

Analysis of Resilient Modulus of Dense- and Open-Graded Aggregates

ANDREW G. HEYDINGER, QINGLU XIE, BRIAN W. RANDOLPH, AND
JIWAN D. GUPTA

The results of analyses of laboratory resilient modulus testing conducted on dense-graded and open-graded aggregates are presented. The testing program included three different aggregate materials (crushed limestone, natural stone, and slag), five different gradation specifications, and three different moisture conditions (dry, moist, and saturated). In addition to the five aggregate specifications, test specimens were prepared so that they would satisfy the lower, central, and upper bounds for the gradations. Resilient modulus tests were conducted as closely as possible according to Strategic Highway Research Program Protocol P-46 (AASHTO T 294-92 I). The test results were analyzed using log-linear regression analysis with two-parameter (bulk stress) and three-parameter (bulk stress and octahedral shear stress) expressions for resilient modulus. The results of the testing indicate that the resilient modulus of aggregates and regression constants vary significantly depending on the type of material and vary less significantly depending on material gradation and moisture condition. The natural stone aggregates had the higher moduli and the slag aggregate had the lowest moduli. The resilient modulus does not vary significantly as the moisture content increases unless the aggregate becomes saturated. The R^2 values are consistently higher using a three-parameter expression than a two-parameter expression.

The Ohio Department of Transportation (ODOT) specifies the gradational characteristics of dense-graded and open-graded aggregates that are unstabilized or stabilized with asphalt or portland cement. Important engineering properties such as hydraulic conductivity and resilient modulus were required. Therefore, a project was initiated to investigate several aggregates for permeability and resilient modulus (1). The resilient moduli of unstabilized base and subbase materials were investigated as a function of material variation for this study.

The resilient modulus is an elastic modulus obtained from dynamic loading, defined as the ratio of the cyclic deviator stress to the resilient (recoverable) strain. It provides an indication of the degree of compliance of a layer in a pavement system under repeated traffic loading. Generally, a high resilient modulus for a base material will increase the usable pavement life. Therefore, it is important to have knowledge about the resilient properties of the pavement materials.

Design for pavements and rehabilitation of layered pavement systems use resilient modulus as an essential parameter for pavement design. Design procedures for determining layer thicknesses for flexible pavements include resilient moduli (2,3). According to the AASHTO 1993 design guide for roadbed materials, laboratory resilient modulus tests must be performed on representative samples in stress and moisture conditions simulating those of the primary moisture seasons (2). An interim test method for laboratory testing of unbound materials, Strategic Highway Research Program (SHRP)

Protocol P46 (AASHTO T 294-92 I), has been developed (4,5). The resilient modulus is an important parameter determined from non-destructive pavement testing and back-calculation analysis (6).

SCOPE OF INVESTIGATION

This investigation includes results of laboratory resilient modulus tests on unstabilized dense- and open-graded aggregates. Specimens of various aggregate types, gradations, and moisture conditions were tested to investigate material effects on resilient modulus. Test procedures detailed in SHRP Protocol P46 (AASHTO T 294-92 I) were followed for the testing wherever possible. The results were analyzed using two- and three-parameter log-linear regression analysis.

MATERIALS TESTED

The aggregates used for the testing were supplied by ODOT. The aggregates have been used for construction in northern Ohio. The types of aggregates included crushed limestone ($G_s = 2.70$), natural sand and gravel ($G_s = 2.66$), and slag ($G_s = 2.50$). The slag is an air-cooled blast furnace slag. The material gradations shown in Table 1 are ODOT specifications 304 and 310 soils, AASHTO M43 specification 57 (No. 57) aggregates, the New Jersey test base materials (NJ Mix), and the Iowa Department of Transportation granular base specification 41-21 (Iowa Mix). For the gradations, the lower (L)- and upper (U)-bound gradations were the minimum and maximum percentages, respectively. The central (C) gradation percentages are the averages of the lower and upper bounds. The central gradations were used for all test specimens for specification 57 and NJ Mix.

TEST PROGRAM

Specimens were prepared and tested as shown in Table 2. One specimen was tested for each moisture content indicated. Moist samples were prepared by saturating the samples and subsequently allowing the water to drain freely from the samples until drainage was completed. Tests were conducted on dry or moist specimens, except for two specimens, which were tested under saturated conditions.

SAMPLE PREPARATION

The testing required compacting test specimens to dry densities typically achieved on construction projects in Ohio. All test specimens

TABLE 1 Specifications for Material Gradations

Sieve	No. 304			No. 310			Iowa Mix			NJ Mix	No. 57
	L	C	U	L	C	U	L	C	U		
2 1/2"	-	-	-	100	100	100	-	-	-	-	-
2"	100	100	100	-	-	-	-	-	-	-	-
1 1/2"	-	-	-	-	-	-	-	-	-	100	100
1"	70	85	100	70	85	100	100	100	100	95-100	95-100
3/4"	50	70	90	-	-	-	-	-	-	-	-
1/2"	-	-	-	-	-	-	50	65	80	60-80	25-60
3/8"	-	-	-	-	-	-	-	-	-	-	-
#4	30	45	60	25	62.5	100	-	-	-	40-55	0-10
#8	-	-	-	-	-	-	10	22.5	35	5-25	0-5
#16	-	-	-	-	-	-	-	-	-	0-8	-
#30	7	18.5	30	-	-	-	-	-	-	-	-
#40	-	-	-	5	27.5	50	-	-	-	-	-
#50	-	-	-	-	-	-	0	7.5	15	0-5	-
#200	0	6.5	13	0	5	10	0	3	6	0	-

Legend: L - Lower Bound Gradation; C - Central Gradation; U - Upper Bound Gradation

were prepared by compacting air-dried aggregates in compaction molds. Required proportions of the aggregate sizes were obtained using a mechanical sieve shaker. A compaction mold measuring 152 mm (6 in.) in diameter by 304 mm (12 in.) long was lined with a rubber membrane before compaction. Test specimens were then compacted on a vibratory table in the mold using several lifts. A vacuum of 103.4 kPa (15 psi) was applied to the specimen before it was placed in the triaxial cell. Water was added to the samples through the base to achieve moist and saturated conditions.

TEST PROCEDURES

A triaxial pressure chamber and a closed-loop electrohydraulic testing system was used for the testing. The following procedures used for this test program were developed for the SHRP Protocol P-46 (5).

Conditioning

Apply 500 cycles of load sequence 0 (see Table 3) using a haversine load impulse, to be described. The sample conditioning reduces the effects of sample preparation and ensures better contact between the sample cap and the test specimen.

TABLE 2 Resilient Modulus Tests

Specification	Gradation	Limestone	Gravel	Slag
No. 57	C	D,M	D,M	D,M
NJ Mix	C	D,M	D,M	D,M
	L	D,M		
Iowa Mix	C	D,M,S	D,M	D,M
	U	D,M		
No. 304	L		D,M	
	C	D,M,S	D,M	D,M
No. 310	U		D,M	
	L			D,M
Grading A	C	D,M	D,M	D,M
	U			D,M

LEGEND: D - Air Dried; M - Moist; S - Saturated

TABLE 3 Testing Sequences

Sequence	Maximum		No. of
	Confining	Deviator	
No.	Stress	Stress	Cycles
	kPa	kPa	
0	103.4	103.4	500
1	20.7	20.7	100
2	20.7	41.4	100
3	20.7	62.1	100
4	34.5	34.5	100
5	34.5	68.9	100
6	34.5	103.4	100
7	68.9	68.9	100
8	68.9	137.9	100
9	68.9	206.8	100
10	103.4	68.9	100
11	103.4	103.4	100
12	103.4	206.8	100
13	137.9	103.4	100
14	137.9	137.9	100
15	137.9	275.8	100

1 psi = 6.89 kPa

Testing

Apply 100 cycles for each load sequence. Numbers 1 through 15 (see Table 3). Each load cycle, applied for a duration of 1 sec, consisted of (a) a static confining stress provided by the triaxial chamber pressure, (b) an axial deviator stress applied using a haversine-shaped load pulse for a duration of 0.1 sec, and (c) a rest period of 0.9 sec in which a deviator stress (contact stress) equal to 10 percent of the maximum deviator stress is maintained. The contact stress ensures that the loading ram will remain in contact with the top loading platen. In Table 3 the maximum deviator stress is the maximum applied stress in excess of the confining stress and the maximum cyclic stress is equal to the difference between the maximum deviator stress and the contact stress.

TEST RESULTS

A data acquisition system, electronic load cell, and two electronic displacement transducers (LVDTs) were used to record the load-time and displacement-time histories. The actual applied loads as measured by the load transducer were used for all stress calculations. Values of maximum cyclic stress and resilient deformation were determined for each test sequence for each of the last 5 sec (95 to 100 sec) using the load-time and displacement-time histories and the averages of the two displacement transducers. Examples of the histories are shown in Figures 1 and 2. The computed maximum cyclic stress and resilient strain were used to compute resilient modulus. An example of the results from one test specimen is shown in Table 4. The particular specimen is a crushed limestone aggregate prepared using the central bound of the No. 57 specification and tested in the moist con-

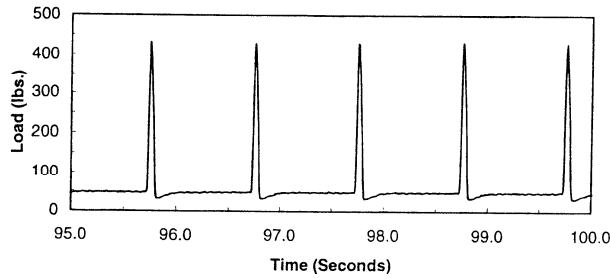


FIGURE 1 Example of load-time history.

dition. The resilient modulus values were determined by averaging the last five load cycles from each load sequence. The minimum and maximum values of resilient modulus for all test specimens are shown in Table 5, and values of resilient modulus are provided for all test specimens for Sequence 11. In all cases the minimum values of resilient modulus occurred during Sequence 1, and the maximum values were obtained during Sequence 15.

ANALYSIS OF TEST RESULTS

The resilient modulus of aggregate materials is a function of the state of stress. A two-parameter equation has been proposed to characterize the resilient modulus of untreated aggregate materials in terms of the bulk stress (5-9).

$$M_r = k_1(\theta)^{k_2} \quad (\text{MPa}) \quad (1)$$

where

- θ = bulk stress, the sum of principal stresses, $\sigma_1 + \sigma_2 + \sigma_3$;
- σ_1 = maximum vertical stress;
- σ_2, σ_3 = confining stress; and
- k_1, k_2 = regression constants.

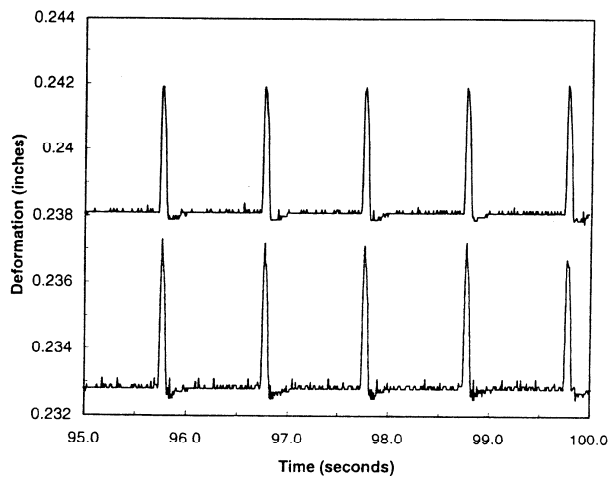


FIGURE 2 Example of deformation-time history.

TABLE 4 Calculation of Resilient Modulus

Sequence No.	Bulk Stress	Actual Maximum Cyclic Stress	Average Resilient Strain	Resilient Modulus
	kPa	kPa	-	MPa
1	81.2	17.0	0.000356	47.6
2	101.9	36.3	0.000363	100.1
3	123.0	55.9	0.000436	128.3
4	141.8	35.4	0.000343	103.3
5	175.7	66.1	0.000419	157.8
6	216.6	103.1	0.000566	182.3
7	275.9	62.0	0.000298	207.9
8	339.8	120.0	0.000469	255.8
9	411.8	183.8	0.000671	274.0
10	382.3	64.5	0.000303	212.8
11	414.9	93.1	0.000335	278.2
12	507.7	175.3	0.000549	319.2
13	526.3	101.1	0.000323	313.5
14	543.5	114.3	0.000355	322.0
15	702.0	257.1	0.000651	395.2

1 psi = 6.89 kPa

For triaxial conditions, the bulk stress reduces to $\sigma_1 + 3\sigma_3$. Reported values of the regression constants are given in Table 6.

A three-parameter equation was used for this study to characterize resilient modulus in terms of the bulk stress and the octahedral shear stress.

$$M_r = k_3(\theta)^{k_4}(\tau_o)^{k_5} \quad (\text{MPa}) \quad (2)$$

where

- τ_o = octahedral shear stress, $1/3[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$ and
- k_3, k_4, k_5 = regression constants.

For triaxial conditions, the octahedral shear stress is equal to $\sqrt{2}/3$ times deviator stress. The maximum cyclic stress was used for the deviator stress.

Results were analyzed using Equations 1 and 2. Figures 3 and 4 are examples of logarithmic plots of resilient modulus versus bulk stress and octahedral stress. Log-linear regression analyses were performed for both the two- and three-parameter expressions using computer spreadsheet software. The analyses were performed using units of kilopascals for stress and megapascals for resilient modulus. Results of two- and three-parameter regression analyses of all test specimens are given in Tables 7 and 8.

Additional regression analyses were conducted after reviewing the resilient modulus data in Table 5 and the regression analysis data in Tables 7 and 8. For example, the variations in resilient modulus are not significant for specimens with the same specifications and gradations but with different moisture conditions (D, M). Variations also are not large when comparing specimens with the same specification but with different gradations (L, C, U) and when comparing specimens with different specifications and gradations. Therefore, additional regression analyses were conducted using several combinations of the data. The results are shown in Table 9 for the two-parameter equation and in Table 10 for the three-parameter equation.

TABLE 5 Results of Resilient Modulus Testing

Specification	Gradation	Moist. Cond.	Limestone		Gravel		Slag	
			Range of M_r (MPa)	1M_r (MPa)	Range of M_r (MPa)	1M_r (MPa)	Range of M_r (MPa)	1M_r (MPa)
No. 57	C	D	51.4 - 429.7	298.4	73. - 509.	357.6	30.4 - 194.6	163.9
	C	M	47.6 - 394.9	278.	70.3 - 501.7	349.1	27.5 - 185.5	156.3
NJ Mix	C	D	60.8 - 411.9	305.4	79.4 - 460.4	381.1	30.3 - 197.1	163.7
	C	M	58.7 - 386.3	288.2	71.1 - 438.8	363.1	33.6 - 192.6	163.1
Iowa Mix	L	D	41.6 - 283.	215.	69.7 - 460.3	344.9	37.2 - 232.3	187.9
	L	M	42.8 - 261.7	206.2				
	C	D	45.3 - 278.4	214.8				
	C	M	44.1 - 283.7	212.7	58.7 - 430.9	313.4	35.2 - 236.8	188.2
	C	S	29.7 - 285.6	196.2				
	U	D	50.4 - 295.9	218.7				
	U	M	51. - 307.	216.5				
No. 304	L	D			71.5 - 470.3	403.4		
	L	M			69.1 - 451.2	349.3		
	C	D	50.4 - 314.9	234.5	70.2 - 447.9	324.	33.4 - 237.8	190.6
	C	M	47.6 - 300.1	236.7	58.3 - 426.9	316.6	33.3 - 252.	188.2
	C	S	36.5 - 293.2	236.8				
	U	D			67.6 - 481.7	347.1		
	U	M			68.3 - 453.2	354.2		
No. 310 Grading A	L	D					26.9 - 212.4	168.
	L	M					29.7 - 215.5	161.9
	C	D	47.4 - 298.1	224.4	75.7 - 526.2	391.9	29.4 - 211.9	169.9
	C	M	49.6 - 299.	214.7	70.6 - 501.7	386.	31.5 - 213.9	166.3
	U	D					36.2 - 218.3	177.2
U	M					34.9 - 219.8	172.6	

¹ M_r = Resilient modulus in for Sequence No. 11 with both confining stress and maximum deviator equal to 103.4 kPa (15 psi).

CONCLUSIONS

The resilient modulus of aggregates is dependent on material type, gradation, and moisture condition. On the basis of the results shown in Table 5, the gravel aggregate consistently has the highest resilient modulus, followed by limestone and then slag. For the limestone aggregate, the open-graded specifications had higher moduli than the dense-graded specifications. The moduli were highest for the upper gradation and lowest for the lower gradation for the Iowa mix. The sensitivity to gradation and moisture condition was most pronounced at the lower stress levels. For the gravel aggregate, there was no strong trend for the variation of moduli with respect to gradation. The moduli obtained from moist samples usually were lower than those from the dry samples, particularly at the lower stress levels. For the slag aggregate, the denser gradations tended to have high moduli. At lower stress levels, the moduli increased as the gradation varied from the lower to the upper bound for the Number 310 specification. There was no consistent trend for the variation of modulus with moisture condition.

The results of the two-parameter regression analyses shown in Table 7 were used to investigate the dependence of resilient modulus on the level of stress. Because the parameter k_2 is the slope of the line, a high value of k_2 indicates high sensitivity to the level of stress. For the limestone aggregate, the open-graded specifications had higher values of k_2 and R^2 than the dense-graded specifications. For

TABLE 6 Two-Parameter Regression Coefficients

¹ k_1	k_2	Reference
1600 - 5000	0.57 - 0.73	Hicks and Monismith (7)
2900 - 7750	0.46 - 0.65	Monismith et al., (10)
1300 - 2000	0.69 - 0.778	Albright, (11)
1800 - 4400	0.51 - 0.62	Zhou et al. (12)
3000 - 8000	0.50 - 0.70	AASHTO, 1993 (2)

¹Values of k_1 , in psi, do not convert directly to kPa.

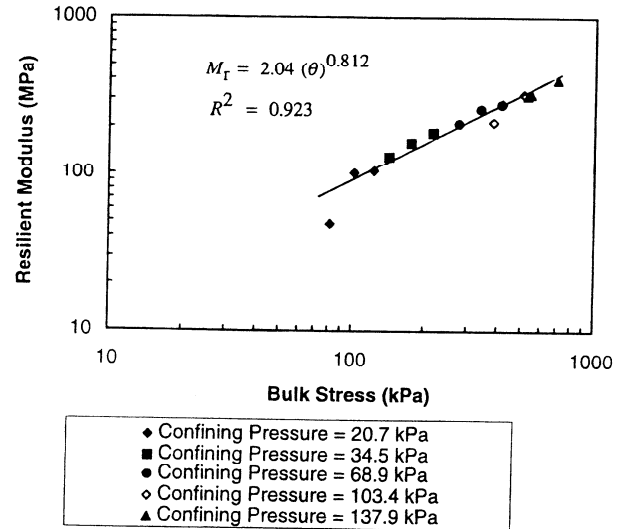


FIGURE 3 Resilient modulus versus bulk stress.

the Iowa Mix, the constants decreased as the gradation varied from the lower to the upper bound. Values of k_2 generally decrease with an increase in moisture. For the gravel aggregate, there is no consistent trend in the variation of the constants k_2 and R^2 with variation of the specifications or the gradations. There are variations with moisture condition, but the variation also is not consistent. For the slag aggregate, the dense-graded specifications tended to have higher constants than the open-graded specifications. The values of k_2 decreased as the gradation varied from the lower to the upper bounds for the Number 310 specification. The effects of moisture condition are not consistent.

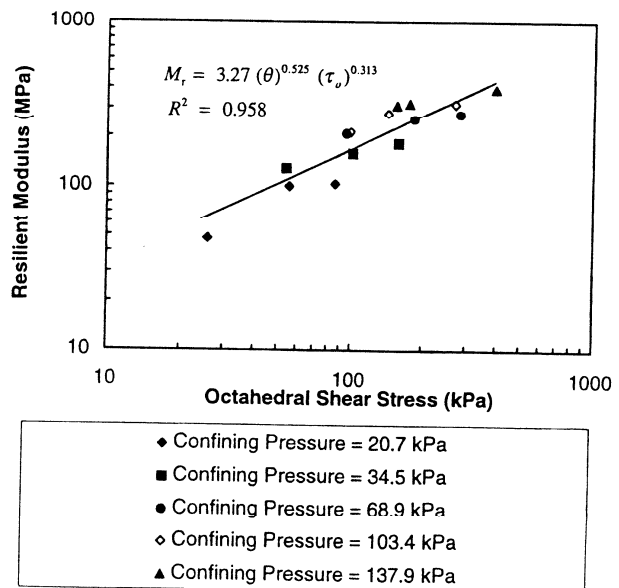


FIGURE 4 Resilient modulus versus octahedral shear stress.

TABLE 7 Regression Constants for Two-Parameter Equation

Specifi- cation	Grada- tion	Moist. Cond.	Limestone			Gravel			Slag		
			k ₁	k ₂	R ²	k ₁	k ₂	R ²	k ₁	k ₂	R ²
No. 57	C	D	1.94	.829	.932	4.31	.730	.903	2.49	.678	.865
	C	M	2.04	.812	.923	4.09	.736	.904	2.06	.702	.868
NJ Mix	C	D	3.91	.716	.900	6.5	.659	.865	2.02	.711	.885
	C	M	4.6	.681	.877	5.74	.673	.865	3.19	.636	.847
Iowa Mix	L	D	2.79	.712	.892	4.27	.720	.897	3.11	.667	.867
	L	M	3.52	.664	.873						
	C	D	4.04	.652	.861						
	C	M	3.77	.664	.867						
	C	S	0.84	.898	.942						
	U	D	4.9	.627	.854						
No. 304	L	D	4.46	.654	.859	4.68	.718	.881	1.88	.751	.900
	L	M				5.52	.680	.868			
	C	D				5.27	.679	.883			
	C	M				4.25	.659	.852			
	C	S				1.96	.776	.897			
	U	D				4.1	.731	.903			
No. 310 Grading A	L	D	3.28	.691	.885	4.37	.717	.893	2.58	.684	.883
	L	M				1.29	.794	.908			
	C	D				1.69	.748	.903			
	C	M				1.77	.744	.888			
	U	D				2.17	.708	.889			
	U	M				2.85	.670	.874			

The results of the three-parameter regression analyses shown in Table 8 were used to investigate the dependence of resilient modulus on both stress level and octahedral shear stress using the k_4 and k_5 constants. Since both constants k_2 and k_4 are dependent on the level of stress, it could be expected that the conclusions observed from the three-parameter analyses should parallel those of the two-parameter analyses mentioned above. Comparing Tables 7 and 8, it can be seen that this is the case. The dependence of resilient modulus on the maximum cyclic (octahedral shear) stress can be observed from Figure 4 and Table 8. There are small variations of the constant

k_5 in Table 8 ($0.301 < k_4 < 0.353$). There are no consistent trends in the variations of the constants. The values of R^2 were consistently higher for the three-parameter analyses than for the two-parameter analyses. This indicates that the modulus depends both on the level of stress and the deviator stress.

Use of the regression constants in Tables 9 and 10 would be more representative of the variations that occur on construction projects. The equations have greater statistical significance since they are obtained using larger data bases. Values of variance R^2 were greater than 0.8 for all cases including when dense- and open-graded bases are analyzed. However, there are differences between dense- and open-graded gradations that merit further investigation.

The two limestone specimens tested at a saturated condition have significantly lower moduli, particularly at low stress levels. This illustrates the importance of designs that are effective in preventing saturation in the base and subbase layers.

The results of this testing program can serve as a guide in selecting values for resilient modulus. The precision and bias of the test procedures are not known. There was only one source each for the crushed limestone—natural stone and slag aggregates that were used for the testing. Therefore one could expect deviations from the results for aggregates obtained from other sources. The deviations could be significant if an aggregate is close to being out of specification with respect to other material properties.

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TABLE 8 Regression Constants for Three-Parameter Equation

Specifi- cation	Grada- tion	Moist. Cond.	Limestone				Gravel				Slag			
			k ₃	k ₄	k ₅	R ²	k ₃	k ₄	k ₅	R ²	k ₃	k ₄	k ₅	R ²
No. 57	C	D	3.11	.550	.301	.962	6.91	.440	.319	.947	4.41	.356	.338	.918
	C	M	3.27	.525	.313	.958	6.6	.443	.320	.948	3.67	.378	.342	.920
NJ Mix	C	D	6.43	.419	.323	.943	10.62	.357	.331	.921	3.38	.409	.325	.932
	C	M	7.86	.366	.337	.931	9.49	.371	.328	.919	5.25	.333	.330	.906
Iowa Mix	L	D	4.72	.406	.328	.940	6.79	.430	.320	.944	5.21	.358	.333	.921
	L	M	5.89	.357	.332	.929								
	C	D	6.69	.342	.340	.922								
	C	M	6.54	.347	.339	.924								
	C	S	1.31	.630	.291	.967								
	U	D	7.9	.322	.337	.917								
No. 304	L	D	9.81	.282	.353	.894	7.49	.427	.318	.924	3.04	.458	.320	.941
	L	M	9.23	.371	.333	.921								
	C	D	7.36	.345	.339	.919								
	C	M	7.19	.343	.344	.912								
	C	S	3.41	.464	.329	.938								
	U	D	6.94	.426	.325	.947								
No. 310 Grading A	L	D	7.04	.426	.318	.938	7.81	.428	.320	.938	2.19	.490	.326	.947
	L	M	2.74	.454	.321	.946								
	C	D	5.46	.393	.319	.933								
	C	M	6.59	.453	.319	.941								
	U	D	4.61	.372	.325	.926								
	U	M	4.26	.384	.323	.933								

TABLE 9 Regression Constants for Two-Parameter Equation

Specification	Gradation	Moist. Cond.	Limestone			Gravel			Slag		
			k ₁	k ₂	R ²	k ₁	k ₂	R ²	k ₁	k ₂	R ²
No. 57	C	D,M	1.98	.821	.926	4.2	.733	.903	2.26	.690	.864
NJ Mix	C	D,M	4.25	.698	.884	6.11	.666	.863	2.53	.674	.864
Iowa Mix	L	D,M	3.13	.688	.881	3.67	.739	.895	2.81	.685	.873
	C	D,M	3.9	.658	.864						
	U	D,M	5.26	.618	.836						
No. 304	L	D,M	4.35	.657	.855	5.08	.699	.871	1.72	.767	.908
	C	D,M				4.31	.709	.887			
	U	D,M				4.23	.724	.898			
No. 310	L	D,M	3.7	.671	.876	4.5	.731	.894	1.48	.771	.905
	C	D,M							1.96	.726	.888
	U	D,M							2.71	.677	.878
Iowa, No. 304	C	S	1.3	.834	.900						
No. 57, NJ Mix	C	D,M	2.9	.760	.898	5.06	.700	.882	2.39	.682	.863
Iowa, No. 304, No. 310	L,C,M	D,M	4.	.659	.851	4.32	.721	.875	2.07	.725	.877
Iowa, No. 304, No. 310	L,C,M	D,M,S	3.32	.688	.846						
All Data			3.21	.706	.814	4.52	.715	.876	2.15	.713	.866

TABLE 10 Regression Constants for Three-Parameter Equation

Specification	Gradation	Moist. Cond.	Limestone				Gravel				Slag			
			k ₃	k ₄	k ₅	R ²	k ₃	k ₄	k ₅	R ²	k ₃	k ₄	k ₅	R ²
No. 57	C	D,M	3.19	.537	.308	.959	6.72	.442	.320	.947	4.03	.366	.341	.917
NJ Mix	C	D,M	7.08	.395	.327	.934	10.05	.364	.329	.918	4.21	.370	.329	.917
Iowa Mix	L	D,M	5.28	.381	.330	.932	6.	.441	.325	.940	4.75	.375	.332	.925
	C	D,M	6.6	.345	.340	.923								
	U	D,M	8.78	.304	.342	.902								
No. 304	L	D,M	7.29	.343	.342	.915	8.33	.398	.326	.919	2.82	.474	.316	.947
	C	D,M					7.16	.404	.330	.935				
	U	D,M					7.	.426	.321	.943				
No. 310	L	D,M	6.09	.371	.325	.929	7.18	.439	.321	.939	2.45	.472	.324	.946
	C	D,M									3.27	.423	.325	.933
	U	D,M									4.43	.378	.324	.929
Iowa, No. 304	C	S	1.91	.561	.293	.928								
No. 57, NJ Mix	C	D,M	4.74	.467	.317	.938	8.22	.403	.324	.931	4.11	.368	.336	.916
Iowa, No. 304, No. 310	L,C,M	D,M	6.71	.348	.337	.908	7.12	.419	.328	.921	3.43	.424	.324	.921
Iowa, No. 304, No. 310	L,C,M	D,M,S	5.52	.384	.329	.895								
All Data			5.31	.405	.326	.859	7.4	.415	.327	.923	3.61	.407	.330	.913

REFERENCES

- Randolph, B. W., A. G. Heydinger, and J. D. Gupta. *Permeability and Stability of Base and Subbase Material*. Draft Report. Department of Civil Engineering, University of Toledo, Toledo, Ohio, 1995.
- The AASHTO Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1993.
- Yoder, E. J., and M. W. Witzczak. *Principles of Pavement Design*, 2nd ed. John Wiley and Sons, New York, 1975.
- Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils—SHRP Protocol P46* (AASHTO Designation: T 294-92 I), FHWA, U.S. Department of Transportation, 1992.
- Interim Specifications for Transportation Materials and Methods of Sampling and Testing*. AASHTO, Washington, D.C., 1992.
- Sargand, S. M., G. A. Hazen, B. E. Wilson, and A. C. Russ. *Evaluation of Resilient Modulus by Back-Calculation Technique*. Department of Civil Engineering, Ohio University, Athens, Oct. 1991.
- Hicks, R. G., and C. L. Monismith. Factors Influencing the Resilient Response of Granular Materials. In *Highway Research Record 345*, HRB, National Research Council, Washington, D.C., 1971.
- Thompson, M. R., and K. L. Smith. Repeated Triaxial Characterization of Granular Bases. In *Transportation Research Record 1278*, TRB, National Research Council, Washington, D.C., 1990.
- Rada, G. and M. W. Witzczak. Comprehensive Evaluation of Laboratory Resilient Moduli Results for Granular Material. In *Transportation Research Record 810*, TRB, National Research Council, Washington, D.C., 1981.
- Monismith, C. L., J. A. Epps, D. A. Kasianchuk, and D. B. McLean. *Asphalt Mixture Behavior in Repeated Flexure*. Report TE 70-5. University of California, Berkeley, Jan. 1972.
- Albright, S. *Evaluation of Crushed Aggregate Specifications Used by the Alaska Department of Transportation and Public Facilities*. M.S. thesis. Department of Civil Engineering, Oregon State University, Corvallis, 1986.
- Zhou, H., L. Moore, J. Huddleston, and J. Gower. *Free Draining Base Materials Properties*, Research Unit/Pavements Unit, Oregon Department of Transportation, Salem, March 1992.

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tion such that available flail-space and other key measures are placed in the computerized file. Concentrate this effort to capture impact situations not now captured (i.e., angle, speed, and vehicle size gaps in the analysis file).

2. Attempt to identify additional crash-test conditions from non-FHWA or new FHWA-NCHRP tests not now in the library, concentrating on combinations that increase the variability of the test conditions.

3. Consider future (research, rather than compliance) funding for tests that increase the variability in the crash-test data by varying the vehicles and the speed and impact angles tested. For research, the vehicles tested within the weight classes should constitute as large a share of vehicles in the existing population as possible. This could be determined by examination of vehicle registration files supplemented by knowledge of possible clones.

4. Examine the possible use of other accident files, such as the National Accident Sampling System or the Longitudinal Barrier Special Study, which include information on estimated impact speed and angle and enhanced injury data, or the possibility of new large-scale crash reconstruction efforts targeted to vehicles used in crash testing. (Sample size will be a problem in the existing files if the clone requirement is retained.)

5. Consider alternative methodology involving "pseudo" measures of injury such as Head Injury Criteria and that of the Texas Transportation Institute through comparison of flail-space or traditional measures with data from anthropomorphic dummies. Problems with such dummy-related measures exist (e.g., correlation with injury and variability due to out-of-position dummies) and must be considered carefully in such research.

In summary, this has been a limited effort at attempting to define relationships between crash-test measures and occupant severity. Although it was not successful, there remains a clear need to determine whether the measures currently used in the design and testing of roadside features indeed maximize protection for occupants of the vehicles while minimizing cost.

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REFERENCES

1. Michie, J., *NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*. TRB, National Research Council, Washington, D.C., March 1981.
2. Shoemaker, N. *Summary Report of Highway Barrier Analysis and Test Programs*. Report VJ-1472-V-3. Cornell Aeronautical Laboratory, Cornell University, Buffalo, N.Y., 1961.
3. Bronstad, M., and J. Michie. *NCHRP Report 153: Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances*. TRB, National Research Council, Washington, D.C., 1974.
4. *Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances*. Transportation Research Circular 191. TRB, National Research Council, Washington, D.C., 1978.
5. Ross, H., E. Post, E. Nixon, D. Hustace, and E. Kristaponis. E. V. Warrents for Guardrails on Embankments. In *Highway Research Record 460*, TRB, National Research Council, Washington, D.C., 1973, pp. 85-96.
6. Young, R., E. Post, and R. Holcomb. *Simulation of Vehicle Impact with the Texas Concrete Median Barrier, Vol. 1. Test Comparison and Parameter Study*. Texas Transportation Institute, College Station, Tex., 1972.
7. Cook, J., and A. Bodocsi. *Criteria for Yielding Sign Supports*. University of Cincinnati, Cincinnati, Ohio, 1970.
8. Michie, J. Collision Risk Assessment Based on Occupant Flail Space Model. In *Transportation Research Record 796*, TRB, National Research Council, Washington, D.C., 1981.
9. Begeman, P., A. King, P. Weigt, and W. Patrick. *Safety Performance of Asymmetric Windshields*. SAE Paper 791009. Society of Automotive Engineers, New York, 1978.
10. Kornhauser, M. and A. Gold. Application of Impact Sensitivity Method to Animate Structures. *Impact Acceleration Stress*. NRC Publication 977. National Research Council, Washington, D.C., 1961, pp. 333-344.
11. Chi, M. *Assessment of Injury Criteria in Roadside Barrier Tests*. Report FHWA-RD-75-74. Federal Highway Administration, Washington, D.C., 1976.
12. Snyder, R. *State-of-the-Art—Human Impact Tolerance*. SAE Paper 700398. Society of Automotive Engineers, New York, May 1970.
13. *Branham Automobile Reference Book*. Branham Publishing Co., Santa Monica, Calif., various years.
14. *Vehicle Damage Scale for Traffic Accident Investigators (Third Edition)*. National Safety Council, Chicago, Ill., 1984.
15. Rouse, W., and F. Gendre. *Field Experience and Evaluation of the TAD Vehicle Damage Rating Scale*. University of North Carolina, Highway Safety Research Center, Chapel Hill, 1969.
16. Vilardo, F. *Vehicle Damage Scale for Traffic Accident Investigators: An Investigation of Its Use and Potential for Predicting Driver Injury*. University of North Carolina, Highway Safety Research Center, Chapel Hill, August 1972.

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