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Cyclic Testing of Aggregates for Pavement Design

Paper No. 1.19

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SYNOPSIS Two most commonly encountered aggregates that are used as subbases/bases of roadways in Oklahoma were selected and tested under cyclic loading to evaluate their Resilient Modulus (RM). Following the repeated triaxial RM testing, the specimens were subjected to the triaxial compression tests from which the parameters of cohesion (C), and friction angle (ϕ) were obtained. A good statistical correlation was established between RM and C and ϕ. The repeated triaxial RM testing procedure serves as a "conditioning" prior to the static triaxial compression and it simulates the loads imposed by the moving vehicle. The effects of conditioning on C and ϕ were investigated. The strength increase through conditioning was found to vary from 18 to 85 percent, depending confining pressure and aggregate type. Also, it was found that C increased and ϕ decreased because of conditioning.

1 INTRODUCTION

To accurately predict the pavement response subjected to moving traffic loads, it is necessary to properly characterize the dynamic behavior of the pavement components. However, due to the difficulties in sample preparation and testing, very few studies have been conducted on investigating unbound granular materials under cyclic loading. Traditionally, testing and evaluation of properties of aggregates and of aggregate layers have been conducted in a static manner that does not simulate the repetitive nature of the actual loads imposed by moving vehicular traffic [Chen et al., 1994; Zaman et al., 1994]. Furthermore, the moving traffic loadings induce repeated deformations that can cause cracking of pavement structure [Pezo et al., 1992]. To correct this deficiency and in order to improve the reliability of pavement design and enhance pavement performance, the American Association of State Highway and Transportation Officials (AASHTO) proposed an improved pavement design method [1] and a material testing procedure (T274-82) [2] in 1986 to account for the repetitive nature of traffic loading. Resilient Modulus (RM) is the property that describes this behavior of pavement materials and is defined as the deviatoric dynamic stress (due to the moving vehicular traffic) divided by the resilient (recoverable) strain. Thus, the RM is considered to be a required input for determining the stress-strain characteristics of pavement structures subjected to traffic loading. However, laboratory testing of RM is generally time consuming and requires special equipment. Therefore, it is desirable to establish relationships between the RM and other index properties {namely, cohesion, friction angle, Young's modulus (E) and California bearing ratio (CBR)} that are relatively easy and inexpensive to determine. This is also in line with the AASHTO proposal [1] that agencies using the design guide establish such correlations. CBR has in the past been correlated with the RM; however, the load-deformation characteristics are so different between the CBR and the RM tests that many researchers [Laguros et al, 1993; Rada and Witczak, 1981; Zaman et al., 1994] reported unsatisfactory experiences in establishing and using such correlations.

In this study, two most commonly encountered aggregates (one sandstone from Choctaw County and one Rhyolite from Murray County) that are used as subbases/bases of roadways in Oklahoma were tested under cyclic loading to evaluate the Resilient Modulus (RM) by using the updated methods AASHTO T292-91I (proposed in 1991) and T294-92I (proposed in 1992). The number of repetitions required in T292-91I and T294-92I is 1900 and 2500, respectively. Following the repeated triaxial RM testing, the specimens were subjected to the static triaxial compression tests from which the cohesion (C) and the friction angle (ϕ) parameters were obtained. A statistical correlation was established between RM and C and ϕ. The repeated triaxial RM testing procedure serves as a "conditioning" prior to the static triaxial compression and it simulates the loads imposed by the moving vehicular traffic. The effects of conditioning on C and ϕ were investigated for these two aggregate types.

2 SPECIMEN PREPARATION

From the published literature it is evident that using T180-90D as the compaction method to prepare the aggregate specimens for RM testing can cause the breakage of particles. For example, in a study reported by the author [Laguros et al., 1993], the 1/2" particle was reduced in size by an average of 19% and as much as 23% reduction in particle having 3/8" size was found to occur due to compaction. A more recent AASHTO publication, the interim methods for RM testing of unbound granular base/subbase materials (T294-92I and T292-91I), suggests that for granular-type soils it is desirable to use a vibratory compaction method to prevent the breakage of particles. Changes in maximum dry density do not affect the RM values significantly as compared to the changes caused by the stress level and the moisture content. Soil structure effects on RM are generally unimportant for granular type soils as compared to effects due to a change in moisture content and confining pressure; this aspect has been well documented in the literature [Rada and Witczak, 1981; Thompson, 1989].

In this study, a split mold was designed and fabricated to enhance sample preparation. The compaction method employed essentially involves a trial-and-error adjustment in the weight of the aggregate materials per layer, the number of compacted layers, and the vibrating period for each layer to produce specimens of the desired densities. Based on this trial and error approach a suitable sample preparation procedure was devised. The specimens were prepared in ten layers having approximately 1,600 grams of aggregate mixes per layer. The vibrating time is approximately 30 seconds per layer for the first 8 layers and 4 minutes per layer for the last 2 layers. All specimens investigated in this study were compacted to 95% of the maximum dry density and at an optimum moisture content that was determined from the AASHTO T180-90D method. In order to meet the ODOT 1988 specifications [9] and to ensure consistent gradation for each specimen among various aggregate types, a gradation curve was selected for the purpose of sample preparation. Also, gradation of aggregate materials can be an important factor when comparing the RM values. The selected gradation curves employed in this study and the gradation required by ODOT [9] are presented in Table 1.

3 RESILIENT MODULUS VALUES OBTAINED FROM THE EXPERIMENTAL PROGRAM

The procedure for the determination of RM has not yet been standardized, however, guidelines are given in the AASHTO Test

Methods T274-82 [2], T292-91I [3], and T294-92I [4]. The basic differences between these two testing procedures are particularly in terms of : (1) sample conditioning prior to testing; (2) number of loading cycles; (3) wave form; (4) location of LVDT; and (5) applied stress sequence.

Thompson [1989] reported that the same specimen can be used to measure the RM over a wide range of stress levels and the stresses can be applied in any order, with the limitation that the repeated stress states are not greater than approximately 60% of the ultimate shear strength of the material. Huang [1993] reported that because the applied load is usually small, and the Resilient Modulus test is a nondestructive test, the same specimen can be used for many tests under different loading and environmental conditions. From the static triaxial tests conducted by Laguros et al. [1993], it is found that for the specimen prepared at the optimum moisture content failed at axial stress around 130-160 psi, depending on the aggregate sources, when tested under a confining pressure of 15 psi. From Refs. [2,3,4], it is evident that both T292-91I and T294-92I test methods possess the highest deviatoric stress of 40 psi and therefore they have satisfied Thompson's [1989] suggestions. Furthermore, it is observed that T292-91I starts with a higher confining pressure and deviatoric dynamic stress and ends with a lower confining pressure and deviatoric dynamic stress, while T294-92I starts with a lower confining pressure and deviatoric dynamic stress and ends with a higher confining pressure and deviatoric dynamic stress. The study conducted by Mohammad et al. [1994] found that the T292-91I procedure causes more stress dependency and disturbance to the specimen resulting in lower RM values than those of the T294-92I and thus contradicting Thompson's [1989] suggestion that the stresses can be applied in any order.

In this study, an attempt was also made to investigate the effects of the applied stress sequence on the RM values. Two aggregate types were selected and six tests were conducted under T294-92I and T292-91I. All specimens were prepared at the same gradation that meets the ODOT 1988 specifications [9] for Type A materials. The square wave form with a fixed cycle duration of 1.8 seconds was selected to provide a 0.6 second loading duration and 1.2 second relaxation between the end and beginning of consecutive load repetitions. To eliminate another unknown, the square wave form was selected for both methods. It should be noted that the T294-92I test method requires a haversine loading wave form. Also, in this study, the LVDT is externally mounted at the end of the specimen for both T292-91I [3] and T294-92I [4] test methods. It is important to note that T292-91I and T294-92I suggest different locations for the LVDT. The average RM values for two aggregate types from six tests are grouped together and presented in Fig. 1. For both aggregate types investigated, the T294-92I testing procedure yields higher Resilient Moduli than those obtained by using the T292-91I testing procedure, possibly because the stress sequence in T294-92I has a stiffening and strengthening effect on the specimen structure as the stress level increases from low to high. The amount of increase of RM values due to testing method varies with the type of aggregate. For example, aggregates from Murray County exhibited a higher degree of increase (about 35-55%) when using the T294-92I testing method than the aggregates from Choctaw County (about 15-34%). The aggregates from Murray County, when using the T294-92I method, experience a higher variability in the RM values (with MCOV 26%) than when using the T292-91I method (with MCOV 20.6%). MCOV is defined as the maximum coefficient of variation which is the highest among all bulk stress levels considered. In contrast, aggregates from Choctaw County exhibit a lower variability in the RM values (with MCOV 18.9%) when using T294-92I than those when using T292-91I (with MCOV 19.7%).

4 TRIAXIAL COMPRESSION TESTS

Following the repeated triaxial testing, the static triaxial compression tests were performed to obtain the cohesion and friction angle of the material (aggregate). The repeated triaxial tests served as a "conditioning" of the sample for triaxial compression test as it could be imposed by the moving vehicles. Thompson and Smith [1990] reported that the shear strength of an unconditioned specimen does not represent the strength of an in service compacted granular base material subjected to traffic loading. They found that this strength increase, induced by the dynamic stress repetitions, varies from 34 to 217 percent. However, the number of repetitions and the magnitude of the dynamic stress required to replicate the field conditions are not completely understood or finalized at present. The Mohr circles were drawn based on the conventional triaxial compression test results and the shear strength parameters {cohesion (intercept) and friction angle (slope)} obtained are presented in the Table 2. The cohesion and friction angle of the material obtained from triaxial compression tests with "conditioning" were used as the data base to establish correlations with RM values.

Table 1 Gradations Required by the Oklahoma Department of Transportation [9] and Those Used in the Present Study

Sieve Size	Percent Passing ODOT Requirement (Type A)	Presently Used
1.5"	100	
1"		100
3/4"	40-100	82
1/2"		68
3/8"	30-75	55
#4	25-60	44
#40	8-26	17
#200	4-12	6

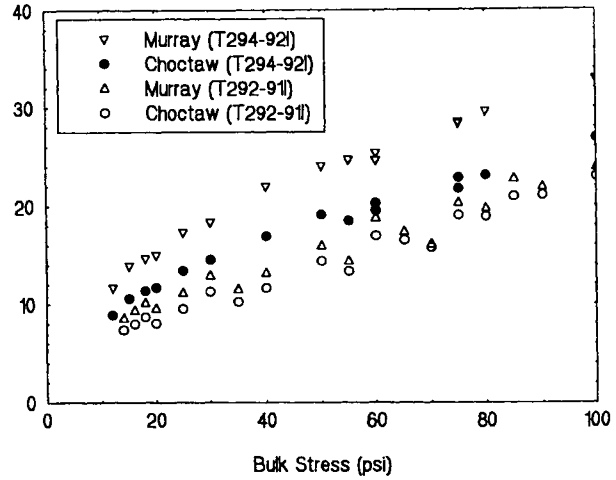

Fig. 1 Comparison of Average Resilient Modulus for Different Testing Procedures (AASHTO T292-91I and T294-92I) and Different Aggregate Sources (Murray and Choctaw Counties)

An attempt was made to investigate the strength increase through conditioning, induced by the dynamic stress repetitions for the two aggregates. The conventional triaxial compression test results with conditioning and without conditioning are presented in Tables 2 and 3, respectively. To determine the amount of strength increase, the average maximum stresses for with and without conditioning are grouped together and presented in Table 4. Evidently, the strength increase through "conditioning" was found to vary from 18 to 85 percent, depending upon the confining pressure and aggregate type. Based on the data shown in Table 4, when the confining pressure is low, both aggregate types exhibit a greater percent of strength increase due to "conditioning". For all three confining pressures (5, 10, and 15 psi) used, the effects of conditioning on maximum stresses are more significant for Choctaw aggregates than that the Murray aggregates. Based on the results shown in Table 3, the Mohr circles were also drawn for specimens without conditioning. The shear strength parameters without conditioning for the Choctaw aggregate were C= 5.2 psi and ϕ= 49 degree, and for the Murray aggregate without

Table 2 Triaxial Compression Data for Aggregates from Choctaw and Murray Counties (with conditioning)

Choctaw		Murray	
Confining Pressure (psi)	Maximum Stress (psi)	Confining Pressure (psi)	Maximum Stress (psi)
5	112.2	5	120.9
5	125.5	5	120.9
5	98.8	5	101.5
5	114.6	5	111.1
5	107.6	5	103.7
		5	104.8
10	166.8	10	142.7
10	166.0	10	141.9
10	167.3	10	151.5
10	143.7	10	142.7
10	136.6	10	134.5
10	132.7	10	140.9
		10	130.3
15	186.2	15	175.2
15	190.2	15	182.2
15	182.8	15	175.2
15	174.6	15	174.3
15	167.8	15	168.9
Choctaw C=12 psi φ= 46 degree		Murray C=16 psi φ= 46 degree	

Table 3 Triaxial Compression Data for Aggregates from Choctaw and Murray Counties (without conditioning)

Choctaw		Murray	
Confining Pressure (psi)	Maximum Stress (psi)	Confining Pressure (psi)	Maximum Stress (psi)
5	63.7	5	81.9
5	66.7	5	76.5
5	51.0	5	65.9
10	109.7	10	85.4
10	97.4	10	115.2
10	88.2	10	107.1
15	147.0	15	157
15	130.4	15	148
15	133.6	15	140.7

Table 4 Effect of Conditioning on Maximum Stress for Aggregates from Choctaw and Murray Counties

		With Conditioning	Without Conditioning	Strength Increase Due to Conditioning
County	Confining Pressure (psi)	Maximum Stress (psi)	Maximum Stress (psi)	(%)
Choctaw (Sandstone)	5	111.7	60.5	84.6
	10	152.2	98.4	54.7
	15	179.5	137	31.0
Murray (Rhyolite)	5	110.5	74.8	47.7
	10	140.6	102.6	37.0
	15	175.2	148.6	17.9

conditioning C= 8 psi and φ= 48.5 degree. Thus, the effect of "conditioning" is an increase in C and a decrease in φ.

5 STATISTICAL CORRELATIONS

Statistical correlations between RM and engineering index properties (cohesion, friction angle) are useful in practice because the engineering index properties are less difficult and expensive to evaluate. The RM values are neither intimately related to the Plasticity Index (PI) of the granular materials nor to the conventional classification system used (such as the AASHTO and the Unified Classification Systems) [Zaman et al., 1991], therefore this correlation was not attempted.

Thompson [1989] stated that RM of granular materials display more "generic" types of behavior and show less variation than fine-grained soils. Gradation, shape/angularity/surface texture (crushed-uncrushed), and moisture content (especially for high fines content materials) influence the RM of granular materials. The magnitude of the repeated stress state (as expressed by the bulk stress θ) is the most dominating and significant factor (Thompson [1989]). These findings were confirmed in this study and are presented in Figs. 1, 2, and 3 which also attest to the RM increasing with the bulk stress. This is similar to the shear stress increasing with the normal principal stresses according to the principles of the Mohr failure envelope. Thus, for a better correlation with the RM value of the granular material, a model including the variables of stress state and moisture content variation is desirable. However, in this study due to the lack of RM values for the variation of moisture content, the variable of moisture content was not included in the correlations. The effect of variation of moisture content on RM values is currently being studied by the authors. Therefore, in the present study, a proposed model relating cohesion (C) and friction angle (φ) with RM in terms of the major principal stress σ_1 and the bulk stress θ was formulated and is given in the form

$$\text{RM (in psi)} = A_0 + A_1 * C + A_2 * \sigma_1 * \tan\phi + A_3 * \theta \qquad (1)$$

where $A_0 \sim A_3$ are the regression constants and θ is the bulk stress defined by $\theta = \sigma_1 + \sigma_2 + \sigma_3$. The following numerical values of the regression constants were obtained :

$A_0 = 2860.94$ psi; $A_1 = 275.0$; $A_2 = 128.0$; and $A_3 = 118.0$

The same C and φ values given in Table 2 were used in the prediction for these two aggregates. A comparison between the experimental observations and the model predictions for the two aggregates is presented in Figs. 2 and 3, respectively. In few occasions, for the same bulk stresses there was more than one RM value because the same bulk stress can have more than one combinations of σ_1 and σ_3. It is found

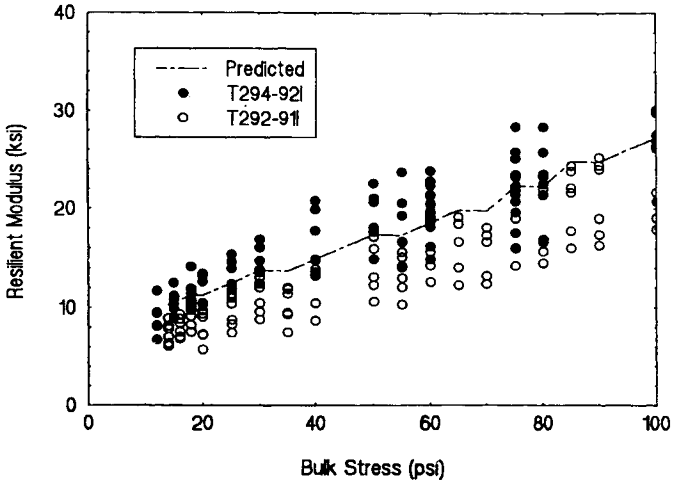

Fig. 2 Resilient Moduli for the Aggregate from Choctaw County (Sandstone) and Their Comparison with Model Prediction (Eq. 1)

from Figs. 2 and 3 that overall the model fits the experimental data extremely well.

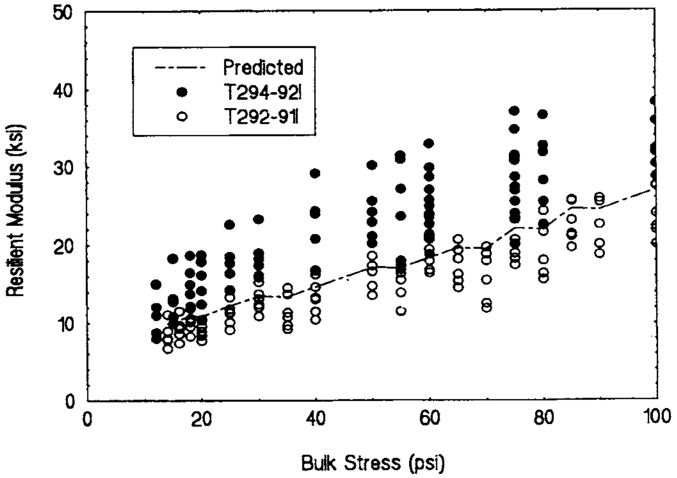

Fig. 3 Resilient Moduli for the Aggregate from Murray County (Rhyolite) and Their Comparison with Model Prediction (Eq. 1)

6 CONCLUSIONS

To account for the repetitive nature of traffic loading and for a better understanding of material behavior, two aggregate types were tested under cyclic loading following the AASHTO guideline. The effect of testing procedures (T292-91I and T294-92I) on RM values and the effects of conditioning on C and ϕ were investigated. The RM values were correlated with C and ϕ. Based on the data obtained the following observations were made:

1. The T294-92I testing procedure gave higher resilient moduli than those obtained by using the T292-91I testing procedure, possibly because the cyclic stress had a stiffening and strengthening effect on the specimen structure as the stress level increased from low to high.

2. The strength increase due to conditioning was found to vary between from 18 to 85 percent, depending upon the confining pressure and the aggregate type. For all three confining pressures (5, 10, and 15 psi) used, the aggregates from Choctaw County yielded higher percentage increase due to conditioning than those from Murray County.

3. For both aggregates from Choctaw and Murray Counties, it was found that C increased while ϕ decreased because of conditioning induced by the dynamic stress repetitions.

4. It is possible to establish a satisfactory correlation did exist between the RM values and the cohesion and friction angle.

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