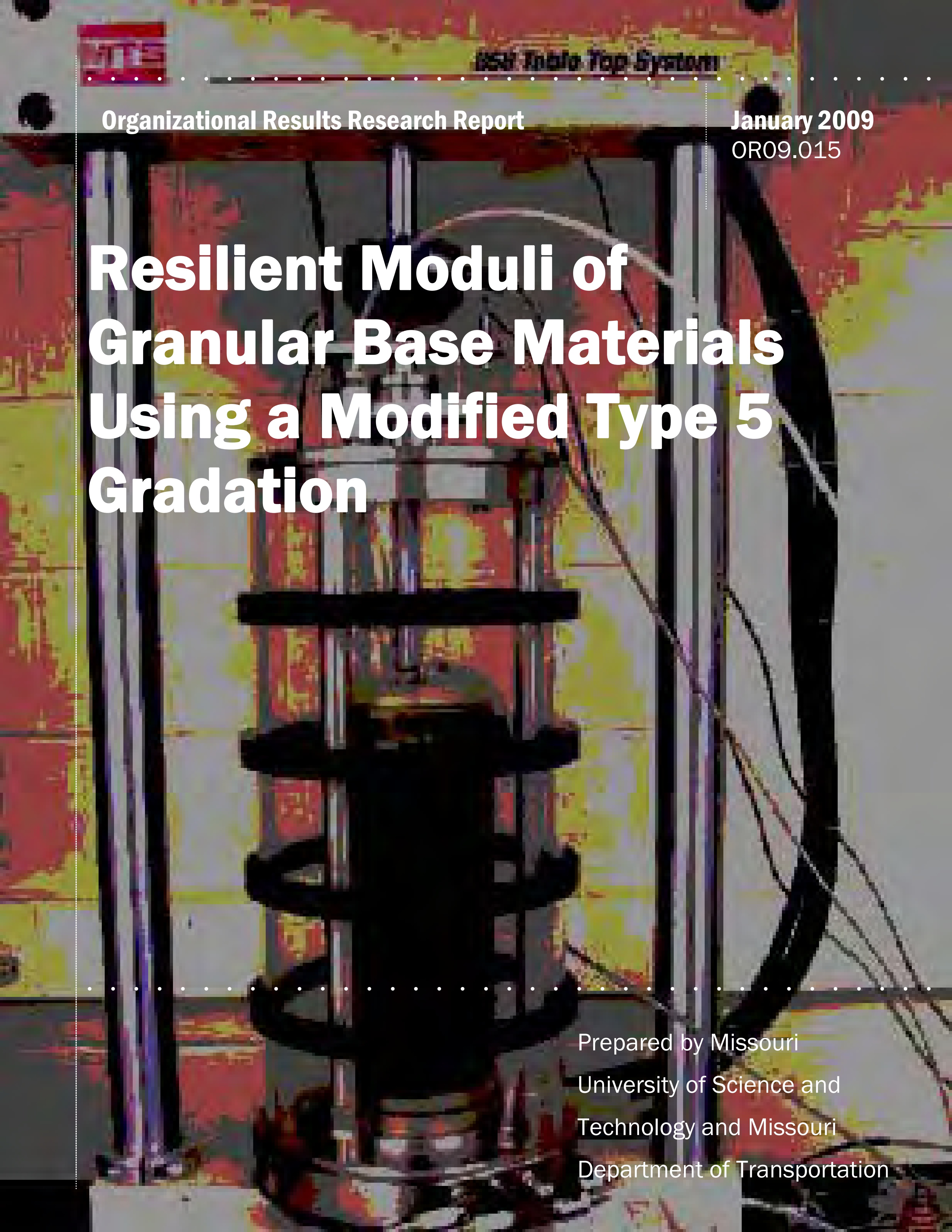

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Resilient Moduli of Granular Base Materials Using a Modified Type 5 Gradation

Prepared by Missouri University of Science and Technology and Missouri Department of Transportation

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The Missouri Department of Transportation (MoDOT) in collaboration with the Missouri Limestone Producers Association (MLPA) was interested in determining what effect a change in the Type 5 aggregate base gradation specification would have on the resilient modulus (M_r) of said aggregate. The proposed change would lower the minimum allowable total percentage of material passing the #4 (4.75 mm mesh) sieve from 35% to 25%, and the #30 (0.600 mm mesh) sieve from 10% to 5%. The remainder of the gradation specification would remain unchanged. The rationale for this proposed change is that some aggregate producers believe the change could help lower their costs of producing a Type 5 aggregate base material.

To investigate the proposed gradation specification change, an experimental gradation was devised which followed the lower bounds of the proposed gradation specification on the #4, #30, and #200 sieves, and approximated the as-delivered gradations of two aggregate formations previously tested for MoDOT on the 3/8, ½, ¾, and 1 inch sieves, making it a relatively open-graded material. Thus, two different aggregate sources were tested.

In the previous study for MoDOT, two gradations were analyzed: as-delivered Type 5 materials, and gradations with elevated fines contents. Both gradations could be considered to be high-fines content materials, with minus #200 contents between 11 and 18%. As a result of changing the gradation to fit the lower proposed specification limits, the experimental gradation in the present study contained no minus #200 material, and had significantly more #4 retained material, but less #8 retained material. The resulting M_r values in this study were greater than the results from the previous study for the same aggregates. Besides a change in gradation, the degrees of saturation for the proposed, more open-graded gradation were significantly lower than seen in the previous study for the same aggregate types.

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Resilient Moduli of Granular Base Materials Using a Modified Type 5 Gradation

Prepared for the

Missouri Department of Transportation
Organizational Results

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January 2009

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EXECUTIVE SUMMARY

The Missouri Department of Transportation (MoDOT) in collaboration with the Missouri Limestone Producers Association (MLPA) was interested in determining what effect a change in the Type 5 aggregate base gradation specification would have on the resilient modulus (M_r) of said aggregate. The proposed change would lower the minimum allowable total percentage of material passing the #4 (4.75 mm mesh) sieve from 35% to 25%, and the #30 (0.600 mm mesh) sieve from 10% to 5%. The remainder of the gradation specification would remain unchanged. The rationale for this proposed change is that some aggregate producers believe the change could help lower their costs of producing a Type 5 aggregate base material.

To investigate the proposed gradation specification change, an experimental gradation was devised which followed the lower bounds of the proposed gradation specification on the #4, #30, and #200 sieves, and approximated the as-delivered gradations of two aggregates previously tested for MoDOT on the 3/8, ½, ¾, and 1 inch sieves, making it a relatively open-graded material. Two different aggregate sources were tested.

M_r, a material stiffness characterization test, was determined in accordance with the American Association of State Highway and Transportation Officials (AASHTO) test method T 307-99 (2003), “Determining the Resilient Modulus of Soils and Aggregate Materials.” MoDOT contracted with Missouri S&T to test three replicate specimens per aggregate type according to T 307. Target dry unit weights and moisture contents at which to prepare the M_r specimens were determined through reviewing the literature and some trial and error testing.

In the previous study for MoDOT, two gradations were analyzed: as-delivered Type 5 materials, and gradations with elevated fines contents. Both gradations could be considered to be high-fines content materials, with minus #200 contents between 11 and 18%. As a result of changing the gradation to fit the lower proposed specification limits, the experimental gradation in the present study contained no minus #200 material, and had significantly more #4 retained material, but less #8 retained material. The resulting M_r values in this study were greater than the results from the previous study for the same aggregates. Besides a change in gradation, the degrees of saturation for the proposed, more open-graded gradation were significantly lower than seen in the previous study for the same aggregate types.

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INTRODUCTION

The Missouri Department of Transportation (MoDOT) in collaboration with the Missouri Limestone Producers Association (MLPA) was interested in determining what effect a change in the Type 5 aggregate base gradation specification would have on the resilient modulus of said aggregate. The proposed change would lower the minimum allowable total percentage of material passing the #4 (4.75 mm mesh) sieve from 35% to 25%, and the #30 (0.600 mm mesh) sieve from 10% to 5%. The remainder of the gradation specification would remain unchanged. The rationale for this proposed change is that some aggregate producers believe the change could help lower their costs of producing a Type 5 aggregate base material.

MoDOT's Type 5 aggregate base was originally developed to be a more drainable (permeable) base material when compared with MoDOT's Type 1 aggregate base. Currently, the only difference in gradation specifications between a Type 5 and a Type 1 aggregate base material is that there is an upper limit on the amount of fines (i.e. that material that passes the #200 or 0.074 mm mesh sieve) that can be present in a Type 5 material. However, with a current upper limit of 15% fines, many of the Type 5 stockpiles around the state contain material that is essentially non-drainable when used as a pavement base aggregate. Figure 1 is a histogram showing the percent passing the #200 sieve (P200) for Type 5 base aggregates used in Missouri in the recent past. The data supplied by MoDOT represents 1811 gradation analyses that reported a P200 value.

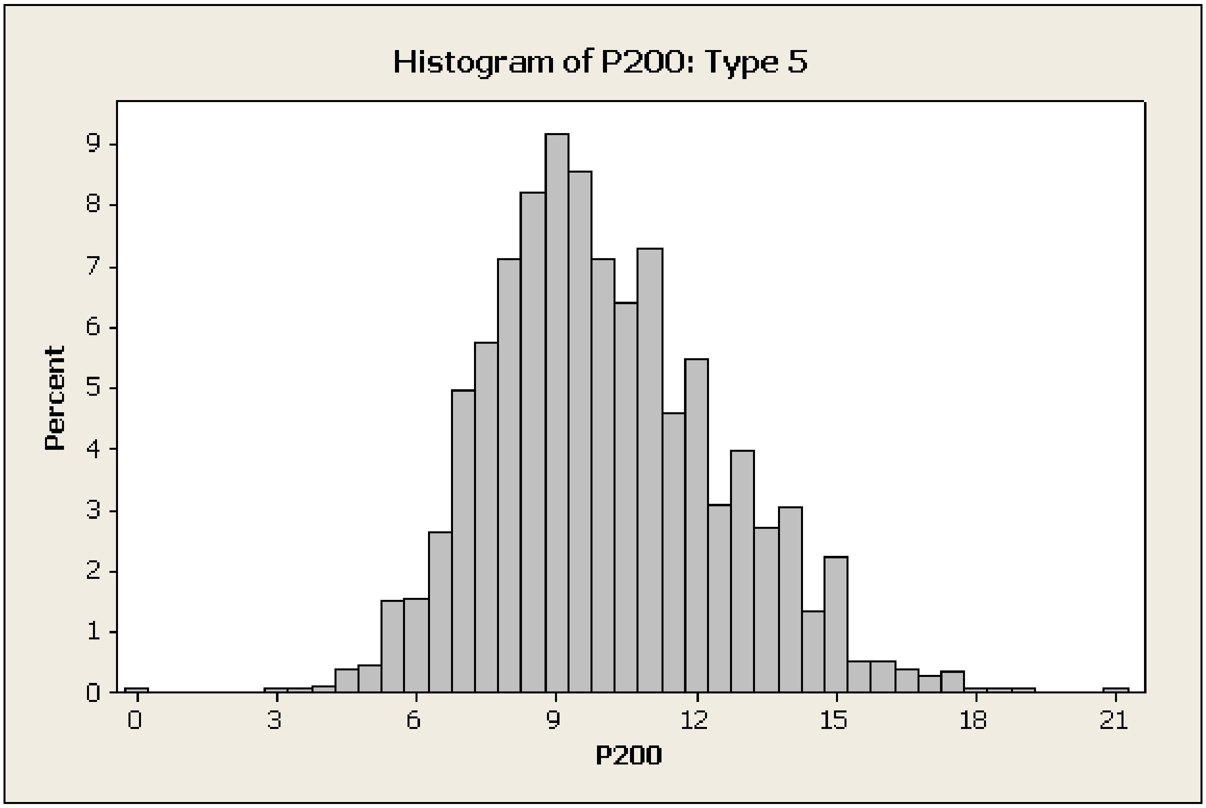


Figure 1: Histogram of Percent Fines for Type 5 Aggregate Used Statewide

The median value for the data depicted in Figure 1 is 9.7% fines with the mean being 10.0% fines. The majority of the data exceeds 6% fines. This data hardly represents a drainable material. For those aggregate producers who believe the proposed Type 5 gradation specification change could save them money by reducing some or all aspects of processing a Type 5 material, it seems logical that those producers would also see a lowering of the amount of fines produced for that particular process. This lowering of the fines content could help improve the drainability of that particular Type 5 product.

To investigate the proposed gradation specification change, an experimental gradation was devised which followed the lower bounds of the proposed gradation specification on the #4, #30, and #200 sieves, and approximated the as-delivered gradations of two aggregates previously tested for MoDOT (*1*) on the 3/8, ½, ¾, and 1 inch sieves, making it a relatively open-graded material. Two different aggregate sources were tested.

The resilient modulus (M_r), a material stiffness characterization test, was determined in accordance with the American Association of State Highway and Transportation Officials (AASHTO) test method T 307-99 (2003) (*2*). MoDOT contracted with Missouri S&T to test three replicate specimens per aggregate type according to test method T 307.

OBJECTIVES

The objective of this project is to determine the M_r of the two base aggregates when the gradations are constructed to basically follow the lower bounds of the proposed gradation specification then compare those M_r to previously determined M_r for the same aggregates but tested in the as-delivered condition.

TECHNICAL APPROACH

General

The technical approach included choice of materials, determination of the gradation, dry unit weight, and moisture content at which to perform M_r testing, specimen fabrication, and M_r testing.

Materials

The two crushed aggregates chosen to be tested were a Gasconade Formation dolomite and a Bethany Falls Formation limestone. Of the five aggregates tested in the previously mentioned M_r study for MoDOT (*1*), these two were selected for this project mainly because the wide range in M_r behavior, coupled with wide differences in Los Angeles Abrasion (LAA = resistance to impact and abrasion) values and absorptions (P_a). The LAA values were supplied by MoDOT and the P_a values were determined during the previous MoDOT M_r study. Table 1 summarizes the material names, designations used throughout the remainder of this paper, and the LAA and P_a values.

Table 1: Project Materials

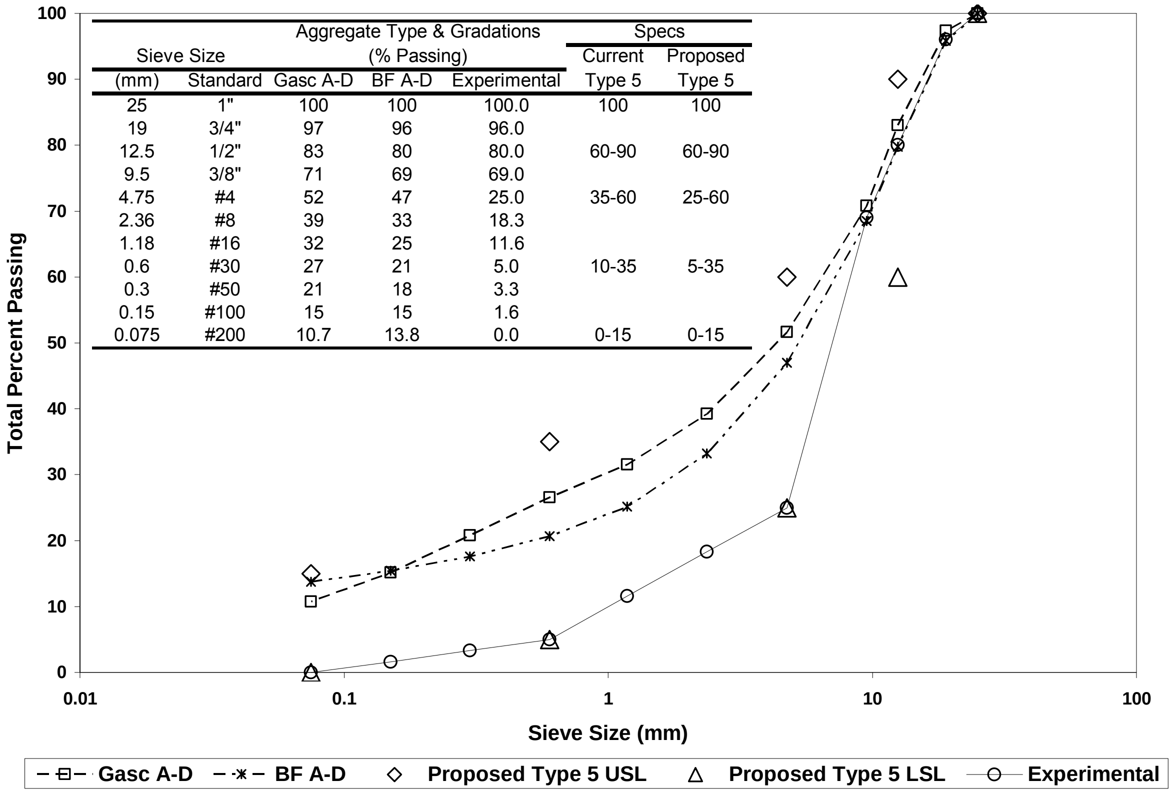
Name	Designation	P_a (%)	LAA (%)
Bethany Falls, as-delivered	BF A-D	1.89*	24
Bethany Falls, open-graded	BF O-G	1.91**	
Gasconade, as-delivered	Gasc A-D	3.84*	30
Gasconade, open-graded	Gasc O-G	3.80**	

*Based on testing a combined sample (coarse and fine aggregate) using the CoreLok® method
**Based on AASHTO T 85 (coarse aggregate only) (*3*)

Target Resilient Modulus Specimen Properties

<u>Gradation</u>

The as-delivered gradations of the Gasconade and Bethany Falls material met the current Type 5 specifications and were fairly similar, especially on those sieve sizes larger than the #4. They also exhibited percent minus #200 values approaching the upper limit of the specification. The experimental gradation used in this study follows the lower bounds of the proposed gradation on the #4, #30, and #200 sieves and is considered open-graded. Because the proposed specification change only applies to the #4 and #30 sieves, the idea was to isolate the effect of the proposed change on M_r by keeping percentages passing the larger sieve sizes of the two aggregates the same as or similar to the as-delivered gradations, thus keeping any M_r comparisons between the experimental and as-delivered gradations mostly a function of the minus 3/8 in. portion of the particle size distribution. Figure 2 summarizes the as-delivered and experimental gradations, and the current and proposed upper and lower specification limits (USL and LSL, respectively).



Sieve Size		Aggregate Type & Gradations (% Passing)			Specs	
(mm)	Standard	Gasc A-D	BF A-D	Experimental	Current Type 5	Proposed Type 5
25	1"	100	100	100.0	100	100
19	3/4"	97	96	96.0		
12.5	1/2"	83	80	80.0	60-90	60-90
9.5	3/8"	71	69	69.0		
4.75	#4	52	47	25.0	35-60	25-60
2.36	#8	39	33	18.3		
1.18	#16	32	25	11.6		
0.6	#30	27	21	5.0	10-35	5-35
0.3	#50	21	18	3.3		
0.15	#100	15	15	1.6		
0.075	#200	10.7	13.8	0.0	0-15	0-15

Figure 2: Gradation Summary

Figure 3 expresses the gradations in terms of Individual Percent Retained, which more clearly depicts the differences in the gradations. The as-delivered and proposed gradations are essentially the same except the percent #4 retained is greater for the proposed gradation, and the percents retained on the #8 and #200 are less.

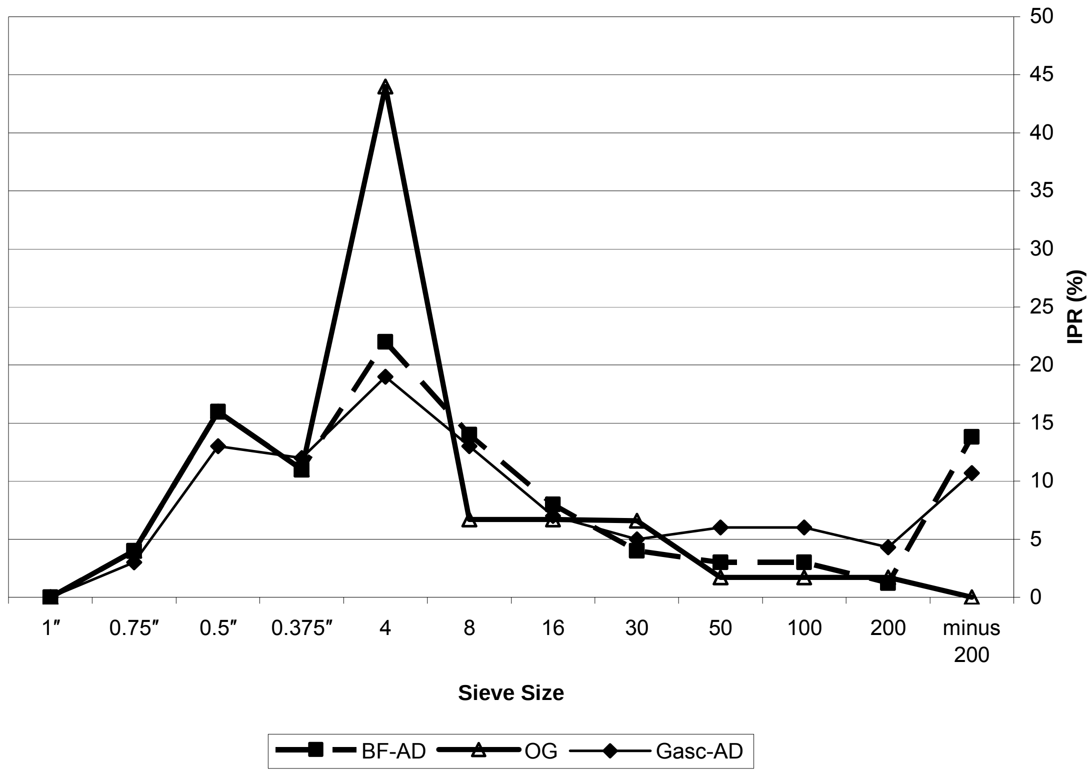


Figure 3: Individual Percent Retained Gradations

In order to accurately construct the experimental gradation containing no material passing the #200 sieve, it was necessary to first perform some processing of the as-delivered material. The bagged aggregates were dry-sieved into the different size fractions shown in the table within Figure 2. Each size fraction was then individually washed over the associated sieve and then oven-dried. This process produced washed, oven-dried aggregate fractions that were then re-combined in the appropriate percentages and amounts to build test specimens with the experimental gradation.

Dry Unit Weight and Moisture Content

A considerable portion of the work involved determining the dry unit weight and moisture content at which to perform the M_r testing. Because the experimental gradation was open and cohesionless, the initial thought was to obtain the maximum dry unit weight using American Society of Testing and Materials (ASTM) test method D 4253-00 (*4*). Within this test specification, there are two basic methods: one using oven-dry aggregate (method 1A) and the other using wet aggregate (method 1B). The decision was made to use method 1B because it was assumed it would result in the densest particle configuration; i.e. a higher dry unit weight. However, because of the wide range of particle sizes in the specimen, major segregation occurred during the test resulting in a non-uniform densification of the aggregate particles; the smaller particles were in the bottom of the mold with the larger particles on top. It was also assumed that this same phenomenon would have occurred if method 1A had been used. Therefore, the results from ASTM D 4253 were deemed invalid and were not used to determine the specimen conditions for M_r testing.

It seemed that the logical alternative to ASTM D 4253 for determining the maximum dry unit weight of the experimental gradation was the standard proctor test, AASHTO T 99 (*5*). Although the use of T 99 for open-graded aggregates can result in no definite moisture-density relationship, it seemed appropriate to try T 99 with the experimental gradation because MoDOT specifies this particular test method for determination of field densities. However, knowing that the highly-drainable nature of the experimental gradation would limit the amount of water that could be added to the material without it simply seeping out of the bottom of the proctor mold, a one-point or single moisture content proctor was investigated.

Having decided to attempt a one-point T 99, the next issue was determining what moisture content to use during compaction. The thought was to look at how other state DOT's that actually specify open-graded, unbound granular material base courses determine what compactive effort/method and moisture content to specify for construction of such base courses.

In a 2004 report published by the Iowa State University Center for Transportation Research and Education (CTRE) in collaboration with the Iowa Department of Transportation (*6*), results of a survey show that 6 states use permeable bases only, 11 use only dense-graded bases, and 29 states use both permeable and dense-graded bases. However, this survey does not indicate the percentage or number of these permeable bases that are treated (asphalt or cement) or non-treated (unbound) aggregate bases. MoDOT's Type 5 base aggregate is an unbound material. A review of the highway construction specifications of a few of the states listed in the survey as using permeable bases seemed to indicate that very few use unbound, open-graded, permeable bases in pavement construction; most use asphalt or cement treated aggregates.

In the latest on-line-available specifications, special provisions, supplements, etc., Michigan, Oregon, and Wisconsin (and there could be more) do specify unbound, open-graded, permeable bases in pavement construction. Excerpts from these states' specifications are given in Appendix A. It appears that Michigan has replaced a compaction method based on roller-type and roller patterns to a percent compaction determination (*7*), but has not clearly specified how to determine the reference or maximum dry unit weight (*8*).

The Oregon specification also indicates a percent compaction of maximum "density" for the dense-graded aggregates and does not directly indicate the method to be used to determine said maximum density. However, in an earlier sub-section, reference is made to T 99 and an optimum moisture content. The amount of water required for the "mix design" is normally 5 to 10%, with a field tolerance of ± 2% (*9*).

It appears that the use of unbound, open-graded base courses has recently been discontinued in Ohio. However, they do specify using field test sections to determine maximum dry unit weight of unbound granular base materials. The test section method utilized depends on whether or not the aggregate has a definite moisture-density relationship (determined using various optional methods). If there is a definite moisture-density relationship, T 99 is used to determine the optimum moisture content and then the test sections are built at that moisture content and rolled until a maximum dry unit weight is achieved. If there is not a definite moisture-density relationship, test sections are built at various moisture contents (starting at 0 to 3% moisture and increasing by 2% for every test section), rolled until a maximum dry unit weight for each moisture content is achieved, and then the maximum dry unit weight determined for the field testing (essentially, a field proctor curve) is used for base construction purposes (*10*).

Wisconsin specifies a "standard" compaction method for unbound, open-graded aggregates that is a roller-type and roller-pattern method (*11*). However, Wisconsin requires laboratory permeability testing on aggregates to be used in open-graded base courses and specifies a target unit weight which is achieved when the material is compacted at 6% moisture content using T-99 Method C (*12*).

Thus, for the purposes of choosing a unit weight and moisture content for preparation of Mr specimens, the use of a 6% moisture content seemed reasonable in that, for most base aggregates, absorption would be satisfied and there would be sufficient particle surface moisture for compaction lubrication purposes, but there would not be so much water as to flush the finer fractions during compaction (i.e. segregate the particles). This level of moisture also relates fairly well to one of the recommendations in the CTRE report (*6*):

"As an alternative to trimming equipment (e.g. Gomaco type), use a motor grader with GPS assisted grading (i.e. stakeless grading control). If trimming equipment must be used, however, ensure that the aggregate is delivered to the site with sufficient water content (7%–10 %) to bind the fines during trimming."

This recommendation was in response to one of the findings of the CTRE report in that segregation of the open-graded base aggregates was found to occur during trimming of the compacted base course; i.e. the aggregate was too dry during trimming and, thus, the vibration of the trimmer caused the fines to segregate downward leaving coarser aggregate particles on the surface. Therefore, it seems that, for unbound, open-graded base aggregates, there needs to be sufficient moisture in the delivered material to provide lubrication for compaction and "bind the fines" to the coarse aggregate to prevent segregation, but not excessive moisture that would prevent maximum densification or cause segregation to occur due to fluid flow.

Thus, the decision was made to compact the M_r specimens at 6% moisture and at a dry unit weight determined using T 99, Method D (but with no scalping or removal of any size fraction), also at 6% total moisture. Initially, this strategy worked well for the

Gasc O-G material but not so well for the BF O-G material. The Gasc O-G T 99 test resulted in a dry unit weight of 111.2 lb/ft^3, with no significant moisture seepage or segregation. M_r tests on the Gasc O-G material under these conditions were also non-problematic.

The BF O-G T 99 test resulted in a dry unit weight of 112.7 lb/ft^3, with no visible seepage from the bottom of the proctor mold or major segregation of the compacted aggregate. However, the first BF O-G M_r test specimen prepared at 6% moisture and 112.7 lb/ft^3 dry unit weight experienced significant loss of moisture through the drainage line of the triaxial cell (~170 ml relative to ~25 ml for all other M_r tests).

Behavior of unbound granular material in regard to compaction moisture is analogous to that of hot mix asphalt (HMA), i.e. part of the HMA's total binder is absorbed, leaving the balance ("effective binder") to function as the lubricant. Thus, two mixes can have the same total binder content, but different effective binder contents, depending on the absorption of the aggregate. The amount of effective binder dictates, in part, the lubrication and hence the behavior under compaction. Unbound granular base materials act in a similar manner. Two different aggregates, with the same total moisture, can behave differently during compaction if they have significantly different absorptions. The difference between the behavior of the Gasconade and the Bethany Falls aggregates in the M_r testing, regarding the ability to hold moisture, could be attributed to the difference in their absorptions: the Gasc O-G aggregate has absorption ~2% higher than the BF O-G aggregate. Because total moisture is the sum of absorption and surface ("effective") moisture, the surface moisture of the BF O-G aggregate was also ~2% higher than the Gasc O-G, thus the excessive seepage of the BF O-G. Therefore, to keep the surface moisture of the BF O-G consistent with that of the Gasc O-G, the total moisture content to be used for the BF O-G T 99 test, and subsequently the M_r test, was lowered to 4.0 %, as shown in Table 2.

Table 2: Total and Effective Moisture Contents

Aggregate	Total Moisture	Absorption	Effective Moisture
Gasconade	6.0	3.8	2.2
Bethany Falls	4.0	1.9	2.1

Actually, 3.9% was the moisture for the BF O-G specimens content as it was adjusted slightly from 4.0% due to actual post-M_r test moisture contents. Re-running the T 99 test on the BF O-G aggregate when prepared at a 3.9% moisture content resulted in a dry unit weight of 115.5 lb/ft^3, an increase from 112.7 lb/ft^3 when compacted at 6% moisture.

Therefore, in summary, the target dry unit weights and as-compacted moisture contents for the M_r specimens were as follows:

- Gasc O-G dry unit weight = 111.2 lb/ft^3: 6.0% total moisture content
- BF O-G dry unit weight = 115.5 lb/ft^3: 3.9% total moisture content.

Resilient Modulus Testing

Equipment

The M_r testing equipment was in conformance with AASHTO T 307-99 (2003) (*2*) for Type I materials (granular bases), which specifies that test specimens shall be 6 in. in diameter. The equipment consisted of a Geotechnical Consulting and Testing Systems (GCTS) control system, an MTS 858 closed-loop servo-hydraulic load system, a GCTS triaxial chamber capable of housing a 6 in. diameter specimen while subjected to cyclic loads, and a GCTS data acquisition system. Load was measured with an external 2200 lb load cell located between the actuator and the chamber piston rod.

Deformation was measured by two Schaevitz MHR-250 linear variable differential transducers (LVDTs) mounted externally to the cell. The range of the LVDTs was ± 6.35 mm.

Air was used as the confining fluid. Triaxial cell pressure was controlled manually via a pressure regulator, and measured with a pressure transducer linked to the GCTS data acquisition system. The test setup is shown in Figure 4.

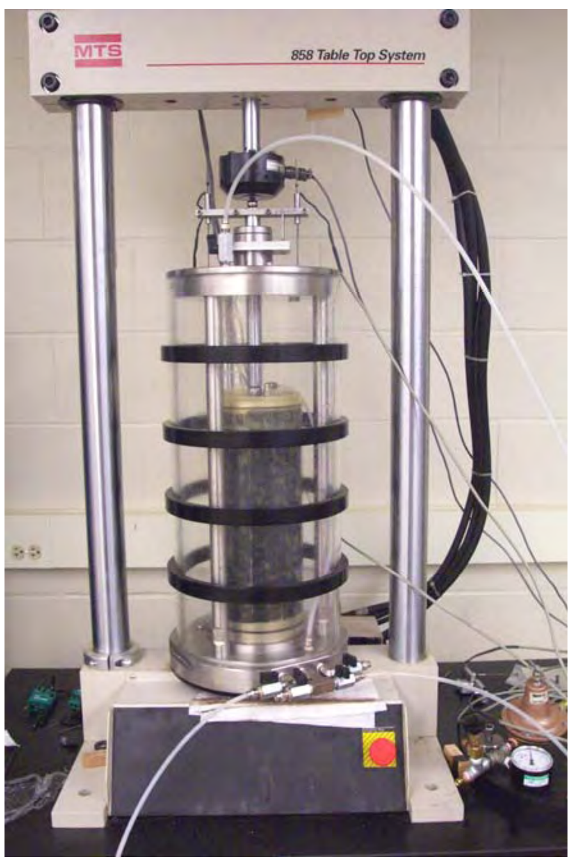


Figure 4: Triaxial Chamber and Measurement Devices

Specimen Fabrication

Knowing the target dry unit weights and moisture contents, the existing moisture content of the material (essentially oven-dry), and the target compacted volume of the specimen, enough material was obtained to produce seven “lifts”; six to be compacted into the mold and one to be used for the as-compacted moisture content determination. The calculated amount of each size fraction necessary to build the experimental gradation was placed into a large pan and water was added to bring the material to the target moisture content plus a small amount to account for moisture loss. After thorough mixing, the aggregate was covered and allowed to cure for at least 15 minutes (usually longer). After curing, a square point scoop was used to systematically remove the calculated amount of moist material from the pan and place it into the mold to be compacted as a lift. After compaction of the six lifts, the remaining material was used for as-compacted moisture content determination.

The specimen mold was 6 in. nominal diameter. The actual compacted specimen diameter was 5.82 in. This met the requirement that the diameter be equal to or greater than five times the maximum particle size, which was 1 in. for the experimental gradation. The material was compacted into the mold using a hand-held mechanical hammer-drill (meeting T 307 specifications) and bearing on a steel plate. An under-compaction principle was utilized to assure uniform compacted density throughout the height of the specimen. This principle requires that the first or bottom lift be under-compacted to some degree (either 1.5 or 2.0% for the material in this study) and each successive lift be decreasingly under-compacted resulting in the top lift thickness being exactly 1/6 of the specimen height. The mold was an aluminum vacuum split mold mounted directly on the triaxial cell pedestal. The specimens were compacted to a height of approximately 11.70 in., which met the requirement of at least two times the specimen diameter.

A 6 in. diameter, 0.025 in. thick latex rubber membrane was placed onto the triaxial cell pedestal and secured with an O-ring. The split mold was then secured onto the pedestal. Sufficient vacuum was applied to the membrane to hold it against the interior mold wall. Prior to adding material to the mold, the membrane was protected from damage during compaction by securing a series of 0.08 in. thick, approximately 2 in. wide, and 12 in. long nitrile rubber strips against the membrane using a small amount of vacuum grease. T 307 specifies membrane thickness between 0.25 and 0.79 mm (0.0098 in. to 0.0311 in.). Because the protective nitrile rubber was cut into strips and placed side-by-side around the interior perimeter of the membrane, it was reasoned that although the combined thickness of the membrane and the rubber nitrile strips exceeded the T 307 specifications, the rubber nitrile strips did not add any confining pressures to the specimen; only the rubber membrane could supply any confining pressure and it met T 307 thickness specifications.

Stress States/Testing Sequence

Stress state is considered the most important variable that affects the modulus of granular materials. The three principal stresses are σ_1, σ_2, and σ_3 , where σ_1 is the major principal stress, σ_2 is the intermediate principal stress, and σ_3 is the minor principal stress. In a triaxial type test, σ_1 is provided by the total vertical stress, and σ_2 equals σ_3 for a cylindrical specimen. In the triaxial state, the difference between the total vertical stress (σ_1) and the confining pressure (σ_3) is called the deviator stress or stress difference (σ_d). A small static load ($0.1\sigma_d$) provides the "overburden" pressure while the cyclic deviator stress ($0.9\sigma_d$) provides the "vehicle" momentary stress. The sum of the three principal stresses is known as the bulk stress (θ).

M_r is calculated as $(0.9\sigma_d)/ \varepsilon_r$, where ε_r is the resilient (recovered) axial strain. For each specimen, resilient modulus was determined at fifteen stress states where confining pressure ranged from 3 to 20 psi and σ_d varied from 3 to 40 psi. This resulted in a range of bulk stress from 12 to 100 psi, which is considered adequate to represent the range in stress states likely to be encountered under field conditions. The testing sequence and stress state schedule is shown in Table 3.

Table 3: Testing Sequence for Granular Base Material

Sequence No.	σ_3 (psi)	σ_d (psi)	0.9 σ_d (psi)	0.1 σ_d (psi)	Θ (psi)	No. load applications
0	15	15	13.5	1.5	60	500
1	3	3	2.7	0.3	12	100
2	3	6	5.4	0.6	15	100
3	3	9	8.1	0.9	18	100
4	5	5	4.5	0.5	20	100
5	5	10	9.0	1.0	25	100
6	5	15	13.5	1.5	30	100
7	10	10	9.0	1.0	40	100
8	10	20	18.0	2.0	50	100
9	10	30	27.0	3.0	60	100
10	15	10	9.0	1.0	55	100
11	15	15	13.5	1.5	60	100
12	15	30	27.0	3.0	75	100
13	20	15	13.5	1.5	75	100
14	20	20	18.0	2.0	80	100
15	20	40	36.0	4.0	100	100

Testing Procedure

The resilient modulus testing procedure involved the following steps: specimen compaction, assembly of the triaxial cell, application of confining pressure, stress conditioning at a given stress state (see stress sequence "zero" in Table 3), and load application through 15 additional stress states. Conditioning was used to eliminate the effects of any specimen disturbance due to specimen preparation procedures. It also aided in minimizing the effects of initially imperfect contact between end platens and the test specimen. In this study, conditioning load applications were limited to 500 because the decrease in specimen height had ceased by then. Load and deformation data were taken for every load application over the entire sequence of stress states, but only the last five applications were used for calculation of M_r.

The load duration for each repetition was 0.1 sec followed by 0.9 sec rest. The stress pulse shape was haversine in nature. The drainage valves were left open. Repeated load equipment deflection was determined through the use of an aluminum dummy specimen and was subtracted from total deflections for each stress state. The change in specimen height was continuously monitored. None of the specimens approached the maximum allowable permanent strain of five percent.

To verify that the moisture condition of each of the three replicates tested per aggregate type was substantially the same, moisture contents were obtained on each specimen after the M_r test had been completed. M_r test specimens were divided into three approximately equal portions (top, middle, and bottom 4 in.) and moisture contents were determined on each third. Also, moisture contents used for calculation of reported actual (as-tested) dry unit weights were based on the entire specimen. As mentioned previously, for every M_r specimen, enough material was prepared to produce seven layers or lifts; six to be compacted in the vacuum split mold and one to be used as a check on the as-compacted moisture content. A summary of the target, as-compacted, and actual (post-M_r test) moisture contents, target and actual dry unit weights, and calculated degrees of saturation are given in Table 4 in the Results and Discussion section.

RESULTS AND DISCUSSION

Compaction Parameters

Three types of test results were generated during the course of this study: target dry unit weight for M_r testing (using AASHTO T 99), as-compacted and post-M_r test moisture content, and resilient modulus. T 99 results were presented in the Technical Approach section. Table 4 shows a summary of the target, as-compacted, and actual (post-M_r test) moisture contents, target and actual dry unit weights, and calculated degrees of saturation. As can be seen, the specimens lost very little moisture from drainage during the tests, both aggregate types had about the same effective moisture contents (1.8%), and the actual dry unit weights were very close to the target unit weights. Also included in Table 4 are results for the as-delivered materials that were tested in the previous MoDOT M_r study (*1*). The large difference in saturation between the open graded gradations in the present study and the as-delivered gradations in the previous study should be noted. Also shown are the regression coefficients generated from fitting the M_r data to the constitutive model as described in Part 2 Chapter 2 of the Mechanistic-Empirical Pavement Design Guide (M-E PDG) (*13*). These will be discussed below.

Regression Coefficients

Additional information from the testing includes the computation of the regression coefficients (k_1, k_2, k_3) which were generated by fitting the M_r data to the model shown in Eq. 1:

$$Mr = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \qquad (1)$$

Where

M_r = resilient modulus, psi
θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$, psi
σ_1 = major principal stress, psi
σ_2 = intermediate principal stress = σ_3 for M_r test on cylindrical specimen, psi
σ_3 = minor principal stress/confining pressure, psi
τ_{oct} = octahedral shear stress = $\frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}$, psi
p_a = normalizing stress (atmospheric pressure; in this case, 14.7 psi)
k_1, k_2, k_3 = regression coefficients

In other words, a given specimen is tested at 15 different stress states. θ, τ_{oct}, and M_r are calculated from the data. Using the above model (Eq. 1), the regression constants k_1, k_2, k_3 are determined for each specimen. A non-linear regression analysis procedure included in a statistical software package called SigmaStat® was used for this portion of the work. Data used for the regressions are included in Appendix B

Quality of the Testing Program

Per recommendations in the M-E PDG, regressions are performed on individual specimen data to evaluate the validity of the test. The M-E PDG recommendation is that the goodness-of-fit statistic, R^2, be at least 90% for each set of individual specimen tests (15 stress states, one specimen). Because R^2 is not the most appropriate goodness-of-fit statistic when using non-linear regression techniques, the statistic S_e/S_y was also included in the results. S_e is the standard deviation of the residuals (the difference between the predicted and observed M_r values), and S_y is the standard deviation of the observed M_r values. Smaller S_e/S_y values indicate a better fit. Regression coefficients were also determined by pooling the data (45 sets of stress states [15 stress states per replicate specimen, three replicate specimens] and resulting M_r values) from all three replicates and fitting it to Eq. 1. The pooled regression coefficients will be used for comparison purposes in this section.

Table 4: Summary of Results

Specimen and Statistics	Target Dry Unit Weight (pcf)	Target Moisture (%)	As-Compacted Moisture [7th lift] (%)	Actual Dry Density (pcf)	Actual Moisture (%)	Actual Saturation* (%)	k_1	k_2	k_3	R^2	Se/Sy
Gasc A-D1	133.7	9.4	9.8	133.9	8.9	92.6	1456.506	0.783	-0.353	0.998	0.050
Gasc A-D2	133.7	9.4	9.9	133.8	8.8	91.6	1429.921	0.752	-0.323	0.997	0.058
Gasc A-D3	133.7	9.4	9.8	133.7	8.9	92.4	1298.257	0.796	-0.325	0.996	0.068
Average			9.8	133.8	8.9	92.2	Pooled Regression				
St Dev.			0.0828	0.0647	0.0491	0.5420	1394.519	0.777	-0.334	0.989	0.110
Coeff. Var (%)			0.8424	0.0484	0.5511	0.5877					
Gasc O-G1	111.2	6.0	6.4	111.5	5.6	28.7	1997.677	0.724	-0.340	0.988	0.134
Gasc O-G2	111.2	6.0	6.2	111.5	5.6	28.8	1782.632	0.724	-0.215	0.991	0.102
Gasc O-G3	111.2	6.0	6.5	111.4	5.6	28.9	2130.596	0.664	-0.403	0.990	0.108
Average			6.4	111.5	5.6	28.8	Pooled Regression				
St Dev.			0.1165	0.0603	0.0265	0.0914	1966.229	0.703	-0.316	0.979	0.092
Coeff. Var (%)			1.8302	0.0541	0.4725	0.3177					
BF A-D1	138.0	7.4	7.2	138.2	6.8	86.1	2044.140	0.632	-0.320	0.994	0.086
BF A-D2	138.0	7.4	7.3	138.3	6.8	86.4	2281.441	0.541	-0.321	0.987	0.122
BF A-D3	138.0	7.4	7.3	138.3	6.7	85.9	2098.281	0.610	-0.328	0.988	0.120
Average			7.2	138.3	6.8	86.1	Pooled Regression				
St Dev.			0.0800	0.0779	0.0223	0.2767	2139.855	0.594	-0.322	0.985	0.125
Coeff. Var (%)			1.1045	0.0564	0.3291	0.3213					
BF O-G1	115.5	3.9	4.5	115.5	3.7	22.0	3050.980	0.563	-0.265	0.995	0.080
BF O-G2	115.5	3.9	4.0	115.6	3.7	21.8	2741.661	0.637	-0.304	0.995	0.080
BF O-G3	115.5	3.9	4.3	115.4	3.6	21.3	2882.995	0.589	-0.293	0.992	0.098
Average			4.3	115.5	3.7	21.7	Pooled Regression				
St Dev.			0.2296	0.0531	0.0537	0.3323	2891.444	0.596	-0.287	0.989	0.083
Coeff. Var (%)			5.3978	0.0460	1.4531	1.5307					

*A-D Saturations based on CoreLok specific gravities; O-G Saturations based on T 85 results

Before performing the pooled regressions, variability among the replicate specimens of the Gasc O-G and BF O-G materials was analyzed using a one-way analysis of variance (ANOVA). Three parameters were analyzed relative to the effect that differences among the replicate specimens may have on them: M_r, deviator stress (σ_d), and confining pressure (σ_3). Table 5 shows the results of the basic ANOVA.

Table 5: Replicate One-Way Anova

Material	M_r vs. Replicate		σ_d vs. Replicate		σ_3 vs. Replicate	
	p-value	R^2 (%)	p-value	R^2 (%)	p-value	R^2 (%)
Gasc O-G	0.921	0.39	1.000	0.00	1.000	0.00
BF O-G	0.936	0.31	1.000	0.00	1.000	0.00

The higher the p-value is (1.000 is maximum; 0.000 is minimum) or the lower the R^2 value is (1.000 is maximum; 0.000 is minimum), the lower the probability that the replicates are different. To verify that any differences between the M_r values (per stress state, per replicate) are strictly a function of the replicate specimen material conditions, the stress parameters (σ_d and σ_3) were analyzed in regard to the replicates. In all cases, the differences in the σ_d and σ_3 values were so small as to be completely insignificant, which makes sense, as these parameters are not really responses but computer-controlled inputs. Based on the p-values and R^2 values, and comparing the two aggregates, the Gasc O-G aggregate possessed the most M_r variability between replicate specimens. However, the replicate M_r variability for both aggregates was highly insignificant at an alpha = 0.05 (95% confidence) level; i.e. the p-values for both were much greater than 0.05, meaning that the replicates were very similar per aggregate.

Effect of Gradation on M_r

Looking only at k_1 (the intercept or scaling factor for Eq. 1) from the pooled regressions in Table 4, one can see that, for both aggregates, the O-G aggregate k_1 values were considerably higher than those of the corresponding A-D aggregate, indicating that the O-G material was much stiffer. A major factor in this increased stiffness is the much lower degree of saturation present in the O-G specimens relative to the A-D specimens. Haynes and Yoder (*14*) showed that 80-85% saturation was the general range at which the deflection (i.e. stiffness) properties of dense-graded base materials used in the AASHO Road Test began to be severely affected. This is the primary advantage of open-graded base courses; provided they remain permeable, there is a practical upper limit to the degree of saturation thereby insuring long-lasting stability of the pavement structure.

Table 6 shows a comparison of the two materials in regard to M_r (as calculated by Eq. 1 and using the pooled regression coefficients) for a stress state of θ = 12 psi (σ_1 = 6 psi, σ_2 and σ_3 = 3 psi each). For discussion purposes, Table 6 also includes M_r values reported in the previous MoDOT M_r study (*1*) that resulted from testing specimens with a higher fines content (W-F) created with a blend of as-delivered material (95%) and additional fines (5%).

Table 6: Resilient Moduli at θ = 12 psi

Material	Properties	Gradations			Δ M_r (%) [(O-G) – (A-D)]
		W-F	A-D	O-G	
Bethany Falls	M_r (psi)	22776	27071	36682	+35.5
	P200 (%)	17.6	13.8	0	
Gasconade	M_r (psi)	17101	16980	24344	+43.4
	P200 (%)	14.2	10.7	0	

As reported in the previous MoDOT M_r study (*1*), a decreased fines content had mixed effects: some materials experienced an increase in M_r (at a particular stress state) and some experienced a decrease in M_r. At θ = 12 psi, this is the case for the Gasconade and Bethany Falls material as reflected in Table 6: the Bethany Falls aggregate had a higher M_r with a reduction in fines while the Gasconade had a slightly lower M_r with a reduction in fines at elevated levels (i.e. when reducing P200 from 14.2 to 10.7%) that might be statistically insignificant. However, when the fines content was reduced to zero percent, a significant increase in M_r (relative to the A-D condition) occurred for both the Bethany Falls aggregate (35.5% increase) and the Gasconade aggregate (43.4% increase), again, for this particular stress state.

Figures 5 through 8 show the plots of M_r versus θ, and M_r versus τ_{oct} using the pooled data from the three replicate M_r tests per aggregate. The three series on each plot represent the three gradations that have been investigated in this and the previous MoDOT M_r study. As can be seen, in general, the trend is that as fines decrease from the W-F (14.2 -17.7% fines) to A-D (10.7 -13.8% fines) to O-G (zero fines), at a given stress state, M_r increases.

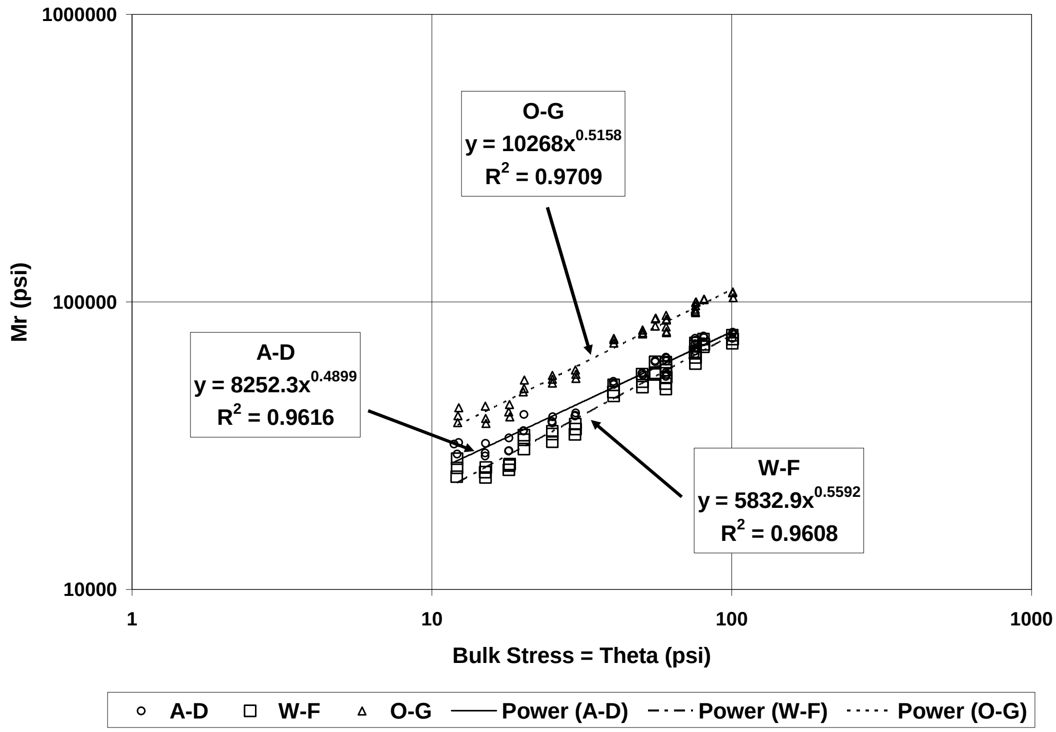


Figure 5: Bethany Falls; Pooled M_r vs θ; O-G, A-D, and W-F Gradations

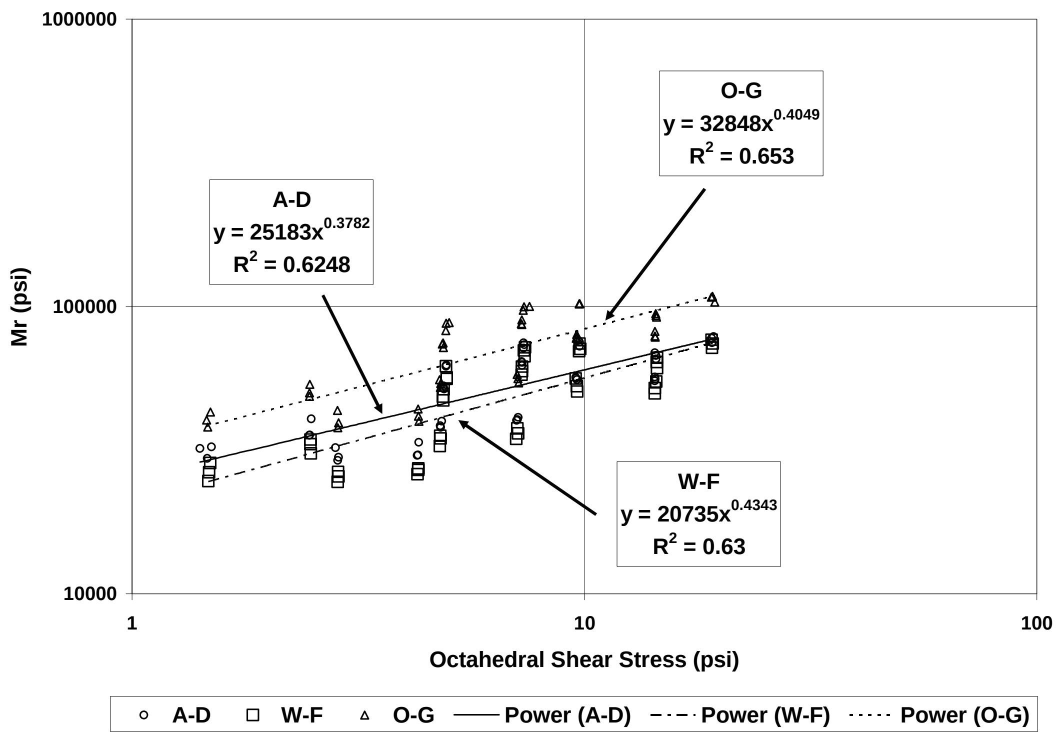


Figure 6: Bethany Falls; Pooled M_r vs τ_{oct}; O-G, A-D, and W-F Gradations

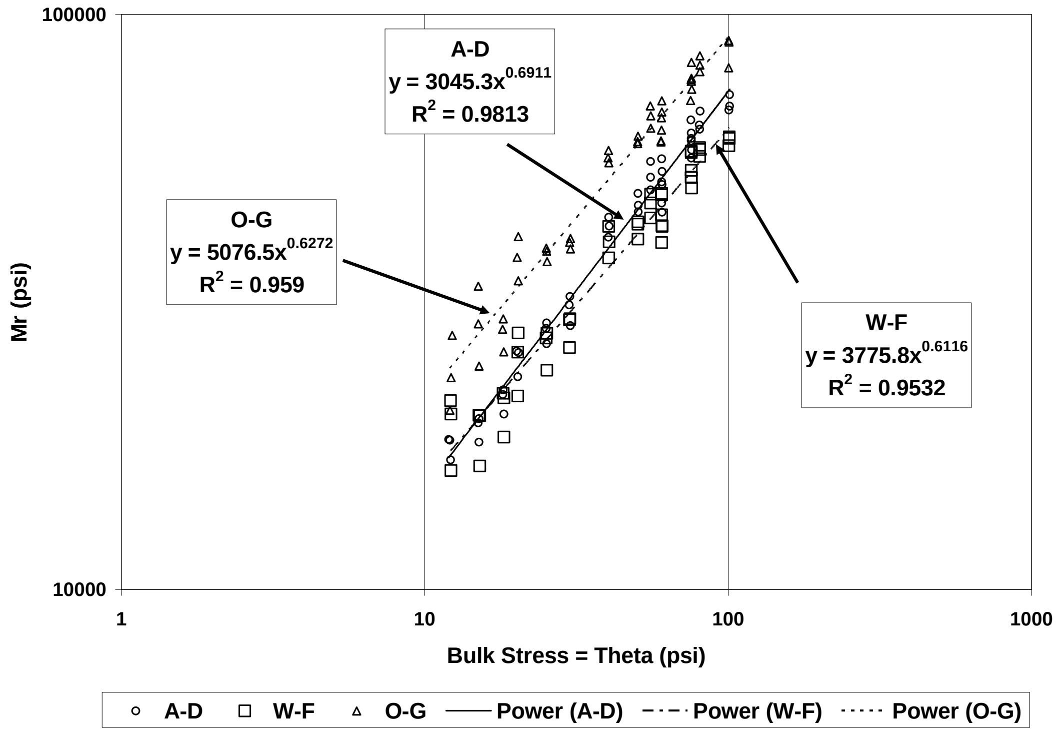


Figure 7: Gasconade; Pooled M_r vs θ; O-G, A-D, and W-F Gradations

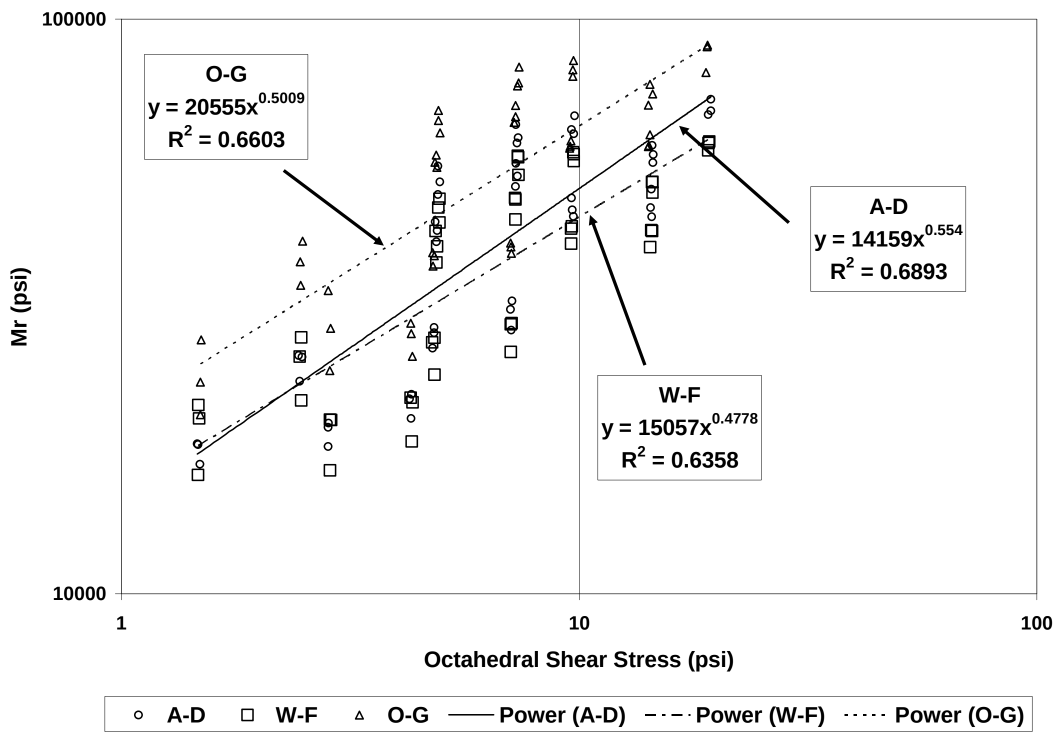


Figure 8: Gasconade; Pooled M_r vs τ_{oct}; O-G, A-D, and W-F Gradations

Optimum Fines Content

Past studies have shown that there is an optimum amount of fines for maximum strength and stiffness of unbound granular base materials. Yoder and Witczak (*15*) showed an optimum range of 6 to 9% fines for maximum CBR. The National Crushed Stone Association classical study (*16*) of the effect of various parameters on triaxial shear strength reported optimums of 8 to 12%. For resilient modulus, Jorenby and Hicks (*17*) reported optimum fines around 5%. For the present study, it could be argued that the two fines contents tested in the two studies performed for MoDOT were on the low side (zero %) and the high side (11 and 14%) of what would have been the optimum. A plot of M_r versus P200 based on data in Table 6 is given in Figure 9.

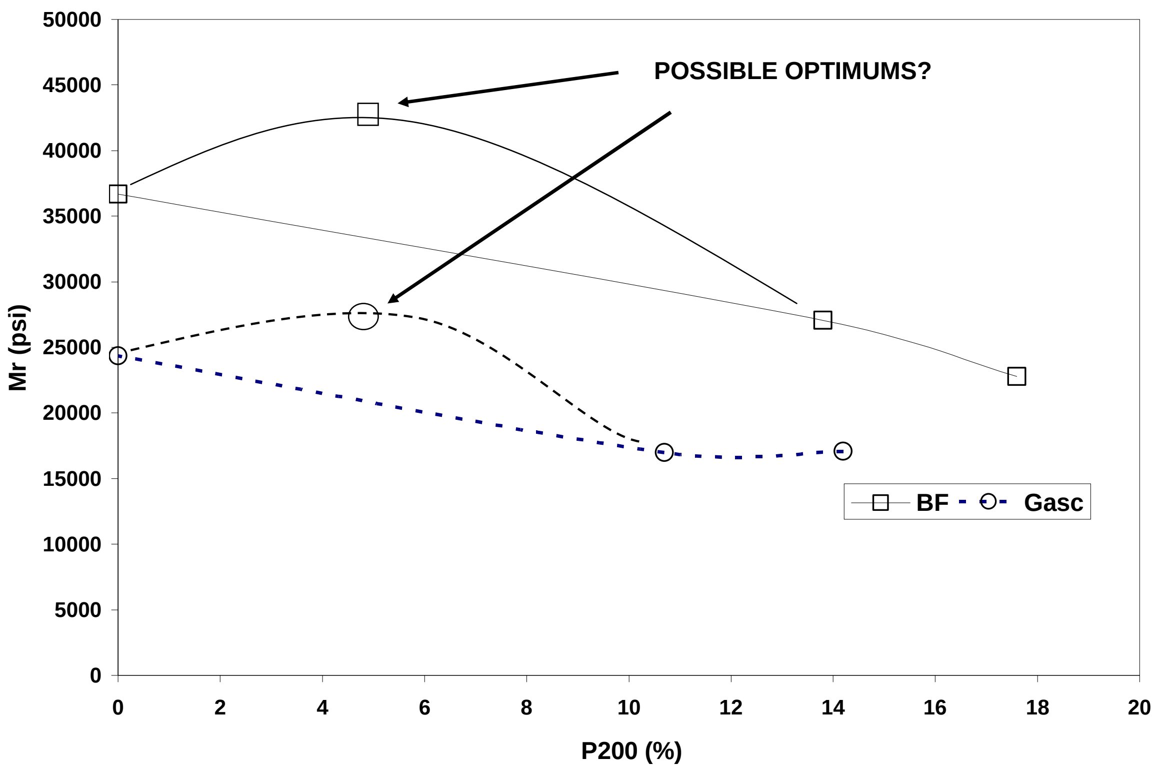


Figure 9: M_r (at θ = 12 psi) versus P200

As indicated in Figure 9, one could postulate that there may be an optimum fines content for a particular aggregate, with a particular overall gradation, a particular degree of saturation, and at a particular stress state that would produce the maximum M_r for such conditions. More testing on these aggregates is needed to address this question.

Comparison to Past Studies

The issue of the effect of fines (and gradation in general) on M_r has been addressed in the literature review of a previous study for MoDOT by Richardson and Kremer (*18*), where it was reported that as fines content increases, resilient modulus decreases (*19-22*). There was some support of the idea that a high degree of saturation generated pore pressures which lowered M_r (*19*), thus explaining the reason why some open-graded mixtures have greater M_r values than dense-graded materials, although some studies showed the opposite (*19, 22*) or at least that gradation is of a negligible significance (*23*). Others, as noted above, report that an optimum fines content exists. More recent studies have shown a decrease in M_r upon an increase in fines from 6 to 12% (*24*).The Richardson and Kremer study itself reported that of the four aggregates tested, two showed an increase in M_r when moving from a dense gradation to an open gradation, one showed essentially no change, and one showed a decrease.

In a more recent literature review, Liang (*25*) cited Hicks and Monismith (*26*), Barksdale (*19*), Thom and Brown (*23*), Barksdale and Itani (*27*), Rada and Witczak (*28*), Knutson and Thompson (*29*), Raad, et al. (*30*), Thompson and Smith (*22*), Kamal, et al. (*31*), Tian, et al. (*32*), and Heydinger, et al. (*33*). The conclusions in the cited references varied in regard to the effect of fines content (or gradation in general) on M_r. Excerpts from Liang's literature review are inserted below:

<u>Hicks and Monismith</u>: Hicks and Monismith, among others, studied M_r by using the previously popular bulk stress model given as

$$Mr = k_1(\theta)^{k_2} \qquad (2)$$

Where

M_r = resilient modulus, psi
θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$, psi
k_1, k_2, = regression coefficients

Liang's comments are as follows:

"[Hicks and Monismith] indicated that the bulk stress model parameters k_1 and k_2 were affected by the fines content. The manner in which k_1 changes depends on the aggregate type. For the partially crushed aggregate, k_1 generally decreased as the fines content was increased. For the crushed aggregate, however, k_1 increased with increasing fines content. The same trends were also observed for the partially saturated and saturated test series. For k_1, it appeared that it decreased slightly as fines content increased. They also found that k_1 was always larger for the crushed aggregate than the partially crushed material, regardless of aggregate gradation."

<u>Barksdale; Thom and Brown; Barksdale and Itani</u>: According to Liang, these studies generally agreed with Hicks and Monismith:

"Their [Hicks and Monismith] test results seemed to agree with later studies [Barksdale; Thom and Brown; Barksdale and Itani] who observed a decrease in the value of resilient modulus as the fines content was increased."

Rada and Witczak: Liang's comments are as follows:

"On the other hand, [Rada and Witczak] found that the effect of aggregate gradation showed no general trend regarding the influence of fines (percentage pass No.200 sieve) on resilient modulus. For the angular base materials (DGA and CR-6 aggregate), there appeared to be little change in either k_1 or k_2 for P200 values in the range of 7-17%. For bank-run gravel, an optimum k_1 value was apparently near the dense condition, and a marked decrease in k_1 occurred as the P200 value increased. In contrast, k_2 appeared to increase with an increase in fines content. Although no pronounced changes occurred in $k_1$and k_2 for the base materials, increase in P200 beyond the 16-18 percent range would eventually lead to pronounced change in the M_R response of these materials."

Knutson and Thompson: Knutson and Thompson studied railroad ballast, an open-graded aggregate. Liang's comments are as follows:

"[Knutson and Thompson] found no difference in resilient modulus between an ASTM No. 4 and No. 5 very open graded railway ballast aggregate. The tested aggregate grading presented lower resilient moduli than conventional well-graded aggregate. The No. 4 and No. 5 ballast were practically insensitive to change in water content due to their high permeability."

Raad, et al.: Liang's comments are as follows:

"[Raad, et al.] found that the densest graded aggregate exhibit the highest M_R values, and the open graded aggregate has the lowest values. However, the saturated granular materials will develop excess pore water pressure under undrained conditions, which could lead to a decrease in M_R values. Open-graded aggregates are more resistant to pore water pressure buildup than are dense graded aggregate and therefore are less likely to induce damage in pavement under saturated conditions."

Although the M_r test results in this study are contrary to the results cited in the above Raad, et al. excerpt, the commentary about pore water pressure is important to understand. Although T 307 is performed with the drainage lines open, this does not necessarily insure "drained" conditions within dense-graded specimens. Loading times in the M_r test are so quick that pore water pressure may not fully dissipate during the 0.1 second stress pulse thereby lowering the instantaneous vertical effective stress (i.e. σ_d') experienced by the specimen and, therefore, reducing the M_r. The likelihood of pore water pressure building in open-graded aggregates is, even for very short periods of time, much less than in dense-graded aggregates.

Thompson and Smith: Liang's comments are as follows:

"[Thompson and Smith] reported that for gradations that differ only in the permissible amount passing sieve No.200, limited differences in M_R were noted among the various granular materials."

Kamal, et al.: Liang's comments are as follows:

"[Kamal, et al.] found that resilient modulus will increase from the finer to the coarser mix and there is a slight increase in resilient modulus with increasing deviator stress. The resistance to shear and volumetric strains tends to increase from the finer to the coarser end of the proposed grading envelopes."

Tian, et al.: Liang's comments are as follows:

"[Tian, et al.] indicated that the coarse gradation limit will produce the highest resilient modulus."

Heydinger, et al.: Liang's comments are as follows:

"[Heydinger et al.] found that resilient modulus of aggregate was affected by aggregate gradation. They found that for limestone aggregate, the open graded specification had higher moduli than the dense graded specification. The moduli were highest for the upper gradation and lowest for the lower gradation for the Iowa mix. For gravel there was no strong trend for the variation of resilient moduli with respect to gradation."

As indicated in the previous excerpts, the effect of fines on M_r depends on other variables, some of which are not obviously evident. In the case of the two aggregates tested in this study, however, there is a definite increase in M_r with a reduction in fines from the levels present in the A-D gradations to the level present in the O-G gradation; i.e. no fines. However based on issues discussed in the literature review excerpts above, one must consider that the increase in M_r from the A-D condition to the O-G condition could be a function of the differences in the overall gradations, not just the difference in fines content.

Constructibility

When contemplating the use of unbound, open-graded base courses, one must also consider how the material will behave under construction traffic. In general, as the fines content decreases, cohesion of the compacted aggregate also decreases. This poses the potential for significant disturbance or deformation of the compacted, unbound, open-graded base course as dump trucks, trimmers, pavers, etc. travel across it. In a sub-section of the 2003 Michigan special provision cited in the Technical Approach section of this report (*7*), the Michigan DOT addresses this issue of construction equipment travel on an open-graded base course as follows:

"Equipment Travel - Delete subsection 303.03.C of the Standard Specifications for Construction and replace with the following.

Equipment travel on the OGDC for placement of OGDC will be permitted provided that a minimum of 2 inches of additional OGDC aggregate is placed. All costs associated with placement of the additional aggregate and removal or trimming thereof will be borne by the Contractor. Any removed OGDC aggregate, which will be re-used on this or any MDOT project, must be stockpiled and re-tested to verify the aggregate meets the specification requirements for the intended item of use.

Where no lateral space exists due to permanent physical obstructions, maintaining traffic requirements or other unavoidable conditions, concrete or Hot Mix Asphalt delivery to the paver via OGDC will be permitted provided that:

A. the specified in-place OGDC gradation is maintained and no other damage to the grade, subbase or subgrade occurs; and

B. varied truck routes or paths are used to minimize the potential for damage to the roadbed.

Correct all observed degradation to the OGDC resulting from equipment travel, according to subsection 303.02.E.2 of the Standard Specifications for Construction. Protect the underdrain system from damage at all entry and exit points."

Wisconsin, too, writes into its specifications detailed instructions on constructing and maintaining base courses, both dense and open-graded (*11*):

"301.3.4 Constructing Base
301.3.4.1 General
(1) Place aggregate in a manner that minimizes hauling on the subgrade. Do not use vehicles or operations that damage the subgrade or in-place base. Deposit material in a manner that minimizes segregation.
(2) Construct the base to the width and section the plans show. Shape, and compact the base surface to within 0.04 feet (12 mm) of the plan elevation.
(3) Ensure there is adequate moisture in the aggregate during placing, shaping, and compacting to prevent segregation and achieve adequate compaction.
(4) Maintain the base until paving over it, or until the engineer accepts the work, if paving is not part of the contract. The contractor is not responsible for maintaining material placed on detours, unless the special provisions specify otherwise."

The issue of damage to unbound, open-graded base courses due to construction traffic is probably the reason many states have moved to or adopted asphalt or cement treated permeable bases. If unbound permeable bases are to be used, the trick is to specify a gradation that strikes a balance between stability and drainability. Table 7 shows the Michigan, Oregon, and Wisconsin open-graded aggregate gradation specification relative to MoDOT's current and proposed Type 5 gradation specification, and the experimental gradation used for this study.

Comparison of Experimental Gradations to Other DOT Gradations

The first thing one notices in Table 7 is the significantly smaller maximum allowable P200 that Michigan, Oregon, and Wisconsin specify relative to Missouri, the greatest being 6% *maximum* allowed by Michigan. In referring back to Figure 1, 6% is essentially the *minimum* P200 being produced in Missouri for a Type 5 base aggregate. Although the experimental gradation was built with washed aggregates and 0% fines, it is unrealistic to expect 0% fines in the crushed aggregates produced in Missouri, and especially once they are in-place in the pavement structure. Even if one started with perfectly clean aggregate at the quarry, handling, trucking, dumping, shaping, and compacting the base material would generate significant fines.

Table 7: Various State Specifications for Open-Graded Aggregates

Sieve Size		States and Gradation Specifications (% Passing)					
					Missouri		
					Current	Proposed	
(mm)	Standard	Michigan	Oregon	Wisconsin	Type 5	Type 5	Experimental
37.5	1.5"	100					
25.0	1"		100	90-100	100	100	100.0
19.0	3/4"	60-80	80-98				96.0
12.5	1/2"	35-65	60-85		60-90	60-90	80.0
9.50	3/8"		30-65	45-65			69.0
4.75	#4			15-45	35-60	25-60	25.0
2.36	#8	10-25					18.3
2.00	#10		5-20	0-20			
1.18	#16						11.6
0.600	#30	5-18			10-35	5-35	5.0
0.425	#40		0-6	0-10			
0.300	#50						3.3
0.150	#100		0-3*				1.6
0.075	#200	0-6		0-5.0	0-15	0-15	0.0

* Dry Sieved Basis

Another interesting observation in Table 7 is that Wisconsin has the greatest number of control sieves on the finer side of the gradation spectrum (#4 to #200, inclusive). It has been argued that it is the mid-sized fine aggregate fractions (say, #8 to #40) that really contribute to establishing the balance between stability and drainability. Having a relatively well-graded particle distribution, especially in the mid-sized sands range, helps with aggregate interlock and thereby increases stability while, at the same time, limiting the fines content contributes to increased drainability.

In looking again at the experimental gradation used in this study, one notices that the size fraction dominating the overall particle size distribution is that aggregate fraction passing the 3/8" sieve and retained on the #4; 44% of the entire gradation falls in this narrow fraction. This is mostly a function of choosing to build the gradation in such a way as to isolate the effects of the proposed gradation change on the M_r of the material to the finer side of the gradation. However, the particle distribution of the material passing the #4 correlates fairly well with the specifications of the other three states. Although permeability testing was not in the scope of this investigation, one could argue that the permeability of the experimental gradation would approach that of the open-graded aggregates specified by the other states.

It should be noted that the M_r specimens built to the experimental O-G gradation required compactive effort comparable to the stiffest A-D specimens and the particle size distribution throughout the M_r specimens remained visibly homogenous. The non-segregation of aggregate particles during vibratory compaction is believed to be the result of compacting at a moisture content ~2% greater than the absorption of the aggregate thereby providing sufficient, but not excessive, moisture to bind the finer particles to the coarser particles. However, the almost total lack of cohesion of the aggregate particles was apparent during scarification of each lift after vibratory compaction. When scarifying the A-D M_r specimens during the previous MoDOT M_r study (*1*), a stainless steel laboratory spatula had to be used for scarifying (cutting) the top of each lift prior to compaction of the successive lift (per T 307) because the surface of the lift was hard and bound tightly. When scarifying each lift of the O-G M_r specimens, a rubber tipped kitchen spatula was used to lightly disturb the surface of each lift, which came apart with very little effort. This demonstrated the issue discussed earlier about the problem of stability (or maybe better defined as fragility) of the open-graded material under construction equipment.

CONCLUSIONS

Based on the results of the testing performed for this investigation, limited as it was, one can conclude the following:

- M_r results in this study (coarser, lower percent fines gradation) increased when compared to test results from the previous MoDOT M_r study in which the same aggregates were tested but typical Type 5 gradations (denser, higher fines) were investigated. A major factor in the increased M_r most likely was the lower degree of saturation present in the relatively open-graded specimens of this study in comparison to the dense-graded specimens examined in the previous study.
- For those aggregate producers that could benefit from the proposed specification change, it seems likely that fewer fines would be generated during production thereby increasing the probability of a more drainable base aggregate.
- Constructibility is of concern. However, compacting open-graded aggregates at a moisture content ~2% above absorption 1) provides sufficient particle surface moisture for compaction lubrication purposes and for binding the finer particles to the coarser particles through apparent cohesion (i.e. high negative pore pressure caused by small menisci radii) thereby reducing the probability of dry-aggregate segregation, but 2) limits excess water that could hinder maximum densification or flush the finer fractions during compaction (i.e. segregate the particles).

RECOMMENDATIONS – FUTURE RESEARCH

- If drainability is still the main purpose for specifying a Type 5 base aggregate, *consideration should be given to lowering the maximum percentage passing* on certain control sieves. Aggregate producers could possibly generate this material by blending two (or more) lower-quality aggregates already in production.
- The concept of compaction of open-graded aggregates at a moisture content ~2% above absorption needs more study.
- To better characterize the change in M_r that the proposed Type 5 gradation specification will cause, M_r tests should be performed along the lower bounds of the current Type 5 specification.
- As M_r tests might not be the best measure of determining the effects of the change in the Type 5 gradation specification on pavement performance, thus other types of tests (e.g. triaxial shear, CBR, cyclic total deformation) should be investigated.
- More M_r testing is required to determine the optimum fines content for particular aggregates under particular conditions. Regression equations could be developed to determine those fines content levels that would maximize M_r.

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APPENDIX A

In the latest on-line-available specifications, special provisions, supplements, etc., Michigan, Oregon, and Wisconsin (and there could be more) do specify unbound, open-graded, permeable bases in pavement construction. An excerpt from a 2003 Michigan special provision (*7*) is as follows:

“c. Construction. Construct the open-graded drainage course (OGDC) according to Section 303 of the Standard Specifications for Construction with the following modifications.
1. Placement and Compaction - Place and compact a control strip as specified in section (c.3.A) of this Special Provision to establish a placement and rolling pattern that will achieve at least 95 percent compaction. If a thickness greater than 8 inches is specified, place the OGDC in two approximately equal lifts. Compact each layer to not less than 95 percent of its maximum unit weight. Finish the surface of the OGDC as specified in subsection 303.03.B of the Standard Specifications for Construction.”

This particular sub-section of the special provision does not indicate the test method to use to determine maximum dry unit weight. Referring to Section 303 of the Standard Specifications for Construction (*8*) in hopes of finding guidance on how to determine maximum unit weight yielded the following:

“303.03 Construction.
A. Preparation. Furnish and install the separation treatment, as specified on the plans, between the OGDC and the subbase.
B. Placement and Compaction. Place open-graded aggregate according to subsection 302.03 except that the density requirements are replaced by the following. Compact the open-graded aggregate with three complete passes of a minimum 10-ton, steel drum tandem roller. One complete pass will be down and back in the same path.”

So, assuming special provisions supersede standard specifications, it seems Michigan has replaced a compaction method based on roller-type and roller patterns to a percent compaction determination, but has not clearly specified how to determine the reference or maximum dry unit weight.

Oregon and other states also use the roller-type and roller-pattern method of compacting unbound, open-graded aggregates. An excerpt from Oregon’s 2003 Standard Specifications Section 00641 (*9*) is as follows:

“00641.44 Shaping and Compacting:
(a) Aggregate Base Courses:
(1) Dense-graded Aggregates - Begin compaction of each layer of dense-graded aggregates immediately after the material is spread and continue until a density of not less than 100% of the maximum density has been achieved when tested according to the MFTP.
(2) Open-graded Aggregates - Compact the surface of each layer of open-graded aggregates using rollers conforming to 00641.24. Roll until there is no appreciable reaction or yielding under the compactor.”

The Oregon specification also indicates a percent compaction of maximum "density" for the dense-graded aggregates and does not directly indicate in this sub-section the method to be used to determine said maximum density. However in an earlier sub-section, reference is made to T 99 and an optimum moisture content:

"00641.12 Limits of Mixture - Provide a mixture of aggregate and water having a uniform moisture content sufficient to obtain the required compaction. Water may be introduced in a mixing plant, or on the grade. Determine the proportion of aggregate and water according to AASHTO T 99 and AASHTO T 224. Proportions will be in percentages by weight and will be known as the "Mix Design". The amount of water required in the mix design will normally be within a range of 5% to 10% of the mixture, based on dry weight of the aggregates. The mixture furnished shall conform to the mix design with a tolerance in optimum water content of plus or minus 2%. Any mixture having water content in excess of 2% over the Mix Design may be accepted for use, according to 00641.80(d), if approved."

It appears that the use of unbound, open-graded base courses has recently been discontinued in Ohio. However, they do specify using field test sections to determine maximum dry unit weight of unbound granular base materials. The test section method utilized depends on whether or not the aggregate has a definite moisture-density relationship (determined using various optional methods). If there is a definite moisture-density relationship, T 99 is used to determine the optimum moisture content and then the test sections are built at that moisture content and rolled until a maximum dry unit weight is achieved. If there is not a definite moisture-density relationship, test sections are built at various moisture contents (starting at 0 to 3% moisture and increasing by 2% for every test section), rolled until a maximum dry unit weight for each moisture content is achieved, and then the maximum dry unit weight determined for the field testing (essentially, a field proctor curve) is used for base construction purposes (*10*).

Wisconsin specifies a "standard" compaction method for unbound, open-graded aggregates that is a roller-type and roller-pattern method (*11*). However, Wisconsin requires laboratory permeability testing on aggregates to be used in open-graded base courses which, in Section 4.1 of the Construction and Materials Manual, Procedure 4-15-32, specifies the following (*12*):

"The target unit weight is defined as the unit weight which is achieved when the material is compacted at 6% moisture content in accordance with the methods and procedures contained in AASHTO T-99, Method C."

The specification of a 6% moisture content seemed reasonable in that, for most base aggregates, absorption would be satisfied and there would be sufficient particle surface moisture for compaction lubrication purposes, but there would not be so much water as to flush the finer fractions during compaction (i.e. segregate the particles). This level of moisture also relates fairly well to one of the recommendations in the CTRE report (*6*):

"As an alternative to trimming equipment (e.g. Gomaco type), use a motor grader with GPS assisted grading (i.e. stakeless grading control). If trimming equipment must be used, however, ensure that the aggregate is delivered to the site with sufficient water content (7%–10 %) to bind the fines during trimming."

This recommendation was in response to one of the findings of the CTRE report in that segregation of the open-graded base aggregates was found to occur during trimming of the compacted base course; i.e. the aggregate was too dry during trimming and, thus, the vibration of the trimmer caused the fines to segregate downward leaving coarser aggregate particles on the surface. Therefore, it seems that, for unbound, open-graded base aggregates, there needs to be sufficient moisture in the delivered material to provide lubrication for compaction and "bind the fines" to the coarse aggregate to prevent segregation, but not excessive moisture that would prevent maximum densification or cause segregation to occur due to fluid flow.

APPENDIX B

Sequence	Sig3 (psi)	SigD (psi)	Theta (psi)	Mr 1 (psi)	Mr 2 (psi)	Mr 3 (psi)	Mr 4 (psi)	Mr 5 (psi)	Mr AVG (psi)	MrN	MrN Pred
1	3.04	3.16	12.28	43134	45887	42982	40100	42573	42935	2920.748	2687.507
2	3.01	6.03	15.06	43068	43013	43130	44622	43093	43385	2951.361	2951.274
3	3.01	9.09	18.12	43966	44003	43939	43966	43960	43967	2990.952	3207.323
4	5.04	5.24	20.36	56299	53489	53577	53551	50988	53581	3644.966	3517.268
5	5.02	10.15	25.21	56774	55334	56813	55239	53807	55593	3781.837	3836.146
6	5.02	15.06	30.12	59041	57921	57932	56839	57880	57923	3940.34	4116.106
7	10.04	10.32	40.44	72492	75041	75056	75085	75080	74551	5071.497	5000.022
8	10.04	20.39	50.51	79712	79713	81111	79672	79695	79981	5440.884	5349.806
9	10.04	30.34	60.46	81906	81904	81934	81908	81864	81903	5571.633	5649.374
10	15.04	10.65	55.77	87475	87511	89219	89201	85541	87789	5972.041	5979.286
11	15	15.41	60.41	87713	90280	90233	90295	90277	89760	6106.122	6078.378
12	15.01	30.49	75.52	94246	94289	94333	94248	94185	94260	6412.245	6398.857
13	20.03	16.04	76.13	98925	98980	98911	102039	101904	100152	6813.061	6899.12
14	20.03	20.69	80.78	103168	103199	100793	100765	103264	102238	6954.966	6957.948
15	20.03	40.47	100.56	107052	106988	106864	108472	108289	107533	7315.17	7225.32

Generalized NCHRP 1-28A Model (M-E Design Guide)

MrN = Mr normalized to atmospheric pressure (14.7 psi)

k1	3050.980	(from SigmaStat analysis)
k2	0.563	(from SigmaStat analysis)
k3	-0.265	(from SigmaStat analysis)
Rsq	0.995	(from SigmaStat analysis)
Se	124.925	(from SigmaStat analysis)
Se/Sy	0.080	

Sy =	1560.792

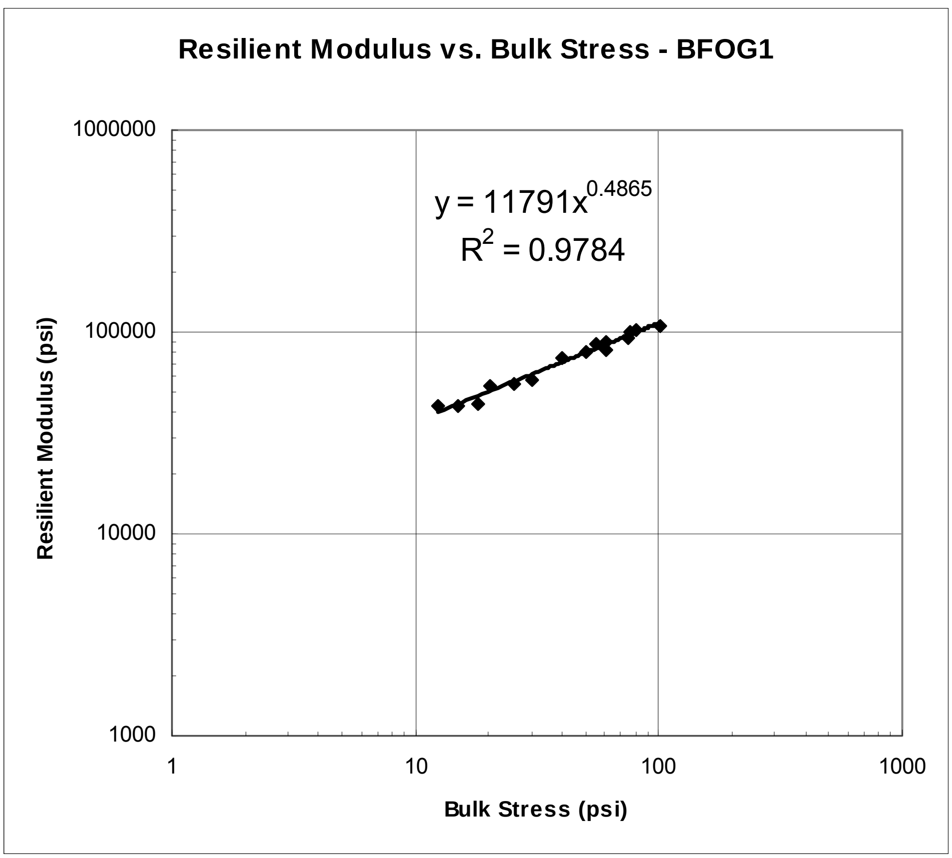

Figure 10B: BF O-G1 M_r Data, Eq. 1 Regression Results, & Eq. 2 Plot

Sequence	Sig3 (psi)	SigD (psi)	Theta (psi)	Mr 1 (psi)	Mr 2 (psi)	Mr 3 (psi)	Mr 4 (psi)	Mr 5 (psi)	Mr AVG (psi)	MrN	MrN Pred
1	3.02	3.12	12.18	37632	37606	37413	37623	39732	38001	2585.102	2362.654
2	3.03	6.05	15.14	36949	38104	38067	38026	38135	37856	2575.238	2647.049
3	3.03	9.13	18.22	40455	39529	39526	40402	39555	39893	2713.81	2907.355
4	4.99	5.23	20.2	48669	48703	48570	48491	48572	48601	3306.19	3202.364
5	5.01	10.18	25.21	51354	51409	52704	52687	52638	52158	3548.163	3547.61
6	5.01	15.17	30.2	53452	54388	54362	53492	55314	54201	3687.143	3844.687
7	10.04	10.35	40.47	72943	70532	70450	72951	72988	71973	4896.122	4790.009
8	10.04	20.38	50.5	78094	78157	78101	78100	78198	78130	5314.966	5164.522
9	10.04	30.39	60.51	78873	77872	79866	78843	78861	78863	5364.83	5490.776
10	15.03	10.49	55.58	87926	87865	84421	87886	87912	87202	5932.109	5856.813
11	15.04	15.42	60.54	85112	87298	85137	87329	87334	86442	5880.408	5977.883
12	15.04	30.51	75.63	91326	94097	92737	92733	94021	92983	6325.374	6325.297
13	20.05	15.59	75.74	101754	101688	101479	95351	98247	99704	6782.585	6887.092
14	20.05	20.65	80.8	100415	102683	102671	102589	102738	102219	6953.673	6956.088
15	20.05	40.68	100.83	110708	105349	109164	105205	110596	108205	7360.884	7252.599

Generalized NCHRP 1-28A Model (M-E Design Guide)

MrN = Mr normalized to atmospheric pressure (14.7 psi)

k1	2741.661	(from SigmaStat analysis)
k2	0.637	(from SigmaStat analysis)
k3	-0.304	(from SigmaStat analysis)
Rsq	0.995	(from SigmaStat analysis)
Se	133.940	(from SigmaStat analysis)
Se/Sy	0.080	

Sy =	1682.696

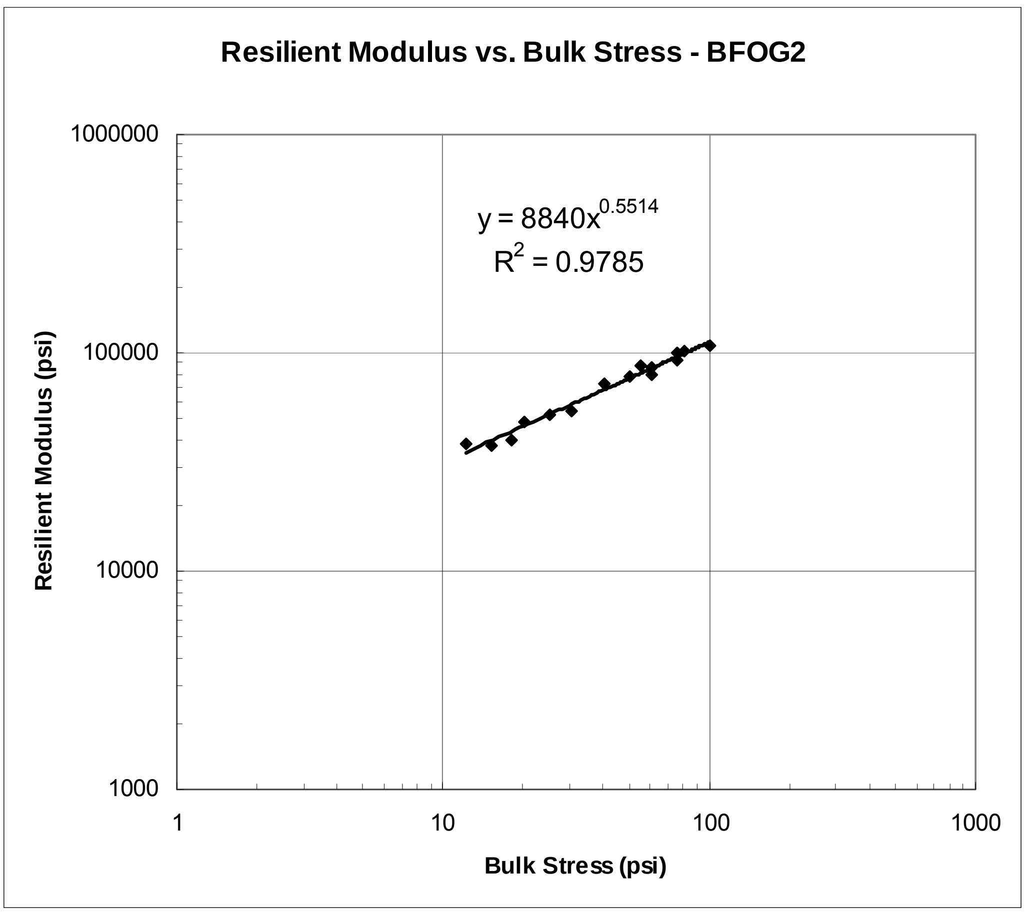

Figure 11B: BF O-G2 M_r Data, Eq. 1 Regression Results, & Eq. 2 Plot

Sequence	Sig3 (psi)	SigD (psi)	Theta (psi)	Mr 1 (psi)	Mr 2 (psi)	Mr 3 (psi)	Mr 4 (psi)	Mr 5 (psi)	Mr AVG (psi)	MrN	MrN Pred
1	3.04	3.1	12.22	39632	42405	39519	39617	39662	40167	2732.449	2514.89
2	3.02	6.07	15.13	39252	39298	39311	39294	39286	39288	2672.653	2783.473
3	2.98	9.11	18.05	42104	42137	41230	40418	41191	41416	2817.415	3018.18
4	5.03	5.23	20.32	50911	50918	48641	48602	50909	49996	3401.088	3333.735
5	5.01	10.21	25.24	54141	52849	54179	54252	54083	53901	3666.735	3648.24
6	5.03	15.11	30.2	56064	56039	56028	56003	56081	56043	3812.449	3924.105
7	10.05	10.29	40.44	75100	70007	74985	77831	72306	74046	5037.143	4813.033
8	10.04	20.33	50.45	77766	77785	77753	77763	76338	77481	5270.816	5145.246
9	10.04	30.44	60.56	78051	78075	77990	78113	78086	78063	5310.408	5436.577
10	15.04	10.47	55.59	84354	84398	81170	81095	81000	82403	5605.646	5797.744
11	15.04	15.38	60.5	87096	87074	87085	87044	87096	87079	5923.741	5898.348
12	15.04	30.59	75.71	91685	91695	91656	91711	91731	91696	6237.823	6196.265
13	20.05	15.54	75.69	98131	98087	95080	95059	98061	96884	6590.748	6723.473
14	20.05	20.67	80.82	102887	100449	100254	102790	102848	101846	6928.299	6778.17
15	20.05	41.15	101.3	100295	106599	101466	106602	101628	103318	7028.435	7023.139

Generalized NCHRP 1-28A Model (M-E Design Guide)

MrN = Mr normalized to atmospheric pressure (14.7 psi)

k1	2882.995	(from SigmaStat analysis)
k2	0.589	(from SigmaStat analysis)
k3	-0.293	(from SigmaStat analysis)
Rsq	0.992	(from SigmaStat analysis)
Se	152.379	(from SigmaStat analysis)
Se/Sy	0.098	

Sy =	1560.585

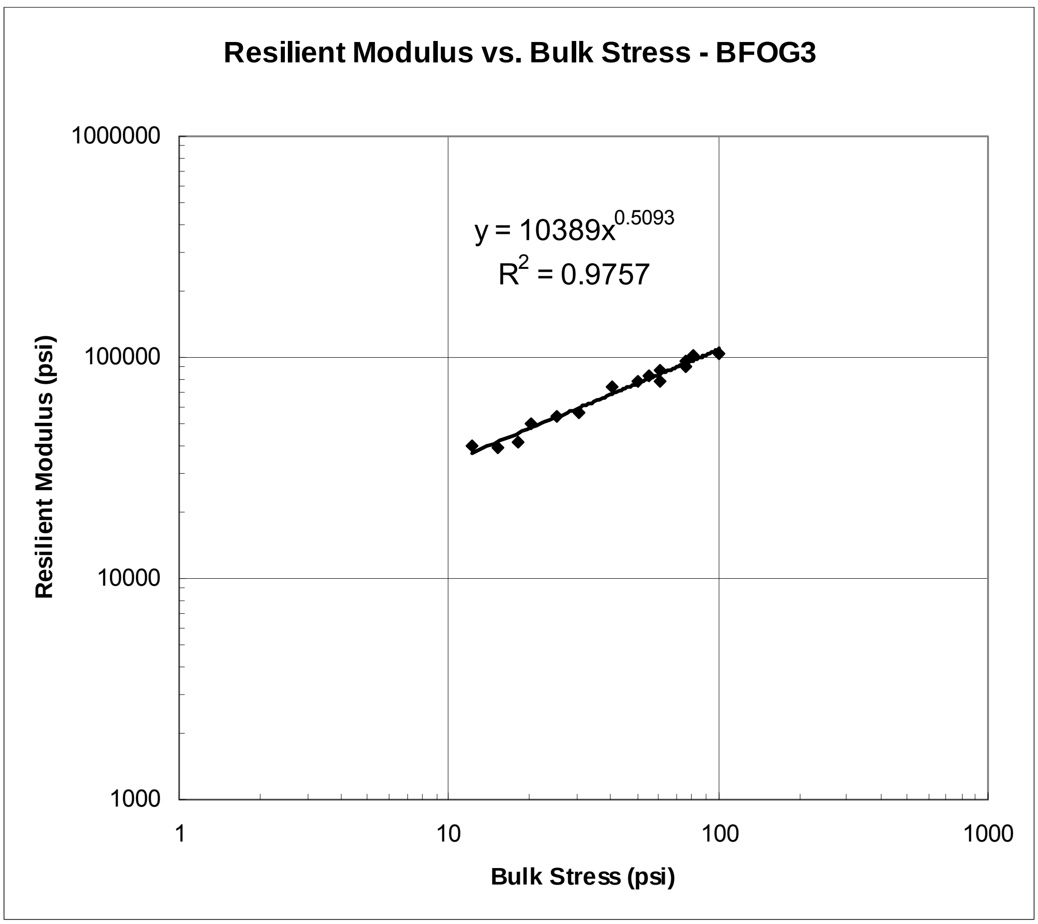

Figure 12B: BF O-G3 M_r Data, Eq. 1 Regression Results, & Eq. 2 Plot

Sequence	Sig3 (psi)	SigD (psi)	Theta (psi)	Mr 1 (psi)	Mr 2 (psi)	Mr 3 (psi)	Mr 4 (psi)	Mr 5 (psi)	Mr AVG (psi)	MrN	MrN Pred
1	2.98	3.16	12.1	22982	23041	22974	23024	23017	23008	1565.17	1679.08
2	3.01	6.01	15.04	22180	22572	22605	22589	22560	22501	1530.68	1912.892
3	2.98	9.11	18.05	24275	24280	24331	24279	24306	24294	1652.653	2124.376
4	4.99	5.22	20.19	33259	33260	32202	33219	33210	33030	2246.939	2384.8
5	5.01	10.16	25.19	34410	35007	34414	34444	33889	34433	2342.381	2680.604
6	5.05	15.04	30.19	35909	36292	36352	36337	36329	36244	2465.578	2942.316
7	10.01	10.33	40.36	50093	50133	51300	50093	51328	50590	3441.497	3765.704
8	10.02	20.35	50.41	55305	54636	54619	55300	54661	54904	3734.966	4109.92
9	10.02	30.31	60.37	55127	56114	55942	56018	55600	55760	3793.197	4409.957
10	15	10.45	55.45	56891	56836	56705	58446	60112	57798	3931.837	4734.738
11	15.01	15.41	60.44	61544	61505	61460	61526	61464	61500	4183.673	4850.317
12	15.01	30.32	75.35	68507	68011	68092	68801	67984	68279	4644.83	5177.309
13	20	15.68	75.68	73657	71940	71892	73581	71929	72600	4938.776	5696.661
14	20.01	20.63	80.66	76331	74980	74952	74990	74921	75235	5118.027	5765.431
15	20.01	40.49	100.52	81002	80782	82554	82497	81710	81709	5558.435	6055.229

Generalized NCHRP 1-28A Model (M-E Design Guide)

MrN = Mr normalized to atmospheric pressure (14.7 psi)

k1	1997.677	(from SigmaStat analysis)
k2	0.724	(from SigmaStat analysis)
k3	-0.340	(from SigmaStat analysis)
Rsq	0.988	(from SigmaStat analysis)
Se	181.907	(from SigmaStat analysis)
Se/Sy	0.134	

Sy =	1360.866

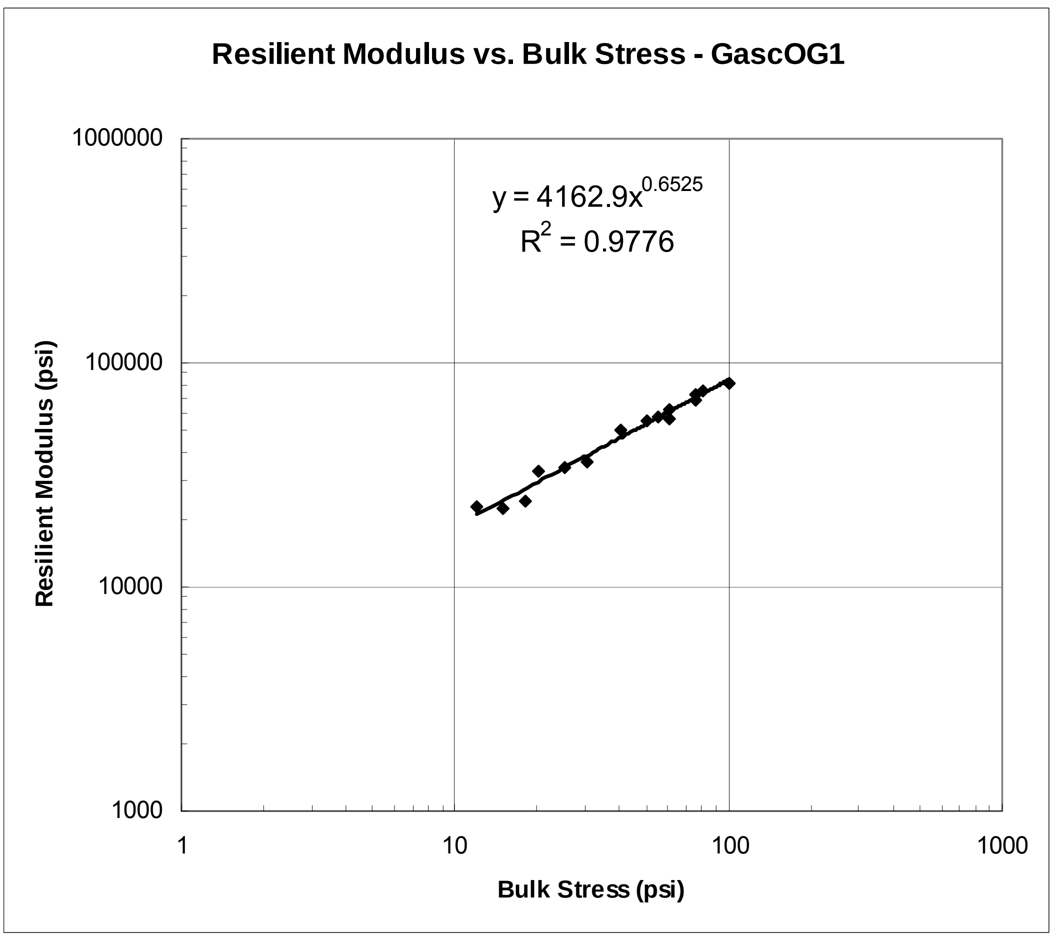

Figure 13B: Gasc O-G1 M_r Data, Eq. 1 Regression Results, & Eq. 2 Plot

Sequence	Sig3 (psi)	SigD (psi)	Theta (psi)	Mr 1 (psi)	Mr 2 (psi)	Mr 3 (psi)	Mr 4 (psi)	Mr 5 (psi)	Mr AVG (psi)	MrN	MrN Pred
1	3.02	3.16	12.22	22838	23586	23349	23165	23831	23354	1588.707	1527.393
2	3.02	6.05	15.11	24522	24534	24609	24548	24049	24452	1663.401	1750.469
3	3.01	9.16	18.19	25818	25820	25766	25770	26187	25872	1760	1967.865
4	5.04	5.23	20.35	34427	34350	34416	34365	34398	34391	2339.524	2181.961
5	5.04	10.17	25.29	36900	37504	37646	36966	36834	37170	2528.571	2484.864
6	5.03	15.1	30.19	39198	39194	39229	39191	38715	39105	2660.204	2757.223
7	10.04	10.38	40.5	52889	55889	55878	55685	55649	55198	3754.966	3490.535
8	10.02	20.26	50.32	60554	59720	59726	59719	60570	60058	4085.578	3901.592
9	10.02	30.07	60.13	59352	60434	60281	59831	59880	59956	4078.639	4275.103
10	15.03	10.54	55.63	64211	64173	62222	64135	62188	63386	4311.973	4388.738
11	15.02	15.29	60.35	66110	66178	66105	66113	66195	66140	4499.32	4548.612
12	15.03	30.71	75.8	73749	74628	73653	73655	74540	74045	5037.075	5044.225
13	20.04	15.57	75.69	76530	76597	76493	76431	76493	76509	5204.694	5352.19
14	20.04	20.56	80.68	81972	80351	80338	83550	81934	81629	5552.993	5484.502
15	20.04	40.42	100.54	90439	87742	88488	90577	90509	89551	6091.905	5997.912

Generalized NCHRP 1-28A Model (M-E Design Guide)

MrN = Mr normalized to atmospheric pressure (14.7 psi)

Sy =	1492.374

k1	1782.632	(from SigmaStat analysis)
k2	0.724	(from SigmaStat analysis)
k3	-0.215	(from SigmaStat analysis)
Rsq	0.991	(from SigmaStat analysis)
Se	151.850	(from SigmaStat analysis)
Se/Sy	0.102	

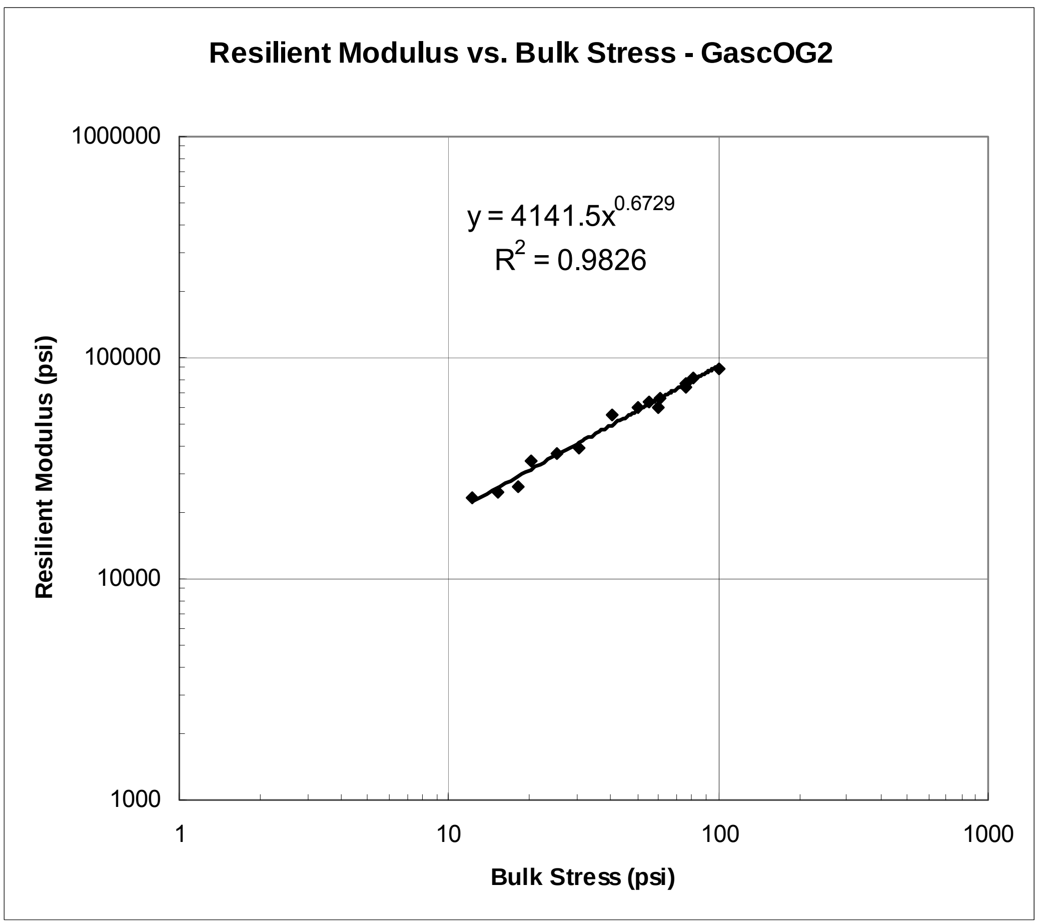

Figure 14B: Gasc O-G2 M_r Data, Eq. 1 Regression Results, & Eq. 2 Plot

Sequence	Sig3 (psi)	SigD (psi)	Theta (psi)	Mr 1 (psi)	Mr 2 (psi)	Mr 3 (psi)	Mr 4 (psi)	Mr 5 (psi)	Mr AVG (psi)	MrN	MrN Pred
1	3.05	3.17	12.32	26858	28042	26955	28077	28321	27650	1880.952	1822.314
2	2.98	6.08	15.02	29259	29176	28606	29233	28593	28973	1970.952	2011.572
3	3.02	9.1	18.16	29654	29662	29116	29653	29707	29559	2010.816	2211.264
4	5.01	5.28	20.31	41470	41285	39890	41316	41490	41090	2795.238	2479.388
5	5	10.23	25.23	39189	38475	38489	38509	39184	38769	2637.347	2720.313
6	5	15.06	30.06	40573	40061	40064	40057	40043	40159	2731.905	2922.962
7	9.97	10.27	40.18	56573	56585	56621	56610	55132	56304	3830.204	3703.731
8	10.01	20.23	50.26	59654	59633	59666	59623	59576	59631	4056.531	3940.048
9	10.02	30.13	60.19	60047	60072	60628	60576	59980	60261	4099.388	4136.88
10	15.03	10.46	55.55	67818	65797	65707	67852	65774	66590	4529.932	4584.022
11	15.04	15.41	60.53	68339	66865	68181	66721	68282	67677	4603.878	4638.177
12	15.04	30.05	75.17	71232	71228	70374	71172	70376	70876	4821.497	4797.233
13	20.04	15.64	75.76	77129	77039	77052	77076	78931	77445	5268.367	5372.855
14	20.03	20.54	80.63	78876	78974	80472	78903	80470	79539	5410.816	5379.618
15	20.03	40.18	100.27	81790	82004	76576	81038	81996	80681	5488.503	5461.105

Generalized NCHRP 1-28A Model (M-E Design Guide)

MrN = Mr normalized to atmospheric pressure (14.7 psi)

Sy =	1300.067	
k1	2130.596	(from SigmaStat analysis)
k2	0.664	(from SigmaStat analysis)
k3	-0.403	(from SigmaStat analysis)
Rsq	0.990	(from SigmaStat analysis)
Se	140.404	(from SigmaStat analysis)
Se/Sy	0.108	

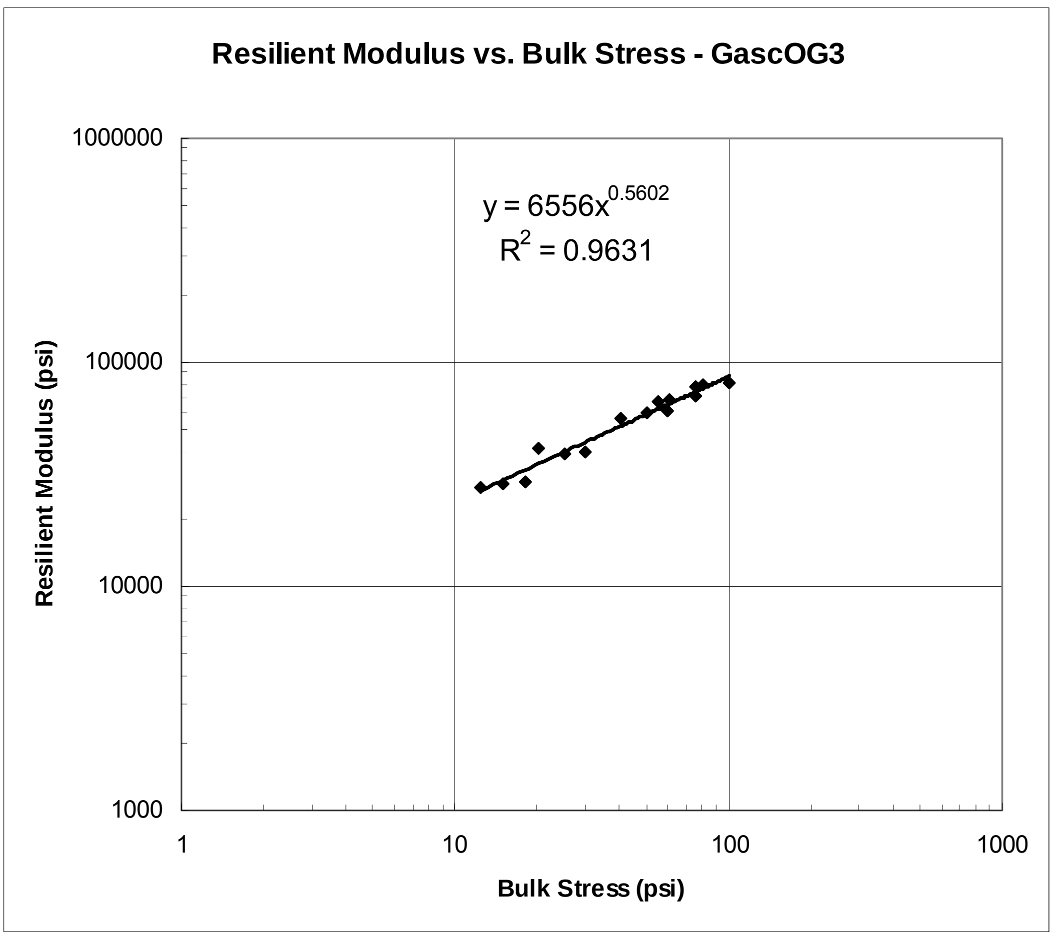

Figure 15B: Gasc O-G3 M_r Data, Eq. 1 Regression Results, & Eq. 2 Plot

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