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EFFECT OF AGGREGATE SOURCE AND GRADATION ON THE RESILIENT BEHAVIOR OF BASES AGGREGATE

Abdulrahman Al-Suhaibani

King Saud University, Riyadh, Saudi Arabia

ABSTRACT

The recent AASHTO Guide for the structural design of flexible pavement uses resilient modulus as the input property for different pavement layers. Different aggregate sources as well as the relatively wide range of gradation (as set by specifications of the Saudi Ministry of Transportation) of aggregates to be used for base layer make it necessary to study the effect of these two factors on the resilient behavior of these aggregates. Two models were used to describe the resilient behavior of tested aggregates. The main regression constants (K1 and K3) of both models were found to be significantly affected by aggregate type but not by aggregate gradation. Regression models were also developed to relate these constants to aggregates' physical properties.

دليل أشتو الحديث لتصميم الرصف المرن يستخدم معامل الرجوعية لتوصيف المواد المستخدمة في طبقات الرصف. إن اختلاف مصادر الحصى المستخدم في طبقة الأساس وتدرجها الحبيبي الواسع نسبيا (كما هو محدد في مواصفات وزارة النقل السعودية) يتطلب دراسة تأثير هذه العوامل على خواص الرجوعية لهذه المواد. وقد تم استخدام نموذجين لوصف سلوك الرجوعية للحصى. وقد وجد أن هناك تأثيرا معتبرا لنوع (مصدر) الحصى على الثابت الرئيس في النموذجين (K1, K3) بينما لا يوجد مثل هذا التأثير للتدرج الحبيبي. وقد تم تطوير نماذج انحدارية لربط هذه الثوابت بالخواص الفيزيائية للحصى.

Keywords: Aggregate, Aggregate Type, Aggregate Gradation, Resilient Modulus, Aggregate Properties.

1. INTRODUCTION

In recent pavement design methods, materials used in different layers are characterized in terms of resilient modulus (M_R). This includes subgrade, subbase, base and surface layers. As far as unbound base layer is concerned, variation of aggregate gradation could have a significant effect on aggregate resilient modulus. The Source of aggregate might have an effect on the values of resilient modulus of aggregate. In this paper, the effect of aggregate source and gradation was investigated.

A number of studies have investigated the aggregate resilient behavior (Rada and Witczak (1981), Uzan, J. (1985), Heydinger et al. (1997) and Tian et al. (1998)). Some of these studies were concerned with the effect of aggregate gradation, while others investigated the aggregate source effect. Rada and Witczak (1981) investigated 271 test results for granular materials resilient modulus. Six different granular materials were evaluated. They used the bulk stress to model M_R ($M_R = K_1\ \theta^{K2}$) behavior and they found that the gradation effect on values of K_1 and K_2 depends on the type of aggregate.

Uzan, J. (1985) characterized granular material. He concentrated on modeling the resilient behavior using bulk and deviator stresses as independent variables. Chen et al. (1994) studied the variability of M_R values due to aggregate source and testing method. He reported that variability up to 50% was found due to aggregate source and the variability due to the testing procedure was higher than that due to the aggregate source. Heydinger et al. (1997) presented a study in which the effect of type and gradation of aggregate on resilient behavior was investigated. There was significant variation in M_R due to aggregate type, while the variation due to aggregate gradation was less. Tian et al. (1998) found that the aggregate gradation effect on M_R depends on aggregate type. There was a variation up to 50% for some types of investigated aggregates due to changes in gradation.

2. OBJECTIVES AND SCOPE OF WORK

Since aggregate sources are continuously changing as aggregate quarries are depleted and other mines are used. Furthermore, aggregate at different regions of the Kingdom are of different types. In addition, the range of the acceptable gradation for aggregates to be used as base courses is relatively wide and variation in properties is expected. Therefore, the objectives of this paper are to study the effect, if any, of changing the source and gradation of aggregates to be used as base courses on resilient behavior of these materials.

3. EXPERIMENTAL WORK

Three sources of aggregates from three regions in the Kingdom, namely; Eastern, Central (Riyadh) and Western regions, were obtained and used in this study. Each of the aggregates was subjected to various characterization tests. These tests include specific gravity, absorption and Los Angles abrasion test. Results are shown in Table 1. The Eastern and Central aggregates were of limestone origin, while the western aggregate was of basalt origin.

Table 1 MOT Grading III for Aggregate Bases (MRDTM 204)

Sieve Size	Grading III limits	Percent Passing		
		Upper Limit	Mid-point	Lower Limit
25 mm (1 inch)	100	100	100	100
19 mm (3/4 inch)	70-100	100	85	70
4.75 mm (No.4)	35-65	65	50	35
0.425 mm (No.40)	15-25	25	20	15
0.075 mm (No.200)	3-10	10	6.5	3

Aggregates were obtained in three sizes; coarse, fine and filler. They were sieved and recombined according to base course gradation III as specified by Ministry of Transportation (MOT). Within the gradation three levels were used; upper limit, lower limit and at midpoint between the upper and lower limits. The three gradation levels are shown in Table 1. At each gradation level, aggregates were compacted using modified Proctor method. Maximum dry densities and optimum moisture contents are shown in Table 2.

Using maximum dry density and optimum moisture content, for each aggregate level and for each of the three aggregate types, samples were prepared and tested for resilient modulus and unconfined compressive strength. The results are shown in Table 3. The unconfined compressive strength for the Central aggregate is much higher than the other two sources, especially for midpoint and lower gradations (possesses higher percentages of fines). Unconfined compressive strength values for Eastern and Western aggregates are somewhat close to each other. The unconfined compressive strength is related to cohesion component, therefore its values increase as the clay quantity increases. This is noticeable by comparing unconfined compressive strength for upper limit (high fines), midpoint (medium fines) and low limit (low fines) gradations in Table 3.

Table 2 Properties of Aggregates from Different Sources

Aggregate Source	Aggregate Property	Gradation		
		Upper	Middle	Lower
Central	Bulk Sp. Gr.	2.535	2.555	2.564
	Apparent Sp. Gr.	2.721	2.693	2.691
	Absorption, %	2.702	2.018	1.838
	Abrasion, % loss	30.35	30.35	30.35
	Optimum Moisture Content, %	6.4	6.35	6.2
	Maximum Dry Density, Kg/m^3	2.18	2.22	2.25
Eastern	Bulk Sp. Gr.	2.503	2.567	2.548
	Apparent Sp. Gr.	2.698	2.684	2.638
	Absorption, %	2.881	2.183	1.927
	Abrasion, % loss	33.43	33.43	33.43
	Optimum Moisture Content, %	6.8	6.3	6.2
	Maximum Dry Density, Kg/m^3	2.09	2.22	2.25
Western	Bulk Sp. Gr.	2.841	2.856	2.855
	Apparent Sp. Gr.	2.936	2.945	2.938
	Absorption, %	1.127	1.045	0.990
	Abrasion, % loss	19.5	19.5	19.5
	Optimum Moisture Content, %	5.4	5.0	4.7
	Maximum Dry Density, Kg/m^3	2.38	2.40	2.40

Table 3 Unconfined Compressive Strength of Aggregates

Aggregate Source	Gradation		
	Upper limit	Midpoint	Lower limit
Central	201.00*	172.55	88.60
Eastern	89.50	78.84	50.88
Western	93.20	81.48	73.35

* in KPa

4. RESULTS OF RESILIENT MODULUS TESTING

Resilient modulus test is a dynamic test that is assumed to simulate traffic loading that the pavement material is subjected to in the field. It is assumed that pavement materials behave as an elastic material if the loading period is relatively short such as moving vehicle at the range of speeds usually encountered in the field. Elastic materials deform due to loading but this deformation almost fully recovered after load removal. It is this concept that is used in resilient modulus testing where the dynamic stress is divided by resilient (recovered) strain to obtain the resilient modulus. Unbound materials are relatively weak and can not withstand repeated loading without lateral confinement, thus confining pressure is applied on the specimen. In this study, the resilient modulus device manufactured by OEM, Inc., Corvallis, Oregon, USA was used to measure resilient modulus. A schematic diagram of the apparatus is shown in Figure 1.

The stress sequence recommended by AASHTO Test T 294-92 I method for unbound bases was used. The stress sequence is shown in Table 4. Loading time equals 0.1 sec. and a rest period of 0.9 sec. The specimens were compacted to maximum dry density at optimum moisture content. Specimens were about 200 mm high by 100 mm in diameter. Three to five specimens were tested for each gradation. Test results were collected and analyzed by computer, which is connected to resilient modulus apparatus.

Resilient modulus results usually modeled in terms of applied stresses. The conventional method of modeling M_R for granular pavement materials is to relate M_R to bulk stress. This model is recommended by the standard test method, AASHTO T 294-92I. The model is of the form:

$$M_R/100 = K1\ (\theta/100)^{K2} \qquad (1)$$

where

MR is the resilient modulus (KPa) at a specific confining, $\sigma3$ (KPa) and deviator stresses, σd (KPa)

θ is bulk stress ($\sigma d + 3\sigma3$), in KPa, and

K1 and K2 are regression constants.

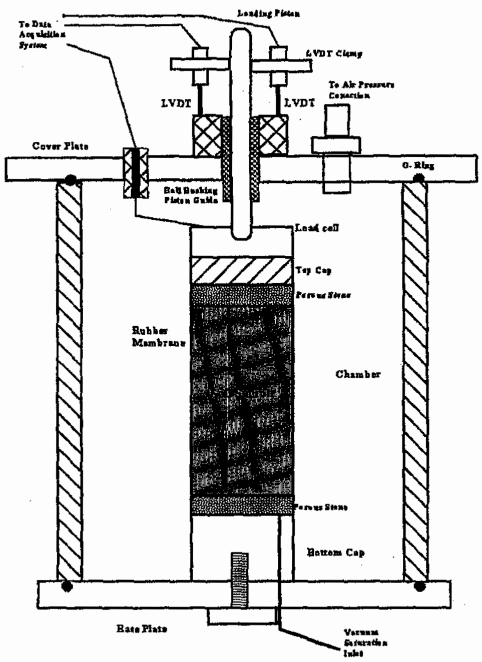

Fig. 1 Schematic Diagram of Resilient Modulus Apparatus

Both M_R and bulk stress were divided by the atmospheric pressure (≈100 KPa) in order to obtain values for K1 independent of units used for M_R and bulk stress. This model fits M_R data relatively well and is very widely used. In this study, regression analysis was conducted between M_R and bulk stress to obtain regression constants K1 and K2. The average correlation coefficient, R^2, for all samples is 0.713. The average values for K1 and K2 for each gradation are shown in Figures 2 and 3, respectively.

The letters used in figures to indicate aggregate type refer to the first letter of the aggregate source and the first letter of gradation. For example, "cl" refers to Central aggregate and lower limit gradation. The results show that K1 values for the Western aggregate are about the same for all three gradations and less than those for the Central and Eastern aggregates. No clear difference between Central and Eastern aggregates. K2 values for Western aggregate, especially low limit and midpoint gradations, are somewhat higher than those for Central and Eastern aggregates. These differences could be attributed to the differences between the characteristics of Western aggregate and those of Central and Eastern aggregates such as maximum dry density, optimum moisture content and abrasion loss.

The values of K1 and K2 were subjected to statistical analysis to show whether there are significant differences among aggregates of various sources and gradations.

The analysis of variance (ANOVA) results are shown in Tables 5 and 6 for K1 and K2, respectively. ANOVA results for K1 shows that there is a significant difference among aggregates of various sources at a significance level of 95%. This supports the conclusion obtained above by looking into Figure 2. Gradation, however, did not show any effect on K1 values.

Table 4 Testing Sequence for AASHTO Type I Soil and Base Course(AASHTO T 294-92I)

Sequence No.	Confining Pressure, psi (KPa)	Deviator Stress, psi (KPa)	Number of Load Applications
0	15 (103.43)	15 (103.43)	1,000
1	3 (20.69)	3 (20.69)	100
2	3 (20.69)	6 (41.37)	100
3	3 (20.69)	9 (62.06)	100
4	5 (34.48)	5 (34.48)	100
5	5 (34.48)	10 (68.95)	100
6	5 (34.48)	15 (103.43)	100
7	10 (68.95)	10 (68.95)	100
8	10 (68.95)	20 (137.90)	100
9	10 (68.95)	30 (206.85)	100
10	15 (103.43)	10 (68.95)	100
11	15 (103.43)	15 (103.43)	100
12	15 (103.43)	30 (206.85)	100
13	20 (137.90)	15 (103.43)	100
14	20 (137.90)	20 (137.90)	100
15	20 (137.90)	40 (275.8)	100

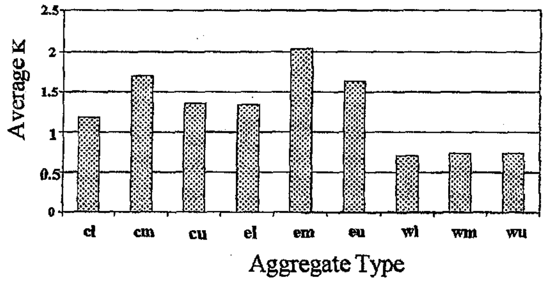

Fig. 2 Average K1 Values for Various Aggregates (Equation 1)

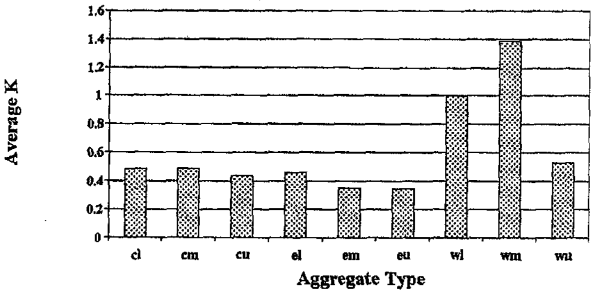

Fig. 3 Average K2 Values for Various Aggregates (Equation 1)

Table 5 Analysis of Variance for K1 (Equation 1)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
AGGR[1]	2	2.856	2.1837	1.092	7.47	0.003
GRAD (AGGR)[1]	6	0.485	0.4848	0.081	0.55	0.763
Error	26	3.801	3.8013	0.146		
Total	34	7.142				

[1] AGGR = aggregate source and GRAD = gradation (upper, midpoint and lower)

Table 6 Analysis of Variance for K2 (Equation 1)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
AGGR	2	0.5146	0.244	0.122	1.74	0.195
GRAD (AGGR)	6	0.9258	0.926	0.154	2.20	0.075
Error	26	1.8237	1.824	0.070		
Total	34	3.2641				

Results of pairwise comparison of K1 and K2 values are shown in Tables 7 and 8, respectively. For K1 values, Table 7 shows that Western aggregate is significantly different from both Central and Eastern aggregates. No significant differences were found between Central and Eastern aggregates. For K2 values (Table 8) no significant differences were found among aggregates at 95% significance level.

Rafael Pezo (1993) suggested a general model (named here model 2) that can be used for both granular as well as fine grained pavement materials. The model relates M_R to both confining as well as deviator stress. The model was found to have better fitting capability than the above-mentioned model (model 1 above) (e.g. Al-Suhaibani et al., 1997). The model is of the form:

$$M_R/100 = K3\,(\sigma_d/100)^{K4}\,(\sigma_3/100)^{K5} \qquad (2)$$

where all parameters were as defined earlier.

Table 7 Pairwise Comparisons for K1 Among Levels of AGGR (Equation 1)

AGGR = C* subtracted from: Level AGGR:	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
E*	0.2559	0.1678	1.525	0.2960
W*	-0.4213	0.1587	-2.655	0.0345
AGGR = E subtracted from: W*	-0.6772	0.1795	-3.773	0.0024

* C, E and W refer to Central, Eastern and Western sources of aggregates, respectively

In this model, the effect of deviator and confining stresses on M_R were separated. As for model 1 above, M_R and deviator and bulk stresses were divided by atmospheric pressure ($\approx$ 100 KPa) in order for K3 to be dimensionless. K3, K4 and K5 were determined from regression analysis. The model fits almost all data very well. The average R^2 is 0.84. This value is higher than the average R^2 for Equation 1(0.71) above, indicating preference of Equation 2 over Equation 1.

Table 8 Pairwise Comparisons for K2 Among Levels of AGGR (Equation 1)

AGGR = C subtracted from: Level AGGR	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
E	-0.04053	0.1162	-0.3487	0.9353
W	0.16969	0.1099	1.5439	0.2876
AGGR = E subtracted from: W	0.2102	0.1243	1.691	0.2277

Bar charts for K3, K4 and K5 values are shown in Figures 4, 5 and 6, respectively. There is no clear variation of K3 values as either aggregate or gradation change. However, K3 values seem to be less for Western than those for Central and Eastern aggregates.

Figure 5 shows that K4 value for each aggregate type decrease as gradation gets finer. As for the effect of aggregate type, Western aggregate has higher K4 values than the other two aggregates. In other words, the effect of deviator stress on M_R gets higher as gradation becomes coarser. Furthermore, deviator stress has more effect on M_R for Western aggregate than for the others.

Figure 6 shows effect of aggregate type and gradation on K5. For a given aggregate, and with the exception of upper limit gradation for Western aggregate, K5 increases as gradation becomes finer. K5 is an index of confining stress effect on M_R. This behavior could be due to the higher optimum moisture content for finer gradations.

K3, K4 and K5 data were subjected to analysis of variance (ANOVA) to investigate whether there is a significant difference among their means for various aggregates. Table 9 shows the ANOVA results for K3. Values in the table indicate a significant difference among K3 values for different aggregates at 95% significant level. However, pairwise comparison shows that the significant difference is only between Eastern and Western aggregates (Table 10). Differences in K3 within each aggregate type are not significant as seen in Table 9. Tables 11 through 14 present the ANOVA and pairwise comparison results for K4 and K5. For both parameters, no significant differences were found among the three aggregate types. However, there are significant differences within each aggregate type (between gradations). This conclusion agrees with that obtained from bar charts above.

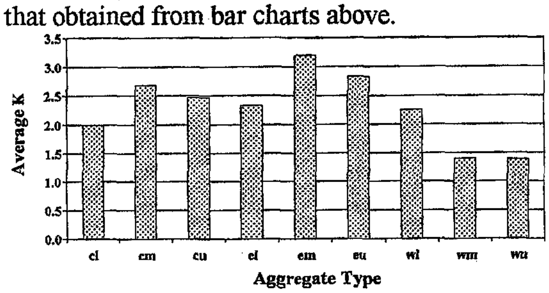

Fig. 4 Average K3 Values for Various Aggregates (Equation 2)

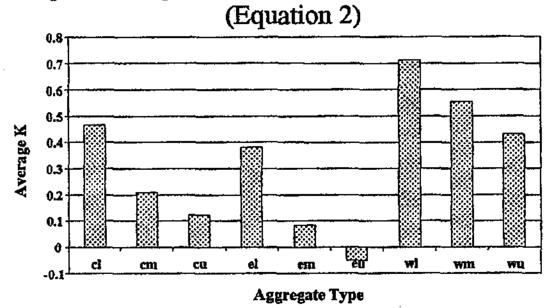

Fig. 5 Average K4 Values for Various Aggregates (Equation 2)

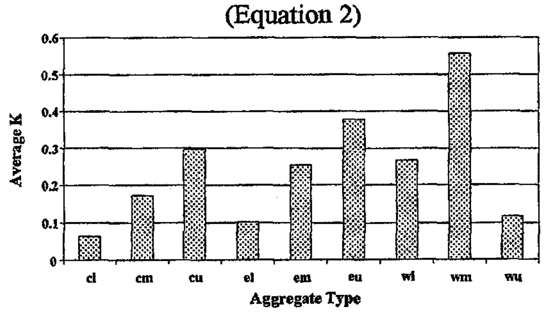

Fig. 6 Average K5 Values for Various Aggregates (Equation 2)

Table 9 Analysis of Variance for K3 (Equation 2)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
AGGR	2	4.813	4.798	2.399	4.27	0.024
GRAD (AGGR)	6	4.955	4.955	0.826	1.47	0.224
Error	29	16.31	16.31	0.563		
Total	37	26.08				

Table 10 Pairwise Comparisons for K3 Among Levels of AGGR (Equation 2)

AGGR = C subtracted from: Level AGGR	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
E	0.3756	0.3045	1.234	0.4435
W	-0.5291	0.2940	-1.799	0.1876
AGGR = E subtracted from: W	-0.9047	0.3129	-2.891	0.0192

Table 11 Analysis of Variance for K4 (Equation 2)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
AGGR	2	0.49757	0.38274	0.19137	2.29	0.122
GRAD (AGGR)	6	1.62227	1.62227	0.27038	3.23	0.017
Error	26	2.17618	2.17618	0.0837		
Total	34	4.29601				

Table 12 Pairwise Comparisons for K4 Among Levels of AGGR (Equation 2)

AGGR = C subtracted from: Level AGGR	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
E	-0.1680	0.1194	-1.407	0.3519
W	0.1024	0.1239	0.827	0.6902
AGGR = E subtracted from: W	0.2704	0.1288	2.100	0.1095

Table 13 Analysis of Variance for K5 (Equation 2)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
AGGR	2	0.02963	0.03455	0.01728	0.58	0.566
GRAD (AGGR)	6	0.55135	0.55135	0.09189	3.09	0.020
Error	26	0.77237	0.77237	0.02971		
Total	34	1.35335				

Table 14 Pairwise Comparisons for K5 Among Levels of AGGR(Equation 2)

AGGR = C subtracted from: Level AGGR	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
E	0.07451	0.07114	1.0474	0.5545
W	0.01697	0.07380	0.2299	0.9713
AGGR = E subtracted from: W	-0.05754	0.07672	-0.7500	0.7363

5. RELATING M_R MODELS CONSTANTS TO AGGREGATE PROPERTIES

There have been several attempts (e.g. Rada, G. and Witczak, M. 1981; Tian, P. et al., 1998; Mohammad, L. et al. 1999) to relate M_R of pavement materials to their physical properties, either by relating M_R directly or by relating the constants of M_R predictive equation to material's properties. Stepwise regression was used to relate K3, K4 and K5 values to one or more of aggregate physical properties, namely; optimum moisture content, maximum dry density, water absorption, bulk specific gravity, apparent specific gravity, CBR and unconfined compressive strength. The obtained equations are as follows:

$$K3 = 67.1 - 13.13*APP - 6.96*MDD - 2.554*OMC + 0.03896*Q \quad (3)$$

where

APP = apparent specific gravity, MDD = maximum dry density, OMC = optimum moisture content, Q = unconfined compressive strength

$R^2 = 0.915$ Adj. $R^2 = 0.83$ SE = 0.252

F = 10.74 Sig. F = 0.0205

$$K4 = -0.016 + 1.92*APP - 0.0129*Q \quad (4)$$

where

APP and Q as defined above

$R^2 = 0.956$ Adj. $R^2 = 0.942$ SE = 0.06

F = 65.36 Sig. F =0.0001

$$K5 = -4.815 + 0.337*ABSRP + 1.675*Bulk \quad (5)$$

where

ABSRP = water absorption, Bulk = bulk specific gravity.

$R^2 = 0.453$ Adj. $R^2 = 0.27$ SE = 0.132

F = 2.48 Sig. F = 0.164

Although one of the predictive equations has relatively low coefficient of determination, these equations do give indication of the importance of the independent variables in affecting M_R behavior of tested aggregates. The best predictive equation is that of K4 (equation 4), which explains the role of deviator stress on M_R behavior. Apparent specific gravity and unconfined compressive strength are the aggregate properties that explain most this role of deviator stress on M_R. The next best equation is that for K3 that represents the constant term in M_R equation. Below each equation are regression results that show how much variability of Ks is explained by the independent variables and the goodness of the equations in predicting the correct Ks values.

6. CONCLUSIONS

1. Analysis of variance of K1 values (Equation 1) shows a significant effect for aggregate type on these values. However, no significant effect was found for aggregate gradation.
2. Results of pairwise comparison of K1 and K2 values show that, for K1 values, Western aggregate is significantly different from both Central and Eastern aggregates. However, no significant differences were found between K1 values for Central and Eastern aggregates. For K2 values, no significant differences were found among aggregates at 95% significance level.
3. There is significant difference among K3 values for different aggregates at 95% significant level. However, pairwise comparison shows that the significant difference is only between Eastern and Western aggregates.
4. Results for K4 and K5 show that no significant differences among the three aggregate types. However, there are significant differences between gradations for various aggregates.
5. With the exception of upper limit gradation for Western aggregate, K5 increases as gradation becomes finer.
6. K4 value for each aggregate type decreases as gradation gets finer.
7. For the effect of aggregate type, Western aggregate has higher K4 values than the other two aggregates. In other words, the effect of deviator stress on M_R gets higher as gradation becomes coarser.
8. Deviator stress has more effect on M_R for Western aggregate than for the other types.
9. There is no clear variation of K3 values as either aggregate type or gradation change. However, K3 values seem to be less for Western aggregate than those for Central and Eastern aggregates.
10. By relating Ks values to aggregate properties, it was found that the best predictive Equation is that of K4 (equation 4), which explains the role of deviator stress on M_R behavior. Apparent specific gravity and unconfined compressive strength are the aggregate properties that explain most the role of deviator stress on M_R.
11. The next best equation is that of K3 that represents the constant term in M_R equation.

7. REFERENCES

[1] Al-Suhaibani, A., Al-Refeai, T. and Noureldin, A. S. (1997), "Characterization of Subgrade Soils in Saudi Arabia; A Study of Resilient Behavior," Final Report submitted to King Abdulaziz City for Science and Technology (KACST), Project No. AR-12-51, Riyadh, Saudi Arabia.

[2] Chen, D., Zaman, M. and Laguros, J. (1994), " Resilient Moduli of Aggregate Materials: Variability Due to Testing Procedure and Aggregate Type," paper presented at the 73rd Annual Meeting of Transportation Research Board, January 9-11, Washington, D.C.

[3] Heydinger, A., Xie, Q., Randolph, B. and Gupta, J. (1997), "Analysis Of Resilient Modulus of Dense- and Open-Graded Aggregate," Transportation Research Record 1547, Transportation Research Board, Washington, D.C., pp. 1-6.

[4] Mohammad, L., Huang, B., Puppala, A. and Allen, A. (1999), "A Regression Model for Resilient Modulus of Subgrade Soils," paper presented at the 78th Annual Meeting of Transportation Research Board, January 11-14, Washington, D.C.

[5] Pezo, R. F. (1993), "A General Method of Reporting Resilient Modulus Tests of Soils. A Pavement Engineer's Point of View," paper presented at the 72nd Annual Meeting of Transportation Research Board, January 10-14, Washington, D.C.

[6] Rada, G. and Witczak, M. (1981), "Comprehensive Evaluation of Laboratory Resilient Moduli Results For Granular Material," Transportation Research Record 810, Transportation Research Board, Washington, D.C., pp. 23-33.

[7] Tian, P., Zamman, M. and Laguros, J. (1998), "Gradation And Moisture Effects on Resilient Modulus of Aggregate Bases," paper presented at the 77th Annual Meeting of Transportation Research Board, January 11-15, Washington, D.C.

[8] Uzan, J. (1985), "Characterization of Granular Material," Transportation Research Record 1022, Transportation Research Board, Washington, D.C., pp. 52-59.