Resilient Modulus Properties of Asphalt Rubber Mixes from Field Demonstration Projects in Maryland

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Results of resilient modulus (M_r) response obtained from field cores of a newly constructed Maryland State Highway Administration demonstration project concerning the performance of asphalt rubber mixtures are presented. The test project involves over 12.5 km of US-340 and MD-140 highways, contains 30 test sections, and utilizes 14 different mixtures (1 conventional control mix and 13 rubber mixes). Six types of plant-blended wet process asphalt rubber mixtures, two types of manufacturer preblended asphalt rubber (Neste SAR and Bitumar Ecoflex), two types of dry process patented Plus Ride, and three types of a generic dry process rubber-modified mix were evaluated. The analysis of 180 field cores with the Baladi indirect test fixture with three transducers directions is presented. In addition to describing the results of the M_r test program for all of the mixtures investigated, statistical analysis of variance (ANOVA) studies were conducted to evaluate field core horizontal anisotropy, compare among the five M_r prediction models currently available, and quantify five sources of variance associated with the M_r field evaluation program. It was found that no horizontal anisotropy is present in field cores. Another study conclusion was the fact that the assumption of a Poisson's ratio value when using only horizontal or longitudinal transducers yields statistically different results for the M_r response compared with models that calculate the Poisson's ratio based on both vertical and horizontal deformations or models that use only the vertical measurements in conjunction with an assumed Poisson's ratio. Finally, the component variance analysis indicated that the largest source of variability is associated with the orientation of the diametral plane during the M_r test. This variance was found to be greater than even the within-section, between-section, and between-mix sources of variability.

Unlike many other types of solid waste, tires are not categorized as biodegradable and result in long-term disposal problems because they cannot be effectively buried or incinerated (*1*). In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) set minimum use requirements for asphalt rubber within pavements as a partial solution to the environmental problem. However, serious technical and economical questions emerged from the basic guidelines of the legislative resolution.

To obtain answers for those questions and effectively implement the decision, several state and public agencies initiated studies on the use of rubber in pavement construction. In the state of Maryland, a project between the Maryland Department of Transportation (MDOT) and the University of Maryland (UM) was established with the primary objective of providing essential information on asphalt rubber binder characterization, mix design, and field performance.

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Field performance is being evaluated through two demonstration projects on US-340 and MD-140 north of Baltimore. These projects involve the design, construction, testing, and monitoring of 30 sections that include both wet and dry processes in 14 different mix types. All projects were constructed between August and November 1993.

Laboratory characterization of the mixtures as actually placed is being conducted. Field cores obtained from the sections were used to establish the resilient, strength, and permanent deformation properties. This study focuses on the resilient properties of the asphalt rubber mixtures obtained from those field cores.

MIX TYPES USED

Thirteen types of asphalt rubber mixes and one conventional control were used in this study (*2*). Among these were six wet process, five dry process, and two preblended wet process mixes. The wet blend mixes were divided into two categories, one with AC-20 and the other with AC-10 type asphalt cement. Within these groups, three levels of rubber percentage—10, 15, and 20 percent—were used along with the appropriate percentage of extender oil. The dry process mixes were also divided into two groups: the patented Plus Ride and a dry generic mix developed at UM. The Plus Ride mixes were the No. 12 and No. 16 mixtures, each having 3 percent rubber. Rubber percentages of 0.75, 1.5, and 2.25 percent were used in the dry generic mixes investigated. In addition, two types of manufacturer preblended wet mixes, Neste SAR 10/10 and Bitumar (Ecoflex), were examined. Table 1 summarizes the mix design characteristics for each mix type used in the test sections.

FIELD CORING

The demonstration projects on US-340 and MD-140 consist of 30 test sections (cells). Each section is approximately 0.3 km (1,000 ft) long (*2*). The plant-mixed wet process mixtures were placed on US-340 in 14 sections. For each of the seven mix types, including a control, there were two sections. Five different dry-process mixes were laid on the eastbound lane of MD-140 in 12 sections, including two controls. Finally, the two preblended wet mixes were placed in four sections on the westbound lane of MD-140. Half of the sections constructed with the plant-mixed wet and dry processes were placed in two 38-mm (1.5-in.) lifts. The remaining sections were built in a single 38-mm (1.5-in.) layer.

Two groups of six cores each, 100 mm (4 in.) in diameter, were extracted from each test section by MDOT personnel. This resulted

TABLE 1 Mix Design Properties

Mix Process	Mix Type	Type Asphalt	Design AC (%)	Rubber (%)	Extender Oil (%)	Density Gmb (kg/m3)	Stability (N)	Flow Value (0.25 mm)	Stab/Flow Ratio (kN/mm)	Air Voids Va(%)	Voids Min. Agg. VMA (%)	Voids Filled VFB (%)
	Control	AC-20	4.8	NA	NA	2427	9679	12.2	3.17	4.0	13.3	72.0
Wet	AC-10 rp10	AC-10	6.1	10	1.0	2393	11227	17.0	2.64	3.4	16.6	79.5
	AC-10 rp15	AC-10	6.1	15	3.0	2393	9955	17.0	2.34	3.4	16.6	79.3
	AC-10 rp20	AC-10	6.3	20	7.0	2384	9701	16.0	2.43	3.6	16.5	79.5
	AC-20 rp10	AC-20	6.6	10	1.0	2379	11615	19.0	2.45	3.5	17.4	80.5
	AC-20 rp15	AC-20	6.6	15	3.0	2387	11770	20.0	2.35	3.3	17.2	80.7
	AC-20 rp20	AC-20	6.6	20	7.0	2380	10965	18.0	2.44	3.6	16.7	78.7
Dry	G0.75	AC-20	5.4	0.75	NA	2369	8566	21.2	1.62	4.0	15.6	74.0
	G1.50	AC-20	6.5	1.5	NA	2335	6232	26.5	0.94	4.0	18.2	78.0
	G2.25	AC-20	7.5	2.25	NA	2283	4363	29.0	0.60	4.0	20.8	81.9
	PR12	AC-20	7.1	3	NA	NA	NA	NA	NA	3.0	18.5	NA
	PR16	AC-20	7.5	3	NA	NA	NA	NA	NA	3.0	19.0	NA
Pre Blended	SAR10	AC-20	5.4	10	NA	2403	7454	NA	NA	4.0	16.4	NA
	ECO10	AC-20	5.1	10	NA	2420	11125	8.0	5.56	4.0	16.0	NA

TAI MS-2 Conventional AC Mix Criteria (75 blow Marsh)

Stability -	8006 N Min.
Flow -	8 to 14 (1/4 mm)
Va % -	3 to 5
Vma % -	14 Min.
Max agg. siz	25 mm
Vfa % -	65 to 75

Note: % rubber in wet and preblended mixes refer to the asphalt content

in a total of 360 core samples from the entire project. Each core group was taken from a location approximately 30 to 60 m (100 to 200 ft) from the ends of a given test section. Within each core group, the six cores were extracted as close as possible from each other. All cores were obtained at the center of the paving lane. When the coring was performed, the diameter in the direction of traffic was clearly marked to be used as a reference for load application during the laboratory tests.

The cores were processed at the UM laboratory so that only the top 38-mm (1.5-in.) lift was used for the laboratory testing. After the sawing process, the specimens were measured and weighted. Three thickness and two diameter measurements were taken from the samples. The air, water, and surface-dry weights were also defined. After the geometric and gravimetric measurements, the specimens were placed inside sealed plastic bags to avoid contact with the air before testing.

From the 360 cores, half were used to define the resilient and strength properties. The remaining specimens are being tested for permanent deformation properties and will be the subject of later reports.

LABORATORY TESTS

Equipment

A diametral (indirect) device was used to determine the resilient and strength properties of the specimens. Field cores with a 100-mm (4-in.) nominal size were tested using the Baladi fixture. An MTS closed-loop servo-hydraulic system equipped with an environmental chamber was used for the load application. The loading form applied by the hydraulic system was programmed on a 458.20 MTS controller. Actual loads were measured through a 1 360-kg (3,000-lb) capacity load cell. The environmental chamber was used to test specimens at the desired temperature level

An A/D (analog-to-digital) card was available to link the testing system to a microcomputer, converting the analog voltage signals from the load cell and linear variable differential transformers (LVDTs) into digital voltage numbers. The data acquisition and specimen property computations were automatically obtained through a PC 486-66-type computer using specific data analysis programs (*3*) developed at UM.

Resilient Modulus Test

A repetitive haversine pulse load with 0.1-sec duration and 0.9-sec dwell time was used to obtain the total and instantaneous resilient moduli. Vertical, horizontal, and longitudinal deformations were recorded through five transducers mounted on each side of the specimen, as shown schematically in Figure 1.

The prediction of the resilient moduli as well as the Poisson's ratios used five different approaches, which are functions of the number and type of LVDTs used. The computations are based on the following LVDT sequence:

1. Using only one vertical LVDT,
2. Using only the two horizontal LVDTs,
3. Using the vertical and two horizontal LVDTs,
4. Using the two longitudinal LVDTs, and
5. Statistical regression model using all five LVDTs.

The peak, instantaneous, and valley values for each cycle were determined by the software developed at UM. The series of equations related to each of the five measurement approaches previously described may be found in the Baladi indirect test fixture reference

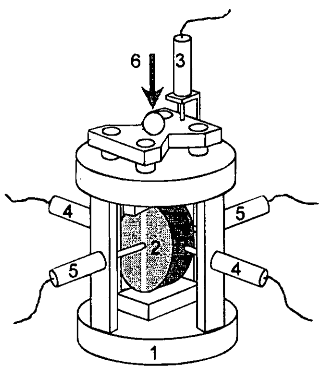

FIGURE 1 Schematic diagram of test configuration.

manual (*4*). They are not presented or discussed here because of space limitations.

TESTING AND ANALYSIS PLAN

The method used to perform the evaluation of M_r and tensile strength is based on ASTM D4123. The following overall sequence was used to test each of the cores:

1. Store the core in the environmental chamber at the test temperature 24 hr before the test;
2. Perform resilient modulus test so that the load is applied in the axis marked with the direction of traffic (0-degree orientation);
3. Perform resilient modulus test so that the load is applied transversely to the direction of traffic (90-degree orientation); and
4. Without moving the specimen from the previous position, conduct an indirect tensile strength test.

A 1-Hz cycle load was used in the dynamic tests. Each cycle consisted of a 0.1-sec load time and a 0.9-sec dwell time. The load and the number of cycles were specific and constant for each test temperature. Table 2 summarizes the test conditions at each temperature.

Three cores within a core group location were used to determine the resilient and strength properties of the mixes. The tests were performed at the three different temperatures described in Table 2. One specimen was tested at each temperature for each location, making up two cores per temperature per section. Modulus values were computed with the last five load cycles of each test. In summary, there were five repetitions for each plane and orientation test, two plane and orientation tests for each core and location, two cores and locations for each section, and two sections (except for the control, which had four sections) per mix type at each of the three different temperatures.

ANALYSIS OF RESULTS

Summary of Results

A summary of the results obtained for each test section mixture type is shown in Table 3. The values for M_r and Poisson's ratios represent the average for each mix type and each temperature. Results were computed using Prediction Model Number 3 (vertical and horizontal deformations). As indicated, each core was submitted to two M_r tests and one indirect tensile strength test. The strength tests are not reported or discussed in this paper.

Statistical Analysis

The development of the field coring plan was based upon the ability to conduct rigorous statistical data analysis in the form of an ANOVA. For the M_r analysis, it should be recognized that a total of 18,000 separate M_r predictions were obtained from the field cores (i.e., 180 cores, five repetitions per plane, two planes, five prediction equations, and two types: total and instantaneous M_r).

Horizontal Anisotropy Effect

Several prior research studies have suggested the possibility that anisotropic moduli in the horizontal direction are present in constructed pavement systems. In order to investigate this possibility statistically, M_r determinations on each core were made on two planes of the core. The 0-degree orientation was associated with the M_r response measured in the direction of traffic, whereas the 90-degree orientation was associated with the M_r response perpendicular to traffic.

In this analysis, the only statistical parameter of interest is the plane orientation effect. Because of this, a one-way ANOVA (at 5 percent level of significance) was undertaken between the 0-degree and 90-degree orientation results within each core. Table 4 summarizes the results of this analysis for each of the three test temperatures studied. Based on the results shown, it is evident that the *F*-statistic is lower than the critical *F*-value at each temperature analyzed. It can therefore be concluded that no horizontal anisotropic effect is present in field cores from the construction process. The plane-to-plane variability of M_r testing is a completely random process. As a consequence, it is not necessary to record the direction of traffic in field cores before the coring operation.

TABLE 2 Resilient Modulus Test Conditions

Temperature °C (°F)	Maximum Dynamic Load N (lb)	Total Number of Cycles
4.4 (40)	4450 (1000)	100
21.1 (70)	1335 (300)	75
37.8 (100)	312 (70)	45

TABLE 3 Laboratory Test Results—Average Values per Mix Type

Temperature (deg. C)	Mix Type	Instantaneous Mr (kPa)				Total Mr (kPa)			
		0 degree Orientation	90 degree Orientation	Average	Poisson	0 degree Orientation	90 degree Orientation	Average	Poisson
	Control	4934653	5508136	5221395	0.156	4264059	4555847	4409953	0.171
	AC-10 rp10	4094463	4283399	4188932	0.215	3334135	3418880	3376508	0.271
	AC-10 rp15	4908605	4248479	4578324	0.294	3905233	3389582	3647755	0.365
	AC-10 rp20	3322248	3668465	3495356	0.106	2808004	3000645	2904324	0.157
	AC-20 rp10	4561869	4375307	4468590	0.121	3834145	3724345	3779246	0.155
	AC-20 rp15	3880141	5625756	4752948	0.239	3147519	4417350	3782438	0.266
4.4	AC-20 rp20	3535197	4350117	3942656	0.087	3085688	3646675	3366182	0.112
	G0.75	3326344	5362036	4344190	0.103	2896454	4475513	3685983	0.117
	G1.50	4409882	4221844	4315863	0.170	3650648	3488135	3569389	0.198
	G2.25	3663117	3616108	3639615	0.174	2989233	2909873	2949552	0.208
	PR12	3170904	3090480	3130694	0.106	2611772	2544897	2578334	0.127
	PR16	3949110	4436538	4192823	0.134	3269696	3635505	3452600	0.168
	SAR10	4444562	3972355	4208459	0.134	3671881	3291902	3481893	0.171
	ECO10	3674633	3567873	3621253	0.278	2962195	2889880	2926037	0.311
	Control	3278571	3621455	3450013	0.219	2608693	2793772	2701232	0.265
	AC-10 rp10	2165909	4188753	3177331	0.479	1704464	2670101	2187282	0.508
	AC-10 rp15	3039661	2717709	2878685	0.314	2213967	2073814	2143891	0.384
	AC-10 rp20	2670171	3014263	2842217	0.257	2043526	2203326	2123422	0.313
	AC-20 rp10	3474835	3205519	3340177	0.342	2516276	2418662	2467471	0.395
	AC-20 rp15	2683610	4538352	3610981	0.350	2023791	3035638	2529713	0.382
21.1	AC-20 rp20	2563673	2841386	2702529	0.142	2030896	2250665	2140781	0.208
	G0.75	3431583	3356024	3393804	0.337	2522996	2515713	2519356	0.397
	G1.50	2909383	3248144	3078764	0.389	2070040	2312630	2194310	0.448
	G2.25	2277291	2590780	2434035	0.436	1643237	1737152	1690195	0.516
	PR12	3060318	2386110	2723214	0.249	2150064	1720516	1935289	0.299
	PR16	2255324	3171743	2713533	0.375	1674225	2071670	1872947	0.452
	SAR10	2756899	3167350	2962125	0.461	2116770	2350701	2233736	0.525
	ECO10	2673775	2675244	2674509	0.311	1953386	1968485	1960934	0.362
	Control	1147706	1582365	1365036	0.152	949222	1271816	1110519	0.144
	AC-10 rp10	1086872	1675112	1380990	0.533	877648	1352560	1115105	0.525
	AC-10 rp15	1071602	1256367	1163985	0.370	879509	1053615	966560	0.406
	AC-10 rp20	1240794	904002	1072399	0.148	1017288	741199	879243	0.185
	AC-20 rp10	1603163	1248973	1426070	0.255	1198931	1023616	1111273	0.281
	AC-20 rp15	1002118	1150637	1093943	0.228	831551	975255	903613	0.246
37.8	AC-20 rp20	980540	1596065	1304842	0.027	786552	1122426	1069340	0.065
	G0.75	1400060	1370066	1385062	0.228	1166942	1098089	1132516	0.231
	G1.50	1147562	1287766	1235664	0.155	938028	1115555	1024414	0.202
	G2.25	1035247	1077198	1056221	0.208	837540	853619	845579	0.275
	PR12	2041318	1426478	1757736	0.611	1785345	1109421	1533132	0.705
	PR16	1220112	1367620	1293790	0.446	1001055	1086768	1043926	0.508
	SAR10	1199194	983952	1091571	0.380	1026774	825589	926183	0.363
	ECO10	1163034	1035701	1093150	0.289	920826	828311	874568	0.331

Notes: Mix type specifications on Table 1
Parameters computed using vertical and horizontal transducers (Model 3)

TABLE 4 ANOVA One-Way Analysis—Total Modulus—Plane Orientation Effect

Temperature (deg. C)	Source of Variation	SS	df	MS	F	P-value	F crit
	Between Planes	2.97E+10	1	2.97E+10	1.4505	0.2309	3.9215
4.4	Within Planes	2.41E+12	118	2.05E+10			
	Total	2.44E+12	119				
	Between Planes	2.59E+10	1	2.59E+10	3.0068	0.0855	3.9215
21.1	Within Planes	1.02E+12	118	8.61E+09			
	Total	1.04E+12	119				
	Between Planes	3.31E+08	1	3.31E+08	0.1428	0.7062	3.9215
37.8	Within Planes	2.73E+11	118	2.32E+09			
	Total	2.74E+11	119				

where SS = sum of squares
df = degrees of freedom
MS = mean square
F = F-Statistic test
F crit = critical F
P-value = level of significance for which F = F crit

Note Computed values from Mr in psi

Validity of Five M_r Predictive Models

As previously noted, the M_r value can be determined by one of five different models developed by Baladi (*4*). Each of these models depends on the direction and combination of the transducers used during the test. The test fixture used in the study contained vertical, horizontal, and longitudinal transducers that allowed M_r predictions by all five equations.

The identification of the formula number and type or types of transducers used are as follows:

1. Formula 1: V (vertical transducer),
2. Formula 2: H (horizontal transducers),
3. Formula 3: V + H (vertical and horizontal transducers),
4. Formula 4: L (longitudinal transducers), and
5. Formula 5: V + H + L (all transducers).

It is very important to note that the Poisson's ratio can only be calculated in those formulas that include at least the vertical and horizontal deformations. In this case, Formulas 3 and 5 used a calculated Poisson's ratio, whereas Formulas 1, 2, and 4 used an assumed value of 0.35 across all test temperatures.

Similar to the previous analysis, the average total M_r for the last five repetitions (within plane) were computed for each of the five different predictive models. A one-way ANOVA, with 5 percent level of significance, was performed to obtain the results presented in Table 5.

In the first analysis, for each type of M_r, the groups containing the results from all five formulas were used in the ANOVA. In this case, for all temperatures, the *F*-statistic value is much higher than the critical *F*, showing that there are significant differences between results estimated by at least one of the five models studied.

The second analysis was performed with the groups representing only Formulas 1, 3, and 5. In this case the *F* values, as shown in Table 5, are much lower than the critical value. This demonstrates that the inclusion of Formula 2 (horizontal deformation), Formula 4 (longitudinal deformation), or both, is the cause for the significant differences obtained in the first statistical test.

A third analysis was completed with the results computed for a group containing Models 1, 2, 3, and 5. In this case the test statistics resulted in differences (*F* value greater than F_{crit}) at 40°F. This indicates that the inclusion of Model 4 is causing statistical differences in M_r as predicted by the four different models. Another strong indication in support of this conclusion is the analysis of the coefficients of variation (CVs) among the prediction models. Although the average CV for all three temperatures among Formulas 1, 3, and 5 is only 0.25 percent, the average value among Models 1, 2, 3, and 5 increases to 14 percent.

In a final analysis, Formulas 1, 3, 4, and 5 were also examined through an ANOVA one-way test. In this case the *F* values were significantly higher than the critical *F* across all three test temperatures. Figure 2 clearly shows the results and conclusions of this study at each of the test temperatures.

Based on the results of this analysis, it may be concluded that the use of longitudinal measurements to predict M_r is highly questionable [at least for the nominal core thicknesses of 1.5 in. (38 mm) used]. Even though Formula 5 incorporates longitudinal deformations, an analysis of this equation indicated that the major sensitivity of M_r is a result of the vertical and horizontal deformations.

Despite the lack of significant differences in the test statistics at 70°F and 100°F with prediction Model 2 (horizontal deformation only), the analysis of the CVs indicates that significantly lower variability among the prediction models is obtained when Prediction Model 2 is excluded from the group containing Formulas 1, 3, and 5.

It is therefore recommended that Formulas 1 and 3 be considered most representative as predictive models. Although the immediate benefit of Formula 1 is its simplicity because it is only necessary to measure vertical deformations, the added complexity of mounting a test apparatus to measure horizontal deformations has the advantage that it allows for the computation not only of the M_r value but of the Poisson effect as well. Though Formula 5 also satisfactorily

TABLE 5 ANOVA One-Way Analysis—Differences on Total *M*, Results Obtained by Five Different Formulas

Temperature (deg.C)	Source of Variation	All Formulas					Formulas 1, 3 & 5				
		df	*MS*	*F*	*P-value*	*F crit*	*df*	*MS*	*F*	*P-value*	*F crit*
	Between Formulas	4	1.95E+12	83.8104	1.31E-48	2.3999	2	2.17E+07	0.0011	9.99E-01	3.0430
4.4	Within Formulas	320	2.32E+10				192	1.98E+10			
	Total	324					194				
	Between Formulas	4	2.14E+11	16.9759	1.53E-12	2.4022	2	7.82E+06	0.0012	9.99E-01	3.0470
21.1	Within Formulas	295	1.26E+10				177	6.47E+09			
	Total	299					179				
	Between Formulas	4	1.13E+11	35.5769	1.32E-25	2.3932	2	1.01E+07	0.0047	9.95E-01	3.0316
37.8	Within Formulas	420	3.17E+09				252	2.15E+09			
	Total	424					254				

Temperature (deg.C)	Source of Variation	Formulas 1, 2, 3 & 5					Formulas 1, 3, 4 & 5				
		df	*MS*	*F*	*P-value*	*F crit*	*df*	*MS*	*F*	*P-value*	*F crit*
	Between Formulas	3	5.20E+11	22.2166	8.10E-13	2.6399	3	1.48E+12	72.0517	8.16E-34	2.6399
40	Within Formulas	256	2.34E+10				256	2.05E+10			
	Total	259					259				
	Between Formulas	3	3.07E+07	0.0039	1.00E+00	2.6428	3	2.66E+11	20.9737	4.43E-12	2.6428
70	Within Formulas	236	7.91E+09				236	1.27E+10			
	Total	239					239				
	Between Formulas	3	1.96E+09	0.8273	4.80E-01	2.6315	3	1.31E+11	40.8933	1.49E-22	2.6315
100	Within Formulas	336	2.37E+09				336	3.20E+09			
	Total	339					339				

where df = degrees of freedom
MS = mean square
F = F-Statistic test
F crit = critical F
P-value = level of significance for which F = F crit

Note Computed values from Mr in psi

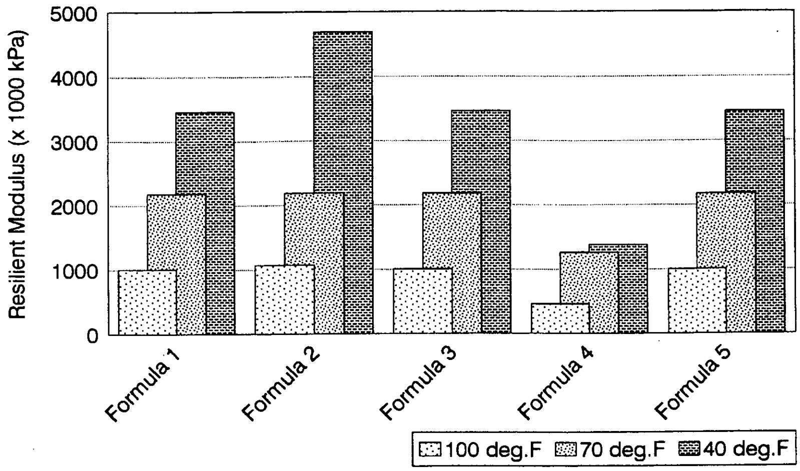

FIGURE 2 Average total resilient modulus values computed by five prediction models.

portrays both M_r and μ, no additional benefits are obtained compared with Model 3.

As a consequence of this analysis, the assumption of a Poisson's ratio value in a model that includes only vertical deformation (Formula 1) allows satisfactory M_r predictions. On the other hand, the same is not true for a model containing only horizontal measurements in the cylindrical specimen.

Analysis of Variability Components

An important element of any testing program is the quantification of the relative variability components of any measurement. Once this is accomplished, the most cost-effective and technically accurate sampling and testing program can be developed. The experimental field coring program was developed to determine estimates of the variance components associated with the field core evaluation of the M_r parameter.

This was accomplished through a five-level nested (hierarchical) ANOVA one-way balanced design model. The total variance model used is

$$\sigma^2_{\text{total}} = \sigma^2_r + \sigma^2_p + \sigma^2_c + \sigma^2_{bs} + \sigma^2_m$$

where

- σ^2_r = within-plane variance associated with the number of repetitions (cycles),
- σ^2_p = variance associated with the number of planes (diametrals) within a core,
- σ^2_c = variance associated with the number of core locations within a given section,
- σ^2_{bs} = variance associated between sections of the same mix type, and
- σ^2_m = variance associated between the different mixtures used in this study.

The ANOVA was conducted separately for each test temperature for both the total and instantaneous M_r results. Table 6 summarizes the results of this analysis, and Table 7 is a summary of the variance components expressed by the CV. In the ANOVA, some negative variances are obtained. This merely indicates that the mean square for the effect level is less than that for the nested level immediately below and, as a consequence, the estimated variance is approximately 0.

A review of the average CV component values shown in Table 7 clearly indicates that the greatest source of variability in M_r measurements is associated with the plane or diametral effect within any given core. This variation can be seen to approximately six times that associated with the within-section (cores-within-section) component. In contrast, the least significant variation is associated with the number of cycles (repetitions) used to establish the M_r within a given core diametral. Finally, the variability among all of the different mixtures evaluated in this study was surprisingly low (CV_m = 2.3 and 5.8 percent). This result is discussed further in the next section.

To illustrate the application of the results obtained, classical statistical limit-of-accuracy curves were developed for a unique statistically homogeneous section. In this analysis it has been assumed (as an approximation) that the CV_i parameter is valid across all temperature ranges. With this assumption, the relationship for the limit of accuracy (R) expressed as a percentage of the true section mean can be derived from statistical principles to be

$$\left(\frac{R}{X}\right) = K_\alpha \left[\frac{CV_r^2}{n_r n_p n_c} + \frac{CV_p^2}{n_p n_c} + \frac{CV_c^2}{n_c} \right]^{\frac{1}{2}} \tag{2}$$

where

- K_α = standard normal deviate,
- CV_i = coefficient of variation for the ith component,
- n_i = number of observations for the ith component, and
- r, p, c = within-plane repetitions, between-plane and between-core (within-section) effects.

Figure 3 represents the solution of this limit-of-accuracy relationship for K_α = 1.96 (95 percent confidence); n_r = 5 cycles and CV_r = 1.5 percent, CV_p = 30 percent and CV_c = 5.0 percent. Use of

TABLE 6 ANOVA One-Way Nested Five Levels—Variance Model for M_r

Temperature deg C		Variance Component	Deg of Freedom	Sum of Squares	Mean Square	Est Comp Variance	Est Comp Std Dev
4.4	Total MR	Mix Types	13	1.7713E+12	1.3626E+11	160099563.1	12653.05
		Sections in Mix Type	14	1.8179E+12	1.2985E+11	4188147585	64715.9
		Cores in Section	28	1.2905E+12	4.609E+10	-3568756205	-
		Planes in Core	56	4.5795E+12	8.1777E+10	16351772785	127874.1
		Repetitions	448	8206237630	18317494.7	18317494.71	4279.894
	Instantaneous MR	Mix Types	13	2.4089E+12	1.853E+11	-329072664.1	-
		Sections in Mix Type	14	2.7785E+12	1.9846E+11	5974071843	77292.12
		Cores in Section	28	2.2114E+12	7.898E+10	-7098925281	-
		Planes in Core	56	8.3983E+12	1.4997E+11	29980952599	173150.1
		Repetitions	448	2.8986E+10	64700819.2	64700819.21	8043.682
21.1	Total MR	Mix Types	13	7.6086E+11	5.8528E+10	149344660.3	12220.67
		Sections in Mix Type	14	7.3575E+11	5.2554E+10	50719090.48	7121.734
		Cores in Section	28	1.4431E+12	5.1539E+10	2264713322	47589
		Planes in Core	56	1.618E+12	2.8892E+10	5774968707	75993.21
		Repetitions	448	7779400070	17364732.3	17364732.3	4167.101
	Instantaneous MR	Mix Types	13	1.0105E+12	7.7734E+10	-2320500715	-
		Sections in Mix Type	14	2.3878E+12	1.7055E+11	592487867.5	24341.07
		Cores in Section	28	4.4437E+12	1.587E+11	4760975417	68999.82
		Planes in Core	56	6.2213E+12	1.1109E+11	22210345210	149031.4
		Repetitions	448	1.9137E+10	42716199.4	42716199.36	6535.763
37.8	Total MR	Mix Types	13	2.5842E+11	1.9879E+10	259295003.9	16102.64
		Sections in Mix Type	14	1.331E+11	9506936996	7332560.273	2707.87
		Cores in Section	28	2.6209E+11	9360285791	-252889896.3	-
		Planes in Core	56	6.6579E+11	1.1889E+10	2375901778	48743.22
		Repetitions	448	4334787475	9675864.9	9675864.899	3110.605
	Instantaneous MR	Mix Types	13	3.5777E+11	2.7521E+10	159109654.7	12613.87
		Sections in Mix Type	14	2.9619E+11	2.1157E+10	299201507.4	17297.44
		Cores in Section	28	4.2483E+11	1.5173E+10	-329519810.3	-
		Planes in Core	56	1.0342E+12	1.8468E+10	3687574870	60725.41
		Repetitions	448	1.3434E+10	29987616.3	29987616.31	5476.095

* "-" represents square root of negative value
** variance values in psi (1 psi = 6.89 kPa)

these values leads to a solution that represents a fairly accurate, though approximate, analysis for M_r evaluation at any temperature or type of M_r (total or instantaneous). It should be apparent that the limit of accuracy is nearly insensitive to the M_r value used but that it is highly sensitive to the number of planes (diametrals) tested within a core. As an example, it can be observed from Figure 3 that similar accuracies (i.e., 20 percent) can be achieved either by a combination of two cores and five diametral planes per core or by five cores and two diametral planes per core. Although both testing programs yield the same accuracy, it would obviously be much more economical to select only two core locations and test each core sample in five random plane orientations.

TABLE 7 Summary of Variance Components by CV Value

Mr Type	Variance Component	CV Value at Temperature 4.4 deg.C	21.1 deg.C	37.8 deg.C	Average CV (%)
Total	Between mixes	2.6	3.9	10.9	5.8
	Between sections	13.2	2.3	1.8	5.8
	Cores within sections	0.0	15.0	0.0	5.0
	Planes within cores	26.0	24.0	32.9	27.6
	Repetitions within planes	0.9	1.3	2.1	1.4
Instantaneous	Between mixes	0.0	0.0	7.0	2.3
	Between sections	13.0	5.6	9.5	9.4
	Cores within sections	0.0	15.9	0.0	5.3
	Planes within cores	29.1	34.3	33.5	32.3
	Repetitions within planes	1.4	1.5	3.0	2.0

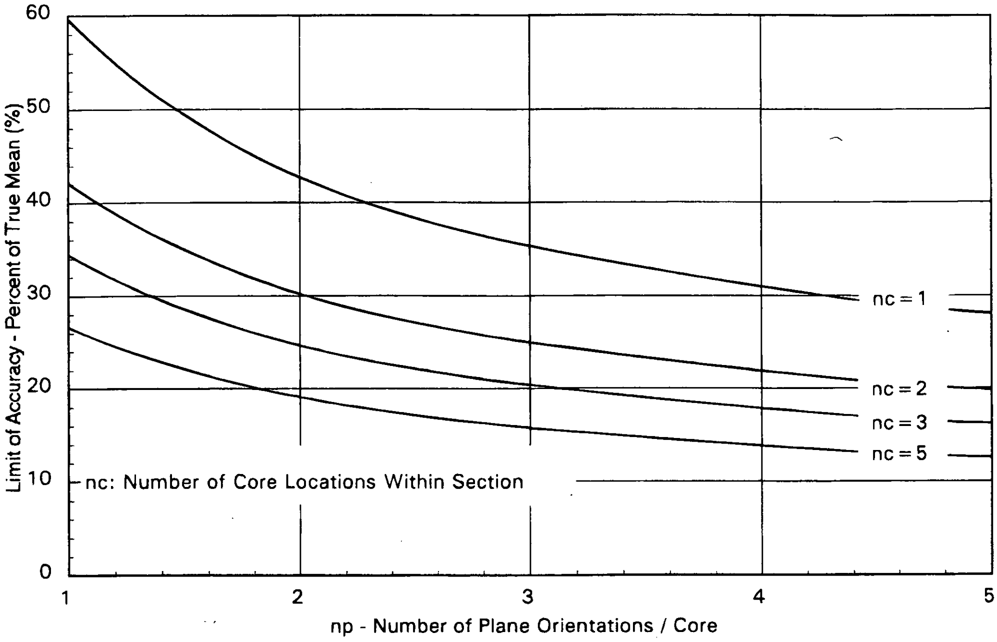

FIGURE 3 Limit of accuracy relationship for M_r evaluation of field cores.

Influence of Mixture Types

The summary of M_r results has been shown in Table 3 for the 14 different mixtures placed in the demonstration test sections. Figures 4 through 8 graphically portray these results. In Figures 4 through 6, the average instantaneous and total M_r, by mix type, are shown for each of the three test temperatures used [4.4°C (40°F), 21.1°C (70°F), and 37.8°C (100°F)]. Figures 7 and 8 show ratios of the M_r results relative to the control mix used. This control mix was an MSHA "SC" dense-graded surface course mix using a Chevron AC-20 binder.

With only a few exceptions, the control mix exhibited the largest M_r values between mixtures, M_r types, and across all temperatures. The most notable exception was both M_r responses, at 37.8°C, for the Plus Ride No. 12 mixture. Modulus ratios of 1.3 to 1.4 times the control mix were obtained.

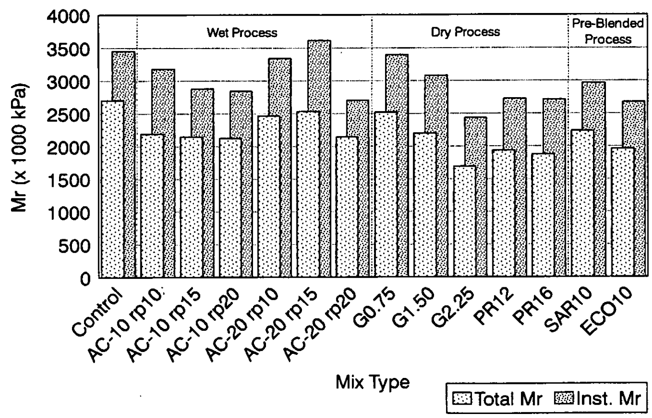

FIGURE 5 Instantaneous and total resilient modulus versus Mix Type—21.2°C.

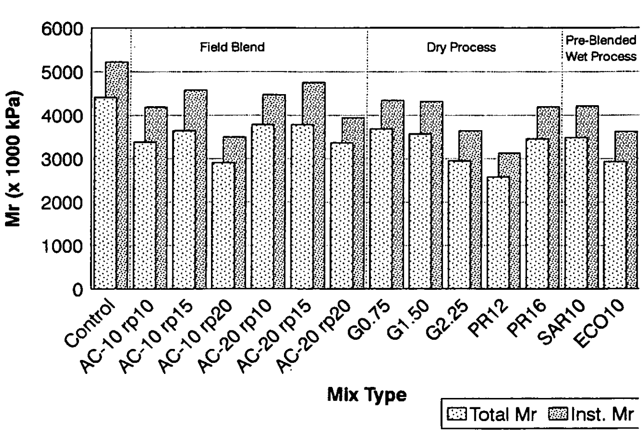

FIGURE 4 Instantaneous and total resilient modulus versus mix type—4.4°C.

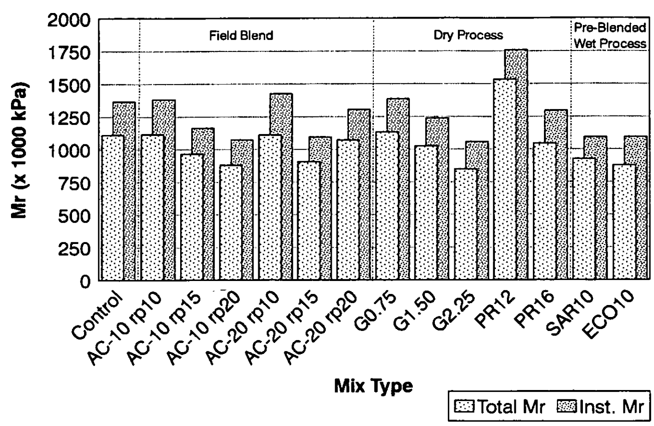

FIGURE 6 Instantaneous and total resilient modulus versus mix type—37.8°C.

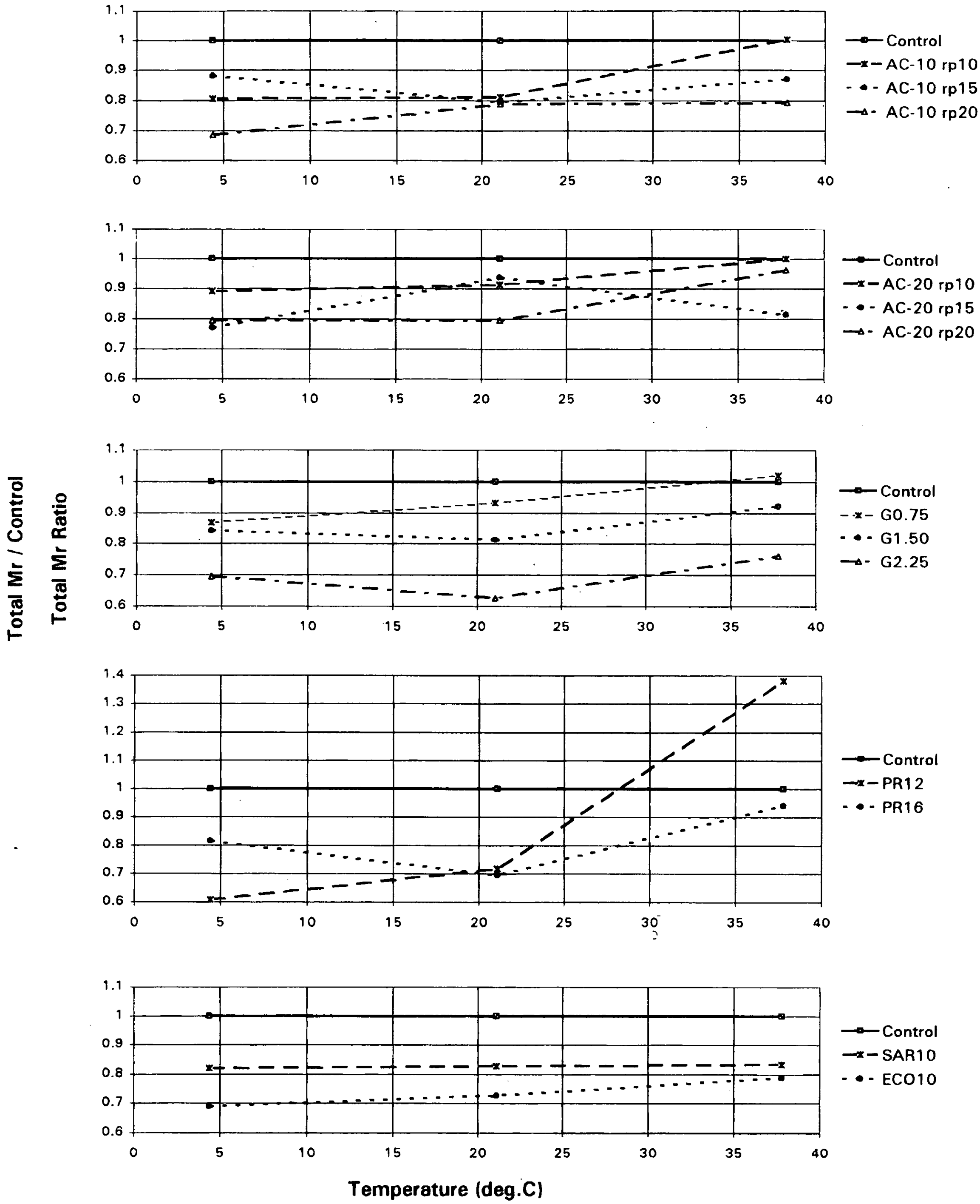

FIGURE 7 Total M_r/control total M_r ratio versus temperature.

For the field-blended wet asphalt rubber mixtures, it is difficult to observe distinct trends in the M_r value as the rubber percentage was increased from 10 to 20 percent. In general, the AC-20 blends gave slightly higher M_r values compared with comparable AC-10 field blends. Additionally, the M_r ratios were about 0.8 at the cold (4.4°C) temperature and increased with temperature to approximately 0.9 to 0.95 at the warm (37.8°C) temperature. At the cool temperature, it appeared that the maximum M_r value occurred at the 15 percent rubber additive for both the AC-10 and AC-20 blends. However at the warmest test temperature, the maximum M_r was associated with the 10 percent rubber additive for both the AC-10 and AC-20 blends.

The manufacturer preblended wet asphalt rubber mixtures (Neste SAR 10/10 and Bitumar Ecoflex) both contain 10 percent rubber additives. As shown in all the figures, the M_r ratio response was about 0.85 across all temperatures for the SAR

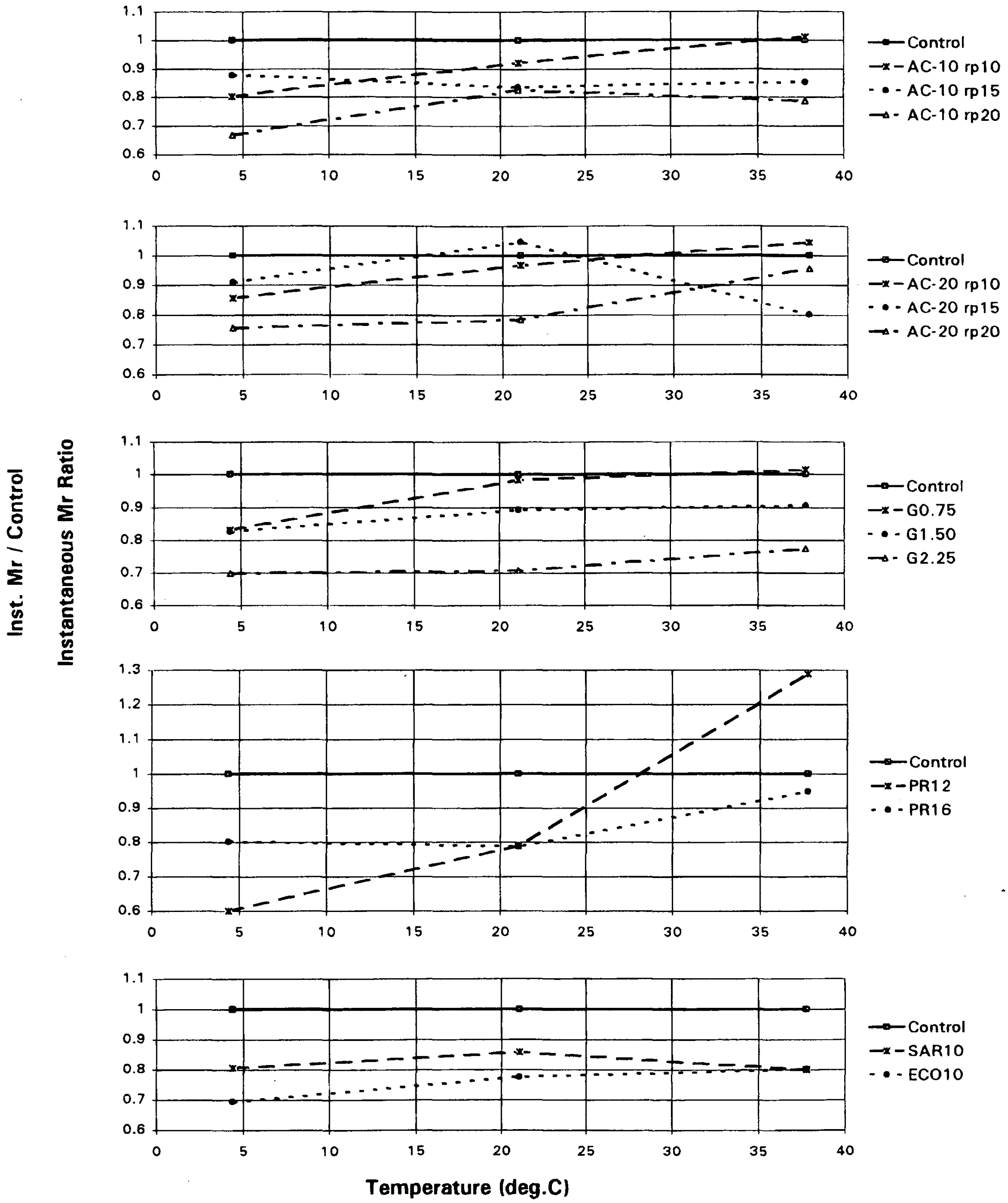

FIGURE 8 Instantaneous M_r/control instantaneous M_r ratio versus temperature.

10/10 and between 0.70 (cool) to 0.80 (warm) for the Ecoflex binder.

For the dry process generic rubber-modified mixtures, the M_r ratio generally decreased with increasing rubber content. For the 0.75 percent rubber blend, the ratio was 0.85 to 0.90 at the cool temperature and approached the control mix modulus at higher temperatures. In contrast, the 2.25 percent rubber blend had M_r ratios between 0.7 and 0.8.

The patented Plus Ride mixes, especially PR No. 12, resulted in the most significant temperature susceptibility to M_r values for all of the mixtures evaluated. The M_r ratio for PR No. 12 mix was found to be about 0.6 at the low temperature and increased to about 1.3 to 1.4 at the warm temperature. In general, PR No. 16 had a larger modulus at 4.4°C than PR No. 12. This trend was reversed at the high temperature (37.8°C) and at the intermediate temperature (21.1°C) both PR mixtures yielded equivalent modulus values.

CONCLUSIONS

The laboratory M_r responses on 180 field cores were obtained from a newly constructed field demonstration project by the Maryland State Highway Administration. This project involves the construction of over 12.5 km of highway composed of 30 separate test sections and 14 different asphalt rubber mixtures. The M_r evaluation of cores was accomplished with the Baladi indirect test fixture using vertical, horizontal, and longitudinal transducers.

Based on the analysis, the following conclusions can be drawn:

1. A statistical ANOVA showed that there is no horizontal anisotropy of the M_r response of the field cores. Thus, the M_r response is independent of the diametral (plane) orientation. As a consequence, there is no need to reference the direction of traffic on cores sampled from field sections.
2. The test analysis allowed for the prediction of five separate sets of M_r estimates, depending upon the type and combination of transducers used. Based upon an ANOVA, it was concluded that the use of only horizontal or longitudinal transducers (three core axis) to determine the M_r response gave significantly different values compared to models that include the vertical measurements. Use of either vertical or both gave statistically identical estimates of the M_r response. It is recommended that the use of both vertical and horizontal transducers be used to accurately measure both the M_r and Poisson's ratio values. For simplicity, if only the M_r response is of interest, the model that includes only vertical measurements can satisfactorily be used in conjunction with an assumed Poisson's ratio value.
3. ANOVA techniques were used to determine the magnitude of five separate variance components within the M_r test. These components are (*a*) repetitions (cycles), (*b*) plane (orientation), (*c*) within section, (*d*) between sections, and (*e*) mix types. It was found that the repetition effect had the smallest source of variation and the plane/diametral orientation had the largest source of variation.
4. Limit of accuracy curves were developed for M_r field core test results within a statistically homogeneous section using the variance (coefficient of variation) values found from the component ANOVA study. As an example, for equivalent accuracy of the M_r response, it was found that it is much more cost-effective to maximize the number of diametral planes tested within a given core relative to increasing the number of cores within a given highway project.
5. In general, the M_r response of the MSHA dense graded (AC-20) control mix resulted in the largest M_r results, across all temperatures, compared with the 13 asphalt rubber mixes investigated. The most notable exception was a Plus Ride No. 12 mix at 37.8°C (100°F) where M_r ratios (relative to the control mix) were 1.3 to 1.4. For all asphalt rubber mixtures, typical M_r ratios varied, on the average, between 0.8 and 0.9. Lower M_r ratios were normally observed at the low test temperature of 4.4°C (40°F), whereas the larger ratios occurred at the high test temperatures. M_r values were generally decreased as the percentage of rubber increased.

Although this study is devoted exclusively to discussions of the M_r response of asphalt rubber mixtures, further studies dealing with tensile strength and permanent deformation behavior are currently being conducted. These results, taken together with the results of nondestructive deflection tests, skid/friction measurements, visual condition surveys, and quality control data, will allow for a more comprehensive evaluation of the field performance of the asphalt-rubber mixtures used in the demonstration project.

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REFERENCES

1. Witczak, M. W. *State of the Art Use of Ground Rubber in Hot Mix Asphalt.* Synthesis Report to the Maryland Department of Transportation, University of Maryland at College Park, 1991.
2. Witczak, M. W. *Field Coring and Test Plan* (Manual). Maryland State AWO-093-360-046, Maryland Department of Transportation, SHA, 1993.
3. Mirza, M. W., and M. W. Witczak. *Bituminous Mix Dynamic Material Characterization-Data Acquisition and Analysis Programs Using 45820 MTS Controller.* Program Background and Users' Guide, University of Maryland at College Park, 1994.
4. Gilson Company, Inc. *Baladi INTT Fixture—Instructions for Test Procedures, Analytical Analysis, Maintenance and System Verification* (Manual).

The views and opinions presented are those of the authors and not those of the Maryland Department of Transportation.

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