Soil-Property-Based Subgrade Resilient Modulus Estimation for Flexible Pavement Design

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Subgrade soils play an integral part in pavement performance. The nature and properties of subgrade soils must be considered in structural pavement design. Many highway agencies, particularly those that administer local or low-volume pavements, do not have the resources to conduct comprehensive subgrade evaluation programs. The use of soil index properties obtained from county soil surveys published by the Soil Conservation Service to estimate the subgrade resilient modulus for structural pavement design is investigated. Soils data and nondestructive pavement testing data from five counties in Illinois were used in the analyses. Subgrade resilient modulus is estimated from soil index properties by using relationships developed for Illinois subgrade soils. Resilient modulus is also estimated from pavement surface deflections by using equations developed from the ILLI-PAVE finite-element pavement model. Soil-property-based modulus estimates are compared with deflection-based modulus estimates. Two methodologies are described that were used to adjust soil-property-based modulus estimates to design values for pavements based on comparisons with deflection-based modulus estimates. One method is based on the natural drainage class of the soil. The second method uses the moisture adjustment ratio, which is the ratio of the design in situ moisture condition of the soil to the soil's optimum moisture content. For many of the soils investigated, design soil-property-based subgrade modulus estimates relate well to the corresponding deflection-based modulus estimates. However, local soils are best represented by soil-property-based modulus estimates when the methodologies described are applied specifically to local conditions rather than when generic or blanket relationships developed for a wide range of soils are relied upon.

Subgrade soil characterization is one of the critical factors in structural pavement design. Most methods of determining pavement thickness requirements for projected traffic loading include a subgrade input, whether as an explicit variable or implicitly in design curves. Ideally a subgrade investigation program would be conducted for each pavement project to determine classification and strength data for each soil encountered on the project. Unfortunately, time and monetary considerations generally preclude such investigations or severely limit their scope. This is true particularly for agencies involved in the design and construction of low-volume roads.

The primary subgrade property of interest in the structural pavement design of flexible pavements is the resilient modulus, E_R. In the absence of subsurface exploration or nondestructive pavement testing programs, highway agencies (particularly local agencies) need methods of obtaining or developing reasonable estimates of the subgrade resilient modulus. Techniques for estimating E_R from soil index properties such as plasticity index (PI) and percent clay have been developed. A large body of index property data for soils exists and is readily available to the pavement designer. In this paper methodologies are described for estimating the subgrade resilient modulus for pavement design purposes by using established techniques and readily available soil property information. Soil-property-based estimates of the subgrade resilient modulus are compared with modulus values estimated from the results of nondestructive pavement testing. On the basis of the comparisons, soil-property-based estimates are adjusted to design values for use in pavement design activities.

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The following items should be noted concerning the analyses that follow:

1. The methodologies presented are based on soils and conditions in Illinois. Because of the relatively uniform soil conditions present in Illinois, typically only three or four soil series are encountered per mile on a project. Extrapolation to areas in which soil and climatic conditions are substantially different from those in Illinois must be performed with caution.
2. The primary application of the methodologies presented is to low-volume roads, in which the pavement is typically constructed directly on the natural subgrade soil.
3. The analyses described in this paper demonstrate an approach to modulus estimation; they are not intended to be a cookbook procedure for providing the resilient modulus of the subgrade soil.
4. The methodologies described are not intended to replace field investigation of subgrade soils; however, they may provide a workable alternative to the do-nothing option when fieldwork is not feasible.

ESTIMATING RESILIENT MODULUS

Using Soil Index Properties

A number of studies have been conducted to develop subgrade modulus predictive equations based on soil properties such as Atterberg limits and percent clay. An excellent summary of the major efforts is contained in the Final Report of NCHRP Project 1-26 (*1*), on which the following discussion is based.

Drumm et al. (*2*) developed subgrade modulus predictive equations based on standard soil tests using 11 typical Tennessee soils. Resilient modulus was related to the soil's plasticity, percent fines, density, saturation, and unconfined compressive strength. The authors concluded that the modulus predictive equation provides "a good characterization of response for the soils investigated."

Elliott et al. (*3*) tested 15 typical Arkansas soils for resilient modulus. Subgrade modulus predictive equations were developed for repeated deviator stress levels of 27.5 and 55 kPa (4 and 8 psi). The subgrade modulus was related to the percent clay, PI, and optimum moisture content. The resilient modulus data used in developing the predictive equations represented soils at approximately 120 percent AASHTO T-99 moisture content and 95 percent compacted dry density.

Farrar and Turner (*4*) published the results of a laboratory resilient modulus testing program for 13 typical Wyoming subgrade soils. The subgrade modulus was related to the degree of saturation, repeated deviator stress, confining pressure, PI, and percent passing the No. 200 sieve.

Thompson and Robnett (*5*), in the first comprehensive study of its type, investigated the repeated load behavior of 50 typical Illinois fine-grained soils. The subgrade modulus was significantly correlated with liquid limit, PI, group index (from the AASHTO soil classification system), silt content, clay content, specific gravity, and organic carbon content. A stepwise regression analysis was performed on the data to develop modulus predictive equations from soil properties. Thompson and LaGrow (*6*) proposed using the following regression equation for conventional flexible pavement design:

$$E_{Ri}(\mathrm{OPT}) = 4.46 + 0.098C + 0.119\mathrm{PI}$$

$$(R^2 = 0.63, \mathrm{SEE} = 2.7 \text{ ksi}) \qquad (1)$$

The regression algorithm is improved if soil organic carbon content is included:

$$E_{Ri}(\mathrm{OPT}) = 6.90 + 0.0064C + 0.216\mathrm{PI} - 1.97\mathrm{OC}$$

$$(R^2 = 0.76, \mathrm{SEE} = 2.3 \text{ ksi}) \qquad (2)$$

where

E_{Ri}(OPT) = subgrade resilient modulus (ksi) at AASHTO T-99 optimum moisture content and 95 percent compaction,
C = percent clay (<2 μm),
PI = plasticity index (percent),
OC = percent organic carbon,
R^2 = coefficient of determination, and
SEE = standard error of the estimate.

Thompson and Robnett (*5*) modeled the stress softening behavior of fine-grained soils as a bilinear curve (Figure 1). Their modulus equations (Equations 1 and 2) predict the breakpoint resilient modulus (E_{Ri}), which commonly occurs at approximately 41.3 kPa (6 psi) deviator stress for Illinois soils (*5*). E_{Ri} is a good indicator of soil resilient behavior. The slope values in Figure 1, k_1 and k_2, display less variability and influence pavement structure response to a smaller degree than does E_{Ri} (*7*).

The E_{Ri} estimate obtained from the predictive equations for Illinois soil represents a soil at optimum moisture content and 95 percent compaction (AASHTO T-99). Subgrade soils, particularly fine-grained ones, are moisture sensitive. In other words, the resilient modulus of the soil depends on the moisture content of the soil. Relationships between E_{Ri} and the degree of saturation of the soil (*5*) demonstrate that subgrade modulus decreases with increasing moisture content.

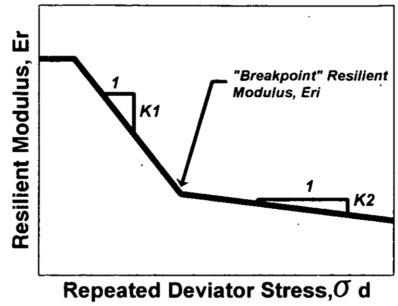

FIGURE 1 Bilinear model of resilient behavior of fine-grained soils (*5*).

Thompson and LaGrow (*6*) analyzed the Illinois data (*5*) to develop moisture adjustment factors based on the U.S. Department of Agriculture (USDA) textural classification of the soil. The moisture adjustment factor represents the decrease in E_{Ri} (in kips per square inch) for each 1 percent increase in moisture content above the optimum moisture content. In general, soils with higher values of clay content and PI (textural classification groups clay, silty clay, and silty clay loam) showed less sensitivity to changes in the degree of saturation. The moisture adjustment factors proposed by Thompson and LaGrow are shown in Table 1.

It is apparent from the preceding discussion that subgrade resilient modulus can be estimated from soil properties (percent passing a No. 200 sieve, percent <2-μm clay, PI, percent OC), moisture density conditions (consolidated in percent saturation), and stress state conditions. There is a difficulty in applying many of the predictive equations to everyday design situations, however. Many of the equations contain one or more quantities that are not routinely measured, such as values from unconfined compression or repeated load triaxial testing, and therefore represent information that is not readily available. Ideally, reasonable estimates of E_{Ri} could be made by using soil index properties (e.g., grain size and plasticity), which are used in the equations for Illinois soils (Equations 1 and 2).

TABLE 1 Moisture Adjustment Factors (*6*)

USDA Textural Class	Moisture Sensitivity (ksi / %)
clay silty clay silty clay loam	0.7
silt loam	1.5
loam	2.1

Notes: Moisture Adjustment Factor represents the decrease in Eri (ksi) for each 1% moisture increase above optimum

1 ksi = 6890 kPa

Sources of Soil Property Information

Equations 1 and 2 relate subgrade resilient modulus to laboratory test values of soil index properties. It is certainly ideal to conducting laboratory tests of the actual soils encountered on a paving project; however, in the absence of field sampling and laboratory testing, soil property information may yet be readily available. Perhaps the single largest source of soil property information is the USDA Soil Conservation Service (SCS). The SCS maintains records on more than 17,000 soils mapped in the United States. The primary source of SCS soils data most accessible to the pavement designer is the SCS county soil survey (the county soils report).

The SCS county soils report contains a significant amount of information concerning local soils. Tables in the county soils report list items such as USDA textural class, Unified and AASHTO classifications, grain size distribution, Atterberg limits, percent clay, and percent organic matter. Most soil property data items are listed as a range of values, which reflect the variability of the property for that soil in the county. Soils are listed in the county soils report on the basis of their pedologic classifications. *Pedology* is a field of study involving the processes of soil genesis, classification, morphology, survey, and interpretation (*8*). Studies have indicated that pedology-based subgrade classification can be advantageous to pavement design activities (*5,6,9*). In addition, many state highway agencies (SHAs) are using pedologic concepts in subgrade evaluation. A summary of current SHA efforts is given elsewhere (*7*).

Using Nondestructive Testing Data

The subgrade resilient modulus can be back-calculated by using pavement surface deflections generated from a falling-weight deflectometer (FWD). There are many methods of back-calculating subgrade modulus from pavement surface deflections, including direct-solution procedures, elastic layer program (ELP)-based procedures, and stress-dependent finite-element model (FEM)-based procedures. The question of the best method for back-calculating subgrade modulus from deflection data has received much attention in the pavement engineering community. The focus of this research is to relate back-calculated values of modulus to soil-property-based modulus values, not to assess back-calculation procedures. A brief discussion of the procedures used in this research follows.

Studies at the University of Illinois (*10,11*) have resulted in algorithms for estimating the subgrade resilient modulus from pavement surface deflections. The algorithms, which relate E_{Ri} to D_3 [the surface deflection (in mils) at 914 mm (36 in.) from the point of loading], are regression equations developed from a data base of pavement responses to load. The data base was generated by the ILLI-PAVE finite-element structural pavement model. Equations 3 through 6 show the E_{Ri} back-calculation algorithms:

For surface treatment/granular base pavements:

$$E_{Ri} = 24.2 - 5.71D_3 + 0.35D_3^2 \quad (R^2 = 0.98,\ \text{SEE} = 0.57\ \text{ksi}) \quad (3)$$

For conventional flexible pavement (3-in.-minimum asphalt concrete/granular base):

$$E_{Ri} = 25.0 - 5.25D_3 + 0.29D_3^2 \quad (R^2 = 0.97,\ \text{SEE} = 0.76\ \text{ksi}) \quad (4)$$

For full-depth asphalt concrete pavements:

$$E_{Ri} = 24.7 - 5.41D_3 + 0.31D_3^2 \quad (R^2 = 0.98,\ \text{SEE} = 0.64\ \text{ksi}) \quad (5)$$

For all flexible pavements:

$$E_{Ri} = 24.1 - 5.08D_3 + 0.28D_3^2 \quad (R^2 = 0.97,\ \text{SEE} = 0.76\ \text{ksi}) \quad (6)$$

The ILLI-PAVE-based algorithms shown have been used in many studies conducted at the University of Illinois and give reasonable estimates of subgrade modulus (*9*).

DATA ANALYSIS

Results from FWD testing (pavement surface deflections) are used to estimate the subgrade resilient modulus by using the ILLI-PAVE algorithms given above. The subgrade modulus is also estimated by using soil index properties obtained from county soil surveys for pedologic soil series encountered by FWD testing. The two estimates of subgrade modulus, deflection-based and soil-property-based, are compared to determine whether a relationship exists.

Soil property and FWD data from Champaign County, Illinois are used to develop relationships between soil-property-based and deflection-based estimates of E_{Ri}. The relationships developed with the Champaign County data are verified with soil property and FWD data from four additional counties in Illinois: Sangamon, Livingston, Mercer, and Marion.

Development of Relationships: Deflection-Based Versus Soil-Property-Based E_{Ri}

FWD Results: Deflection-Based Estimates of Subgrade Modulus

In March 1992 a nondestructive (FWD) pavement testing program was performed on approximately 68.4 lane-km (42.5 lane-mi) of flexible pavement located in Champaign County. Testing sites were identified by using soil maps contained in the Champaign County soil survey (*12*). A total of 15 sites located in five county soil associations were identified and tested. The testing program was designed to obtain test results for the major pedologic soil series of the county. A complete description of the testing program is given elsewhere (*9*). The soil series encountered during testing represents the soils on approximately 89 percent of the total county area. For major soil series, relatively long continuous segments are typically encountered. On a typical pavement project only a small number of soil series needs to be considered.

The ILLI-PAVE-based algorithm appropriate for the pavement structure present at each FWD testing site is used to estimate E_{Ri}. If the specific pavement structure is not known, Equation 6 is used. Within each testing site (or project) the E_{Ri} values representing a particular soil series are grouped into a mean value (the project mean). Analyses performed for this research and by others have indicated that the project mean is an appropriate level at which to consider E_{Ri} data (*9,13*). Table 2 shows the results of FWD data analysis for Champaign County.

Soil-Property-Based Estimates of Subgrade Modulus

The subgrade modulus is estimated from soil index properties by using Equations 1 and 2. Mid-range soil index properties are obtained from the Champaign County soil survey (*12*). An E_{Ri} estimate is generated for each of the soil's genetic horizons. Equation 1 is used to estimate E_{Ri} for B and C horizons, whereas Equation 2 is used to estimate E_{Ri} for A horizons [the surficial horizon that typically has a significant amount of organic matter (OM)]. For use in Equation 2, OM is expressed as OC through the following relationship (*9*):

$$\text{Percent OC} = \frac{\text{percent OM}}{1.7} \qquad (7)$$

For routine purposes agronomists typically assume that the OC content is 58 percent of the total OM content.

Table 3 shows midrange values of soil properties and E_{Ri}(OPT) estimates for the major soil series in Champaign County. The designation E_{Ri}(OPT) is used to denote the fact that Equations 1 and 2 yield the subgrade modulus at optimum moisture content.

The moisture adjustment factors shown in Table 1 are used to adjust E_{Ri}(OPT) estimates to moisture contents in excess of the optimum. The adjustment factor is a function of the USDA textural class of the soil, which is given in the county soil survey. Table 3 shows the major soil series of Champaign County, with estimates of E_{Ri}(OPT) and for moisture contents up to (OPT+6 percent). Because of differences in the textural class of horizons within the same soil series, the E_{Ri}(OPT) estimate of each horizon

TABLE 2 Results of FWD Data Analysis for Champaign County

FWD Site	Soil Series	No. Obs	Mean Erl (ksi)	Std Dev	COV (%)
1-1	152 Drummer	6	0.93	0.04	5
	153 Pella	13	0.92	0.03	3
	154 Flanagan	19	1.29	0.85	66
	171 Catlin	2	1.70	0.44	26
1-2	152 Drummer	13	4.47	1.66	37
	153 Pella	5	4.64	1.38	30
	154 Flanagan	36	5.22	1.85	35
1-3	152 Drummer	38	3.19	2.61	82
	154 Flanagan	11	4.68	1.64	35
	198 Elburn	5	1.82	0.70	39
1-4	152 Drummer	32	1.63	0.72	44
	153 Pella	5	2.92	0.59	20
	154 Flanagan	16	2.66	1.39	52
1-5	67 Harpster	2	1.65	0.38	23
	150 Onarga	2	5.48	0.66	12
	152 Drummer	31	2.57	1.09	43
	153 Pella	10	1.81	0.61	34
	154 Flanagan	6	3.06	0.91	30
	171 Catlin	2	2.19	0.11	5
2-1	148 Proctor	4	2.58	1.26	49
	152 Drummer	20	2.48	2.18	88
	481 Raub	5	3.48	1.69	49
2-2	148 Proctor	1	8.67	0.00	0
	152 Drummer	10	7.01	2.12	30
	221 Parr	8	6.89	2.73	40
	481 Raub	1	10.21	0.00	0
2-3	148 Proctor	6	5.76	0.48	8
	149 Brenton	4	6.93	1.24	18
	152 Drummer	10	5.27	0.77	15
	481 Raub	2	5.28	1.03	20
2-4	146 Elliott	7	10.08	1.40	14
	152 Drummer	5	9.17	1.04	11
3-1	56 Dana	18	5.19	4.11	79
	152 Drummer	9	1.21	0.59	49
	221 Parr	12	5.81	3.45	59
	481 Raub	13	3.02	2.34	77
5-1	152 Drummer	42	0.93	0.06	6
	198 Elburn	11	1.81	1.28	70
5-2	148 Proctor	2	5.94	0.87	15
	149 Brenton	2	1.84	0.81	44
	152 Drummer	23	1.02	0.27	27
5-3	152 Drummer	16	1.94	1.43	74
	154 Flanagan	17	3.99	2.81	70
	198 Elburn	12	2.49	1.09	44
	199 Plano	5	3.28	0.46	14
	221 Parr	1	7.80	0.00	0
7-1	146 Elliott	22	6.73	1.25	19
	152 Drummer	2	4.92	0.06	1
	223 Varna	6	6.96	2.52	36
	232 Ashkum	10	6.31	1.37	22
	330 Peotone	3	8.19	1.14	14
	402 Colo	2	7.78	1.07	14
	481 Raub	4	6.61	3.15	48
	490 Odell	4	7.77	2.45	32
7-2	56 Dana	4	5.41	0.98	18
	146 Elliott	23	5.82	2.20	38
	232 Ashkum	27	4.97	2.54	51

NOTE: 1 ksi = 6890 kPa

TABLE 3 Average Soil Properties and E_{Ri} Estimates for Champaign County Soils

Soil Series	Horizons Thick (in)	Sym	USDA Textural Class	Average Values PI (%)	%CL	%OC	Eri (OPT) (ksi)	Eri (ksi) @ OPT+ : 1	2	3	4	5	6
56 Dana	12	A	SiL	10	17	1.50	6.2	4.7	3.2	1.7	1.0	1.0	1.0
	22	B	SiCL	26	31		10.6	9.9	9.2	8.5	7.8	7.1	6.4
	5	IIB	CL	24	31		10.3	9.3	8.3	7.3	6.3	5.3	4.3
	21	IIB/IIC	L	8	21		7.5	5.4	3.3	1.0	1.0	1.0	1.0
	COMPOSITE:						8.6	7.2	5.9	4.4	3.9	3.6	3.3
146 Elliott	12	A	SiL	13	26	2.65	4.7	3.2	1.7	1.0	1.0	1.0	1.0
	29	IIB	SiC,SiCL	19	40		10.6	9.9	9.2	8.5	7.8	7.1	6.4
	19	IIC	SiCL,CL	18	31		9.6	8.9	8.2	7.5	6.8	6.1	5.4
	COMPOSITE:						9.1	8.2	7.4	6.7	6.1	5.6	5.0
152 Drummer	14	A	SiCL	23	31	3.50	5.1	4.4	3.7	3.0	2.3	1.6	1.0
	27	B	SiCL	23	31		10.2	9.5	8.8	8.1	7.4	6.7	6.0
	6	IIB	L,SiL,CL	23	28		9.8	8.3	6.8	5.3	3.8	1.0	1.0
	13	IIC	SaL/SiCL	14	24		8.4	7.7	7.0	6.3	5.6	4.9	4.2
	COMPOSITE:						8.6	7.8	7.0	6.2	5.5	4.6	3.9
154 Flanagan	18	A	SiL	23	25	2.65	6.7	5.2	3.7	2.2	1.0	1.0	1.0
	27	B	SiCL	23	39		10.9	10.2	9.5	8.8	8.1	7.4	6.7
	15	IIB/IIC	L,CL,SiL	18	25		9.0	7.5	6.0	4.5	1.0	1.0	1.0
	COMPOSITE:						9.2	8.0	6.9	5.7	4.2	3.9	3.6
232 Ashkum	17	A	SiCL	28	40	3.50	6.2	5.5	4.8	4.1	3.4	2.7	2.0
	22	B	SiCL,SiC	28	40		11.7	11.0	10.3	9.6	8.9	8.2	7.5
	21	IIB/IIC	SiCL	23	35		10.6	9.9	9.2	8.5	7.8	7.1	6.4
	COMPOSITE:						9.8	9.1	8.4	7.7	7.0	6.3	5.6
481 Raub	18	A	SiL	10	24	1.80	5.7	4.2	2.7	1.2	1.0	1.0	1.0
	14	B	SiCL	28	31		10.8	10.1	9.4	8.7	8.0	7.3	6.6
	8	IIB	CL,SiCL	20	31		9.9	9.2	8.5	7.8	7.1	6.4	5.7
	20	IIB/IIC	L,CL	8	26		7.9	6.4	4.9	3.4	1.0	1.0	1.0
	COMPOSITE:						8.2	7.0	5.8	4.6	3.4	3.2	2.9

NOTE: 1 ksi = 6890 kPa

is adjusted before a composite estimate of the subgrade modulus is calculated. The composite E_{Ri} estimate is calculated as a weighted average of the horizons by using horizon thickness as the weighting factor (*9*).

Comparison of Deflection-Based and Soil-Property-Based Subgrade Modulus Estimates

Table 3 shows subgrade modulus estimates for soils at moisture conditions ranging from optimum to 6 percent wet of optimum. The natural, in situ moisture condition of subgrade soils is not likely to be constant but a function of soil properties such as plasticity and grain size. Arbitrarily assigning a moisture condition to all subgrade soils (i.e., OPT + 3) may lead to errors in the soil-property-based modulus estimate. The question becomes, At what moisture condition should the pavement designer consider subgrade soils for design purposes? A comparison of soil-property-based subgrade modulus estimates and deflection-based estimates sheds some light on this question.

Figure 2 shows soil-property-based E_{Ri} estimates for a number of OPT + n moisture conditions and deflection-based E_{Ri} estimates for Champaign County soils. An estimate of the OPT + n condition or conditions required for soil-property-based modulus estimates to accurately reflect deflection-based estimates can be obtained from Figure 2. Soil series 56 Dana requires approximately OPT + 2 conditions. Soil series 146 Elliott is well represented by OPT + 4 moisture conditions, whereas soil series 152 Drummer requires approximately OPT + 7 conditions. A moisture condition of approximately OPT + 4 is required for soil series 154 Flanagan. Soil series 232 Ashkum is best represented by about OPT + 7 conditions, and soil series 481 Raub requires about OPT + 3 conditions.

The moisture condition required for deflection-based and soil-property-based subgrade modulus estimates to agree can be expressed in terms of a degree of saturation for the soil series. To do this, the optimum moisture content (w_{opt}) and maximum dry density (γ_d) of the soil are required. The Illinois Department of Transportation has developed equations for estimating w_{opt} and γ_d from soil index properties (*14*). The Illinois Department of Transportation equations, shown in Equation 8 (w_{opt}) and Equation 9 (γ_d), are based on data obtained for Illinois subgrade soils.

$$w_{opt} = 0.499\,LL - 0.354\text{PI} + 0.044P200 + 1.86 \quad (R^2 = 0.928) \qquad (8)$$

$$\gamma_d = -1.10LL + 0.769\text{PI} - 0.062P200 + 138.96 \quad (R^2 = 0.921) \qquad (9)$$

where

w_{opt} = optimum moisture content, (percent),
γ_d = maximum dry density [pcf (1 pcf = 159 N/m^3)],
LL = liquid limit (percent),
PI = plasticity index (percent),
$P200$ = percent passing a No. 200 sieve, and
R^2 = coefficient of determination.

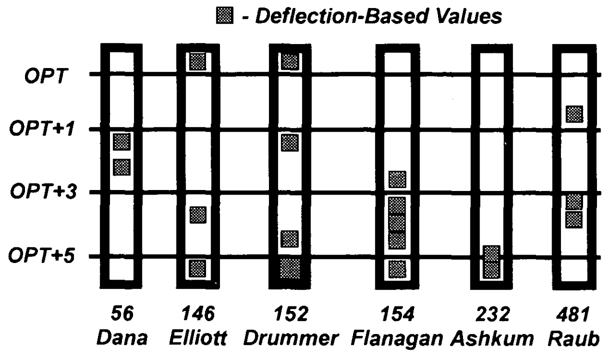

FIGURE 2 Soil-property-based and deflection-based subgrade modulus estimates for Champaign County soil series.

By using estimates of the optimum moisture content and maximum dry density obtained with Equations 8 and 9, the degree of saturation required for soil-property-based E_{Ri} estimates to reflect deflection-based estimates is determined. The required degree of saturation is related to the USDA natural drainage class of the soil. Table 4 shows the Champaign County soil series and the requirements for soil-property-based and deflection-based modulus estimates to relate, expressed in terms of moisture condition (OPT + n) and degree of saturation, and the soil's natural drainage class. By using Table 4, it is possible to identify the following relationships: poorly drained soils (152 Drummer and 232 Ashkum) are nearly 100 percent saturated, somewhat poorly drained soils (146 Elliott, 154 Flanagan, and 481 Raub) are nearly 90 percent saturated, and moderately well drained soils (56 Dana) are nearly 80 percent saturated. Note that the degree of saturation required to relate E_{Ri} estimates increases as the natural drainage of the soil gets poorer. This trend is not surprising; for a given position of the water table, amount of precipitation, and so on, soils with poorer natural drainage characteristics will show higher degrees of saturation.

Another method of developing design soil-property-based modulus values uses the difference between the predicted E_{Ri}(OPT) value and the deflection-based value for a particular soil series. This difference, when divided by the moisture adjustment factor (Table 1) appropriate for the soil, is expressed as the required moisture adjustment for the soil (literally, the n in the OPT + n required for E_{Ri} estimates to relate). The required moisture adjustment for a particular soil series is related to the soil's optimum moisture content. The moisture adjustment ratio (MAR) is the ratio of the required moisture adjustment to the optimum moisture content of the soil.

Table 5 shows the required moisture adjustment and MAR for each Champaign County soil series used in this study. An average MAR of 0.29 is calculated for Champaign County soils. The average MAR is used to determine design soil-property-based E_{Ri} values for the soil series shown. The MAR is multiplied by the optimum moisture content to determine design moisture conditions (the n in OPT + n). The design value of E_{Ri} either can be determined from a table such as Table 3 or can be calculated directly by using the appropriate moisture adjustment factor (Table 1). Table 5 shows design E_{Ri} values determined by both methods.

MAR values calculated for Champaign County soil series exhibit relatively large variabilities (coefficient of variation equal to about 45 percent), most likely because of the relative lack of uniformity of soil parent material across the county. Soil series mapped in regions with more uniform parent materials may show less variable MAR values.

Validation of Relationships

Validation Methodology

Four sets of soils data and corresponding FWD test data are used to validate relationships between soil-property-based and deflection-based estimates of subgrade modulus developed with Champaign County data. The validation data represent soils located in Sangamon, Livingston, Mercer, and Marion counties in Illinois. The analyses conducted for each set of data involve five basic steps, as follows.

1. E_{Ri} is back-calculated from FWD deflection data by using the appropriate ILLI-PAVE-based algorithm (Equations 3 through 6).
2. E_{Ri}(OPT) is estimated for each soil horizon by using soil index properties obtained from the appropriate county soil survey and Equations 1 and 2.
3. The E_{Ri}(OPT) estimate is adjusted for moisture contents above optimum (OPT + n) by using the appropriate moisture adjustment factor from Table 1.
4. A composite E_{Ri} estimate is developed for each moisture condition to account for soil horizonation by using the relative horizon thickness for all horizons.

TABLE 4 Relationship Between USDA Drainage Class and Degree of Saturation for Champaign County Soils

Soil Series	USDA Natural Drainage Class	Design Moisture Condition (OPT+n)	Req'd Deg. of Saturation (%)	Design Deg. of Saturation (%)	Design Eri (ksi)
56 Dana	Mod. Well	1.9	79	80	4.2
146 Elliott	SW Poor	3.7	93	90	6.9
152 Drummer	Poor	5.8	107	100	4.4
154 Flanagan	SW Poor	3.9	88	90	3.6
232 Ashkum	Poor	6.5	102	100	5.9
481 Raub	SW Poor	4.0	86	90	2.4

NOTE: 1 ksi = 6890 kPa

TABLE 5 Moisture Adjustment Ratios for Champaign County Soils

Soil Series	Moisture Adjustment Factor (Table 1)	Required Moisture Adjustment	Optimum Moisture Content (%)	Moisture Adjustment Ratio MAR	Design Moisture Condition* OPT+ :	Design Eri** (ksi)	Design Eri*** (ksi)
56 Dana	1.9	1.68	13.6	0.12	3.94	1.6	0.2
146 Elliott	0.7	4.29	17.6	0.24	5.10	6.0	5.9
152 Drummer	0.7	7.14	13.6	0.53	3.94	5.6	5.6
154 Flanagan	1.4	3.57	14.6	0.24	4.23	1.7	3.1
232 Ashkum	0.7	7.00	18.9	0.37	5.48	6.9	6.6
481 Raub	1.4	3.21	12.8	0.25	3.71	1.5	2.8

NOTES: * *Determined using Champaign County average MAR = 0.29*
** *Determined from Table 5*
*** *Calculated Value*

1 ksi = 6890 kPa

5. Design soil property-based E_{Ri} values are estimated by using the relationship between soil drainage class and degree of saturation and MAR concepts developed for Champaign County soils.

Evaluation of Validation Results

Comparisons of soil-property-based E_{Ri} values and deflection-based modulus estimates produce mixed results. In many cases soil-property-based estimates compare favorably with deflection-based estimates. However, for some soil series the E_{Ri} values estimated by using soil properties overestimate or underestimate the subgrade modulus compared with those obtained by using deflection-based estimates.

MAR-Based Design E_{Ri} Figure 3 shows a comparison of deflection-based E_{Ri} values and soil-property-based E_{Ri} values calculated by using the Champaign County average MAR (0.29). Ideally, points would group around the 1:1 line, indicating good agreement between different estimates of the subgrade modulus. Most of the points shown in Figure 3 fall below the 1:1 line, indicating that values of E_{Ri} calculated with the Champaign County average MAR underestimate the subgrade modulus compared with those calculated with deflection-based estimates. A best-fit line developed by linear regression is shown on Figure 3. This line reflects a rather poor fit (r^2 = 0.06; correlation coefficient, 0.25) to the data. Although some soils are adequately represented in Figure 3, it is apparent that use of the MAR relationship developed for one area (e.g., Champaign County) to estimate the E_{Ri} for soils in other areas may not give accurate, consistent results.

The overall average and standard deviation MAR determined with information from all soils investigated are 0.24 and 0.12, respectively (coefficient of variation = 50 percent). The large variability in MAR values, as indicated by the relatively high coefficient of variation, suggests that a single value of MAR cannot adequately represent all subgrade soils. Linear regression performed on soil-property-based E_{Ri} values calculated by using the overall MAR average and corresponding deflection-based values shows a better fit to the data (r^2 = 0.11; correlation coefficient, 0.33), but many soils continue to be poorly represented.

Soil-property-based E_{Ri} values calculated with a single MAR value may adequately estimate the subgrade modulus for some soil series, whereas they may significantly overestimate or underestimate the modulus for other soil series. It is apparent from the analyses that the most promising method of using MAR concepts is to establish individual MAR relationships for regions (e.g., counties) containing relatively uniform soils. Figure 4 is a plot similar to that shown in Figure 3, with soil property-based E_{Ri}

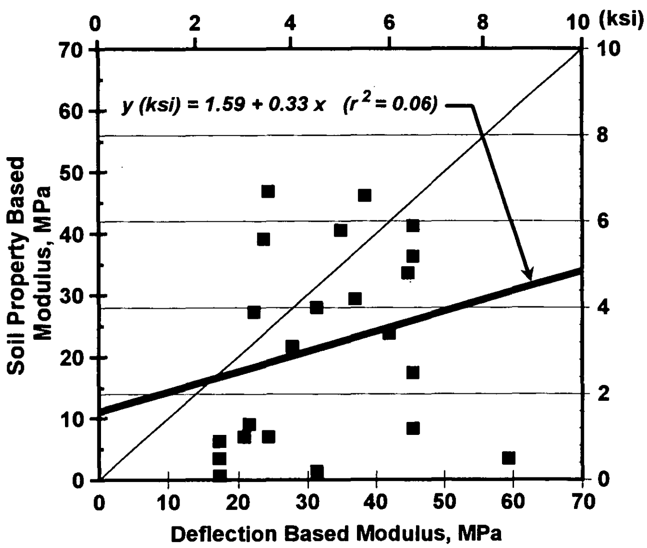

FIGURE 3 Comparison of design soil-property-based and deflection-based subgrade modulus using Champaign County average MAR.

values calculated by using the specific "county MAR average" for the county (or testing site) in which the soil is encountered. The plot shown in Figure 4 is the best relationship between MAR-based E_{Ri} values and deflection-based values. The linear regression fit is characterized by an r^2 value of 0.31 and a correlation coefficient of 0.56.

Natural Drainage Class–Degree of Saturation Based E_{Ri} There is a relationship between the natural drainage class of the soil and the in situ moisture conditions required for soil-property-based E_{Ri} estimates to match FWD deflection-based estimates. In general, less-well-drained soils relate to higher moisture conditions. The natural drainage–moisture condition relationships developed by using information on Champaign County soils may or may not apply to many of the soils from other Illinois counties. Figure 5 shows soil-property-based E_{Ri} values determined by using the Champaign County drainage class–degree of saturation relationship plotted against corresponding FWD deflection-based E_{Ri} estimates. Many of the points group closely to the 1:1 line, but there are a number of outlying points. A line fit to the data by linear regression (r^2 = 0.008; correlation coefficient, 0.091) suggests that adjusting soil-property-based modulus estimates by using degree of saturation relationships yields results similar to those obtained by using the overall average MAR adjustment.

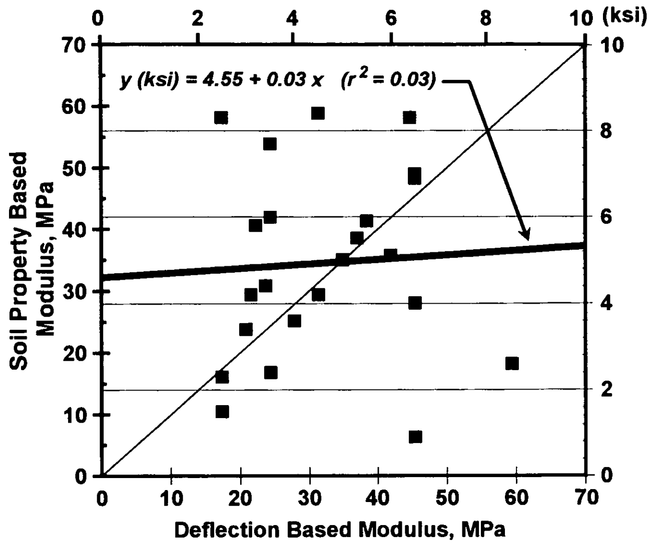

FIGURE 5 Comparison of design soil-property-based and deflection-based subgrade modulus using relationship between natural drainage class and degree of saturation.

SUMMARY

Two methods were developed to relate soil-property-based E_{Ri} estimates and FWD deflection-based E_{Ri} estimates. The methods include the use of an MAR, which is a function of the optimum moisture content of the soil, and a relationship between the soil's natural drainage class and the required degree of saturation.

Figures 3 through 5 illustrate the relationship between soil-property-based and target FWD deflection-based values of E_{Ri}. The points shown in the figures represent the 23 major pedologic soil series encountered during FWD testing in Champaign, Sangamon, Livingston, Mercer, and Marion counties in Illinois. Analyses of the data indicate that the best method of using the MAR is to determine the average MAR for the specific county in which FWD testing is performed.

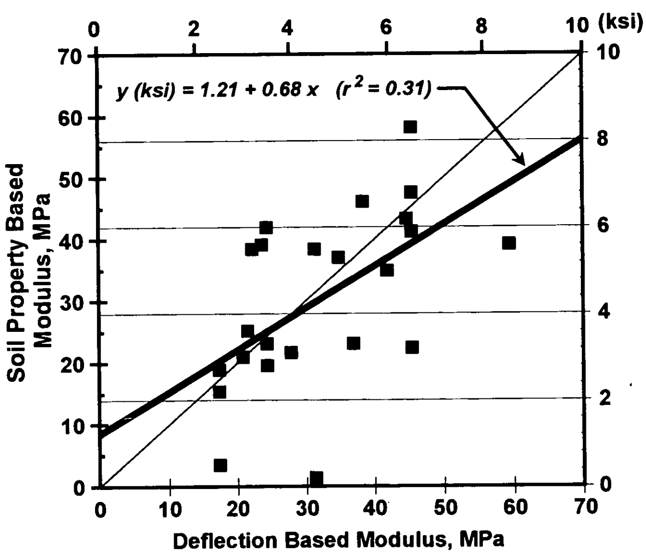

FIGURE 4 Comparison of design soil-property-based and deflection-based subgrade modulus using individual county average MAR.

The average difference between soil-property-based and deflection-based E_{Ri} estimates for the points shown in Figures 3 through 5 are as follows: Figure 3, 15.2 MPa (2.2 ksi); Figure 4, 9.7 MPa (1.4 ksi); and Figure 5, 13.1 MPa (1.9 ksi). A difference in E_{Ri} of 10.3 to 13.8 MPa (1.5 to 2.0 ksi) may represent only 1 percent moisture in subgrade soils on the basis of the moisture adjustment factors shown in Table 1. In addition sensitivity analyses performed on current flexible pavement design procedures indicate for most cases that a variation in E_{Ri} of 6.9 to 13.8 MPa (1 to 2 ksi) is not significant in pavement design (*9*). The coefficients of variation for average differences in soil-property- and deflection-based E_{Ri} values for Figures 3 to 5 range from about 80 percent to about 100 percent, indicating a wide range of differences. However, it should be noted that in situ subgrade modulus values within a given project will vary; in the present study the coefficient of variation of deflection-based modulus estimates for a particular soil series ranged from about 10 percent to as high as about 80 percent, with a typical range of values being 30 to 50 percent (*9*). In many cases the principles developed in the research for determining design E_{Ri} values on the basis of soil index properties give reasonable estimates of the subgrade modulus.

There are difficulties in comparing values of subgrade modulus that are estimated by dissimilar procedures. In the present study the differences between soil-property-based and deflection-based modulus estimates are analyzed solely on the basis of moisture content and the moisture adjustment factors shown in Table 1. It is apparent that factors other than moisture content should be considered to totally explain the observed differences in the modulus estimate. One example of other considerations concerns the fact that soil properties are listed in the county soil survey as ranges of values. The present analysis used midrange values for soil properties. The variation in soil properties within a particular soil series explains some of the differences in modulus estimates.

Another consideration in analyses such as those described in this paper concerns the time of year in which deflection testing is performed to estimate in situ subgrade modulus. The FWD testing for the present study was performed in March, which could be considered the worst time of year with respect to subgrade moisture in central Illinois. Whether an agency decides to use extreme subgrade conditions to develop a conservative design or average conditions with an applied reliability factor, care must be taken to ensure that the actual subgrade conditions are representative of the target conditions. The time of year of FWD testing will have an impact on the relationship between deflection-based modulus estimates and soil-property-based estimates.

The analyses described in this paper suggest that the relationship between soil-property-based E_{Ri} and deflection-based E_{Ri} depends somewhat on the predominant soil series of an area. The most reliable and consistent method of characterizing the resilient properties of soil series in a particular area requires deflection testing in the area to correlate with soil-property-based subgrade modulus estimates. The use of generic or blanket relationships between soil-property-based and deflection-based E_{Ri} estimates may lead to less accurate modulus estimates for local soils. The methodologies presented here are easily adapted by pavement agencies to local conditions, potentially providing a valuable alternative to doing nothing with regard to subgrade evaluation for pavement design.

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