Effect of Selecting Subgrade Resilient Modulus Values on Asphalt Overlay Design Thicknesses

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Design pavement overlay thicknesses were calculated for primary roads located in the state of Wyoming. Subgrade resilient modulus values were determined on the basis of laboratory testing at a deviator stress of 41.4 kPa (6lb/in.^{2}) laboratory testing at the actual field deviator stress, and backcalculation from deflection measurements. Several pieces of relevant field and laboratory information were also collected on all sections. Asphalt overlay thicknesses were then calculated on the basis of the *AASHTO Guide for Design of Pavement Structures*. The data analysis indicated that the three calculated resilient modulus values at each test section did not result in significantly different overlay thicknesses.

The 1993 *AASHTO Guide for Design of Pavement Structures* (*1*) requires selection a of subgrade resilient modulus (M_R). The determination of the subgrade M_R is essential for designing overlay thicknesses for existing pavement sections. If the selected design M_R value is too high, the thickness of the pavement layer will be insufficient. If the design M_R value is too low, the thickness will be too conservative and not cost-effective. The two most commonly used methods for determining subgrade M_R values are actual laboratory testing and backcalculation procedures described in the *AASHTO* Guide for Design of Pavement Structures (*1*).

Laboratory testing is normally performed with different combinations of confining and deviator pressures. A design M_R value is then selected from a plot of M_R versus deviator stress. An important aspect of choosing a design M_R value is making sure that the selected value is consistent with the assumptions made in the design performance equation for the AASHO Road Test subgrade. The AASHTO guide uses a value of 20 684 kPa (3,000 lb/in.^{2}) to represent the subgrade for the AASHO Road Test, but it does not justify its selection. This value is one of the underlying assumptions of the flexible pavement performance model. Based on a study by Thompson and Robnett (*2*), this value is appropriate when the AASHO soil is about 1 percent wet of optimum and subjected to a deviator stress of about 41.4 kPa (6 lb/in.^{2}) or more. Thompson and Robnett (*2*) also showed that M_R values from deviator stresses of less than 41.4 kPa (6 lb/in.^{2}) vary significantly, whereas M_R values from deviator stresses of more than 41.4 kPa (6 lb/in.^{2}) tend to remain constant. Therefore, when selecting an M_R value from laboratory testing, use of a zero confining pressure and a 41.4-kPa (6-lb/in.^{2}) deviator stress is suggested (*3*).

When adequate field data are available, actual field deviator stresses can be calculated. These calculations normally incorporate some assumptions about applied loadings, tire pressures, and pavement material properties and layer thicknesses. Typically, computer programs such as BISAR (*4*) can be used to determine the stresses in a pavement's subgrade soil. Design M_R values can then be determined from laboratory testing on the basis of the actual deviator stresses rather than the assumed value of 41.4 kPa (6 lb/in.^{2}).

M_R values can also be backcalculated. The AASHTO guide recommends use of the following formula to determine the resilient modulus value for subgrade soils based on deflection measurements:

$$M_R = \frac{0.24P}{d_r r}$$

where

M_R = backcalculated subgrade resilient modulus,
P = applied load,
d_r = deflection at a distance r from the center of the load, and
r = distance from center of load (sensor location).

The resulting M_R value is normally adjusted with a correction factor to make it consistent with the 20 684-kPa (3,000-lb/in.^{2}) assumption (*1*).

The University of Wyoming and the Wyoming Department of Transportation (DOT) conducted a joint research project to (a) compare actual subgrade field deviator stresses with the 41.4-kPa (6-lb/in.^{2}) deviator stress assumed in determining a design M_R value from laboratory testing and (b) determine the effect of selecting an M_R value on the design overlay thicknesses for typical pavement sections in Wyoming. This paper presents the main findings of that study.

DESIGN OF EXPERIMENT

Figure 1 shows the data collection process and overall evaluation strategies followed in the project. During the summer of 1992 and spring of 1993 several types of field data were collected on nine pavement test sections. These sections were chosen to represent typical cohesive subgrade soil conditions on primary roads throughout the state of Wyoming. The field evaluation included pavement coring, subgrade coring, and deflection measurements. Table 1 shows the locations and thicknesses of the sections included in the experiment. Pavement cores were used mainly to confirm the thicknesses of the different layers in the pavement structures. These thicknesses were then used to calculate the actual field stress conditions on the subgrade soil at each test site. Laboratory resilient modulus testing was then performed on the subgrade samples. Subgrade M_R values were then determined on the basis of the assumed deviator stress of 41.4 kPa (6 lb/in.^{2}), the actual field deviator stress,

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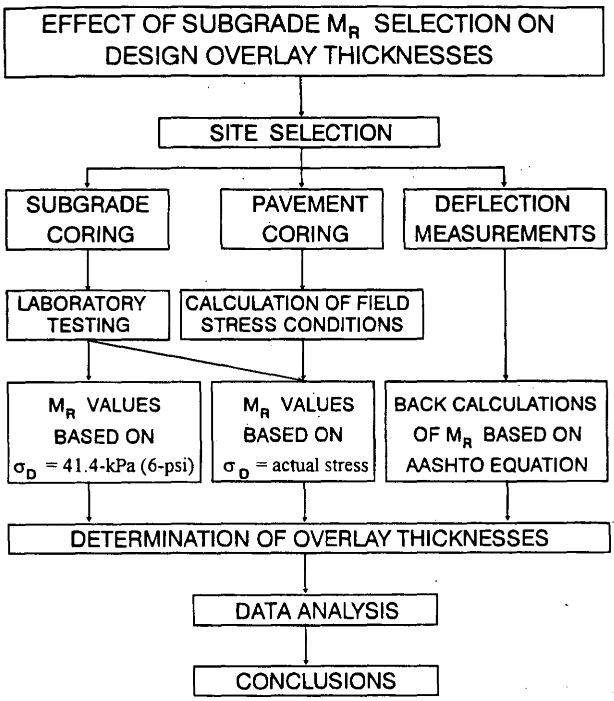


FIGURE 1 Data collection and analysis strategies.

and deflection measurements. Statistical analyses were then performed to determine if differences existed between M_R values calculated by using an assumed deviator stress of 41.4 kPa (6 lb/in.^{2}) and the actual deviator stresses. Next, these M_R values were used to calculate overlay thicknesses for all nine pavement test sections. Further analyses were then completed to examine the differences in the resulting design overlay thicknesses on the basis of laboratory M_R values and the AASHTO M_R backcalculated values.

DATA COLLECTION AND LABORATORY TESTING

Field Data Collection

Extensive field data were collected on all test sections included in the present research study. First, pavement deflection measurements were obtained by using standard loads on the Wyoming DOT's KUAB 2-m falling weight deflectometer. Pavement and air temperatures were also recorded for later use in correcting the temperature to the standard value of 21°C (70°F). Second, three pavement cores were taken from each section to examine the characteristics of the asphalt layers and to verify the thicknesses. These data were later used in the AASHTO overlay design procedures. Finally, three Shelby tube samples were taken from the subgrade at each test section. The soil samples were used to determine M_R values by laboratory testing procedures. Sieve analysis, liquid limit, plastic limit, and water content tests were also performed on the soil samples.

Resilient Modulus Testing

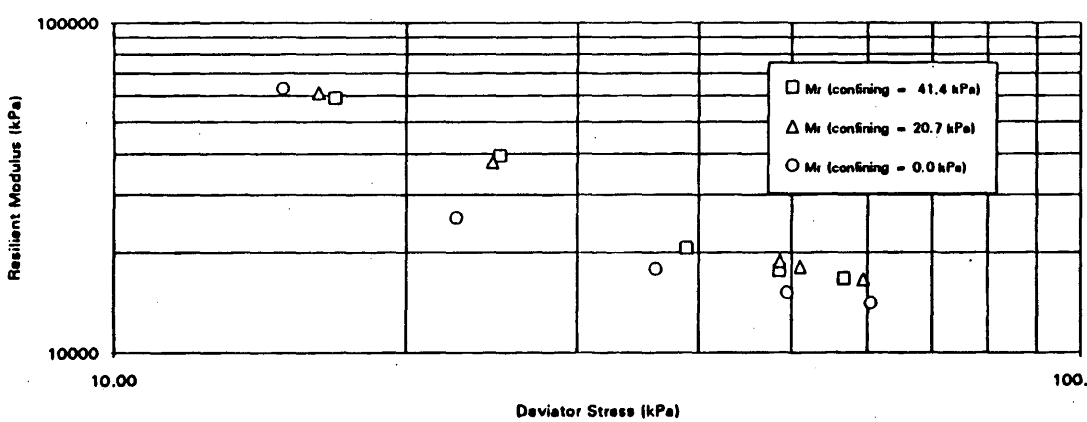
Laboratory soil resilient modulus tests were performed on the Wyoming DOT machine manufactured by the Interlaken Technology Corporation. This system has a Series 3300 98-kN (22-kip)-capacity test frame, a Series 3230, 16-channel data acquisition system, and a Series 3200 controller. The interim method of test for resilient modulus of unbound granular base/subbase materials and subgrade soils (Strategic Highway Research Program Protocol P46; AASHTO standard T 294-92 I) outlines the latest testing procedure. Soil samples were extracted from the Shelby tubes and were tested under Type II (cohesive) subgrade soil conditions. The amount of deformation in the soil samples was recorded by using two linear variable differential transducers (LVDTs) mounted outside of the testing chamber on the loading piston. All samples tested were 71 mm (2.8 in.) in diameter and 152 mm (6 in.) in height. These measurements, a height not less than 2 times the diameter and a minimum diameter of 71 mm (2.8 in.) or 5 times the nominal particle size, were selected in accordance with current specifications (*5*). Deformation and applied load readings were digitally recorded for the last five loading cycles. Several spreadsheets were developed to accept these data as well as the length and diameter of each sample. Figure 2 shows an example of the M_R summary spreadsheet developed for the study. The upper half of the spreadsheet shows the measured values under different testing conditions. These values include mean deviator load, mean applied deviator stress, mean recoverable deformation from each LVDT, mean resilient strain, and mean M_R value. By entering these data the M_R values were calculated automatically for each testing condition and test section. A logarithmic plot of M_R versus deviator stress was also created by using these values, as shown in the lower left-hand corner of Figure 2. In addition, a simple linear regression analysis was performed to develop a general equation for determining the M_R values as a func-

TABLE 1 Locations and Thicknesses of Test Sections

Roadway	Mile Post	Pavement Thicknesses	
		Surface (mm)	Base (mm)
US-30	48	305	305
US-30	70	140	152
US-287	416	152	152
US-26	108	127	152
US-20/26	15	127	203
US-20	163	76	64*
US-16	229	152	203*
US-16	244	58	191*
US-85	197.4	152	203**

*Asphalt Treated Base (ATB) **Cement Treated Base (CTB)

CHAMBER CONFINING PRESSURE (kPa)	NOMINAL DEVIATOR STRESS (kPa)	MEAN DEVIATOR LOAD (N)	STANDARD DEVIATION OF LOAD (N)	MEAN APPLIED DEV. STRESS (kPa)	MEAN RECOV. DEF. LVDT #1 (m)	MEAN RECOV. DEF. LVDT #2 (m)	MEAN RECOV. DEF. LVDT #3 (m)	MEAN RECOV. DEF. (m)	STD. DEV. OF RECOV. DEF. (m)	MEAN OF RESILIENT STRAIN (m/m)	MEAN OF Mr (kPa)	STD. DEV. OF Mr (kPa)
41.4	13.8	70.2855	0.3634	16.92	4.40282E-05	4.37182E-05		4.38732E-05	6.93317E-07	2.88122E-04	58720	802.1
41.4	27.6	103.9076	0.3634	25.01	9.70484E-05	9.58081E-05		9.64283E-05	8.83790E-07	6.33259E-04	39492	285.3
41.4	41.4	161.5086	0.1942	38.87	2.89595E-04	2.83394E-04		2.86494E-04	1.69844E-06	1.88145E-03	20661	138.8
41.4	55.2	201.9946	0.3071	48.61	4.25400E-04	4.11139E-04		4.18269E-04	1.29738E-06	2.74684E-03	17698	49.8
41.4	68.9	235.7035	0.4953	56.73	5.24620E-04	5.06016E-04		5.15318E-04	1.38639E-06	3.38417E-03	16763	33.0
20.7	13.8	67.5922	0.4952	16.27	4.03075E-05	4.09277E-05		4.06176E-05	4.24599E-07	2.66742E-04	60990	651.5
20.7	27.6	101.9964	0.5664	24.55	9.85986E-05	9.89087E-05		9.87537E-05	1.03994E-06	6.48530E-04	37854	385.2
20.7	41.4	201.9076	0.6444	48.59	3.95634E-04	3.88194E-04		3.91914E-04	1.29738E-06	2.57376E-03	18880	57.2
20.7	55.2	212.2464	0.5828	51.08	4.32841E-04	4.23540E-04		4.28191E-04	1.29632E-06	2.81199E-03	18166	50.7
20.7	68.9	246.9111	0.7892	59.42	5.46943E-04	5.37022E-04		5.41983E-04	8.48641E-07	3.55928E-03	16696	54.5
0.0	13.8	62.1187	0.4344	14.95	3.53466E-05	3.72069E-05		3.62768E-05	1.49104E-06	2.38235E-04	62833	2443.4
0.0	27.6	93.6561	0.3887	22.54	1.36426E-04	1.33325E-04		1.34875E-04	1.09622E-06	8.85747E-04	25449	138.3
0.0	41.4	150.5618	0.9517	36.24	3.09439E-04	3.06338E-04		3.07888E-04	3.39596E-06	2.02195E-03	17922	84.1
0.0	55.2	205.6435	0.5827	49.49	4.99194E-04	4.90513E-04		4.94853E-04	2.29954E-06	3.24978E-03	15230	57.8
0.0	68.9	251.6026	0.7139	60.55	6.59185E-04	6.46162E-04		6.52673E-04	1.55067E-06	4.28621E-03	14128	16.6



APPLICATIONS

EXPRESSION OF THE MODULUS

$MR = 930697\ (Sd)^{-1.021}$

STATISTICS

$R^2 = 0.908$

SUMMARY

SAY Sd = 41.4 kPa
MR (design) = 20822 kPa
R value = 30.0
R value Specimen Height = 66.6 mm
Rcorrected = 32.0

TYPE OF SAMPLE: THAWED

FILENAME: T341511A.XLS

FIGURE 2 Summary spreadsheet for calculating subgrade M_R.

tion of the deviator stress [$M_R = f(\sigma_d)$]. After obtaining the equation a deviator stress of 41.4kPa (6 lb/in.^{2}), suggested in the literature, was substituted into the equation to determine a design M_R value. Table 2 summarizes the M_R values on the basis of the 41.4-kPa (6-lb/in.^{2}) deviator stress. Variations among samples at each test site are documented elsewhere (*6*).

Laboratory M_R Values Based on Actual Field Stresses

Actual field deviator stresses were calculated on the basis of the thicknesses and material characteristics of the different layers in each pavement test section. Table 3 summarizes the characteristics of different material types commonly used by the Wyoming DOT. The BISAR (*4*) computer program was used to calculate field deviator stresses. As shown in Figure 3, stresses were calculated on the basis of a 40-kN (9,000-lb) wheel load, a 689-kPa (100-lb/in.^{2}) tire pressure, and a three-layer pavement structure. This program computes the stresses for an *n*-layer pavement structure by considering the vertical and horizontal loads. Table 4 summarizes the calculated average field deviator stresses for all test sections. These actual field stresses were entered into the M_R equations developed in the laboratory testing, and M_R values based on actual stress conditions were calculated. Table 5 summarizes these M_R values.

Backcalculated M_R Values Based on AASHTO Procedure

M_R values were also determined on the basis of the AASHTO backcalculation equation described earlier. In that equation the minimum distance between the deflection sensors and the loading plate is determined with the following formula:

$$r \geq 0.7a_e$$

where r is the distance from the center of the load and a_e is the radius of the stress bulb at the subgrade-pavement interface. After backcalculating M_R values with the AASHTO equation, a correction factor of 0.33 was applied to all calculated M_R values. This correction factor is specified in the AASHTO design guide (*1*). Table 6 summarizes the backcalculated M_R values for all test sections.

Calculating Overlay Thicknesses

Several spreadsheets were developed to determine the overlay thicknesses for all test sections. The following subgrade M_R values were available for calculating overlay thicknesses: laboratory M_R based on 41.4-kPa (6-lb/in.^{2}) deviator stress, laboratory M_R based on actual field deviator stress, and backcalculated M_R based on AASHTO equation (referred to as LAB, FIELD, and AASHTO, respectively). Tables 2, 5, and 6 list these M_R values. All three sets of M_R values were used in the calculations of overlay thicknesses. The following values were used to calculate the overlays: 85 percent reliability factor, 0.45 standard deviation, and 2.5 as the change in present serviceability index. Overlay thicknesses were calculated at the following three different traffic levels: 800,000, 3,000,000, and 5,000,000 equivalent single axle loads corresponding to low, medium, and high traffic levels, respectively. All design overlay thicknesses were obtained by using a layer coefficient (a_{ol}) of 0.44. Table 7 summarizes the overlay thicknesses (D_{ol}) resulting from this analysis.

DATA ANALYSIS

Comparison Between M_R Values Calculated on the Basis of Actual and Assumed Deviator Stresses

Because laboratory M_R values were calculated by using two different stress conditions, one would want to know if there is any statistical difference between using the actual deviator stress and the assumed value of 41.4kPa (6lb/in.^{2}). Therefore, the test for differences for paired data was performed. The data were placed in two groups, granular and treated, because four of the nine sites had some type

TABLE 2 Laboratory M_R Values (in kPa) Based on 41.4-kPa (6-lb/in.^{2}) Deviator Stress

Roadway	Mile Post	$M_{R\ LAB}$
US-30	48	25793
US-30	70	52704
US-287	416	42941
US-26	108	31199
US-20/26	15	14672
US-20	163	10728
US-16	229	59495
US-16	244	46664
US-85	197.4	60019

TABLE 3 Material Properties Commonly Used by Wyoming DOT

Layer in Pavement Structure	Young's Modulus (MPa)	Unit Weight (kN/m^3)	Poisson's Ratio
Asphalt Cement Mix	2758	23.1	0.35
Granular Base	124	22.8	0.40
Cement Treated Base	5516	22.0	0.25
Asphalt Treated Base	2413	23.1	0.37

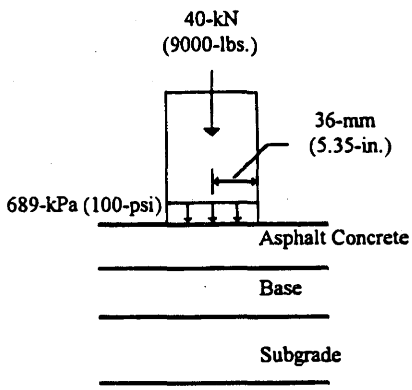


FIGURE 3 Assumptions made in calculating actual field stresses.

of treated base, either asphalt-treated base or cement-treated base. After completing this separation comparisons were performed on all the sites within each group and then by each site individually. Tables 8 and 9 summarize the results for the granular and treated sites, respectively. Both tables indicate that there is not a statistical difference between the two data sets. However, by examining the variances one would favor using the computed field deviator stresses over the assumed 41.4-kPa (6-lb/in.^{2}) values because of the reduction in the amount of variance. By determining actual deviator stresses, the resulting M_R values were more consistent with each test site.

Effect of M_R Selection on Overlay Thicknesses

With three different methods for determining M_R (AASHTO, LAB, and FIELD) it might also be of interest to know if there are any sta-

TABLE 4 Calculated Average Field Deviator Stresses (in kPa)

Roadway	Mile Post	Averaged Field Deviator Stress (σ_d)
US-30	48	13.3
US-30	70	47.7
US-287	416	41.3
US-26	108	43.5
US-20/26	15	30.4
US-20	163	41.8
US-16	229	24.6
US-16	244	49.9
US-85	197.4	14.3

TABLE 5 Laboratory M_R Values (in kPa) Based on Actual Deviator Stresses

Roadway	Mile Post	$M_{R\ FIELD}$
US-30	48	59584
US-30	70	46202
US-287	416	43003
US-26	108	30723
US-20/26	15	19733
US-20	163	16030
US-16	229	96478
US-16	244	39328
US-85	197.4	56516

TABLE 6 Backcalculated M_R Values (in kPa) Based on AASHTO Equation

Roadway	Mile Post	$M_{R\ AASHTO}$
US-30	48	22180
US-30	70	26193
US-287	416	41562
US-26	108	17099
US-20/26	15	20119
US-20	163	28758
US-16	229	51014
US-16	244	33577
US-85	197.4	59805

TABLE 7 Overlay Thicknesses (in mm) for All Test Sections

		Traffic Level								
		Low			Medium			High		
Roadway	Mile Post	AASHTO D_{ol}	LAB D_{ol}	FIELD D_{ol}	AASHTO D_{ol}	LAB D_{ol}	FIELD D_{ol}	AASHTO D_{ol}	LAB D_{ol}	FIELD D_{ol}
US-30	48	-133	-144	-198	-88	-100	-162	-69	-82	-147
US-30	70	87	42	50	131	78	88	149	94	104
US-287	416	48	46	46	87	84	84	103	101	100
US-26	108	163	120	121	211	161	162	232	179	180
US-20/26	15	121	146	122	167	195	169	186	216	188
US-20	163	90	167	134	132	221	182	150	243	203
US-16	229	-103	-112	-138	-67	-77	-107	-51	-62	-94
US-16	244	118	97	107	158	134	146	176	150	163
US-85	197.4	-203	-203	-200	-168	-168	-165	-153	-154	-149

TABLE 8 Testing Significance of Differences Between M_R Values for Granular Base Sites

Roadway	Mile Post	M_R (41.4-kPa) Variance	M_R (field) Variance	t	df	p-value
US-30	48	4.25E+06	3.24E+08	3.11	1	0.198
US-30	70	4.33E+08	1.38E+08	1.71	3	0.184
US-287	416	8.53E+07	5.68E+07	0.403	5	0.744
US-26	108	3.08E+08	1.44E+08	0.064	7	0.951
US-20/26	15	2.20E+07	1.60E+07	6.06	5	0.002
Pooled		3.50E+08	2.49E+08	1.07	25	0.293

TABLE 9 Testing Significance of Differences Between M_R Values for Treated Base Sites

Roadway	Mile Post	M_R (41.4-kPa) Variance	M_R (field) Variance	t	df	p-value
US-20	163	3.41E+06	2.23E+06	0.916	1	0.528
US-16	229	1.42E+08	1.65E+09	1.197	1	0.443
US-16	244	4.37E+08	4.00E+08	6.084	10	0.0001
US-85	197.4	3.49E+07	4.32E+08	0.094	1	0.941
Pooled		5.31E+08	8.53E+08	0.630	16	0.537

tistical differences in the calculated overlay thicknesses due to the method used. The negative thicknesses were left in the analysis to provide a better indication of the differences among methods. A repeated measures analysis showed no evidence of differences (null hypothesis) among the methods at low, medium, or high traffic levels ($F_{2,24} = 2.16$, p-value $= 0.1367$; $F_{2,24} = 2.18$, p-value $= 0.1351$; and $F_{2,24} = 2.18$, p-value $= 0.1349$, respectively). Huynh-Feldt epsilon values were calculated to account for any model violations and to make adjustments to the denominator degrees of freedom (df). The values, 0.8690, 0.8725, and 0.8733 for the low, medium, and high traffic levels, respectively, were near 1, indicating that violations were minor.

Even though there were no differences among the methods, one might also want an idea for a given difference in thickness, if one could detect that the methods were not the same. Therefore, the power of the F test was performed to determine the probability of accepting the alternative hypothesis (H_a) that the methods are different. Suppose one is interested in determining if a maximum difference of 25.4 mm (1.0 in.) could be detected. At the low traffic level there was a 0.92 probability that differences would be detected among the three different methods. Overall, 19.1-mm (0.75-in.) maximal differences could be detected with 80 percent probability.

Besides the above test the Tukey procedure for pairwise comparisons was also completed. The following 95 percent confidence intervals were obtained (μ_3 is the treatment mean for AASHTO, μ_2 is the treatment mean for LAB, and μ_1 is the treatment mean for FIELD) for the low traffic level:

$$-0.49 \le \mu_3 - \mu_2 \le 1.01$$
$$-0.13 \le \mu_3 - \mu_1 \le 1.37$$
$$-0.40 \le \mu_2 - \mu_1 \le 1.11$$

These intervals suggest that AASHTO M_R values give the lowest overlay thicknesses. Similar results were obtained at the medium and high levels of traffic, as shown below by the 95 percent confidence intervals, respectively.

$$-0.56 \le \mu_3 - \mu_2 \le 1.17$$
$$-0.15 \le \mu_3 - \mu_1 \le 1.58$$
$$-0.45 \le \mu_2 - \mu_1 \le 1.27$$

$$-0.59 \le \mu_3 - \mu_2 \le 1.23$$
$$-0.16 \le \mu_3 - \mu_1 \le 1.66$$
$$-0.48 \le \mu_2 - \mu_1 \le 1.34$$

SUMMARY AND CONCLUSIONS

Comprehensive field and laboratory evaluations were performed on nine different sites representing typical primary roads in the state of Wyoming. M_R values were obtained from laboratory testing based on 41.4-kPa (6-lb/in.^{2}) deviator stress, laboratory testing based on actual field deviator stresses, and the AASHTO backcalculation equation based on deflection measurements. These values were then used to determine the required overlay thickness at each pavement test site. Based on the extensive data analysis performed in this research project, the following conclusions are drawn:

1. M_R values based on actual deviator stresses did not statistically differ from values based on the assumed deviator stress of 41.4 kPa (6 lb/in.^{2}). However, by computing actual deviator stresses the resulting M_R values within each testing site were more consistent.
2. The three calculated M_R values at each test section did not result in significantly different overlay thicknesses. Among the three, however, the AASHTO M_R value gave the lowest overlay thicknesses.

These conclusions are applicable to all traffic levels considered in the study. Overall, similar overlay thicknesses can be obtained by using backcalculated M_R, laboratory M_R based on a 41.4-kPa (6-lb/in.^{2}) deviator stress, or laboratory M_R based on the actual field deviator stresses.

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