall project objective was to develop correlations for predicting subgrade resilient modulus values from basic soil tests or newly developed tests or procedures. This study was undertaken so that a quick method for estimating subgrade resilient modulus would be available to practicing Forest Service engineers.

SCOPE OF STUDY

The project included three general work areas:

1. Collecting existing data from the literature,
2. Establishing correlation models using this data base, and
3. Testing several soils to help verify the new models.

The significant results of this study are the correlation equations summarized in this paper.

LITERATURE REVIEW AND DEVELOPMENT OF DATA BASE

A literature search was made on the Highway Research Information Service (HRIS) data base, and approximately 100 references were collected and reviewed for the establishment of a data base. Although it was initially hoped that extensive data would be reported in the literature for correlation testing between resilient modulus tests and other strength tests such as the California bearing ratio (CBR) test, such was not the case. Therefore resilient modulus test results were recorded in the data base along with more basic soil parameters such as the plasticity index (PI), water content (%W), and amount of material passing the No. 200 sieve. The data base contained more than 3,300 records of resilient modulus test results for more than 250 different soils at specific confining pressures and deviator stresses.

However, the literature study indicated that a more general form was needed for implementation in the Surfacing Handbook. Fortunately, other researchers (7) have proven that simpler relationships based on fundamental soil properties can be developed.

ESTABLISHMENT OF CORRELATION MODELS

Regression studies were initially made for individual soil types according to the unified soil classification (USC) system. Several problems with the data were encountered in the development of the regression equations, including (a) missing observations, (b) different test procedures, (c) lack of range in predictor values, (d) collinearity, (e) confounding of data, and (f) inconsistent sample sizes.

The data were divided according to individual soil types within the USC system and models were developed for each soil type for which data were available. The following symbols and units are used in the equations:

M_R = resilient modulus (ksi),
PI = plasticity index,
%W = percentage water,
CS = confining stress (psi),
DS = deviator stress (psi),
T = bulk stress (psi) (DS + 3CS),
DD = dry density (pcf),
S200 = percentage passing No. 200 sieve, and
SS = soil suction.

Using the best subsets of data found in the analysis of individual soil types, a general equation was sought that would encompass all soil types. Combining all the soil types to accomplish this objective did not yield reasonable results. It was decided to create two broad classes of soils: fine grained (Group 1) and coarse grained (Group 2). The coefficient for deviator stress tends to be negative for Group 1 and positive for Group 2. Specifically, Group 1 consisted of cohesive (fine-grained) soil types including CH, MH, ML, and CL, and Group 2 consisted of granular (coarse-grained) soil types GW, GP, GM, GC, SW, SP, SM, or SC. The following general equations were found after several trial combinations.

Cohesive Soils

The general model is as follows:

$$M_R = 37.431 - 0.4566(PI) - 0.6179(\%W) - 0.1424(S200) + 0.1791(CS) - 0.3248(DS) + 36.422(CH) + 17.097(MH)$$

where

CH = 1 for CH soil
= 0 otherwise (for MH, ML, or CL soil);
MH = 1 for MH soil
= 0 otherwise (for CH, ML, or CL soil);

and the other terms are as defined previously. Here,

R^2 = 0.759,
standard error (SE) = 5.277, and
N = 418 observations.

Ranges of the variables are given in the following table.

	Soil Type			
	CH	MH	ML	CL
PI	21-55	13	2-12	13-20
%W	11-36	37-51	6-24	9-21
S200	79-91	86	80-93	60-92
CS	2-20	2-6	0.5-4.5	2.5-40
DS	2-15	1-12	0.5-9.0	3.0-40

Granular Soils

The general model is as follows:

$$\log M_R = 0.523 - 0.0225(\%W) + 0.544(\log T) + 0.173(SM) + 0.197(GR)$$

where

SM = 1 for SM soils
= 0 otherwise;
GR = 1 for GR soils (GM, GW, GC, or GP)
= 0 otherwise;

TABLE 1 Soil Samples Tested for Resilient Modulus

Soil No.	USC[a]	Dry of Optimum Water Content (%)	Optimum Water Content (%)	Wet of Optimum Water Content (%)	Liquid Limit (%)	Plastic Limit (%)	Percentage Passing No. 200 Sieve
10607	GW-GM	4.48 (4.0)	5.21 (8.0)		NP	NP	5
10600	GW	19.53 (19.2)	25.22 (25.0)		39	35	20
10823	SP-SM	8.48 (8.5)	12.08 (13.3)		NP	NP	8
10799	SM		13.15 (15.0)	17.84&17.90 (19.0)	35	NP	28
10604	SC		14.58 (14.3)	16.63 (16.4)	35	21	43
10756	CL		13.36 (14.0)	16.05 (16.0)	40	16	68
10755	CL		12.07 (10.3)	11.4 (17.0)	44	14	81
10825	CH		19.78 (19.4)	20.07 (21.0)	61	15	91

Note: Laboratory compaction efforts were aimed at obtaining the water content shown in parentheses; the actual value obtained appears first.

[a]Unified soil classification system.

and the other terms are as defined previously. Here,

R^2 = 0.836,
SE = 0.1627, and
N = 583 observations.

Ranges of the variables are given in the following table.

	Soil Type NP	SM	GR
%W	4.0-8.8	8.7-37.8	5.7-12.3
CS	1.0-20.0	1.0-23.0	1.0-20.0
DS	1.0-20.0	1.0-30.0	5.0-90.0
T	4.0-75.0	3.4-116.0	8.0-114.8

SOILS TESTING FOR MODEL VERIFICATION

The Forest Service provided the researchers with a number of soil samples of a range of material types collected at random by the Region 5 laboratory. Basic soil test results were provided by the Forest Service. Table 1 gives the soil samples, the USC classifications, and the water contents used for the M_R tests that were run.

The new AASHTO test method T274-82 for the resilient modulus of subgrade soils was used in testing. When the moisture-density relationship was known, laboratory test specimens were compacted to two density values selected for testing: (a) the maximum density at the optimum water content and (b) one other density either wet of optimum or dry of optimum. ARE, Inc., soil testing produced more than 300 M_R values for the different deviator stress and confining stress combinations. The actual values were compared with the predicted values from the two general equations (for cohesive soils and for granular or nonplastic soils). Figures 1 and 2 show the results of these comparisons. For the limited range of soils tested, the models do a fair job of estimating M_R. Although the scatter is broad, there do not appear to be any major trends in the data that would cause a rejection of the equations. Some of the scatter obviously could be attributed to the fact that before AASHTO T274-82 no standard procedure existed; hence the scatter or error of the "prediction." The engineer should always use these equations with engineering judgment.

The models presented have been adopted for use in the new Forest Service Surfacing Handbook (FSH 7709.56a). These models are the most applicable ones available at this time. Certainly, caution must be used when using these or any regression equations to ensure that the input information is within the inference space from which the equations were developed. By using these equations, the engineer can estimate subgrade strength as a function of moisture content for each season of the year. The Surfacing Handbook design procedure allows for such variations in subgrade modulus.

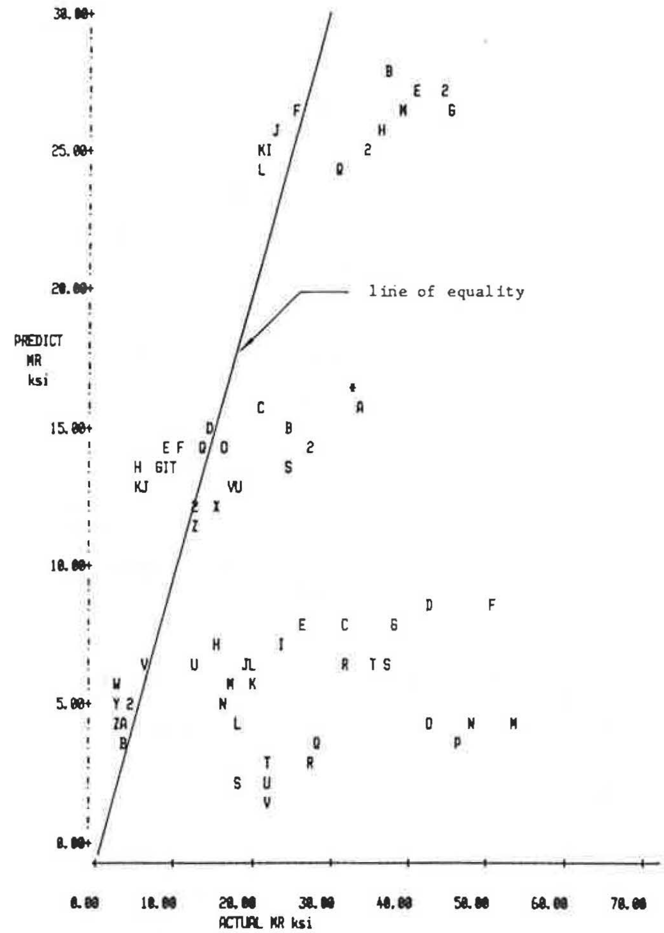

FIGURE 1 Modulus of resilience results from testing of cohesive soils versus predictions from general cohesive equation.

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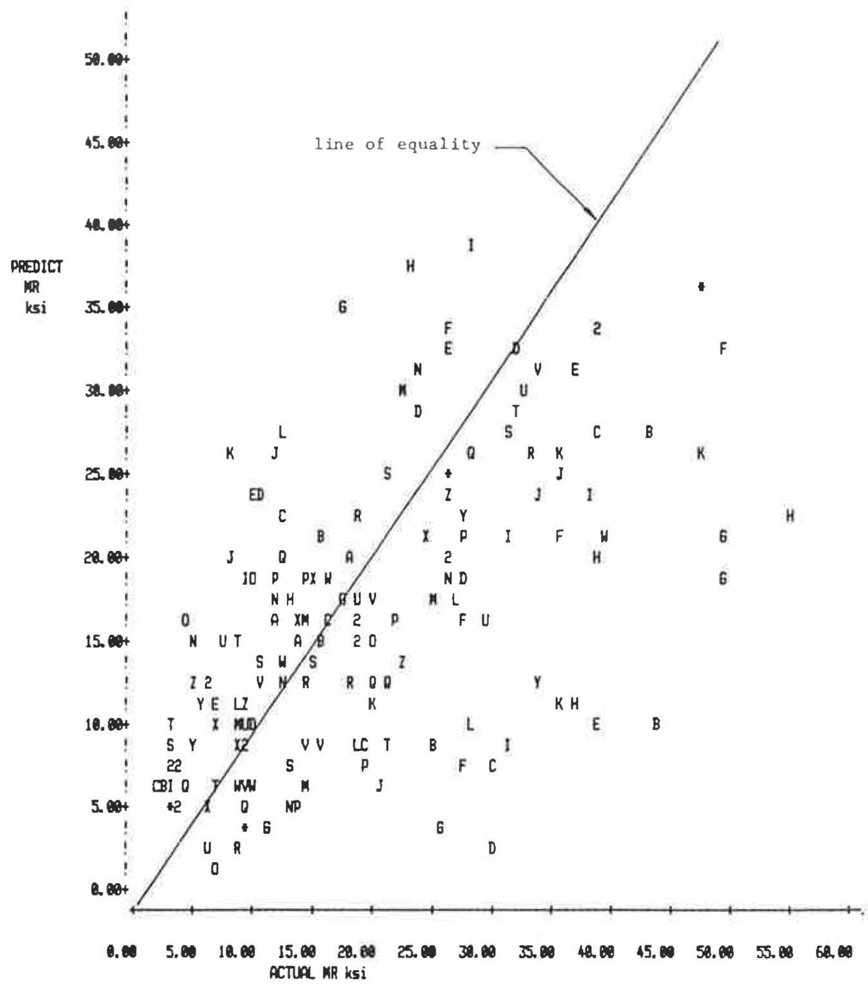

FIGURE 2 Modulus of resilience results from testing of granular soils versus predictions from general equation.

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REFERENCES

1. T.G. McGarragh and W.R. Hudson. A Pavement Design and Management System for Forest Service Roads--A Conceptual Study. Research Report 12. Council for Advanced Transportation Studies, The University of Texas at Austin, July 1974.
2. F.L. Roberts, B.F. McCullough, H.J. Williamson, and W.R. Wallin. A Pavement Design and Management System for Forest Service Roads--A Working Model. Research Report 43. Council for Advanced Transportation Studies, The University of Texas at Austin, Feb. 1977.
3. B.F. McCullough and D.R. Luhr. A Pavement Design and Management System for Forest Service Roads--Implementation. Research Report 60. Council for Advanced Transportation Studies, The University of Texas at Austin, Jan. 1979.
4. B.F. McCullough and D.R. Luhr. The New Chapter 50 Revisions to the Transportation Engineering Handbook and New Pavement Design and Management System. Draft Report Project FSH 7709.11. Center for Transportation Research, U.S. Department of Transportation; Forest Service, U.S. Department of Agriculture, June 1982.
5. Transportation Engineering Handbook, Chapter 50. Forest Service, U.S. Department of Agriculture.
6. U.S. D.A. Forest Service. Forest Service Geotechnical Workshop. EM7170-2. Proceeding of a Conference held in Denver, Colo., June 1982.
7. T.C. Johnson, D.G. Cole, and E.J. Chamberlain. Influence of Freezing and Thawing on the Resilient Properties of Silt and Soil. CRREL Report 78-23. U.S. Army Corps of Engineers, Sept. 1978.

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