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Effect of sample size on resilient modulus of cohesive soils

Effet de la taille de l'échantillon sur le module réversible de sols cohésifs

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ABSTRACT
This paper presents the results of research conducted to investigate the effect of the sample size on the resilient modulus of cohesive soils as determined by the repeated load triaxial test. Soil samples from three different sites within the State of Wisconsin were collected and then subjected to standard laboratory tests to evaluate their properties. Soil specimens of 35.6, 71, and 101.6 mm diameter (with length to diameter aspect ratio of 2:1) were prepared according to the standard procedure described by AASHTO T 307 and then were subjected to repeated load triaxial test to determine their resilient modulus values. Test results showed that the specimen size has a significant influence on the resilient modulus of the investigated cohesive soils. Soil specimens with 35.6 mm diameter exhibited the highest resilient modulus values while the specimens with 101.6 mm diameter exhibited the lowest values. The resilient modulus variation with specimen diameter was significant at low deviator stress levels and decreased with the increase of the deviator stress.

RÉSUMÉ
Cet article présente les résultats de travaux de recherches ayant pour but de déterminer l'effet de la taille de l'échantillon sur le module de deformation réversible de sols cohésifs déterminé á l'aide de l'appareil triaxial á chargement répété. Des échantillons de sols en provenance de plusieurs sites dans l'Etat de Wisconsin ont été collectes et soumis aux essais standards pour évaluer leurs propriétés géotechniques. Les échantillons de tailles 35.6, 71, et 101.6 mm de diamètre (avec un élancement de 2:1) ont été préparés selon les standards décrits par les normes AASHTO T 307 et soumis á des essais de chargements répétés au triaxial pour déterminer leurs modules réversibles. Les résultats montrent que la taille des échantillons á un rôle significatif. Les échantillons de diamètres 35.6 mm montrent les plus fortes du module réversible tandis que les échantillons de diamètres 101.6 mm montrent les plus faibles valeurs. La variation du module réversible selon le diamètre des échantillons est plus marque quand le niveau du déviateur des contraintes est faible et cette même variation diminue avec la baisse du déviateur des contraintes.

1 INTRODUCTION

Design of pavements on subgrade soils requires a significant amount of input data such as traffic loading characteristics, properties of materials (base, subbase and subgrade soil), environmental conditions and construction procedures. Properties of subgrade soils are often evaluated by laboratory tests such as California Bearing Ratio (CBR), which do not represent the nature of repeated dynamic traffic load on subgrade soil. Recognizing this deficiency, the American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures (1986 and 1993) and the 2002 AASHTO Guide for the Design of New and Rehabilitated Pavement Structures incorporated the resilient modulus for characterizing subgrade soils in flexible pavement design.

Resilient modulus of subgrade soils can be determined by laboratory testing such as the repeated load triaxial test. The AASHTO T 307 (Determining the Resilient Modulus of Soils and Aggregate Materials) is the current standard procedure designated by AASHTO for determining the resilient modulus of subgrade soils using the repeated load triaxial test. According to this standard procedure, the specimen size (diameter and length) depends upon the soil type as classified from particle size analysis and consistency limits. In addition, for type 2 materials (fine-grained soils), compacted specimens should be prepared in a mold that will produce a specimen of minimum diameter equals to five times the maximum particle size with an aspect ratio of length to diameter of not less than 2:1.

In this paper, the effect of specimen size on resilient modulus of cohesive soils is investigated. Cohesive soil samples were collected and subjected to laboratory tests to evaluate their physical properties, compaction characteristics, and resilient modulus. Repeated load triaxial test was conducted on soil specimens of three different diameters, namely: 35.6, 71, and 101.6 mm. The length to diameter ratio of all samples was maintained at 2:1.

2 EXPERIMENTAL PROGRAM AND RESULTS

The soils considered in this study were collected from different locations within the State of Wisconsin. Standard laboratory tests were conducted to classify these soils and determine their properties. Laboratory testing consisted of particle size analysis (mechanical sieving and hydrometer analysis), specific gravity, consistency limits, organic content, and standard Proctor compaction test. Moreover, the repeated load triaxial test was used to determine the resilient modulus of these soils.

2.1 *Soil Properties*

Laboratory tests were conducted on the investigated soils following the standard procedures of the American Society for testing and Materials (ASTM). The standard Proctor compaction test was conducted using the AASHTO T 99 procedure. Table 1 present a summary of test results. Test results showed that the selected soils are classified as lean clay (A-6 according to AASHTO) with small variation in properties.

2.2 *Repeated Load Triaxial Test*

Preparation and testing of soil specimens were conducted in accordance with AASHTO T 307. A five-lift static compaction procedure was used to prepare each soil sample. This method provided a uniform compacted lifts while using the same mass of soil for each lift. All soil samples were prepared under the optimum moisture content and maximum dry unit weight. The measured unit weight of the different specimens indicated that the same level of compaction has been achieved.

In order to investigate the effect of sample size on resilient modulus, all other factors that might affect the test results were kept constant. Repeatability of the test results was achieved in a previous phase by the same operator using the same equipment (Elias et al. 2004).

3 DETERMINATION OF RESILIENT MODULUS

The repeated load triaxial test consists of applying a cyclic deviator stress (σ_d) on a cylindrical sample under constant confining pressure (σ_3) and measuring the recoverable axial strain (ε_r). The repeated axial load is applied in fixed 1-second cycles in which 0.1 second is a load duration. The specimen is first subjected to a minimum of 500 conditioning cycles to eliminate permanent deformation.

Resilient modulus determined from the repeated load triaxial tests is defined as the ratio of the repeated axial deviator stress to the recoverable or resilient axial strain. Equation (1) shows the definition of the resilient modulus.

$$M_r = \frac{\sigma_d}{\varepsilon_r} \quad (1)$$

The results of repeated load triaxial test on Antigo, Dodgeville and Miami soils are presented in Tables 2, 3 and 4 respectively. Only the test results of Antigo clay are presented in graphical format. Figures 1 to 3 show the variation of the resilient modulus of Antigo clay with the deviator stress at different confining pressures and sample sizes.

Table 1. Properties of investigated soils

Soil Location	Passing Sieve #200 (%)	LL (%)	PL (%)	PI (%)	G_s	w_{opt} (%)	γ_{dmax} (kN/m^3)	USCS Classification	GI	AASHTO Classification
Antigo clay	91	30	19	11	2.63	14.5	17.5	CL (Lean clay)	9	A-6
Dodgeville clay	97	37	25	12	2.55	19.6	15.9	CL (Lean clay)	13	A-6
Miami Silt Loam	96	39	22	17	2.57	18.4	16.5	CL (Lean clay)	18	A-6

Legend: LL: liquid limit, PL: plastic limit, PI: plasticity index, G_s: specific gravity, w_{opt}: optimum moisture content, γ_{dmax}: maximum dry unit weight, USCS: Unified Soil Classification System, GI: group index.

Table 2. Summary of test results for Antigo clay

Sequence No.	Confining Pressure (kPa)	Sample Diameter, D=35.6 mm		Sample Diameter, D=71 mm		Sample Diameter, D=101.6 mm	
		Deviator Stress (kPa)	M_r (MPa)	Deviator Stress (kPa)	M_r (MPa)	Deviator Stress (kPa)	M_r (MPa)
1	41.4	16.9	170	12.6	94	13.0	88
2		30.4	141	25.1	97	25.3	81
3		41.4	118	37.4	94	37.6	73
4		55.4	105	49.6	87	49.4	66
5		66.1	92	61.5	81	61.3	62
6	27.6	17.3	163	12.6	88	12.7	72
7		30.3	128	24.8	86	24.9	64
8		42.7	108	37.1	82	36.8	59
9		55.2	94	49.3	78	48.6	56
10		67.2	84	61.2	75	60.9	54
11	13.8	18.7	157	12.3	79	12.6	52
12		29.4	113	24.6	74	24.6	47
13		43.6	98	36.7	72	36.4	45
14		55.4	84	48.6	69	48.5	44
15		67.1	74	60.5	66	60.7	43

Table 3 Summary of test results for Dodgeville clay

Sequence No.	Confining Pressure (kPa)	Sample Diameter, D=35.6 mm		Sample Diameter, D=71 mm		Sample Diameter, D=101.6 mm	
		Deviator Stress (kPa)	M_r (MPa)	Deviator Stress (kPa)	M_r (MPa)	Deviator Stress (kPa)	M_r (MPa)
1	41.4	20.8	159	12.4	75	13.1	50
2		30.5	106	24.7	73	25.0	46
3		42.1	73	37.3	71	36.9	43
4		53.2	58	49.2	65	48.0	39
5		63.7	50	60.6	59	60.6	34
6	27.6	20.6	142	12.4	70	13.2	41
7		31.0	93	24.5	65	24.9	37
8		41.3	62	36.6	61	36.6	34
9		51.0	49	48.5	57	48.5	32
10		63.6	42	60.1	53	60.4	31
11	13.8	19.7	114	12.2	62	13.1	41
12		32.5	78	24.3	55	25.0	36
13		42.6	53	36.1	52	36.2	33
14		51.2	41	47.6	48	48.1	31
15		62.2	34	49.2	46	60.9	30

Table 4 Summary of test results for Miami silt loam

Sequence No.	Confining Pressure (kPa)	Sample Diameter, D=35.6 mm		Sample Diameter, D=71 mm		Sample Diameter, D=101.6 mm	
		Deviator Stress (kPa)	M_r (MPa)	Deviator Stress (kPa)	M_r (MPa)	Deviator Stress (kPa)	M_r (MPa)
1	41.4	18.2	181	12.5	101	12.8	67
2		29.3	134	25.3	103	25.3	67
3		40.6	113	37.3	99	37.3	61
4		54.3	94	49.2	92	48.8	54
5		65.6	83	61.0	86	60.2	50
6	27.6	17.7	162	12.4	95	12.7	49
7		31.0	121	25.1	93	24.5	48
8		42.6	101	37.0	90	36.4	45
9		54.6	85	49.1	86	47.8	43
10		65.3	74	60.9	82	59.5	41
11	13.8	18.6	155	12.5	86	12.5	36
12		30.1	110	24.8	82	24.6	36
13		43.0	89	36.8	81	36.4	35
14		51.9	71	48.8	78	48.5	34
15		63.4	63	60.7	76	60.5	33

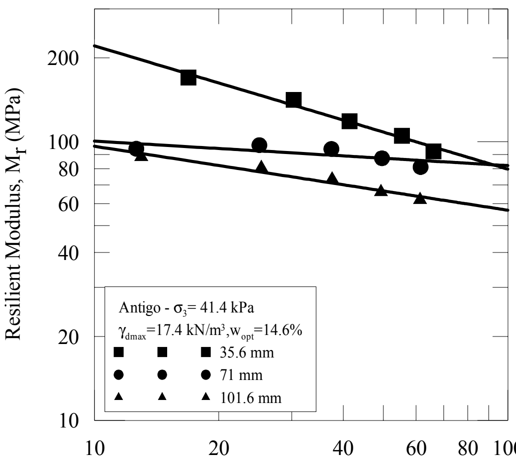

Figure 1. Results of repeated load triaxial test on Antigo clay under different specimen sizes and confining stress of 41.4 kPa

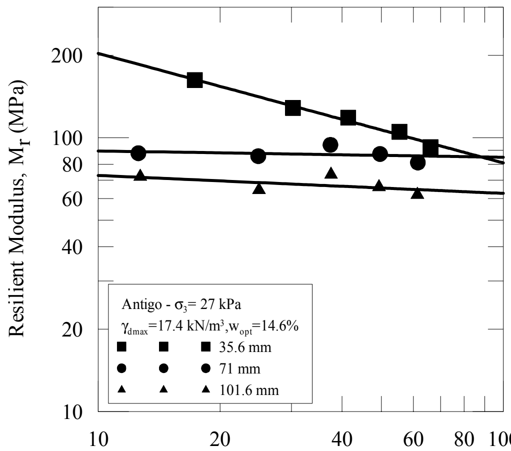

Figure 2. Results of repeated load triaxial test on Antigo clay under different specimen sizes and confining stress of 27.6 kPa

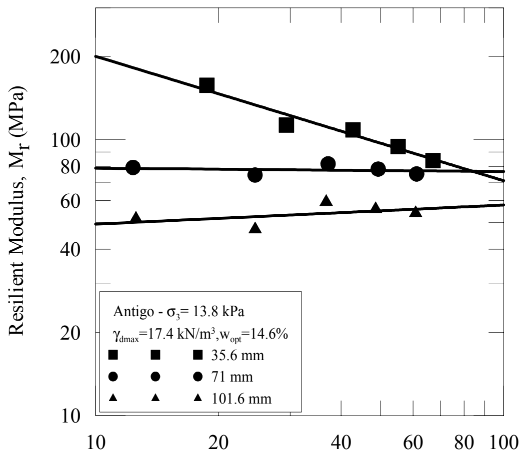

Figure 3. Results of repeated load triaxial test on Antigo clay under different specimen sizes and confining stress of 13.8 kPa

As presented in Figure 1, the resilient modulus of Antigo clay vary with deviator stress from 92 to 170 MPa for the 35.6 mm specimen; from 81 to 94 MPa for the 71 mm specimen and from 62 to 88 MPa for the 101.6 mm specimen. The variation shows a decreasing trend in the resilient modulus with the increase in the sample diameter for the same deviator stress. This decrease is significant and ranges from 33 to 67% for Antigo clay; from 29 to 88% for Dodgeville clay; and from 23 to 60% for Miami silt loam. In addition, the variation is more pronounced at low deviator stress levels and is decreasing with the increase of the deviator stress.

Examination of test result presented in Tables 2 to 4 indicates that the 35.6 mm diameter specimens of the investigated soils exhibited the highest resilient modulus values compared to the 71 and 101.6 mm diameter specimens. The authors believe that the test results of soil specimens with 71 and 101.6 mm diameter are more reliable compared to the test results of the 35.6 mm diameter specimens. This is because all specimens were tested using the same load cell of 5 kN capacity, which may affected the measurement accuracy and resulted in an unoptimized auto-toning for the smaller specimen size particularly at the minimum applied load of 13.8 N. In order to achieve better test results, a load cell of lower capacity should be used when testing the 35.6 mm diameter specimens. The test results of the other investigated soils showed the same effect of specimen size on the resilient modulus.

4 REGRESSION ANALYSIS OF THE RESILIENT MODULUS TEST RESULTS

There are several models that were developed for the estimation of resilient modulus of subgrade soils and base/subbase materials. A new "harmonized" resilient modulus test protocol is being developed through the NCHRP project 1-28A for implementation at the AASHTO 2002 pavement design guide. The new protocol uses the universal nonlinear model that is applicable for all types of subgrade soils. The model is given by (NCHRP Project 1-37A, 2002):

$$M_r = k_1 P_a \left(\frac{\sigma_b}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3} \quad (2)$$

where M_r is the resilient modulus, σ_d is the deviator stress, σ_b is the bulk stress (= $\sigma_1+\sigma_2+\sigma_3$), τ_{oct} is the octahedral shear stress, P_a is the atmospheric pressure (used to normalize M_r units), and k_1, k_2 and k_3 are material constants.

In this paper, the universal nonlinear model was used to characterize the resilient modulus of the investigated soils. In order to achieve this, a linear regression analysis was conducted to evaluate the material constants k_1, k_2 and k_3. Results of the statistical analysis are summarized in Table 5.

Table 5 Variation of material constants with sample size for tested soils

Sample Diameter D (mm)	Material Constant	Antigo Clay	Dodgeville Clay	Miami Silt Loam
35.6	k_1	2,138	2,754	2,399
	k_2	0.24	0.48	0.304
	k_3	-3.95	-8.38	-5.11
71	k_1	977	813	1,047
	k_2	0.3	0.35	0.24
	k_3	-1.8	-2.21	-1.31
101.6	k_1	851	513	631
	k_2	0.63	0.28	0.71
	k_3	-0.3	-2.37	-2.7

Inspection of Table 5 indicates that the values of the material constants (k_1, k_2 and k_3) for the investigated soils vary significantly with samples diameter. For example, k_1 vary from 2,138 for specimens of 35.6 mm diameter to 851 for specimens of 101.6 mm diameter for Antigo clay. In addition, the material constant k_1 value for the 35.6 diameter specimen is the highest among the three tested sizes while k_3 value is the lowest. The coefficient of determination (R^2) was calculated also to provide information about the regression analysis. For Antigo clay, R^2 values obtained from the results of the specimens with 35.6, 71 and 101.6 mm diameter are 97%, 95% and 99%, respectively. Statistical analysis of the results of Dodgeville clay and Miami silt loam showed similar levels of R^2.

5 CONCLUSION

Repeated load triaxial test was conducted on three different soils collected from different sites within the State of Wisconsin. In order to investigate the effect of samples size on resilient modulus, soil specimens with diameters of 35.6, 71, and 101.6 mm were considered. Soil specimens were subjected to resilient modulus test in accordance with AASHTO T 307. Test results showed that the resilient modulus for cohesive soils is significantly affected by the size of the soil specimen tested. Soil specimens with 35.6 mm diameter exhibited the highest resilient modulus values while the specimens with 101.6 mm diameter exhibited the lowest values. The resilient modulus variation with specimen diameter was significant at low deviator stress levels and decreased with the increase of the deviator stress.

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