J. King Saud Univ., Vol. 14, *Eng. Sci.* (2), pp.165-182, Riyadh (A.H. 1422/2002)

Factors Affecting Resilient Behavior of Subgrade Soils in Saudi Arabia

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(Received 13 May, 2000; accepted for publication 24 April, 2001)

Abstract. This paper presents a study of the effect of relative density and moisture content on the resilient behavior of subgrade soils in Saudi Arabia. Thirteen representative soil samples, representing subgrade soils from all over the Kingdom, were tested at two different relative densities (93% and 96%) and the corresponding moisture contents on the compaction curves in addition to the optimum moisture content and maximum density. The results show that the resilient behavior depends on soil type (fine grained or granular) as well as moisture content and relative density. The study shows that both moisture content and relative density governs the effect of deviator and confining stresses on MR behavior. The study emphasized the importance of using a model that describes correctly the dependency of M_R on both confining and deviator stresses.

Keywords: resilient modulus, subgrade soil, modeling,

Introduction

In recent years, considerable attention has been given to the characterization of subgrade soil using the resilient modulus test. The 1986 AASHTO Guide for Design of Pavement Structures provided substantial impetus to the test by declaring that resilient modulus (M_R) is the definitive property to characterize both subgrade soil and flexible paving materials.

Resilient modulus of subgrade soils has been found to be very sensitive to type of soil, moisture content, density and stress level to which the soil is subjected. Many studies have reported relationships between M_R and other soil properties that are a function of local soil properties and based on local environment and experience. Thompson and Robnett [1] conducted an extensive study of the resilient properties of Illinois soils. Rada and Witczak [2] presented a comprehensive evaluation of variables that influence the resilient modulus response of granular materials. Several studies have been conducted to study the influence of density and/or water content on the resilient behavior for Florida subgrade soils (Elfino and Davidson, [3]), Arkansas subgrade soils (Elliot and Thornton, [4]), Texas subgrade soils (Pezo and Hudson [5]), and Tennessee subgrade soils (Drumm *et al.* [6]). However, the effects of density and water content on the resilient behavior of a particular soil cannot be accurately predicted without testing that soil to account for its geological origin in representative environment.

Unfortunately, to the best knowledge of the authors, no information was available concerning the resilient behavior of soils in Saudi Arabia. Consequently, in 1992, King Abdulaziz City for Science and Technology (KACST) sponsored a three-year laboratory and field study of resilient behavior of soil indigenous to Saudi Arabia. The study was conducted by a research team from King Saud University (KSU) and the Ministry of Communications. All tests were performed at the laboratories of Civil Engineering Department in KSU. The objectives of the study were: (1) to investigate typical resilient modulus (M_R) values of various roadbed soils encountered in the different regions of the Kingdom; (2) to correlate M_R values with other physical and mechanical properties of soil (e.g. soil classification and soil strength) at typical field and loading conditions (i.e. moisture content, relative density, confining stress and deviator stress level); and (3) to address the effect of soil classification, moisture content, relative compaction, anticipated loading and confining pressure on M_R values for these roadbed soils. More detailed information on the study is available elsewhere (Al-Suhaibani *et al.* [7]).

The purpose of this paper is to study the effect of moisture content, relative compaction, anticipated loading and confining pressure on M_R values for thirteen representative soil samples, representing subgrade soils from all over the Kingdom.

Testing Program

Site selection, sample collection and characterization

The Kingdom of Saudi Arabia is divided into 14 highway districts. Sampling points were located at fixed intervals of 40 km along selected roads that were believed to provide comprehensive coverage of the various Kingdom's districts.

Soil samples were retrieved from about 0.5 meters below the ground surface at approximately 20 meters from the pavement edge. Field (natural) moisture contents for all samples and field densities for some samples were determined.

From each AASHTO class encountered, a minimum of two samples was randomly selected (except A-7-6, since there was only one sample encountered). A total of 13 samples were selected as shown in Table 1.

Table 1. Selected samples from each AASHTO soil class

AASHTO classification	Total No. of samples	No. of selected samples
A-1-a	7	2
A-1-b	24	2
A-2-4	85	4
A-3	23	2
A-4	17	2
A-7-6	1	1

A laboratory-testing program was established to characterize collected soil samples. Geotechnical characteristics included:

- Sieve analysis (washed and oven-dry) together with the determination of percentage of sand, silt and clay (AASHTO T88).
- Atterberg limits (AASHTO T89 and T90)
- Classification according to AASHTO and Unified classification systems.
- Specific gravity (G_s) (AASHTO T85 and T100)
- Moisture-density analysis (including determination of optimum moisture content and maximum dry density) (AASHTO T99 Method D).
- Minimum and Maximum density for clean dune sand (A-3) (ASTM D4254 and STM D4253).
- Unsoaked California Bearing Ratio (CBR) (AASHTO T193) at optimum moisture content and maximum dry density.
- SHRP classification as type 1 and 2(AASHTO 294).

The results from the testing program for the selected soil samples are summarized in Table 2.

Resilient modulus testing

For resilient modulus testing, 100 mm diameter and 200 mm high test specimens were used for all types of soil. All tests were conducted in a resilient modulus testing apparatus with an electropneumatic-loading frame. Specimens were subjected to a repeated deviator stress of fixed magnitude using a haversine shaped load pulse consisting of a 0.10 second load followed by a 0.90 second rest period. The deviator stress was measured with a load cell mounted within the triaxial cell, thereby eliminating load-measuring errors caused by the friction between the load piston and the top of the triaxial cell.

Table 2. Summary of soil properties

Sample	Soil classification		Type	Gs	SAND %	SILT %	CLAY %	Atterberg limits			Compaction test		CBR
	AASHTO	UNIFIED						LL	PL	PI	MDD	OMC	
B-09	A-1-a	SP	1	2.711	53.9	3.3	1.6			NP	2.136	8	53
H-01	A-1-a	GP-GM	1	2.764	38	8	2.8			NP	2.118	10.3	17
A-03	A-1-b	SM-SC	2	2.663	55.5	14.3	7	22.7	17.5	5.2	2.048	8.9	9
B-19	A-1-b	SM	2	2.669	69	10.4	3.5			NP	2.04	9.5	36
B-08	A-2-4	SM	2	2.721	70.7	19.9	7			NP	1.915	12.6	21
F-04	A-2-4	SP-SM	2	2.695	71.8	7.5	4	15.5	15.3	NP	2.06	9.2	26
I-03	A-2-4	SM	2	2.811	75.3	18.3	4			NP	2.054	9	46
K-12	A-2-4	SM-SC	2	2.645	59.2	18.4	8	21.7	17.5	4.2	1.944	10.8	26
K-05	A-3	SP-SM	2	2.613	91.4	5.7	2.9			NP	1.883	0*	37
N-02	A-3	SP-SM	2	2.717	82.9	6.5	3.3			NP	1.843	0	30
E-06	A-4	SC	2	2.769	27.9	24.4	17	31.5	22.4	9.1	1.863	15	5
H-02	A-4	SM	2	2.807	19.8	29.2	8	25.6	23	2.6	1.924	13	7
D-06	A-7-6	SC	2	2.751	43.6	18.2	27	42.3	25.3	17	1.773	15.5	5

*omc for dune sand

Air was used as the confining fluid in the plexiglass cell and pressure was measured by an air-pressure gauge mounted at the base of the triaxial cell. Externally mounted Linear Variable Differential Transducers (LVDTs) were used to measur recoverable axial deformations. The resilient moduli were calculated for each loading sequence using a personal computer with a data reduction and analysis program. The soil was mixed at the target moisture content. The soil samples were then placed in sealed double plastic bags allowing 24 hours for equilibrium. Static compaction and tamping were used to densify five layers of cohesive and cohesionless soils, respectively, to achieve the target density level. All samples were tested enclosed inside two rubber membranes.

For the purpose of the M_R tests, soils were classified as Material Type 1 or Type 2. Material Type 1 are those which have less than 70% passing the No. 10 sieve and 20% maximum passing the No. 200 sieve. Material Type 2 are all other soil materials. Testing sequences used are shown in Table 3.

Table 3. Summary of conditioning and loading sequences (AASHTO294)

Type 1 soil	**Confining stress σ_3(KPa)**	**Deviator stress σ_d(KPa)**	**No. of cycles**
Conditioning	103.4	103.4	1000
Testing	20.7	20.7,41.4,62.1	100 each
	34.5	34.5,69,103.4	
	69	69,137.9,206.9	
	103.4	69,103.4,206.9	
	137.9	103.4,137.9,275.8	
Type 2 soil	**σ_3(Kpa)**	**σ_d(KPa)**	**No. of cycles**
Conditioning	41.4	27.6	1000
Testing	41.4	13.8,27.6,41.4,55.2,69	100 each
	20.7	13.8,27.6,41.4,55.269	
	0	13.8,27.6,41.4,55.2,69	

M_R testing at variable moisture content and density

The measured M_R of a soil can vary enormously depending on how soil is compacted and on the water content and density at which the specimen is compacted. It is necessary to consider how well test samples simulate the probable condition of a soil in an actual pavement with regard to water content and density. To study the effect of moisture content, M_R tests were conducted at two different moisture contents on the dry side of the compaction curve. Soil samples were collected during one year of the study and some of them during the rainy season from 157 sites throughout Saudi Arabia. These sites encompassed a wide range of topography and environmental conditions. For all samples, except two, the optimum moisture content (OMC) was greater than the natural moisture content (NMC). Similar observations were obtained by Fatani *et al.* [8] for subgrade soils recovered from under existing pavements in eastern, central and western regions of the Kingdom as shown in Table 4. Preliminary plans were to test samples at moisture contents above OMC; however, in light of the above and since there is an annual excess of potential evaporation over precipitation in the Kingdom, the moisture contents at which the selected samples were tested for M_R were optimum and dry of optimum at density corresponding to 100%, 96%, and 93% of maximum dry density (AASHTO T-99). Figure 1 shows the combination of moisture contents and densities at which M_R tests were conducted. Figure 1 shows paths "ca" and "db" having constant dry density but variable moisture content. On the other hand, path "be" has a constant moisture content (OMC) but variable dry density. Furthermore, constant compaction effort could be obtained along the path "dce". Each one of the 13 samples was tested at each point shown in Fig. 1. However, since the optimum moisture content for "A-3" samples is zero percent, tests for those samples were conducted along the path "be" only.

Table 4. Natural and optimum moisture of subgrade soils in Saudi Arabia

	Resilient behavior study (Al-Suhaibani, *et al.* [7])		National rutting study (Fatani *et al.* [8])	
	NMC(%)	OMC(%)	NMC(%)	OMC(%)
No. of samples	157	157	22	22
Range	0.2 – 17.3	0* - 21.7	1.1 – 6.4	5.6 – 11.4
Mean	4.1	9.3	3.9	7.1
Std. Dev.	2.99	4.51	1.10	1.50

*OMC for clean dune sand (A-3)

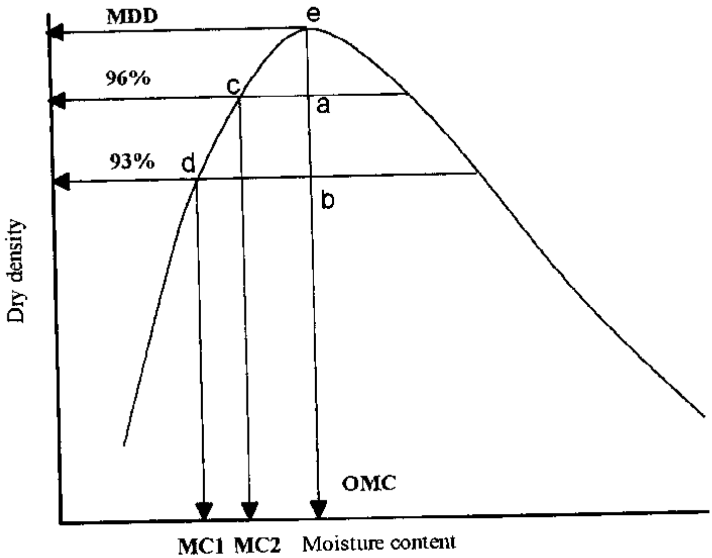

Fig. 1. Combination of moisture content and dry density for resillient modulus testing.

Analysis of Results

Resilient behavior

Typical results from the test program are plotted in Figs. 2 and 3 as specified by AASHTO 294. Figure 2 presents the logarithmic plot of resilient modulus (M_R) versus bulk stress (0) for Type 1 materials. Similarly Fig. 3 shows the logarithmic plot of resilient modulus versus deviator stress (σ_d). According to AASHTO 294, for Type 1 and 2 materials, the resilient modulus is expressed by equations 1 and 2, respectively.

$$M_R = K_3'(\theta)^{K_4'} \tag{1}$$

$$M_R = K_1'(\sigma_d)^{K_2'} \tag{2}$$

Where K'_1, K'_2, K'_3, and K'_4 are regression coefficients derived from laboratory test results.

Type 1 material exhibited the usual behavior found with granular soils where the resilient modulus increases with increasing both confining and bulk stresses as shown in Fig. 2. Type 2 materials displayed the typical stress-softening resilient behavior of cohesive soils under repeated loading, where the resilient modulus increases with increasing the confining stress and decreases with increasing the deviator stress as shown in Fig. 3. However the effect of confining stress on resilient properties for Type 2 material is not considered by the model in equation (2).

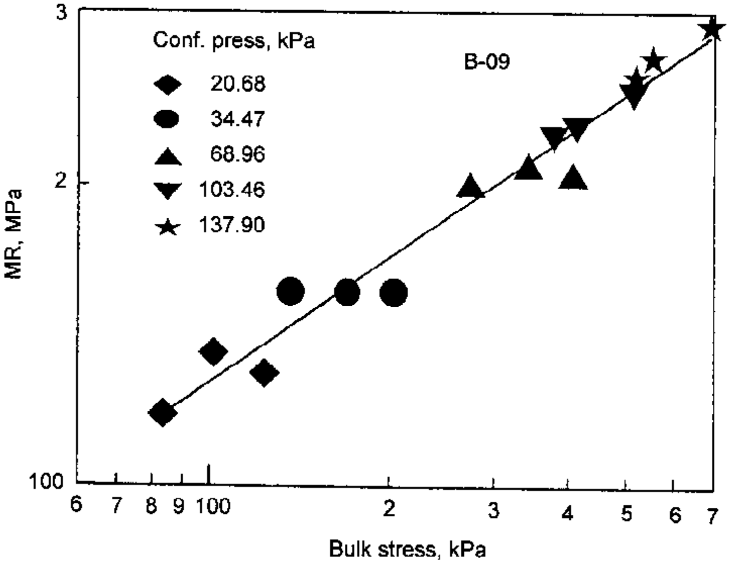

Fig. 2. Typical plot of MR vs. bulk stress for type 1 samples.

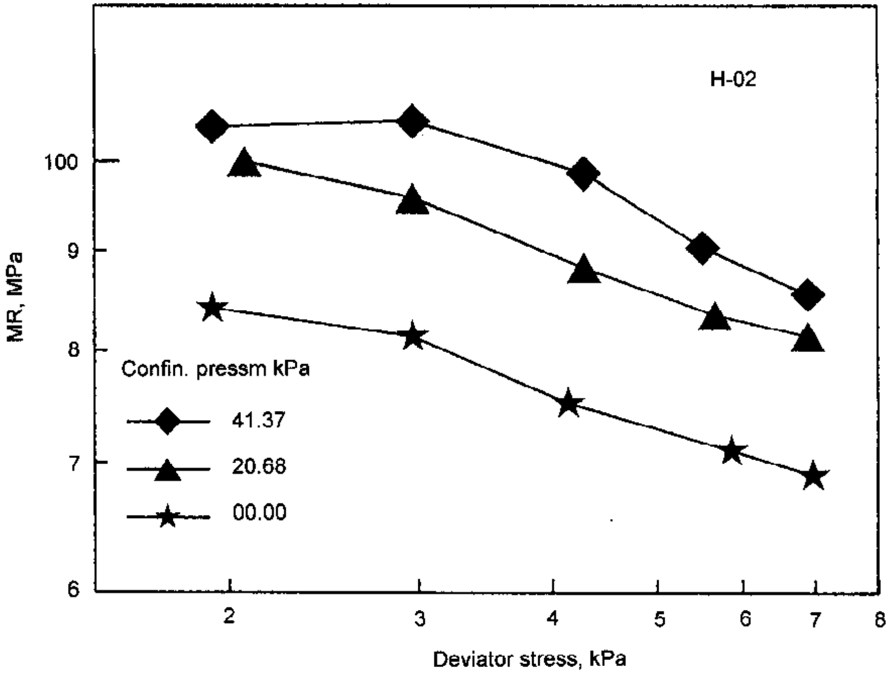

Fig. 3. Typical plot of MR vs. deviator stress for type 2 samples.

Thus the constitutive equation proposed by Pezo [9] might be considered more appropriate to model the resilient behavior of soil in Saudi Arabia, since it reflects both the confining and deviatoric stresses sensitivity characteristics of any soil. The constitutive equation for resilient modulus as proposed by Pezo is given by

$$M_R = K_1(\sigma_d)^{K_2} (\sigma_3)^{K_3} \tag{3}$$

where K_1, K_2 and K_3 are laboratory-derived regression constants reflecting material type and physical properties.

Table 5 contains a summary of regression constants, coefficient of determination (R^2) and standard error of estimate (SEE) for Type 1 and Type 2 soils where the resilient modulus test results were interpreted according to equation 1 or 2 and 3. The trends presented in this table which are typical of those obtained in the study conducted by Al-Suhaibani *et al.* [7] confirm the ability of Pezo's model to predict the resilient properties of tested soils with a high degree of accuracy as reflected by the high values of R^2 and the relatively small values of SEE.

Table 5. Summary of regression constants for two soil types

Sample	Model	R^2	SEE
B-09 (Type 1)	$M_R = K'_3(\theta)^{K'_4} = 17.55\,\theta^{.427}$	0.97	9.77
	$M_R = K_1(\sigma_d)^{K_2}(\sigma_3)^{K_3} = 33.77(\sigma_d)^{.076}(\sigma_3)^{.343}$	0.99	6.21
H-02 (Type 2)	$M_R = K'_1(\sigma_d)^{K'_2} = 159.64(\sigma_d)^{-.164}$	0.36	9.43
	$M_R = K_1(\sigma_d)^{K_2}(\sigma_3)^{K_3} = 107.32(\sigma_d)^{-.156}(\sigma_3)^{0.126}$	0.93	2.41

Effect of water content and density on K_1

It was stated earlier that the M_R results could best be modeled using Pezo's model. The model constants; namely K_1, K_2 and K_3, will be used here to study the effect of water content and density on M_R. Regression analysis was performed on data of each M_R test results to obtain the regression constants, K_1, K_2 and K_3. K_1 represents the value of M_R at unit deviator and confining stresses, while K_2 and K_3 equal the rate of change of M_R with deviator and confining stresses, respectively. Unlike K_2 and K_3, K_1 is not dimensionless and must have dimensions controlled by the dimensions of M_R, σ_3 and σ_d in order for the equation to be dimensionally correct.

Figure 4 shows the line plots of K_1 against relative density (relative to the maximum dry density). Data points shown were all at optimum moisture content (along the path "be" Fig. 1). A general trend of an increase in K_1 value as density increases can be observed. This trend was expected and agrees with that reported in the literature (Seed *et al.* [10] and Hicks and Monismith, [11].

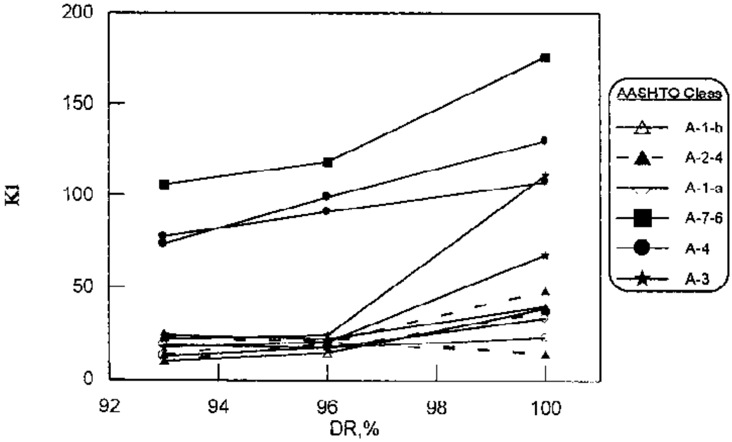

Fig. 4. Effect of Dr on K1 at OMC.

Plots of K_1 with moisture content at both 96% and 93% relative densities are very similar as can be seen in Figs. 5 and 6, respectively. Both plots show that K_1 decreases with increasing moisture content for all granular soil. An opposite trend is observed for fine-grained soil in which K_1 increases with increasing compaction moisture content.

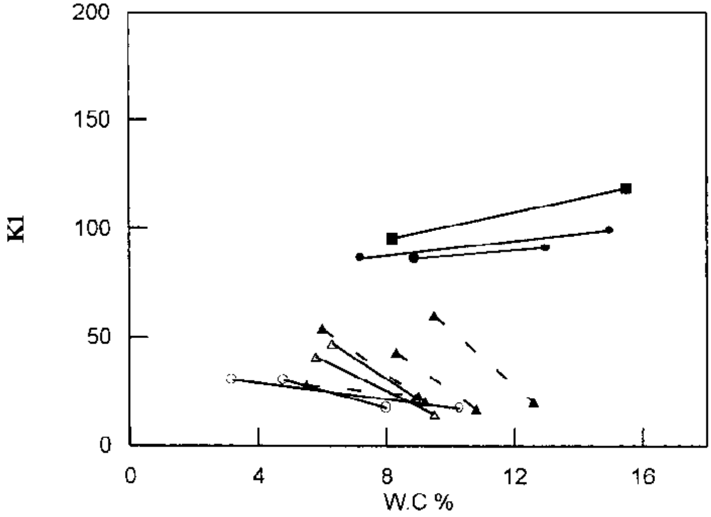

Fig. 5. Effect of WC on K1 at Dr = 96%.

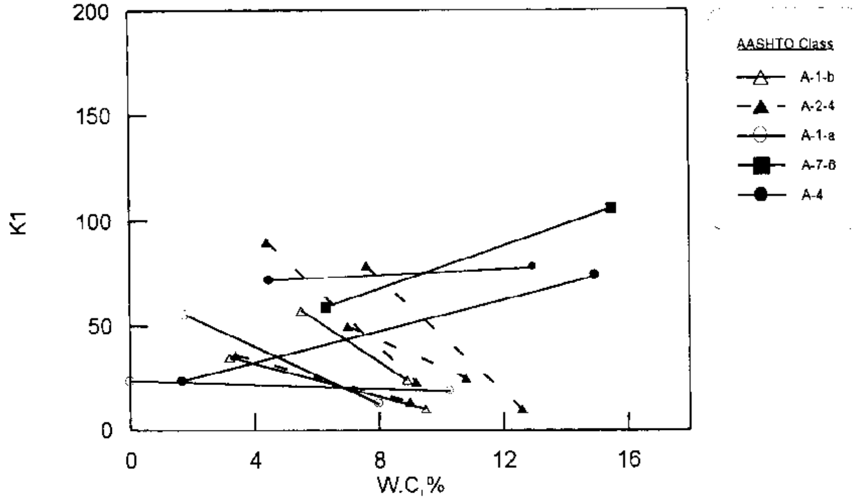

Fig. 6. Effect of WC on K1 at Dr = 93%.

Effect of moisture content and density on K_2

As stated earlier K_2 represents the effect of σ_d. For small values of $|K_2|$, the subgrade resilient modulus is less sensitive to changes in deviator stress. On the other hand, large values of $|K_2|$ are indicative of highly sensitive resilient modulus. To investigate the effect of moisture content on K_2, plots were prepared for K_2 against moisture content. Figures 7 and 8 show plots of K_2 versus moisture content for relative densities of 96 and 93%, respectively. At 96% relative density, general trends are such that for fine-grained soils (A-4, A-7-6) K_2 tends to decrease as moisture content increases, while for granular soils K_2 tends to increase or do not change as moisture content increases. However, in contrast to the relatively minor influence of moisture content on K_2 for granular material, the influence of moisture content on K_2 values for fine-grained soil is significant. At 93% relative density, K_2 generally decreases slightly or stays the same as moisture content increases for both granular and fine-grained soils. This means that the effects of deviator stress on M_R may or may not be the same at different moisture contents depending on soil properties. However, it seems that M_R for fine-grained soil is more sensitive to changes in moisture content regardless of density as deviator stress changes.

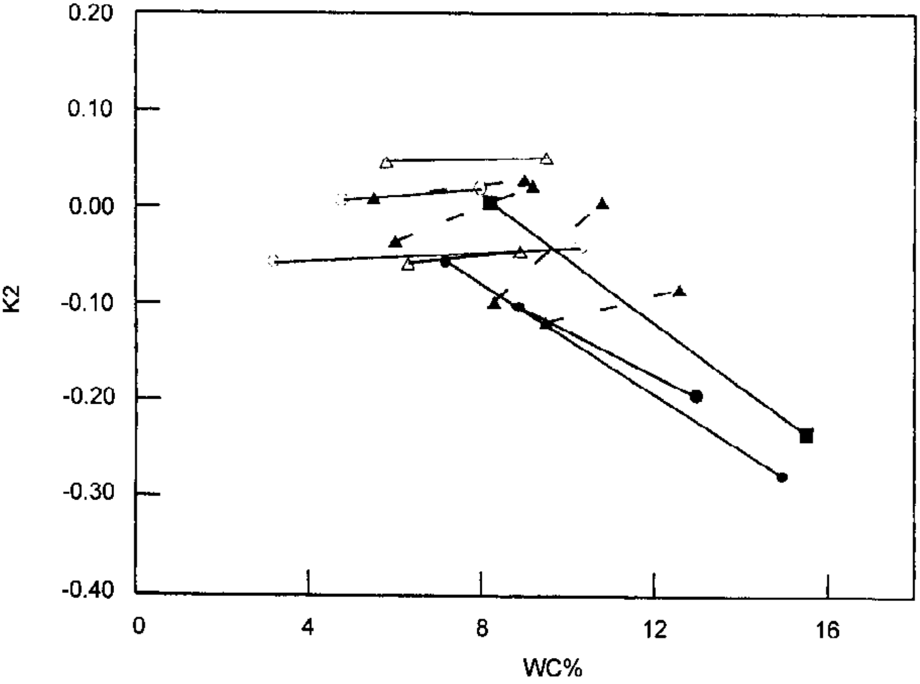

Fig. 7. Effect of WC on K2 at Dr = 96%.

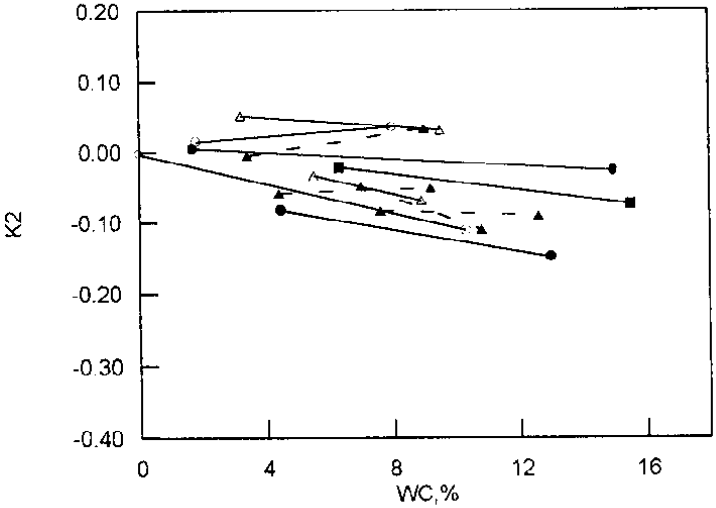

Fig. 8. Effect of WC on K2 at Dr = 93%.

The effect of changing density on K_2 can be seen in Fig. 9. Note that, although changes in K_2 are not large, the influence of moisture content on K_2 value is seen to vary even within the same soil type. There is, however, no uniform trend among all soils tested. This Fig. clearly shows that changing density while keeping moisture content the same has no effect on K_2. This means the effect of deviator stress on M_R is almost the same regardless of the sample density if the moisture content is kept constant.at the optimum.

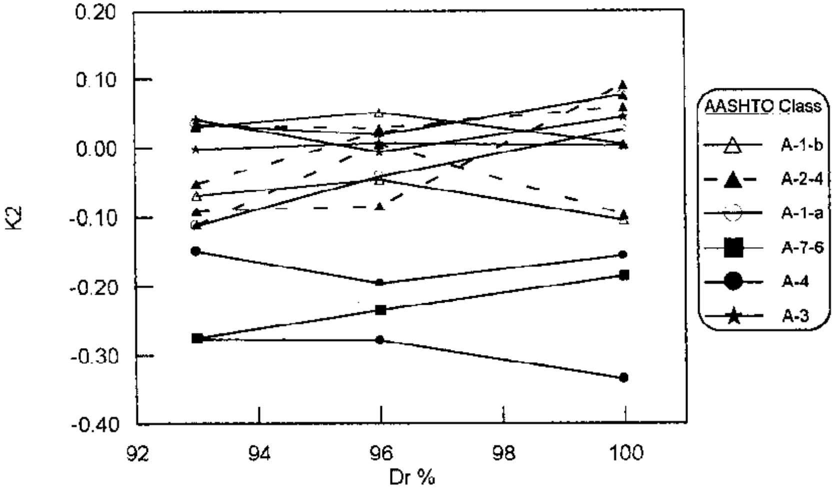

Fig. 9. Effect of Dr on K2 at OMC.

Effect of moisture content and density on K_3

Figures 10 and 11 illustrate the influence of moisture content on K_3 at relative densities of 96% and 93% respectively. Figures 10 and 11 indicate that for granular soils the value of K_3 increases with increases in the moisture content regardless of relative density. However for fine-grained soil, K3 values do not vary appreciably as the moisture content increases at relative density of 96%, whereas at 93% relative density, K_3 values decreased with increasing moisture content values. Thus influence of magnitude of σ_3 on M_R is mainly related to moisture content of the soil. The sample density, as can be seen in Fig. 12, also influences K_3. It is clear that K_3 decreases as density increases. This is logical since it indicates that the relative importance of σ_3 decreases as density increases.

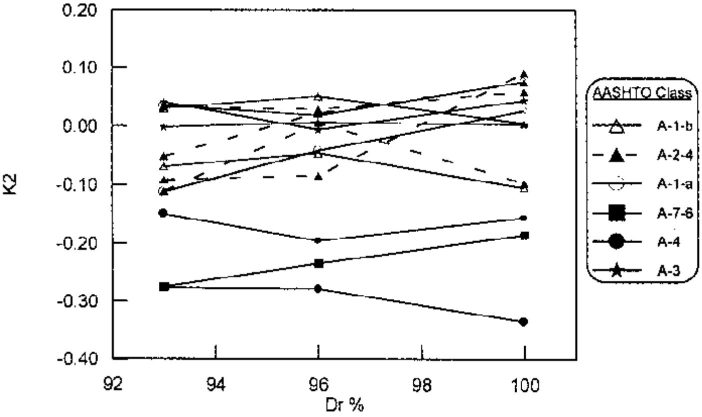

Fig. 10. Effect of Dr on K3 at Dr = 96%.

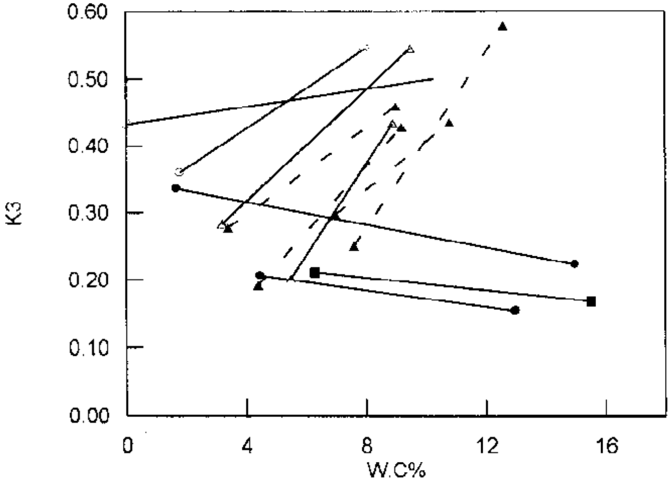

Fig. 11. Effect of WC on K3 at Dr = 93%.

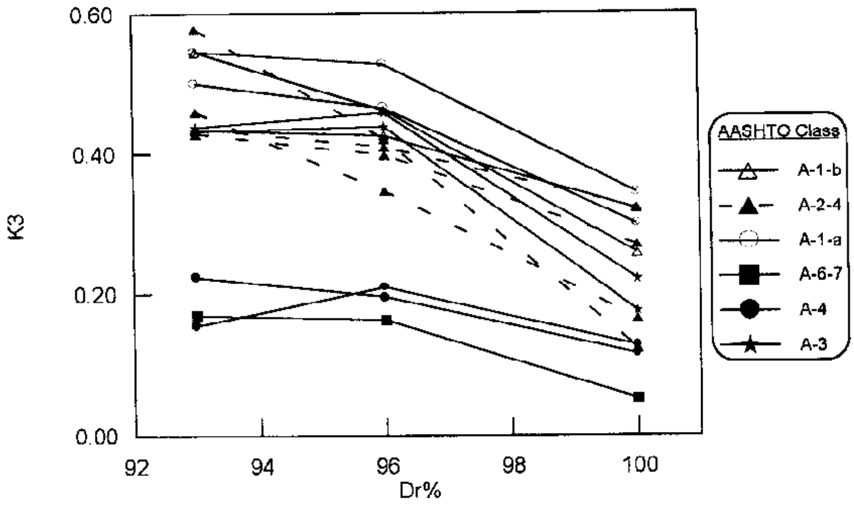

Fig. 12. Effect of Dr on K3 at OMC.

Estimation of M_R changes in the field

The typical cross sections used in roadway construction in Saudi Arabia consist of a 150-mm asphalt concrete layer and 300 mm of selected material above the natural subgrade. Stresses on the top of the subgrade due to an 80 kN standard axle load (18 kip) were found to be in the vicinity of 41.4 kPa (6 psi) vertically and 20.7 kPa (3 psi) horizontally when using the ELSYM 5 computer program. These typical field values of σ_d and σ_3 were substituted in Pezo's model along with the values of regression constants (K_1, K_2 and K_3) obtained in the laboratory at different moisture contents and relative densities to calculate expected field MR values. The influence of increasing moisture content for 93 and 96% relative densities on the resilient modulus of the predominant subgrade soil in Saudi Arabia (A-2-4) is shown in Fig. 13 with results of sample A-4 for comparison purposes. The resilient modulus values are normalized by their respective values corresponding to maximum dry density and optimum moisture content. From Fig. 13 it can be observed that the normalized resilient modulus decreases with increasing water content irrespective of relative density. For the granular soil the relative density has less effect on the reduction in M_R than for the fine-grained soil. Inspection of Fig. 13 shows that reduction in M_R for the fine-grained soil obtained under high relative density of A-4 soil is greater than that at low density. This result is probably due to weakening of the soil fabric as moisture content is increased. This behavior was anticipated and consistent with those reported by several authors (Seed *et al.* [10] and Li and Selig, [12].

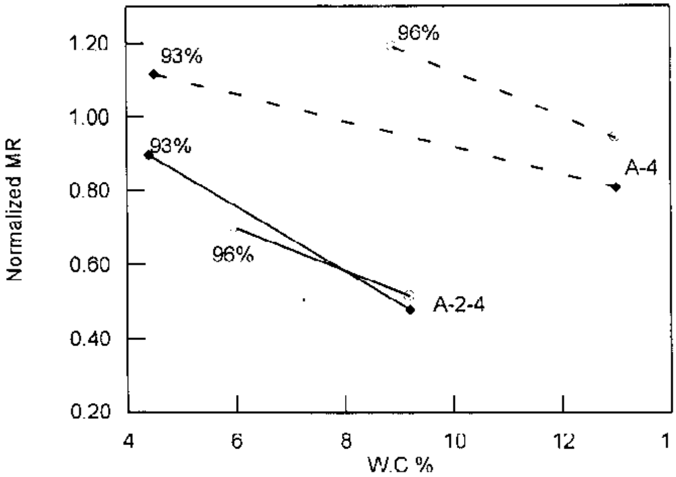

Fig. 13. Effect of WC on normalized MR.

Figure 14 depicts the effects of the relative density at optimum moisture content on the increase in resilient modulus of granular and fine-grained soils. The figure shows the significant effect that increasing density has on the resilient modulus of the granular soil. However resilient modulus increases slightly with increases of relative density in the case of the fine-grained soil.

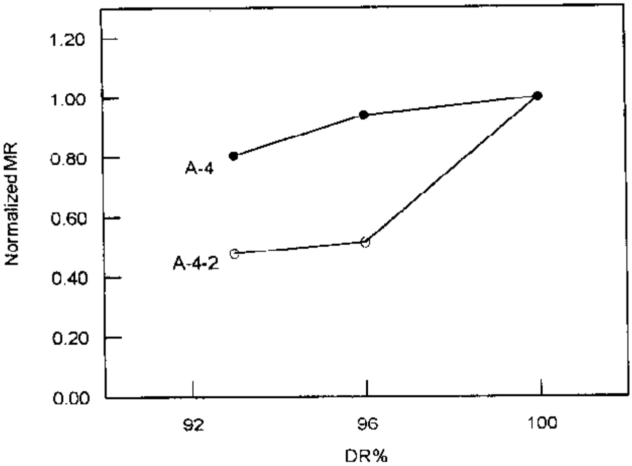

Fig. 14. Effect of DR on normalized MR.

Conclusions

The study reported herein was undertaken to evaluate the resilient behavior of typical Saudi subgrade soils under moisture content and stresses that simulate environment and traffic loading on highway pavements in Saudi Arabia, respectively. From the testing conducted in this study, the following conclusions can be made:

1. No evidence was obtained to suggest that resilient moduli of subgrade soils in the arid climates of Saudi Arabia should be evaluated for compaction wet of optimum especially for highway pavements outside urban areas.
2. The model suggested by AASHTO for resilient modulus for type 2 material is not sufficient to describe the resilient behavior of this soil since the effect of confining stress on the resilient properties is not considered.
3. The constitutive equation used as proposed by Pezo appears to be suitable to model the resilient characteristics of subgrade soils in Saudi Arabia.
4. Resilient modulus at unit deviator and confining stresses (K_1) generally increases as the soil density increases when keeping the moisture content at the optimum.
5. Resilient modulus at unit deviator and confining stresses (K_1) decreases as moisture content increases for granular soils. The trend for fine-grained soils is the opposite.
6. The contribution of the deviator stress to the resilient modulus value (K_2) is largely dependent on the molding moisture content, the density of the soil and the type of soil (granular or fine-grained). However, this contribution does not change with density if the moisture content is kept constant.at the optimum.
7. Increasing moisture content at a relative density of 96% increases the effect of confining stress (K_3) on resilient modulus, while increasing density but keeping moisture content constant (at optimum) reduces this effect.
8. Increasing moisture contents tend to decrease resilient moduli of cohesive (A-4) and coarse- grained (A-2-4) soils under expected service stresses. However, as the relative density increases, the resilient modulus increases for both types of soils.

Acknowledgment. The research described in this paper was financially supported by King Abdulaziz City for Science and Technology (KACST) under grant No. AR-12-51. The authors wish to express their appreciation to KACST. Also, thanks are extended to King Saud University for providing the laboratory facilities. Thanks are also expressed to the staff of the Civil Engineering Laboratories at KSU for their effort in laboratory work.

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العوامل المؤثرة على سلوك الرجوعية للقاعدة الترابية في المملكة العربية السعودية

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الرياض ١١٤٢١ ، المملكة العربية السعودية

(قدم للنشر في ١٣/٠٥/٢٠٠٠م، وقبل للنشر في ٢٤/٠٤/٢٠٠١م)

ملخص البحث. تعرض هذه الورقة دراسة تأثير كل من الكثافة النسبية ومحتوى الرطوبة على خواص الرجوعية للقاعدة الترابية للرصف في المملكة العربية السعودية. لقد تم اختيار ثلاثة عشر عينة ممثلة لأنواع القاعدة الترابية في جميع أنحاء المملكة واختبارها عند كثافة نسبية مقدارها ٩٣٪ ، ٩٦٪ و١٠٠٪وما يقابلها من المحتوى المائي على منحنى الدمك. وبينت النتائج أن سلوك الرجوعية للقاعدة الترابية يعتمد على نوع التربة من حيث هي تربة ناعمة أو تربة حبيبية وكذلك على الكثافة النسبية والمحتوى المائي. أظهرت الدراسة أيضا أن تأثير الضغط الرأسي المتردد والضغط الجانبي يعتمد على كل من الكثافة النسبية ومحتوى الرطوبة. أخيرا ، أكدت الدراسة على أهمية استخدام النموذج المناسب لوصف علاقة معامل الرجوعية بكل من الضغط الرأسي المتردد والضغط الجانبي.