FACTORS INFLUENCING THE DETERMINATION OF A SUBGRADE RESILIENT MODULUS VALUE

by

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Disclaimer

Preface

This report describes a study jointly conducted by the University of Wyoming and the Wyoming Department of Transportation to examine the factors influencing the determination of a subgrade resilient modulus (M_R) value. The objectives of this study were to first, 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 cohesive, subgrade soils in Wyoming.

This study consisted of selecting nine test sites with cohesive subgrade soils in the state of Wyoming, conducting laboratory testing on subgrade cores obtained in 1992 and 1993, determining several fundamental soil properties on these cores, and using deflection data from these nine sites to determine resilient modulus values from 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.

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CHAPTER 1

INTRODUCTION

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" (AASHTO, 1993). Numerically, it is the ratio of the deviator stress to the resilient or recoverable strain ($M_R = \sigma_d/\varepsilon_r$). This value may be based either on laboratory testing, back calculation programs using deflection measurements, resilient modulus correlation studies, or original design and construction data (Darter et al., 1992). In many cases, agencies lack the large capital required for the laboratory equipment and/or their pavement engineers are unfamiliar with this new subgrade soil property (Elliott, 1992). 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 (1993) recommends that "user agencies acquire the necessary equipment to measure M_R."

Several factors must be taken into consideration when selecting a design M_R value. According to Darter et al. (1992), "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 1993 guide uses a value of 20,684-kPa (3,000-psi), but does not justify its selection. However, Elliott (1992) presented the findings of several researchers as to why this value was chosen to represent the AASHO Road Test subgrade. Based on a study by Thompson and Robnett (1976), this value is appropriate when the AASHO soil is about 1% wet of optimum and subjected to a deviator stress of about 6 psi or more. Besides using 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. In order to make these non-destructive 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 (Elliott, 1992). The need for a correction factor resulted from the fact that most NDT programs assume 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 6 psi, giving a higher resilient modulus value. By reducing the back calculated resilient modulus value, the underlying assumption in the overlay equation is satisfied.

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 (1989) reported variations in the resilient modulus value of 10-60% due to differences in moisture conditions. 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.

OBJECTIVES

The University of Wyoming and the Wyoming Department of Transportation conducted this joint research project to first, 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 cohesive, subgrade soils in Wyoming. This interim report presents the preliminary findings of this study.

CHAPTER 2

DESIGN OF EXPERIMENT

Figure 2.1 shows the data collection process and overall evaluation strategies followed in this research. Initially, twenty-eight pavement test sections were selected in the state of Wyoming. During the summer of 1992 (Period A) and spring of 1993 (Period B), 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 and because the recommended correction factor (C) of 0.33 or less is for cohesive soils, all sections with granular subgrade material were dropped from the study. More laboratory tests, including resilient modulus, were later conducted only on the remaining sites with cohesive subgrades. Table 2.1 shows the locations and thicknesses of the reduced number of 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 from the following three back calculation programs: MODULUS (Uzan et al., 1988), EVERCALC (Lee, 1988), and BOUSDEF (Haiping et al., 1990). All the above 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.

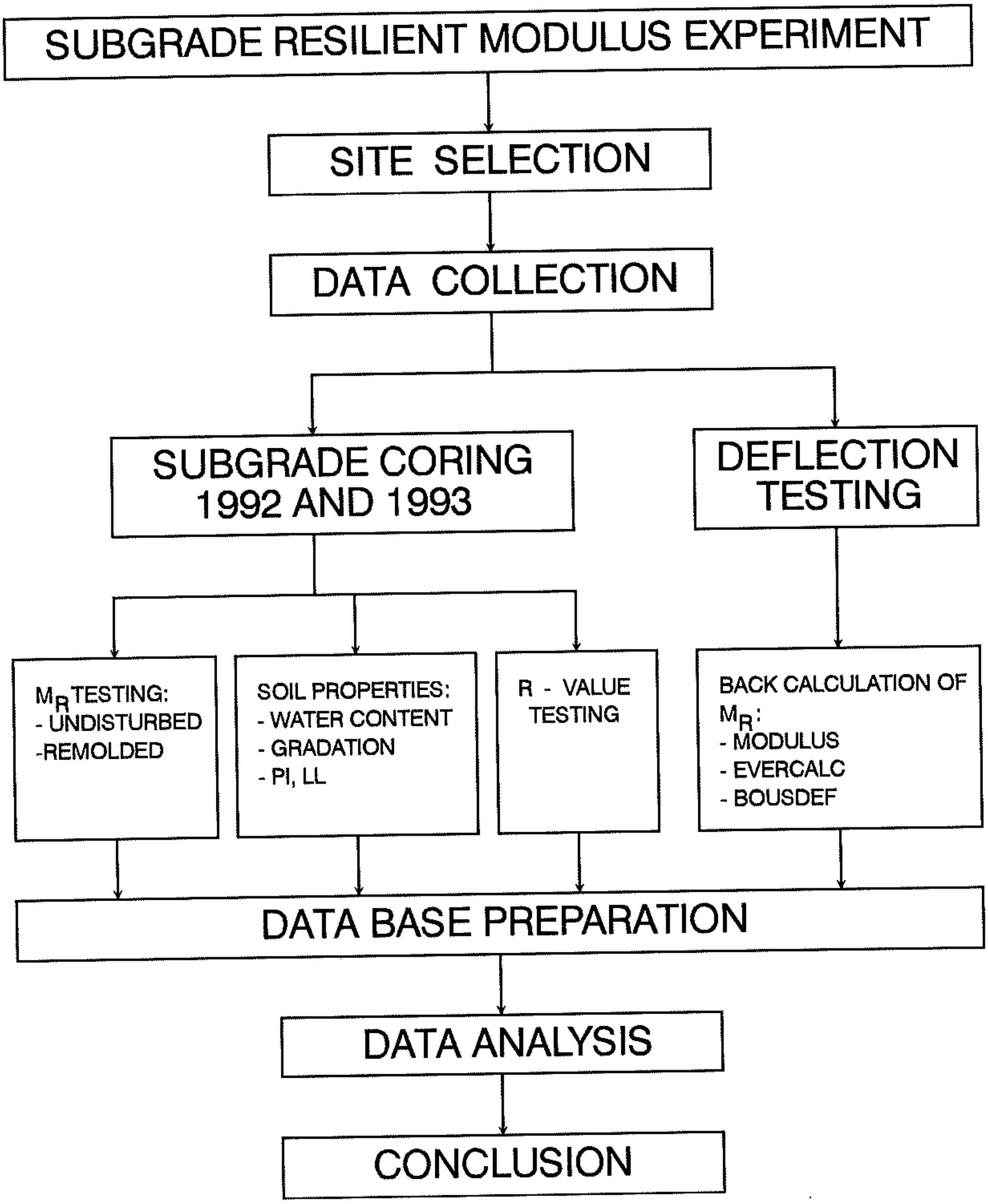

Figure 2.1. Data Collection and Analysis Strategies

Table 2.1. Locations and Thicknesses of Test Sections

Roadway	Milepost		Pavement Thicknesses	
	From	To	Surface	Base
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	6.0"	0.0"
US-16	226.300	233.700	14.0"	0.0"
US-16	241.990	246.590	6.0"	4.0"
US-85	195.760	202.690	14.0"	0.0"

CHAPTER 3

DATA COLLECTION AND LABORATORY ANALYSIS

Field Data From Design of Experiment

Extensive field data were collected on all test sections included in this research study. First, pavement deflection measurements were obtained by using standard loads on the Wyoming DOT Kuab 2m-Falling Weight Deflectometer (FWD). Second, three pavement cores were obtained from each section to examine the characteristics of the asphalt layers and to verify layer thickness. This information was used later in determining the back calculated resilient modulus values. Third, 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 Iterim 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 fifteen 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 linear variable differential transducers (LVDT's) outside of the testing chamber. However, the original AASHTO T-274 specifications required 2 LVDT's within the test chamber. These LVDT's are placed at a specified gage length depending on the size of the soil sample. 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 research project, deformation readings were recorded at two different locations during the laboratory testing. First, from 2 LVDT's located outside of the triaxial cell on the loading piston (referred to as the actuator in this paper) outside of the testing chamber, and second, from 3 LVDT's located on the rings inside of the testing chamber. Even though some testing programs automatically average these signals during testing, readings were averaged after completing 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 tested were 15.2-cm (6-inches) in length and 7.1-cm (2.8-inches) in diameter.

Subgrade cores obtained from the summer of 1992 were tested in undisturbed (thawed) and remolded (disturbed) conditions. Due to the fact that the soils were left in the Shelby tubes for months prior to testing, normal extraction could not be performed without disturbing the samples. The solution to this problem was to freeze the tubes, extract the soil samples, and let the cores thaw for twenty-four hours prior to testing. Overall, this procedure was successful and allowed soil samples to be removed from the tubes without disturbance. Resilient modulus testing was performed on some of the frozen soil samples, but reasonable M_R values were difficult to obtain because of the low stresses applied to the samples and the high stiffness of the frozen cores. As a result, the frozen condition was later dropped from the analysis.

Subgrade cores from the spring of 1993 were tested for resilient modulus shortly after obtaining them from the field. Again, two conditions were tested, undisturbed and remolded (disturbed). Unlike the first set of subgrade cores, these soils were easily removed from the Shelby tubes. LVDT measurements during M_R testing were also taken outside and inside the testing chamber.

After the laboratory testing was completed, deformation and applied load readings from the last five cycles of loading condition were retrieved from the data files created during laboratory testing. Several spreadsheets were developed to accept these data as well as the length and diameter of each sample. By entering this information, 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 (PI), soil classification, group index (GI), and water content. Equation 3.1, occasionally used by the Wyoming DOT, was used in estimating the optimum water content of each sample:

$$\omega = 0.477(LL) + 2 \tag{3.1}$$

Where: ω = optimum water content (%),

LL = liquid limit.

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

Back Calculations of Resilient Modulus

Deflection data collected from the nine test sites were used to obtain M_R values from three back calculation computer programs: MODULUS, EVERCALC, and BOUSDEF. All of 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 upon a layered elastic code called WES5. This code creates a large database 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 the layered elastic computer program called CHEVRON. 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. Both of these back calculation programs, EVERCALC and BOUSDEF, use an iterative approach in back calculating the M_R values. Overall, by matching the deflection basin measured in the field, a M_R value is calculated for each section's surface, base, and subgrade layers (Mahoney et al., 1991).

CHAPTER 4

DATA ANALYSIS

As mentioned above, data were gathered during two different time periods, Period A (summer of 1992) and Period B (spring of 1993), and 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 class, group index, actual and optimum water contents, and plasticity index). The most consequential difference between periods A and B is that the resilient modulus in Period A was measured using frozen/thawed soils and remolded (disturbed) soils, while in Period B, it was measured using fresh, undisturbed soil samples and remolded soils. The inclusion of different sites also constituted some inconstancy in soil types between periods. The analyses below account for these differences as necessary. All analyses were based upon $\log_{10}(M_R)$, 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. Because thawed and fresh samples are expected to respond similarly, correlations were also measured for data pooled from the two periods. Table 4.1 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

Table 4.1. Correlations between LMR and R-value

	Thawed or Fresh (Undisturbed)		Homogenized (Disturbed)		Sample Size
	Ring	Actuator	Ring	Actuator	
Period A	0.630	0.749	-0.041	-0.089	16
Period B	0.334	0.437	-0.219	-0.273	23
Pooled	0.380	0.509	-0.136	-0.142	39

soils between Periods A and B may distort comparisons <u>between</u> these rows. The most important aspect of Table 4.1 is that in disturbed soils LMR's are not significantly correlated with the R-value, but fresh and thawed soil LMR's are correlated with the R-value. Correlations between undisturbed and disturbed LMR's (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. Only undisturbed LMR's were used in remaining analyses, unless noted otherwise.

The Effect of Sensor Location on M_R Measurements

The correlations shown in Table 4.1 also suggest that the placement of LVDT's 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 (Snedecor & Cochran, 1989) 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 can be explained by the fact that it is difficult to obtain good contact between the LVDT's on the ring and the soil sample. Analyses are henceforth made using actuator measures only.

Although measurements at the actuators appear to be preferable, the relationship between actuator and ring measures is of interest. Ring and actuator measurements of LMR (designated as LMRR and LMRA, respectively) are highly correlated as shown in Table 4.2.

Table 4.2. Relations between LMRR and LMRA

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

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 thawed and fresh samples ($p = 0.206$), and the pooled analysis is consequently considered to be acceptable. Note that a constant difference between LMR's would correspond to a multiplicative relationship between M_R's.

The Effect of Sample Condition on M_R Values

It is also of interest to know whether freezing and thawing a sample alters it significantly from its fresh state. Because thawed and fresh samples were gathered in different years, it is impossible to obtain conclusive evidence of differences between these methods. Never-the-less, by ensuring that only comparable sites are used for comparisons and questionable values are excluded, some heuristic comparisons are possible. In this case, the regression line of LMR onto R for thawed samples is not statistically different from that for fresh samples. More liberal inclusion of data points does result in significantly different lines, however, and results are considered to be inconclusive. Further research is recommended to determine the effects of freezing and thawing on M_R measurements.

Another 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, then one would expect that surface layer measures may differ in quality from lower layer measures. Data available do not yield evidence of such differences (repeated measures analysis $F_{2,13} = 1.27$, $p = 0.3126$). Assuming 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 values of M_R 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 an additional reference criterion.

Relationships Between Back Calculated and Laboratory M_R Values

M_R values can be obtained indirectly, via back calculations from non-destructive testing instead of laboratory tests. As mentioned earlier, the following three back calculation programs were utilized 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 to laboratory LMR values. The Site-by-Period mean LMR from intact 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 4.3.

Table 4.3. Back Calculation Correlations (N = 13)

	Weighted Correlations with LMR	Cross-Correlations		
		LMR-MP	LMR-EP	LMR-BP
LMR-MP	0.526	1.000	0.744	0.941
LMR-EP	0.735	0.744	1.000	0.799
LMR-BP	0.590	0.941	0.799	1.000

Note that the EVERCALC program appears to be slightly superior to the other two back calculation methods, although more extensive data would be needed to make conclusive recommendations. All back calculated values match better with each other than they do with the laboratory measurements.

Assuming constant differences between logs of back calculated and "true" values, the best estimated differences appear in Table 4.4, along with implied relationships between correct and back calculated values of M_R. A 95% confidence interval for the appropriate correction factor (C) for subgrade soils in Wyoming, based on the EVERCALC program, is [0.20, 0.32], where $M_R = C * [\text{back calculated value}]$.

Table 4.4. 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)

Relationships Between M_R Values and Soil Properties

The final question considered is the relation between soil factors 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 one was ultimately considered for describing Soil-M_R relationships, Group Index (GI).

Moisture and LMR are related, and their relationship depends on soil type. Similar strengths of the relationship between soil factors and responses were found for both undisturbed and remolded samples, and also for R-values (Refer to Table 4.5). 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 very little change in the measured values. There is a possibility that there was a lack of data available for this type of subgrade soil below the optimum water content, and, therefore, these results are considered to be inconclusive (Refer to Table 4.6).

Table 4.5. Coefficients of Determination for Soil-M_R Relations

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

Table 4.6. Parameter Estimates ± Standard Error for Model with GI

Soil Classification	Parameter Estimates	Undisturbed Samples LMR	Remolded Samples LMR	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

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Based on the extensive data analysis performed in this research project, the following preliminary conclusions are drawn:

1. Based upon the data obtained in this study, layers within Shelby tubes do not differ significantly from one another. Therefore, averaging the resilient modulus values from all layers will give more reliable results compared to the value from one layer.

2. Some fundamental soil properties do influence the measured M_R value. Resilient modulus values for type A-4 and A-6 subgrade soils in this study decreased as water content increased.

3. M_R measurements made with the LVDT's on the ring located inside the testing chamber consistently gave higher values compared to the actuator LVDT's located on the loading piston.

4. The EVERCALC back calculation program appears to give somewhat better 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 the State of Wyoming.

6. Further research should be completed to determine whether or not freezing and thawing cycles influence the M_R measurement.

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