Factors Influencing Determination of a Subgrade Resilient Modulus Value

JAMES M. BURCZYK, KHALED KSAIBATI, RICHARD ANDERSON-SPRECHER, AND MICHAEL J. FARRAR

Factors influencing the determination of a subgrade resilient modulus value were evaluated. Nine test sites with cohesive subgrade soils were selected in the state of Wyoming, and laboratory testing was conducted on subgrade cores obtained in 1992 and 1993. Several fundamental soil properties of these cores were determined and deflection data from these nine sites were used to determine resilient modulus values with three back calculation programs. The data analysis resulted in several important conclusions about factors that influence the selection of a design subgrade resilient modulus value.

The 1993 *AASHTO Guide for Design of Pavement Structures* requires selecting a value for the design subgrade resilient modulus (M_R). Resilient modulus is a "measure of the elastic property of soil recognizing certain nonlinear characteristics" (*1*). Numerically, it is the ratio of the deviator stress to the resilient or recoverable strain ($M_R = \sigma_d/\epsilon_r$). This value may be based on laboratory testing, back-calculation programs using deflection measurements, resilient modulus correlation studies, or original design and construction data (*2*). In many cases, agencies lack the capital required for the laboratory equipment, or their pavement engineers are unfamiliar with this new subgrade soil property (*3*). As a result, equations have been developed to convert values from soil tests, such as California bearing ratio (CBR) and R-value, to resilient modulus values. Even though this method of obtaining M_R values is acceptable, AASHTO recommends that "user agencies acquire the necessary equipment to measure M_R" (*1*).

Several factors must be taken into consideration when selecting a design M_R value. According to Darter et al. (*2*), "Regardless of the method used, the design subgrade M_R value must be consistent with the value used in the design performance equation for the AASHO Road Test subgrade." The 1986 guide uses a value of 20 684 kPa (3000 psi), but does not justify its selection. Elliott, however, presented the findings of several researchers on the reason this value was chosen to represent the AASHO Road Test subgrade (*3*). Based on a study by Thompson and Robnett (*4*), this value is appropriate when the AASHO soil is about 1 percent wetter than optimum and is subjected to a deviator stress of about 41.4 kPa (6 psi) or more. Besides the usefulness of this observation in selecting a design M_R value from laboratory testing, it also plays an important role in determining a value from back-calculation programs using deflection data. To make these nondestructive testing (NDT) values consistent with the 20 684-kPa (3000-psi) value, the calculated M_R value is multiplied by a correction factor (C) less than or equal to 0.33 for cohesive soils (*3*). The need for a correction factor resulted from the fact that most NDT programs assume that the measured deflection, at a certain distance away from the loading plate, is attributable solely to the subgrade. In many cases, the amount of stress at this point is less than 41.4 kPa (6 psi), giving a higher resilient modulus value. Reducing the back-calculated resilient modulus value satisfies the underlying assumption in the overlay equation.

Because the intent of laboratory testing is to simulate conditions in the field, other factors, such as water content, soil type, and sample condition, must also be considered. First, water content is important because of its effect on M_R values obtained either above or below the optimum value. In 1989 Elfino and Davidson (*5*) reported variations in the resilient modulus value of 7 to 41 percent from soils at different water contents. Second, whether the sample is undisturbed or disturbed will influence the M_R. Third, soil type may influence the M_R because of the differences in quality and soil strength.

The University of Wyoming and the Wyoming Department of Transportation (DOT) conducted a joint research project, first to investigate the importance of several fundamental soil properties in determining a design subgrade resilient modulus value, and second to define the actual relationship between back-calculated and laboratory-based M_R values for typical subgrade soils in Wyoming. The main findings of this study are presented here.

EXPERIMENT DESIGN

Figure 1 shows the data collection process and overall evaluation strategies followed in this research. Initially, a large number of pavement test sections were selected in the state of Wyoming. During the summer of 1992 and spring of 1993, different types of field data were collected on all sections. This field evaluation included pavement and subgrade coring, deflection measurements, and condition surveys. Several laboratory tests were later conducted on the soil cores to determine the types of subgrade at each site. As a result of this laboratory testing, all sections with granular subgrade material were dropped from the study. More laboratory tests, including resilient modulus, were later conducted only on the sites that had cohesive subgrades. Table 1 shows the locations and thicknesses of the sections included in this experiment. In addition to the laboratory analysis, the deflection data collected in 1992 and 1993 were used to determine M_R values with the following three back-calculation programs: MODULUS (*6*), EVERCALC (*7*), and BOUSDEF (*8*). All data were summarized in a computerized data base. Statistical analyses were then performed to determine how fundamental soil properties, linear variable differential transducer (LVDT) placement during M_R testing, and sample condition influence the resilient modulus value. Further analyses were completed to examine the relationship between laboratory and back-calculated M_R values.

J.M. Burczyk, K. Ksaibati, and R. Anderson-Sprecher, University of Wyoming, Laramie, Wyo. 82071. M.J. Farrar, Wyoming Department of Transportation, P.O. Box 1708, Cheyenne, Wyo. 82002–9019.

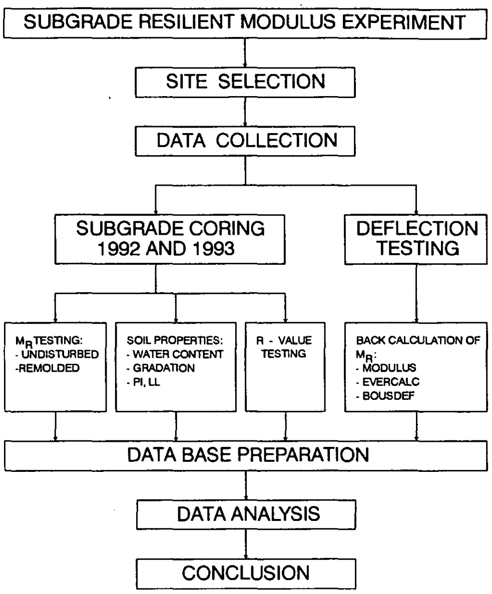

FIGURE 1 Data collection and analysis strategies.

DATA COLLECTION AND LABORATORY TESTING

Field Data Collection

Extensive field data were collected on all test sections included in this study. Pavement deflection measurements were obtained by using standard loads on the Wyoming DOT Kuab 2-m falling weight deflectometer. Then, three pavement cores were obtained from each section to examine the characteristics of the asphalt layers and to verify the thicknesses. This information was used later in determining the back-calculated resilient modulus values. Next, pavement condition surveys were completed to record each section's surface condition. Finally, three Shelby tubes were taken from the subgrade at each test section. The soil samples were used to conduct resilient modulus testing, obtain R-values, and perform other tests for certain fundamental soil properties.

Resilient Modulus Testing

Laboratory M_R values are normally obtained with repeated-load triaxial testing. The Interim Method of Test for *Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils—SHRP Protocol P46* (AASHTO: T 294–92 I) outlines the latest testing procedure. This specification separates subgrade material into two different categories: Type I (granular) and Type II (cohesive). Each type of soil has a different conditioning cycle and 15 loading sequences varying in confining and deviator stresses. Overall, Type I soils undergo higher stresses, both confining and deviator, because of their higher resistance to deformation. The amount of deformation in the soil sample is recorded using two LVDTs outside of the testing chamber. However, the original AASHTO T-274 specifications required two LVDTs within the test chamber. These LVDTs are placed at a specified gauge length depending on the size of the soil sample. Figure 2 shows the two different LVDT locations used in this study. The M_R value is then calculated by using the averaged deviator load and deformation from the last five cycles of each testing condition.

In this project, deformation readings were recorded at two different locations during the laboratory testing: from two LVDTs

TABLE 1 Locations and Thicknesses of Test Sections

Roadway	Milepost		Pavement Thicknesses	
	From	To	Surface (inches)	Base (inches)
US-30	67.063	76.819	5.5	6.0
US-30	45.984	48.786	12.0	12.0
US-287	411.890	419.270	6.0	6.0
US-26	105.642	109.677	5.0	6.0
US-20/26	10.360	21.237	5.0	8.0
US-20	162.120	164.094	3.0	2.5[1]
US-16	226.300	233.700	6.0	8.0[1]
US-16	241.990	246.590	2.3	3.5[1]
US-85	195.760	202.690	6.0	8.0[2]

[1] Asphalt Treated Base (ATB)

[2] Cement Treated Base (CTB)

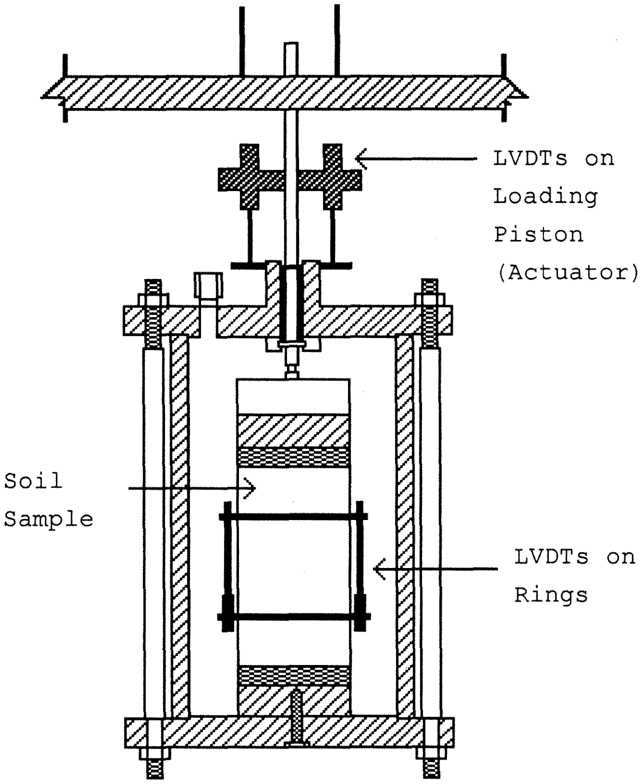

FIGURE 2 Location of LVDTs on testing equipment.

located outside the triaxial cell on the loading piston (referred to as the actuator in this paper) and from three LVDTs located on the rings inside the testing chamber. Even though some testing programs automatically average these signals during testing, readings were averaged after completion of testing. This procedure was useful in eliminating inconsistent readings. Three segments of subgrade soil from each Shelby tube were extracted for testing. All subgrade cores were tested in undisturbed and disturbed conditions, and each sample was 15.2 cm (6 in.) in length and 7.1 cm (2.8 in.) in diameter.

After laboratory testing was completed, deformation and applied load readings from the last five cycles of each loading condition were retrieved from the data files. Several spreadsheets were developed to accept these data as well as the length and diameter of each sample. After this information was entered the resilient modulus values were calculated automatically for each testing condition and test section.

Other Laboratory Tests

After completing the resilient modulus testing, each soil sample was tested to determine its R-value, liquid limit (LL), plasticity index, soil classification, group index, and water content. Table 2 shows some typical values observed in this study. The following equation, occasionally used by the Wyoming DOT, was used in estimating the optimum water content of each sample:

$$\omega = 0.477\,(LL) + 2 \qquad (1)$$

where ω is the optimum water content (percent) and LL is the liquid limit.

All laboratory tests were conducted in accordance with their respective ASTM and AASHTO specification.

Back Calculations of Resilient Modulus

Deflection data collected from the nine test sites were used to obtain M_R values with three back-calculation computer programs: MODULUS, EVERCALC, and BOUSDEF. These programs compare the deflection basins based on field data to theoretical basins in order to determine back-calculated M_R values. However each program computes these moduli using different methodologies and assumptions. The first program, MODULUS, was developed at Texas A&M University. MODULUS determines M_R values based on a layered elastic code called WES5. This code creates a large data base of theoretical deflection basins and matches, through interpolation, the best basin to the field data. The second program, EVERCALC, was developed at the University of Washington. In this program theoretical deflections are based on CHEVRON as the layered elastic solution. The third program, BOUSDEF, was developed at Oregon State University. This program uses the method of equivalent thicknesses, assuming one thick, uniform layer of material, and the Boussinesq theory to determine theoretical basins. Overall, by matching the deflection basin measured in the field, the M_R value is calculated for each section's layers (surface, base, and subgrade) (*9*).

DATA ANALYSIS

Data were gathered during two different periods, Period A (summer 1992) and Period B (spring 1993), at nine different sites. Five of these sites were common to both time periods; one was specific to Period A; and three were specific to Period B. Aside from designations of the sampling variables (period, site, tube, and layer), the measured variables included the resilient modulus (measured in various manners), R-value, and certain soil characteristics (soil classification, group index, actual and optimum water contents, and plasticity index). The inclusion of different sites made for some inconstancy in soil types between periods. The analyses below account for these differences as necessary. All analyses were based on $\log_{10}(M_R)$, abbreviated as LMR, instead of M_R itself.

Relationship Between Resilient Modulus and R-Values

Accurate values of LMR are expected to correlate fairly well with R-values. Because of this assumption correlations were obtained for measured R-values and the four measurements of LMR for Periods A and B. Table 3 shows the observed correlations. Within rows of this table correlations are comparable because they are based on the same soil samples. However differences in base soils between Periods A and B may distort comparisons between these rows. The most important aspect of Table 3 is that the disturbed soils' LMRs are not significantly correlated with the R-value, but undisturbed soils' LMRs are correlated with the R-value. Correlations between undisturbed and disturbed LMRs (not shown) were modest to nonexistent. Therefore samples should be retained intact if the resilient modulus is to be a meaningful measure for pavement design.

TABLE 2 Typical Soil Characteristics, Spring 1993

Water Content (%)	Optimum Water Content (%)	Soil Classification	Plasticity Index (PI)
14.2	13.9	A-4(1)	10
15.9	18.7	A-6(13)	22
11.9	14.4	A-6(1)	13
10.8	14.9	A-4(0)	7
11.5	14.4	A-4(0)	6
13.2	14.4	A-4(0)	8
13.9	14.4	A-4(0)	5
12.8	14.4	A-4(0)	7
15.5	17.7	A-6(9)	18
15.8	13.0	A-4(3)	9
16.8	15.4	A-6(6)	14
15.4	20.1	A-6(13)	23
19.7	25.9	A-7-6(26)	26
20.1	28.2	A-7-6(30)	28
18.7	26.3	A-7-6(29)	29
20.7	22.0	A-7-6(16)	16
20.6	23.5	A-7-6(23)	22
20.8	22.5	A-7-6(15)	15
15.9	17.7	A-6(7)	17
23.7	19.6	A-6(7)	13
20.7	24.4	A-7-6(21)	23
25.3	19.6	A-6(3)	11
21.1	17.3	A-7-6(26)	28
20.9	24.4	A-7-6(23)	26
19.8	26.3	A-7-6(27)	29
11.3	21.1	A-6(16)	23
17.4	22.5	A-7-6(20)	25
12.8	21.6	A-7-6(17)	23
15.5	22.0	A-7-6(17)	23
19.3	21.1	A-6(16)	22
16.2	22.0	A-7-6(16)	22
15.2	23.5	A-7-6(21)	25
13.8	14.9	A-4(5)	9
17.4	25.9	A-7-6(25)	31
12.7	15.4	A-4(4)	7

TABLE 3 Correlations Between LMR[1] and R-Value

	Undisturbed		Disturbed		Sample Size
	Ring	Actuator	Ring	Actuator	
Period A[2]	0.630	0.749	-0.041	-0.089	16
Period B[3]	0.334	0.437	-0.219	-0.273	23
Pooled[4]	0.380	0.509	-0.136	-0.142	39

[1] Log$_{10}$ (Resilient Modulus Values)

[2] Summer 1992

[3] Spring 1993

[4] Pooled (1992 & 1993)

Only undisturbed LMRs were used in the remaining analyses unless noted otherwise.

Effect of Sensor Location on M_R Measurements

The correlations shown in Table 3 also suggest that the placement of LVDTs outside the testing chamber may be more suitable than placement on the ring. Observed differences in the correlations with R-value are not, however, extreme, and placements were also compared on the basis of measurement precision. To ensure that all variability measured was attributable to differences in measurement methods, values were adjusted for site, period, and sample tube. The test for differences in variances for paired data (*10*) showed the ring variance to be greater than the actuator variance ($t = 2.238$, $df = 20$, $p = 0.0368$): The greater variation in ring measurements is a result of the difficulty in obtaining good contact between the LVDTs on the ring and the soil sample. Analyses are henceforth made using actuator measurements only.

Although measurements at the actuators appear to be preferable, the relationship between actuator and ring measures is of interest. Actuator and ring measurements of LMR are highly correlated, as shown in Table 4. A *t*-test of paired differences indicates that ring measures are consistently higher than actuator measures. Repeated measures analysis indicates that differences between ring and actuator measurements are similar for undisturbed samples ($p = 0.206$), and the pooled analysis is consequently considered acceptable.

Effect of Sample Location on M_R Values

An issue relevant to M_R measurement is the selection of samples from tubes. If layers systematically differ from each other, with surface layers having consistently higher or lower values than deeper layers, one would expect that surface-layer measures would differ in quality from lower-layer measures. Available data do not yield evidence of such differences (repeated measures analysis $F_{2,13} = 1.27$, $p = 0.3126$). Assuming that layers are in fact similar to each other, averaging LMR values will give more reliable results than will readings from any single layer. It may still be that M_R values at one level of the soil are particularly important for highway considerations, but it is not possible with available data to select one layer over another without additional reference criteria.

Relationships Between Back-Calculated and Laboratory M_R Values

M_R values can be obtained indirectly, via back calculations from nondestructive testing instead of laboratory tests. As mentioned earlier, the following three back-calculation programs were used in this research: MODULUS (MP), EVERCALC (EP), and BOUSDEF (BP). To consider the quality of these three programs, logs of back-calculated values (designated as LMR-MP, LMR-EP, and LMR-BP, respectively) were compared with laboratory LMR values. The site-by-period mean LMR from undisturbed samples measured on the actuator was used as the best available value for the "true" resilient modulus, the one exception being a single site for which only ring measurements were available in Period A. Because means were calculated from different numbers of observations, a weighted analysis was used (weight = sample size). Results are shown in Table 5. Note that the EVERCALC program appears to be slightly superior to the other two back-calculation methods. All back-calculated values match each other better than they do the laboratory measurements.

Assuming constant differences between logs of back-calculated and "true" values, the best estimated differences appear in Table 6, along with implied relationships between laboratory and back-calculated values of M_R. A 95 percent confidence interval for the appropriate correction factor (C) for subgrade soils in Wyoming, based on the EVERCALC program, is (0.20, 0.32) where $M_R = C*$ (back calculated value).

Relationship Between M_R Values and Soil Properties

The final question considered was the relationship between soil characteristics and the resilient modulus. The possible relationship between LMR and four factors, moisture (actual water content − optimum water content), soil classification, group index, and plasticity index were analyzed. Because the group and plasticity indices were highly correlated, only the group index was ultimately considered for describing soil–M_R relationships.

TABLE 4 Relations Between LMRR[1] and LMRA[2]

	Correlation	Mean Diff.	t	df	p-value
Period A[3]	0.858	0.0987	2.94	17	0.009
Period B[4]	0.906	0.1576	5.11	22	<0.0001
Pooled	0.885	0.1317	5.75	40	<0.0001

[1] Log_{10} (Resilient Modulus Value for Ring Measurements)

[2] Log_{10} (Resilient Modulus Value for Actuator Measurements)

[3] Summer of 1992

[4] Spring of 1993

TABLE 5 Back Calculation Correlations (N = 13)

	Weighted Correlations with LMR[1]	Cross-correlations		
		LMR-MP	LMR-EP	LMR-BP
LMR-MP[2]	0.526	1.000	0.744	0.941
LMR-EP[3]	0.735	0.744	1.000	0.799
LMR-BP[4]	0.590	0.941	0.799	1.000

[1] Log_{10} (Resilient Modulus Values)

[2] Log_{10} (Resilient Modulus Values from MODULUS Program)

[3] Log_{10} (Resilient Modulus Values from EVERCALC Program)

[4] Log_{10} (Resilient Modulus Values from BOUSDEF Program)

Moisture and LMR are related, and their relationship depends on soil type. Similar strengths in the relationship between soil factors and responses were found for both undisturbed and remolded samples, and also for R-values (see Table 7). All of the test sections had one or more of the following types of subgrade soil: A-4, A-6, and A-7. For each of these soil classifications correlations were developed to determine the effect of moisture on the measured values. Overall values for undisturbed and remolded M_R values and R-values from A-4 and A-6 soils decreased as water content increased. The A-7 subgrade soils showed little change in the measured values (see Table 8).

CONCLUSIONS AND RECOMMENDATIONS

On the basis of data analysis performed in this project, the following conclusions are drawn:

1. Layers within Shelby tubes do not differ significantly from one another. Averaging the resilient modulus values from all layers will give more reliable results than measuring the value from one layer.
2. Some fundamental soil properties influence the measured M_R value. Resilient modulus values for type A-4 and A-6 subgrade soils decreased as water content increased.

TABLE 6 Back Calculation Relationships (N = 13)

Computer Program	Diff.	Standard Error	95% CI	Relation	Bounds on C (M_R = C * [X])
MODULUS (MP)	0.408	0.073	(0.249, 0.567)	M_R = 0.39MP	(0.27, 0.56)
EVERCALC (EP)	0.599	0.049	(0.492, 0.706)	M_R = 0.25EP	(0.20, 0.32)
BOUSDEF (BP)	0.503	0.059	(0.374, 0.632)	M_R = 0.31BP	(0.23, 0.42)

TABLE 7 Coefficients of Determination for Soil–M_R Relations

Models (linear models with interaction)	Undisturbed samples LMR[1]	Remolded samples LMR[1]	R-value
Moisture and Soil Classification	0.427	0.436	0.478
Moisture and Group Index	0.479	0.286	0.321

[1] Log_{10} (Resilient Modulus Values)

TABLE 8 Parameter Estimates ± Standard Error for Model with Group Index

Soil Classification	Parameter Estimates	Undisturbed Samples LMR^1	Remolded Samples LMR^1	R-value
A-4	Intercept	4.50 ± 0.0740	4.35 ± 0.0893	47.1 ± 1.21
	Slope(Moisture)	-0.102 ± 0.0286	-0.0803 ± 0.0383	-0.845 ± 0.619
A-6	Intercept	4.38 ± 0.0548	4.685 ± 0.0524	37.9 ± 1.96
	Slope(Moisture)	-0.0682 ± 0.0148	-0.0401 ± 0.0162	-2.04 ± 0.570
A-7	Intercept	4.54 ± 0.151	4.73 ± 0.0435	31.0 ± 1.97
	Slope(Moisture)	0.0110 ± 0.0250	-0.00492 ± 0.00699	-0.762 ± 0.316

^{1}Log$_{10}$ (Resilient Modulus Values)

3. M_R measurements made with LVDTs on the ring inside the testing chamber consistently gave higher values than the actuator LVDTs located on the loading piston.
4. The EVERCALC back-calculation program appears to give more accurate M_R values than do the other two computer programs.
5. The recommended correction factor (C) of 0.33 or less appears to be adequate for subgrade soils in Wyoming.

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