Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Messrs. Harold Von Quintus, Jagannath Mallela, and Prithivi Kandhal assisted with the literature search and telephone interviews. Drs. Jim W. Hall, Jr., Michael I. Hammons, and Walter Barker helped develop the work plan. Messrs. Prithivi Kandhal, Leet Denton, and Rick Sniegowski served as consultants for all project tasks. Laboratory tests were conducted by Boudreau Engineering, Inc., under the supervision of Mr. Richard L. Boudreau.

Several state departments of transportation and their contractors provided recycled material for laboratory testing; their contribution to this research effort is acknowledged.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report contains recommendations for performance-related procedures to test and select recycled hot-mix asphalt (HMA) and portland cement concrete (PCC) materials for use in unbound layers of highway pavements. The report provides a comprehensive description of research intended to help materials engineers evaluate and select the reclaimed asphalt pavement (RAP) and reclaimed concrete pavement (RCP) materials that should contribute to good performing pavements. Also, the report describes procedures for the recommended tests. The contents of this report will be of immediate interest to materials engineers, researchers, and others concerned with the construction and performance of asphalt and PCC pavements.

The use of RAP and RCP and materials reclaimed from structures in unbound pavement layers should provide technical, economic, and other benefits. Although a great deal of research has been performed on the properties of aggregates used in pavement construction, limited research has addressed the use of recycled aggregates in unbound pavement layers. For example, research performed under NCHRP Project 4-23, and reported in *NCHRP Report 453,* "Performance-Related Tests of Aggregates for Use in Unbound Pavement Layers," evaluated aggregate tests and identified a set of aggregate tests that relate to performance of unbound pavement layers. However, the project dealt only with virgin aggregates; it did not consider the use of recycled materials. Because RAP and RCP materials are reclaimed from highway pavements, they contain binders and contaminants that are not found in virgin aggregates. This difference in material constituents, the long exposure of RAP and RCP materials to the elements, and constructability concerns raise questions about the validity of the tests intended for evaluating virgin aggregates for use in evaluating RAP and RCP materials.

Under NCHRP Project 4-31, "Tests of Recycled Aggregates for Use in Unbound Pavement Layers," Applied Research Associates, Inc. was assigned the task of recommending procedures for performance-related testing and selection of recycled HMA and PCC materials for use in unbound pavement layers. To accomplish this objective, the researchers reviewed relevant domestic and foreign literature; identified aggregate properties that influence the performance of pavements; identified and evaluated, in a laboratory investigation, the aggregate tests currently used in the United States and other countries as well as potential new aggregate tests to measure performance-related properties; and recommended a set of performance-related tests for evaluating recycled aggregates. The report documents the work performed under NCHRP Project 4-31 and discusses the linkage between the recommended tests and the performance of asphalt and concrete pavements.

The recommended set of aggregate tests can be used to evaluate and select RAP and RCP materials for use in the unbound layers of asphalt and PCC pavements. The report includes descriptions of those recommended test methods that are not currently being used in the United States. These test methods will be particularly useful to highway agencies and, therefore, may be considered for adoption by AASHTO as standard test methods.

Appendixes A through C contained in the research agency's final report are not published herein. These appendixes are available on the TRB website as *NCHRP Web-Only Document 119.* These appendixes discuss the following:

Appendix A: Literature Review and Background Information
Appendix B: Recommended New Aggregate Tests
Appendix C: Surface Dielectric Measurements

CONTENTS

SUMMARY

Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers

Unbound pavement layers in flexible and rigid pavements generally serve to provide (1) a working platform, (2) structural layers for the pavement system, (3) drainage layers, (4) frost-free layers, and (5) select fill material (sometimes as part of the working platform). The properties of recycled aggregates (recycled asphalt pavement [RAP] and recycled concrete pavement [RCP]) greatly influence their performance as unbound granular pavement layers.

Failure of an unbound pavement layer results in pavement distresses. Fatigue cracking, rutting/corrugations, depressions, and frost heave of flexible pavements are distresses (performance parameters) that can result from poor performance of aggregate in unbound base and subbase layers. Similarly, cracking, pumping/faulting/loss of support, frost heave, and erosion in rigid pavements can result from poor performance of subbase layers.

Factors contributing to distresses in both rigid and flexible pavements due to the poor performance of unbound layers include (1) shear strength, (2) density, (3) gradation, (4) fines content, (5) moisture level, (6) particle angularity and surface texture, (7) degradation during construction, under repeated load and freeze-thaw cycling, and (8) drainability. Recycled aggregate properties that were determined to affect performance of unbound pavement layers are shear strength, frost susceptibility, durability, stiffness, and toughness.

For this study, tests were conducted on RAP and RCP containing three different constituent aggregates (i.e., crushed limestone, granite, and gravel) to provide a range of materials with poor to excellent performance. The recycled materials were blended with a virgin aggregate known to provide good performance in unbound pavement layers.

Laboratory test data were analyzed. The following tests were found to produce statistically significant performance indicators of recycled aggregates in unbound pavement layers:

- Screening tests for sieve analysis and the moisture-density relationship,
- Micro-Deval for toughness,
- Resilient modulus for stiffness,
- Static triaxial and repeated load at optimum moisture content and saturated condition for shear strength, and
- Frost susceptibility (tube suction).

Requirements for test parameters for recycled materials were established to evaluate recycled materials' suitability for use in particular traffic and climatic conditions. The research team developed a decision chart incorporating aggregate shear strength, stiffness, toughness, and frost susceptibility to provide a measure of the performance potential of a particular aggregate.

The researchers also developed a validation plan to evaluate the research results in the long term. This plan proposes accelerated pavement testing of specially constructed pavement sections and long-term performance monitoring of in-service test pavements.

CHAPTER 1

Background and Research Approach

Project Background

When used appropriately, recycled materials provide good-quality, cost-effective road construction materials that benefit the environment and lessen the use of raw materials. In most cases, the use of recycled materials offers economic benefits, because recycled materials often cost less than virgin aggregate materials, particularly when used in reclamation jobs, and may also save transportation and disposal-related costs. The societal benefits of using recycled materials include saving available natural resources and extending the life of available landfill space. Although much research has been conducted on using recycled materials, especially reclaimed asphalt pavement (RAP) and reclaimed concrete pavement (RCP), in bound pavement layers, limited research has been reported on the use of RAP and RCP in unbound pavement layers.

Research Objective

The objective of this research was to recommend procedures for performance-related testing and selection of recycled hot-mix asphalt (HMA) and portland cement concrete (PCC) materials for use as aggregates in unbound pavement layers, singularly or in combination with other materials. The research included evaluating existing aggregate tests known to predict pavement performance for their applicability to RAP and RCP and to develop new tests or modify existing tests.

Scope of Study

The research consisted of nine tasks as described below.

Task 1. Review *NCHRP Report 453,* and collect and review other relevant domestic and foreign literature, research findings, performance data, current practices, and other information relative to the use, testing, and evaluation of recycled HMA and PCC materials in unbound pavement layers.

Task 2. Identify the performance parameters of pavements that may be affected by the properties of recycled aggregates used in unbound layers, including consideration of the layer's structural behavior, constructability, and related environmental concerns.

Task 3. Identify and discuss the recycled aggregate properties that influence the performance parameters identified in Task 2. Chemical, mechanical, mineralogical, and physical properties shall be considered.

Task 4. Identify and evaluate—with consideration of performance predictability, precision, accuracy, practicality, cost, and other pertinent factors—those test procedures currently used for measuring the performance-related properties identified in Task 3.

Task 5. Identify—with consideration of practicability, accuracy, and other relevant factors—potential new procedures or modifications of current test procedures for measuring those performance-related properties for which no suitable test method has been identified in Task 4 and recommend procedures for further evaluation.

Task 6. Prepare a detailed work plan for an experimental investigation to evaluate and validate the most promising procedures for measuring recycled aggregate properties that relate to pavement performance.

Task 7. Execute the work plan and, based on the results of this work, recommend sets of tests for evaluating recycled aggregates used in unbound pavement layers and provide criteria for interpreting test results and assessing recycled aggregate acceptability for use in unbound pavement layers.

Task 8. Develop protocols for the tests recommended in Task 7 for which standards are not currently available, in a format suitable for consideration and adoption by AASHTO.

Task 9. Submit a final report that documents the entire research effort.

Research Approach

The research approach included a literature search and phone interviews with individuals representing state highway agencies and relevant industry groups. *NCHRP Report 453* (*1*) served as the initial guide for the literature search. The telephone interviews provided information on agencies' practices regarding recycling of RAP and RCP as unbound aggregate in base/subbase layers. The approach also included the selection of pavement performance parameters that may be influenced by the properties of recycled aggregate in unbound pavement layers, the identification and evaluation of recycled aggregate properties that affect pavement performance parameters, and identification and evaluation of current aggregate test procedures and potential techniques that can be used to measure relevant recycled aggregate properties.

Report Organization

Chapter 2 of this report discusses pavement performance and recycled aggregate properties that affect pavement performance. Chapter 3 describes the methodology used to select candidate test methods and candidate recycled materials. Chapter 4 presents the laboratory test data. Data analysis is presented in Chapter 5. Chapter 6 provides research conclusions, recommendations, and a validation plan.

Appendix A provides details of the literature search and the telephone interviews with state DOTs. Testing protocols for the recommended test methods are presented in Appendix B. Appendix C presents the results of surface dielectric measurements. Appendixes A through C are not published herein but are available as *NCHRP Web-Only Document 119* on the TRB website.

CHAPTER 2

Pavement Performance and Recycled Aggregate Properties

Background

Unbound pavement layers are used in flexible and rigid pavements to provide one or more of the following functions:

- A working platform for construction,
- A frost blanket (frost-free layers),
- A drainage layer, and/or
- A structural layer for the pavement system.

Fatigue cracking, rutting/corrugations, depressions, and frost heave of flexible pavements can be attributed, at least in part, to poor performance of granular base and subbase layers. Cracking, pumping/faulting/loss of support, frost heave, and erosion of rigid pavements can also be attributed to poor performance of granular base and subbase layers. These distresses and granular base/subbase contributing factors are described in Table 2.1 for flexible pavements and Table 2.2 for rigid pavements.

Flexible Pavements

Flexible pavements with thin and thick HMA surfaces over unbound aggregate bases may exhibit different failure modes. Flexible pavements with thick HMA surfaces usually exhibit rutting failure while thin HMA surfaced flexible pavements often exhibit fatigue cracking.

Depressions are localized pavement surface areas with elevations slightly lower than those of the surrounding pavement. Depressions are generally the result of localized areas in the base or subgrade caused by low initial density that have further compacted under traffic load repetitions or depressed into the weakened subgrade.

Frost heave causes differential surface movement, which results in cracking and uneven surface conditions. Thick ice lenses are formed due to slow freezing during winter causing the pavement surface to distort. These ice lenses melt during the spring thaw releasing water that causes the subgrade to weaken and pavement layers to subside or some residual differential settlement to remain.

Rigid Pavements

Cracks in PCC slabs occur when the flexural strength of the concrete is exceeded by the imposed stresses. PCC pavements usually show fatigue failure due to repeated applications of stresses less than the flexural strength. Fatigue cracking occurs in the form of longitudinal cracks and corner breaks attributed to poor unbound material performance. Load associated longitudinal cracks along the wheel paths are due to a combination of factors including wheel load and thermal stresses and moisture variations. Corner breaks are usually caused by a loss of support due to pumping of unbound materials and/or reduced strength from increased moisture content.

Pumping in rigid pavements usually results in erosion and migration of the unbound material from underneath the concrete slabs leading to a gradual reduction in slab support and slab faulting in extreme cases. Frost heave can also cause shear strength loss in unbound layers resulting in pavement roughness and faulting. Frost action, with slow freezing and available water, results in the formation of ice lenses which release large amounts of water during spring thaw, weakening the unbound layer/subgrade and leading to cracking, pumping, and faulting.

RAP and RCP Properties

The performance of pavements built with unbound base and subbase layers incorporating recycled aggregates can be affected by physical, chemical, and mechanical properties of the recycled aggregate particles and the proportion in which they are mixed with virgin aggregate (zero to 100 percent). Some of the properties are listed in Table 2.3.

Table 2.1. Flexible pavement performance parameters and contributing factors.

Distress	Description of distress	Unbound layer failure mechanism	Contributing factors
Fatigue Cracking	Fatigue cracking first appears as fine, longitudinal hairline cracks running parallel to one another in the wheel path and in the direction of traffic; as the distress progresses the cracks interconnect, forming many-sided, sharp angled pieces; eventually cracks become wider and, in later stages, some spalling occurs with loose pieces prevalent. Fatigue cracking occurs only in areas subjected to repeated loadings.	Lack of base stiffness causes high deflection/strain in the HMA surface under repeated wheel loads, resulting in fatigue cracking of the HMA surface. High flexibility in the base allows excessive bending strains in the HMA surface. The same result can also be due to inadequate base thickness. Changes in base properties (e.g., moisture induced) with time can render the base inadequate to support loads.	Low modulus of the base layer Low density of the base layer Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads and freeze-thaw cycling
Rutting/Corrugation	Rutting appears as a longitudinal surface depression in the wheel path and may not be noticeable except during and following rains. Pavement uplift may occur along the sides of the rut. Rutting results from a permanent deformation in one or more pavement layers or subgrade, usually caused by consolidation and/or lateral movement of the materials due to load.	Inadequate shear strength in the base allows lateral displacement of particles with applications of wheel loads and results in a decrease in the base layer thickness in the wheel path. Rutting may also result from densification of the base due to inadequate initial density. Changes in base (mainly degradation producing fines) can result in rutting. The base can also lose shear strength from moisture-induced damage, which will cause rutting.	Low shear strength Low base material density Improper gradation High fines content High moisture level Lack of particle angularity and surface texture Degradation under repeated loads and freeze-thaw cycling High moisture content coupled with traffic can contribute to stripping
Depressions	Depressions are localized low areas in the pavement surface caused by settlement of the foundation soil or consolidation in the subgrade or base/subbase layers due to improper compaction. Depressions contribute to roughness and cause hydroplaning when filled with water.	Inadequate initial compaction or nonuniform material conditions result in additional reduction in volume with load applications. Changes in material conditions due to poor durability or frost effects may also result in localized densification with eventual fatigue failure.	Low density of base material Low shear strength of the base material combined with inadequate surface thickness
Frost Heave	Frost heave appears as an upward bulge in the pavement surface and may be accompanied by surface cracking, including alligator cracking with resulting potholes. Freezing of underlying layers resulting in an increased volume of material cause the upheaval. An advanced stage of the distortion mode of distress resulting from differential heave is surface cracking with random orientation and spacing.	Ice lenses are created within the base/subbase during freezing temperatures, particularly when freezing occurs slowly, as moisture is pulled from below by capillary action. During spring thaw large quantities of water are released from the frozen zone, which can include all unbound materials.	Freezing temperatures Source of water Permeability of material high enough to allow free moisture movement to the freezing zone, but low enough to also allow suction or capillary action to occur

Properties of recycled aggregate that are considered relevant to its use in unbound pavement layers are listed in Table 2.4. Table 2.5 shows the links between performance parameters and laboratory test measures.

Mass Properties

The properties listed in Table 2.4 are properties of aggregate mass (mass properties) that describe the behavior of the aggregate layer as a continuum. In flexible pavements, shear strength is the most important property, although stiffness is also important (shear strength is very closely related to stiffness). For rigid pavements, permeability is an important mass property to prevent pumping and faulting. However, adequate shear strength is also needed for construction purposes and to provide protection from base shear under pavement joints (*1*). Aggregate mass properties are affected by aggregate particle properties, particularly gradation, shape, texture and angularity, freeze-thaw durability, and toughness.

Shear Strength

Aggregate shear strength has been identified as the single most important aggregate mass property of unbound pavement layers for both flexible and rigid pavements (*1*). Shear strength of unbound pavement layers is typically measured in

Table 2.2. Rigid pavement performance parameters and contributing factors.

Distress	Description of distress	Unbound layer failure mechanism	Contributing factors
Cracking	Cracks transverse to the pavement centerline, generally within the center one-third of the slab. Corner breaks and diagonal cracks appear as top down hairline cracks across slab corners where the crack intersectsthe joints less than 6 ft from the corner; cracking progresses to result in several broken pieces with spalling of crack and faulting at the crack or joint up to ½ in. or more. The corner break is a crack completely through the slab (as opposed to corner spalls, which intersect the joint at an angle).	Inadequate support or loss of support from the unbound aggregate base/subbase resulting from settlement or erosion can increase tensile stresses in the slab under repeated wheel loads and result in increased transverse or corner or diagonal cracking which initiates at the bottom or top of the slab (corner cracks at the top). When a crack develops, increased load is placed on the base, resulting in deformation within the base and surface roughness of the pavement; the crack introduces moisture to the base, resulting in further loss of support and possibly erosion and faulting thereby resulting in further deformation and roughness. Corner breaks (and associated faulting) are caused by lack of base support from erosion and pumping of the base material and freeze-thaw softening of the base.	Low base stiffness and shear strength Pumping of base/subgrade fines causing loss of support Low density in base Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads and freeze-thaw cycling
Pumping/Faulting	Pumping and faulting begin as water seeping or bleeding to the surface at joints or cracks and progress to fine material being pumped to the surface; the ultimate condition is an elevation differential at the joint termed faulting. Pumping action is caused by repeated load applications that progressively eject particles of unbound material from beneath the slabs.	Pumping involves the formation of a slurry of fines from a saturated erodible base or subgrade, which is ejected through joints or cracks in the pavement under the action of repetitive wheel loads.	Poor drainability (low permeability) Free water in base Low base stiffness and shear strength Highly erodible base High fines content Degradation under repeated loads and settlement
Frost Heave	Differential heave during freezing and formation of ice lenses causes roughness due to uneven displacement of PCC slabs; thaw weakening results in loss of support from base and subgrade which may cause pumping and faulting and corner breaks; under heavy loads, the loss of support can result in cracking of slabs.	Ice lenses are created within the base/subbase during freezing temperatures, particularly when freezing occurs slowly, as moisture is pulled from below by capillary action and migrates toward the freezing front. During spring thaw, large quantities of water are released from the frozen zone, which can include all unbound materials.	Freezing temperatures Capillary source of water Permeability of material high enough to allow free moisture movement to the freezing zone

Table 2.3. Recycled aggregate particle properties that influence pavement performance.

Physical properties	Chemical properties	Mechanical properties
Particle gradation and shape (max/min sizes) Particle surface texture Pore structure, absorption, porosity Permeability (hydraulic properties) Specific gravity Thermal properties Volume change (in wetting & drying) Freezing/thawing resistance Deleterious substances	Solubility Base exchange Surface charge Chemical reactivity (resistance to attack by chemicals, chemical compound reactivity, oxidation and hydration reactivity, organic material reactivity) Chloride content pH-level	Particle strength Particle stiffness Wear resistance Resistance to degradation Particle shape of abraded fragments

Table 2.4. Relevance of recycled material mass properties for various applications.

Mass Property of Material	Relevance of Mass Property to the Use of Recycled Material as					
	Structural Layer	Construction Platform	Drainage Layer	Frost Blanket	Control Pumping	Select Fill
Shear Strength	Y	Y	N	N	N	N
California Bearing Ratio (CBR)	Y	Y	N	N	N	Y
Cohesion & Angle of Internal Friction	Y	N	N	N	N	N
Resilient or Compressive Modulus	Y	Y	Y	Y	Y	Y
Density	Y	Y	N	Y	Y	Y
Permeability	N	N	Y	Y	Y	N
Frost Resistance	Y	N	Y	Y	N	Y
Durability Index	Y	N	Y	Y	Y	N
Resistance to moisture damage	Y	N	N	N	N	N

Y: Relevant; N: Not relevant

the "drained" condition (pore pressures allowed to dissipate during testing). The Shear strength, *s*, is mainly a function of angle of internal friction, ϕ, and to a smaller degree its cohesion, c, and may be described by the Mohr-Coulomb equation:

$$s = c + \sigma \tan\phi$$

in which σ is the normal effective stress on the failure plane.

Factors influencing the shear strength of an aggregate include gradation, density, plasticity index, particle geometric characteristics (shape, angularity, surface texture), and moisture content (*2*). Of these, construction and in situ conditions dictate moisture and density. It is important that the measures of internal friction angle and cohesion reflect the conditions that are likely to occur during the life of the pavement. Important aspects of the state-of-stress are the stress magnitude, number of stress repetitions, and rates of loading. In general, static testing procedures are not appropriate for characterizing the behavior of aggregate materials subjected to the impulse type repeated loading caused by moving wheel loads. If the pavement is subject to water infiltration, the measure of shear strength must reflect severe moisture conditions. If the aggregate layer is

Table 2.5. Links between aggregate properties and performance.

<table>
<tr><th>Pavement type</th><th>Performance parameter</th><th>Related aggregate property</th><th>Test measures</th></tr>
<tr><td rowspan="6">Flexible</td><td>Fatigue Cracking</td><td>Stiffness</td><td>Resilient modulus, Poisson's ratio, gradation, fines content, particle angularity and surface texture, frost susceptibility degradation of particles, density</td></tr>
<tr><td>Rutting, Corrugations</td><td>Shear Strength</td><td>Failure stress, angle of internal friction, cohesion, gradation, fines content, particle geometrics (texture, shape, angularity), density, moisture effects</td></tr>
<tr><td rowspan="4">Fatigue Cracking, Rutting, Corrugations</td><td>Toughness</td><td>Particle strength, particle degradation, particle size, gradation, high fines</td></tr>
<tr><td>Durability</td><td>Particle deterioration, strength loss</td></tr>
<tr><td>Frost Susceptibility</td><td>Permeability, gradation, percent minus 0.02 mm size, density, nature of fines</td></tr>
<tr><td>Permeability</td><td>Gradation, fines content, density</td></tr>
<tr><td rowspan="6">Rigid</td><td rowspan="5">Cracking, Pumping, Faulting</td><td>Shear Strength</td><td>Failure stress, angle of internal friction, cohesion, gradation, fines content, particle geometrics (texture, shape, angularity), density, moisture effects</td></tr>
<tr><td>Stiffness</td><td>Resilient modulus, Poisson's ratio</td></tr>
<tr><td>Toughness</td><td>Particle strength, particle degradation, gradation</td></tr>
<tr><td>Durability</td><td>Particle deterioration, strength loss</td></tr>
<tr><td>Permeability</td><td>Gradation, fines content, density</td></tr>
<tr><td>Cracking, Pumping, Faulting, Roughness</td><td>Frost Susceptibility</td><td>Permeability, gradation, percent minus 0.02 mm size, density, nature of fines</td></tr>
</table>

subject to freezing and the material is even moderately frost susceptible, then the measure of shear strength must reflect strength loss due to freeze-thaw.

Resistance to permanent deformation, which is nearly synonymous with shear strength, is an important characteristic for aggregates that are to be used as base course materials in pavements. The Aggregate Handbook states that, although considerable emphasis is being placed on resilient moduli, permanent deformation characteristics are often more important from a practical viewpoint (*2*). This property refers to an aggregate's ability to resist permanent deformation under repeated loads, which is quantified by repeated load tests.

Stiffness

The stiffness of the aggregate layer in flexible pavements is important, because the aggregate layer is an integral part of the pavement structural system. Because aggregate properties that influence shear strength also influence stiffness, results of shear strength and stiffness tests are expected to be highly correlated. The shear strength test procedure can usually be adapted to also measure the resilient modulus.

Density

Density of unbound aggregate layers typically refers to the bulk dry unit weight of a compacted mass of aggregate particles. Insufficient density will cause depressions and rutting due to densification. Other mass properties are greatly affected by the mass density and, therefore, mass density must be considered during the measurement of the other mass properties. Increasing density results in increased shear strength and increased stiffness, but it may lead to a reduction in permeability.

Permeability

Permeability refers to the ability of the aggregate layer to allow water to flow through it; the rate of flow is usually different in the horizontal direction than in the vertical direction. The quantity of flow increases as the coefficient of permeability increases. When an aggregate layer is used in a rigid pavement to prevent pumping, the permeability of the aggregate mass is the primary mass property that dictates the performance of the aggregate layer. Aggregate properties that influence the coefficient of permeability include gradation, compacted density (including void ratio and porosity), and degree of saturation. Changing the aggregate particle properties to increase permeability can affect shear strength and stiffness adversely. Permeability also influences the ratio of dry to wet shear strength and stiffness. Unbound pavement layers with low permeability values usually retain water and may, under repeated dynamic loads, develop pore pressures that cause shear strength and stiffness to decrease. The increased pore pressures, along with the lubricating effect of the retained water, could lead to rapid degradation of the aggregate.

Frost Susceptibility

Frost susceptibility refers to the degree to which a soil mass is affected by the action of freeze-thaw in the presence of water. Frost action occurs in frost-susceptible soils when freezing temperature penetrates into the pavement structure and source of water exists.

Frost heave is usually not uniform; generally differential heaving occurs, causing surface irregularities, roughness, and possible cracking. Non-frost-susceptible aggregate layers are used in pavements to limit the frost from reaching frost-susceptible soils and/or by reducing the volume of frost-susceptible subgrades subjected to freezing temperatures. However, the shear strength and stiffness of the material is greatly reduced in the spring when frost-susceptible materials thaw.

The frost susceptibility of an aggregate mass depends primarily on its permeability. Frost-susceptible materials have permeability that permits the movement of capillary water from a water source to the freeze front such that ice lenses are formed. If the permeability is sufficiently low, moisture can move at a rate to form ice of a magnitude to be detrimental. Fines content defines the permeability and thus the frost susceptibility of an aggregate mass.

Particle Properties

Particle Size Distribution

Particle size distribution or gradation is a measure of the relative size distributions of different particles in the aggregate mass and is an important indicator of field performance (*1*). Aggregate gradation can be dense graded to provide high shear strength and stiffness or open-graded and free draining to reduce damage due to excessive moisture and frost action. The amount of material passing the No. 200 sieve and the nature of that material are usually controlled to limit frost susceptibility and to provide sufficient permeability. Particle size distribution also affects constructability.

Measuring gradation is influenced by particle shape and texture (*3*). Rod-shaped elongated particles may not pass through square sieve openings because of their orientation during a sieve test, making gradation appear coarser.

Particle Shape, Texture, and Angularity

Lees (*4*) defines the shape of aggregate particles as cubical, equi-dimensional, blade, disk, or rod-shaped. Angular-shaped particles provide higher internal friction and shear strength; thus, it is desired that a certain percentage of particles be crushed. The mineral and geological properties of the rock formation and the crushing process define the shape of the crushed particles.

Surface roughness and irregularities are termed as particle texture. Contrasts of texture are a smooth river gravel with polished surface as compared to a crushed limestone or granite with harsh surfaces. Thompson (*5*) has shown that the texture of both coarse and fine aggregate particles is important to achieve field shear strength. Current practice often does not consider particle texture directly. The Index of Aggregate Particle Shape and Texture (ASTM D 3398) considers particle texture indirectly.

Toughness and Abrasion Resistance

An aggregate's ability to resist mechanical degradation during hauling and construction operations is termed toughness, and abrasion resistance is a measure of toughness. Impact, repeated stresses, and continuous abrasion cause mechanical degradation. Aggregates are subjected to impact stresses during handling, processing, and compaction and repeated stresses during the service life of a pavement. Aggregate stresses, which are transmitted through particle contacts, are highest when they are supporting the loads of passing vehicles.

Mechanical degradation of aggregate with low toughness causes aggregate gradation changes and a decrease in permeability, decrease in wet shear strength, or an increase in mass density. An increase in mass density of very open-graded material can lead to rutting in flexible pavements or faulting in rigid pavements. The LA abrasion test is a commonly used method for obtaining a relative measure of mechanical toughness. Other testing options include repeated triaxial tests and cyclic loading by a gyratory test machine.

Durability and Soundness

An aggregate's ability to resist degradation due to environmental or chemical effects is measured in terms of its durability and soundness. Chemical attack of unbound aggregate bases is very unusual and was not considered in this study. The aggregate particles' resistance to the cumulative effects of cyclic wetting and drying and freeze-thaw is a common concern. Sulfate soundness tests are often used to obtain a relative measure of an aggregate's durability. Although the particle degradation during this test is caused by crystallization pressures from magnesium or sodium sulfate, it provides a measure of resistance to damage caused by wet-dry or freeze-thaw cycles. Degradation of the base material and the changes in its related properties (i.e., stiffness and shear strength) can lead to pavement distress (*1*). The sulfate soundness test does not evaluate environmental effects on RAP and RCP well and is usually waived with the assumption that the aggregate used in the original HMA and PCC pavement had been tested for durability and had to meet the durability specifications (*6*).

Plasticity of Fines Fraction

Plasticity of fines fraction may indicate the effect of moisture on aggregate performance. Fines with high plasticity tend to attract and retain greater quantities of water and cause greater loss of shear strength and stiffness than will fines of low plasticity. Because the fines produced during processing RAP and RCP are relatively low and are non-plastic, the influence of the plasticity of the fines on the performance is low but the magnitude of the fines is important.

In-Service Factors Affecting RAP and RCP Performance

In-service performance of RAP and RCP as aggregate in unbound pavement layers is influenced by moisture conditions, state of stress, processing and construction method, loading rate, and freeze thaw—factors that generally also have similar effects on virgin aggregate material. Particle size gradation, quality of original aggregate, production process, and binder content may also affect their performance as unbound pavement layers.

Moisture Conditions

The adverse effects of water in the pavement structure can be reduced by improving drainage and by selecting aggregate materials that are least affected by the presence of water. For good performance, aggregate must possess adequate shear strength and stiffness when wet and subjected to repeated loadings. This can be achieved by controlling the amount of material passing the No. 200 sieve to less than about 8 percent (*1*). This aspect is not a concern for RAP and RCP because of the relatively small amount of fines produced during processing. RAP is also susceptible to the presence of water in that the asphalt coating may start to strip from the aggregate, raising permeability problems.

Liu et al. (*7*) and Liu and Lytton (*8*) stated that a drainage time of 5 hours to reach 85 percent saturation from 100 percent saturation is acceptable for a base material, drainage times in excess of 10 hours were unacceptable, and those between 5 and 10 hours were marginal. Thompson (*9*) noted that the quantity and nature of the fines fraction directly influence moisture sensitivity and permeability. A base course with high fines is likely to have low permeability, especially if the fines consist of clay-sized particles. The use of more open-graded aggregates for pavement base courses can decrease moisture sensitivity of RAP material (less fines, more film thickness) and thus the probability of stripping of asphalt because of aggregates' ability to limit high pore pressures.

State of Stress

The performance of unbound aggregate must be judged at the state-of-stress representative of field conditions (*2*). In flexible pavements, an unbound aggregate layer may be used as a structural layer. If a base or a subbase is used as a structural layer, the unbound aggregates are subjected to high vertical and shear stresses. In rigid pavements, the unbound aggregate layer is often placed directly under the PCC slab.

Unbound aggregate layers used in rigid pavements and as subbases in flexible pavement are subjected to large confining stress but relatively low shear stress; the most severe stress conditions occur during construction.

Repeated load triaxial tests used to characterize the response of granular materials have shown that open-graded granular materials with larger maximum sizes typically display a "stiffer" response than dense-graded materials with a smaller maximum size as indicated by the resilient response under repeated loads (*1*). During repeated-load testing, granular materials exhibit a plastic strain component (or permanent deformation). The permanent deformation response of granular material tested under fixed conditions of density and moisture depends on the magnitude of the repeated stress state. Both the maximum principal stress, σ_1, and the stress ratio, σ_1/σ_3, influence the permanent deformation behavior of granular materials. For a given confining stress (σ_3), permanent deformations will increase for higher values of σ_1. For a given stress ratio, permanent deformations will increase with the corresponding increases in both σ_1 and σ_3 (*1*).

Construction Method

Pavement structures, particularly flexible pavements designed for heavier wheel loads and larger numbers of load applications, typically use high density in the aggregate mass. Because more compactive effort is required to achieve these higher densities, the aggregate is subjected to higher stresses during construction that can result in aggregate degradation. However, Chini and Kuo (*10*) stated that, irrespective of its strength, crushed concrete does not break down during handling and compaction.

A comparison of RAP and RCP degradation due to compaction to that of virgin aggregate material determined that RAP and RCP do not degrade during construction, possibly because the asphalt coating on RAP particles acts as a stress absorber and hardened cement paste on RCP particles provide additional degradation/abrasion resistance. The increase in fines content for RAP (0.60 percent) and RCP (1.6 percent) was much less than that of virgin aggregate (3.6 percent) (*11*).

Other aspects of construction, such as crushing, handling, and stockpiling of RAP and RCP can significantly alter the mass strength, stiffness, permeability, or frost susceptibility. It is not practical to use equipment and methods that simulate construction practice in the laboratory for routine aggregate evaluation. Therefore, the aggregate tested for mass properties should match the final aggregate in the pavement.

Freeze-Thaw

Freezing and thawing can be extremely detrimental to aggregate mass properties. However, the performance of RAP and RCP as aggregate in unbound layers in a freeze-thaw environment will depend on in-service conditions and the number of freeze-thaw cycles. Another in-service factor is the uniformity of the aggregate mass. Uniform layers may heave at a uniform rate and, thus, may not present a functional problem for the pavement. Reduced mass density due to frost heave can cause reduced shear strength. Frost susceptibility tests that simulate the number of freeze-thaw cycles, rate of freezing, availability of water, and degree of drainage have been developed. These tests are complex and difficult to run and are not suited for routine aggregate classification (*1*).

Loading Rate

Aggregate layers in pavements are subject to many cycles of moving wheel loads. The rate of loading varies from static and slow-moving loads experienced in parking lots, at stoplights, and at highway intersections, to fast rates of loading corresponding to interstate highway speeds. Increased loads may also be experienced due to wheel impacts at bumps or corrugations. Much work has been done to estimate the loading rates that correspond to highway traffic loading for use in strength and stiffness tests. Also test procedures have been developed for measuring stiffness, both in the laboratory and in the field, when the material has reached a steady-state condition under cyclic loading. For granular material and normal highway speeds, the rate of loading has been shown to have insignificant influence on the strength and stiffness properties of the aggregate mass. The stiffness of unbound base materials with high amounts of RAP can be affected by temperature and frequency or loading rate. Several researchers have found that a steady-state, similar to field conditions, occurs after relatively few cycles of loading (*1*).

CHAPTER 3

Selection of Candidate Test Methods and Materials

Selection and Description of Test Methods

Laboratory tests are used to characterize aggregates as a construction material, to ensure specification compliance, and to evaluate the strength and durability properties. A number of laboratory tests have been developed, mostly along empirical lines, to estimate performance and to identify potentially poor performers. The proportions and properties of RAP and RCP in the unbound pavement layers define the performance of the unbound pavement layer. Due to the particulate nature of unbound aggregate layers, their mechanical properties also depend on stress state and environmental conditions. For pavement applications, tests have been developed to measure four categories of aggregate properties and characteristics: (1) stiffness or modulus, (2) shear strength, (3) permanent deformation, and (4) durability.

This section discusses the test methods selected to determine the performance-related properties of RAP and RCP. Performance predictability, precision, accuracy, practicality, and cost were considered. Laboratory tests recommended in *NCHRP Report 453* (*1*) were re-evaluated for applicability to RAP and RCP; results are shown in Table 3.1.

Selected tests for laboratory investigation are shown in Table 3.2. These tests had a high composite rating in the evaluation shown in Table 3.1. The selected tests can be used to evaluate factors that influence the performance of recycled aggregate and differentiate between good and poor performance potential. The selected test methods could be performed by most state DOTs at a reasonable cost.

The tests listed in Table 3.2 are discussed in the following section; additional detail is provided elsewhere (*1, 2*).

Screening Tests

Screening tests included sieve analysis (AASHTO T 27 and T 11) and moisture-density relations (AASHTO T 180). Aggregate mass gradation is an indicator of aggregate performance and is used by most agencies in aggregate selection. The gradation is an indicator of permeability, frost susceptibility, and shear strength.

Laboratory compaction is used to determine the anticipated density achievable in the field and for fabrication of laboratory specimens for other tests. Compaction of aggregate materials generally results in increasing density, shear strength, and stiffness and decreasing permeability. Density increases with increasing moisture content to a point of maximum density at the optimum moisture content (OMC), beyond which density decreases. The OMC is a function of compactive effort.

Shear Strength Tests

Shear strength was identified in *NCHRP Report 453* (*1*) as the single most important property governing unbound pavement layer performance. The shear strength tests selected for the laboratory investigation were the static triaxial shear tests (AASHTO T 296) and the repeated load triaxial test recommended by *NCHRP Report 453.*

The static triaxial test is simple to conduct and is well accepted in geotechnical applications. The test is conducted on specimens compacted to 95 percent of the maximum dry density at the OMC as determined by AASHTO T 180.

Repeated load triaxial tests are conducted on triplicate samples prepared at 95 percent of the maximum dry density at OMC as determined by AASHTO T 180 and on saturated samples (prepared at OMC) using a closed-loop servo-hydraulic test system. The test provides a relative measure of an aggregate's ability to resist permanent deformation. The repeated load tests are conducted at a confining pressure of 15 psi. An array of load increments is applied, with 1,000 repetitions at each load level (Table 3.3). The load level is increased until the aggregate sample fails in shear or the permanent deformation reaches 10 percent. The test time depends on the selected number of load cycles per load level,

Table 3.1. Rating of potential test methods for evaluating recycled aggregates.

Property measured	Test	Performance predictability	Accuracy	Practi-cality	Com-plexity	Precision	Cost	Composite
Shear Strength	Static Triaxial Shear	F	G	H	FS	G	M	H
	Repeated Load Triaxial	G	G	H	C	G	M	H
	Texas Triaxial	F	G	M	FS	F	M	M
	Illinois Rapid Shear	F - G	G	M	FS	G	M	M – H
	Confined Compression	F	F	M	S	F	L	M
	Direct Shear	F	F	L	FS	F	M	M
	Gyratory Shear	F	F	M	C	F	M	M
	k-Mould	G	G	M	C	F	M	M
	CBR	F	F	M	S	F	L	M
	Hveem Stabilometer	F	F	M	S	F	L	M
	Hollow Cylinder	G	G	L	VC	L	H	L
	Dynamic Cone Penetrometer	F	F	M	S	F	L	M
	Lab Rut-Tester	G	F	L	C	F	H	M
Stiffness	Resilient Modulus	G	G	H	C	G	M	H
	Var. Conf. Pres. Modulus	F	F	L	VC	F	H	L
	Resonant Column	P	P	L	C	P	M	L
Frost Susceptibility	Frost Susceptibility Test	F	F	L	C	P	H	L
	Tube Suction Test	G	G	M	FS	G	M	H
	Index Tests	F	G	H	S	F	L	H
Permeability	Constant Head	F	F	M	FS	F	L	M
	Falling Head	F	F	H	FS	F	L	M
	Pressure Chamber	F	F	H	FS	F	M	M
	Horizontal Permeameter	F	F	H	FS	G	M	M
Toughness	LA Abrasion	F	F	M	S	F	L	M
	Aggregate Impact Value	F	F	F	S	F	L	M
	Aggregate Crushing Value	F	F	F	S	F	L	M
	Aggregate Abrasion Value	P	P	P	FS	P	L	L
	Micro-Deval	G	F	M	S	F	L	H
	Durability Mill	P	P	P	FS	P	L	L
	Gyratory Test	P	P	P	FS	F	M	L
Durability	Tube Suction Test	G	G	M	FS	G	M	H
	Sulfate Soundness	P	P	P	F	F	L	L
	Freezing and Thawing	P	P	P	FS	F	M	L
	Canadian Freeze-Thaw	G	G	M	FS	F	L	H
	Aggregate Durability Index	F	F	H	FS	F	L	M
	Unconfined Freeze Thaw	F	F	H	FS	F	M	M
Particle Geometric Properties	Shape/ Surface Texture Index	F	F	M	S	F	L	M
	Flat and Elongated Particles	P	P	L	C	P	L	L
	Percent Fractured Particles	P	P	L	C	P	L	L
	Uncompacted Void Content	P	P	L	C	P	L	L
	Digital Image Analysis	P	P	L	C	F	H	L
	Atterberg Limits	F	F	M	S	F	L	M

Rating Scale:
Performance Predictability - G = good, F = fair, P = poor
Accuracy - G = good, F = fair, P = poor
Practicality - H = high, M = medium, L = low, F = fair, P = poor
Complexity Levels - S = simple, FS = fairly simple, C = complex, VC = very complex
Precision - G = good, F = fair, P = poor, L = low
Cost - H = high, M = medium, L = low
Composite – H = high, M = medium, L = low (based on relative ratings of other factors)

Notes:
1. All ratings are average subjective evaluations of research team.
2. The composite rating is based on the relative ratings for each category.

Table 3.2. Tests selected for the laboratory test program.

Aggregate property	Test method	Test reference	Test parameter
Screening Tests	Sieve Analysis	AASHTO T 27 and T 11	Particle size distribution
	Moisture-Density Relationship	AASHTO T 180	Maximum dry density and optimum moisture content
Shear Strength	Static Triaxial Shear	AASHTO T 296	c, ϕ, shear strength
	Repeated Load Triaxial	*NCHRP Report 453* (*1*)	
Permeability	Saturated Repeated Load Triaxial	*NCHRP Report 453* (*1*)	
Stiffness	Resilient Modulus	*NCHRP Report 453* (*1*)	
Frost Susceptibility	Tube Suction Test	*NCHRP Report 453* (*1*)	
	Index Method	U.S. Army Corps of Engineers, F categories	
Toughness Tests	Micro-Deval	AASHTO TP 58	
Durability	Canadian Freeze-Thaw	MTO LS-614	

Table 3.3. Stress control for repeated load triaxial test.

Sequence No.	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	No. of Cycles
PC	15	1	10	50
1	15	1	10	1000
2	15	1	20	1000
3	15	1	40	1000
4	15	1	60	1000
5	15	1	80	1000
6	15	1	100	1000
7	15	1	120	1000
8	15	1	140	1000
9	15	1	160	1000
10	15	1	180 *	1000

* A 5,000-pound load cell can accommodate a load equivalent to about 180 psi of axial stress on a nominal 6-inch diameter test specimen (approximately 5,110 pounds).

the load cycle rate, and the number of load levels. The number of load cycles per load level and the load cycle rate can be set, but the number of load levels depends on the strength of the aggregate sample. To keep the testing time reasonable, 1,000 cycles at each load level are applied at a rate of 60 cycles per minute (Table 3.3), thus requiring approximately 17 minutes to complete each load level.

A haversine load pulse of 0.1-sec load duration, shown in Figure 3.1, is used to apply load to the test specimen. Each load pulse is followed by a 0.9-sec relaxation period. This procedure does not allow for sample conditioning, but the first few load cycles at each load increment are considered conditioning for that load increment.

Stiffness and Permeability Tests

The repeated load triaxial tests are conducted to obtain resilient modulus (M_R), a measure of stiffness. Data from cycles 96-100 of each 1,000-cycle loading level are used to compute the M_R (per the procedure described in AASHTO T 307-99). This allows 95 cycles of conditioning prior to measuring strain response to loading. For determining design param-

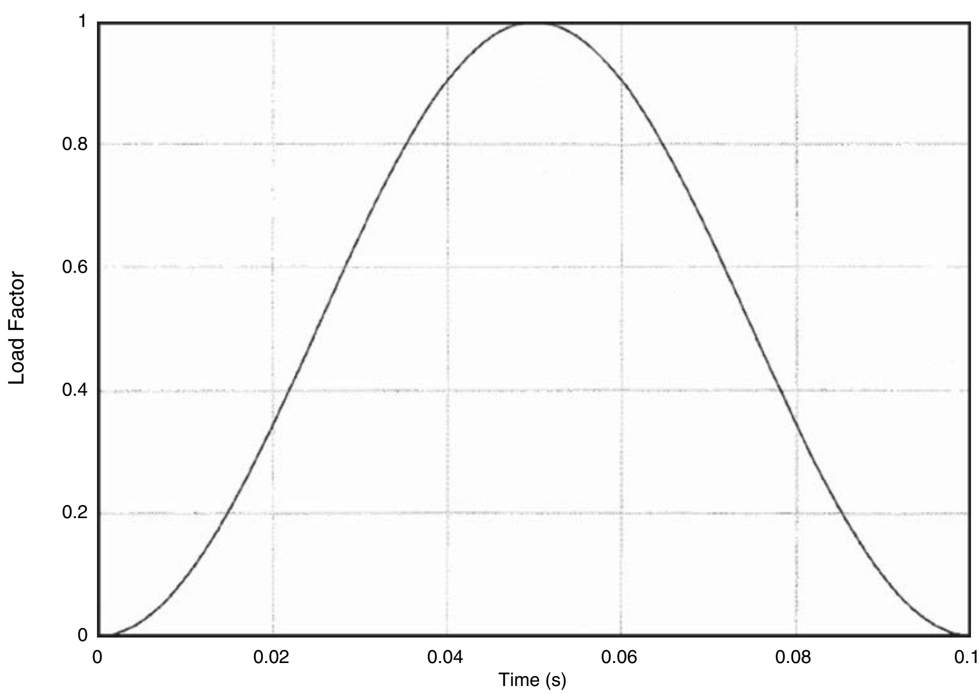


Figure 3.1. Load pulse for repeated load triaxial tests.

eters, conducting a full M_R test to determine the stiffness as a function of the state-of-stress is not necessary. The saturation phase of the saturated repeated load triaxial tests provides a measure of material permeability.

Frost Susceptibility

Frost susceptibility of the materials is determined using the tube suction test (Texas Method 144 E), which determines the moisture retention potential of an aggregate based on the surface dielectric values of a compacted specimen after a 10-day capillary soak in the laboratory. For materials with high suction potential and sufficient permeability, substantial amounts of unbound water rise within the aggregate matrix during soaking and lead to higher dielectric values in the test. Conversely, non-frost-susceptible materials allow little moisture to reach the surface and have lower dielectric values at the end of testing. The tube suction test procedure requires preparing two samples compacted at OMC. On the first sample, a triaxial strength is measured at OMC. On the second sample, a full 10-day tube suction test is run, after which the sample is subjected to triaxial strength testing. The change in triaxial strengths provides a measure of the material's loss in strength after exposure to moisture.

Durability

The Canadian Freeze-Thaw test (MTO LS-614) was selected to evaluate recycled aggregate durability. The test assesses aggregate durability by cyclic freezing and thawing in the presence of moisture. The test is conducted by placing three fractions of aggregate into separate 1-liter jars (¾ inch to ½ inch [1,250 grams], ½ inch to ⅜ inch [1,000 grams], and ⅜ inch to No. 4 [500 grams]). Aggregate samples are soaked for 24 hours in a 3-percent NaCl solution before application of freeze and thaw cycles. After the 24-hour soak period, the samples are drained, sealed and cycled 5 times, frozen for 16 hours at 0°F, and thawed at room temperature for 8 hours. The material is then drained, dried, and re-sieved using the original sieve sizes. The weighted average loss for the sample is then determined from the original grading and the percent loss from all three fractions.

Toughness and Abrasion Resistance

The aggregate toughness and abrasion resistance is determined using the Micro-Deval test (AASHTO TP 58-00). The test is performed on an aggregate sample consisting of 750 grams of ¾- to ½-inch (19- to 13-mm) material and 750 grams of ½- to ⅜-inch (13- to 9.5-mm) material. The sample is soaked in water for 24 hours and then placed in a jar mill with 2.5 liters of water and an abrasive charge consisting of 11 pounds (5 kg) of ⅜-inch-diameter (9.5-mm) steel balls. The jar, aggregate, water, and abrasive charge are revolved at 100 rpm for 2 hours. The sample is then washed and dried. The amount of material passing the No. 16 sieve is determined, and the loss, expressed as a percent by weight of the original sample, is calculated.

Selection and Description of Candidate Recycled Materials

Tests were conducted on RAP and RCP containing three different constituent aggregates (crushed limestone, granite, and gravel) to provide a range of performance, as shown in Table 3.4. The recycled materials were blended with a virgin aggregate that is known to provide good performance when used in unbound pavement layers.

RCP with Limestone

RCP with limestone (RCP-LS-IL) was obtained from a section of Dan Ryan Expressway (Interstate 94/90) that extends from downtown Chicago through south Chicago. This section

Table 3.4. Selected materials and expected performance potential.

Proposed Materials		Expected Performance Potential
100 % RCP (granite)		Excellent
Limestone aggregate (virgin - for blending)		
100 % RCP (limestone)	50 % RCP (granite) + 50 % limestone aggregate	Very Good
50 % RCP (limestone) + 50 % limestone aggregate		
100 % RCP (gravel)	50 % RAP (limestone) + 50 % limestone aggregate	Good
100 % RAP (limestone)	50 % RAP (gravel) + 50 % limestone aggregate	
50 % RAP (granite) + 50 % limestone aggregate		Fair
100 % RAP (granite)		
50 % RAP (gravel or soft limestone) + 50 % limestone aggregate		Poor
100 % RAP (gravel or soft limestone)		

Table 3.5. Gradation for Illinois DOT CA 6 coarse aggregate.

Sieve Size	Percent passing (percent finer)
1.5 in (37.5 mm)	100
1.0 in (25 mm)	95 ± 5
3/4 in (19 mm)	-- [b]
1/2 in (12.5 mm)	75 ± 15
3/8 in (9.5 mm)	-- [b]
No. 4 (4.75 mm)	43 ± 13
No. 8 (2.36 mm)	-- [a]
No. 10 (2.00 mm)	-- [a]
No.16 (1.18 mm)	25 ± 15
No. 30 (0.60 mm)	-- [a]
No. 50 (0.30 mm)	-- [b]
No. 60 (0.25 mm)	-- [a]
No. 100 (0.15 mm)	-- [a]
No. 200 (0.075 mm)	8 ± 4

[a] sieve not specified
[b] not tested for CA 6

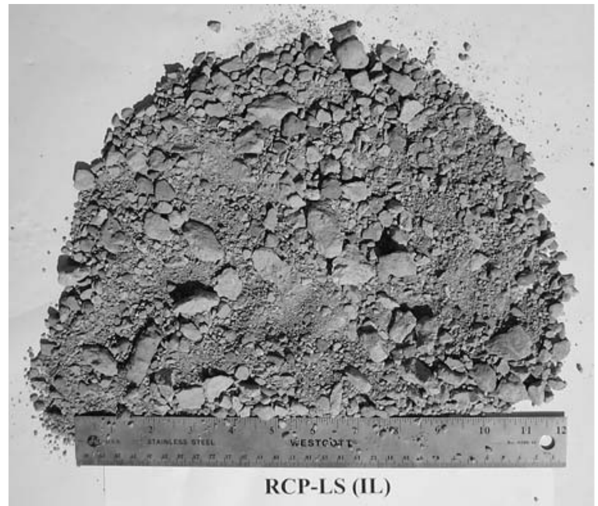


Figure 3.3. Photograph of RCP-LS-IL material used in laboratory testing.

of the expressway was built during the early to mid-1960s. The constitutive aggregate may have been dolomite (a double carbonate of calcium and magnesium [$CaMg(CO_3)_2$]) and not limestone (which is a single carbonate of calcium [$CaCO_3$]) because most of the quarries produced dolomite during the construction period. Calcium and magnesium have very similar properties; the RCP from Illinois is referred to RCP-LS-IL, although the constitutive mineral could have been limestone or dolomite.

The in-place PCC was processed on site to produce "CA 6" aggregate base course meeting the Illinois DOT gradation shown in Table 3.5. The as-received gradation of RCP-LS-IL, shown in Figure 3.2, approximates the typical dense-graded base layer (DGBL) gradation and generally meets the Illinois DOT CA 6 gradation requirements but on the fine side (indicated by the ± limits on the target gradation). Figure 3.3 shows the RCP-LS-IL material.

RCP with Gravel

RCP with gravel (RCP-GV-LA) was obtained from the Louisiana DOT&D's widening and rehabilitation project of State Route 67/US 167 near Ruston. An on-site crushing plant was used to produce RCP; PCC originated from rehabilitation

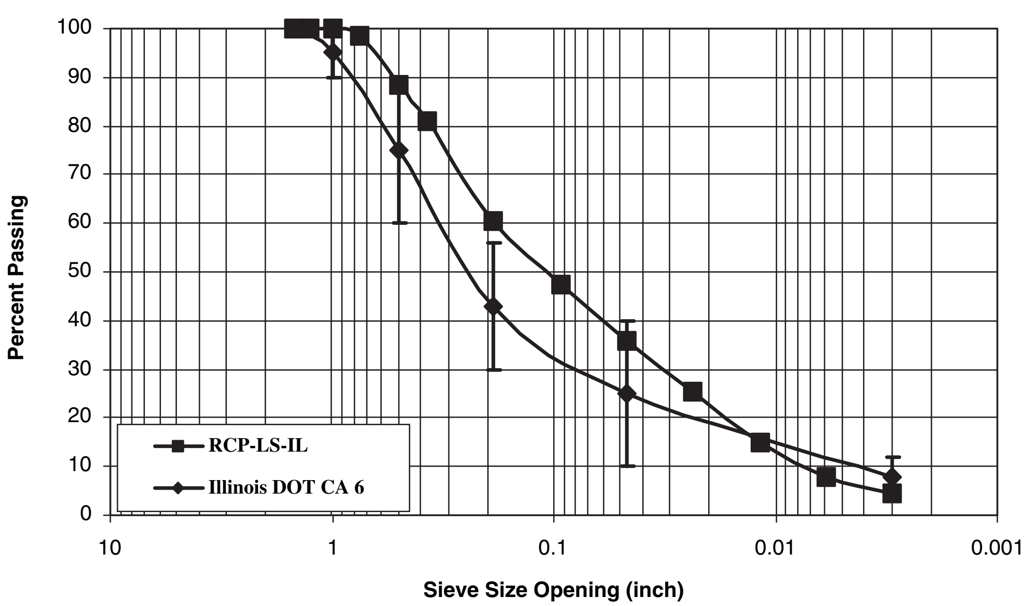


Figure 3.2. RCP-LS-IL as-received gradation and typical Illinois DOT CA 6 gradation.

Table 3.6. Louisiana DOT&D gradation for Class I and II coarse aggregate.

Sieve Size	Percent passing (percent finer)
1.5 in (37.5 mm)	100
1.0 in (25 mm)	95 ± 5
3/4 in (19 mm)	85 ± 15
No. 4 (4.75 mm)	50 ± 15
No. 40 (0.425 mm)	22 ± 10
No. 200 (0.075 mm)	9 ± 4

of I-20 near Monroe, Louisiana. The in-place PCC pavement slabs were in fair to poor condition prior to transportation to the crushing plant. Louisiana DOT&D allows the use of 100-percent RCP or in combination with an approved virgin aggregate.

The existing PCC was crushed to produce RCP meeting the gradation requirements shown in Table 3.6. The as-received RCP-GV-LA gradation closely matches Louisiana DOT&D and typical DGBL gradation requirements (see Figure 3.4). Figure 3.5 shows the RCP-GV-LA material.

RCP with Granite

RCP with granite (RCP-GR-SC) was obtained from rehabilitation and widening of the aircraft parking apron at Columbia Airport in South Carolina. The in-place PCC slabs were in fair condition and were removed as part of the apron expansion and rehabilitation project. The removed PCC slabs were

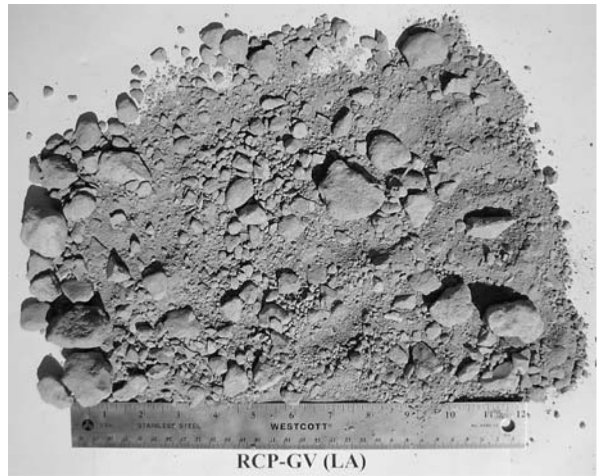


Figure 3.5. Photograph of RCP-GV-LA material used in laboratory testing.

shipped to a central crushing plant in Sumter, South Carolina, for RCP production. PCC was crushed to meet the South Carolina DOT gradation for RCP base course shown in Table 3.7. The as-received gradation of RCP-GR-SC is shown in Figure 3.6. Figure 3.7 shows photograph of RCP-GR-SC material used during laboratory testing.

RAP with Limestone

RAP with limestone (RAP-LS-MS) was obtained from a rehabilitation project on I-59 near Quitman, Mississippi. The

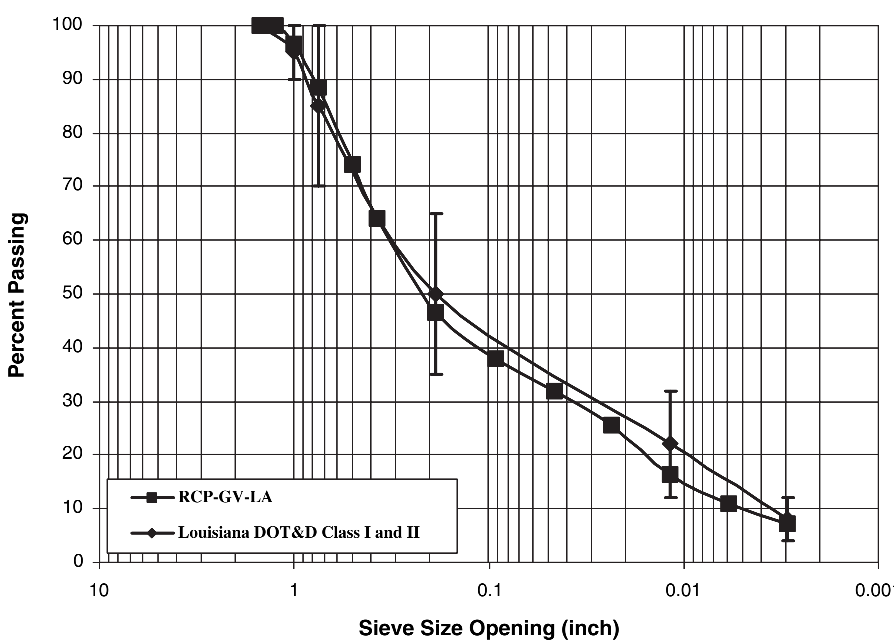


Figure 3.4. RCP-GV-LA as-received and typical Louisiana DOT&D gradations.

Table 3.7. Gradation requirements for South Carolina DOT recycled PCC base course.

Sieve Size	Percent passing (percent finer)
2.0 in (50.8 mm)	100
1.5 in (37.5 mm)	95 - 100
1.0 in (25 mm)	70 - 100
1/2 in (12.5 mm)	48 - 75
No. 4 (4.75 mm)	30 - 50
No. 30 (0.60 mm)	11 - 30
No. 200 (0.075 mm)	0 - 12

in-place HMA surface was in good condition before milling; the as-received RAP-LS-MS gradation is shown in Figure 3.8. Figure 3.9 shows the RAP-LS-MS material used in laboratory testing.

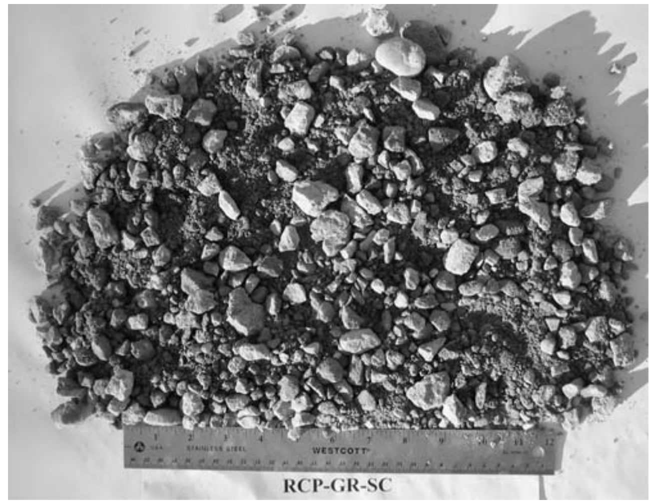


Figure 3.7. Photograph of RCP-GR-SC material used in laboratory testing.

RAP with Granite

RAP with granite (RAP-GR-CO) was obtained by milling 2 inches (50 mm) from the surface of a deteriorated major arterial street in eastern Denver. The as-received gradation of the RAP-GR-CO material is shown in Figure 3.10. Figure 3.11 shows RAP-GR-CO material used during laboratory testing.

RAP with Gravel

RAP with gravel (RAP-GV-LA) was obtained from Rayville, Louisiana; the as-received gradation is shown in Figure 3.12. RAP-GV-LA had a slightly finer gradation than a typical OGDL gradation. RAP was obtained by milling, and the pavement surface was in fair condition. Figure 3.13 shows RAP-GV-LA material used during laboratory testing.

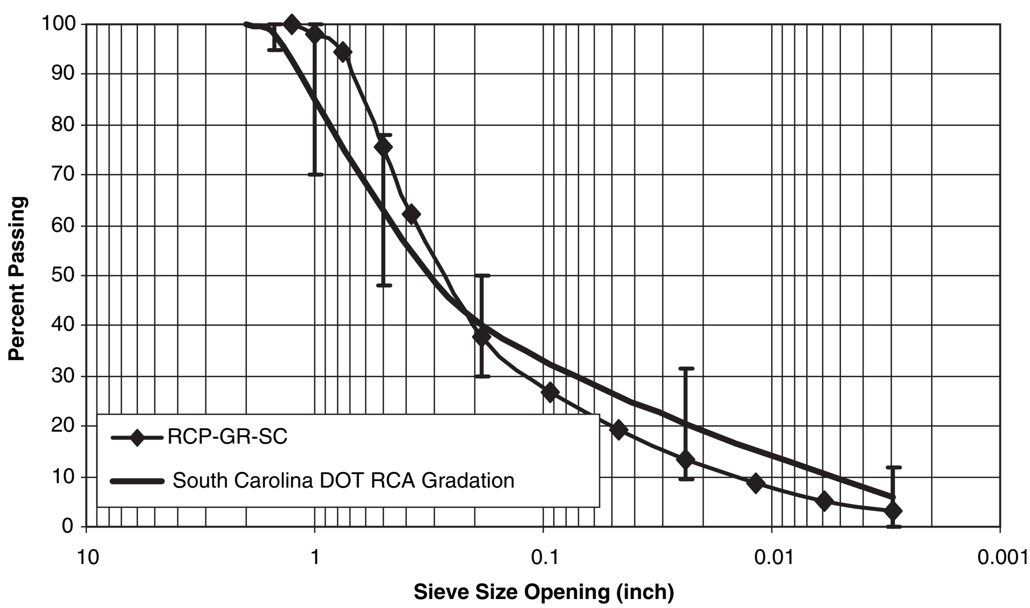


Figure 3.6. RCP-GR-SC as-received gradation and typical SC DGBL gradation.

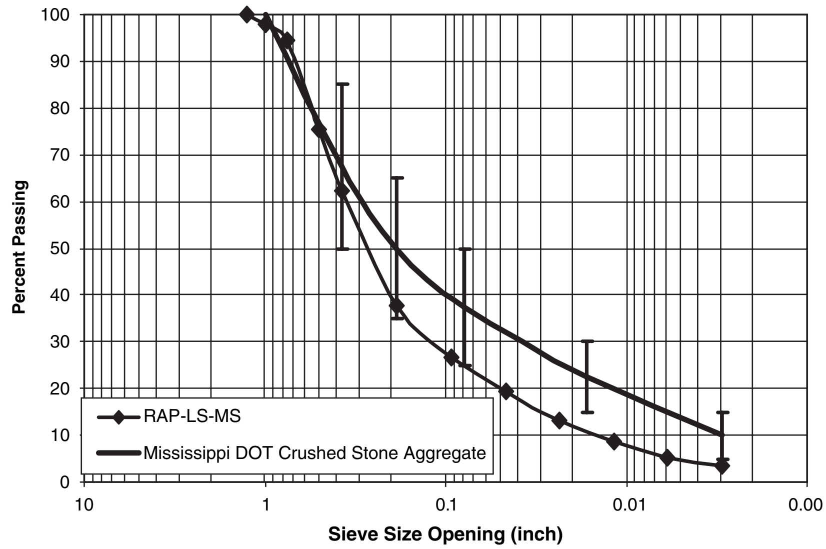


Figure 3.8. RAP-LS-MS as-received and Mississippi DOT aggregate gradations.

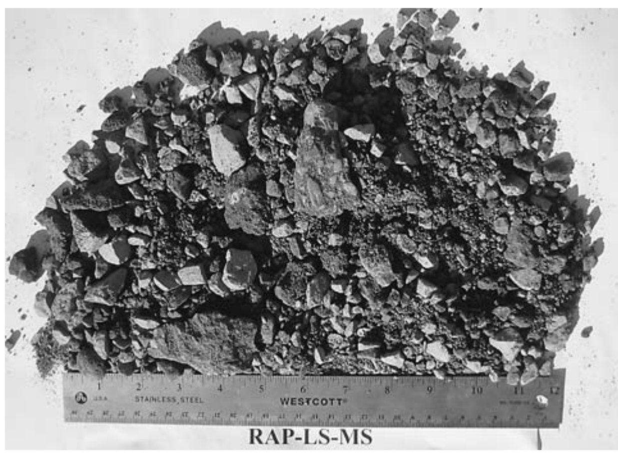


Figure 3.9. Photograph of RAP-LS-MS material used for laboratory testing.

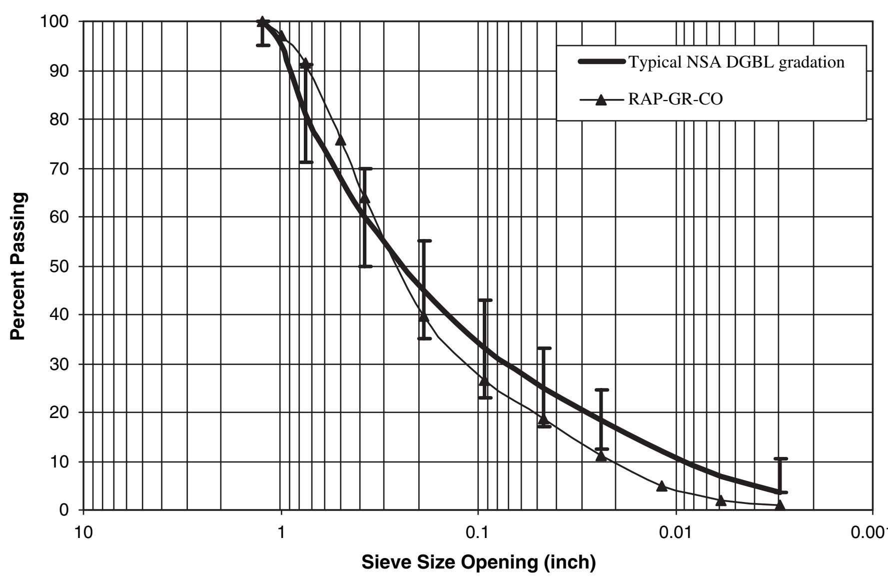


Figure 3.10. RAP-GR-CO as-received gradation and typical NSA DGBL gradation.

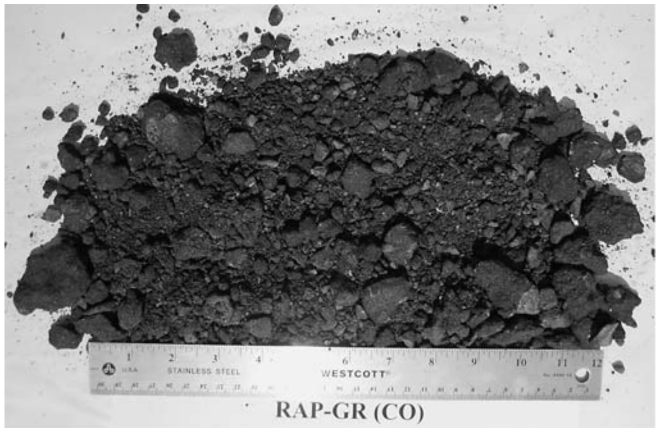


Figure 3.11. Photograph of RAP-GR-CO material used for laboratory testing.

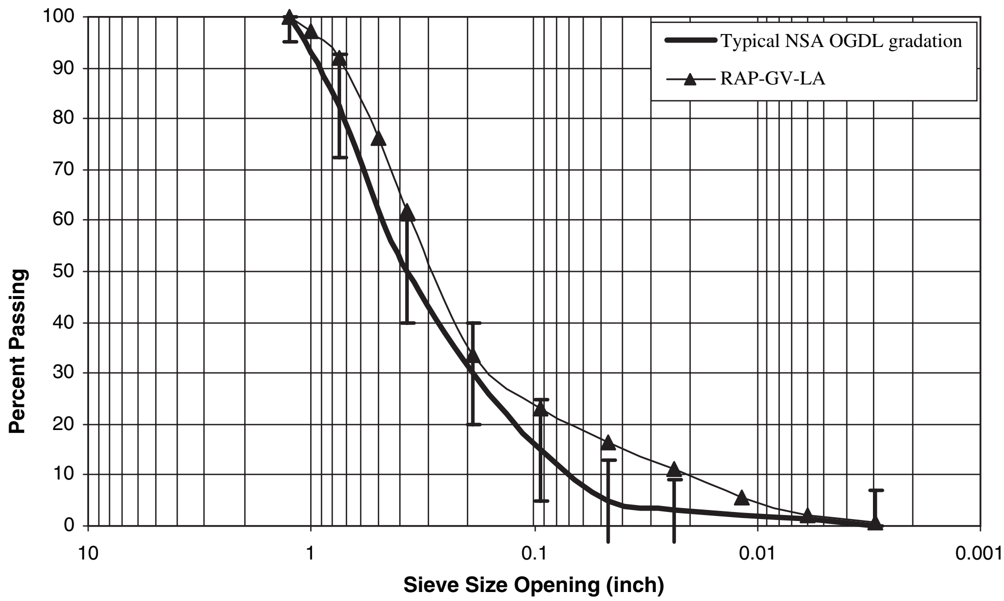


Figure 3.12. RAP-GV-LA as-received and typical NSA OGDL gradation.

Figure 3.13. Photograph of RAP-GV-LA material used for laboratory testing.

CHAPTER 4

Laboratory Test Program and Test Results

Laboratory Investigation

RAP and RCP materials are generally used as an unbound structural layer. Thus, most of the laboratory tests were conducted on samples meeting a target gradation similar to a DGBL; a few tests were conducted on samples prepared to a gradation similar to an OGDL. The target gradations, shown in Table 4.1, are based on typical gradations for virgin materials as provided in the Aggregate Handbook (*2*), which were adjusted based on results of the literature search and consideration of current practices.

RAP and RCP materials meeting the target gradations were procured to allow testing of recycled materials with gradations similar to as-produced gradations. Table 4.2 shows the test conducted and the material combinations that were evaluated.

Results of Laboratory Tests

Grain Size Analysis

All samples met the DGBL and OGDL gradation requirements. The gradations with corresponding target for as-received RCP DGBL, RAP OGDL, and RAP DGBL are shown in Figures 4.1, 4.2, and 4.3, respectively. The gradations for the blended virgin aggregate DGBL and virgin aggregate OGDL samples are shown in Figures 4.4 and 4.5, respectively.

RCP-GR-SC and RAP-GR-CO met the DGBL requirements as-received. These materials were blended to OGDL gradation. The constitutive aggregate in material referred to as RCP-LS-IL (in Figure 4.1 and subsequent figures) could have been dolomite or limestone. Figure 4.4 shows two virgin aggregate samples blended to meet DGBL requirements.

Moisture/Density Relations

Test specimens were prepared by compacting the RAP, RCP, and blends in accordance with test method D of AASHTO T 180. The OMC and the maximum dry densities for each material are listed in Table 4.2. As indicated, the OMCs of two materials (50/50 blend of RCP-GR-SC DGBL#2 and RAP-GR-CO 50/50 OGDL re-blend) were changed from the laboratory-determined values because of the free moisture observed during repeated load triaxial testing.

Static Triaxial Test

The static triaxial test was conducted in accordance with AASHTO T 234 on each sample at confining stresses of 0, 5, and 15 psi (0, 34.5, 103.4 kPa) to determine the shear strengths at OMC. Samples were prepared to approximately 95 percent of the maximum dry density values listed in Table 4.2. Table 4.3 shows the maximum deviator stress at various confining stresses. Coarse DGBL gradation of virgin aggregate (DGBL#1) had a higher maximum deviator stress compared to the finer DGBL gradation (DGBL#2); virgin OGDL had a lower maximum deviator stress compared to the DGBL gradations.

Figure 4.6 shows the maximum deviator stress at 15 psi (103.4 kPa) confining pressure in ascending order. Overall, RCP samples had the greatest maximum deviator stress, followed by virgin aggregate materials and RAP samples. Materials with as-received DGBL gradations also had a higher deviator stress compared to material with OGDL as-received gradations. RAP and RCP with granite aggregate had a higher maximum deviator stress, followed by materials with gravel and limestone.

Repeated Load Triaxial Test Results

The repeated load triaxial tests were conducted to obtain a relative measure of the resistance of tested materials to permanent deformation. The test procedure, described in detail in Appendix B (available as *NCHRP Web-Only Document 119* available on the webpage), is briefly discussed in Chapter 3. At each load level, 1,000 cycles were applied; the deviator stress for the first two load levels was 10 and 20 psi

Table 4.1. Percent passing for laboratory testing.

Sieve size	DGBL	OGDL
1.50 inch (37.5 mm)	95 - 100	100
3/4 inch (19.0 mm)	70 - 89	70 - 95
3/8 inch (9.5 mm)	50 - 70	35 - 65
No. 4 (4.75 mm)	35 - 55	20 - 40
No. 16 (1.18mm)	-- [a]	0 - 10
No. 30 (0.6 mm)	12 - 25	-- [a]
No. 50 (0.3 mm)	-- [a]	0 - 5
No. 100 (0.15 mm)	-- [a]	0 - 3
No. 200 (0.075 mm)	0 - 7	0 - 1

[a] Not recorded

(68.9 and 137.9 kPa) and increased by 20 psi (137.9 kPa) thereafter until failure (defined by a permanent axial strain of 10 percent) occurred or the load-frame limit was reached. Tests were conducted on triplicate OGDL samples prepared at OMC and on triplicate DGBL samples prepared at OMC in the saturated (wet) and unsaturated (dry) conditions. Results for repeated load triaxial tests conducted on RCP-GR-SC in the dry condition (unsaturated) are shown in Figures 4.7 and 4.8.

Figure 4.7 shows the axial strain percent versus deviator stress relationships for the first and last load increments at the beginning and following the 1000th cycle of a repeated stress loading increment. Figure 4.8 shows the magnitude of axial

Table 4.2. OMC and density data.

Material Tested	Tested Gradation	Maximum Dry Density (pcf)	OMC (percent)
Virgin DGBL Blend#1	DGBL#1	150.1	7.4
Virgin DGBL Blend#2	DGBL#2	141.1	6.3
Virgin OGDL Blend	OGDL	132.7	8.8
RAP-LS-MS	OGDL	124.1	6.3
RAP-GV-LA	OGDL	123.5	5.4
RAP-GR-CO	DGBL#2	125.8	10.3
RCP-LS-IL	DGBL#1	123.0	11.0
RCP-GV-LA	DGBL#1	121.7	9.0
RCP-GR-SC	DGBL#2	124.2	9.5
50/50 RAP-LS-MS	OGDL	128.7	6.8
50/50 RAP-GV-LA	OGDL	130.7	5.9
50/50 RAP-GR-CO	DGBL#2	130.3	4.0
50/50 RCP-LS-IL	DGBL#1	130.5	8.1
50/50 RCP-GV-LA	DGBL#1	132.0	7.6
50/50 RCP-GR-SC	DGBL#2	128.8	9.0 [a]
RAP-GR-CO 100%OGDL re-blend	OGDL	123.7	5.6
RAP-GR-CO 50/50 OGDL re-blend	OGDL	127.5	3.5
RCP-GR-SC 100%OGDL re-blend	OGDL	120.2	9.0 [b]
RCP-GR-SC 50/50 OGDL re-blend	OGDL	124.8	9.0

Notes: 1 pcf (pound/ft^3) = 16.02 kg/m^3

[a] OMC was lowered from 13.0 percent to 9.0 percent because of the free moisture observed during repeated load triaxial tests.

[b] OMC was lowered from 15.4 percent to 9.0 percent because of the free moisture observed during repeated load triaxial tests.

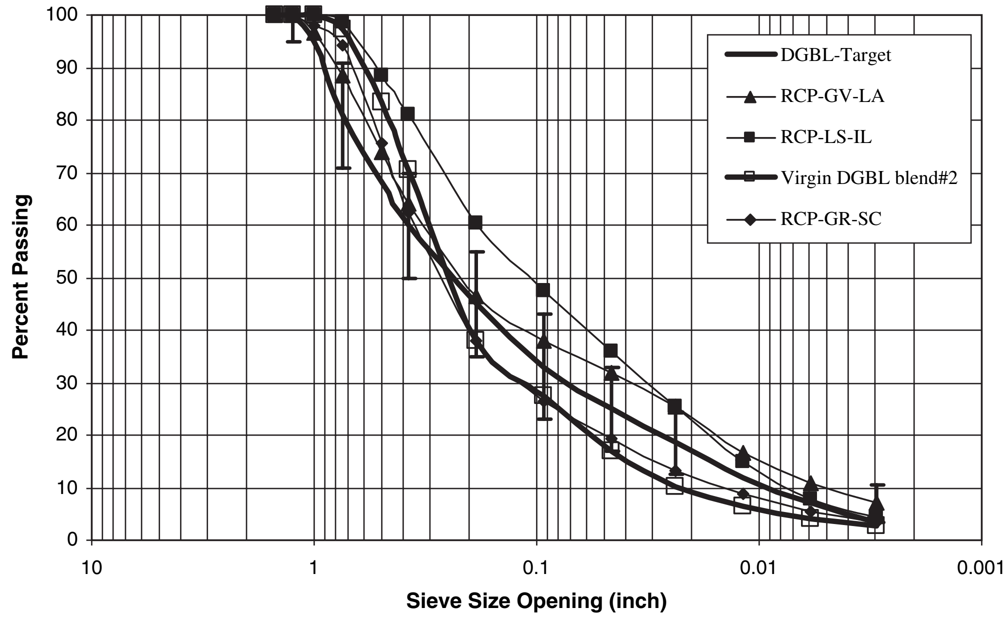


Figure 4.1. Gradation results of RCP as-received DGBL samples.

strain percent versus number of load cycles. Load increments, applied axial stress for each load cycle, and corresponding stress ratios are shown in Table 4.4. The stress ratio is defined as the ratio of major principal stresses (i.e., the ratio between vertical and horizontal stresses); it is equal to the ratio between the axial applied stress and chamber confining pressure (i.e., σ_1/σ_3).

Table 4.5 lists the stress ratios at which a particular permanent strain (1, 3, 7, or 10 percent) occurred for each triplicate sample. A higher stress ratio at lower permanent strain indicates a material with more resistance to permanent deformation.

Stress ratios (average of three tests) obtained from dry (tests conducted at OMC) repeated load triaxial tests are

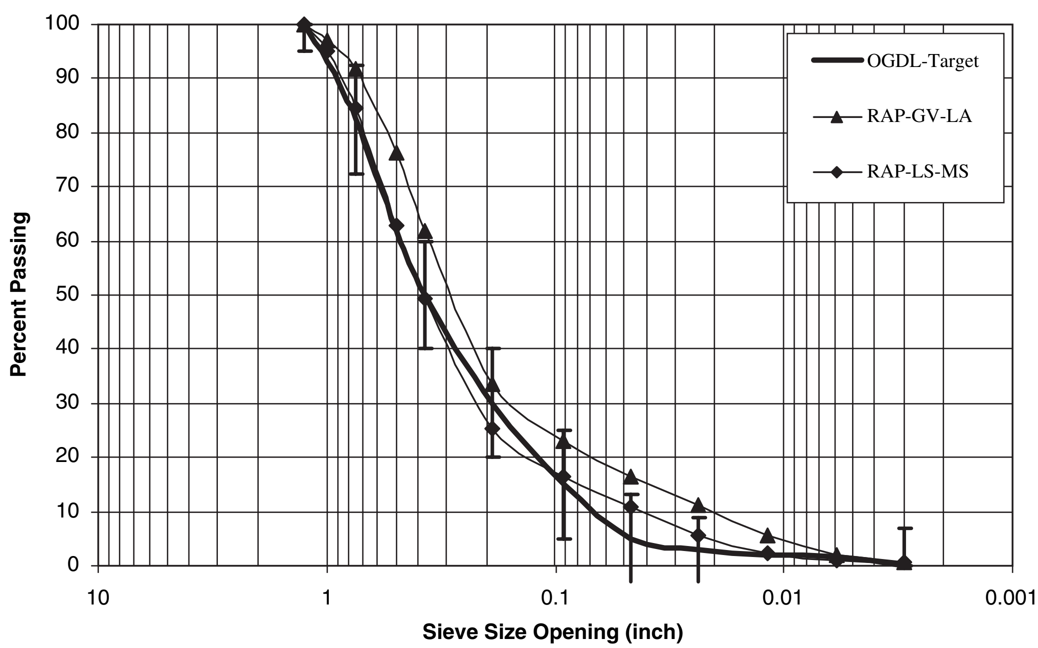


Figure 4.2. Gradation results of RAP as-received OGDL samples.

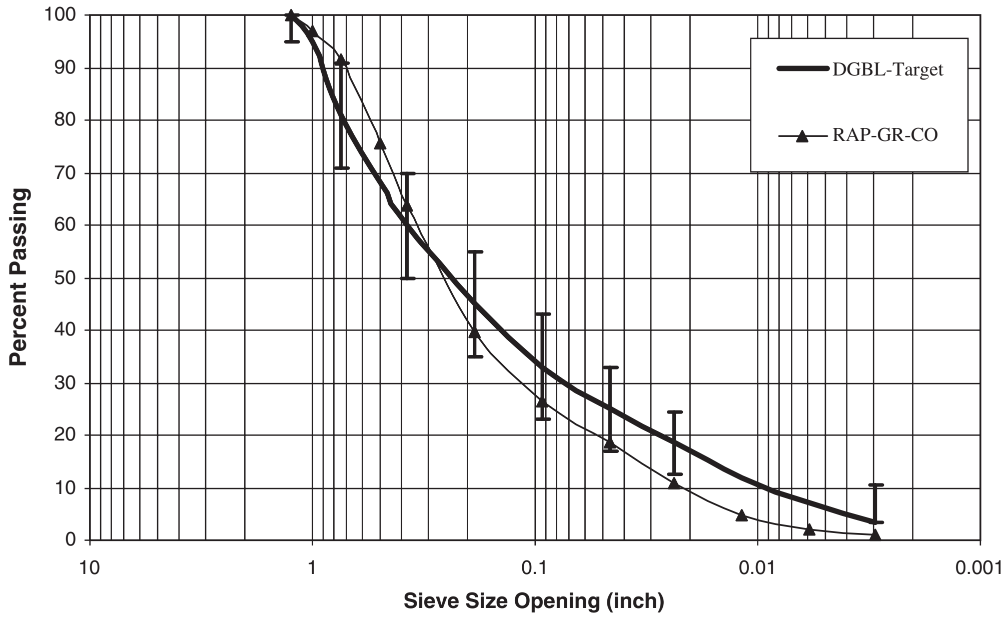


Figure 4.3. Gradation results of as-received RAP DGBL samples.

shown in Figure 4.9 for RAP and Figure 4.10 for RCP and virgin aggregate. The material resistant to permanent deformation has the highest stress ratio at the lowest permanent strain. In dry tests, 50-percent blends of RAP with virgin aggregate exhibited the highest permanent deformation resistance of RAP materials. RCP-GV-LA exhibited the highest overall permanent deformation resistance in the dry test, followed by virgin aggregate DGBL#1 and OGDL gradations. Figures 4.11 and 4.12 show the stress ratios (average of three tests) for wet and dry tests on RAP and virgin aggregate samples (DGBL gradations) and on RCP (DGBL gradations).

Virgin aggregate DGBL#1 exhibited the least permanent strain in dry repeated load triaxial tests, and virgin aggregate DGBL#2 the least permanent strain in wet tests. Of tested

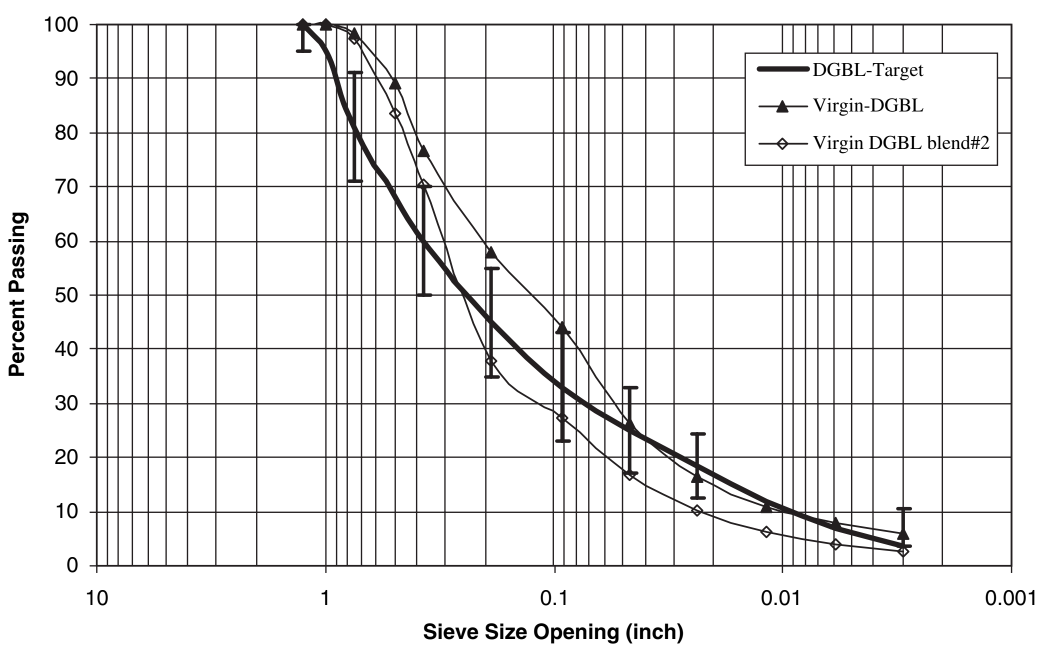


Figure 4.4. Gradation results of virgin aggregate DGBL-blended sample.

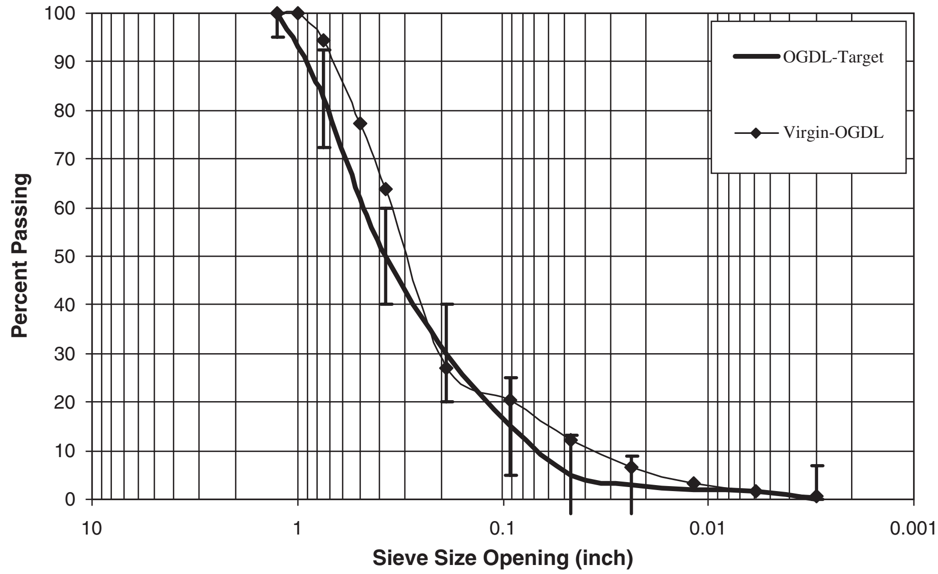


Figure 4.5. Gradation results of virgin aggregate OGDL-blended sample.

Table 4.3. Failure deviator stress.

Sample Identification	Blend	Φ	c (psi)	Confining Pressure (psi)		
				0	5	15
				Max. Deviator Stress, σ_d (psi)		
Virgin DGBL Blend#1	DGBL#1	48.0	5.21	42.09 [a]	69.54 [b]	121.14
Virgin DGBL Blend#2	DGBL#2	49.0	2.08	11.20	44.21	106.40
Virgin OGDL Blend	OGDL	45.0	2.78	27.17 [a]	50.59 [b]	83.51
RAP-LS-MS	OGDL	38.5	4.17	26.86 [a]	41.10 [b]	65.30
RAP-GV-LA	OGDL	39.0	2.78	23.56 [a]	37.82 [b]	61.73
RAP-GR-CO	DGBL#2	41.0	2.08	11.20	32.20	63.96
RCP-LS-IL	DGBL#1	46.0	5.56	39.16 [a]	66.36 [b]	103.20
RCP-GV-LA	DGBL#1	48.0	1.39	25.39 [a]	55.06 [b]	96.05
RCP-GR-SC	DGBL#2	52.0	2.78	19.26	56.33	129.58
50/50 RAP-LS-MS [c]	OGDL	--	--	--	--	--
50/50 RAP-GV-LA [c]	OGDL	--	--	--	--	--
50/50 RAP-GR-CO	DGBL#2	42.0	1.74	6.77	33.52	69.74
50/50 RCP-LS-IL	DGBL#1	50.0	2.08	12.45	50.65	106.22
50/50 RCP-GV-LA [c]	DGBL#1	--	--	--	--	--
50/50 RCP-GR-SC	DGBL#2	50.0	2.08	10.18	50.30	109.63
RAP-GR-CO 100% OGDL re-blend	OGDL	52.0	1.74	8.96	31.49	128.94
RAP-GR-CO 50/50 OGDL re-blend	OGDL	42.0	1.74	6.18	31.17	68.25
RCP-GR-SC 100% OGDL re-blend	OGDL	50.0	2.78	16.88	52.24	111.24
RCP-GR-SC 50/50 OGDL re-blend	OGDL	49.0	1.74	12.40	55.53	103.63

Notes: 1 psi = 6.9 kPa
[a] Maximum deviator stress at confining stress of 3 psi
[b] Maximum deviator stress at confining stress of 7 psi
[c] Not tested

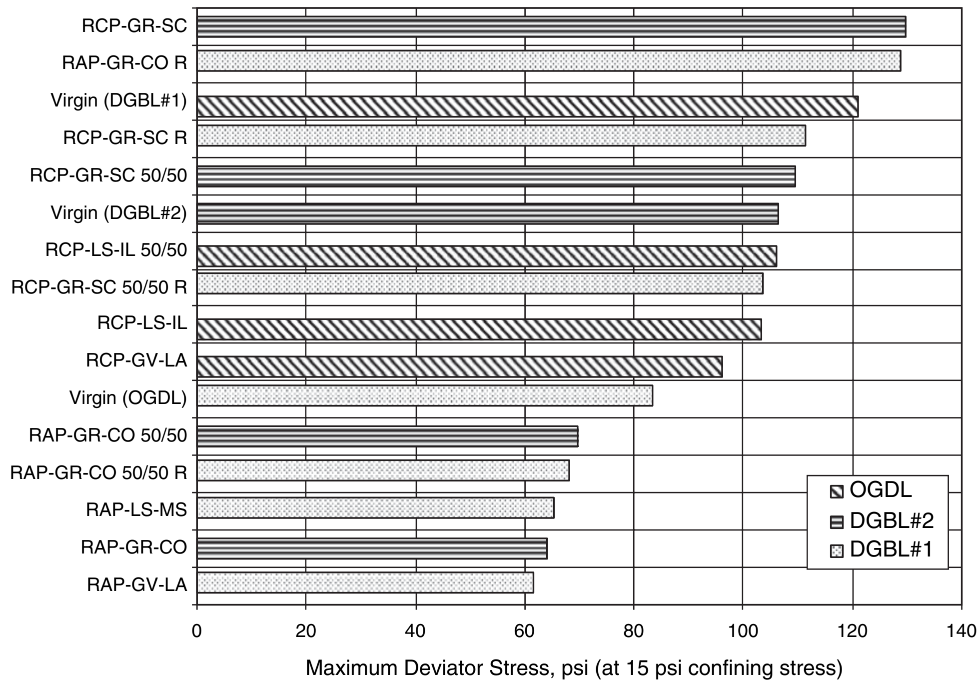


Figure 4.6. Maximum deviator stress in static triaxial tests.

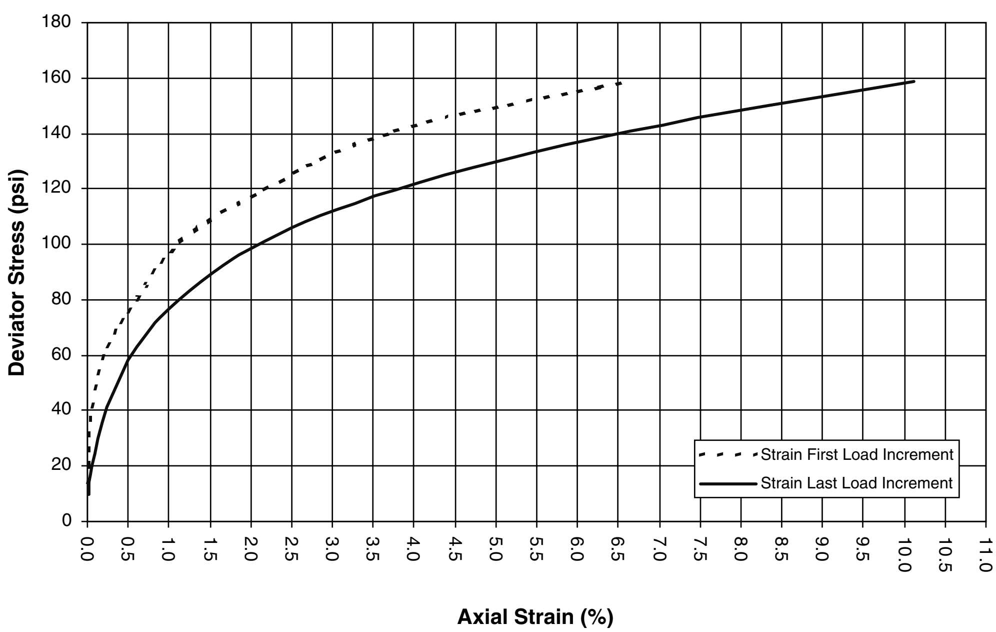


Figure 4.7. Repeated load triaxial test results for RCP-GR-SC at OMC.

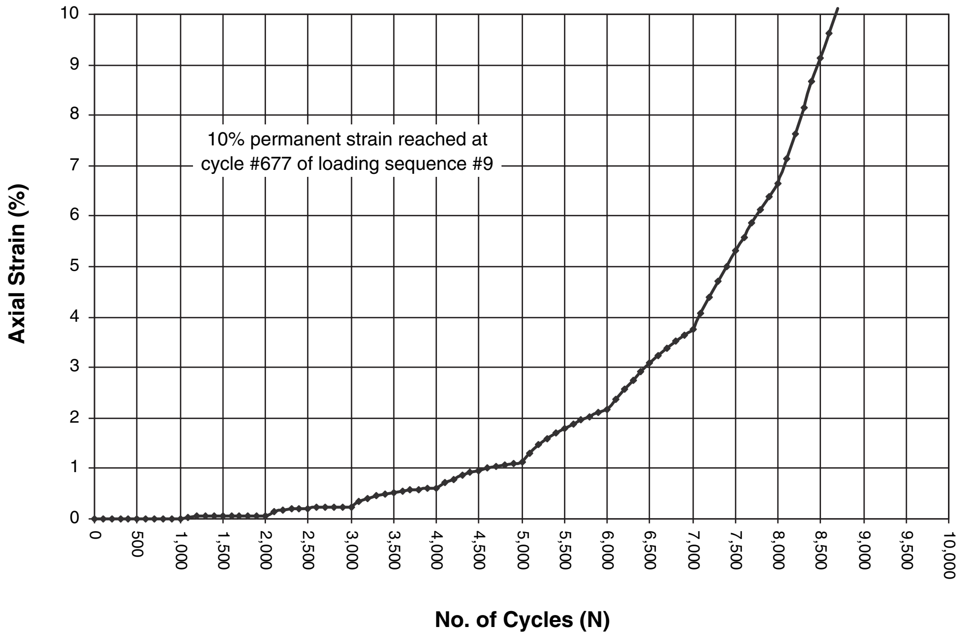


Figure 4.8. Load repetitions versus permanent axial strain for RCP-GR-SC at OMC.

materials, the 50-percent blend of RAP-GR-CO with virgin aggregate was more resistant to permanent deformation in both the wet and dry repeated load triaxial tests compared to as-received RAP-GR-CO material. RCP-GV-LA exhibited the highest permanent deformation resistance in the dry tests of all RCP materials. In wet tests, the RCP-GR-SC material showed better resistance to permanent deformation.

The number of load repetitions required to cause failure (10-percent permanent strain) was also used to evaluate resistance to permanent deformation (Figure 4.13). Virgin aggregate DGBL exhibited the highest resistance to permanent deformation. The test was terminated after 10,000 cycles at which the average permanent deformation was only 3.67 percent. Similar data are presented in Figure 4.14 for wet and dry tests on DGBL gradations.

Table 4.4. Stress ratios for repeated load triaxial test load cycles.

Load Increment	Load cycles	Axial Stress		Stress Ratio
		psi	kPa	
1	0 - 1,000	10	68.9	0.67
2	1,001 - 2,000	20	137.9	2.00
3	2,001 - 3,000	40	275.8	3.33
4	3,001 - 4,000	60	413.7	4.67
5	4,001 - 5,000	80	551.6	6.00
6	5,001 - 6,000	100	689.5	7.33
7	6,001 - 7,000	120	827.4	8.67
8	7,001 - 8,000	140	965.3	10.00
9	8,001 - 9,000	160	1,103.2	11.33
10	9,001 - 10,000	180	1,241.1	12.67

Resilient Modulus Test Results

Resilient modulus (M_R) was obtained using repeated load triaxial test data. M_R values determined for different bulk stresses at an as-tested confining pressure of 15 psi (103.4 kPa) are shown in Figure 4.15. The relationship is expressed by the equation:

$$M_R = K_1 \theta^{K2}$$

where θ is bulk stress (psi)
K_1 and K_2 are the experimental constant and coefficient, respectively

K_1 and K_2 values determined for the tested materials are listed in Table 4.6 in order of stiffness for the dry tests. The M_R values were calculated for 100 psi (689.5 kPa) bulk stress using K_1 and K_2 values determined for dry and wet repeated load triaxial tests. Virgin aggregate has the greatest stiffness, followed by the 50-percent blend of RAP-LS-MS, RCP-GV-LA, RAP-LS-MS, and 50-percent blend of RAP-GR-CO. Most of the materials tested in both and wet dry conditions did not show significant reduction in stiffness in the wet condition. In fact, the stiffness of RAP and RCP samples with granite in

Table 4.5. Stress ratios for different permanent strain levels.

Material	Sample Identification	Load increment for strain achieved and stress ratio (SR)							
		1%	σ_1/σ_3	3%	σ_1/σ_3	7%	σ_1/σ_3	10%	σ_1/σ_3
Virgin DGBL Blend#1	*Dry Test #1*	5	6.0	8	10.0	4.8% strain at cycle #10,000			
	Dry Test #2	5	6.0	10	12.7	3.2% strain at cycle #10,000			
	Dry Test #3	6	7.3	10	12.7	3.0% strain at cycle #10,000			
	Saturated Test #1	4	4.7	7	8.7	9	11.3	10	12.7
	Saturated Test #2	4	4.7	7	8.7	10	12.7	10	12.7
	Saturated Test #3	4	4.7	7	8.7	9	11.3	9	11.3
Virgin DGBL Blend#2	*Dry Test #1*	5	6.0	8	10.0	10	12.7	10	12.7
	Dry Test #2	5	6.0	8	10.0	9	11.3	10	12.7
	Dry Test #3	5	6.0	8	10.0	9	11.3	10	12.7
	Saturated Test #1	5	6.0	7	8.7	8	10.0	8	10.0
	Saturated Test #2	5	6.0	6	7.3	8	10.0	8	10.0
	Saturated Test #3	5	6.0	7	8.7	8	10.0	8	10.0
Virgin OGDL Blend	*Dry Test #1*	6	7.3	8	10.0	9	11.3	9	11.3
	Dry Test #2	5	6.0	8	10.0	9	11.3	9	11.3
	Dry Test #3	5	6.0	8	10.0	9	11.3	10	12.7
RAP-LS-MS	*Dry Test #1*	3	3.3	5	6.0	7	8.7	9	11.3
	Dry Test #2	3	3.3	5	6.0	7	8.7	9	11.3
	Dry Test #3	3	3.3	5	6.0	7	8.7	8	10.0
	100°F Test	3	3.3	5	6.0	7	8.7	9	11.3
RAP-GV-LA	*Dry Test #1*	3	3.3	5	6.0	7	8.7	8	10.0
	Dry Test #2	3	3.3	5	6.0	7	8.7	8	10.0
	Dry Test #3	4	4.7	5	6.0	7	8.7	8	10.0
RAP-GR-CO	*Dry Test #1*	3	3.3	5	6.0	8	10.0	10	12.7
	Dry Test #2	3	3.3	5	6.0	8	10.0	10	12.7
	Dry Test #3	3	3.3	5	6.0	8	10.0	9	11.3
	100°F Test	2	2.0	6	7.3	8	10.0	10	12.7
	Saturated Test #1	3	3.3	5	6.0	8	10.0	10	12.7
	Saturated Test #2	3	3.3	5	6.0	8	10.0	9	11.3
	Saturated Test #3	3	3.3	6	7.3	9	11.3	10	12.7
RCP-LS-IL	*Dry Test #1*	5	6.0	7	8.7	5.4% strain at cycle #8,800			
	Dry Test #2	5	6.0	8	10.0	6.9% strain at cycle #10,000			
	Dry Test #3	5	6.0	7	8.7	9	11.3	10	12.7
	Saturated Test #1	5	6.0	8	10.0	9	11.3	10	12.7
	Saturated Test #2	6	7.3	8	10.0	10	12.7	10	12.7
	Saturated Test #3	6	7.3	8	10.0	9	11.3	10	12.7
RCP-GV-LA	*Dry Test #1*	8	10.0	2.8% strain, cycle #9,001, at > load cell capacity					
	Dry Test #2	8	10.0	10	12.7	4.5% strain at cycle #10,000			
	Dry Test #3	6	7.3	8	10.0	10	12.7	10	12.7
	Saturated Test #1	5	6.0	6	7.3	7	8.7	8	10.0
	Saturated Test #2	5	6.0	6	7.3	8	10.0	8	10.0
	Saturated Test #3	5	6.0	6	7.3	8	10.0	8	10.0
RCP-GR-SC	*Dry Test #1*	5	6.0	7	8.7	9	11.3	9	11.3
	Dry Test #2	5	6.0	7	8.7	9	11.3	9	11.3
	Dry Test #3	5	6.0	7	8.7	9	11.3	10	12.7
	Saturated Test #1	5	6.0	7	8.7	8	10.0	9	11.3
	Saturated Test #2	5	6.0	6	7.3	8	10.0	9	11.3
	Saturated Test #3	5	6.0	7	8.7	8	10.0	9	11.3
50/50 RAP-LS-MS	*Dry Test #1*	4	4.7	6	7.3	8	10.0	9	11.3
	Dry Test #2	4	4.7	6	7.3	8	10.0	9	11.3
	Dry Test #3	4	4.7	6	7.3	8	10.0	9	11.3
	100°F Test	4	4.7	6	7.3	8	10.0	9	11.3
50/50 RAP-GV-LA	*Dry Test #1*	4	4.7	6	7.3	8	10.0	8	10.0
	Dry Test #2	4	4.7	6	7.3	8	10.0	9	11.3
	Dry Test #3	4	4.7	6	7.3	8	10.0	8	10.0

(continued on next page)

Table 4.5. (Continued).

Material	Sample Identification	Load increment for strain achieved and stress ratio (SR)							
		1%	σ_1/σ_3	3%	σ_1/σ_3	7%	σ_1/σ_3	10%	σ_1/σ_3
50/50 RAP-GR-CO	*Dry Test #1*	4	4.7	6	7.3	8	10.0	9	11.3
	Dry Test #2	4	4.7	6	7.3	8	10.0	9	11.3
	Dry Test #3	4	4.7	6	7.3	8	10.0	9	11.3
	100°F Test	3	3.3	5	6.0	8	10.0	9	11.3
	Saturated Test #1	4	4.7	6	7.3	8	10.0	9	11.3
	Saturated Test #2	4	4.7	6	7.3	8	10.0	9	11.3
	Saturated Test #3	4	4.7	6	7.3	8	10.0	9	11.3
50/50 RCP-LS-IL	*Dry Test #1*	4	4.7	7	8.7	9	11.3	10	12.7
	Dry Test #2	5	6.0	7	8.7	9	11.3	10	12.7
	Dry Test #3	5	6.0	7	8.7	9	11.3	10	12.7
	Saturated Test #1	4	4.7	6	7.3	7	8.7	8	10.0
	Saturated Test #2	5	6.0	6	7.3	8	10.0	9	11.3
	Saturated Test #3	5	6.0	6	7.3	7	8.7	8	10.0
50/50 RCP-GV-LA	*Dry Test #1*	5	6.0	7	8.7	9	11.3	9	11.3
	Dry Test #2	5	6.0	7	8.7	9	11.3	10	12.7
	Dry Test #3	5	6.0	7	8.7	8	10.0	8	10.0
	Saturated Test #1	4	4.7	6	7.3	7	8.7	8	10.0
	Saturated Test #2	5	6.0	7	8.7	8	10.0	9	11.3
	Saturated Test #3	5	6.0	6	7.3	8	10.0	8	10.0
50/50 RCP-GR-SC	*Dry Test #1*	5	6.0	7	8.7	10	12.7	10	12.7
	Dry Test #2	4	4.7	7	8.7	9	11.3	9	11.3
	Dry Test #3	4	4.7	6	7.3	8	10.0	9	11.3
	Saturated Test #1	4	4.7	6	7.3	8	10.0	9	11.3
	Saturated Test #2	4	4.7	6	7.3	8	10.0	8	10.0
	Saturated Test #3	4	4.7	6	7.3	7	8.7	8	10.0
RAP-GR-CO 100%OGDL re- blend	*Dry Test #1*	3	3.3	5	6.0	7	8.7	9	11.3
	Dry Test #2	3	3.3	5	6.0	8	10.0	9	11.3
	Dry Test #3	3	3.3	5	6.0	7	8.7	9	11.3
RAP-GR-CO 50/50 OGDL re-blend	*Dry Test #1*	4	4.7	5	6.0	7	8.7	9	11.3
	Dry Test #2	3	3.3	5	6.0	7	8.7	8	10.0
	Dry Test #3	4	4.7	5	6.0	8	10.0	9	11.3
RCP-GR-SC 100%OGDL re-blend	*Dry Test #1*	4	4.7	6	7.3	8	10.0	8	10.0
	Dry Test #2	5	6.0	7	8.7	8	10.0	9	11.3
	Dry Test #3	5	6.0	7	8.7	8	10.0	9	11.3
RCP-GR-SC 50/50 OGDL re-blend	*Dry Test #1*	5	6.0	7	8.7	8	10.0	9	11.3
	Dry Test #2	5	6.0	7	8.7	8	10.0	9	11.3
	Dry Test #3	5	6.0	7	8.7	8	10.0	9	11.3

as-received condition increased slightly under wet conditions. However, the stiffness of the 50-percent blend of RCP-GV-LA, virgin DGBL#1, and RCP-GV-LA was reduced by 15, 20, and 33 percent when tested in wet conditions, respectively, suggesting that these materials may be susceptible to wet conditions.

Toughness and Abrasion Resistance

Aggregate toughness was determined using the Micro-Deval test (AASHTO TP 58-00), which provides an indication of an aggregate's degradation potential. Test results are listed in Table 4.7; data reported for 50-percent blends were calculated using data from tests on as-received gradations.

Durability

Aggregate durability, when subjected to freeze-thaw cycles in the presence of moisture, was determined using the Canadian Freeze-Thaw test (MTO LS-614). Test results are listed in Table 4.7; test results for the 50-percent blends were calculated using data from tests on as-received gradations.

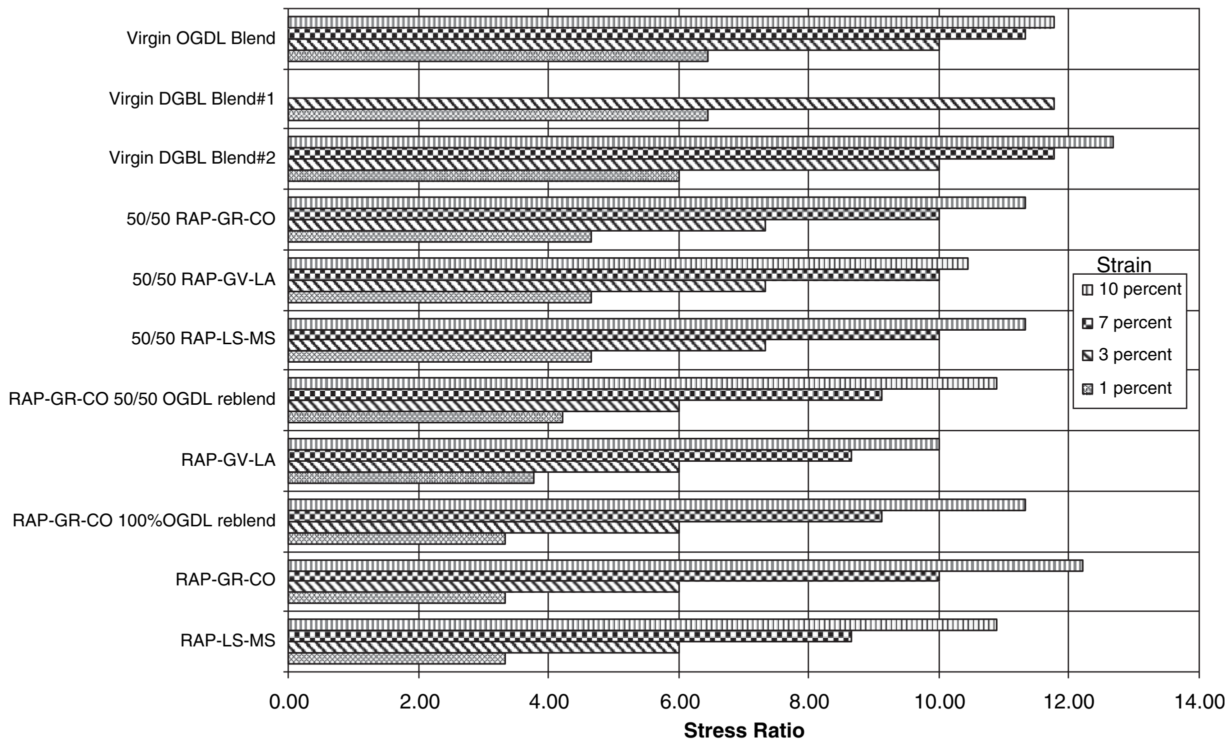


Figure 4.9. Stress ratios for dry triaxial tests on RAP samples.

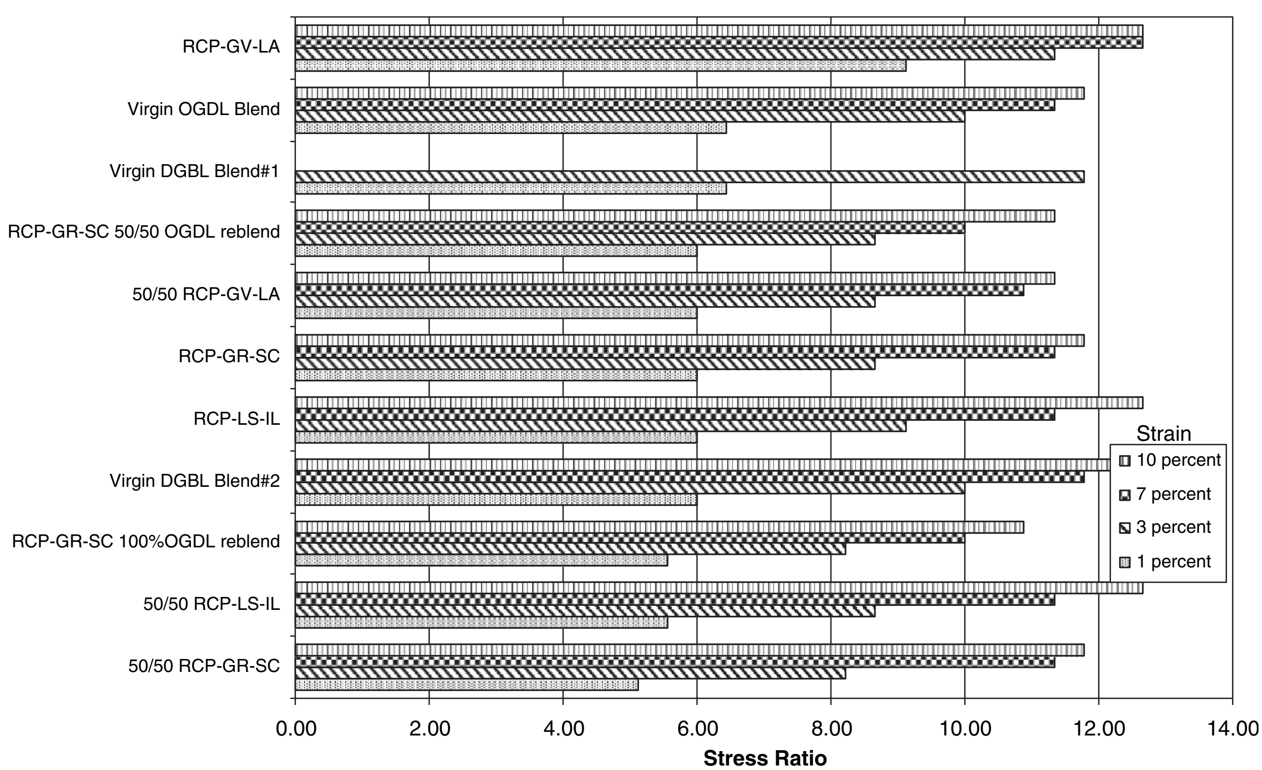


Figure 4.10. Stress ratios for dry triaxial tests on RCP and virgin samples.

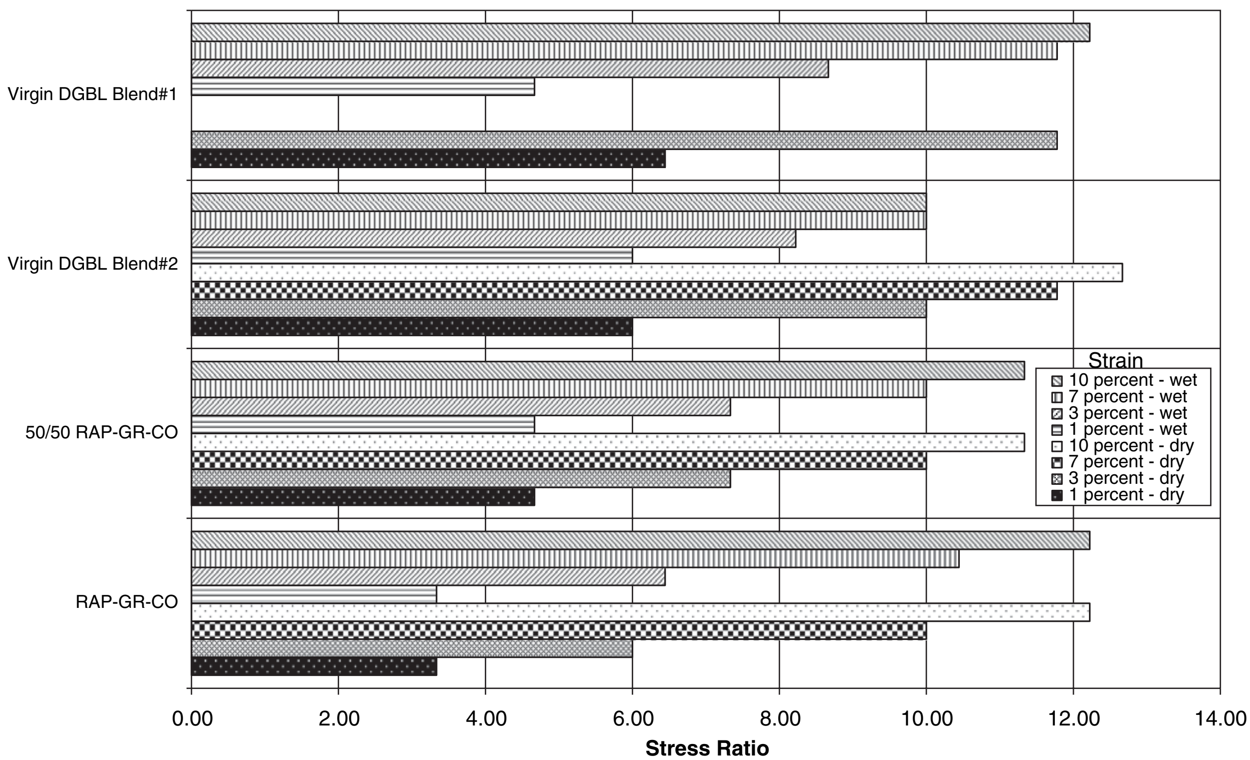


Figure 4.11. Stress ratios for dry and wet triaxial tests on RAP and virgin samples.

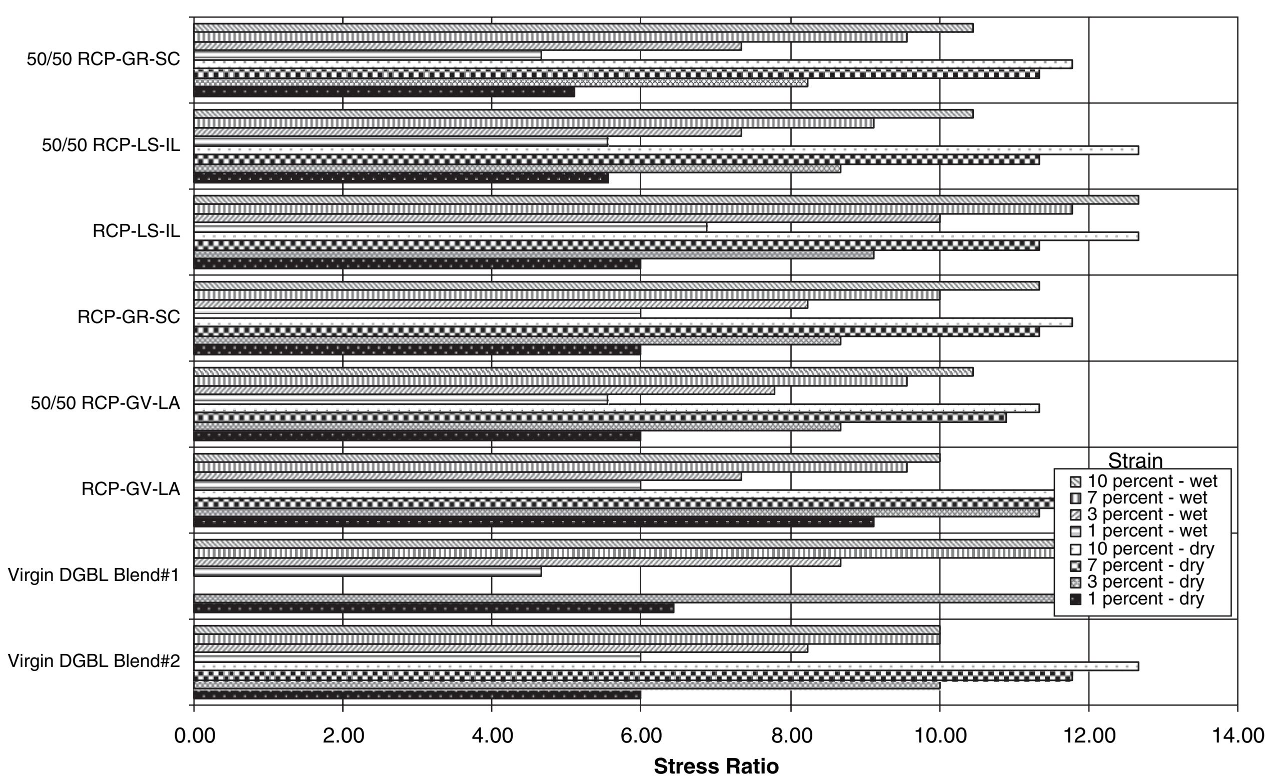


Figure 4.12. Stress ratios for dry and wet triaxial tests on RCP samples.

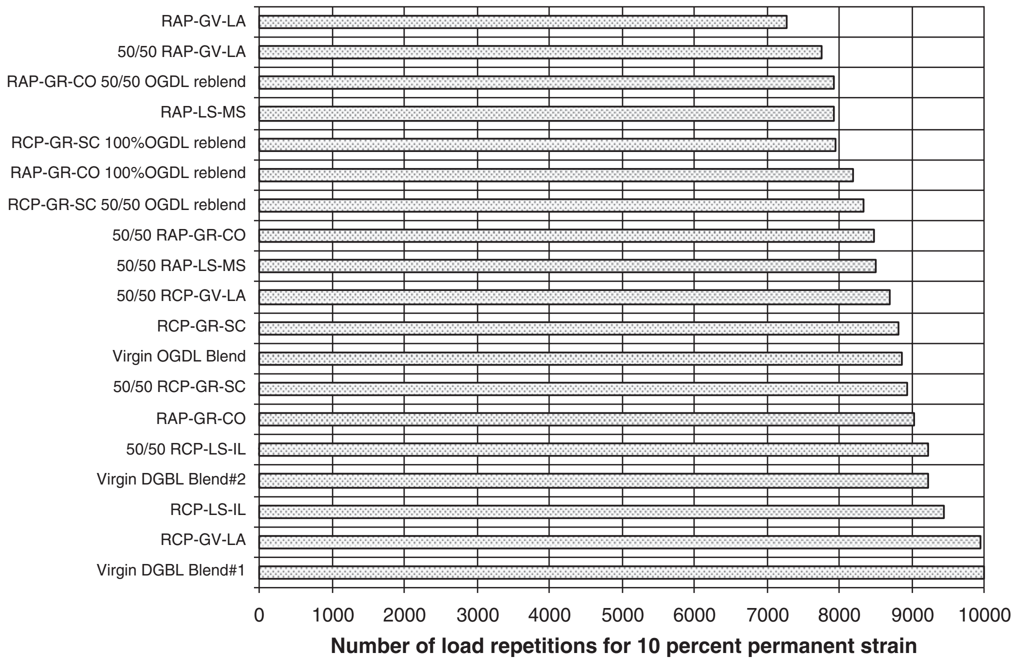


Figure 4.13. Number of load repetitions at 10-percent permanent strain (dry tests).

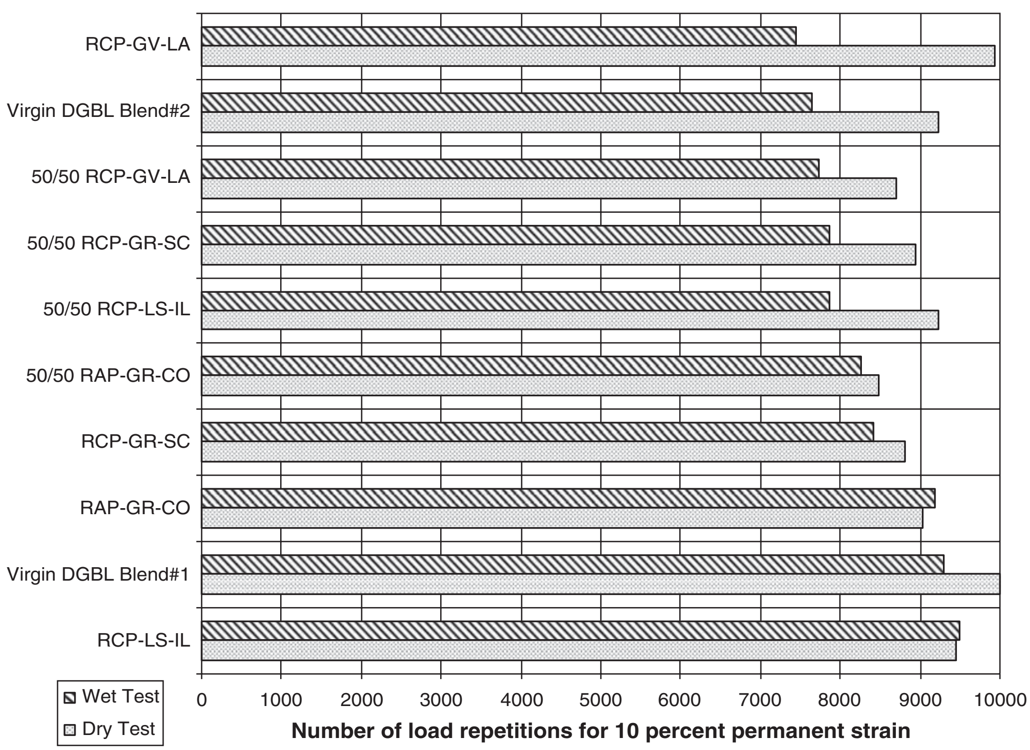


Figure 4.14. Failure load repetitions for wet and dry tests.

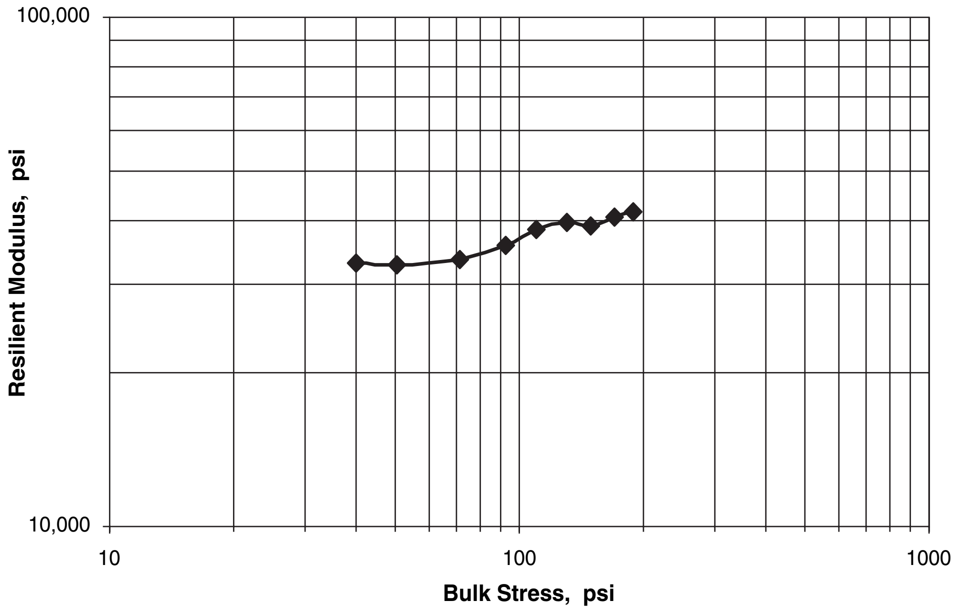


Figure 4.15. Resilient modulus test results for RCP-GR-SC.

Table 4.6. Resilient modulus data from repeated load triaxial testing.

Sample Identification	Dry Tests		Wet Tests		M_R at θ=100 psi	
	K_1	K_2	K_1	K_2	Dry	Wet
Virgin DGBL Blend#1	6,831	0.4897	12,487	0.3113	65,153	52,361
Virgin OGDL Blend	18,172	0.2657	-- [a]	-- [a]	61,785	-- [a]
Virgin DGBL Blend#2	13,348	0.3269	15,338	0.2876	60,139	57,672
50/50 RAP-LS-MS	10,567	0.3691	-- [a]	-- [a]	57,836	-- [a]
RCP-GV-LA	9,717	0.3870	36,947	0.0112	57,749	38,900
RAP-LS-MS	8,611	0.4008	-- [a]	-- [a]	54,545	-- [a]
50/50 RAP-GR-CO	14,559	0.2760	15,010	0.2656	51,906	51,007
50/50 RAP-GV-LA	14,897	0.2666	-- [a]	-- [a]	50,856	-- [a]
RAP-GR-CO 100%OGDL re-blend	9,786	0.3560	-- [a]	-- [a]	50,418	-- [a]
50/50 RCP-GV-LA	19,308	0.2074	23,343	0.1318	50,184	42,824
RAP-GR-CO 50/50 OGDL re-blend	9,337	0.3630	-- [a]	-- [a]	49,692	-- [a]
RCP-LS-IL	14,243	0.2713	25,452	0.1389	49,691	48,245
RAP-GR-CO	6,437	0.4411	8,459	0.3876	49,078	50,420
50/50 RCP-LS-IL	15,791	0.2432	24,468	0.1318	48,397	44,892
RAP-GV-LA	15,003	0.2534	-- [a]	-- [a]	48,202	-- [a]
50/50 RCP-GR-SC	9,980	0.3263	15,576	0.2205	44,852	43,004
RCP-GR-SC 50/50 OGDL re-blend	10,172	0.3084	-- [a]	-- [a]	42,097	-- [a]
RCP-GR-SC 100%OGDL re-blend	21,591	0.1229	-- [a]	-- [a]	38,024	-- [a]
RCP-GR-SC	16,085	0.1848	21,774	0.1258	37,676	38,860

Notes: [a] wet tests on these materials were not included in laboratory investigation.
1 psi = 6.895 kPa

Table 4.7. Percent loss for Micro-Deval and Canadian Freeze-Thaw tests.

Material Identification	Percent Loss	
	Micro-Deval	Canadian Freeze-Thaw
50/50 RCP-LS-IL *	6.40	10.70
Virgin DGBL Blend#1	6.60	0.60
RAP-GV-LA	7.50	1.90
50/50 RCP-GV-LA *	7.80	1.40
Virgin OGDL Blend	8.10	0.90
50/50 RCP-GR-SC *	8.65	12.95
RCP-GR-SC	10.70	25.30
50/50 RAP-GR-CO *	12.65	5.05
50/50 RCP-GV-LA *	13.05	12.25
50/50 RAP-LS-MS *	13.20	0.80
RAP-LS-MS	18.30	0.70
RAP-GR-CO	18.70	9.50
RCP-LS-IL	19.40	22.00
RCP-GV-LA	19.50	23.90

Note: * Percent loss for 50-percent blends are averages of data for as-received gradations

Frost Susceptibility

Tube suction tests were conducted to characterize the moisture susceptibility properties of RAP, RCP, and virgin aggregate materials. The test measures the moisture affinity of a granular material by subjecting the test specimens to a 10-day capillary soak in a water bath, as described in Texas Test Method 144 E (*12*).

Materials with a high affinity for water will imbibe significant amounts of water through suction, sometimes resulting in moisture contents higher than optimum after the capillary soaking period and substantial amounts of unbound, or "free," water in the aggregate matrix. This unbound water will influence the material's ability to resist both traffic loading and freeze-thaw cycling. In this test, specimens are molded at OMC; RAP samples were more difficult to mold as compared to RCP samples. Figure 4.16 shows some of the molded samples.

To monitor the amount of free water, the tube suction test measures the surface dielectric constant of the material, which is an indication of the free water in the aggregate system, and studies (*12*) have shown that materials with a surface dielectric constant value of greater than 10 after the capillary soak can, in some environments, exhibit poor performance in the field. Figure 4.17 shows the apparatus used to make the surface dielectric measurements.

Plots of the surface dielectric constant value versus time for the tested materials are shown in Appendix C. Figures 4.18 and 4.19 show the data for RCP-GV-LA and RAP-GV-LA, respectively; RCP-GV-LA had rapid water absorption compared to RAP-GV-LA. Test results are listed in Table 4.8.

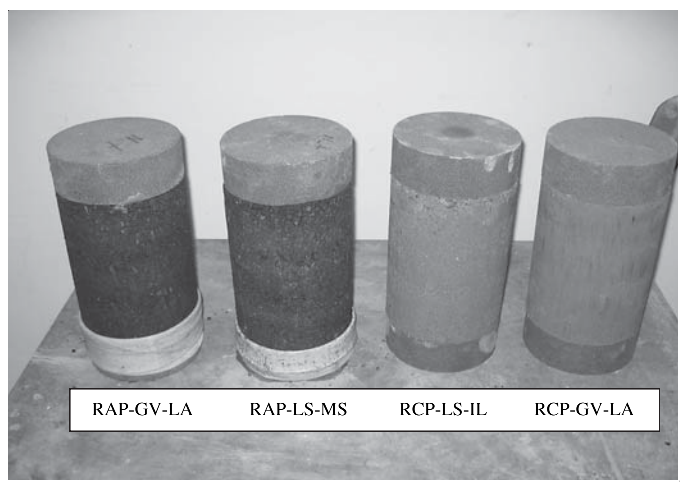


Figure 4.16. Molded RAP and RCP samples.

Figure 4.17. Apparatus used to make surface dielectric measurements.

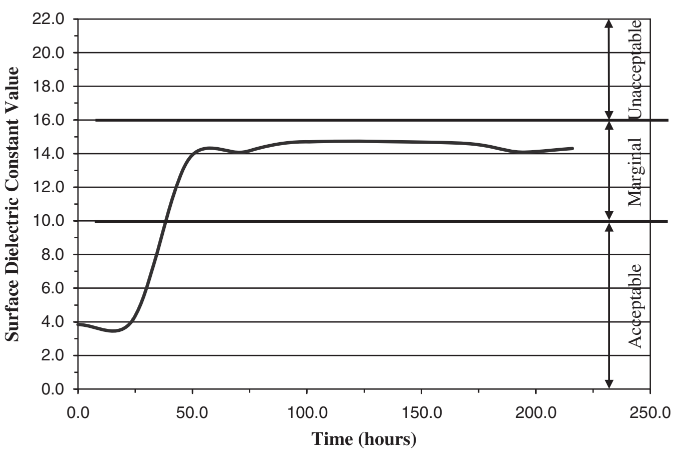


Figure 4.18. Dielectric constant value curve with time for RCP-GV-LA.

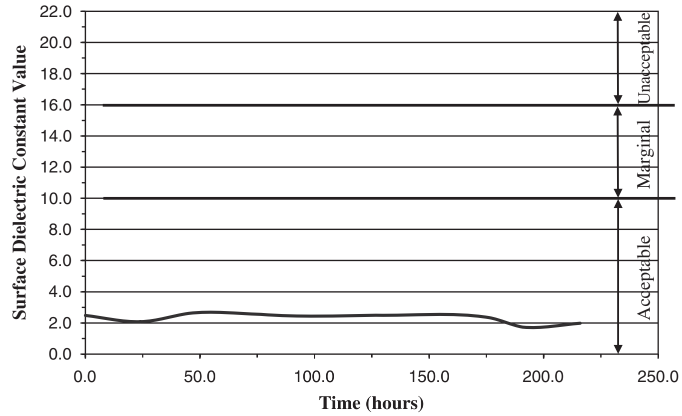


Figure 4.19. Dielectric constant value curve with time for RAP-GV-LA.

Table 4.8. Dielectric constant values from the tube suction test.

Sample Identification	Dielectric Constant Value
RCP-GV-LA	14.3
Virgin DGBL Blend#1	9.6
50/50 RCP-GV-LA	13.5
50/50 RCP-LS-IL	21.6
50/50 RCP-GR-SC	10.0
Virgin DGBL Blend#2	10.6
RCP-LS-IL	16.3
50/50 RAP-GR-CO	3.7
RAP-GR-CO	3.3
RCP-GR-SC	12.1
Virgin OGDL Blend	8.0
50/50 RAP-LS-MS	3.2
RAP-LS-MS	2.1
50/50 RAP-GV-LA	3.6
RAP-GR-CO 100%OGDL re-blend	3.4
RAP-GR-CO 50/50 OGDL re-blend	3.9
RAP-GV-LA	2.0
RCP-GR-SC 50/50 OGDL re-blend	9.5
RCP-GR-SC 100%OGDL re-blend	10.4

Note: Acceptance criterion is dielectric constant value of 10 or less.

CHAPTER 5

Analysis of Test Data

Selection of Performance-Based Test Methods

Laboratory test data were analyzed to identify the tests appropriate for identifying RAP and RCP materials intended for use as unbound pavement layers, singularly or in combination with other materials.

An adequate test method is expected to measure parameters that influence performance and should be capable of differentiating between sources, types, and blends of recycled aggregate.

Toughness and Abrasion Resistance

Recycled materials and virgin aggregate toughness and abrasion resistance characteristics were determined using the Micro-Deval test (AASHTO TP 58-00); percent loss for the different materials are shown in Figure 5.1. RCP and RAP in as-received condition exhibited more material loss than virgin aggregate material or 50-percent blends of recycled materials with virgin aggregate. For the highest material loss, it appears that the test results were affected by the amount of fines produced during testing. The excess fines were not caused by aggregate degradation; therefore, test results are not appropriate. Aggregates that exhibit material loss of 17 percent or more have shown fair or poor field performance. (*1, 13*)

The following two statistical hypotheses were used to determine whether the test method differentiated between RAP, RCP, and virgin aggregates at a statistically significant level (5 percent):

Null hypothesis, H_O: $Mean_{RAP} = Mean_{Virgin}$
Alternate hypothesis, H_A: $Mean_{RAP} \neq Mean_{Virgin}$

Hypothesis testing results on Micro-Deval test data are shown in Table 5.1. These results indicate different material loss for different recycled materials, thus indicating that the test differentiates between different materials.

Durability

Recycled materials and virgin aggregate durability characteristics were determined using the Canadian Freeze-Thaw test (MTO LS-614); percent material loss for different aggregates are shown in Figure 5.2. These data show that RCP samples and 50-percent blends of RCP with virgin aggregate had the largest material loss. It appears that the results are affected by the production of excess fines from recycled materials during testing, resulting from the disintegration of the cement paste on the aggregate particles. Test results show the difference between different recycled materials and their blends with virgin aggregate. Results of statistical evaluation of test data are shown in Table 5.2.

Frost Susceptibility

Frost susceptibility of the recycled and virgin aggregates was determined using the tube suction test. Aggregates were considered acceptable, marginal, or unacceptable if the dielectric constant was less than 10, between 10 and 16, and greater than 16, respectively (*12*).

The order of recycled and virgin aggregate materials with respect to dielectric constant value is shown in Table 5.3. All RAP samples met the dielectric constant criterion; some RCP samples failed this criterion.

The statistical test results are shown in Table 5.4. The tube suction test produced different results for the different material types.

Static Triaxial Test

Figure 5.3 shows the average maximum deviator stress at 15 psi (103.4 kPa) confining pressure sorted by aggregate type,

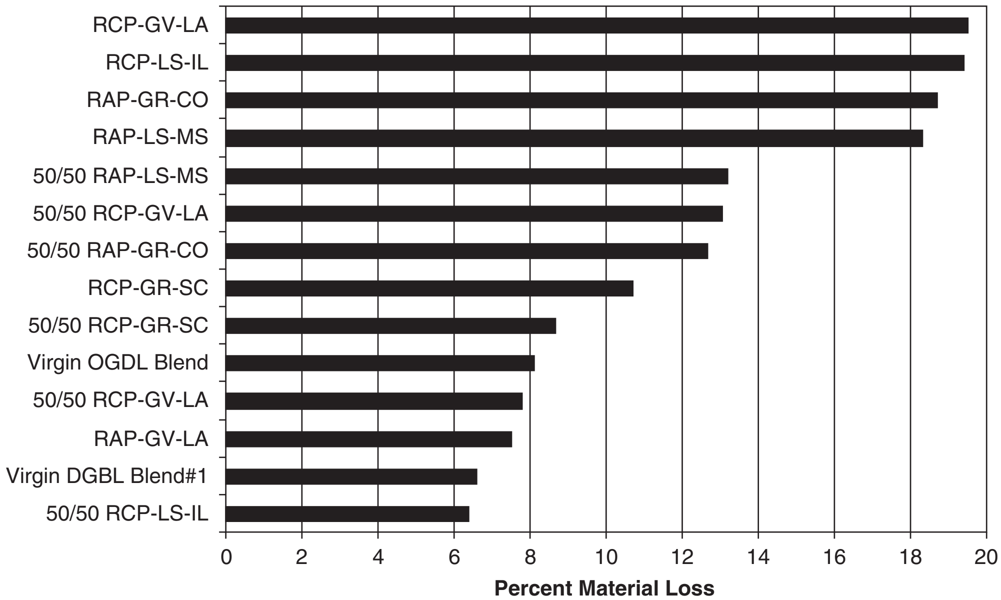


Figure 5.1. Results of Micro-Deval tests.

tested gradation, and material tested. The test yielded different results for different conditions, although similar results were obtained for materials containing limestone and gravel.

Statistical analysis of test data also showed similar trends. Test results were different for RAP and RCP samples with a p-value of 0.027. However, other comparisons indicated mixed results, probably due to limited test data.

Figures 5.4 and 5.5 show the maximum deviator stress at 15 psi (103.4 kPa) confining pressure for different percentages of RAP and RCP recycled materials, respectively. For RAP samples, the results of the static triaxial strength on as-received materials indicated a decrease in deviator stress with increasing recycled material content but not for the re-blended OGDL gradation.

RCP, RCP-GV, and RCP-LS materials exhibited lower failure strengths than those for the virgin aggregate material or the 50-percent blend with virgin aggregate. However, the failure strength of RCP material with granite increased with increased recycled material content.

Results of the static triaxial test at 15 psi (103.4 kPa) confining pressure indicated differences between RAP and RCP and between recycled materials containing different aggregate types.

Repeated Load Triaxial Test

Figure 5.6 shows the "mean" maximum deviator stress at 15 psi (103.4 kPa) confining pressure sorted by aggregate

Table 5.1. Statistical assessment of Micro-Deval test data at 5 percent test significance.

Null Hypothesis, H_o	p - Value	Remarks
$Mean_{RAP} = Mean_{Virgin}$	0.030 (< 5%)	Test method differentiated between RAP and virgin aggregate
$Mean_{RCP} = Mean_{Virgin}$	0.060 (> 5%)	Test method did not differentiate between RCP and virgin aggregate.
$Mean_{Recycled} = Mean_{Virgin}$	0.006 (< 5%)	Test method differentiated between recycled and virgin aggregate
$Mean_{RAP100\%} = Mean_{RAP50\%}$	0.655 (> 5%)	Test method did not differentiate between 100 percent and 50 percent RAP samples.
$Mean_{RCP100\%} = Mean_{RCP50\%}$	0.104 (> 5%)	Test method did not differentiate between 100 percent and 50 percent RCP samples.
$Mean_{RAP} = Mean_{RCP}$	0.537 (> 5%)	Test method did not differentiate between RAP and RCP samples.
$Mean_{RAP50\%} = Mean_{RCP50\%}$	0.068 (> 5%)	Test method did not differentiate between 50 percent RAP and 50 percent RCP samples.
$Mean_{RAP100\%} = Mean_{RCP100\%}$	0.736 (> 5%)	Test method did not differentiate between 100 percent RAP and 100 percent RCP samples.

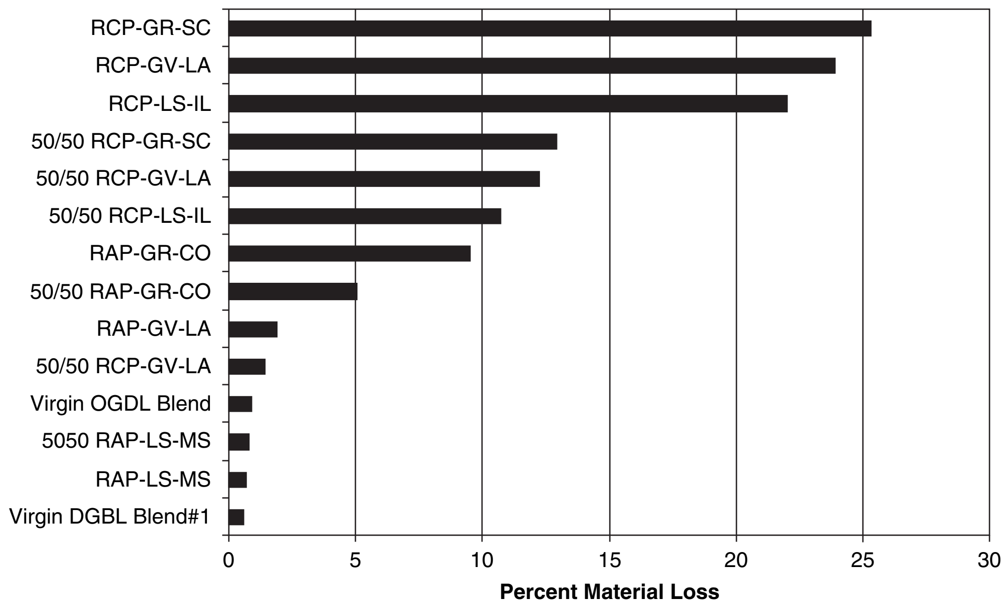


Figure 5.2. Canadian Freeze-Thaw test results.

type, tested gradation, and material for tests conducted on unsaturated and saturated samples (OGDL samples were tested under unsaturated conditions only). Test results indicate differences between different conditions, although the differences between saturated and unsaturated tests were relatively small.

Figure 5.7 shows the results of repeated load triaxial tests conducted at 15 psi (103.4 kPa) confining pressure. The RAP samples with granite exhibited relatively higher deviator stress in as-received gradation compared to when blended with 50-percent virgin aggregate. The capacity of RAP samples with limestone and granite aggregate to resist permanent deformation decreased with an increase in the recycled material content. RAP with granite aggregate exhibited higher deviator stress by itself (100-percent recycled material) compared with RAP blended with virgin aggregate material (50-percent blend). Tests conducted on RAP-GR-CO material in both saturated and unsaturated conditions had similar results.

Figures 5.8 and 5.9 show the results of repeated load triaxial tests on RCP samples. In general, there was decrease in deviator stress when RCP samples were tested in the saturated condition. However, the 100-percent RCP samples had relatively higher deviator stress than the 50-percent blend of RCP with virgin aggregate. For most samples tested in the unsaturated condition, there was a decrease in deviator stress with an increase in recycled material content. When tested under saturated conditions, 100-percent RCP samples exhibited higher deviator stress relative to RCP samples composed of 50-percent virgin aggregate. The mean deviator stress of the

Table 5.2. Statistics for Canadian Freeze-Thaw data at 5-percent test significance.

Null Hypothesis, H_o	p - Value	Remarks
$Mean_{RAP} = Mean_{Virgin}$	0.165 (> 5%)	Test method did not differentiate between RAP and virgin aggregate.
$Mean_{RCP} = Mean_{Virgin}$	0.004 (< 5%)	Test method differentiated between RCP and virgin aggregate.
$Mean_{Recycled} = Mean_{Virgin}$	0.003 (< 5%)	Test method differentiated between recycled and virgin aggregates.
$Mean_{RAP100\%} = Mean_{RAP50\%}$	0.771 (> 5%)	Test method did not differentiate between 100-percent and 50-percent RAP samples.
$Mean_{RCP100\%} = Mean_{RCP50\%}$	0.009 (< 5%)	Test method differentiated between 100-percent and 50-percent RCP.
$Mean_{RAP} = Mean_{RCP}$	0.011 (< 5%)	Test method differentiated between RAP and RCP samples.
$Mean_{RAP50\%} = Mean_{RCP50\%}$	0.142 (> 5%)	Test method did not differentiate between 50-percent RAP and 50-percent RCP samples.
$Mean_{RAP100\%} = Mean_{RCP100\%}$	0.012 (< 5%)	Test method differentiated between 100-percent RAP and 100-percent RCP samples.

Table 5.3. Tube suction test results.

Material Tested	Dielectric Constant Value	Rating
RAP-GV-LA	2.0	Acceptable
RAP-LS-MS	2.1	Acceptable
50/50 RAP-LS-MS	3.2	Acceptable
RAP-GR-CO	3.3	Acceptable
RAP-GR-CO 100%OGDL re-blend	3.4	Acceptable
50/50 RAP-GV-LA	3.6	Acceptable
50/50 RAP-GR-CO	3.7	Acceptable
RAP-GR-CO 50/50 OGDL re-blend	3.9	Acceptable
Virgin OGDL Blend	8.0	Acceptable
RCP-GR-SC 50/50 OGDL re-blend	9.5	Acceptable
Virgin DGBL Blend#1	9.6	Acceptable
50/50 RCP-GR-SC	10.0	Acceptable
RCP-GR-SC 100%OGDL re-blend	10.4	Marginal
Virgin DGBL Blend#2	10.6	Marginal
RCP-GR-SC	12.1	Marginal
50/50 RCP-GV-LA	13.5	Marginal
RCP-GV-LA	14.3	Marginal
RCP-LS-IL	16.3	Unacceptable
50/50 RCP-LS-IL	21.6	Unacceptable

Table 5.4. Statistical test results on Tube-Suction test data at 5-percent test significance.

Null Hypothesis, H_o	p - Value	Remarks
$Mean_{RAP} = Mean_{Virgin}$	0.009 (< 5%)	Test method differentiated between RAP and virgin aggregate.
$Mean_{RCP} = Mean_{Virgin}$	0.033 (< 5%)	The test method differentiated between RCP and virgin aggregate.
$Mean_{RAP} = Mean_{RCP}$	0.000 (< 5%)	The test method differentiated between RCP and RAP samples.

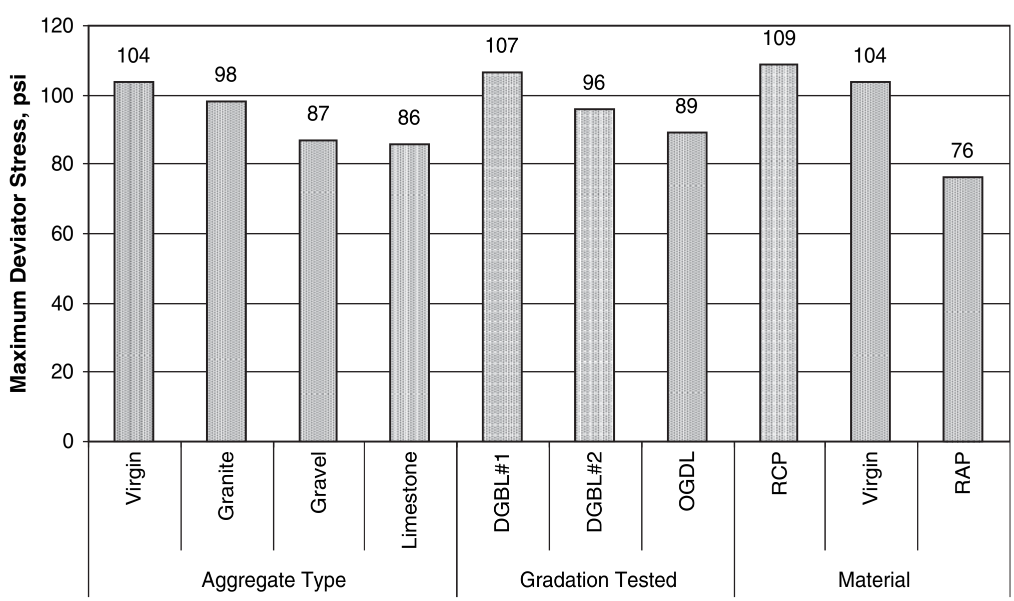


Figure 5.3. Static triaxial test results at 15 psi (103.4 kPa) confining pressure.

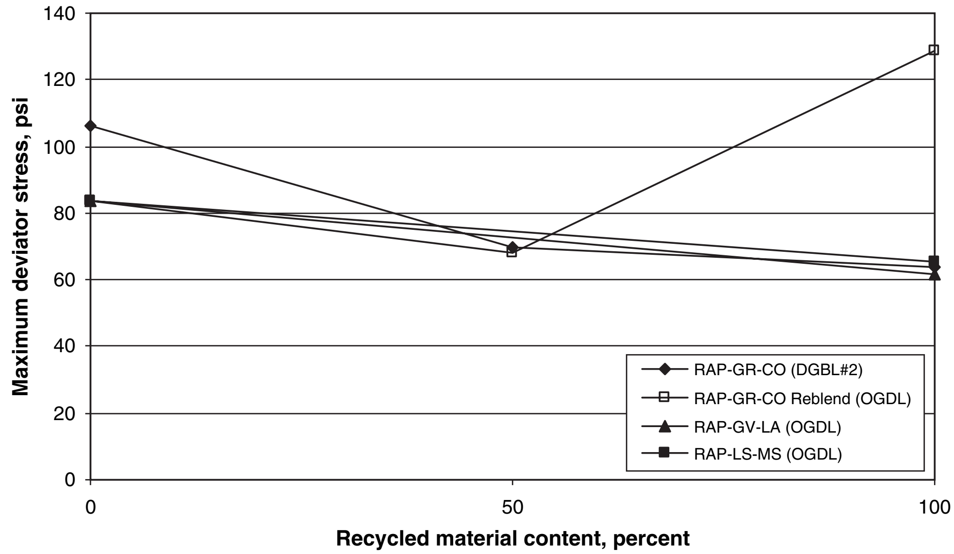


Figure 5.4. Maximum deviator stress versus recycled material content (RAP).

unsaturated test appeared to be unaffected by the amount of RCP in the test sample (165 psi [1138 kPa]) for 50-percent RCP blends with virgin aggregate compared to 163 psi (1124 kPa) for 100-percent RCP.

Statistical significance test results, shown in Table 5.5, indicated similar trends. The test method correctly differentiated between different materials.

Figures 5.10, 5.11, and 5.12 show the order of maximum deviator stress of recycled materials tested in the unsaturated condition in the repeated load triaxial strength at 1-, 2-, and 3-percent strain, respectively. Figure 5.13 shows the shear strengths at 1-, 2-, and 3-percent strain for tests conducted in the saturated condition. Overall, RCP and virgin aggregate exhibited higher maximum deviator stress than RAP material. When tested in the saturated condition, the RCP and virgin aggregate showed higher maximum deviator stress than RAP material.

The materials selected for laboratory tests were expected to provide a range of expected performance as indicated by shear strength. At 1-percent strain, 100-percent RAP material had the lowest strength, followed by 50 percent blends of RAP with virgin aggregate. The 100 percent RCP and virgin aggregate samples had the highest strengths; the 50 percent RCP blends with virgin aggregate had the second highest shear strengths. Shear strengths estimated at 3 percent strain provided somewhat different order.

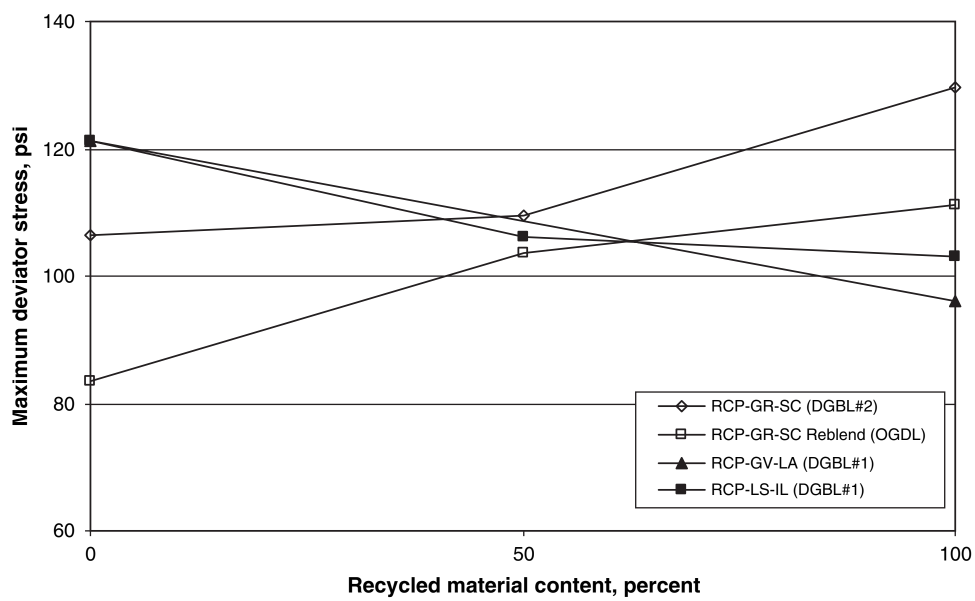


Figure 5.5. Maximum deviator stress versus recycled material content (RCP).

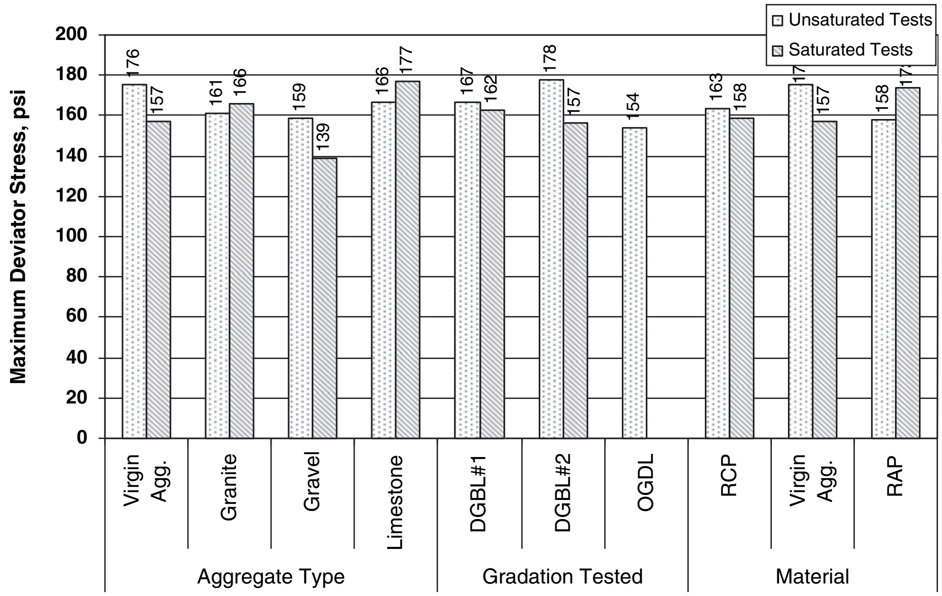


Figure 5.6. Repeated load triaxial test results at 15 psi confining pressure.

The slopes of the deviator stress versus axial strain curve obtained during the load and unload cycles in the repeated load triaxial testing could provide an indication of the performance potential of recycled materials. Figure 5.14 shows typical load/unload curves for RCP and RAP materials. During static triaxial testing, these materials failed at about 4- to 5-percent strain. However, in repeated load triaxial testing, the sample sustained a higher load due to aggregate interlock and resistance characteristics. Good quality materials indicate a large slope (change in deviator stress per unit permanent strain) or low curvature at test initiation. The order of tested materials based on initial slope is shown in Figure 5.15.

Resilient Modulus Test

The resilient modulus (or stiffness) was estimated at different bulk stresses from data obtained during repeated load triaxial tests; results at the bulk stress of 100 psi (689.5 kPa) are shown in Figure 5.16. RCP-GR-SC was the least stiff material. Order-based saturated test results are shown in Figure 5.17. Generally, virgin aggregate and 50-percent blends of recycled materials with virgin aggregate exhibited higher stiffness than 100-percent recycled materials. Statistical analysis of resilient modulus data, shown in Table 5.6, indicate that test data reveal differences between different materials.

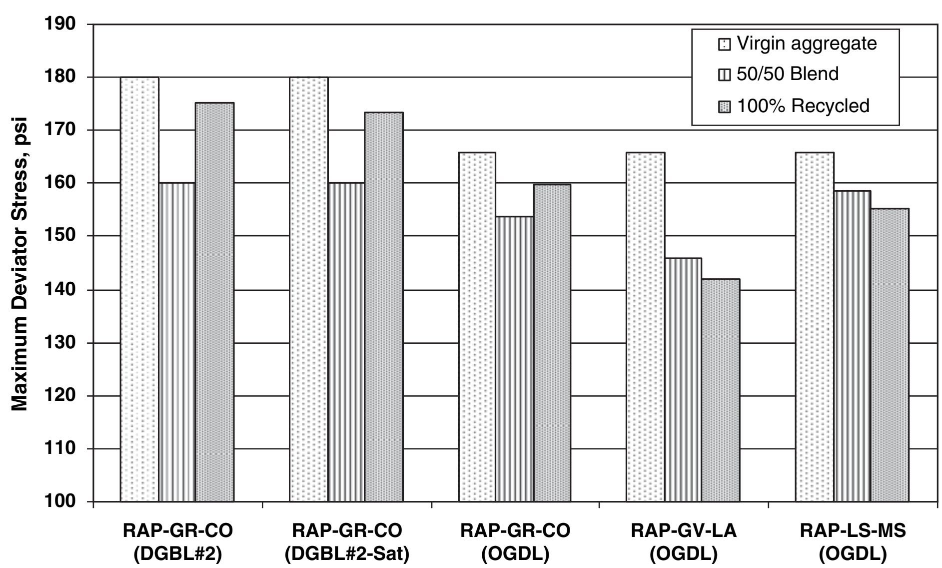


Figure 5.7. Repeated load triaxial test results for RAP samples.

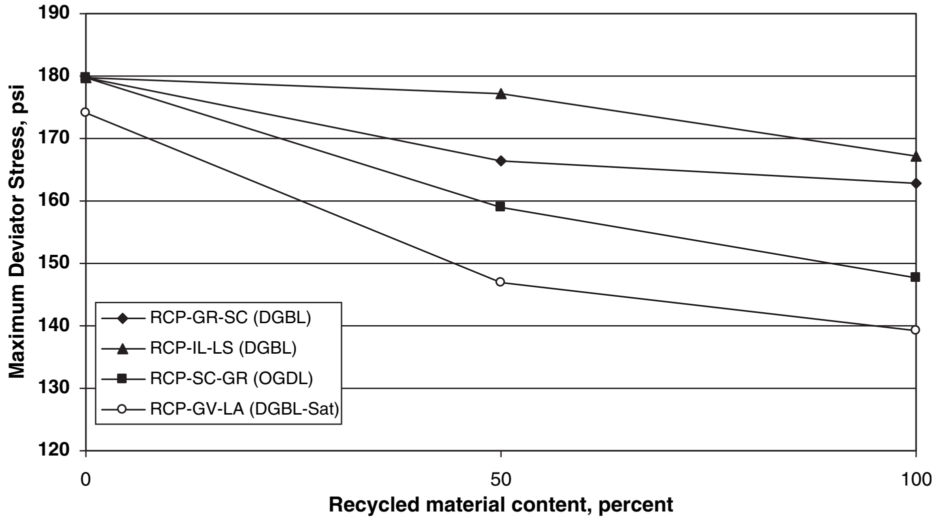


Figure 5.8. Repeated load triaxial test results for RCP samples.

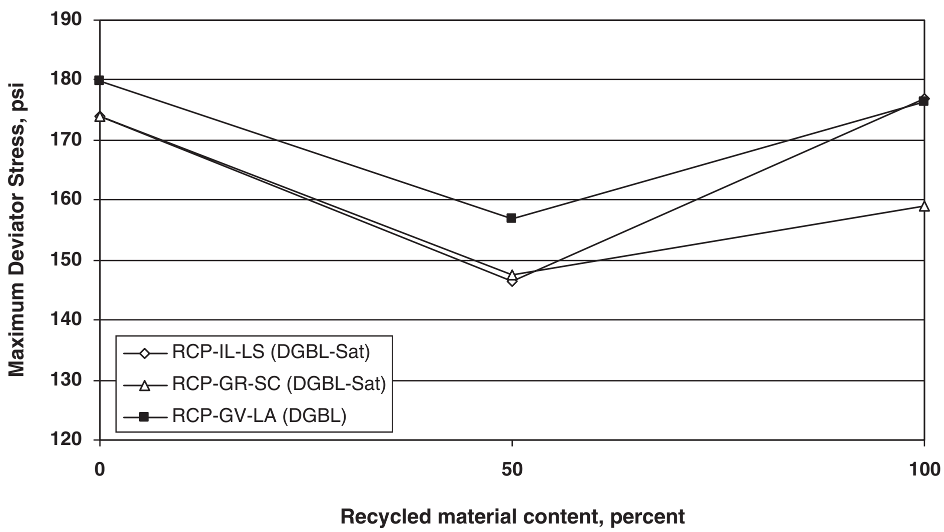


Figure 5.9. Repeated load triaxial test results for RCP-DGBL samples.

Table 5.5. Statistics for repeated load triaxial test data at 5-percent test significance.

Test Condition	Null Hypothesis, H_o	p - Value	Remarks
At OMC	$Mean_{RCP} = Mean_{Virgin}$	0.007 (< 5%)	Test method differentiated between RCP and virgin aggregate.
	$Mean_{RAP} = Mean_{Virgin}$	0.000 (< 5%)	Test method differentiated between RAP and virgin aggregate.
	$Mean_{RAP} = Mean_{RCP}$	0.024 (< 5%)	Test method differentiated between RAP and RCP samples.
Saturated	$Mean_{RCP} = Mean_{Virgin}$	0.653 (> 5%)	Test method did not differentiate between RCP and virgin aggregate.
	$Mean_{RAP} = Mean_{Virgin}$	0.321 (> 5%)	Test method did not differentiate between RAP and virgin aggregate.
	$Mean_{RAP} = Mean_{RCP}$	0.023 (< 5%)	Test method differentiated between RAP and RCP samples.
OMC and saturated	$Mean_{RAP50\%} = Mean_{Virgin}$	.019 (< 5%)	Test method differentiated between 50 percent RAP and virgin aggregate.
	$Mean_{RCP50\%} = Mean_{Virgin}$	0.048 (< 5%)	Test method differentiated between 50 percent RCP and virgin aggregate.

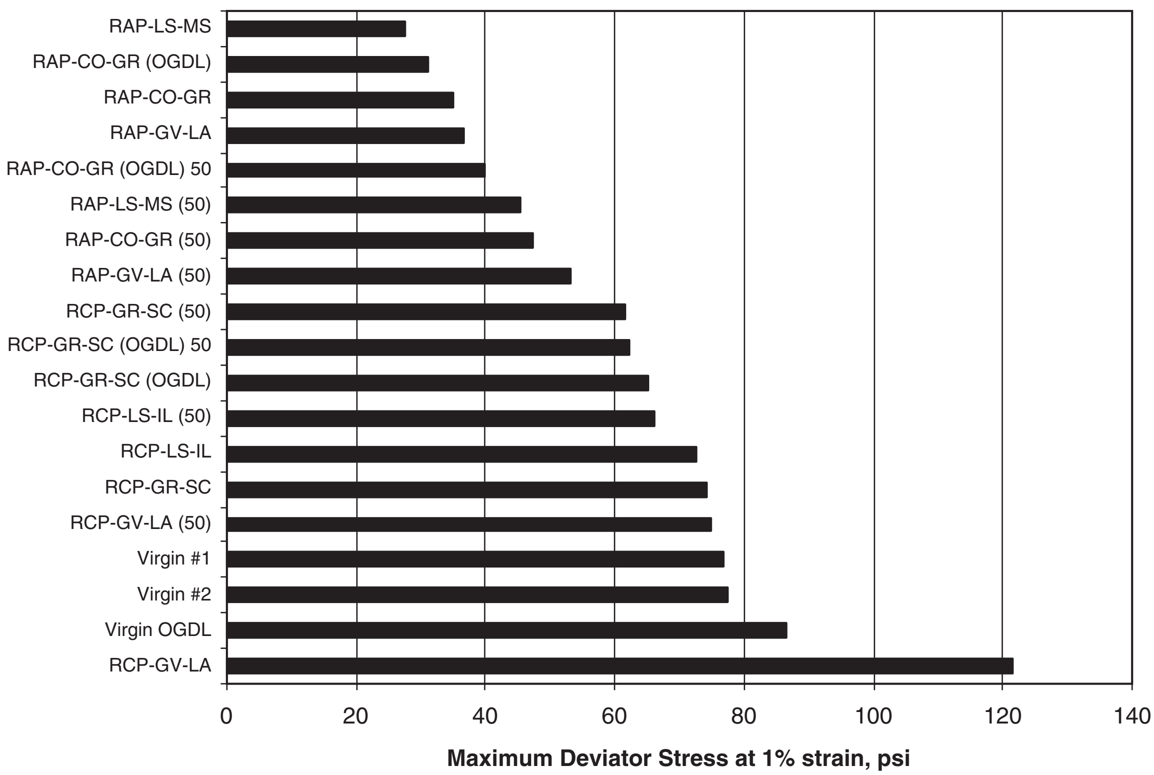


Figure 5.10. Shear strength at 1-percent strain in repeated load triaxial test.

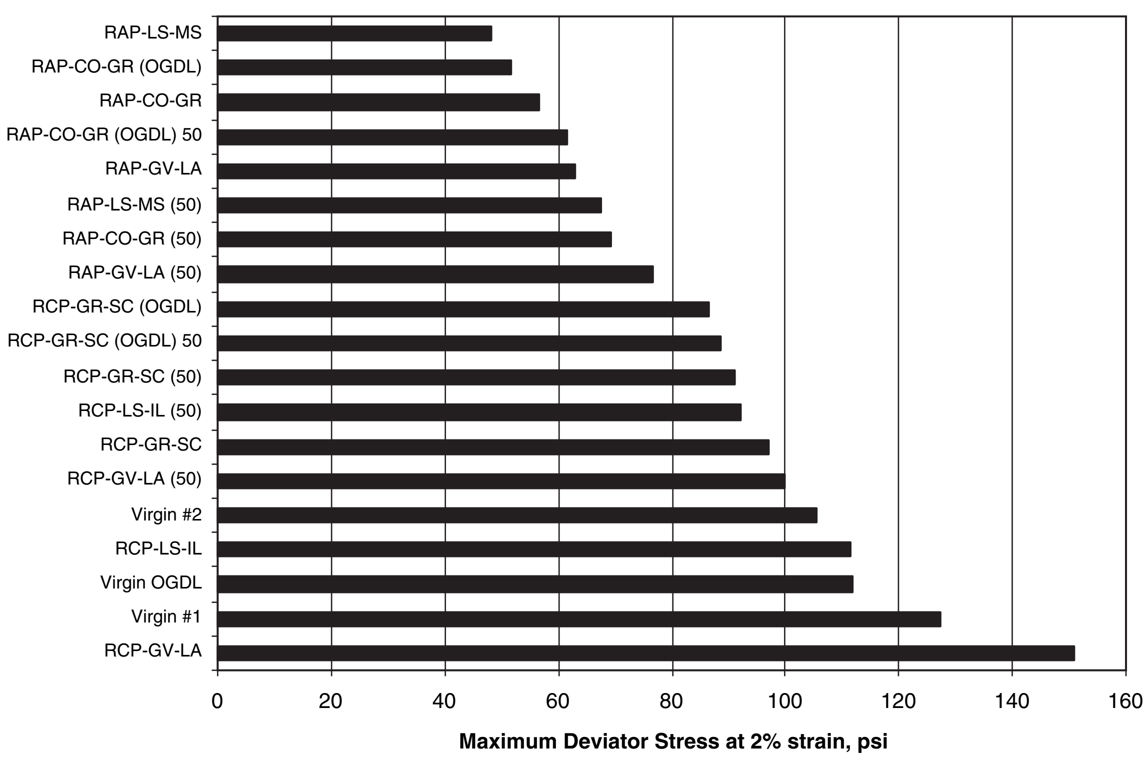


Figure 5.11. Shear strength at 2-percent strain in repeated load triaxial test.

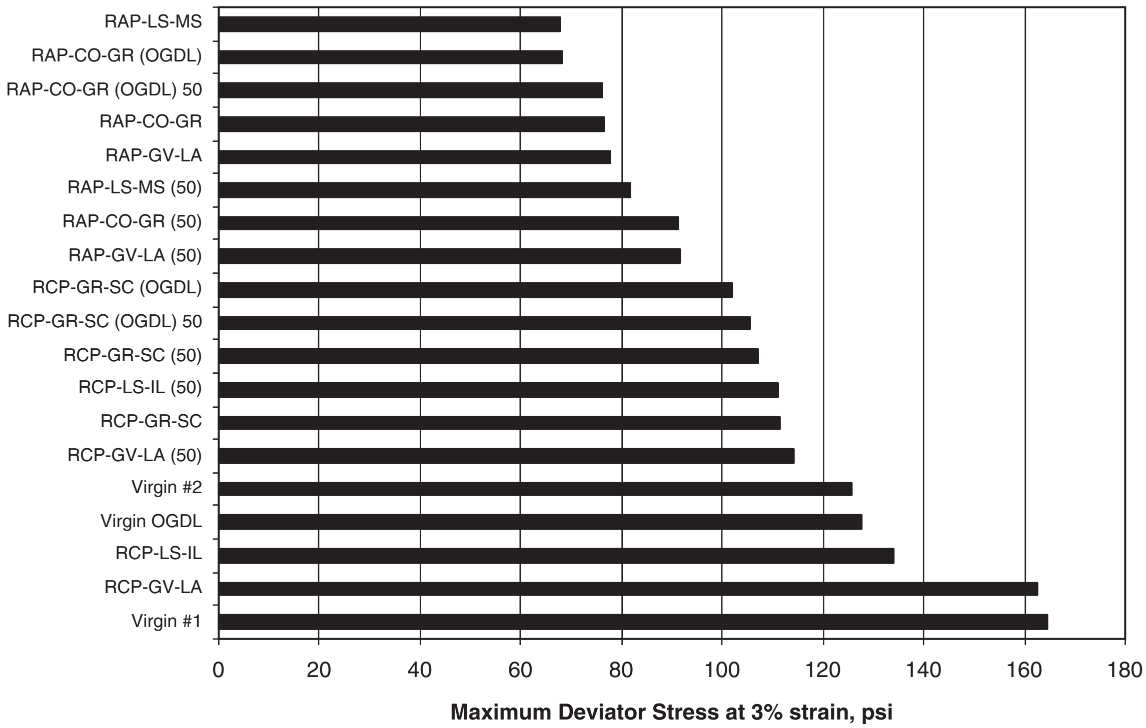


Figure 5.12. Shear strength at 3-percent strain in repeated load triaxial test.

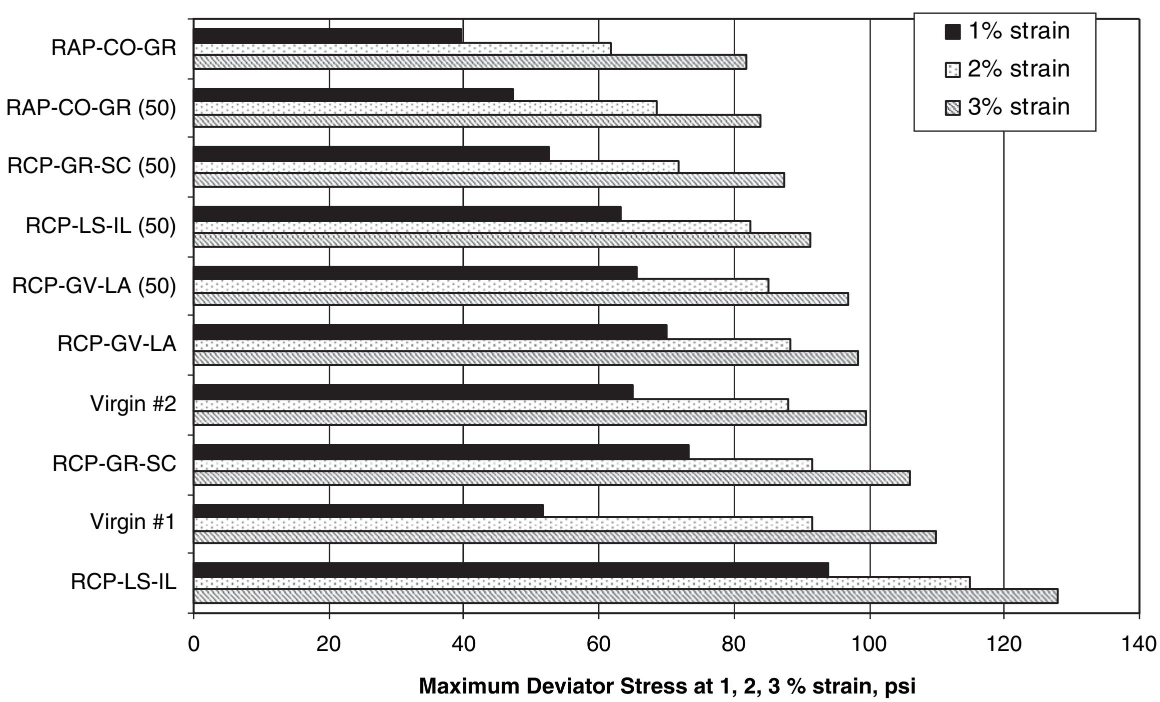


Figure 5.13. Shear strength materials tested saturated in repeated load triaxial test.

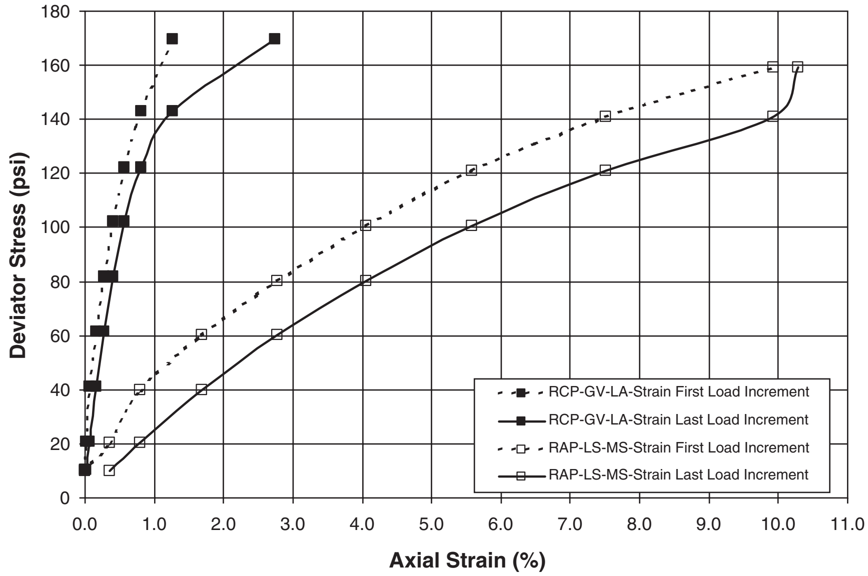


Figure 5.14. Comparison of load/unload curves for typical RCP and RAP materials.

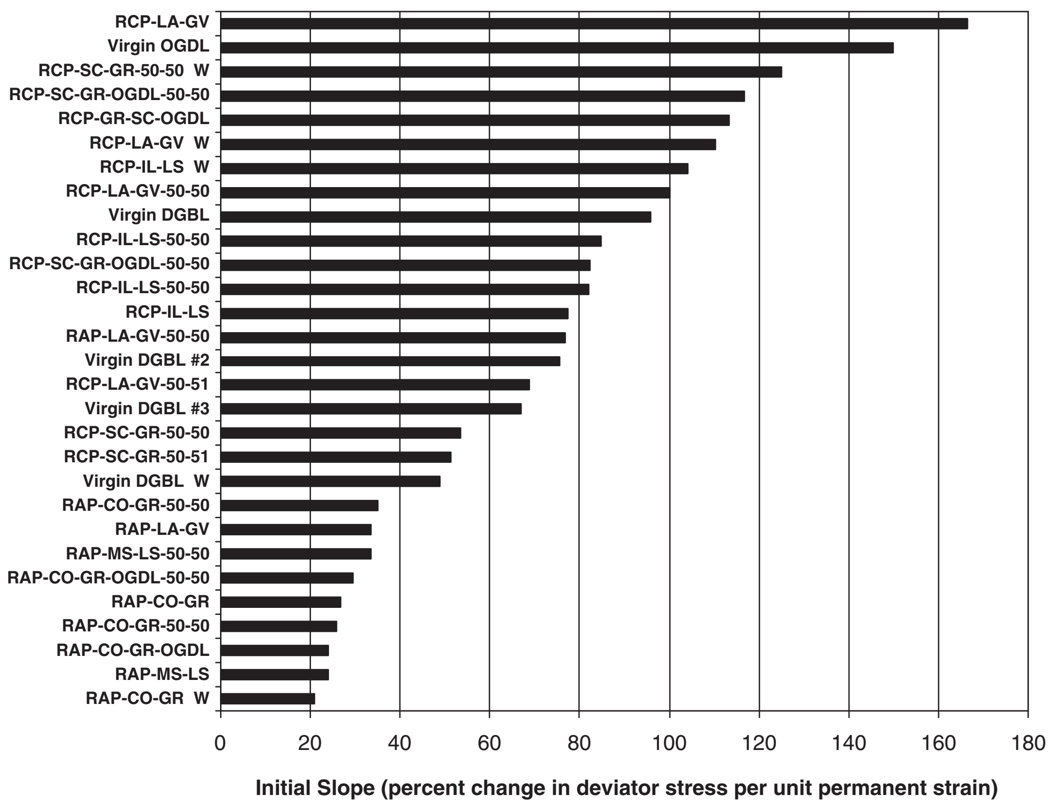


Figure 5.15. Order of materials based on initial load-strain slope.

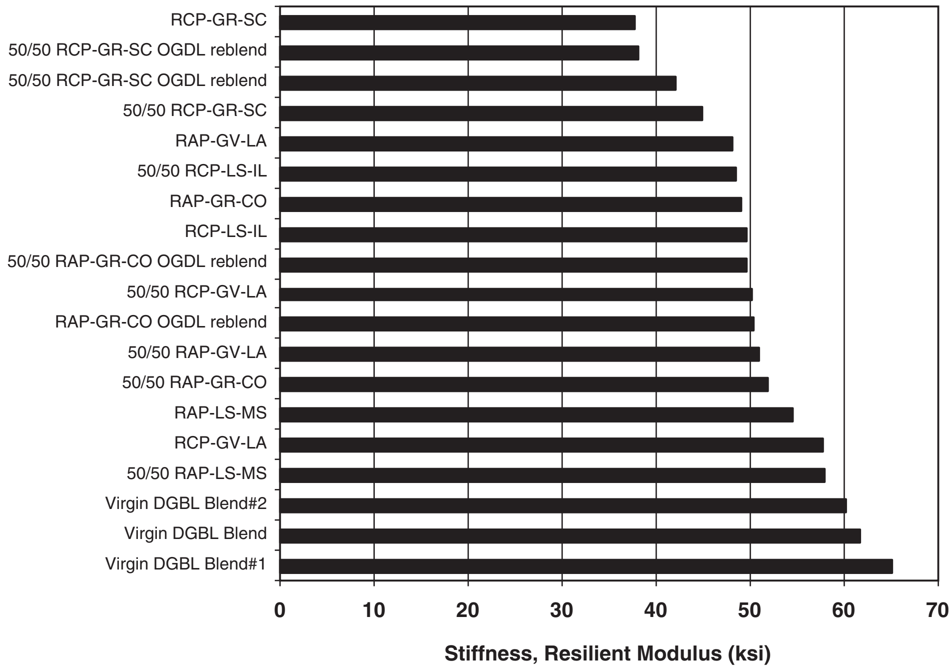


Figure 5.16. Stiffness estimate using repeated load triaxial data at 100 psi bulk stress.

Test Method Selection Summary

The performance potential of an unbound pavement layer depends on its dry and wet shear strength, resistance to freeze-thaw (durability), toughness, and frost susceptibility. These properties were evaluated using selected tests in a laboratory investigation. Also, screening tests were conducted to characterize recycled materials. Based on results of the laboratory investigation, the following tests were found to relate to performance:

- Screening tests for sieve analysis and the moisture-density relationship,

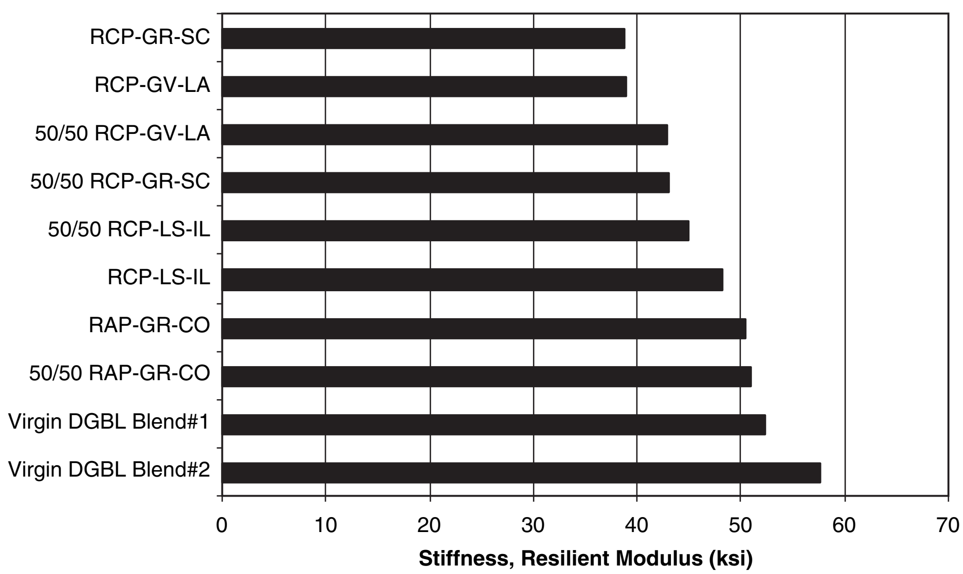


Figure 5.17. Estimated stiffness at 100 psi bulk stress (sat. repeated load triaxial test).

Table 5.6. Statistics for Resilient Modulus data at 5 percent test significance.

Test Condition	Null Hypothesis, H_o	p - Value	Remarks
At OMC	$Mean_{RCP} = Mean_{RAP}$ *	0.066 (> 5%)	Test method did not differentiate between RCP and RAP.
	$Mean_{RAP} = Mean_{Virgin}$	0.003 (< 5%)	Test method differentiated between RAP and virgin aggregate.
	$Mean_{RCP} = Mean_{Virgin}$	0.000 (< 5%)	Test method differentiated between RCP and virgin aggregate.
	$Mean_{RCP50} = Mean_{RAP50}$	0.028 (< 5%)	Test method differentiated between RAP and RCP samples containing 50-percent virgin aggregate.
	$Mean_{RCP100} = Mean_{RAP100}$	0.747 (> 5%)	Test method did not differentiate between 100 percent RCP and 100-percent RAP.
Saturated	$Mean_{RCP} = Mean_{RAP}$ *	0.462 (> 5%)	Test method did not differentiate between RCP and RAP.
	$Mean_{RAP} = Mean_{Virgin}$	0.077 (> 5%)	Test method did not differentiate between RAP and virgin aggregate.
	$Mean_{RCP} = Mean_{Virgin}$	0.020 (< 5%)	Test method differentiated between RCP and virgin aggregate.
OMC and Saturated	$Mean_{RCP} = Mean_{RAP}$ *	0.038 (< 5%)	Test method differentiated between RAP and RCP.
	$Mean_{RAP} = Mean_{Virgin}$	0.000 (< 5%)	Test method differentiated between RAP and virgin aggregate.
	$Mean_{RCP} = Mean_{Virgin}$	0.000 (< 5%)	Test method differentiated between RCP and virgin aggregate.
	$Mean_{RCP50} = Mean_{RAP50}$	0.009 (< 5%)	Test method differentiated between RAP and RCP samples containing 50-percent virgin aggregate.
	$Mean_{RCP100} = Mean_{RAP100}$	0.641 (> 5%)	Test method did not differentiate between 100 percent RCP and 100-percent RAP.

* Includes 100-percent and 50-percent blend recycled material samples.

Table 5.7. Significance level of intended use on aggregate performance potential.

Temperature Condition	Moisture Condition	Traffic		
		High	Medium	Low
Freezing	High	4	4	3
	Low	4	3	2
Non Freezing	High	3	2	2
	Low	3	2	1

Scale of 1 to 4 with 4 = Most significance, 1 = least significant

- The Micro-Deval test for toughness,
- Resilient modulus for stiffness,
- Static triaxial and repeated load at OMC and saturated for shear strength, and
- Tube suction test for frost susceptibility.

Selection of Recycled Materials for Intended Use

Recycled materials can be selected for use in a particular traffic and climatic condition. Rangarajy et al. (*13*) developed an approach for evaluating aggregates using selected test parameters, performance ratings, and traffic and climatic categories. In this approach, tests are conducted in sequence and results are compared to suggested performance levels for specific traffic and climatic ranges. Three traffic levels are proposed:

- Low traffic (<100,000 ESALs/year),
- Medium traffic (100,000–1,000,000 ESALs/year), and
- High traffic (>1,000,000 ESALs/year).

The climatic conditions of moisture (high/low) and temperature (freezing/not freezing) are based on the AASHTO definitions (*14*). Table 5.7 shows the significance levels of traffic, moisture, and climate combinations on a scale of 1 to 4, where 4 is most significant and 1 least significant on aggregate performance potential.

Recycled materials could also be selected for use in a particular pavement structure (e.g., doweled PCC, undoweled PCC, or HMA at various traffic levels and climates) for a particular base/subbase application (e.g., strength layer or construction or drainage layer). Different properties would be required of recycled materials for each unique situation. This level of detail has not been considered in this research.

Table 5.8. Recommended tests and test parameters for levels of intended use.

<table>
<tr><th colspan="2" rowspan="3">Tests
(Test Parameters)</th><th>Traffic</th><th colspan="2">H</th><th colspan="2">M</th><th colspan="2">H</th><th colspan="2">L</th><th>M</th><th>L</th></tr>
<tr><th>Moisture</th><th>H</th><th>L</th><th>H</th><th>L</th><th>H</th><th colspan="2">L</th><th colspan="2">H</th><th>L</th></tr>
<tr><th>Temperature</th><th colspan="4">F</th><th colspan="2">NF</th><th>F</th><th colspan="3">NF</th></tr>
<tr><td colspan="3">Micro-Deval Test (percent loss)</td><td colspan="3">< 5 percent</td><td colspan="4">< 15 percent</td><td colspan="2">< 30 percent</td><td>< 45 percent</td></tr>
<tr><td colspan="3">Tube Suction Test (dielectric constant)</td><td colspan="3">≤ 7</td><td colspan="4">≤ 10</td><td colspan="2">≤ 15</td><td>≤ 20</td></tr>
<tr><td colspan="2" rowspan="2">Static Triaxial Test
(Max. deviator stress)</td><td>OMC, σ_c = 5psi</td><td colspan="3">≥ 100 psi</td><td colspan="4">≥ 60 psi</td><td colspan="2">≥ 25 psi</td><td>Not required</td></tr>
<tr><td>Sat. σ_c = 15psi</td><td colspan="3">≥ 180 psi</td><td colspan="4">≥ 135 psi</td><td colspan="2">≥ 60 psi</td><td>Not required</td></tr>
<tr><td colspan="2" rowspan="2">Repeated Load Test
(Failure deviator stress)</td><td>OMC, σ_c = 15psi</td><td colspan="3">≥ 180 psi</td><td colspan="4">≥ 160 psi</td><td colspan="2">≥ 90 psi</td><td>Not required</td></tr>
<tr><td>Sat. σ_c = 15psi</td><td colspan="3">≥ 180 psi</td><td colspan="4">≥ 160 psi</td><td colspan="2">≥60 psi</td><td>Not required</td></tr>
<tr><td colspan="3">Stiffness Test (Resilient modulus)</td><td colspan="3">≥ 60 ksi</td><td colspan="4">≥ 40 ksi</td><td colspan="2">≥ 25 ksi</td><td>Not required</td></tr>
</table>

Proposed ranges for selected test parameters that relate to performance are shown in Table 5.8 for various levels of climatic and traffic condition. These ranges determine the traffic and climatic conditions where these recycled materials and their blends can be used. However, results from accelerated pavement tests and/or in-service test pavement evaluations are needed to confirm or refine these ranges.

Selection Based on Toughness Test

Recycled materials and virgin aggregate toughness and abrasion resistance characteristics were evaluated using the Micro-Deval test. The test results and recommended test parameter, shown Figure 5.18, indicate that recycled materials are generally appropriate for use in medium to low traffic conditions in non-freezing climates with low and high moisture contents. RCP-GR and RAP-GV seem appropriate for use in high traffic areas with non-freezing temperatures or in low and medium traffic areas in freezing climates with low moisture conditions.

Adding virgin aggregate to recycled materials improves the performance potential (based on the toughness test). For example, virgin aggregates and 50-percent blend of recycled materials with virgin aggregate are appropriate for use in low and medium traffic areas in freezing climates with low moisture conditions or high traffic areas with non-freezing temperatures with high or low moisture conditions. None of the

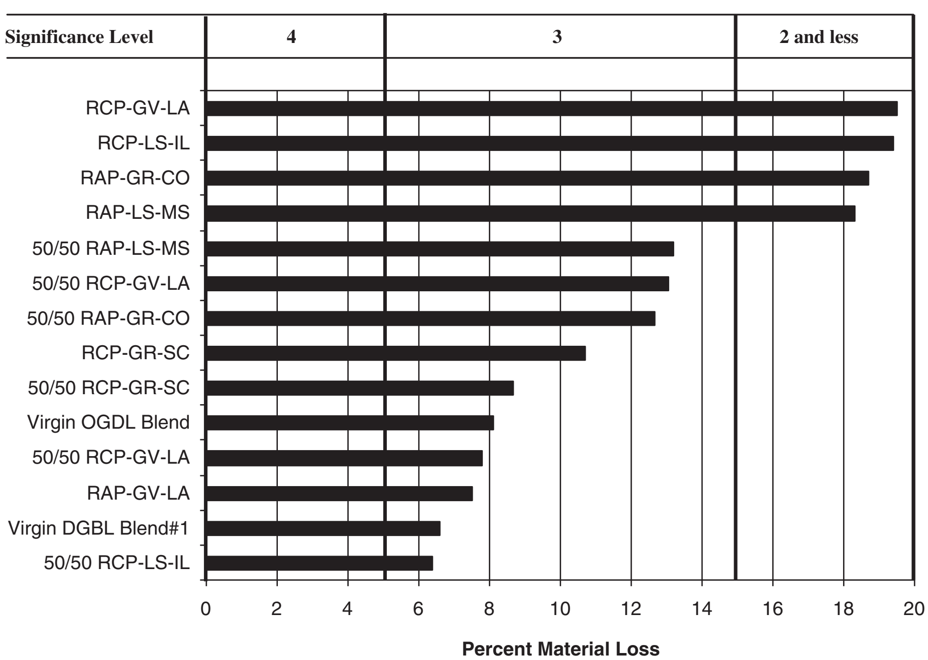


Figure 5.18. Performance potential based on toughness (Micro-Deval) test.

tested materials (virgin, recycled or 50-percent blend of virgin and recycled materials) are appropriate for use in performance significance level 4 (high traffic locations with freezing temperatures and low and high moisture conditions).

Selection Based on Frost Susceptibility Test

Frost susceptibility of different recycled and virgin aggregates was determined using the tube suction test; results are shown in Figure 5.19. The results indicate that RCP materials are appropriate for use only in performance significance level 2 (medium traffic no freezing) and level 1 (low traffic, no freezing, low moisture). Blending RCP with virgin aggregate increased the performance potential to the next level, and thus would be appropriate for use in high traffic (no freezing) and medium traffic (freezing with low moisture condition). RAP and 50-percent blends with virgin aggregate are appropriate for use in high traffic conditions.

Selection Based on Static Triaxial Test

The results of the static triaxial test, shown in Figure 5.20, indicate that most of the RCP materials and their blends with virgin aggregate are appropriate for use in extreme traffic and climatic conditions (significance level 4). RAP, on the other hand, is appropriate for use in conditions representing significance level 3 (i.e., high traffic level in non-freezing temperatures, medium traffic level in freezing temperature in the presence of low moisture, and low traffic level in freezing temperatures).

Selection Based on Repeated Load Triaxial Test

Failure deviator stress for repeated load triaxial tests conducted at OMC, shown in Figure 5.21, indicate that virgin aggregates are appropriate for use in high traffic conditions (significance level 4). RCP and 50-percent RCP blend with LS and GR are appropriate for use in conditions representing significance level 3 (i.e., high traffic level in non-freezing temperatures, medium traffic level in freezing temperature in the presence of low moisture, and low traffic level in freezing temperatures). RAP and 50-percent RAP blends are generally appropriate for use in conditions representing significance level 2.

Failure deviator stress for repeated load triaxial tests conducted in saturation condition, shown in Figure 5.22, indicate that RAP-GR and RCP-LS are appropriate for use in high moisture conditions with low or medium traffic and non-freezing temperatures. The other materials are appropriate for use in conditions representing significance level 2.

Selection Based on Material Stiffness

Most recycled materials and 50-percent blends with virgin aggregate were shown to be appropriate for use in conditions representing significance level 3, as shown in Figure 5.23. Virgin aggregates were shown to be appropriate for use in conditions representing significance level 4.

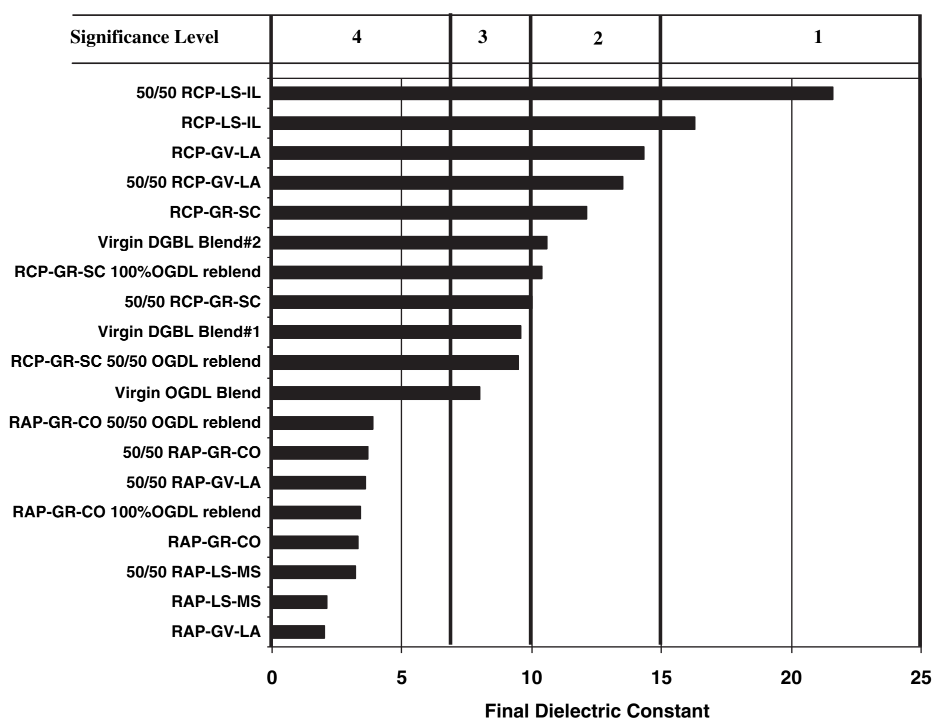
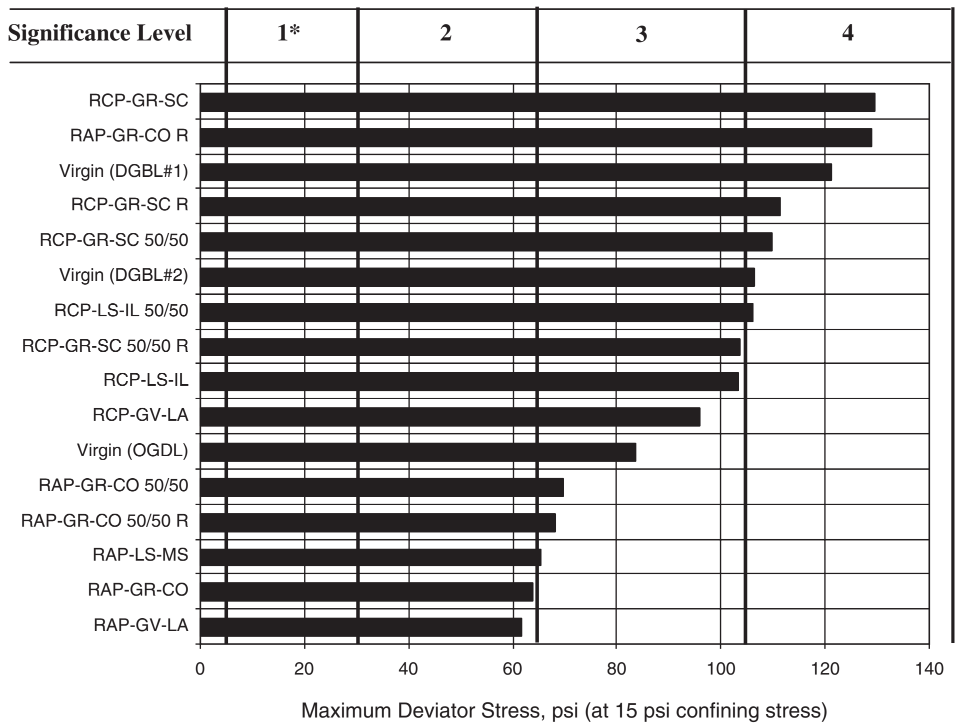
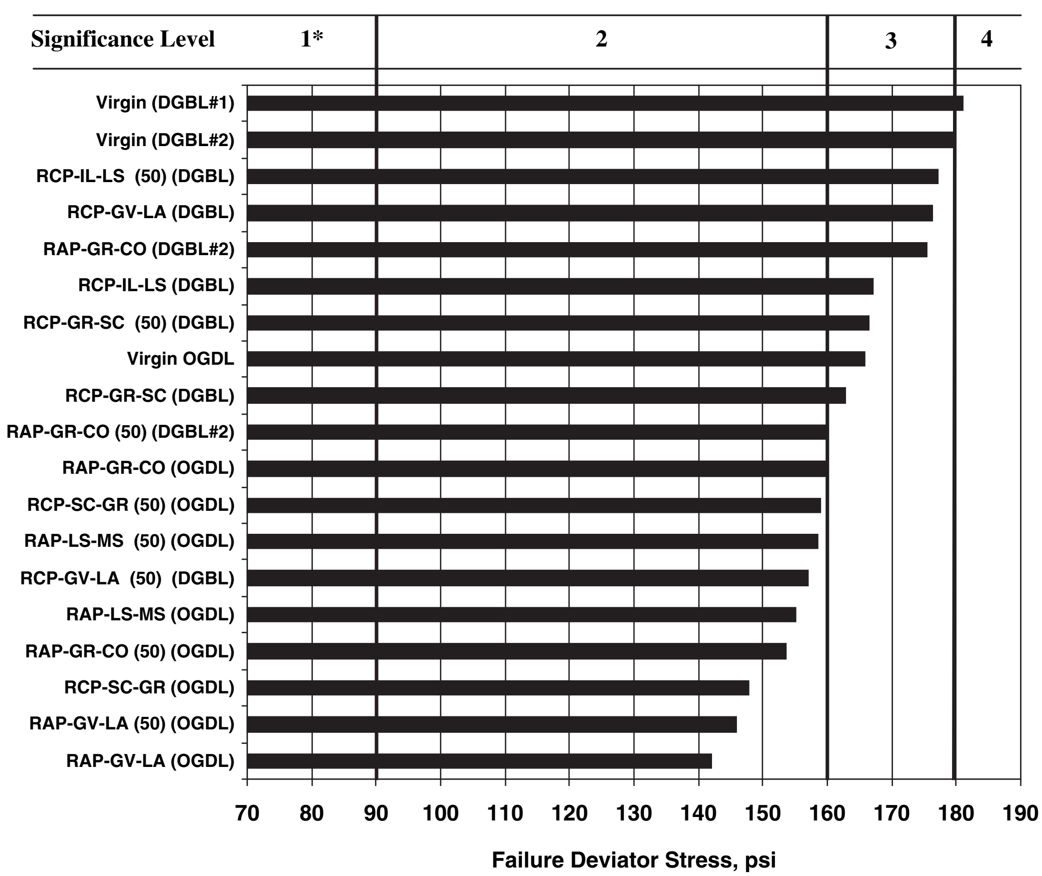


Figure 5.19. Performance potential based on frost susceptibility.



* Test not required for conditions representing significance level 1

Figure 5.20. Performance potential of recycled materials based on static triaxial test.



* Test not required for conditions representing significance level 1

Figure 5.21. Performance potential based on repeated load triaxial test (OMC).

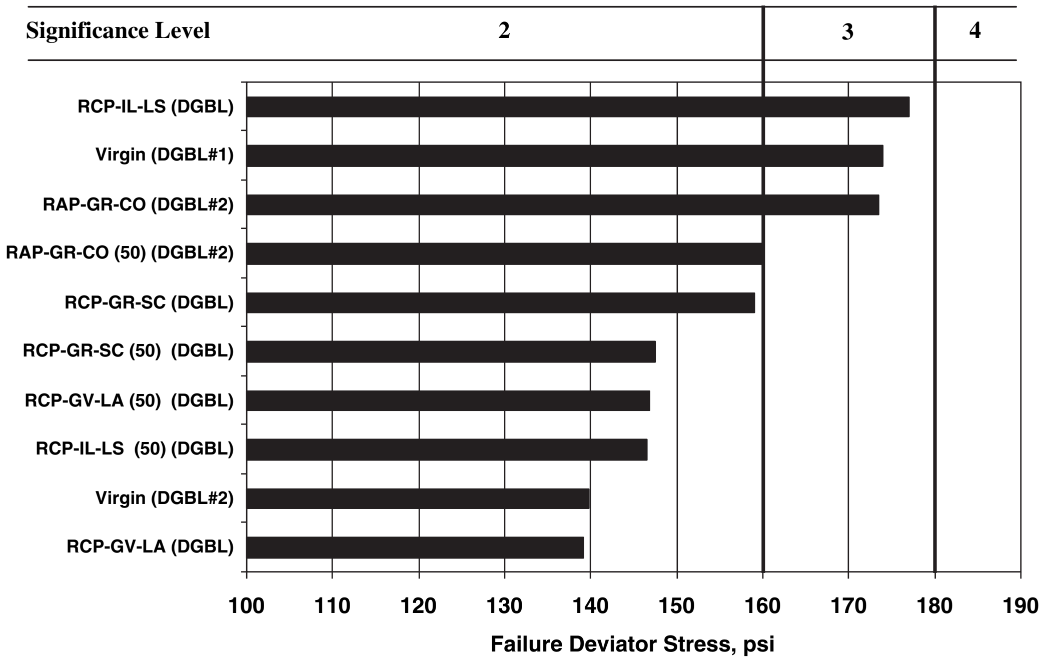
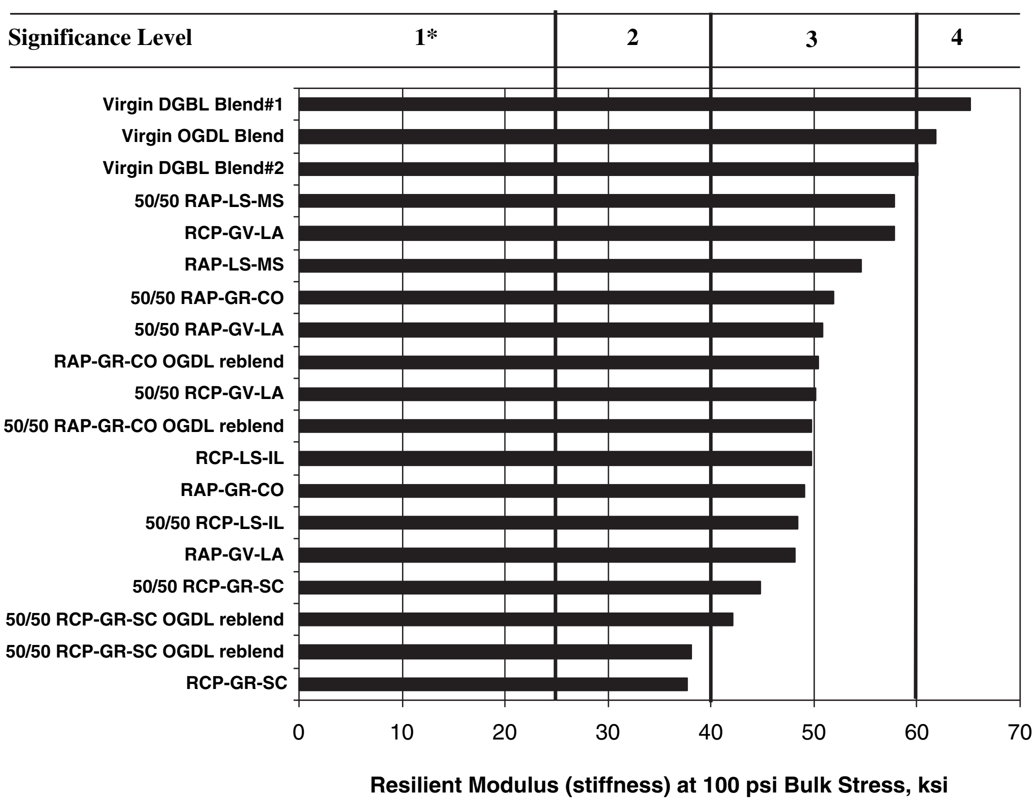


Figure 5.22. Performance potential based on repeated load triaxial test (saturated).



* Test not required for conditions representing significance level 1

Figure 5.23. RAP and RCP performance potential based on stiffness (at OMC).

CHAPTER 6

Conclusions and Suggested Research

Conclusions

Based on the results of the research in this project, the following conclusions are made.

1. Fatigue cracking, rutting/corrugations, depressions and frost heave in flexible pavements and cracking, pumping/faulting, frost heave, and erosion in rigid pavements are distresses associated with poor performance of the recycled aggregates used in the unbound layers of these pavements.
2. Properties of recycled aggregates used in unbound base and subbase pavement layers that affect pavement performance include shear strength, stiffness, toughness, durability, frost susceptibility, and permeability. Shear strength and stiffness (resilient modulus) have a much greater influence on the performance of an unbound aggregate layer than the other properties.
3. The following tests relate to the performance of recycled materials used in unbound pavement layers:
   - Screening tests for sieve analysis and the moisture-density relationship,
   - The Micro-Deval test for toughness,
   - Resilient modulus for stiffness,
   - Static triaxial and repeated load at OMC and saturated for shear strength, and
   - The tube suction test for frost susceptibility.

Suggested Research

Based on the work performed in this project, modifications of the repeated load and moisture content tests are recommended. The modification of the repeated load test will improve the application of the seating load and reduce the interlaboratory variability. The modification of the moisture content test will allow air-drying at ambient temperature using a fan blowing across loosely spread aggregate placed on a tarp. In addition, ranges for selected test parameters were recommended for the use of RAP and RCP materials (or blends with virgin aggregate) in different climatic conditions and traffic levels.

The recommended aggregate tests and the ranges of test parameters were based on laboratory test results. Further research is needed to confirm the validity of these tests and ranges under service conditions.

A field validation plan is suggested to further validate the suitability of using the performance-related tests identified in this research as predictors of performance. The plan makes use of accelerated pavement testing (APT) and in-service pavement test sections.

Accelerated Pavement Testing

Many state DOTs use accelerated pavement testing to evaluate potential construction materials, pavement designs, and other pavement-related features. During APT, wheel loads are applied to specially constructed or in-service pavements to determine pavement response and performance under a controlled and accelerated accumulation of damage in a short time. It is recommended to construct flexible and rigid pavement sections with unbound recycled aggregate layers to evaluate the merits of the reported research findings. By varying the characteristics of recycled aggregates used for unbound pavement layers, the effects of various aggregate properties on the performance of unbound pavement layers can be assessed. This field performance can then be compared with the performance predicted using the methodologies developed in this research.

The primary advantage of this approach is that the factors that affect pavement performance could be more closely controlled. This is particularly important if the test involves studying the effect of a single or a group of factors on pavement performance. The disadvantage of this approach is that long-term strength loss due to poor durability and frost effects cannot be fully assessed.

In-Service Test Pavements

Testing in-service pavements is proposed to evaluate the recommended procedures in actual practice. This approach assesses the adaptability of the recommended tests to state DOTs' current methods of evaluating recycled aggregates and compares the test results. In this study, the performance of pavements incorporating unbound recycled material layers will be used to evaluate performance prediction accuracy.

The study would involve identification of pavement projects currently being designed that represent a range in traffic and climatic conditions. The recycled aggregate used in each project would be tested using the recommended procedures and compared with test results from current DOT evaluation procedures. Construction of the pavement project would be followed to document construction practices; performance of the test pavement would be monitored for future analysis.

There are benefits in testing in-service pavements, but there are also major disadvantages. Testing the in-service pavement can provide the comfort of knowing that the pavement is "real" in all respects. However, in most cases, in-service pavements do not allow for good control of the factors that may affect pavement performance. Testing in-service pavement also limits, or at least makes more difficult, the use of instrumentation installed in the pavement structure to measure response and performance. Also, it will generally take several years before performance data become available.

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation