

HOW TOP-SIZE AFFECTS THE RESILIENT MODULUS OF ROADWAY BASE MATERIALS

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ABSTRACT

The American Association of State Highway and Transportation Officials (AASHTO) uses resilient modulus values as the load-carrying capacity parameter for all pavement materials. However, the maximum sample diameter in standard resilient modulus test specifications is only 150 mm (6 inches). With that limitation, large-sized aggregates can not be tested at their full gradation because if top-size-to-sample diameter ratios exceed 1:5, arching effects occur during sample preparation which adversely affect the results. Thus, little work has been performed on the resilient modulus of large top sized aggregates.

In this study, 305 mm (12 inch) diameter samples of two different aggregates were tested for resilient modulus. The materials were tested at top sizes of 63 mm (2.5 inches), 38 mm (1.5 inches), and 19 mm (0.75 inches). Results indicate that the tests became less repeatable as top size increases, and that resilient modulus does not increase as top size increases. The second result is contrary to the conventional belief that load carrying capacity of aggregates increases with increasing top size.

INTRODUCTION

Today's higher tire pressures lead to greater stresses in all flexible pavement layers and thus to increased overall pavement deflection and shortened pavement life. The higher stresses have also led to increased rutting of these pavements. At transportation conferences and in publications, larger top-sized aggregates and their higher load carrying capacities are put forward as potential solutions to these problems (1, 2).

Resilient Modulus (M_r) is used in the AASHTO flexible pavement design method (3) to characterize the load carrying capacities of paving materials. However, little laboratory work has been done to determine the M_r of gradations with large top-size aggregates because few laboratories have the equipment to

perform the test on the large diameter samples which are needed to avoid arching effects during sample preparation. The only previously-reported resilient modulus testing of 305 mm (12 inch) diameter aggregate specimens was performed at Georgia Institute of Technology. In that work, Itani confirmed that the M_r of unbound granite aggregate from Norcross, Georgia "increases about 25 percent when the maximum aggregate size is increased from $\frac{3}{4}$ to 2.5 inch for the 12 (30.5 mm) inch diameter specimens" (4). Unfortunately, he only tested one type of aggregate, and he only performed one test at $\frac{3}{4}$ inch and one test at 2.5 inches.

The objective of the work described in this paper is to test the effect of large top-sized gradations on the resilient modulus of other unbound highway base materials. This objective was addressed by subjecting 305 mm diameter aggregate specimens with different top-sizes to repeated axial loading and comparing the resulting resilient moduli.

Space here is insufficient to provide complete research results, but a full account is contained in the masters thesis by Townsend (5).

MATERIALS TESTED

Three materials were used in this study. The first was the same crushed granite from a Vulcan Materials Company quarry in Norcross, Georgia used by Itani in his work. The second was crushed limestone from the Vulcan Materials Company Dolcito Quarry in Birmingham, Alabama. The third material was an uncrushed river gravel from a Vulcan Materials Company dredge barge in Chattanooga, Tennessee.

The same three gradations which Itani used in his work were tested for this research (4). These gradations contained top-sizes of 63 mm (2.5 inches), 38 mm (1.5 inches), and 19 mm ($\frac{3}{4}$ inch) and are given in Table 1. The two larger gradations are classified as "GW, well-graded gravel with sand" in the Unified classification system. The third material falls into the "SW, well-graded sand with gravel" classification. The fines content (percent passing the 0.075 mm sieve size) was set at 4% for all samples to exclude the effect of fines.

Table 1: Gradation for the Top Sizes

Sieve Size, mm (U.S. Standard)	Percent Passing		
	63 mm (2.5") Top-Size	38 mm (1.5") Top-Size	19 mm (0.75") Top-Size
63.0 (2.5")	100.0	-	-
38.0 (1.5")	74.5	100	-
19.0 (0.75")	58.2	80	100
9.5 (0.375")	42.6	60	90
4.75 (#4)	31.2	45	80
0.425 (#40)	10.5	13	24
0.075 (#200)	4.0	4	4

EQUIPMENT USED

A Materials Testing System (MTS) servo-hydraulic force frame with a load rating of 245 kN (55 kips) was used to test samples. The system used a 19 liter per minute (5 gpm) servo-valve and 245 kN (55 kip) actuator. Hydraulic pressure was applied to the system with a hydraulic pump of 265 liter per minute (70 gpm) maximum flow capacity and a maximum continuous pressure of 21,000 kPa (3000 psi).

The axial load was placed on the sample through an 89 kN (20,000 pound) capacity load cell mounted internally. Two linear variable differential transformers (LVDTs) of 0.025 mm (0.001 inch) precision were mounted externally to the triaxial cell. The triaxial cell was of sufficient size to accommodate the 305 mm (12") by 610 mm (24") samples used in all the testing.

TEST CRITERIA

Strategic Highway Research Program (SHRP) protocol P 46 was used as the basis for the test procedures (6). Preparation and testing were performed in accordance with that interim SHRP specification with the exception given in the next paragraph. Sample preparation included drying and sieving the material into the proper sizes for the required gradations. Samples were compacted at optimum

water content and maximum dry density as determined by AASHTO T-180 Modified Proctor tests.

One modification was made to the SHRP test protocol during the dynamic testing itself. After sample conditioning is complete, SHRP calls for testing at fifteen different stress states. During testing for this project, five more stress states were added in order to gain extra data.

GRANITE TEST RESULTS

A limited series of tests was performed with granite to determine if Itani's results could be repeated. If results were similar to Itani's results, work would then begin on the two new materials. Tests were performed on 63 mm (2½ inch) top-sized granite. (Three samples were tested to examine the repeatability of testing large-sized samples.) The results of all three tests were plotted on a graph of M_r vs. θ (bulk stress), and a regression line of the form $M_r = k_1 \theta^{k_2}$ was drawn through the data as prescribed in the SHRP P46 procedure. The average test results for the three runs were similar to Itani's results for the one run he performed (4). They are presented below in the form specified by Protocol P46, including M_r at 415 kPa (60 psi).

- Itani: $k_1 = 7,290$; $k_2 = 0.556$; $R^2 = 0.81$
 M_r at $\theta = 415$ kPa (60 psi) is 208 MPa (30 ksi)
- Townsend: $k_1 = 24,345$; $k_2 = 0.356$; $R^2 = 0.45$
 M_r at $\theta = 415$ kPa (60 psi) is 208 MPa (30 ksi)

Agreement at 415 kPa is almost perfect, but the $R^2 = 0.45$ value for Townsend appears low. However, Townsend's three individual tests demonstrated R^2 values of 0.87, 0.87, and 0.61. Additionally, the plots of Itani's and Townsend's regression lines agree very well. For example, results of the regression equations at $\theta = 200$ kPa and $\theta = 600$ kPa (29 psi and 87 psi) give values of 161 MPa and 237 MPa for Townsend, while Itani's equation predicted M_r of 138 MPa and 225 MPa. The closeness of the results convinced the researchers that their experimental techniques and results were comparable to Itani's.

LIMESTONE TEST RESULTS

Nine tests were performed on limestone: three samples each on 63 mm, 38 mm, and 19 mm top-sized gradations. The results from one of the three 38 mm samples are presented in Figure 1, with a regression line ($R^2 = 0.76$) drawn through the data. As expected, the regression line has a positive slope, reflecting increased stiffness with increased confining pressure.

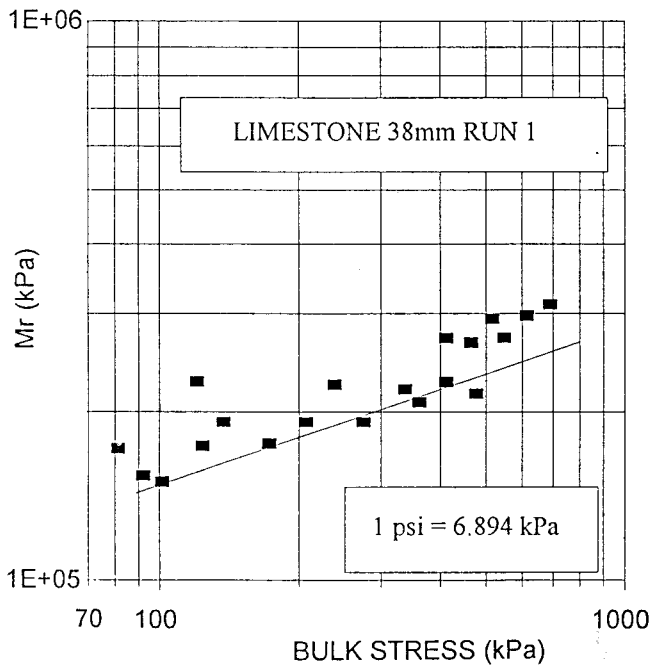


Fig. 1: Limestone 38 mm run 1

Figure 2 shows the result from all three tests on the 38 mm gradation. A regression line ($R^2 = 0.74$) was drawn through the composite data.

The same procedures were repeated for the 63 mm and 19 mm gradations. The composite regression lines for all three gradations of limestone are shown in Figure 3, with the individual data points omitted to avoid confusion. Contrary to expectations, the M_r of the three gradations decreases as top-sized increases. This result will be explored further in the "Statistical Analysis" section.

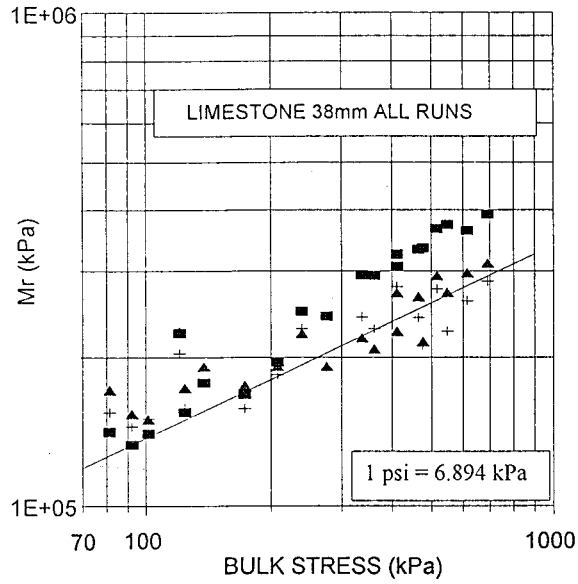


Fig. 2: Limestone 38 mm all runs

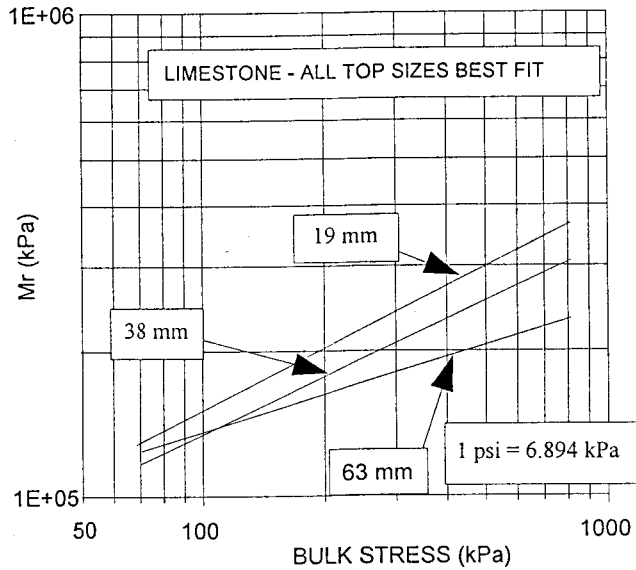


Fig. 3: Limestone - all top-sizes best fit

The data for the three composite regression lines is given below:

- 19 mm: $k_1 = 27,789$; $k_2 = 0.3995$; $R^2 = 0.87$
 M_r at θ 415 kPa (60 psi) is 309 MPa (45 ksi)
- 38 mm: $k_1 = 46,878$; $k_2 = 0.2752$; $R^2 = 0.74$
 M_r at θ 415 kPa is (60 psi) 246 MPa (36 ksi)
- 63 mm: $k_1 = 59,485$; $k_2 = 0.2185$ $R^2 = 0.48$
 M_r at θ 415 kPa (60 psi) is 222 MPa (32 ksi)

As top size increases, R^2 for the composite regression lines decreases. This indicates more scatter in the data. The R^2 value of 0.48 for 63 mm top-size limestone is very similar to the value of 0.45 reported earlier for granite. The researchers believe that arching effects begin to make the data less repeatable as top size increases.

RIVER GRAVEL TEST RESULTS

Three tests were performed on the uncrushed river gravel: one each on a 63 mm, 38 mm, and 19 mm gradation. The results of those three tests are presented in Figure 4. Though the results are not as well defined as in Figure 3, it is again

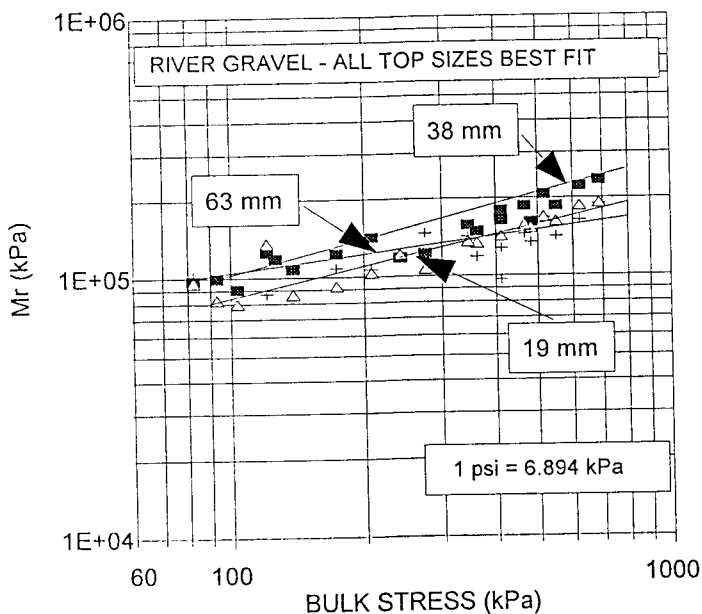


Fig. 4: River gravel - all top-sizes best fit

apparent that M_r did not generally increase as the top-sized increased. The data describing the three regression lines is given below. Note again that R^2 decreases as top size increases.

- 19 mm: $k_1 = 16,799$; $k_2 = 0.3598$; $R^2 = 0.88$
 M_r at $\theta = 415$ kPa (60 psi) is 147 MPa (21 ksi)
- 38 mm: $k_1 = 17,144$; $k_2 = 0.3824$; $R^2 = 0.58$
 M_r at $\theta = 415$ kPa (60 psi) is 172 MPa (25 ksi)
- 63 mm: $k_1 = 38,277$; $k_2 = 0.2164$; $R^2 = 0.58$
 M_r at $\theta = 415$ kPa (60 psi) is 141 MPa (20 ksi)

Nine tests were originally planned for the river gravel, just as had been performed on the limestone. However, only three tests were performed due to the time and effort required to prepare and test samples. Each test sample weighed over 90 kg (200 pounds) and required more than a day to produce. Sieving material to attain the proper sizes was a lengthy process, particularly for the finer fractions.

STATISTICAL ANALYSIS

Figures 3 and 4 indicated that increased top-size did not produce increased resilient modulus. Rather, the reverse appeared true. However, visual examination does not supply adequate proof; a statistical analysis must be performed.

REGRESSION ANALYSIS

Regression analyses were run using the logarithm of the resilient modulus as a dependent variable and the logarithm of both bulk stress and top-size as independent variables. The objective was to gain an insight into the effect of using different top-sizes on the resilient modulus of both crushed limestone and uncrushed river gravel. The R-squared, as the percentage of the variability that can be accounted for using specific independent variables, was calculated for every regression analysis tried. The following table shows all R-squared values calculated.

Material	Using Only Log Bulk Stress	Using Only Log Top Size	Using Both Log Bulk Stress and Top Size
River Gravel	70.23 %	0.18 %	70.69 %
Limestone	45.06 %	20.39 %	64.94 %

The river gravel data indicate that the top size has no effect on the resilient modulus (R-squared = 0.18%), while the limestone data indicate that the top size has a relatively significant effect (R-squared = 20.29%). The following equation resulted from the regression equation involving both top size and bulk stress as dependent variables for the limestone:

$$\log M_r = 4.055 + 0.309 * \log (\text{Bulk Stress}) - 0.282 * \log (\text{Top Size})$$

The negative coefficient of the log Top Size means that increasing the top size decreases the resilient modulus. The conclusion agrees with Figure 3, which indicates that materials with a 0.75 inch top size have the highest resilient modulus while materials with 2.5 inch top size have the lowest resilient modulus.

Figure 4 shows resilient modulus values for the river gravel materials with different top sizes. It shows little significant effect of changing top size on the resilient modulus, which agrees with the results from the regression analysis.

Paired Samples Analysis

Separately for the limestone data and for the river gravel data, a paired t-test was run on every possible two sets of resilient moduli with different top sizes. (For limestone, the average of three tests were used to create both items in each data pair; because river gravel data came from only one test per top size, data pairs were formed without averaging.) The objective was to gain more insight into the effect of every individual top size on the resilient modulus. To perform the analysis, every set of data was compared to another set, and the differences between the resilient modulus values of the data points that have similar bulk stress values were analyzed. The analysis has a null hypothesis which states that the difference in the resilient modulus values between the paired data point has a mean that equals zero. The following two tables summarize the results of the paired analyses.

Limestone

Pair	0.75" Vs. 1.5"	0.75" Vs. 2.5"	1.5" Vs. 2.5"
Mean	5266	9897	4598
Computed t statistic	4.48	7.13	2.00
T value	2	2	2.00

River Gravel

Pair	0.75" Vs. 1.5"	0.75" Vs. 2.5"	1.5" Vs. 2.5"
Mean	-2903	54	2957
Computed t statistic	-5.75	0.09	3.28
T value	2.12	2.12	2.12

If the absolute value of the computed t statistic is bigger than the T value (T is from the T-distribution table), then the null hypothesis is rejected, and there is a difference in resilient modulus values. Additionally, a "+" sign in the t-statistic indicates that the first top size listed at the top of each column has higher resilient modulus values.

The data from the limestone table show that a top size of 0.75" gives the highest resilient modulus and that increasing the top size decreases resilient modulus. The data from the river gravel table indicate that 1.5" top size gives the highest resilient modulus and that there is no significant difference in the resilient modulus values between 0.75" top size and 2.5" top size.

In summary, the regression and paired samples analysis both indicate that either resilient modulus decreases as the top size increases or that top size has no effect on resilient modulus.

PRACTICAL IMPLICATIONS

What are the implications of this research? First, it must be emphasized that the results presented here represent limited work and might not extend to other materials. However, if further work shows that M_r for other aggregate material does not increase with top size, several accepted theories and practices must be called into question. For example, the method of testing highway base materials

may be affected. Currently, large-diameter particles are scalped (removed) from the material before testing. If the large-diameter particles do significantly affect results in unpredictable ways, then those particles must be included in the test samples. If so, then the test molds, triaxial cells, etc. used in the standard M_r tests must be enlarged to make the test results valid. The same would hold true for asphalt concrete mixtures, which are routinely tested with particles over 25 mm (1 inch) in diameter removed.

The usefulness of the M_r test itself may be questioned. Its use is already being questioned in areas such as backcalculating M_r for use in pavement overlay design. The results presented in this paper contradict the conventional wisdom that load carrying capacity of granular materials increases as top size increases. If the results presented here are confirmed by further testing, then either the prevailing wisdom is wrong or M_r does not adequately test the load-carrying capacity of highway base materials. If the reliability and usefulness of the resilient modulus test are questioned, then pavement design methods which depend on the M_r of aggregate and asphalt concrete may also be called into question.

CONCLUSIONS

Testing the effects of large top-size gradations on the resilient modulus of aggregate is a fruitful area for further research. There has been little attention given to this research due to the limited availability of the large-sized laboratory equipment required for the testing. Results presented in this paper cast doubt on the ability of the resilient modulus test to reflect increased load-carrying capacity at increased top size. More material types and gradations need to be tested to fully understand the effects of large size particles on the resilient modulus.

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