FHWA-NJ-2005-003

The Development of a Performance Specification for Granular Base and Subbase Material

FINAL REPORT

Submitted by

Mr. Thomas Bennert*
Research Engineer

Dr. Ali Maher*
Professor and Chairman

* Dept. of Civil & Environmental Engineering
Center for Advanced Infrastructure & Transportation (CAIT)
Rutgers, The State University
Piscataway, NJ 08854-8014

NJDOT Research Project Manager
Mr. Anthony Chmiel

In cooperation with

New Jersey
Department of Transportation
Bureau of Research and Technology
and
U.S. Department of Transportation
Federal Highway Administration

Disclaimer Statement

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA-NJ-2005-003	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Development of a Performance Specification for Granular Base and Subbase Material		5. Report Date Feb - 2005 6. Performing Organization Code CAIT/Rutgers
7. Author(s) Mr. Thomas Bennert, Dr. Ali Maher		8. Performing Organization Report No. FHWA-NJ-2005-003
9. Performing Organization Name and Address New Jersey Department of Transportation CN 600 Trenton, NJ 08625		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation Washington, D.C.		13. Type of Report and Period Covered Final Report 1/2003 – 2/2005 14. Sponsoring Agency Code

15. Supplementary Notes

Email Address: bennert@eden.rutgers.edu; mmaher@rci.rutgers.edu

16. Abstract

The research project encompassed evaluating the performance of NJDOT specified aggregates at the respective NJDOT gradation ranges (high end, middle, and low end) and provide guidance as how to modify the gradation ranges to provide better performance in the field. Currently, the NJDOT specifies the use of granular materials by gradation only. However, it is well known that the gradation of granular materials has a dramatic impact on its performance. Therefore, base and subbase materials were sampled from three regions in the state and evaluated under the following performance tests: permeability (falling and constant head conditions), triaxial shear strength, cyclic triaxial loading, California Bearing Ratio (CBR) and resilient modulus. Testing was also conducted on recycled asphalt pavement (RAP) and recycled concrete (RCA) to evaluate their potential use as base and subbase materials. Materials were tested at their respective natural gradations and at manufactured gradations which represented the NJDOT high, middle, and low areas of the gradation specification in order to provide guidance as how to better refine the current NJDOT gradation specification.

Testing concluded that the gradation has an impact on each material and source tested. On average, permeability increased with increasing coarse fraction and decreasing percent fines. The triaxial strength increased as coarse fraction increased; however, the permanent deformation measured from the cyclic triaxial test indicated that at the gap-graded high end of the gradation band, instability was prevalent for the rounded subbase aggregates. This is most likely due to rounded aggregate particles not interlocking during loading (The gradation of this type of material is very similar to the non-stabilized open graded base layer that the NJDOT has used in the past). The resilient modulus testing followed a similar trend. Overall, the closer the aggregate gradation was to the middle/high side of the NJDOT gradation specification, the better the performance.

The testing of the RAP, RCA, and their blends with the base material, showed that as the % RAP increased in the blend, both the CBR value and permeability decreased. RAP also caused larger permanent deformations during the cyclic triaxial testing. The inclusion of RCA provided the largest CBR, largest resilient modulus, and lowest permanent deformation values. However, as the % RCA increased, the blend's permeability decreased.

17. Key Words Base aggregate, subbase aggregate, resilient modulus, permeability, permanent deformation	18. Distribution Statement

19. Security Classif (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	55	

Form DOT F 1700.7 (8-69)

TABLE OF CONTENTS

Page #

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The research project encompassed evaluating the performance of NJDOT specified aggregates at the respective NJDOT gradation ranges (high end, middle, and low end) and provide guidance as how to modify the gradation ranges to provide better performance in the field. Currently, the NJDOT specifies the use of granular materials by gradation only. However, it is well known that the gradation of granular materials has a dramatic impact on its performance. Therefore, base and subbase materials were sampled from three regions in that state and evaluated under the following performance tests: permeability (falling and constant head conditions), triaxial shear strength, cyclic triaxial loading, California Bearing Ratio (CBR) and resilient modulus. Testing was also conducted on recycled asphalt pavement (RAP) and recycled concrete (RCA) to evaluate their potential use as base and subbase materials. Materials were tested at their respective natural gradations and at manufactured gradations which represented the NJDOT high, middle, and low areas of the gradation specification.

Testing concluded that the gradation has an impact on each material and source tested. On average, permeability increased with increasing coarse fraction and decreasing percent fines. The triaxial strength increased as coarse fraction increased; however, the permanent deformation measured from the cyclic triaxial test indicated that at the gap-graded high end of the gradation band, instability was prevalent for the rounded subbase aggregates. This is most likely due to rounded aggregate particles not interlocking during loading (The gradation of this type of material is very similar to the non-stabilized open graded base layer that the NJDOT has used in the past). The resilient modulus testing followed a similar trend. Overall, the closer the aggregate gradation was to the middle/high side of the NJDOT gradation specification, the better the performance.

The testing of the RAP, RCA, and their blends with the base material, showed that as the % RAP increased in the blend, both the CBR value and permeability decreased. RAP also caused larger permanent deformations during the cyclic triaxial testing. The inclusion of RCA provided the largest CBR, largest resilient modulus, and lowest permanent deformation values. However, as the % RCA increased, the blend's permeability decreased.

INTRODUCTION

The New Jersey Department of Transportation (NJDOT) currently specifies the use of base and subbase aggregates simply by its gradation. As long as the material's gradation meets the NJDOT gradation bands, the material can be classified as suitable for pavement construction. There are some small additional specifications which the material must meet; however, the main acceptance criterion is gradation. The gradation specification for base aggregate (dense graded aggregate base course – DGABC) and subbase aggregate (NJDOT designated I-3) are shown in Figures 1 and 2. The gradations are shown in Table 1. In the figures, as long as the gradation falls within the red-dashed bands, the material is acceptable for use regardless of strength, density, or permeability.

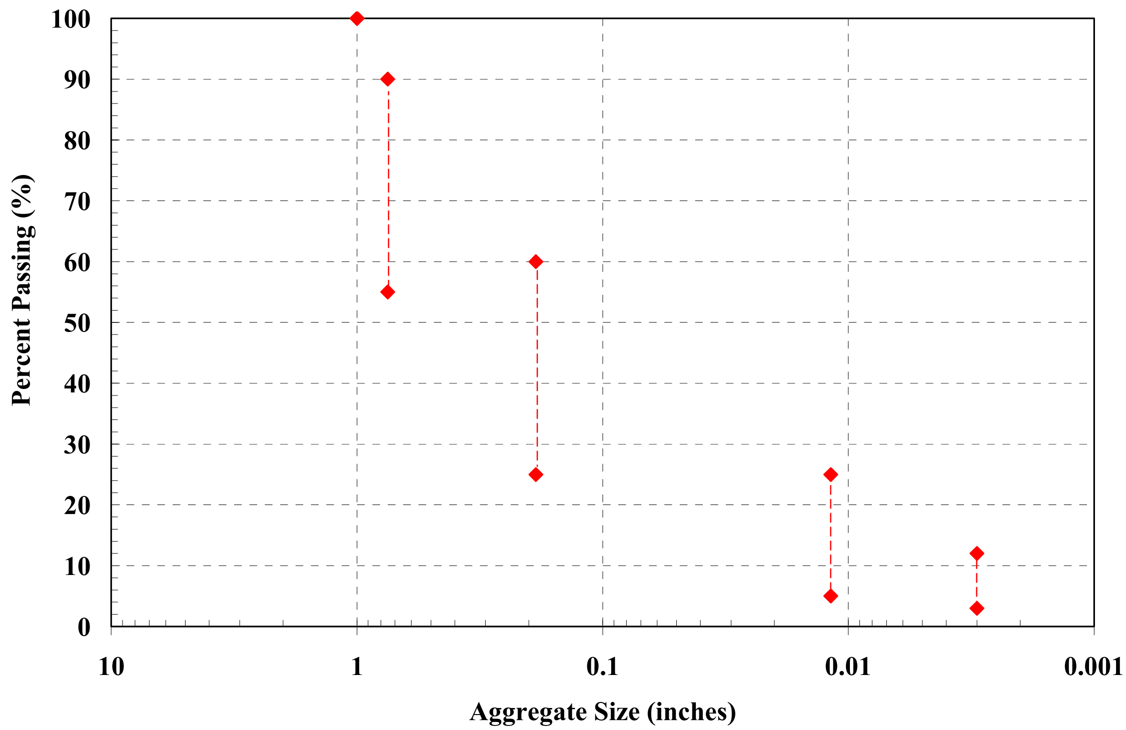


Figure 1 – NJDOT Gradation Specification Bands for DGABC Base Aggregate

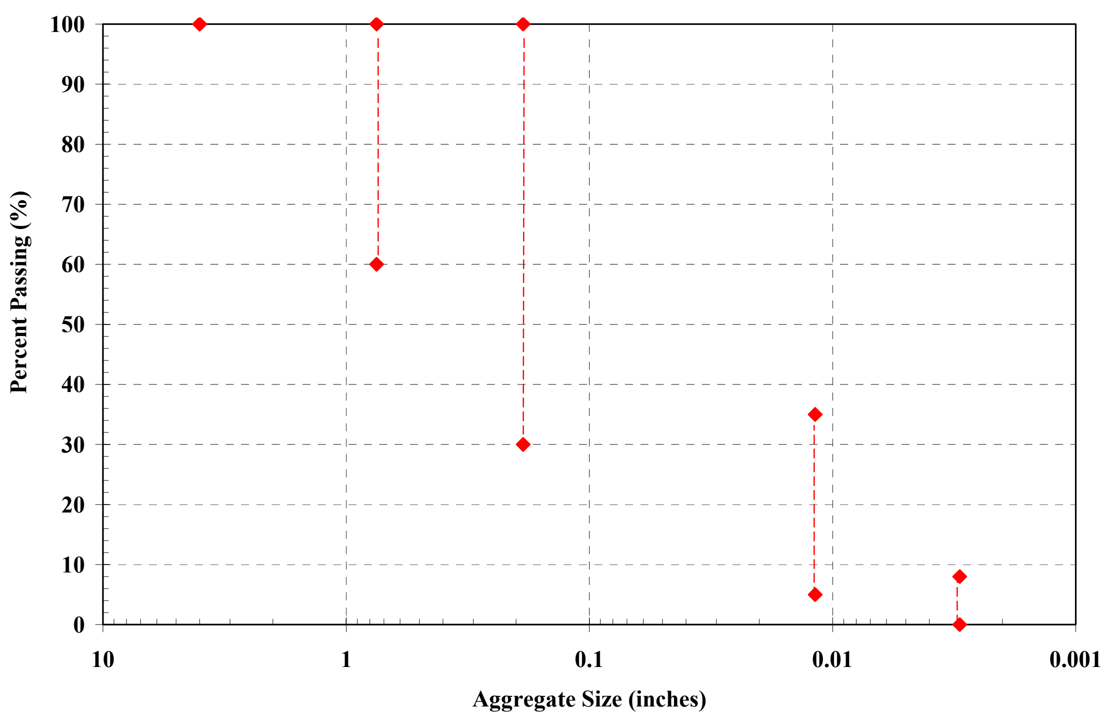


Figure 2 – NJDOT Gradation Specification Bands for I-3 Subbase Aggregate

Table 1. Gradation Bands for NJDOT DGABC and I-3 Aggregates

	Percent Passing	
Sieve Size	DGABC	I-3
4.0 inch	---	100 %
1.0 inch	100 %	---
0.75 inch	55 – 90 %	60 – 100 %
No. 4	25 – 60 %	30 – 100 %
No. 50	5 – 25 %	5 – 35 %
No. 200	3 – 12 %	0 – 8 %

As shown in both Figure 1 and 2, and Table 1, the gradation bands are wide, especially for the No. 4 sieve size where the I-3 gradation can fall anywhere between 100 to 30 percent passing. With the NJDOT gradation bands allowed to be so wide, it is obvious that a wide range of soil characteristics (density, permeability, strength, stiffness, etc.) can be expected.

Another problem that is currently being experienced with the NJDOT is the allowance of recycled materials, especially recycled asphalt pavement (RAP) and recycled concrete (RCA), to be blended with base and subbase aggregates. At the moment, there is no current specification that NJDOT engineers utilize. This is mainly due to there being a lack of understanding as to how the addition of these recycled materials affect of overall performance of the aggregate blend.

<u>Testing Plan – Effect of Allowable Gradation Band</u>

Based on the large gradation specifications, a testing matrix was developed to determine how the material properties might change if they were allowed to vary through out the gradation bands. Each gradation specification, DGABC and I-3, was split into three sections, high end (coarsest) of the band, middle of the gradation band, and the low end (finest) of the gradation band. The natural gradation of the material was also utilized. Both the DGABC and I-3 were sampled from different regions of New Jersey – North, Central and South. The DGABC material was only sampled from the North and Central since the quarried material does not exist naturally in southern New Jersey. Approximately two tons of each material source was delivered to the Rutgers University Asphalt/Pavement Laboratory (RAPL) to conduct the following tests:

1. Moisture-density relationship (Compaction) – modified energy for the DGABC and standard for the I-3, as specified by the NJDOT
2. Permeability - Falling Head and Constant Head
3. Triaxial Shear Strength
4. Cyclic Triaxial Testing – to determine the permanent deformation properties
5. Resilient Modulus

The performance testing was to provide the NJDOT with information regarding how the material properties may vary depending on their respective location within the current gradation band. This could potentially provide the NJDOT with enough evidence to either “tighten up” their gradation specification or to start specifying particular aggregate gradations for different performance applications (i.e. high modulus, high permeability, etc.).

<u>Testing Plan – Recycled Materials</u>

Although not originally included in the research proposal, the research also included the evaluation of recycled asphalt pavement (RAP) and recycled concrete (RCA) for use as aggregates in either the base or subbase pavement layer. Currently, these materials are allowed, with the RCA in the base and the RAP in the subbase, but only as blended materials. However, there has been little work as to the overall performance of these materials and their respective blends. Therefore, most of the performance testing discussed earlier was conducted. Due to the vast amount of material, not all blends were tested under the triaxial, cyclic triaxial (permanent deformation), and resilient modulus. Rather, in order to provide guidance for pavement design, the California Bearing Ratio (CBR) test was conducted. This type of measurement has been used by state officials for years in pavement design. Not to mention there exists a large database of CBR values for different materials and their respective performance. Therefore, the CBR values will also provide a means of comparing the different recycled materials in pavement design.

EXPERIMENTAL PROGRAM

<u>Gradation Analysis</u>

Since the main goal was to evaluate the materials at the extremes and midpoint of the NJDOT gradation bands, the required gradations for the bands needed to be manufactured. Portions of each source material were broken down on the sieve sizes specified for the respective gradation bands. Bulk samples were then batched to provide a material that satisfied the NJDOT gradation band specification.

The natural gradations were also determined to compare the different sources of each material type. Figure 3 shows the natural gradations for the DGABC and Figure 4 shows the natural gradation for the I-3. The North and Central Region DGABC materials show to be similar in their respective natural gradation. The Central and South Region I-3 gradations are very similar; however, the North Region I-3 gradation is very different. This is because this material was a blend of natural aggregate, as well as some recycled materials. If particular, there appeared to be slag particles, as well as shells. The material was also much different is appearance as it was a grayish color, while the other two sources of I-3 were an orange-yellow color.

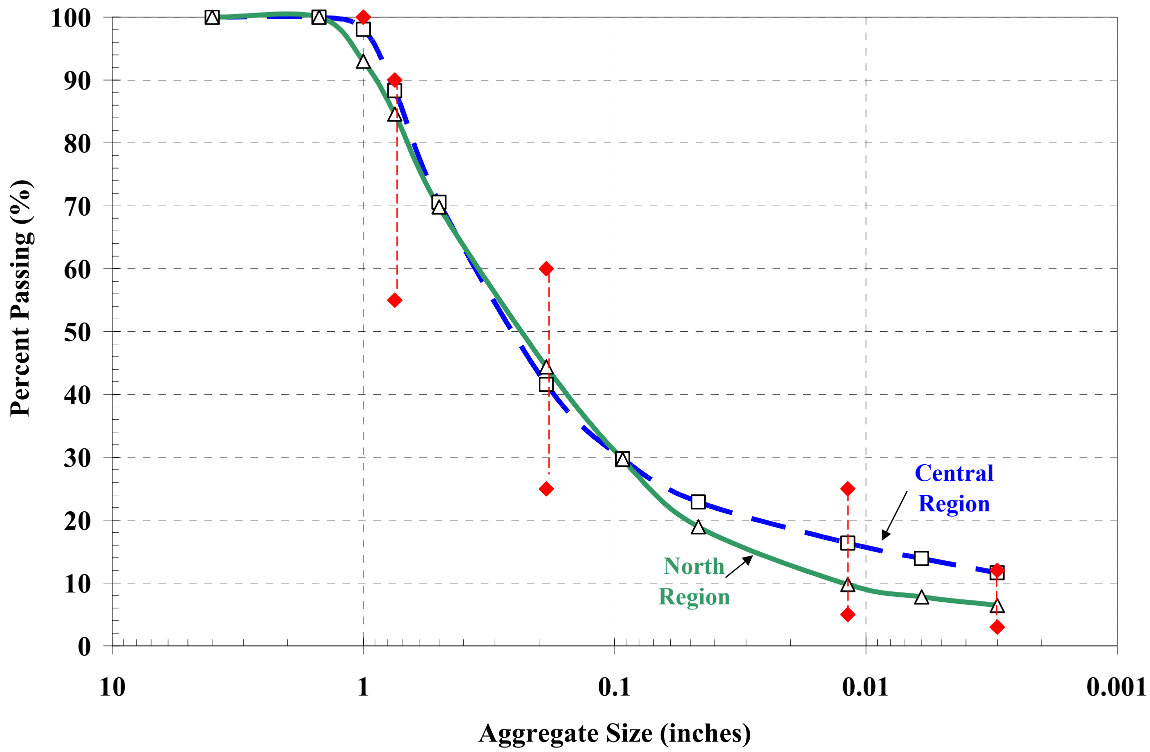


Figure 3 – Natural Gradations for the DGABC Aggregates

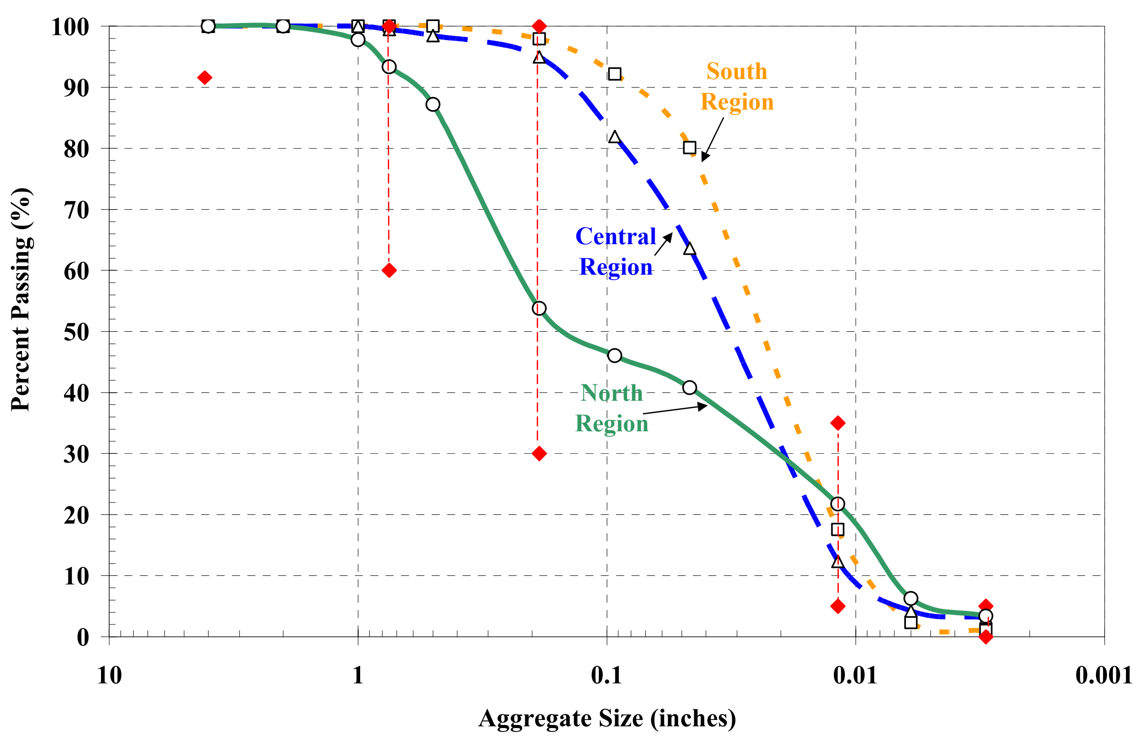


Figure 4 – Natural Gradations for the I-3 Aggregates

After each material source was batched to meet the proper gradation band, a gradation analysis was conducted for each material. Even though the materials were specified to meet the limits and the middle of the gradation bands, fluctuations in-between the specified gradation sizes could occur. Table 2 shows the gradation properties of the DGABC and Table 3 shows the gradation properties of the NJDOT I-3. The tables clearly indicate that even when the limits were targeted, the gradation curves can still be different due to natural gradation of the material between the specified sizes.

Table 2 – Gradation Properties for the DGABC

Region of NJ	Soil Gradation Type	C_C	C_U	D_{85} (mm)	D_{50} (mm)	D_{10} (mm)	Fines (%)
North Region	Natural Gradation	1.77	5.53	31.9	11.7	2.52	0.4
	High End	1.23	17.24	59.2	15.5	1.35	2.2
	Middle Range	4.05	89.47	37.9	6.69	0.118	7.4
	Low End	N.A.	N.A.	14.2	2.93	N.A.	11
Central Region	Natural Gradation	2.23	10.86	20.8	8.05	0.945	1.1
	High End	1.3	17.39	58.7	15.4	1.32	2.1
	Middle Range	4.68	99.06	35.1	6.69	0.104	7.5
	Low End	N.A.	N.A.	14.2	2.98	N.A.	11.7

Table 3 – Gradation Properties for the NJDOT I-3

Region of NJ	Soil Gradation Type	C_C	C_U	D_{85} (mm)	D_{50} (mm)	D_{10} (mm)	Fines (%)
North Region	Natural Gradation	0.18	31.45	11.6	3.96	0.184	3.5
	High End	2.82	47.92	23.1	9.57	0.398	0.1
	Middle Range	0.34	15.59	20.7	1.16	0.188	4
	Low End	0.98	4.65	1.55	0.407	0.117	7
Central Region	Natural Gradation	0.92	4.01	2.7	0.823	0.265	3.4
	High End	3.21	40.18	23	8.93	0.401	0.1
	Middle Range	0.29	16.3	20.8	1.3	0.195	3.9
	Low End	0.76	3.84	1.77	0.439	0.156	6.7
South Region	Natural Gradation	0.95	3.07	1.42	0.6	0.238	0.3
	High End	7.31	17.27	8.35	5.99	0.384	0.1
	Middle Range	0.19	21.01	7.28	2.06	0.192	3.9
	Low End	0.83	3.45	1.38	0.411	0.154	6.7

The gradations were also determined for the Recycled Asphalt Pavement (RAP) and the Recycled Concrete (RCA). The gradation curves are shown in Figures 5 and 6, and the gradation characteristics are shown in Table 4. Figure 5 includes the gradation bands for the NJDOT I-3 aggregate, while Figure 6 includes the gradation bands DGABC. The gradations were not determined for the blended recycled materials since it was assumed that the gradations could be estimated from the percent of each. Both the RAP and RCA met NJDOT I-3 gradation specifications, however, only the RCA met the DGABC gradation specification. The RAP material sampled for this project was too fine to be allowed as a base course material.

Table 4 – Gradation Properties for RAP and RCA

Material Type	Soil Gradation Type	C_C	C_U	D_{85} (mm)	D_{50} (mm)	D_{10} (mm)	Fines (%)
RAP	Natural	1.22	10.85	9.31	4.39	0.516	0.1
RCA	Natural	4.71	52.95	26.4	12.2	0.29	2.8

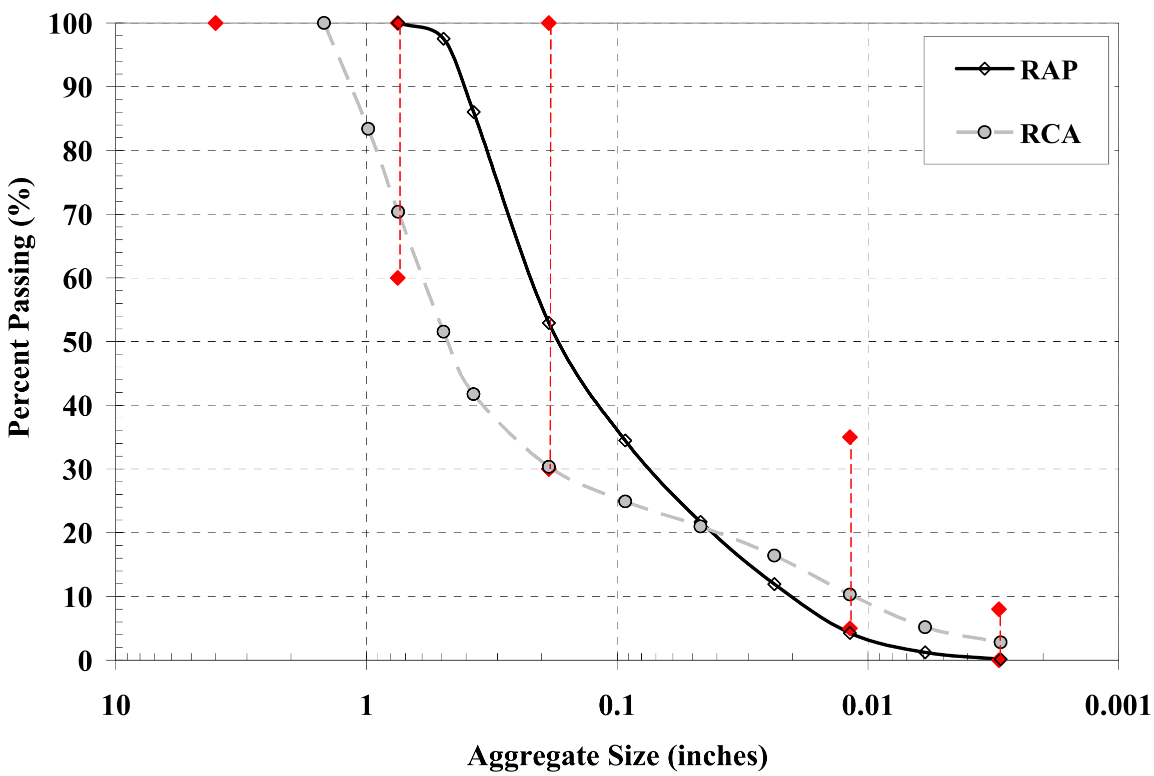


Figure 5 - RAP and RCA Gradations Shown with the NJDOT I-3 Gradation Bands

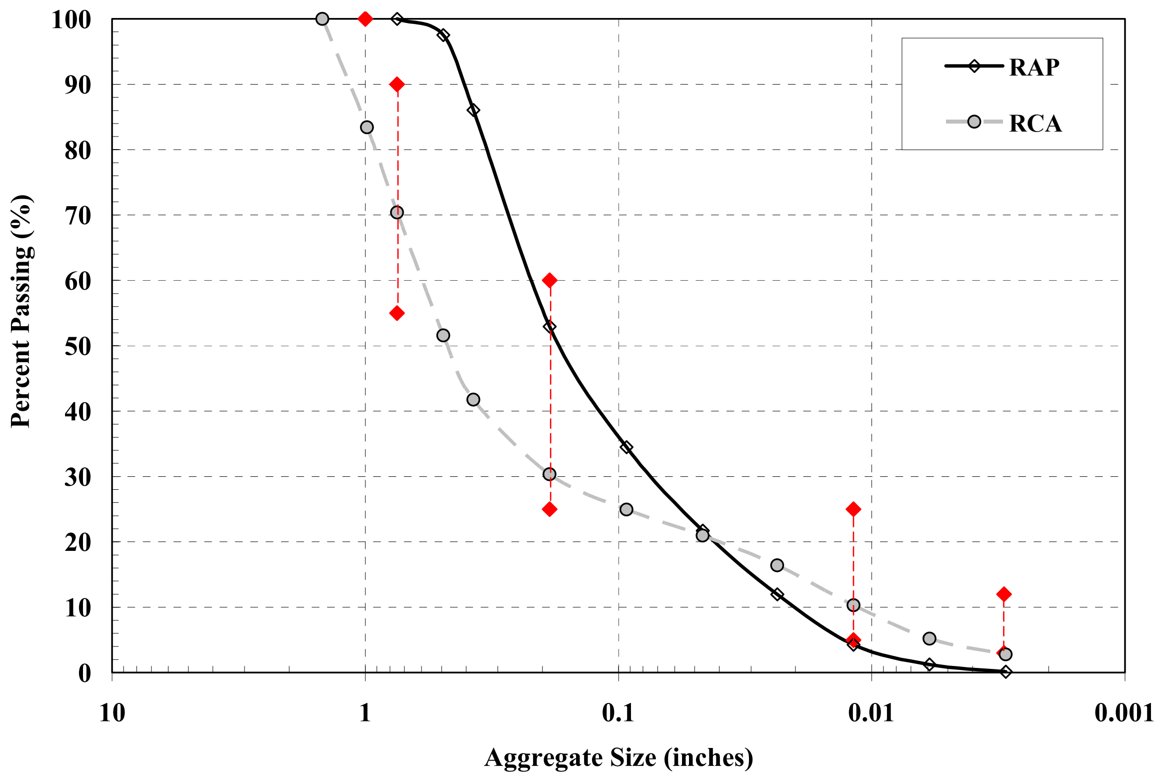


Figure 6 – RAP and RCA Gradations Shown with the DGABC Gradation Bands

Moisture-Density Relationship (ASTM D698 and ASTM D1557)

The moisture-density relationship (compaction test) was determined for all materials tested. The modified energy (56,000 ft-lbf/ft^3) was applied to the materials that would be placed in the base layer, while the standard energy (12,400 ft-lbf/ft^3) was applied to the materials in the subbase. This follows the current practice of the NJDOT.

Table 5 shows the determined maximum dry density and optimum moisture content for both the dense graded aggregate (DGABC) and the NJDOT I-3 subbase aggregate for all regions and gradation.

For the NJDOT I-3 material, a maximum dry density is found at the high end of the gradation band. This is most likely due to the over abundance of coarse aggregate. However, for the DGABC material, the maximum dry density was found for the middle of the gradation band. At the high end, the excessively large amount of coarse aggregate created problems with the overall gradation fitting tightly together. What tends to occur is that the larger sized aggregates seem to “bridge” over one another, actually creating voids within the material. The high end gradation of the DGABC seemed to be very unstable and actually loose when compared to the middle range and low end of the gradation band materials.

Table 5 – Results of Compaction Testing for DGABC and NJDOT I-3 Aggregates

Region of NJ	Soil Gradation Type	NJDOT I-3		DGABC	
		γ_d (pcf)	w (%)	γ_d (pcf)	w (%)
North Region	Natural Gradation	131	4	141	4
	High End	138	3.5	127.3	4.1
	Middle Range	131	4	143.9	6
	Low End	114	6	140.9	7.6
Central Region	Natural Gradation	112.5	4	136.5	6.4
	High End	134	4.75	129.1	4.2
	Middle Range	129	6.5	144.3	7.3
	Low End	115	8	141.1	8.5
South Region	Natural Gradation	106	6	N.A.	N.A.
	High End	120.5	3		
	Middle Range	120.5	6		
	Low End	110	10		

The maximum dry densities and optimum moisture contents were used as the compacted densities of the performance testing.

Permeability

The permeability of the materials was evaluated using both falling head and constant head conditions. Originally, only constant head conditions were to be used. The constant head test has a better control over the testing by limiting the applied hydraulic head to the sample. This ensures that Darcy's Law is satisfied as the test is being conducted. However, as the testing progressed, it was discovered that an extreme range of potential permeability conditions could be encountered when evaluating the extreme ends of the NJDOT gradation range. Therefore, it was hypothesized that perhaps the NJDOT may want to utilize a field permeability unit to provide QA/QC during construction. Unfortunately, a large water supply would need to be provided to conduct constant head testing. However, the falling head test does not require a large tank to attain constant head condition, only enough water to fill the reservoir. The only potential drawback of using the falling head method is that there are no requirements for the hydraulic head conditions. This could provide inaccurate permeability values when "quick" permeability values are expected (i.e. gap-graded to coarse graded). Therefore, testing was conducted using both devices, falling head and constant head, to provide a recommendation as to the validity of using the falling head test for highly permeable aggregates.

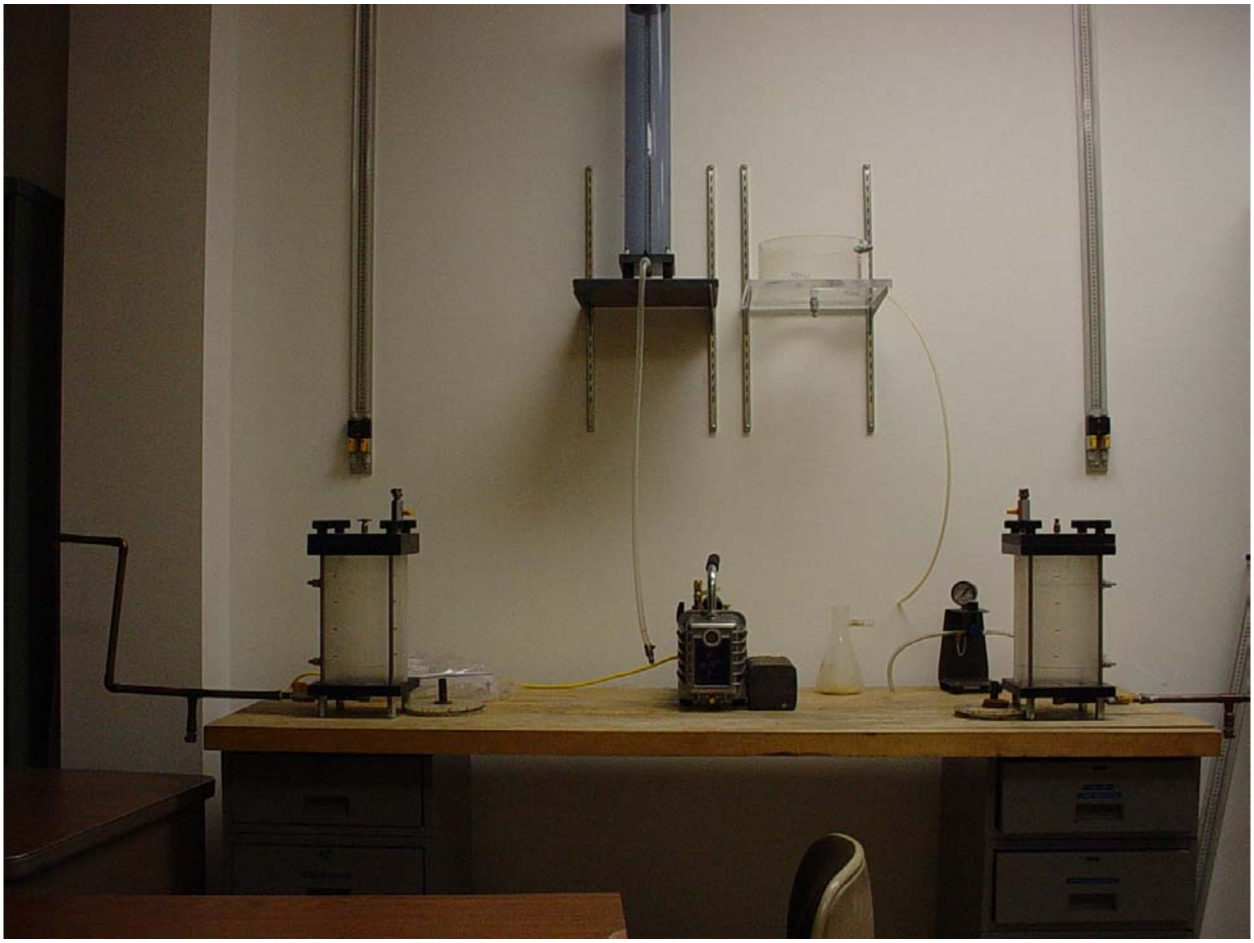


Figure 7 – Permeability Apparatus for Falling and Constant Head Tests

Each material tested was compacted to its maximum dry density and optimum moisture content. The materials were compacted in the mold/cylinders where the materials were tested for permeability. A picture of the test set-up is shown as Figure 7. The falling head unit is on the left, while the constant head set-up is on the right.

Permeability Results – NJDOT I-3 and DGABC

The results of the permeability testing are shown in Table 6. For the I-3 and DGABC materials, as expected, as the gradation changed from the coarser end of the gradation band to the finer end, the permeability decreased. The testing of the NJDOT I-3 subbase aggregate resulted in almost two orders of magnitude change in permeability when compared with the constant head results. The testing of the DGABC base aggregate resulted in an almost three orders of magnitude change in permeability when comparing the constant head results.

Table 6 – Permeability for NJDOT I-3 and DGABC Materials

Region of NJ	Soil Gradation Type	NJDOT I-3		DGABC	
		Constant Head (ft/day)	Falling Head (ft/day)	Constant Head (ft/day)	Falling Head (ft/day)
North Region	Natural Gradation	28.7	25.3	122.9	124.75
	High End	377.5	323.4	2195.9	377
	Middle Range	56.4	48.8	133.1	83.9
	Low End	7.6	5.5	0.86	1.61
Central Region	Natural Gradation	55.8	43.2	172.7	121.05
	High End	143.7	85.4	3264.6	169.625
	Middle Range	18.0	14.9	163.6	43.4
	Low End	6.1	5.9	1.64	2.7
South Region	Natural Gradation	55.7	50.8	N.A.	N.A.
	High End	251.0	107.4		
	Middle Range	10.9	11.7		
	Low End	7.5	6.9		

Another interesting aspect of the testing was that the DGABC (base aggregate) had a higher permeability than the subbase NJDOT I-3. For years, the NJDOT had been designing pavements assuming that the subbase aggregate had a higher permeability than the base course. As shown in Table 6, the average permeability of the NJDOT I-3 aggregate was 46.7 ft/day, while the average permeability of the DGABC was 147.8 ft/day. This was using the values from the constant head test. Comparing the results from the falling head test, the averages are 39.8 ft/day for the NJDOT I-3 and 122.9 ft/day for the DGABC. The base course material is almost three times as permeable as the subbase aggregate.

Figure 8 shows the permeability range with respect to the gradation bands for the NJDOT I-3 material. The high end (coarse side of the gradation band) had permeabilities ranging from 145 to 380 ft/day. The range of values indicates that the permeability is being affected by the particle size of the material with the different specified gradation points. The middle of the gradation band achieved permeabilities of 11 to 56 ft/day, while the low end of the gradation band (fine side of the gradation band) had permeabilities of 6 to 8 ft/day. For the natural gradations tested, both of the central and south region achieved an almost identical permeability, 55.8 and 55.7 ft/day for the central and south region, respectively. This is most likely due to the two regions has a very similar gap-graded gradation. The north region achieved a permeability of 28.7 ft/day.

Figure 9 is for the DGABC material. The high end had permeabilities that ranged from 2200 to 3200 ft/day. The actual testing of these materials was extremely difficult due to the problems with compaction, as well as the fast flow of water moving through the material. The middle range of the gradation bands achieved a permeability of 130 to 170 ft/day, while the low end achieved permeabilities ranging from 0.5 to 2 ft/day. The natural gradations showed to have permeabilities of 123 ft/day for the north region and 170 ft/day for the central region.

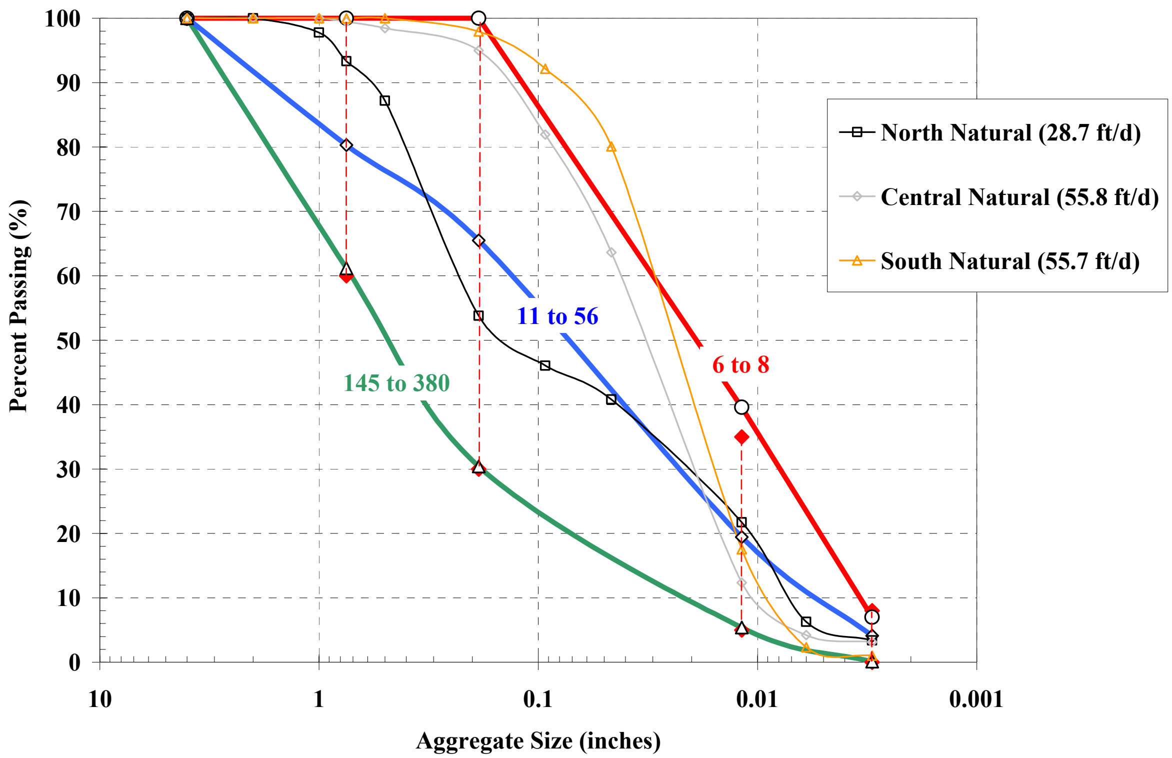


Figure 8 – Permeability of NJDOT I-3 With Respect to the Gradations

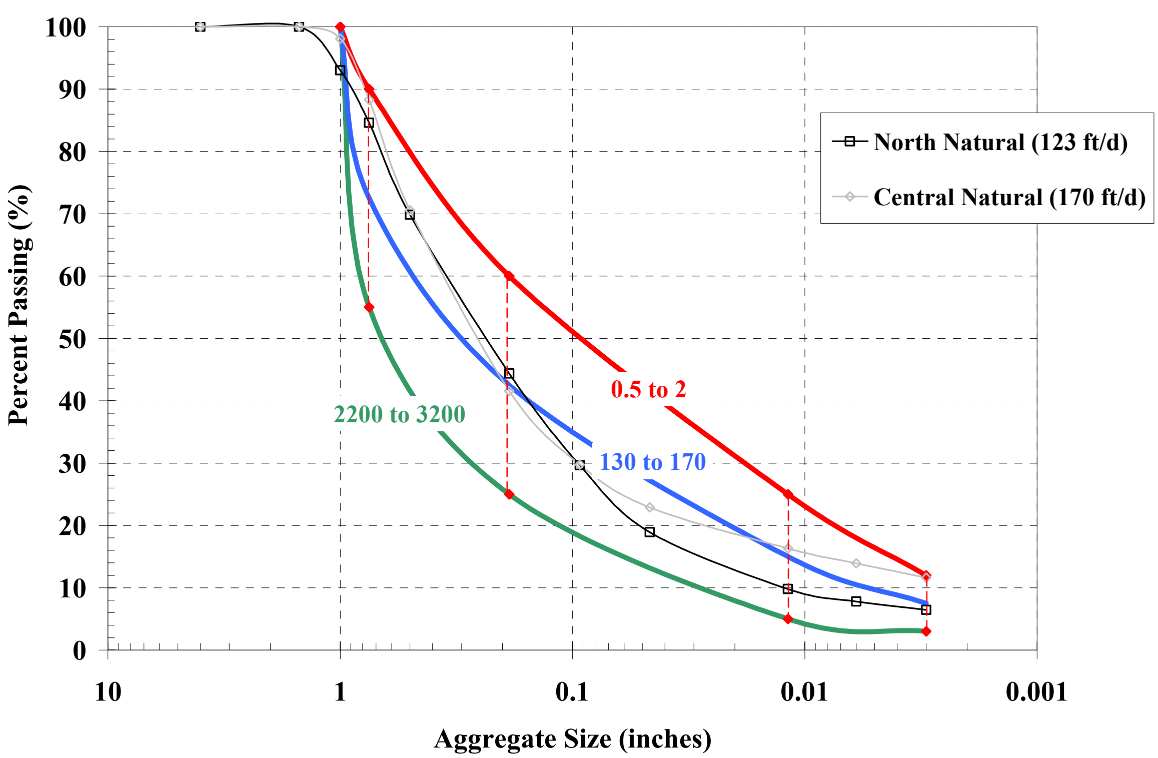


Figure 9 – Permeability of DGABC With Respect to Gradations

Permeability Results – Recycled Materials and Blends

The recycled materials and their respective blends were also tested using both the falling head and the constant head permeability test apparatus. For the blends, only the central region was used for the NJDOT I-3 and DGABC materials. The results of the testing are shown in Table 7. The results indicate the following:

- 100% RAP had a permeability of 16.9 ft/day and the 100% RCA had a permeability of almost 0.0 ft/day. These results were from the constant head test. The RCA did not measure a permeability value from the constant head test because the sample was not able to obtain the required hydraulic head. However, when comparing the falling head test results, the 100% RAP had a permeability of 13.9 ft/day, while the 100% RCA had a permeability of 0.3 ft/day.
- As the percent of RCA blended with DGABC increased, the measured permeability decreased dramatically. 25% RCA and 75% DGABC achieved a permeability of 967.5 ft/day, while 75% RCA and 25% DGABC achieved a permeability of 65.3 ft/day.
- As the percent of RAP blended with DGABC increases, the permeabilities decreased. 75% RAP and 25% DGABC obtained a permeability of 1.7 ft/day, while 25% RAP and 75% DGABC had a permeability of 121.4 ft/day.
- For the subbase, when RAP is blended with I-3, it general has an overall "numbing" effect on the permeability. The blended material all had permeability values that where between 2.2 and 8.3 ft/day for the three blends tested.
- The testing of the recycled material blends, RCA and RAP, provided small permeabilities ranging from 0.7 to 5.4 ft/day.
- **Overall, by adding recycled materials to the natural graded NJDOT I-3 and DGABC, the permeability values decrease.**

Falling Head versus Constant Head Test Results

As stated earlier, the constant head test set-up was originally supposed to be used as the benchmark test. However, if the NJDOT was to utilize a permeability test for QA/QC in the field, a more mobile system was to be needed. The falling head test provides this mobile flexibility. Unfortunately, it was unknown as to how the permeability values would vary between the different test conditions of the falling and constant head tests. Figure 10 shows the comparisons between the two tests. The figure indicates that there exists a very good comparison between the falling head and constant head test results when the permeability measured by the constant head test is less than approximately 100 ft/day. If the constant head measured permeability is greater than 100 ft/day, a large scatter develops. This is most likely due to the falling head not being able to sustain a hydraulic gradient in a range to provide laminar flow through the material. If laminar flow is not present then Darcy's Law does not hold for the calculation of permeability. This would not be a problem for the NJDOT I-3 subbase aggregates, however, this could lead to errors when testing the DGABC materials.

Table 7 – Permeability for Recycled Materials and Their Respective Blends

Region of NJ	Soil Gradation Type	Permeability Test Type	
		Constant Head (ft/day)	Falling Head (ft/day)
DGABC + RAP	100% RAP	16.9	13.9
	75% RAP	1.7	2.1
	50% RAP	113.7	39.0
	25% RAP	121.4	27.8
DGABC + RCA	100% RCA	0.0	0.3
	75% RCA	65.3	65.5
	50% RCA	66.0	65.4
	25% RCA	76.5	79.6
NJDOT I-3 + RAP	100% RAP	16.9	13.9
	75% RAP	3.0	3.3
	50% RAP	8.3	7.7
	25% RAP	2.2	2.4
RAP + RCA	100% RCA	0.0	0.3
	75% RCA	1.0	1.2
	50% RCA	5.4	4.0
	25% RCA	0.7	0.8
	0% RCA (100% RAP)	16.9	13.9

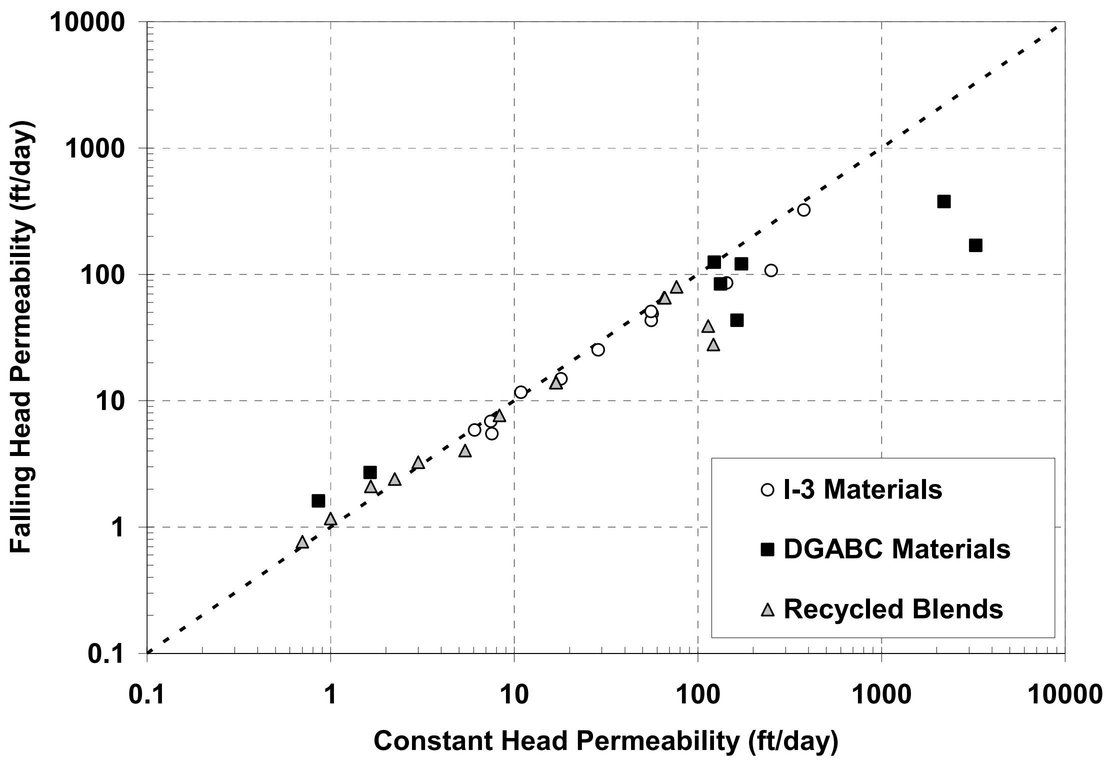


Figure 10 – Comparison of Falling Head and Constant Head Permeability Tests

Permeability Prediction

The use of predictive equations to determine the permeability of the aggregates would be extremely useful for any state agency. Although, for this to be implemented, the prediction equation should be based on simple physical parameters, such as gradation. An attempt was made to develop a regression equation that could be used to predict the permeability of base and subbase aggregates. The prediction was based on the permeability results obtained from the constant head permeability tests. Table 8 shows the Pierson's Correlation Coefficients for the different physical properties of the DGABC and NJDOT I-3. The Pierson's Correlation Coefficient (r) ranges from -1.0 to 0.0 to 1.0. Values of either -1.0 or 1.0 indicate an exact correlation, while a value of 0.0 indicates no correlation exists. The sign (+ or -) in front of the value indicates how the material is correlated. For example, the % fines of the NJDOT I-3 and DGABC shows a correlation coefficient of -0.73 and -0.47, respectively. This means that the permeability and % fines work in the opposite manner (i.e. as the permeability decreases, the % fines increases). A "grouped" analysis was also conducted. If a universal prediction, both DGABC and NJDOT I-3, is to be developed, the grouped correlation would represent which parameters both of the materials have in common.

Table 8 – Pierson's Correlation Coefficient for Gradation Properties vs Permeability

Parameter Evaluated	Correlation Coefficient		
	NJDOT I-3	DGABC	Grouped
Dry Density (γ_d)	0.51	-0.89	0.044
Void Ratio (e)	-0.53	0.85	0.08
C_C	0.73	-0.65	-0.036
C_U	0.67	-0.4	-0.047
D_{85}	0.5	0.86	0.78
D_{50}	0.85	0.83	0.75
D_{10}	0.87	0.22	0.48
% Fines	-0.73	-0.47	-0.25

As can be seen from the table, there are a number of parameters that do not correlate equally. For example, the compacted dry density is negatively related to the permeability of the DGABC; meaning that as the compacted density increases, the permeability decreases. This is rational in that if it was compacted tighter, there would be less flow paths for the water to flow through. However, the opposite occurs with the NJDOT I-3 material. These differences are most likely due to the differences in particle size, shape, and angularity. This difference between the correlations can be further seen by the grouped correlations. When there are to extremes in correlations, such as the dry density, it results in a value that is almost zero for the grouped. Therefore, based on the correlations in Table 8, it does not seem possible to develop an accurate predictive equation that would be universal in nature for base and subbase aggregates.

Even two separate equations for the NJDOT I-3 and DGABC may not be prudent at this time with the small sample population for each prediction.

Loss of Fines Due to Water Flow

With the acceptance of Superpave Mix Design for hot mix asphalt materials, many state agencies have found that the recommended coarse aggregate structure results in an asphalt layer that can be quite permeable. A permeable asphalt layer would allow water flow into the base layer below it.

It has always been hypothesized that base and subbase aggregates having large % fines content (> 6%) may actually have these fines washed out of the pore structure. In fact, fines "pumping" from the base layer underlying PCC pavements are a major pavement distress condition. This eventually leads to a loss of support for the larger aggregates and then for the pavement structure.

Testing was conducted to evaluate if this actually could occur under laboratory conditions. Great care was taken to measure the gradation of the material before and after permeability testing. An aggregate splitter was used to make sure that each compacted layer contained a similar gradation. After the permeability testing was complete, all of the material was taken out of the permeability test set-up. The smaller grained material was even washed out of the mold into a pan. The extracted material was placed in an oven to dry and then a gradation analysis was conducted. This was conducted for two layers; the top and the bottom. For the eight inch tall sample, this constituted the upper and lower four inches of the sample.

The North Region's DAGBC material was evaluated under these conditions. As shown earlier in the gradation specifications, the material is allowed to have as high as 12% fines and still conform to NJDOT gradation specifications. Results of the gradation evaluation after the permeability testing are shown in Figures 11 to 14. For the analysis of the high, middle, and low range gradations, the before gradations meet the respective gradation points.

The figures clearly show a migration of finer material from the top of the sample towards the bottom. While some deviation from the target is expected, there is a noticeable difference when evaluating the No. 100 and No. 200 sieve sizes. The figures also show the overall loss of fines from the sample being tested. The gradation confirms the visual observation of fines being flushed out of the sample during the testing.

Table 9 provides the initial % fines versus the measured % fines. The table also indicates that there exists a migration of fines downward with the flow of water. The average loss of the % fines was calculated for each gradation type of the North Region's DGABC. The loss ranged from 2.8 to 4.6 % of the fines washed out, with an average of 3.8%. If the laboratory test is assumed to model the field condition, 3.8% of the fines can be expected to be washed out or move from their original compacted position. The impact that this may have on the stability of the compacted aggregate structure was not investigated, however, it can be assumed that any volume loss would be detrimental to the overall stability of the aggregate layer.

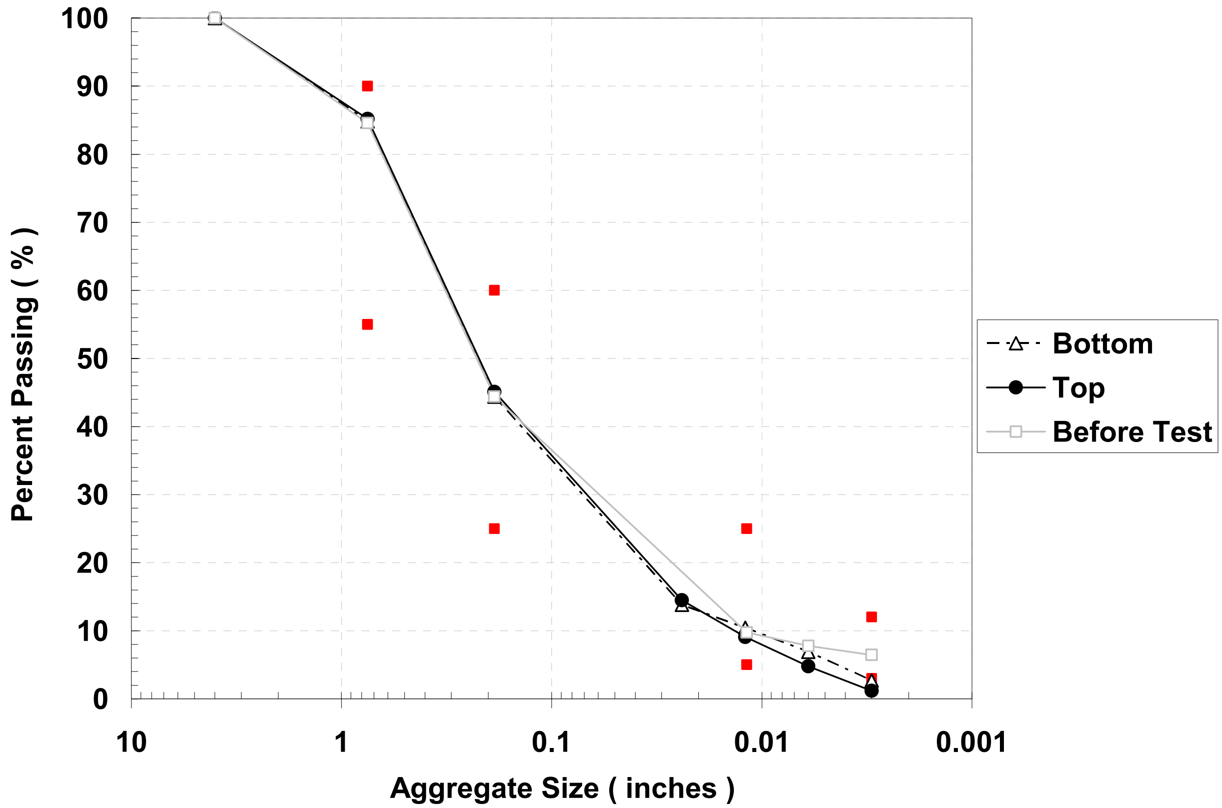


Figure 11 – Natural Gradation of North Region DGABC after Permeability Testing

Table 9 – Fines Movement from Permeability Testing

Gradation Type	% Fines				Average Loss of % Fines
	Initial (Target)	Measured Top	Measured Bottom	Measured Average	
High End (Coarse)	3	0.2	0.3	0.2	2.8
Middle Range	7.5	2.8	3.4	3.1	4.4
Low End (Fine)	12	7.0	10.5	8.7	3.3
Natural Gradation	6.5	1.2	2.7	2.0	4.6

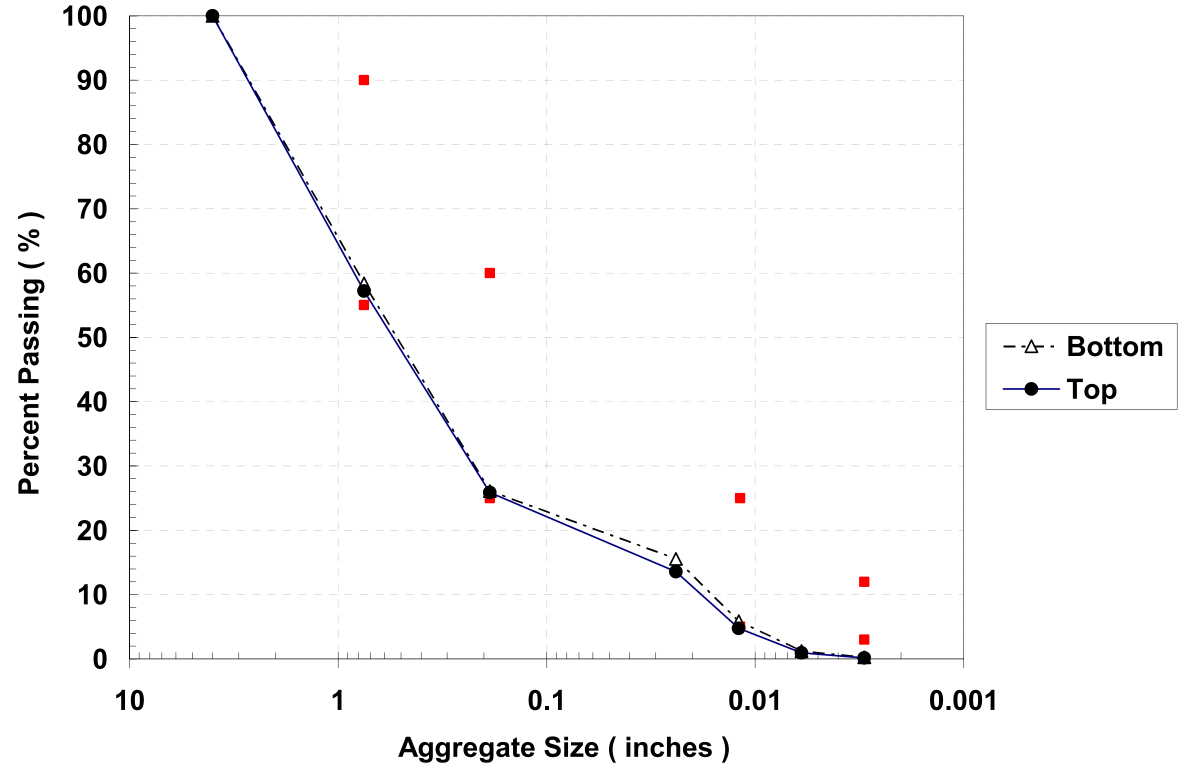


Figure 12 – High End Gradation of North Region DGABC after Permeability Testing

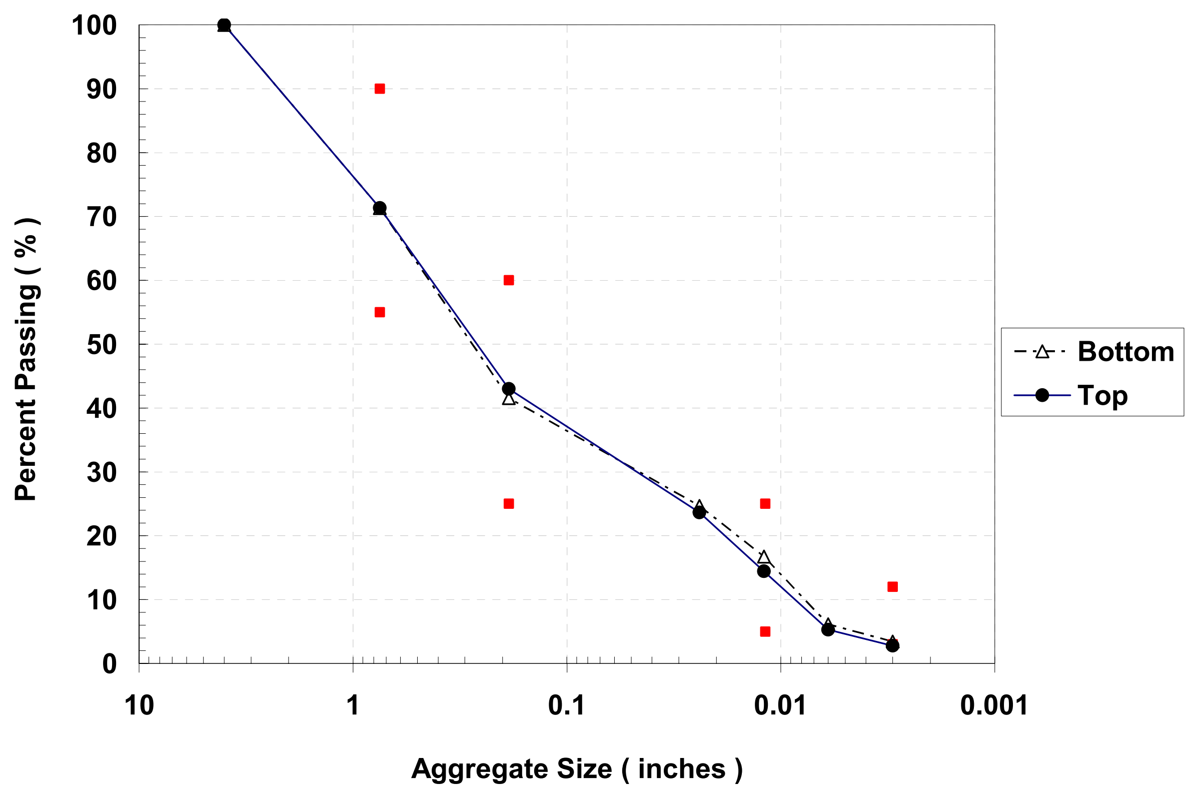


Figure 13 – Mid. Range Gradation of North Region DGABC after Permeability Testing

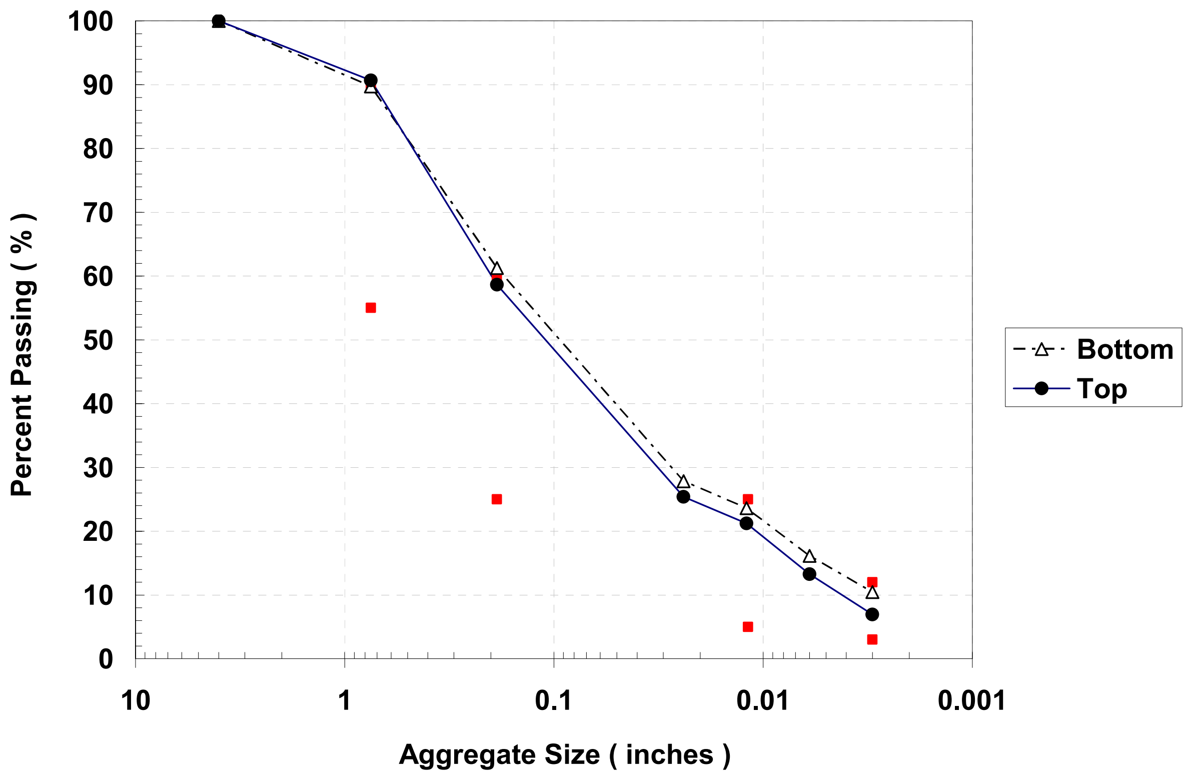


Figure 14 – Low End Gradation of North Region DGABC after Permeability Testing

Summary of Permeability Testing

A total of 37 different materials (gradations and blended materials) were tested under both falling head and constant head permeability conditions. Based on the testing, the following conclusions were drawn.

- The permeability measured by the falling head apparatus and the constant head apparatus had very comparable permeability measurements when the measured permeability was under 100 ft/day. When the permeability, as determined by the constant head test, was greater than 100 ft/day, the falling head measurements under-determined the permeability. This is due to the testing constraints of the falling head apparatus. The permeability can be determined from the falling head test as long as the water flow is laminar. If the permeability is too fast, the water flow becomes turbulent and Darcy's Law is no longer valid. The constant head test ensures laminar flow by specifying an allowable range for the hydraulic gradient. This ensures Darcy's Law is met.
- Varying the gradation of the DGABC to achieve the extreme ends of the NJDOT allowable gradation band produced three orders of magnitude (approximately 1 ft/day for the Low End and approximately 2500 ft/day for the High End). The natural gradation of the DGABC produced an average permeability of 150 ft/day. The Low End permeability for the DGABC was approximately 1.0 ft/day, most

likely due to the high fines content (12%) combined with the finer aggregate gradation.

- The potential gradation range also had a large effect on the permeability characteristics of the NJDOT I-3 aggregate. The extreme ends of the allowable gradation band produced a difference of almost 2 orders of magnitude. The High End of the gradation band had an average permeability of approximately 250 ft/day, while the Low End had an average permeability of approximately 7 ft/day. The natural gradations produced average permeabilities of approximately 50 ft/day.
- The addition of recycled material (RAP and RCA) to the natural aggregates tended to clog up the aggregate structure and decrease the permeability. A 25:75 ratio of RCA to DGABC produces a permeability of 76.5 ft/day, a drop from 172.7 ft/day for the 100% DGABC. The same occurs for the addition of RAP. A 25:75 ratio of RAP to DGABC produces a permeability of 121.4 ft/day. The recycled materials by themselves also had low permeability values. The 100% RAP had a permeability of 16.9 ft/day, while the RCA sample was so “tight”, that the permeability was only able to be determined from the falling head test at 0.3 ft/day.
- For all DGABC samples tested, there was a loss of fines during the testing. The loss was more pronounced in the Middle Range and Natural gradations. The testing also showed that there is vertical movement to the fines as the % fines at the upper half of the sample were always less than the lower half of the sample. Therefore, if the laboratory testing procedure simulates the field performance, it can be expected that the fines in the upper portion of the base layer will migrate with the flow of water. In the case of the laboratory test, it migration path as vertically down. However, since there are no horizontal boundaries in the field, the migration of the fines will simply follow the water flow.

California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) is a parameter that has been used for years by highway engineers for designing pavements. However, it has not been until recently that the pavement design community has recognized that the CBR value should only be used for guidance of material selection, as the parameter has no true mechanistic property.

The CBR testing conducted in this study was conducted following AASHTO specifications. If necessary, the CBR curves were corrected for concavity, which is a function of the loading piston not having full contact to the surface of the aggregate sample. The procedures for correcting the CBR curve for concavity followed those described in AASHTO T193. Two samples of for each material was tested unless the two results varied greatly, then a third test was conducted. Each sample was compacted to its respective maximum dry density and optimum moisture content. For analysis, the CBR value corresponding to 0.1 and 0.2 inches of penetration was used. The load curves for the CBR tests are shown in Appendix A.

The CBR testing was not part of the original testing plan, therefore, only the Central Region's DGABC and I-3 was tested at the different gradation bands. The main purpose of the CBR testing was for the evaluation of the recycled materials and their respective blends.

The testing equipment used to conduct the CBR testing is shown in Figure 15. The loading system is a MTS "soil machine", which consists of an eight foot loading frame and servo controlled hydraulic actuator. The loading frame has a movable crosshead to allow for easy placement and removal of a test specimen. A 22 kip servo controlled actuator is mounted on the movable crosshead with a range of approximately 4 ft. The 22 kip load cell was used while running the CBR test, to allow for the measurement of loads up to 10,000 lbs.

Figure 15 – Testing Set-up Used for the CBR Testing

CBR Results – RAP and RAP Blends

Recycled Asphalt Pavement (RAP) was tested at blend percentages of 0, 25, 50, 75, and 100% RAP with the NJDOT DGABC and also the Recycled Concrete Aggregate (RCA). Figures 16 and 17, as well as Table 10 show the results for the RAP blends. In general, as the percentage of RAP increases, the CBR values decreases.

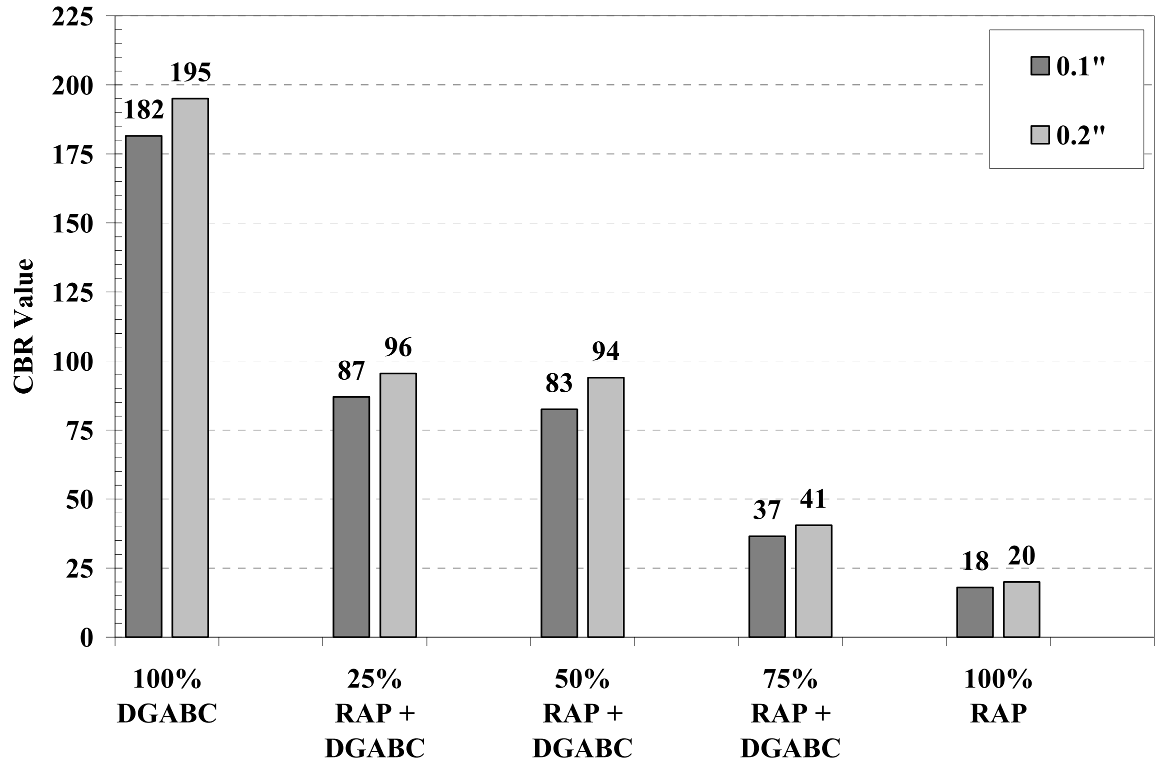


Figure 16 – CBR Values for RAP Blended with DGABC from Central Region

Table 10 – CBR Values for Tested RAP Blends

Material Type	CBR Value	
	0.1" Penetration	**0.2" Penetration**
100% RAP	18	20
75% RAP:25% DGABC	37	41
50% RAP:50% DGABC	83	94
25% RAP:75% DGABC	87	96
100% DGABC	182	195
100% RAP	18	20
75% RAP:25% RCA	29	37
50% RAP:50% RCA	68	87
25% RAP:75% RCA	106	137
100% RCA	169	205

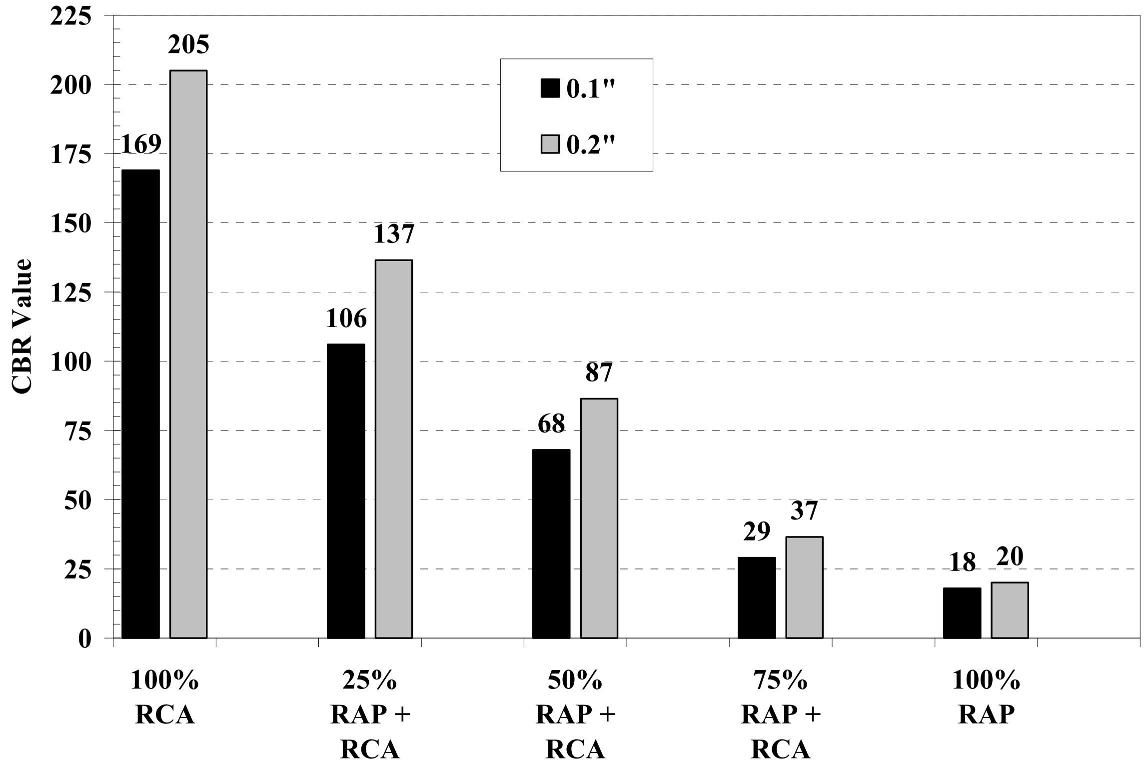


Figure 17 – CBR Values for RAP Blended with RCA

CBR Results – RCA and RCA Blends

Recycled Concrete Aggregate (RCA) was tested at blend percentages of 0, 25, 50, 75, and 100% with NJDOT DGABC, NJDOT I-3, and RAP. The RAP blended results were discussed earlier and where shown in Figure 16. The test results for the remaining RCA blends are shown in Figures 18 and 19, as well as in Table 11.

The addition of RCA increases the CBR values for both the NJDOT I-3, as well as when blended with RAP. Unfortunately, the addition of RCA to the NJDOT DGABC from the Central Region, which has almost identical properties and gradation to the North Region, lowered the CBR values at each blended percentage. The 100% NJDOT DGABC and the 100% RCA had very similar CBR values. However, the differences in gradation and particle shape most likely caused the CBR value to decrease slightly. Figure 18 shows that the lowest CBR value obtained was when the percentage of RCA was 25% and the NJDOT was at 75%. The values steadily increase as the percentage of RCA increases.

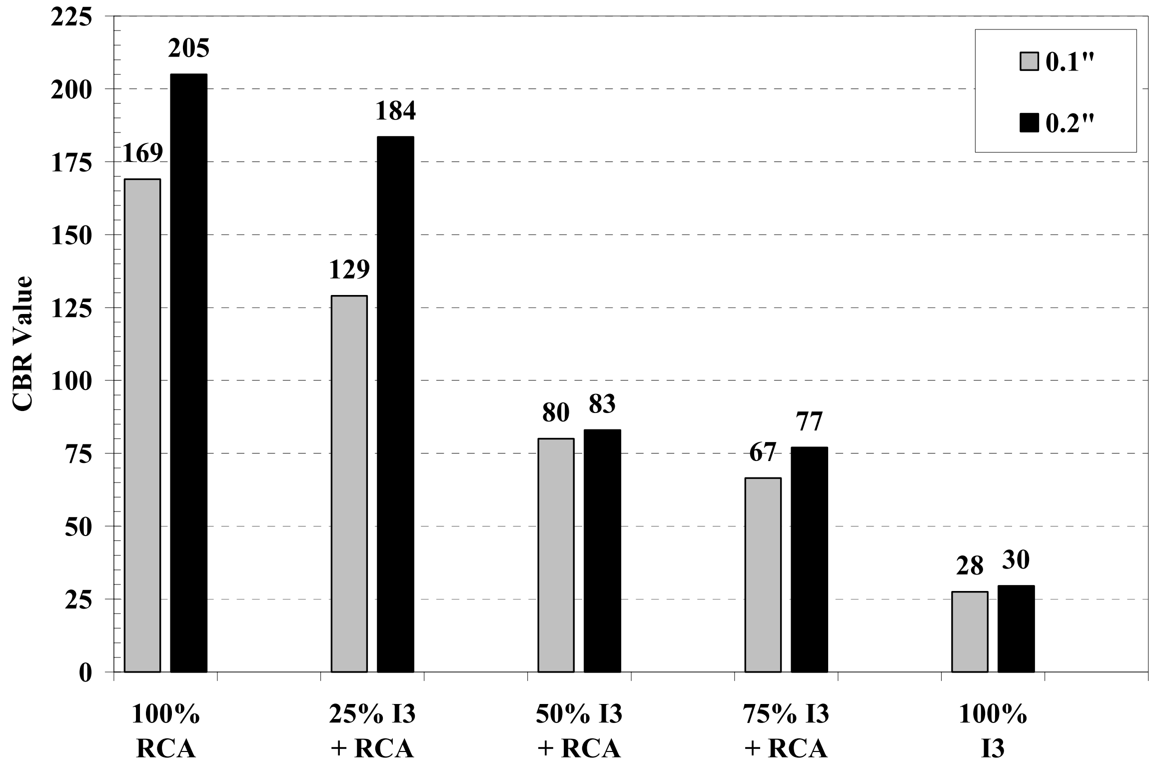


Figure 18 – CBR Values for RCA Blended with NJDOT I-3 from Central Region

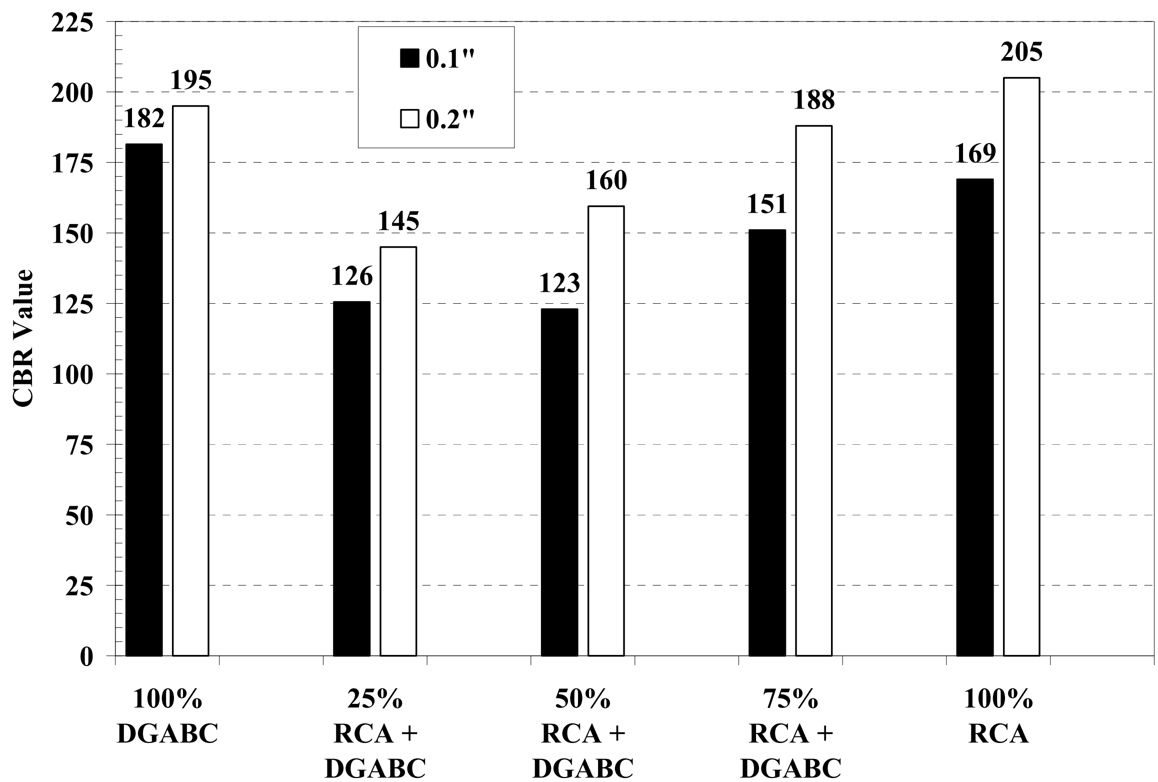


Figure 19 – CBR Values for RCA Blended with DGABC from Central Region

Table 11 – CBR Values for Tested RCA Blends

Material Type	CBR Value	
	0.1" Penetration	0.2" Penetration
100% RCA	169	205
75% RCA:25% DGABC	151	188
50% RCA:50% DGABC	123	160
25% RCA:75% DGABC	126	145
100% DGABC	182	195
100% RCA	169	205
75% RCA:25% I-3	129	184
50% RCA:50% I-3	80	83
25% RCA:75% I-3	67	77
100% I-3	28	30

CBR Results – Effect of Aggregate Gradation for NJDOT DGABC and I-3

The effect of the gradation bands was evaluated using both the NJDOT DGABC and I-3 from the Central Region under the CBR test conditions. Figure 20 shows the effect of the gradation on the CBR values for the DGABC material. As indicated in the figure, the gradation has a great effect on the CBR value. As the gradation moves from the fine side (Low End) to the coarse side (High End), the CBR increases, obviously affected by the aggregate size. The natural gradation obtained the highest CBR value, most likely benefiting from being compacted at a higher dry density.

The same testing was conducted on the Central Region's I-3 subbase aggregate (Figure 21). A similar trend can be noticed with the I-3 aggregate; however, the High End did not achieve a much greater CBR value than the Middle Range or Natural Gradation. This is most likely due to the rounded aggregates not being able to "inter-lock" as the DGABC angular aggregates are able to do. Table 12 provides the values for the effect of gradation for both the DGABC and I-3.

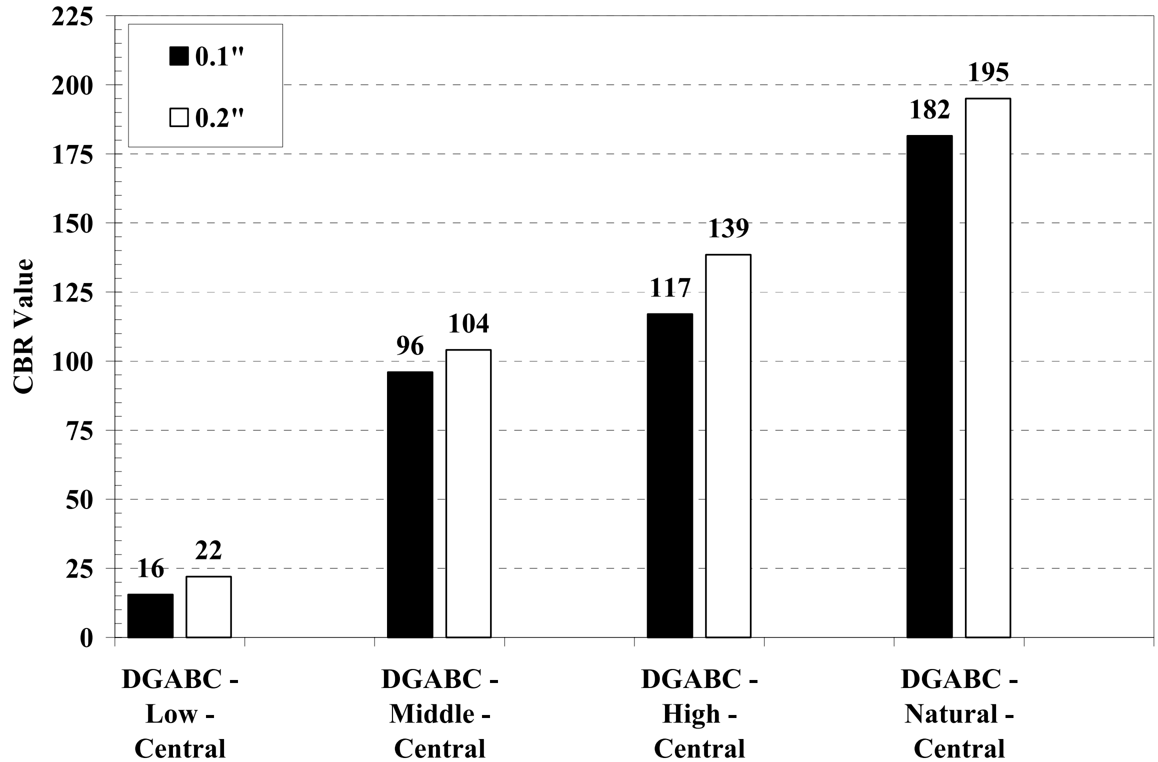


Figure 20 – Effect of Gradation on the CBR Values of DGABC from Central Region

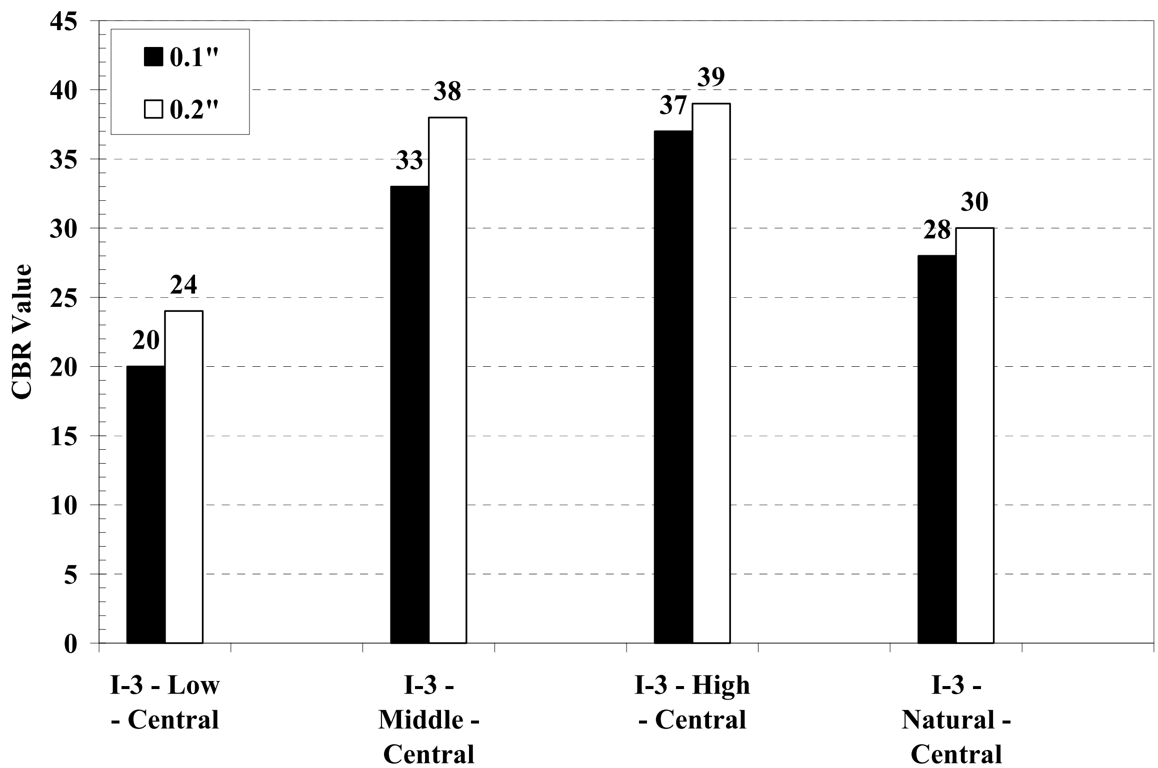


Figure 21 – Effect of Gradation on the CBR Values of NJDOT I-3 from Central Region

Table 12 – CBR Values for Tested Gradations of DGABC and NJDOT I-3

Material Type	CBR Value	
	0.1" Penetration	0.2" Penetration
DGABC - High End	117	139
DGABC - Middle Range	36	44
DGABC - Low End	16	22
DGABC - Natural	182	195
I-3 - High End	37	39
I-3 - Middle Range	33	38
I-3 - Low End	20	24
I-3 - Natural	28	30

Summary of CBR Testing

CBR testing was conducted for the RAP and RCA blends, as well as for the DGABC and NJDOT I-3 aggregates from the Central Region. Based on the testing, the following conclusions were drawn.

- The effect of gradation had a greater impact on the CBR value of the DGABC than the NJDOT I-3. The DGABC Low End gradation only obtained CBR values of 16 and 22 for the 0.1 and 0.2 inch penetration, respectively. Meanwhile, when the gradation becomes coarser to middle of the gradation range, the CBR values increase by approximately 80. The CBR values increased even more at the High End gradation and for the natural gradation. This is most likely due to the allowable percent fines (12%) for the Low End gradation.
- The CBR values were also affected by the type of recycled material blended. **In the case of RAP, as the percent of RAP increased, the CBR values decreased.** The addition of RCA to the natural aggregates had mixed results. As the percent RCA increased in the NJDOT I-3, the CBR values increased. However, the addition of 25% RCA to the DGABC caused an immediate drop in CBR values. Each addition of RCA gradually increased the CBR values, although never reaching the initial CBR value of the DGABC.

Triaxial Shear Strength

The shear strength of the aggregate materials was evaluated using the triaxial test under static loading conditions. It is important for an aggregate to obtain high shear strength to support the pavement and vehicle loading with no to minimal deformation. Therefore, it can be concluded that materials that provide higher shear strength values would also be better foundation aggregates for the pavement structure.

Triaxial tests were conducted using confining pressures of 5, 10, and 15 psi. The maximum deviatoric stress from each confining pressure was used to construct the Mohr Circle diagram for the determination of the friction angle (ϕ) and cohesion (C) (Figure 22). The equation used to determine the final shear strength of the material is in the form of equation 1.

$$\tau = C + \sigma_n \tan(\phi) \qquad (1)$$

where,

τ = shear strength
C = cohesion
σ_n = normal stress
ϕ = friction angle (degrees)

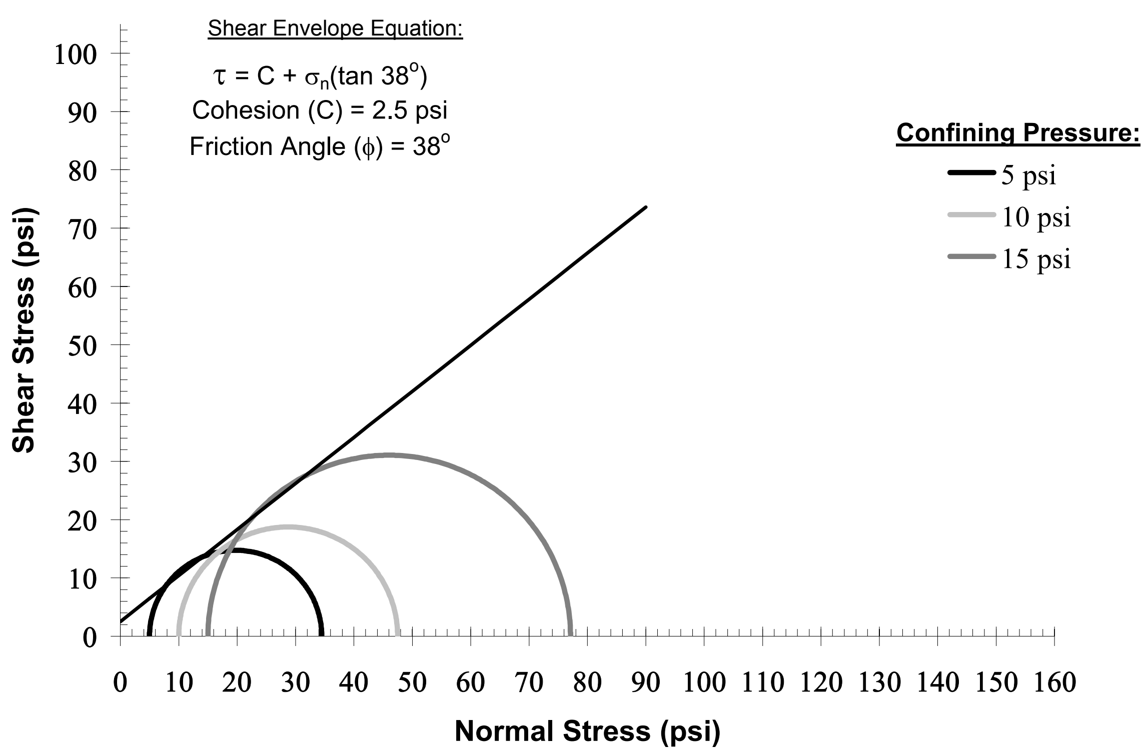


Figure 22 – Mohr's Circle Diagram to Determine Friction Angle (ϕ) and Cohesion (C)

The testing system used to conduct the triaxial test was the same MTS system used for the CBR testing. However, the test set-up was modified to accommodate a triaxial test cell. The triaxial test set-up used to determine the shear strength, as well as the conduct both the resilient modulus and the cyclic triaxial tests (permanent deformation), is shown as Figure 23.

Figure 23 – Test Set-up Used for Triaxial (Static and Cyclic) and Resilient Modulus Testing

The triaxial testing was conducted for the DGABC and the NJDOT I-3 aggregates at the different gradation conditions, as well as for the natural gradation. The RAP and RCA was also tested, although only at 100% blends. Triaxial testing was not conducted on the RAP and RCA blends as was done earlier for the CBR testing.

Triaxial Test Results – Effect of Gradation on NJDOT I-3 and DGABC

Triaxial tests were conducted on the NJDOT I-3 and DGABC for High End, Middle, and Low End of their respective gradation specifications, as well as for the natural gradation conditions. The results for the NJDOT I-3 are shown in Table 13. The table contains the friction angle and cohesion results from the Mohr's Circle analysis.

Table 13 – Triaxial Test Results and Shear Strength Properties of NJDOT I-3

Region of NJ	Soil Gradation Type	NJDOT I-3	
		Friction Angle (degrees)	Cohesion (psi)
North Region	Natural Gradation	49.2	3.9
	High End	46.7	2.4
	Middle Range	40.8	2.9
	Low End	41.9	3.8
Central Region	Natural Gradation	41.0	1.1
	High End	42.6	2.9
	Middle Range	42.7	1.5
	Low End	38.3	3.2
South Region	Natural Gradation	41.8	1.1
	High End	39.7	1.6
	Middle Range	39.2	1.9
	Low End	36.3	2.0

As shown in Table 13, the largest friction angle (which dominates the shear strength of granular materials) is generally largest at the natural gradation. The natural gradation of the materials would be classified as having a slight, gap-graded gradation. The lowest friction angle was typically found when the aggregate gradation was at the low end (fine side).

Table 13 also shows that the North region had friction angle values larger than the Central and South, which had comparable friction angle values. This was most likely due to the North region's I-3 containing angular slag material.

The triaxial test results for the DGABC are shown in Table 14. Unlike the NJDOT I-3, there is no clear trend in shear strength to material gradation. On average, the Middle Range provided the largest friction angle. Once again, the Low End obtained the lowest shear strength values. The low friction angles obtained when testing the Low End gradation was most likely a function of the high fines and smaller percentage coarse aggregate.

Table 14 – Triaxial Test Results and Shear Strength Properties of DGABC

Region of NJ	Soil Gradation Type	DGABC	
		Friction Angle (degrees)	Cohesion (psi)
North Region	Natural Gradation	54.9	2.1
	High End	51.2	3.1
	Middle Range	56.1	1.9
	Low End	40	4.2
Central Region	Natural Gradation	50.3	1.5
	High End	54.6	2.7
	Middle Range	51	2.2
	Low End	38.3	2.5

Triaxial Test Results – 100% Recycled Materials

Triaxial tests were conducted on the 100% RAP and 100% RCA to provide a guide as to the potential shear strength these materials may obtain when blended with virgin aggregates. The 100% RAP and 100% RCA were compacted at their respective optimum moisture contents. The results of the triaxial testing are shown in Table 15. The results show that the RCA provides comparable shear strength properties to the DGABC material, while the RAP provides comparable shear strength properties to the NJDOT I-3 aggregate.

Table 15 – Shear Strength Parameters of 100% RAP and 100% RCA from Triaxial Testing

Material Type	Friction Angle (degrees)	Cohesion (psi)
100% RAP	44.5	2.5
100% RCA	52.7	3.5

Based on comparing the shear strength parameters of the 100% recycled materials to the shear strength parameters of the natural gradation materials, it would appear that 100% RCA could be substituted for the DGABC in the base layer of the pavement. However, the 100% RAP may have too low of a shear strength to be placed in the base layer when compared to the DGABC values. The 100% RAP would provide adequate shear strength in the subbase layer, as the shear strength values are slightly greater than the currently used NJDOT I-3 subbase aggregate.

Summary of Triaxial Test Results

The shear strength of the various aggregates was evaluated using the triaxial test. Each sample was compacted at its respective optimum moisture content and maximum dry density. The results of the triaxial tests showed that:

- Overall, the largest friction angle occurred when the aggregates tested were at their respective natural gradations. This includes both the DGABC and NJDOT I-3 aggregates. When only evaluating the DGABC, the middle gradation provided the highest friction angle (53.6^o), while the low end gradation resulted in the lowest friction angle (39.2^o). On average, the natural, high end, and middle range gradations of the DGABC all provided friction angles that were within 3.0 degrees from one another. When evaluating only the NJDOT I-3 material, the natural gradation provided on the highest friction angle values (45.1^o), while again the low end gradation resulted in the lowest friction angle (39.0^o). On average, the natural, high end, and middle range gradation of the NJDOT I-3 aggregates all had friction angle values that were within 1.4 degrees of one another.
- The generally tight range of results (average) for the NJDOT I-3 and DGABC aggregates, when comparing the natural, high end, and middle range gradation, illustrates the importance of the coarse fraction of the aggregates on the shear strength properties. The average shear strength of the Low End gradation was considerably lower for the DGABC aggregate when compared to the other gradation types. This is most likely due to the larger amount of fines allowed in the DGABC (12%). On average, the Low End friction angle of the DGABC was approximately 13 degrees less than the other gradations, while for the NJDOT I-3, the Low End friction angle was 4 degrees less than the other gradations.
- The source of the aggregate had an impact on the shear strength properties when varying the gradation. This was more evident for the NJDOT I-3 aggregate than the DGABC aggregate. For example, the average friction angle per gradation type of the North Region was approximately 5 to 8 degrees higher when compared to the South Region's NJDOT I-3. This was most likely due to the North Region's stockpile allowing angular slag material.
- The shear strength properties of the 100% recycled material, RAP and RCA, showed that the 100% RAP had similar shear strength properties to the NJDOT I-3 aggregate, while the 100% RCA had similar shear strength properties to the DGABC. Based alone on shear strength, it can be concluded that the 100% RCA could be substituted for DGABC in the base layer of the pavement, while the 100% RAP could be substituted for the NJDOT I-3 in the subbase layer.

Resilient Modulus Testing

Resilient modulus of base, subbase and subgrade materials is determined by repeated load triaxial tests on unbound material specimens. Resilient modulus is the ratio of axial cyclic stress to the recoverable strain. In order to determine the resilient modulus of unbound materials, a cyclic stress of fixed magnitude for a duration of 0.1 seconds must be applied to the specimen followed by a 0.9 seconds rest period. During the test the specimen is subjected to a confining stress provided by means of a triaxial pressure chamber.

The resilient modulus test provides a means of characterizing base, subbase and subgrade material for the design of pavement systems. These materials can be tested under a variety of conditions, some of which include stress state, moisture content, temperature, gradation and density. In order to accurately measure the resilient modulus of these materials, a sophisticated testing system must be utilized.

The definition of resilient modulus is defined in Figure 24. Figure 25 shows the system used to determine the resilient modulus properties of the materials tested in this report. The test sequence conditions used in this study, AASHTO TP46-94, are shown in Table 16.

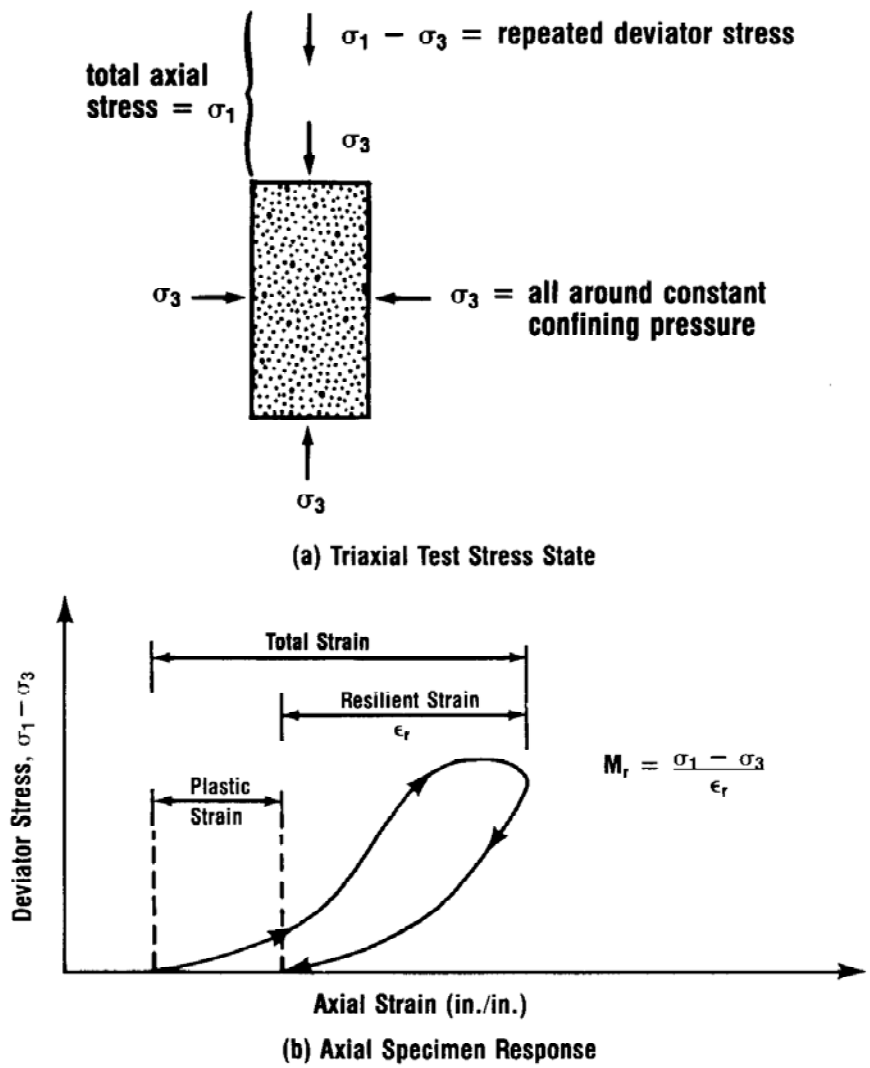


Figure 24 - Definition of Resilient Modulus (Barksdale, 1993)

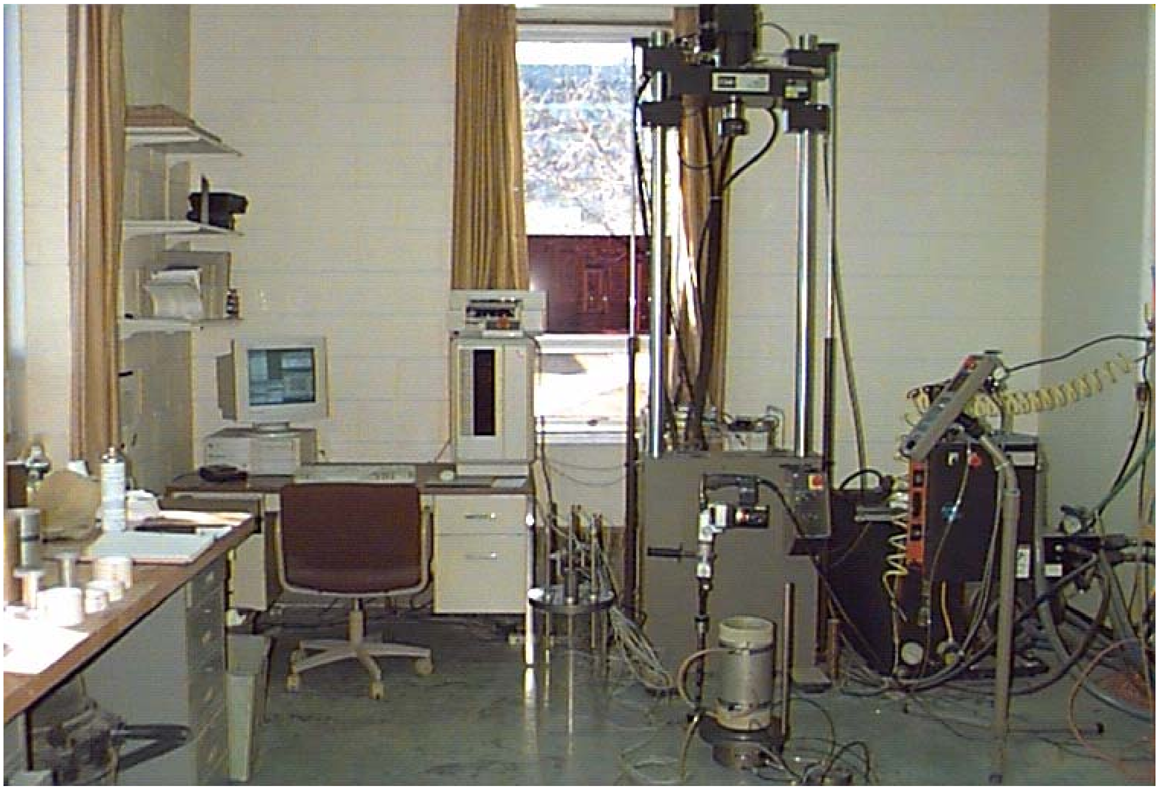


Figure 25 – Test Set-up Used to Conduct Resilient Modulus Testing

Table 16 - Testing Sequence Base/Subbase Materials under AASHTO TP46-94

Sequence Number	Confining Pressure, σ_3 (psi)	Maximum Axial Stress, σ_d (psi)	Cyclic Stress, σ_{cd} (psi)	Contact Stress, σ_d (psi)	Number of Load Applications
Conditioning	15.0	15.0	13.5	1.5	500-1000
1	3.0	3.0	2.7	0.3	100
2	3.0	6.0	5.4	0.6	100
3	3.0	9.0	8.1	0.9	100
4	5.0	5.0	4.5	0.5	100
5	5.0	10.0	9.0	1.0	100
6	5.0	15.0	13.5	1.5	100
7	10.0	10.0	9.0	1.0	100
8	10.0	15.0	13.5	1.5	100
9	10.0	30.0	27.0	3.0	100
10	15.0	10.0	9.0	1.0	100
11	15.0	15.0	13.5	1.5	100
12	15.0	30.0	27.0	3.0	100
13	20.0	15.0	13.5	1.5	100
14	20.0	20.0	18.0	2.0	100
15	20.0	40.0	36.0	4.0	100

For Mechanistic-Empirical Pavement design, the resilient modulus (M_R) is estimated using a generalized constitutive model. The nonlinear elastic coefficients and exponents of the constitutive model are determined by using linear or nonlinear regression analyses to fit the model to laboratory generated resilient modulus data (NCHRP 1-37A). The generalized model developed under NCHRP 1-28 and used within the context of the 2002 Mechanistic Empirical Pavement Design Guide is:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \qquad (2)$$

where,

M_R = resilient modulus
θ = bulk stress = $\sigma_1+\sigma_2+\sigma_3$
σ_1 = major principal stress
σ_2 = intermediate principal stress = σ_3 for M_R test on cylindrical samples
σ_3 = minor principal stress = confining pressure
τ_{oct} = octahedral shear stress
p_a = normalizing stress (atmospheric pressure) = 14.67 psi
k_1,k_2,k_3 = material dependent regression constants

The material dependent regression constants determined for each specimen should have a minimum r^2 value of 0.9. If the value is less than 0.9, then the test results and equipment should be checked for possible errors and/or test specimen disturbance.

The material dependent regression constants should behave in a manner described below:

- The k_1 coefficient is proportional to the elastic modulus. Therefore, k_1 should always be positive.
- As with the k_1 coefficient, the k_2 coefficient should also be positive at all times. The k_2 coefficient is the exponent to the bulk stress term. This parameter emphasizes the material hardening or stiffening of the unbound material due to the applied bulk stress.
- The k_3 parameter is the exponent to the octahedral shear stress values. The k_3 parameter can be either negative or positive depending on the material's response to the increasing shear stress (negative for softening and positive for hardening).

Because the idea of the resilient modulus test is to measure the resilient modulus value at a number of different applied stress conditions and determine a regression equation to fit that data, one resilient modulus value does not exist. Instead, the resilient modulus of the soil will depend on not only its own at rest properties (density, moisture, in-situ stress conditions) but also the applied stresses due to moving traffic loads. Therefore, to provide a way of documenting the resilient modulus of the materials tested, all final values of the resilient modulus data will be shown as simply the materials respective regression constants (k_1, k_2, k_3). The three material dependent regression constants can then be used with equation (2) to determine the resilient modulus for each material at any stress condition.

Resilient Modulus Results – RCA and RCA Blends

Recycled Concrete Aggregate (RCA) was blended with DGABC at percentages of 25, 50, and 75% by total weight. Each blend was compacted to its respective maximum dry density and optimum moisture content. Table 17 compares the resilient modulus results for the RCA blended samples. Since there does not exist simply "one" resilient modulus value for a soil (due to the material property's stress dependency), the material must be evaluated under some type of pavement stress scenario to actually determine a resilient modulus value. For the comparison, a general pavement scenario was selected for the determination of the bulk stress and octahedral shear stress. The properties and dimensions of the pavement were assumed to be as followed:

- HMA Layer = 5 inches, E = 450,000 psi
- Base Aggregate = 12 inches, M_R = 30,000 psi
- Subgrade = 10,000 psi

Using the Elastic Layer computer program EVERSTRESS, both the bulk stress and octahedral shear stress was calculated from an applied 9,000 lb wheel load. The procedure outlined in the FHWA Publication: FHWA-RD-97-077 (Von Quintus and Killingsworth, 1997) was followed. To simplify the analysis, it was assumed that all aggregate materials were subjected to the stress conditions determined above.

Table 17 – Resilient Modulus (M_R) Test Results for RCA Blended Samples

Region of NJ	**Soil Gradation Type**	**Regression Coefficients**			**Resilient Modulus**
		k_1	**k_2**	**k_3**	**M_R (psi)**
RCA Blend	100% RCA	1735.4	0.5362	0.1387	38,975
	75% RCA, 25% DGA	1532.6	0.5431	0.1096	34,044
	50% RCA, 50% DGA	1350.8	0.5996	0.1618	32,018
	25% RCA, 75% DGA	1278.3	0.3863	-0.2482	21,170
	0% RCA (100% DGA)	1023.3	0.4775	-0.0458	20,042

The table clearly shows that as the percent of RCA increases, the resilient modulus also increases. The DGABC source used for all of the recycled blended samples was from the central region source.

Resilient Modulus Results – RAP and RAP Blends

Recycled Asphalt Pavement (RAP) was blended with DGABC at percentages of 25, 50, and 75% by total weight. Each blend was compacted to its respective maximum dry density and optimum moisture content. Table 18 compares the resilient modulus results for the RAP blended samples using the same methodology as the RCA blended samples.

As with the RCA blended samples, there is a trend of increasing resilient modulus with the increase of percent RAP blended. The 100% RAP sample achieved the largest resilient modulus value for all of the RAP blended samples.

Table 18 – Resilient Modulus (M_R) Test Results for RAP Blended Samples

Region of NJ	Soil Gradation Type	Regression Coefficients			Resilient Modulus
		k_1	k_2	k_3	M_R (psi)
RAP Blend	100% RAP	1775.6	0.4598	0.1784	38,738
	75% RAP, 25% DGA	1441.9	0.4931	0.0677	30,311
	50% RAP, 50% DGA	1599.2	0.5144	-0.0082	32,739
	25% RAP, 75% DGA	1582.7	0.3822	-0.1175	28,027
	0% RAP (100% DGA)	1023.3	0.4775	-0.0458	20,042

It should again be stated that the resilient modulus values shown in the tables for comparison are simply the resilient modulus for the pavement section and loading scenario described. There could actually be a multitude of resilient modulus values for a single aggregate sample due to the multitude of potential stress conditions.

Resilient Modulus Test Results – NJDOT I-3 and DGABC

Resilient Modulus testing was conducted in accordance to AASHTO TP46 on DGABC samples compacted to their respective maximum dry density and optimum moisture content. Table 19 shows the material dependent regression coefficients determined from the resilient modulus testing, as well as the calculated resilient modulus values for the given pavement section.

Table 19 – Resilient Modulus (M_R) Test Results for DGABC Samples

Region of NJ	Soil Gradation Type	Regression Coefficients			Resilient Modulus
		k_1	k_2	k_3	M_R (psi)
DGABC North Region	Natural Gradation	1009.8	0.714	-0.049	23,059
	High End	844.1	0.934	-0.159	21,001
	Middle Range	992.4	0.594	-0.0285	21,176
	Low End	987.3	0.498	-0.0547	19,506
DGABC Central Region	Natural Gradation	1023.3	0.4775	-0.0458	20,042
	High End	840.1	0.928	-0.1444	20,982
	Middle Range	950.2	0.526	-0.0271	19,405
	Low End	952.8	0.46	-0.0544	18,364

The range in resilient modulus values clearly shows the dependency of aggregate gradation on the resilient modulus value, although no true trend in test results exists. However, the one trend that is obvious is that the low end of the gradation range resulted in the lowest resilient modulus value. This is most likely due to the excessive fines in the sample. The resilient modulus results for the gradation ranges (high, middle, and low) are relatively close, while a 3,000 psi resilient modulus difference exists between the North and Central Region's natural gradation. The North Region's resilient modulus for the natural gradation was most likely greater due to the coarser nature of the aggregate gradation.

Resilient modulus tests were also conducted for the NJDOT I-3 aggregates with the material dependent regression coefficients and the calculated resilient modulus shown in Table 20.

Table 20 – Resilient Modulus (M_R) Test Results for NJDOT I-3 Samples

Region of NJ	Soil Gradation Type	Regression Coefficients			Resilient Modulus
		k_1	k_2	k_3	M_R (psi)
NJDOT I-3 North Region	Natural Gradation	909.0	0.714	-0.049	17,746
	High End	---	---	---	N.A.
	Middle Range	892.4	0.594	-0.0285	16,656
	Low End	887.3	0.498	-0.0547	15,806
NJDOT I-3 Central Region	Natural Gradation	799.4	0.7585	-0.09	15,736
	High End	---	---	---	N.A.
	Middle Range	810.2	0.642	-0.0271	15,433
	Low End	852.8	0.46	-0.0544	14,953
NJDOT I-3 South Region	Natural Gradation	867.2	0.626	-0.0883	16,159
	High End	---	---	---	N.A.
	Middle Range	850.2	0.526	-0.0245	15,440
	Low End	792.1	0.402	-0.0792	13,473

The most obvious observation from the resilient modulus testing was that the high end gradation from each source could not either complete the conditioning phase or complete a minimum of five test sequences without obtaining less than 5% axial strain. According the AASHTO TP46-94, if the test sample accumulates more than 5% axial strain, the testing should be stopped and the test sample recompacted and retested. Testing was attempted for each source (high end gradation) a minimum of two times with the identical result occurring each time (accumulated permanent strain greater than 5%). It is evident that this type of gradation for the NJDOT I-3 creates a very unstable material under cyclic loading conditions.

The typical trend found with the remaining gradations was that as the gradation became finer, the resilient modulus value decreased. The resilient modulus values of the middle and natural gradations from the Central and South region were very similar, as would be expected since the gradations of the material were also very similar. The resilient modulus values from the North region were shown to be 2,000 to 3,000 psi greater for the same gradations. This is most likely due to both a coarser gradation and higher compacted density.

Summary of Resilient Modulus Test Results

Resilient modulus testing was conducted on NJDOT I-3, DGABC, RAP blends, and RCA blended aggregate samples. Based on the test results, the following conclusions were drawn:

- **The addition of recycled aggregates, RAP and RCA, increased the resilient modulus properties of the DGABC base aggregate material**. The 100% RCA and 100% RAP samples obtained the largest resilient modulus values for the all samples tested in study. The addition of RAP increased the resilient modulus properties of the DGABC at a greater rate than the addition of RCA. To increase the resilient modulus of the DGABC by 12,000 psi, only 25% RAP was needed as opposed to 50% RCA.
- As the gradation of the DGABC samples became finer, the resilient modulus values decreased. The Low End of the gradation range for the DGABC obtained resilient modulus values of similar magnitude to the NJDOT I-3 subbase aggregate. The resilient modulus values of the natural, high end, and middle gradations of the DGABC all obtained resilient modulus values of similar magnitude, although it is evident that no distinct trend in resilient modulus with gradation exists. This is most likely due to the complex interaction of coarse particle percent, density, and angularity on the resilient modulus properties of the DGABC. However, the natural gradation was typically found to provide the better resilient modulus properties.
- A very similar trend was found in NJDOT I-3 resilient modulus as was for the DGABC (i.e. as the gradation became finer, the resilient modulus decreased). Unfortunately, the high end gradation was found to be unstable under the cyclic loading of the resilient modulus. For each source, the high end gradation of the NJDOT I-3 accumulated greater than 5% axial strain with the first five test sequences, including the conditioning sequence. It was therefore concluded, based on the AASHTO TP46-94 testing protocol that the material could not be tested under the resilient modulus test procedure for base and subbase aggregates. For the gradations that could be tested, the Low End of the NJDOT I-3 gradation obtained the lowest resilient modulus properties. A major factor that may have influenced the low resilient modulus of the NJDOT I-3 was its compactive effort. Based on NJDOT recommendations, the NJDOT I-3 only needs to be compacted to 95% of maximum dry density based on the standard proctor compaction energy. If the compaction was increased to the modified energy, the samples would have most likely achieved larger resilient modulus values.
- Since the resilient modulus is a stress dependent property, resulting in a multitude of resilient modulus values for the same material, the recorded resilient modulus values used for comparison is simply just for the loading condition indicated in Figure 24. However, the general trend in resilient modulus for the aggregate gradations of each material source would most likely hold.

Permanent Deformation Testing

Although considerable emphasis has been placed on indexing base and subbase materials by their respective resilient modulus value, the permanent deformation characteristics are often more important since the permanent deformation of the pavement structure is a key factor in its failure (Thompson and Smith, 1990).

The testing system used for the permanent deformation testing was the MTS closed loop servo-hydraulic testing frame shown earlier. A load cell with a capacity of 15 kN was used for accurate load measurements. The system was programmed to record the peak and valley measurement (maximum and minimum) that occurred from the load cell and the vertical deformation measurement for each applied cycle.

The permanent deformation testing utilized a 45 psi haversine stress waveform to a compacted aggregate sample that had a confining pressure of 15 psi. All samples were loaded to 100,000 load cycles or until the sample failed. The level of confining and applied deviatoric stress was selected based on previous work conducted by Garg and Thompson (1998). The authors noted that materials that performed well in the laboratory under these stress conditions also performed well in the field.

In this study, a permanent strain greater than 4.2% is considered to be the pass/fail criteria. Samples that achieve permanent strains greater than 4.2% would result in the pavement structure having a 0.5 inch rut (based on the laboratory sample height equaling 12 inches). The 0.5 inch rut criteria was selected based on the Asphalt Institute's MS-1 manual's recommendation of minimizing the subgrade rutting to 0.5 inches.

Permanent Deformation Results – RCA and RCA Blends

Permanent deformation testing was conducted on RCA and RCA blends which were compacted to their respective maximum dry density and optimum moisture content. The final permanent deformation, as measured after 100,000 loading cycles, is shown as Figure 26. The results clearly show that as the percentage of RCA increases, the permanent deformation after 100,000 loading cycles decrease.

The DGABC used for the blending and for the 100% DGABC sample was the natural gradation material from the Central New Jersey source.

Permanent Deformation Results – RAP and RAP Blends

Permanent deformation testing was conducted on RAP and RAP blends which were compacted to their respective maximum dry density and optimum moisture content. The final permanent deformation, as measured after 100,000 loading cycles, is shown as Figure 27. In contrast to the RCA test results, as the percentage of RAP increases, the accumulated permanent deformation at 100,000 cycles also increases, with the 100% RAP sample achieving the largest permanent deformation for the RAP blends.

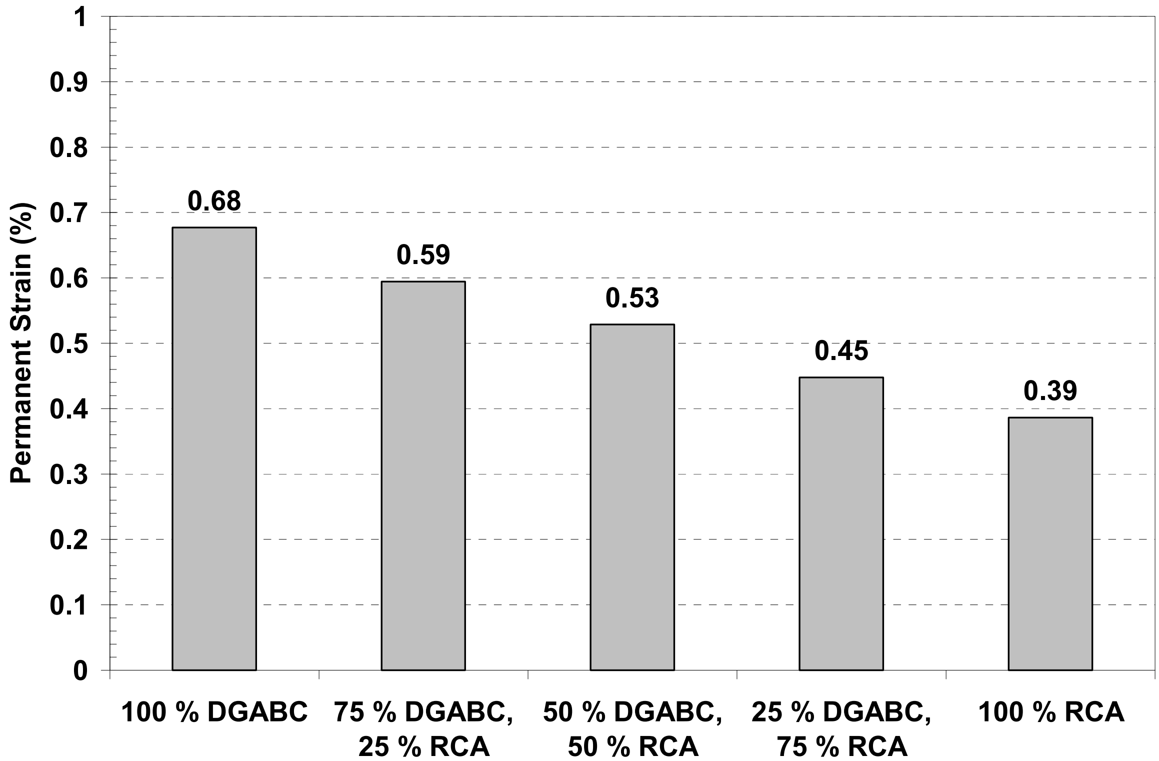


Figure 26 – Permanent Deformation Results for RCA Blended Samples

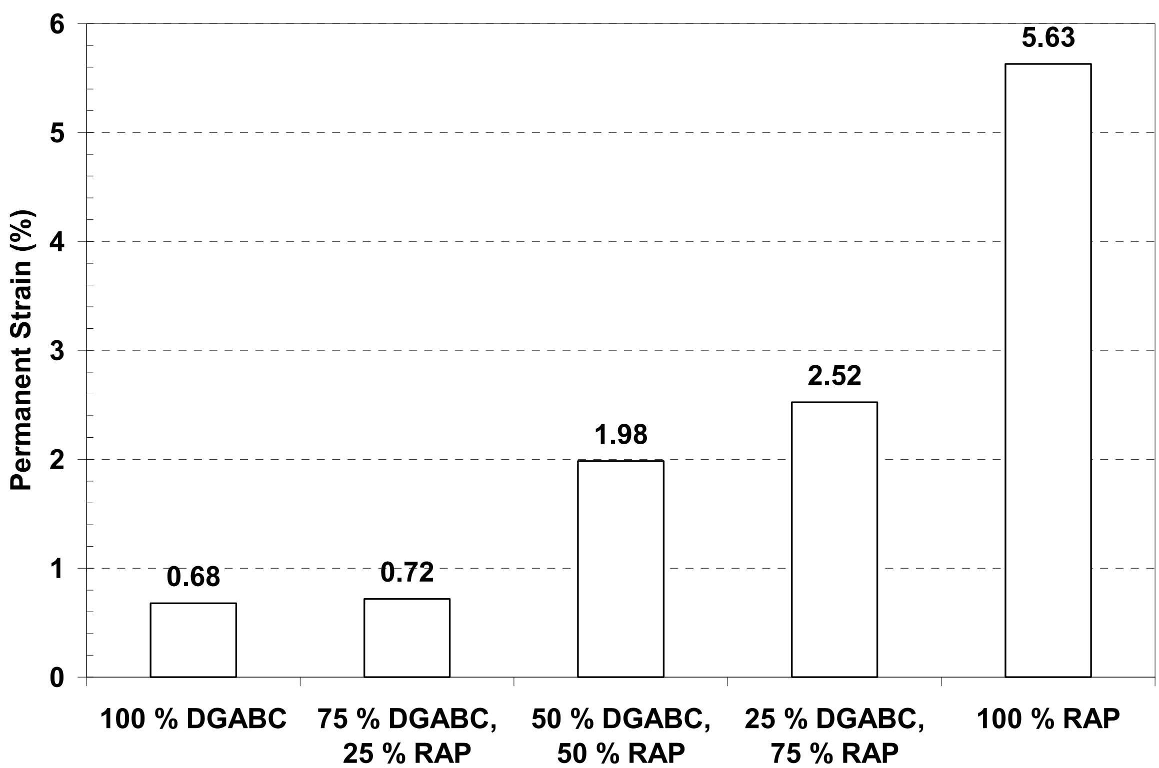


Figure 27 – Permanent Deformation Results for RAP Blended Samples

Permanent Deformation Results – NJDOT I-3 and DGABC

Permanent deformation testing was conducted on DGABC materials which were tested at their respective natural gradation, and also manufactured gradations that represent the high, middle, and low ends of the NJDOT specified gradation range for dense graded aggregate base course (DGABC) materials. The DGABC aggregates were sampled from two different sources (Northern New Jersey and Central New Jersey) and were compacted to their respective maximum dry densities and optimum moisture contents. The results from the permanent deformation testing are shown in Figure 28. Minimal permanent deformation is accumulated in the natural, high, and middle gradations. However, the low end gradations (the finest gradation containing 12% fines) accumulated excessive permanent deformations after 100,000 cycles.

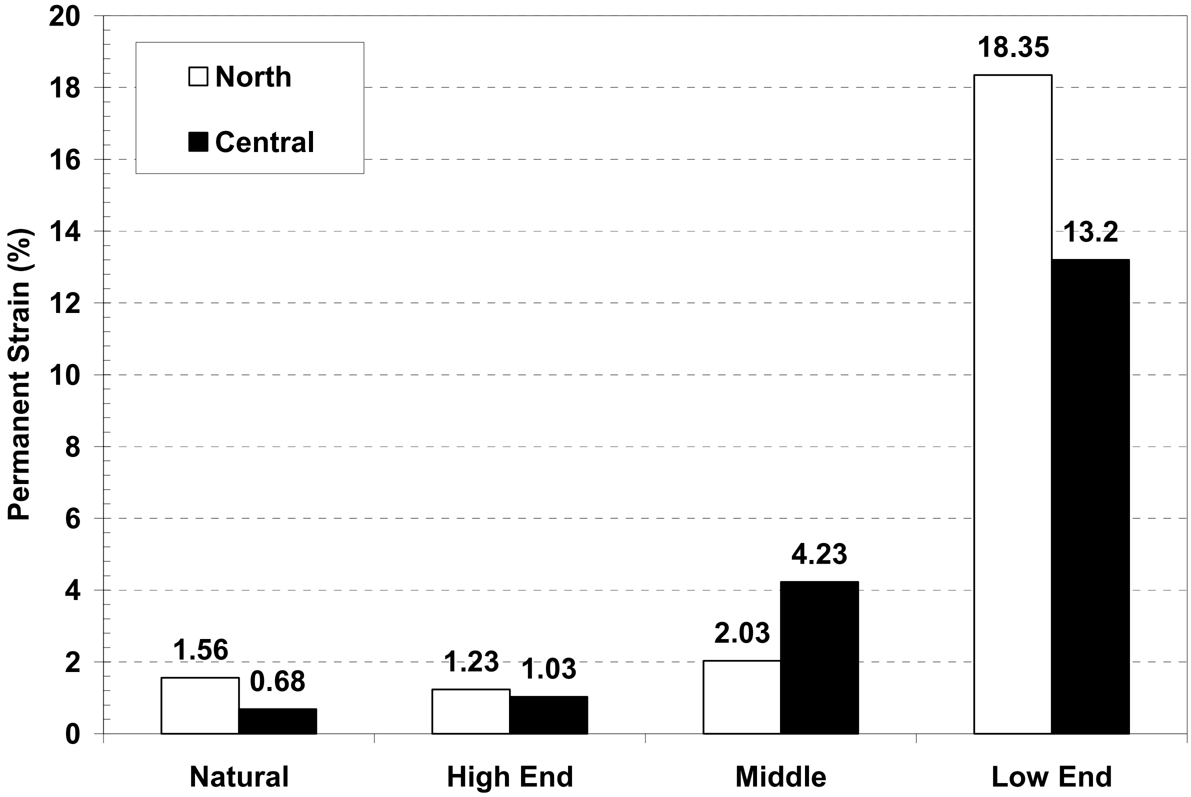


Figure 28 – Permanent Deformation Results for DGABC Materials and Gradations

Permanent deformation testing was also conducted on NJDOT I-3 materials, which again were tested at their respective natural and manufactured gradations. The accumulated permanent deformation test results for the NJDOT I-3 are shown in Figure 29. The results show that overall, greater accumulated permanent strains would be expected in the NJDOT I-3 when compared to the DGABC. In fact, the high end gradation for the Central and South Jersey samples achieved 45% permanent strain much earlier than the 100,000 loading cycles. Figure 30a and b show what an NJDOT I-3 high end gradation sample from Central Jersey looked like before and after testing.

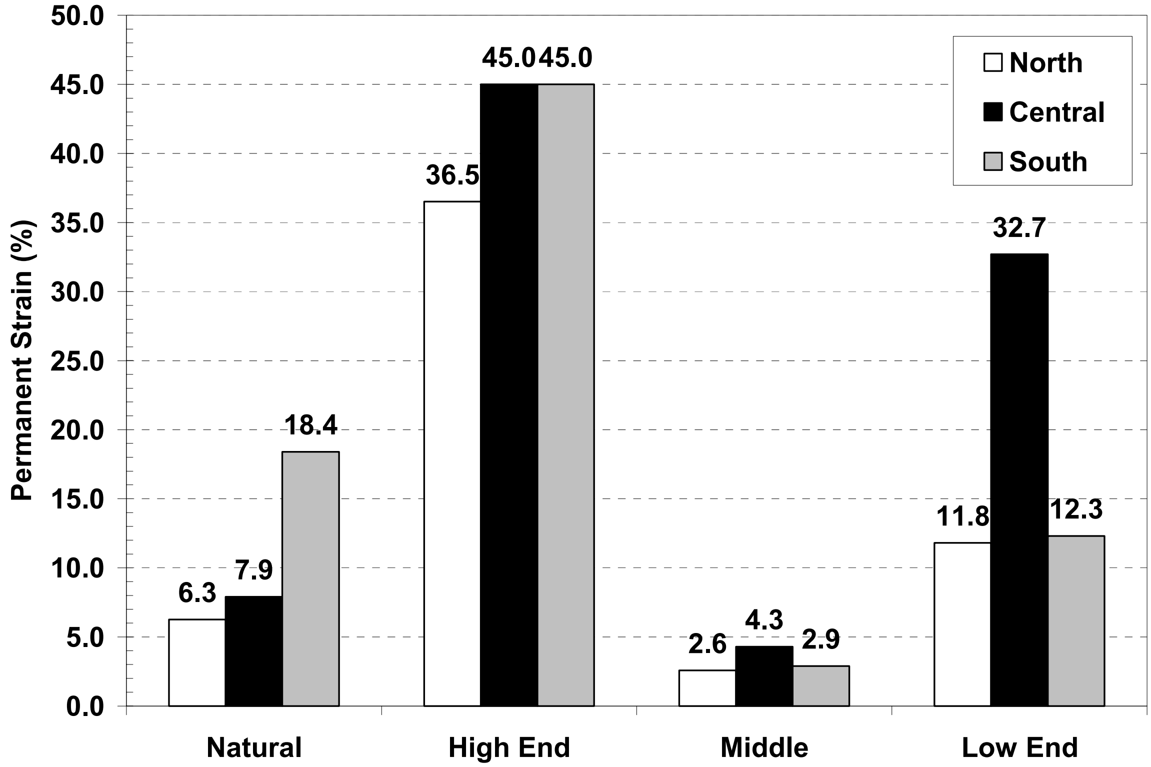
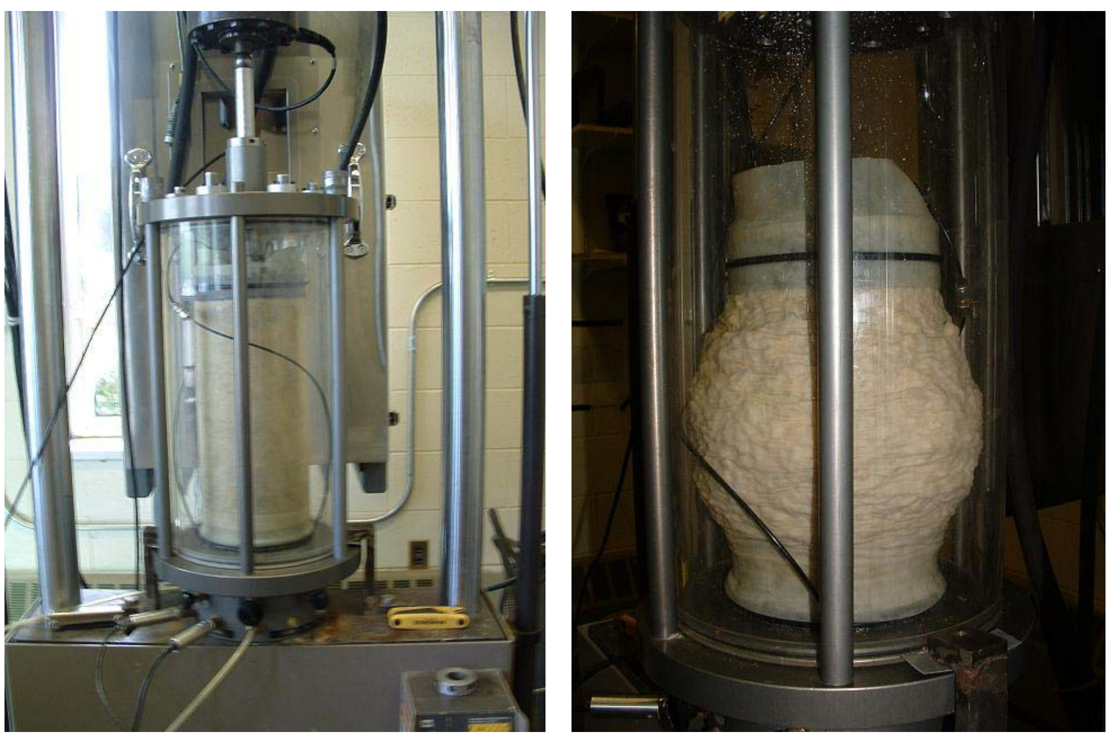


Figure 29 – Permanent Deformation Results for NJDOT I-3 Materials and Gradations



(a) (b)

Figure 30 – (a) NJDOT I-3, Central Jersey High End Gradation Before Testing
(b) NJDOT I-3, Central Jersey High End Gradation After Testing

Summary of Permanent Deformation Testing

The permanent deformation properties of various aggregates and aggregate blends were determined using the cyclic triaxial test with an applied deviatoric stress of 45 psi and a confining pressure of 15 psi. Based on the test results, the following conclusions were drawn:

- **The addition of recycled concrete aggregate (RCA) to the dense graded aggregate base course (DGABC) material decreased the accumulated permanent strain after 100,000 loading cycles when compared to the 100% DGABC sample.** The 100% RCA sample obtained the lowest amount of permanent deformation for all samples tested (0.39% permanent strain).
- **The addition of recycled asphalt pavement (RAP) to DGABC increased the accumulated permanent strain after 100,000 loading cycles when compared to the 100% DGABC sample**. The 100% RAP sample obtained the largest permanent deformation for all recycled blended and natural gradation DGABC samples (5.6% permanent strain). The increase in permanent strain due to the increase in RAP content may be due to a gradual breakdown of the material or even the material becoming more susceptible to compaction from additional cyclic loading.
- The DGABC material accumulated relatively low permanent strains when the aggregate gradation did not fall below the middle of the gradation range (the natural gradation essentially followed the middle gradation). The high angularity and coarse nature of the aggregate structure provided a material resistant to deformation. However, as the general gradation of the DGABC became finer, the permanent strain values increased. The DGABC tested at the low end of the gradation band (finer aggregate and excessive fines = 12%) created an aggregate blend susceptible to permanent deformation.
- **The NJDOT I-3 material accumulated excessive to large permanent strains in all gradation types, except for the middle gradation where all three sources had samples that essentially passed the 4.2% permanent strain criteria.** The high end gradation (poorly graded, coarse) failed to such an extreme level that in two of the samples (Central and South Jersey) the test procedure had to be stopped, resulting in a sample with the appearance previously shown as Figure 30(b). This extreme failure of the high end samples was mostly likely due to the rounded aggregate structure slowly “rolling” downward from the repetitive loading. One reason for the poor performance of the NJDOT I-3 is that the material is currently specified to be compacted to a density determined by the standard proctor test, while the DGABC is placed at a density determined by the modified proctor test (an almost 5 time greater compactive effort over the standard proctor). A greater compactive effort on the NJDOT I-3 would create a more dense material that would be less prone to permanent deformation.

Conclusions

Performance testing, selected to simulate or evaluate aggregate materials from a pavement system, was conducted to evaluate the influence of aggregate gradation on NJDOT I-3 and DGABC and also evaluate the influence of the addition of recycled aggregate, recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP). The main purpose of the study was to provide guidance in the potential modification of the NJDOT specifications for base and subbase aggregates used in the construction of pavements. Based on the testing conducted in the study, the following conclusions were drawn:

- The permeability of the DGABC at a natural gradation was approximately three times faster than the NJDOT I-3 at a natural gradation. NJDOT designs typically assumed the opposite. The permeability of the DGABC and NJDOT I-3 was found to be extremely dependent on the aggregate's gradation. Very fast permeabilities were achieved at the high end of the gradation range (> 250 ft/day for NJDOT I-3 and > 2,000 ft/day for DGABC) while extremely slow permeabilities were found at the Low End of the respective gradations (< 7 ft/day for NJDOT I-3 and < 2 ft/day for the DGABC). For the DGABC, three orders of magnitude in the permeability values can be expected from the extreme ends of the gradation range.
- When the recycled materials were blended with the DGABC, the permeability values decreased. RCA, blended from 25 to 75% of total weight, decreased the permeability by approximately half, while RAP blended at percentages of 25 and 50% lowered the permeability by 1/3. However, the addition of RAP at 75% lowered the permeability to almost less than 1 ft/day. 100% RCA obtained almost no permeability, while the 100% RAP had a permeability value of approximately 16 ft/day.
- The use of either falling head or constant head permeability testing of aggregate materials will provide very similar results until the permeability measured from the constant head test becomes greater than 100 ft/day. Due to the hydraulic gradient within the permeability sample is controlled in the constant head test, Darcy's law is always valid. However, no such control is provided in the falling head test. Therefore, permeability testing of DGABC aggregates is recommended to be conducted in a constant head apparatus, while permeability testing of NJDOT I-3 aggregates can take place in either constant or falling head devices, as long as the gradation of the NJDOT I-3 does not approach the high end of the gradation band.
- It was evident that a migration of fines with the flow of water occurs during the permeability test, and most likely occurs in the field. On average, a 3 to 5% loss of fines occurred, regardless of gradation (high, middle, low and natural) for DGABC samples.
- As the addition of RAP increased, the CBR values greatly decreased. Meanwhile, the addition of RCA minimally lowered the CBR values. The 100% RAP sample obtained the lowest CBR value (20) and the 100% RCA sample obtained the largest CBR value (205) of all samples tested. The effect of gradation on the CBR value was much greater in the DGABC material than the

NJDOT I-3. For the DGABC samples, the CBR value increased as the gradation moved from the Low End to the High End of the gradation range, with the natural gradation obtaining the largest CBR value (195). Meanwhile, a difference of CBR value equaling 15 was found throughout the gradation range of the NJDOT I-3.

- Results from the static triaxial test showed that the high end, middle, and natural gradations obtained similar shear strength properties for the DGABC and NJDOT I-3, respectively. Within these gradations, the DGABC typically obtained friction angles on the order of 50 to 54 degrees, while the NJDOT typically obtained friction angle on the order of 39 to 45 degrees. The NJDOT I-3 sampled from the North region obtained much larger friction angles than the Central and South regions due mainly to its higher degree of angularity (the North region contained a large fraction of slag material and even shell particles). For both aggregate types, the low end of the gradation band resulted in friction angles almost 15% lower than the coarser gradations.
- Static triaxial tests conducted on 100% RAP and 100% RCA samples showed that the 100% RAP samples obtained shear strength parameters similar to the NJDOT I-3, while the 100% RCA obtained shear strength parameters similar to the DGABC aggregates.
- Resilient modulus test results showed that the addition of recycled aggregates, either RAP or RCA, increased the resilient modulus properties of the DGABC base course material. A 50:50 blend of either recycled aggregate with DGABC showed to increase the resilient modulus by approximately 50% for the pavement scenario used in the comparison. Both the 100% RAP and 100% RCA obtained very similar resilient modulus properties and were also found to obtain the largest values in the study.
- The effect of aggregate gradation clearly influenced the resilient modulus properties of the NJDOT I-3 and DGABC aggregate samples, however, the values were more affected when the gradation was at the respective low end of the gradation band. The high end gradation for the NJDOT I-3 was not able to be tested due to its instability with the first 5 test sequences in the resilient modulus test procedure (AASHTO T46-94). The test specification notes that if 5% accumulated axial strain occurs, the test procedure should be stopped and the sample recompacted and again tested. Each high end gradation sample of the NJDOT I-3 was tested a minimum of two times with the same eventual outcome of excessive accumulated axial strain. The natural gradation was typically found to obtain the largest resilient modulus for both the NJDOT I-3 and DGABC samples.
- Permanent deformation testing of the recycled aggregate blends indicated that the addition of RCA to DGABC lowered the accumulated permanent strain after 100,000 loading cycles. In fact, as the percent of RCA increased, the accumulated permanent strain decreased with the 100% RCA obtaining the lowest value of all samples tested. Meanwhile, as the addition of RAP increased in the DGABC, the accumulated permanent strain after 100,000 loading cycles also increased. The 100% RAP sample obtained one of the largest accumulated

permanent strains of all natural gradation materials tested in the study (on the same order of magnitude of the NJDOT I-3 samples).

- The permanent deformation testing of DGABC at varying gradations showed that minimal accumulated permanent strain is obtained at the natural, high end and middle gradation range (typically less than 2% for both North and Central source although the middle range of the Central source obtained 4.2%). The low end of the DGABC gradation band accumulated excessive permanent strain (> 13%). The NJDOT I-3 material showed to be extremely unstable at the high end of the gradation band, with samples showing extreme failure (> 30% permanent strain), and also accumulated excessive permanent strains at the low end of the gradation band (> 12% permanent strain). The middle range and natural gradation (which typically fell on the middle area of the NJDOT I-3 gradation band) accumulated the lowest permanent strains, although still somewhat excessive. However, it should be noted that due to its deeper location in the pavement system, the NJDOT I-3 material would most likely be exposed to lower applied stresses than the DGABC, and therefore perform better.

Recommendations

Based on the various performance testing conducted on both virgin and recycled aggregates of various gradations, the following recommendations are offered:

<u>NJDOT I-3 Aggregate</u>

The gradation specification of the NJDOT I-3 should be tightened to represent more of the middle of the gradation band. Samples at the high end of the gradation band were found to be highly unstable under cyclic loads (similar to past NJDOT problems with non-stablized open graded, NSOG, aggregates). Meanwhile, when the NJDOT I-3 was at the lower end of the gradation band, the permeability was greatly reduced, the shear strength, CBR, and resilient modulus values were the lowest, and the accumulated permanent strain was excessive.

<u>NJDOT DGABC</u>

The gradation specification of the NJDOT DGABC should become coarser. Samples constructed at the low end of the gradation band were found to be highly impermeable, obtain the lowest CBR, shear strength, and resilient modulus, and also accumulate excessive permanent strain. A majority of the problems associated with the low end of the gradation specification for the DGABC can be attributed to the large amount of fines allowed (12%).

<u>Recycled Aggregates and Blends – RAP</u>

The percent by total weight allowed for RAP blended with DGABC should be limited to 50%. At percentages greater than 50%, permeability and CBR values greatly reduce from the DGABC at natural gradation. An even though the resilient modulus increases with the increase in percent RAP added, the accumulated permanent deformation from the cyclic triaxial test actually increases. This contrast in results can be explained by the resilient modulus test ignoring any permanent strains accumulated during the test, simply relying on resilient or elastic strain to compute modulus (resilient modulus). Shear strength and CBR properties of the 100% RAP samples were also found to be similar to that of the NJDOT I-3 materials, also providing evidence that RAP should be included in limited amounts in the base course aggregate layer.

<u>Recycled Aggregates and Blends – RCA</u>

The percent by total weight allowed for RCA blended with DGABC can be blended as high as 75%. The addition of RCA showed to increase CBR and resilient modulus properties and also lower accumulated permanent strain. The shear strength of the RCA was also found to be comparable to DGABC at its respective natural gradations. However, the addition of RCA was found to decrease the permeability of the DGABC, although blended percentages of 25, 50, and 75% were found to decrease the permeability of the DGABC:RCA blend almost equally. Even though the permeability of the DGABC:RCA blends decreased the permeability of the naturally graded DGABC by almost 60%, the final permeability of the DGABC:RCA blend was still found to be of similar to greater magnitude than the NJDOT I-3 at its respective natural gradation. Percents greater than 75% RCA may create a very "tight" aggregate structure that will not allow drainage, as shown by the permeability test results of the 100% RCA which was almost impermeable.

REFERENCES

Barksdale, R.D. *Repeated Load Test Evaluation of Base Coarse Materials*. Georgia Highway Department Research Project 7002. Georgia Institute of Technology, Atlanta, 1972.

Garg, N. and Thompson, M.R. Triaxial Characterization of Minnesota Road Research Project Granular Materials. In *Transportation Research Record 1557,* TRB, National Research Council, Washington, D.C., 1997, pp.27-36.

Thompson, M.R. and Smith, K.L. Repeated Triaxial Characterization of Granular Bases. In *Transportation Research Record 1278,* TRB, National Research Council, Washington, D.C., 1990, pp. 7-17.

Von Quintus, H. and Killingsworth, B., *Design Pamphlet for the Determination of Layer Elastic Moduli for Flexible Pavement Design in Support of the 1993 AASHTO Guide for the Design of Pavement Structures*, Publication No. FHWA-RD-97-077, Federal Highway Administration, 1997, 25 pp.