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GEOTECHNICAL AND MATERIALS ENGINEERING CONSULTANTS

Evaluation of Crushed Concrete Base Strength

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16. Abstract:

This research project was conducted with two primary objectives, which include: 1) determine whether current Mississippi Department of Transportation (MDOT) requirements for recycled concrete aggregates (RCA) provide adequate materials for a roadway granular pavement layer and 2) determine whether RCA materials provide the same structural value comparable to crushed limestone granular layers. In order to accomplish these objectives, seven RCA materials were obtained from Mississippi suppliers for testing and evaluation. For comparison purposes, three limestone samples were also obtained and subjected to the same testing regimen. These ten materials were subjected to typical laboratory characterization tests in order to evaluate each material. In addition, California Bearing Ratio and resilient modulus testing was conducted in order to compare the strength and stiffness of the various materials.

Based upon the results of the research, RCA meeting all applicable current MDOT requirements should be allowed for granular pavement layers. Because RCA materials can have excessive absorption, RCA stockpiles should be maintained in the field at a moisture content representative of a saturated surface dry condition. This should improve the construction and testing in-place RCA granular pavement layers. A protocol was developed to improve the reliability and repeatability of Proctor testing and preparation of strength and stiffness test specimens.

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CHAPTER 1 - INTRODUCTION

1.1 Background

There are several factors that are driving forces to encourage an agency to consider using recycled materials (1) which include:

- Increasing shortage of natural aggregates
- high cost of landfill disposal
- commitment to environment
- conservation of resources
- local availability
- political pressure
- environmental safety

Recycled materials from construction and demolition operations were once disposed of in landfill sites. Concrete, for example, accounts for up to 67 percent, by weight, of construction and demolition waste in the U.S. Yet only about 5 percent is currently recycled (2). However, the availability of landfills for this purpose has rapidly diminished. In 1981, there were 50,000 landfills available in the United States for disposal of waste products. Today there are only 5,000 landfills available for waste product disposal (3). As landfill space becomes more critical, so do the regulations governing their operations. In some cases, tipping fees for waste disposal have increased to the point that other alternatives must be found.

From an environmental perspective, it is also essential that these materials be recycled where possible. The potential exhaustion of natural resources is not acceptable and has caused government and industry leaders to reconsider attitudes and actions concerning recycling. In addition, the permitting process for opening new aggregate quarries has become a burdensome task for suppliers due to increased environmental regulations. Due to the need to conserve our natural resources and preserve the environment, several agencies now provide incentives to those who utilize recycled materials.

There is a need to use recycled aggregate as a supplement to natural aggregates in order to conserve natural resources and keep concrete out of landfills (4). To accomplish this, several U.S. agencies have begun using recycled Portland cement concrete (PCC) materials. Recycled concrete aggregate (RCA) is nothing more than PCC crushed into aggregate-sized particles. These particles consist of the original aggregate particles and the adhered mortar (5). At least 36 states use RCA in highway construction applications. A plausible use of recycled concrete materials within the highway construction industry is to utilize these materials in unbound base course applications (6). A number of European countries have requirements that recycled aggregates be utilized. The United Kingdom put forth an initiative to include 25 percent recycled aggregates in construction (7). The use of recycled materials for unbound pavement layers has been successful around the world.

In order to specify the use of recycled materials for unbound pavement layers, it is important to understand what the function of these layers is within the pavement section. Depending on whether the pavement structure is flexible or rigid, the function of the unbound layer is different. For rigid pavements, the function of the unbound layer is to prevent pumping, protect against frost action, provide a construction platform, drainage of water, prevent volume change of the subgrade, and/or increase structural capacity. To prevent pumping, a base course must be either free draining or resistant to the effects of water. To increase structural capacity, the base course must be able to resist deformation due to loading. The role of the unbound layer for flexible pavements is different in that the primary function is to increase structural capacity.

Within Mississippi, RCA used as aggregate for crushed stone courses is governed by Special Provisions to the Mississippi Standard Specifications for Road and Bridge Construction. Within Special Provision No. 907-703-10, dated June 6, 2012, RCA is defined as "… recycled concrete pavement, structural concrete, or other concrete sources that can be crushed to meet the gradation requirements for Size 825 B… In no case shall waste from concrete production (wash-out) be used as a crushed stone base." This Special Provision also states "If crushed concrete is used, the crushed material shall meet the gradation requirements of Size 825 B with the exception that the percent passing, by weight, of the No. 200 sieve shall be 2-18 percent."

Besides the language described above within the Special Provision, RCA must meet other material properties in accordance with the Mississippi Standard Specifications for Road and Bridge Construction. Coarse aggregate portions (coarser than a No. 8 sieve) must have Los Angeles Abrasion percent loss of less than 45 and a minimum dry-rodded unit weight greater than 70 pcf. For the fine aggregate portion (material finer than No. 8 sieve), the material must be non-plastic.

Construction requirements for RCA layers are identical to those of crushed stone layers. Section 304.03 of the Mississippi Standard Specification for Road and Bridge Construction governs the construction of granular courses. Granular courses are required to average 99.0 percent of the maximum laboratory dry density with no individual test result below 95.0 percent. Project specifications define whether the maximum laboratory dry density is determined using standard or modified efforts; however, in most MDOT cases a standard effort is specified.

Currently, MDOT assigns equal structural value to RCA and crushed limestone base materials providing the RCA meets the gradation and Los Angeles Abrasion Loss requirements. Crushed concrete sources can have a wide range in quality due to the wide range in concrete uses. To date, no formal detailed comparison of the laboratory strengths of RCA materials meeting the gradation and Los Angeles Abrasion Loss requirements to that of crushed limestone materials has been conducted in Mississippi. This formal comparison was needed to address the following concerns/questions: 1) are the current materials requirements adequate to identify RCA materials that perform the intended purpose in the field; and 2) do RCA materials provide the same structural value as crushed limestone materials?

1.2 Objectives

This research project was conducted with two primary objectives, which include:

1) Determine whether RCA materials meeting current MDOT requirements will perform their intended purpose within a granular course; and
2) Determine whether RCA materials provide the same structural value as comparable crushed limestone granular courses.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

The available literature on recycled concrete aggregate (RCA) can be divided into three general areas: use and limitations of recycled materials, current tests and potential performance-related tests, and specifications. The following sections present the results of the literature review for these three categories.

2.2 Use and Limitations of Recycled Concrete Materials

Portland cement concrete (PCC) is becoming a burdensome waste in many areas. Goldstein (9) states that more concrete is consumed per year than any other substance except water. He reports that the equivalent of one ton of concrete is produced for each person on Earth every year. When concrete reaches the end of its lifespan, it must be disposed of properly. Concrete accounts for up to 67 percent, by weight, of construction and demolition waste. Yet, in 1995 only about 5 percent was being recycled (6).

The Federal Highway Administration (FHWA) indicates that approximately 2 billion tons of natural aggregate are produced each year in the US (9). Aggregate production will likely increase to over 2.5 billion tons per year by 2020. This needed volume of aggregate has raised concerns about the availability of natural aggregates in the coming years.

In 2001, NCHRP Project 4-21, “Appropriate Use of Waste and Recycled Materials in the Transportation Industry,” provided a database (10) that showed at least 36 states used reclaimed concrete material in highway construction applications. At least 11 states allowed RCA general use mainly as an aggregate in granular base or subbase applications. An August 2002 survey distributed by the Federal Highway Administration (FHWA) via electronic mail indicated that the transition toward recycling of concrete is now widespread. That survey showed that only 9 states do not currently recycle concrete as indicated in Figure 1. However, some of these states may have little or no concrete pavements available for recycling.

Three states, Alabama, Delaware, and Georgia did not respond to the FHWA survey, but phone contact with each of the three states indicated that recycled concrete was allowed in certain roadway applications. The same FHWA survey showed that only 11 states (Maryland and Oregon were included with the previous nine) did not permit recycled concrete to be used in aggregate base courses. A few of the 11 states indicated previous problems with alkali-silica reactivity (ASR) in some of their concrete products and have, therefore, been cautious about recycling those materials into other roadway materials.

Chesner et al (11) reported on the use of 19 waste and by-product materials reused in the highway construction industry. The report lists properties of these materials, how they are being used, and limitations that may be considered for their use. Recycled concrete aggregate is used in PCC pavement, granular base, and embankment fill. The quality of recycled materials often varies depending on source and may need to be blended with conventional aggregates in order to meet typical strength requirements.

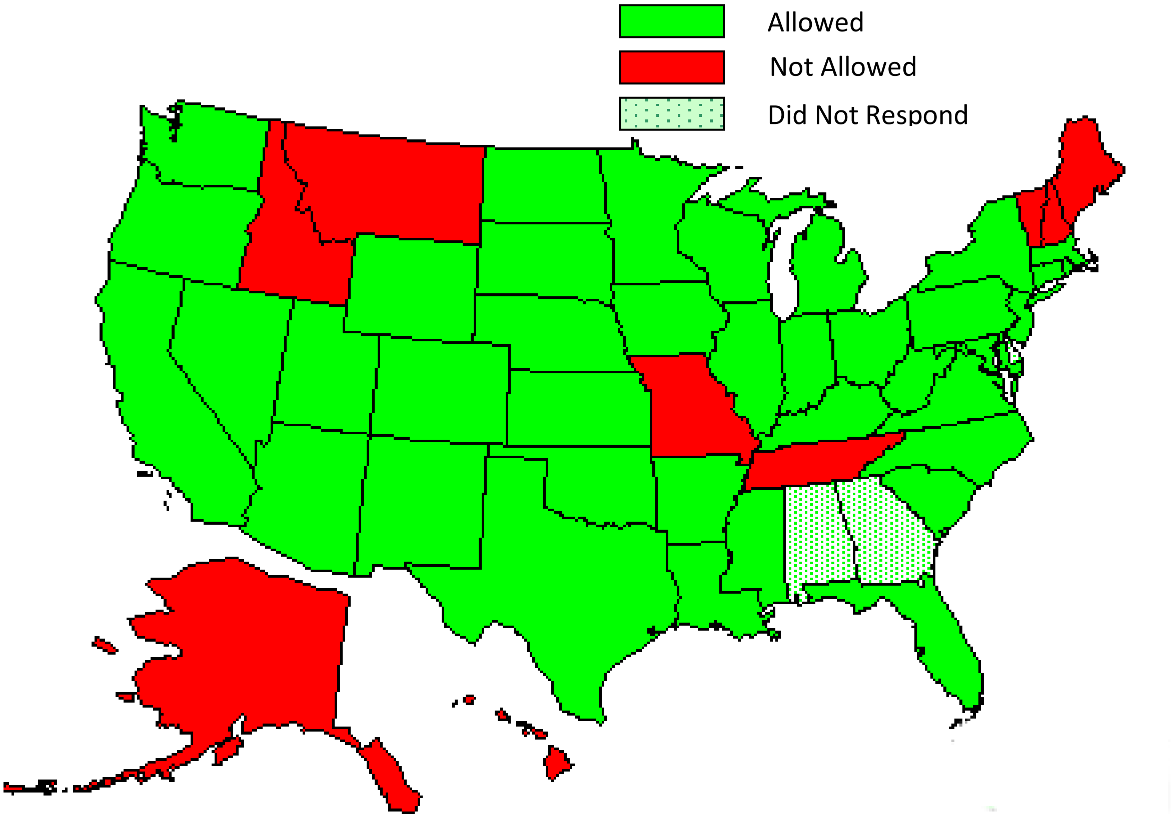

Figure 1: Responses to FHWA Survey Regarding Recycling of Concrete (6)

Work by Bennert et al (12) with New Jersey materials showed that recycled asphalt pavement (RAP) material was much more likely to have higher permanent strain than dense-graded aggregate base course (DGABC) unless it was blended with natural aggregate. In that research, 25 percent RAP performed almost identically to the 100 percent DGABC. As the percent RAP was increased, the permanent strain also increased and at 100 percent RAP the permanent strain accelerated quickly under repeated load conditions as shown in Figure 2. However, the same research showed that the use of 100 percent RCA may actually result in base courses that have less permanent strain under repeated loading than DGABC with conventional aggregate.

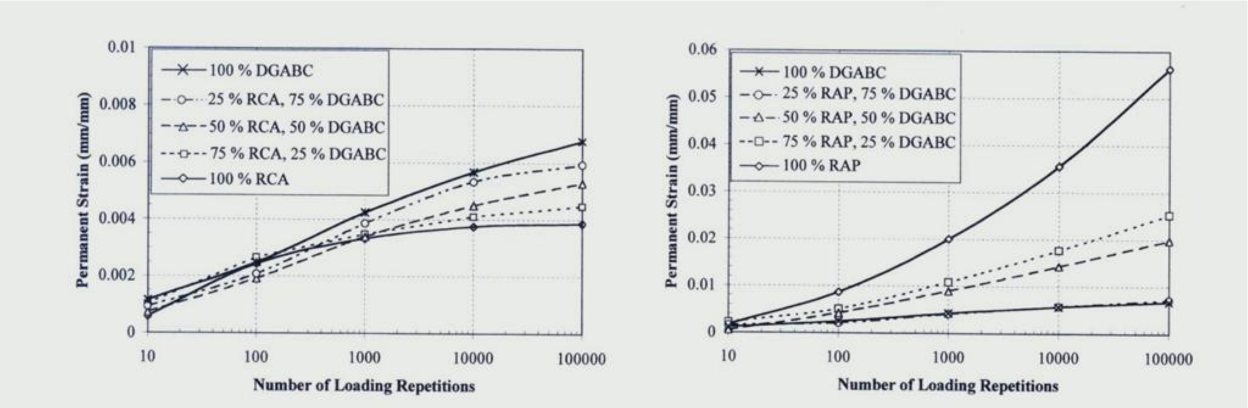

Figure 2: Permanent Strain Results for RCA and RAP Blended Samples (12)

Unlike RAP, RCA material may perform quite well without the need for blending with conventional aggregates. Petrarca (13) investigated the use of RCA on some local projects in New York between 1977 and 1982. Concrete used for recycling in Petrarca's study was crushed from sidewalks, driveways, curbs, and pavements. More than 100 tests were conducted and it was determined that crushed concrete consistently met all requirements for excellent long-term performance as dense-graded aggregate base or subbase. However, the quality of aggregates with sources used to produce RCA will depend on the original intended use of the PCC (10). For example, precast concrete typically uses smaller aggregate size and requires PCC with higher compressive strength than other concrete structures or pavements. Also, factors such as air entrainment may affect the suitability of RCA for highway construction uses.

Petrarca (13) also found that crushing and screening operations had a considerable effect on the stability of RCA granular base materials. For example, when an additional crusher was added to plant operations to increase the quality of crushed particles, California Bearing Ratio (CBR) values increased by 17 percent and density increased by 1.5 lb/ft^3.

There are some concerns with the use of RCA materials in certain pavement layers. Snyder and Bruinsma (14) reported on five field studies and five laboratory studies to evaluate the use of RCA materials in unbound layers underneath pavements. Field studies reported by Snyder and Bruinsma (14) included evaluations of existing pavement drainage systems for pavements utilizing RCA base materials and monitoring of various test sections containing RCA materials and natural aggregates. Based on the field studies, RCA materials within drainage base layers have the potential to precipitate calcium carbonate materials (called calcite). The calcium carbonate precipitates are created from calcium hydroxide ions present in exposed cement paste, water, and atmospheric carbon dioxide (15). These precipitates can significantly reduce the permittivity of drainage filter fabrics used within pavement drainage systems. However, permittivity can also be reduced by insoluble residue that is not related to the use of RCA materials.

Effluent from drainage layers containing RCA materials are generally very alkaline. Snyder and Bruinsma (14) reported pH levels as high as 11 to 12 from some of the field sections and from the laboratory studies. However, laboratory work indicated that the pH levels reached a peak shortly after water was introduced and decreased over time. Reports of vegetation kills near drain outlets were noted. However, Snyder and Bruinsma indicated that insects and frogs were living in the effluent.

The laboratory studies described by Snyder and Bruinsma (14) indicated that the amount of calcium carbonate precipitate was proportional to the amount of RCA materials passing the No. 4 (4.75mm) sieve. Washing RCA during processing practically eliminates the formation of the calcium carbonate precipitates.

There may also be other environmental concerns with the use of RCA. Constituents in the effluent from one RCA stockpile study that are considered hazardous were arsenic, chromium, aluminum, and vanadium (14). These elements were present in quantities that exceed drinking water standards. However, it is not clear if drinking water standards should apply to the pavement base discharge since it will be diluted many times over within a short distance from the point of discharge (14). It should also be stated that the RCA used in this study was created from building demolition and not pavements. High chloride contents in RCA may present problems in areas of the country where de-icing salts are used in winter maintenance operations (11).

The potential for alkali-aggregate or alkali-silica reactivity (AAR or ASR) that may cause expansion and cracking has also limited the use of RCA in some applications. Concrete that has deteriorated as a result of alkali-aggregate reactions (AAR) may raise some concern about its suitably for reuse. This is clearly the case if the recycled material is to be reused in new PCC. For use in unbound base courses, the primary issue would seem to be one of individual particle degradation and, in this sense, would affect unbound base performance in a manner similar to that of freeze-thaw susceptible or moisture-sensitive aggregate particles. Because aggregate particles in unbound aggregate bases are not confined as they are in PCC, the degradation is not expected to cause an overall expansion of the structural material. Rather, it might cause particle breakdown leading to reduced shear strength.

There are two distinct reactions affecting rocks included in AAR. In both cases, the physical response is triggered by chemical reactions involving highly alkaline pore solutions in the concrete and components in the aggregates. The reactions are classified by the specific aggregate type or component involved in the reaction: the breakdown of dolomite in the case of alkali-carbonate reaction (ACR); and dissolution of silica or siliceous components in alkali-silica reaction (ASR) (16). In both cases, the physical response is the development of internal stress within the aggregate particle that can lead to fracturing and expansion of the concrete.

Of the two reactions, ASR is far more prevalent because of the wide variety of rocks that are susceptible. In ASR, highly alkaline pore solution attacks the siliceous components of the aggregates producing an alkali-silica gel. The gel reaction product is hygroscopic and can swell when provided moisture; with swelling potential dependent on its chemistry (17). Although reactive constituents occur in both coarse and fine aggregates, durability problems are more often associated with coarse aggregate particles (18).

The ACR affects a small suite of rock with a very specific set of characteristics: roughly equal amounts of calcite and dolomite, with a significant amount (5-35 percent) of insoluble residue. The rocks exhibit a typical texture of dolomite rhombs floating in a fine-grained matrix of calcite and acid-insoluble minerals (16). The alkaline pore solution attacks the dolomite crystals, releasing magnesium that combines with hydroxyl to form brucite with an increase in volume. The volumetric increase causes fracturing of the aggregate particle leading to increased access of fluid to the interior of the particle.

In the case of massive concrete elements, expansions resulting from AAR can continue for extended periods of time. With pavements and other thin elements, it is suspected that active AAR reactions will usually have ceased prior to removal of the concrete because of chemical factors that lower the alkalinity of the pore solution and, in the case of ASR, transform the gel from a swelling to non-swelling state. In such cases, it seems unlikely the reuse of the material in an unbound base course would reactivate damaging AAR; but, the damaged particles could have an effect on performance that should be picked-up by other tests that evaluate the integrity and resistance to mechanical breakdown of the particles.

In certain situations, concrete may be removed while the AAR is still active. Stockpiling of crushed concrete would likely serve to diminish the potential for further AAR deterioration. This is suspected since alkalis could leach from the paste and exposed paste surfaces and ASR gel would begin to carbonate, thus shifting the chemical balance away from that needed to promote expansion. Thus, the most likely scenario for AAR to affect the performance of an unbound aggregate base exists in situations where the removed concrete was actively undergoing AAR, and the crushed material was quickly reused in the base course. However, this potential period for expansion of particles in a base course would likely be short, since the same processes of leaching and carbonation could proceed in the unbound pavement layer.

There have been published occurrences of sulfate attack in RCA materials. Prior to discussing these published occurrences, a brief description of the mechanisms of sulfate attack is provided. There are a number of chemical compounds common to Portland cement (Table 1). Of particular importance to sulfate attack are tricalcium aluminate (C_3A) and gypsum (C_SH_2). During hydration, the C_3A reacts with sulfate ions that are produced from the dissolution of gypsum (19, 20). The by-product of the reaction between C_3A and gypsum is ettringite. Ettringite is a stable compound as long as there is an ample supply of sulfate ions. When sufficient sulfate ions are not available, the ettringite is converted to monosulfoaluminate.

Sulfate attack only occurs after the concrete has hardened. When the monosulfoaluminates come into contact with a new source of sulfate ions (from soils with high sulfate contents, groundwater, seawater, etc.), the monosulfoaluminates are converted back into ettringite (19). The conversion of monosulfoaluminate to ettringite is accompanied by a large increase in volume (above 200 percent) (20). This increase in volume can lead to massive expansion forces and subsequent cracking within a hardened concrete.

Table 1: Typical Composition of Ordinary Portland Cement (19)

Chemical Name	Chemical Formula	Shorthand Notation	Weight Percent
Tricalcium silicate	$3CaO\ SiO_2$	C_3S	50
Dicalcium silicate	$2CaO\ SiO_2$	C_2S	25
Tricalcium aluminate	$3CaO\ Al_2O_3$	C_3A	12
Tetracalcium aluminoferrite	$4CaO\ Al_2O_3\ Fe_2O_3$	C_4AF	8
Calcium sulfate dehydrate (gypsum)	$CaSO_4\ 2H_2O$	CSH_2	3.5

The American Concrete Institute (ACI) has published requirements for the cements used in concrete exposed to sulfate-containing materials (21). These requirements are based upon limiting the amount of C_3A to reduce the potential of sulfate attack. Table 2 presents the ACI requirements. This table indicates ranges of sulfate exposure based upon the percentage of sulfates within soils and ground/surface water. The four categories include negligible exposure, moderate exposure, severe exposure and very severe exposure. These requirements were developed for building codes; however, at least one state DOT has adopted similar requirements for transportation construction (22). The Mississippi Department of Transportation has adopted similar requirements to the ACI requirements (Table 3).

Table 2: Requirements for Concrete Exposed to Sulfate-Containing Solutions (21)

Sulfate Exposure	Water soluble sulfate (SO4) in soil, percent by weight	Sulfate (SO4) in water, ppm	Cement Type
Negligible	$0.00 \le SO_4 < 0.10$	$0 \le SO_4 \le 150$	
Moderate	$0.10 \le SO_4 < 0.20$	$150 \le SO_4 < 1500$	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)
Severe	$0.20 \le SO_4 \le 2.00$	$1500 \le SO_4 \le 10{,}000$	V
Very Severe	$SO_4 > 2.00$	$SO_4 > 10{,}000$	V plus pozzolan

Table 3: Cementitious Materials for Soluble Sulfate Conditions (22)

Sulfate Exposure	Water-soluble sulfate (SO4) in soil, % by mass	Sulfate (SO4) in water, ppm	Cementitious material required
Moderate & Seawater	0.10 – 0.20	150 – 1500	Type II cement or Type I cement with 25% Class F, FA or 50% GGBFS replacement
Severe	0.20 – 2.00	1500 – 10,000	Type II cement with 25% Class F, FA

Rollings and Rollings (20) presented the results of a forensic investigation at Holloman Air Force Base (AFB) in New Mexico. Site conditions near the construction project included a high water table and local soils (typically silty sands and sandy silts) with relatively high sulfate contents. The project in question consisted of a Portland cement concrete parking ramp, access taxiway, aircraft shelter, maintenance hangar and associated asphalt road and parking lot, concrete sidewalks and landscaped areas.

The authors also indicated that standard construction practices at Holloman AFB included a minimum of 2 ft thick nonexpansive fill and that Type V sulfate resistant cement be used in all concrete that will be near or on the ground. Because of grades and fill requirements for the project, approximately 2 to 5 ft of fill material was needed for the project. The contractor offered and the government accepted the use of some recycled concrete aggregate that was being removed from another AFB as fill materials. The concrete had shown no existing durability problems prior to excavation.

Rollings and Rollings (20) indicate that isolated heaving of some of the constructed structures began shortly after construction. Heaving became progressively worse over time. Samples of RCA removed from the sections showed an abundance of ettringite and thaumasite (similar to ettringite except carbonate and silica is substituted for the alumina). Therefore, sulfate attack of RCA base layers is a concern, especially for layers that are relatively thick.

2.3 Desirable Properties, Current Tests, and Potential Performance-Related Tests

This section describes the desirable properties of granular materials to be used in unbound base layers. The term “granular” is used here because some of the described tests have been used for natural aggregates but not RCA. Current tests used to characterize granular materials are discussed and, finally, potential performance related tests are described.

2.3.1 Desirable Properties of Granular Materials for use in Unbound Layers

Unbound aggregate base layers are commonly utilized within pavement structures. An unbound base course can be defined as a layer of graded aggregate materials that lies immediately below the wearing surface of a pavement, whether the wearing surface is a hot mix asphalt structure or a Portland cement concrete pavement structure. Depending upon whether the pavement system is rigid or flexible, the intended function of an unbound aggregate base layer is different. For rigid pavements, the unbound aggregate base layer is used to: (1) prevent pumping; (2) protect against frost action; (3) drain water; (4) prevent volume change in the subgrade; (5) increase structural capacity; and/or (6) expedite construction (23). With respect to flexible pavements, unbound aggregate base layers are intended to increase structural capacity by providing stiffness and resistance to fatigue (23).

Saeed et al (8) detailed desirable performance related characteristics of unbound granular layers to resist typical distresses common to both rigid and flexible pavements. Tables 4 and 5 describe the common distresses related to granular base layers for rigid and flexible pavements, respectively. For rigid pavements, Saeed et al (24) indicated distresses that can be attributable to unbound granular layers are cracking, pumping/faulting and frost heave. Cracking in rigid pavements includes longitudinal cracks, fatigue cracking, and corner breaks. Longitudinal cracks develop parallel to the pavement centerline, generally within the wheel path. These longitudinal cracks are caused by loads (stresses) applied to the pavement that are higher than the flexural strength of the Portland cement concrete. Fatigue cracking in rigid pavements typically occurs due to repeated loads on the pavement but may also be caused by thermal gradients or moisture variations within the Portland cement concrete. Corner breaks are also structural breaks within the concrete near the corners of pavement panels. As related to underlying granular layers, theses structural cracks that develop within rigid pavements can be caused by inadequate support. Inadequate support provided by the granular layer can be caused by low stiffness/shear strength, pumping of base/subgrade fines, inadequate density (consolidation of base materials), high moisture content, degradation of base materials and/or inadequate particle angularity and surface texture.

Table 4: Rigid Pavement Distresses and Contributing Factors of Unbound Layers (excerpt from 24)

DISTRESS	BASE FAILURE MANIFESTATION	CONTRIBUTING FACTORS
Cracking	Inadequate support can increase tensile stresses within the slab under repeated wheel loads and result in longitudinal cracking; cracking initiates at the bottom of the slab and propagates to the surface and migrates along the slab; when a crack develops, increased load is placed on the base resulting in deformation within the base; the crack introduces moisture to the base resulting in further loss of support and, thereby, further deformation. Corner breaks (and associated faulting) may be caused by lack of base support from erosion or pumping of the base material; freeze-thaw damage of the base may also contribute to loss of support.	Low base stiffness and shear strength Pumping of base/subgrade fines Low density in base Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads or freeze-thaw cycling
Pumping/Faulting	Pumping involves the formation of a slurry of fines from a saturated base, 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 High fines content Degradation under repeated loads
Frost Heave	Ice lenses are created within the base/subbase during freezing temperatures as moisture is pulled from below by capillary action. During spring thaw, large quantities of water are released from the frozen zone.	Freezing temperatures Capillary source of water Permeability of material high enough to allow free moisture movement to the freezing zone.

Pumping involves fines being removed from the base and being transported by water to the surface of a rigid pavement at the location of a joint or crack (23). The action of ejecting the fines/water mix is caused by the action of repeated wheel loads. This action of removing fines results in eroding the base materials near the joint leading to inadequate support. Severe pumping can then lead to faulting at the joint. As related to the underlying granular layers, pumping/faulting can be caused by poor drainage within the granular layer, free water within the granular layer, low stiffness/shear strength, high fines contents and/or degradation of the granular layer under repeated loads.

Frost heave causes uneven displacement of Portland cement concrete slabs resulting in a rough riding surface. The heave is caused by the formation of ice lenses within the pavement structure. Another aspect is that of thaw weakening when the ice lenses melt. The moisture created from the thawing of the ice lenses can cause the base to lose stiffness which can result in pumping, faulting and corner breaks.

Table 5: Flexible Pavement Distresses and Contributing Factors of Unbound Layers (excerpt from 24)

DISTRESS	BASE FAILURE MANIFESTATION	CONTRIBUTING FACTORS
Fatigue Cracking	Lack of base stiffness causes high deflection/strain in the asphalt concrete surface under repeated wheel loads, resulting in fatigue cracking of the asphalt concrete surface. Alligator cracking only occurs in areas where repeated wheel loads are applied. The same result can also be caused by inadequate thickness of the base. Changes in base properties with time can render the base inadequate to support loads	Low modulus base Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads or freeze-thaw cycling
Rutting	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 consolidations of the base due to inadequate initial density. Changes in base properties with time due to poor durability or frost effects can result in rutting.	Low shear strength Low density of base material Improper gradation High fines content High moisture level Lack of adequate particle angularity and surface texture Degradation under repeated loads or freeze-thaw cycling
Depressions	Inadequate initial compaction or nonuniform material conditions result in additional localized reduction in volume with load applications.	Low density of base material
Frost Heave	Ice lenses are created within the base/subbase during freezing temperature 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 Capillary source of water Permeability of material high enough to allow free moisture movement to the freezing zone.

Saeed et al (24) also detailed desirable performance related characteristics of unbound granular layers to resist distresses common to flexible pavements (Table 5). For flexible pavements, fatigue cracking, rutting, depressions and frost heaving are related to the properties of granular base layers. Fatigue cracking is the result of repeated loads on a flexible pavement. Fatigue cracking can be caused by the loss of stiffness in the granular base. Loss of base stiffness will result in large tensile strains developing at the bottom of the hot mix asphalt layer. After repeated wheel loads, the large tensile strains at the bottom of the hot mix asphalt layer will cause cracks to develop that propagate to the surface of the hot mix asphalt layer in the form of fatigue cracks. Properties of the granular base layer related to fatigue cracking include: low modulus materials, improper gradation, high fines content, high moisture level, lack of particle angularity and surface texture and degradation of the granular base materials (24).

Rutting in flexible pavements related to unbound granular layers can be caused by densification of the layer or by loss of shear strength in any of the flexible pavement layers. Densification within pavement layers is caused by insufficient density at the time of construction. Inadequate shear strength within the granular base layer allows lateral displacement of particles which results in a decreased thickness of the base layer within the wheel path. The overlying hot mix asphalt, being flexible, will depress leading to permanent deformation within the wheel path. Properties of the granular layer related to rutting include shear strength, in-place density, stability, lack of particle angularity and surface texture and/or degradation of the material under repetitive loads or freeze-thaw cycles.

Depressions are somewhat similar to rutting in that they are a downward movement of the pavement surface; however, unlike rutting, depressions occur in a localized area. Depressions can be caused by localized areas of low density or by the localized degradation of granular base materials.

Distresses caused by frost heave in flexible pavements are manifested similarly to those for rigid pavements. The heave is caused by the creation of ice lenses. Spring thaw of the ice lenses can also lead to the loss of stability within the granular base layer.

2.3.2 Current Tests

The Federal Highway Administration (11) has published important properties for aggregates used in unbound granular layers. These properties would also be important for RCA materials utilized in unbound pavement layers. Properties identified include gradation, particle shape, stability, permeability, abrasion resistance and resilient modulus. Table 6 presents the linkage between these aggregate properties and pavement performance.

Gradation influences stability, drainage and susceptibility to frost heave. Well-graded aggregates will tend to provide best stability. An aggregate that contains no fines (minus No. 200 sized materials) can develop internal shear strength, but is often difficult to handle during construction (23). Aggregates that contain a large percentage of fines will not develop sufficient internal shear strength because the aggregate particles will essentially float within the fines (23). Aggregates with high fines content are also frost susceptible.

Table 6: Linkage Between Aggregate Properties and Performance (24)

Pavement Type	Performance Parameter	Related Aggregate Property	Test Parameters That May Relate To Performance
Flexible	Fatigue Cracking	Stiffness	Resilient modulus, Poisson's ratio, gradation, fines content, particle angularity and surface texture, frost susceptibility, degradation of particles
	Rutting, Corrugations	Shear Strength	Failure stress, angle of internal friction, cohesion, gradation, fines content, particle geometrics (texture, shape, angularity), moisture effects
	Fatigue Cracking, Rutting, Corrugations	Toughness	Particle strength, particle degradation, particle size, gradation, high fines
		Durability	Particle deterioration, strength loss
		Frost Susceptibility	Permeability, gradation, percent minus 0.02 mm size, fines type
		Permeability	Gradation, fines content
Rigid	Cracking, Pumping, Faulting	Shear Strength	Failure stress, angle of internal friction, cohesion, gradation, fines content, particle geometrics (texture, shape, angularity), moisture effects
		Stiffness	Resilient modulus, Poisson's ratio
		Toughness	Particle strength, particle degradation, particle size, gradation
		Durability	Particle deterioration, strength loss
	Cracking, Pumping, Faulting, Roughness	Permeability	Gradation, fines content
		Frost Susceptibility	Permeability, gradation, percent minus 0.02mm size, fines type

The use of angular aggregates having surface texture and the proper shape are needed to provide a stable unbound granular layer that has the needed shear strength. Desirable aggregate particles for use in unbound granular layers include a high level of angularity, rough surface texture and cubical particles (11). Angular, cubical particles having a high level of surface texture will result in a stable base that has sufficient shear strength to resist lateral displacement (deformation). Aggregates that are thin or elongated are prone to segregation and breakdown during construction.

Granular base layers must have sufficient stability, especially in flexible pavements. Large, angular, cubical and durable aggregates that have a dense grading are needed to provide stability over the design life of a pavement. As stated previously, loss of stability can lead to numerous distresses within both rigid and flexible pavements. The term stability can be considered the combination of shear strength and stiffness.

Permeability within a granular base is important to assist in preventing frost heave. A granular base layer must be free draining to reduce the potential for ice lenses developing in the layer. Also, moisture that does infiltrate into the layer must not become trapped leading to loss of stability.

The presence of plastic fines within an unbound granular layer can significantly reduce the load carrying capacity of the granular layer. Plastic fines are highly susceptible to moisture changes and increases in moisture can cause a significant reduction in shear strength.

Degradation of particles within an unbound granular layer can result in a loss of stability. Hard durable aggregates that are abrasion resistant are needed to ensure that a pavement will reach its intended design life.

The final important property identified by the FHWA includes the resilient modulus. The resilient modulus test can assist in providing design coefficients for inclusion of granular layers within a pavement system. Resilient modulus defines the relationship between stress and strain for a material and, therefore, is related to the stiffness of the material.

There are various test methods that can be used to characterize these important characteristics of granular materials for use under rigid and flexible pavements. Table 7 presents these various tests along with AASHTO and/or ASTM test methods to measure these important properties of granular base materials.

Table 7: Granular Aggregate Test Procedures (excerpt from 11)

Property	Test Method	Reference
Gradation	Sizes of Aggregate for Road and Bridge Construction	ASTM D448/AASHTO M43
	Sieve Analysis of Fine and Coarse Aggregate	ASTM C136/AASHTO T27
Particle Shape	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
	Uncompacted Voids Content of Fine Aggregate (As influenced by Particle Shape, Surface Texture, and Grading	AASHTO T304
	Index of Aggregate Particle Shape and Texture	ASTM D3398
Base Stability	California Bearing Ratio	ASTM D1883/AASHTO T193
	Moisture-Density Relations of Soils Using a 5.5 lb (2.5 kg) Rammer and a 12-in. (305mm) Drop	ASTM D698/AASHTO T99
	Moisture-Density Relations of Soils Using a 10-lb (4.54 kg) Rammer and an 18-in. (457 mm) Drop	AASHTO T180
Permeability	Permeability of Granular Soils (Constant Head)	ASTM D2434/AASHTO T215
Plasticity	Determining the Plastic Limit and Plasticity Index of Soils	ASTM D4318/AASHTO T90
	Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	ASTM 2419/AASHTOT176
Abrasion Resistance	Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131/AASHTO T96
Resilient Modulus	Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46	AASHTO T307

2.3.3 Potential Performance Related Tests

Within Section 2.3.1, the desirable properties of granular base materials were described. Predominantly, granular base materials need to provide stiffness (stability) for support of overlying layers (whether flexible or rigid) and be durable. In order to provide the needed stiffness, the granular base materials should be hard, angular and have adequate surface texture and the proper gradation. Potential performance related tests to evaluate properties related to stiffness could include:

Coarse aggregate angularity (fractured face count)
Coarse aggregate angularity (uncompacted voids)
Fine aggregate angularity
Flat and Elongated Test
Flat or Elongated Test
Los Angeles Abrasion and Impact
Micro-Deval Abrasion
California Bearing Ratio
Shear Strength
Resilient Modulus

Durability is generally defined for granular base layers using sulfate soundness tests, whether it be sodium or magnesium. Variations of the sulfate soundness tests which perform actual freezing have also been used to evaluate the performance of granular base materials. The following sections describe potential performance related tests for unbound granular layer materials.

2.3.3.1 Coarse Aggregate Angularity

Angular coarse aggregates are needed within unbound granular layers to ensure a stable layer that has the needed stiffness to resist deformation due to repetitive loads. There are two primary tests available for evaluating the angularity of coarse aggregates: the fractured face test and the coarse aggregate flow test (or sometimes called uncompacted voids in coarse aggregate test).

The fractured face test is conducted in accordance with ASTM D5821-01, Determining the Percentage of Fractured Particles in Coarse Aggregate. To run this test, a representative sample having a specified mass, depending on the nominal maximum aggregate size, is washed and dried to a constant mass. Individual aggregate particles are then visually inspected to determine whether a particle has a fractured face. A fractured face is defined as an angular, rough or broken surface of an aggregate particle created by crushing, by other artificial means or by nature. A face is considered a “fractured face” only if it has a projected area at least as large as one quarter (25 percent) of the maximum projected area of the particle. Once visually inspected, each aggregate particle is placed within one of two categories: 1) fractured particles and 2) particles without a fractured face. It is also possible to further differentiate the fractured particles as to whether each particle has a single fractured face or two or more fractured faces.

The Uncompacted Voids in Coarse Aggregate (AASHTO T326) method is identical to the fine aggregate angularity test (AASHTO T304) used in the Superpave mix design system, except the equipment size has been increased to accommodate the larger aggregates. The uncompacted voids test is an indirect measure of particle shape, angularity and particle surface texture. These three aggregate characteristics affect the packing characteristics of an aggregate sample. The test is conducted by allowing a sample of coarse aggregate to flow through an orifice of a funnel into a calibrated cylinder. The uncompacted void content is calculated as the air void content between the loosely compacted aggregates. Needed for this calculation are the bulk specific gravity of the coarse aggregate and the volume of the calibrated cylinder. Similar to AASHTO T304, three methods are included for the coarse aggregate flow test. Method A specifies a known gradation, Method B specifies that the test be run on three individual size fractions and Method C specifies the test is run on the "as-received" gradation.

During NCHRP 4-23, Performance Related Tests of Aggregates for Use in Unbound Pavement Layers, Saeed et al (24) recommended the uncompacted voids in coarse aggregate (Method A) as a performance related property. This test was recommended because it could provide a good overall indicator of the potential to resist permanent deformation as results are related to particle shape, angularity and surface texture.

2.3.3.2 Fine Aggregate Angularity

The angularity, shape and texture of fine aggregates is generally evaluated using the fine aggregate flow test (AASHTO T304). This test is based upon the National Aggregate Association Flow Test that was developed to evaluate the effect of fine aggregates on the finishability of Portland cement concrete. The fine aggregate flow test is the predecessor of the coarse aggregate flow test described above.

The test method for uncompacted voids in fine aggregate determines the loose uncompacted void content of fine aggregate by allowing the fine aggregate to flow through an orifice located at the bottom of a specified funnel and fall freely into a calibrated funnel. The uncompacted void content of the fine aggregate is calculated using the mass of aggregate within the calibrated cylinder, bulk specific gravity of the fine aggregate and volume of the calibrated cylinder.

There are three methods for running AASHTO T304. Method A specifies a known gradation, Method B specifies the testing of three size fractions and Method C entails testing the "as-received" materials.

Similar to the coarse aggregate flow test, Saeed et al (24) recommended the use of the fine aggregate flow test for unbound pavement layers (Method A). This test was identified as being related to performance. The combination of the fine aggregate and coarse aggregate flow tests should characterize the combined effect of particle shape, angularity and texture for unbound granular layer materials.

2.3.3.3 Coarse Aggregate Particle Shape

The shape of coarse aggregate particles is generally evaluated in accordance with ASTM D4791, "Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate." Flat and/or elongated particles can break under compaction, thus changing the characteristics of the unbound granular layer materials. A large percentage of flat and/or elongated particles can also affect the workability of the granular materials during construction. The ASTM D4791 method begins by reducing a sample to a minimum test sample mass that is based upon the nominal maximum aggregate size of the material's gradation. For size fractions with at least 10 percent retained, 100 particles are split out for testing. Each particle is then measured to determine length and width. Generally, this is conducted with a proportional caliper in which the length (maximum dimension) is used to set the caliper. Then, the thickness of the particle is compared to the desired ratio by determining if the particle will pass between the other end of the caliper and a fixed post. Flat and elongated particles are placed in one pile and the particles that are not flat and elongated are placed in a separate pile. The percentage of flat and elongated particles, by mass, are then calculated based upon a weighted average for the sample's gradation.

An alternative aggregate property is to measure flat or elongated aggregate particles. The same proportional caliper is used to measure flat or elongated particles as is used to measure flat and elongated particles. Flat particles are determined by setting the larger opening of the caliper to the particles width. The particle is considered flat if the thickness of the particle can be placed within the smaller opening. Elongated particles are determined by setting the larger opening of the caliper to the length. The particle is considered elongated if the width of the particle can be placed within the smaller opening. This test is slightly more time consuming than the flat and elongated test because each particle is measured for both flatness and elongation. However, the flat or elongated test has been recommended over the flat and elongated test for hot mix asphalt aggregates (25).

2.3.3.4 Aggregate Toughness and Abrasion

Aggregates must be resistant to breakdown and abrasion to withstand stockpiling, shipping, placement and compaction. Aggregate breakdown and abrasion changes the gradation of the granular materials which can significantly affect the performance of an unbound granular layer. Within the U.S., the most common method of evaluating the toughness of coarse aggregates is the Los Angeles Abrasion and Impact test (AASHTO T96). The Los Angeles Abrasion and Impact test method entails an aggregate sample being placed inside a large rotating steel drum containing a specific number of spherical steel charges. As the steel drum rotates, the aggregate sample and steel charges are picked up by flights within the drum until they drop a height of approximately 27 inches on the opposite side of the drum. This action subjects the aggregate sample to abrasive forces through the contact of aggregate particles on both other aggregate particles and the steel spheres and impact forces as the aggregates and steel charges are dropped from the flights. The steel drum is rotated at a constant speed of 30 to 33 rpm and is rotated for 500 revolutions. After 500 revolutions, the sample is washed over a sieve coarser than the No. 12 and the retained material dried to determine the percentage of loss.

The Micro-Deval test was developed in France during the 1960's and was based on the Deval test developed in the early 1900's (26). The Micro-Deval test provides a measure of abrasion resistance and durability of mineral aggregates through the actions of abrasion between aggregate particles and between aggregate particles and steel spheres in the presence of water. A standardized test method for the Micro-Deval test is provided in AASHTO T327, Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus. This test method entails abrading the aggregate sample within a small diameter drum with steel charges in the presence of water. The steel charges are smaller in diameter than those used in the Los Angeles Abrasion and Impact test (3/8 in. compared to 2 in.). Test samples are soaked in 2 liters of water for a minimum of one hour prior to testing. Both the aggregates and water are introduced into the drum for testing. The drum is rotated at 100 ±5 rpm for two hours.

Unlike the drum used for the Los Angeles Abrasion and Impact test, there are no flights within the drum. At the conclusion of the test, the aggregate sample is dried to constant mass and, similar to the Los Angeles and Impact test, the mass loss determined.

2.3.3.5 Strength Tests

As stated numerous times within this report, strength, or stability, is a necessary characteristic for all unbound pavement layers. The most common test to evaluate the strength of highway materials is the California Bearing Ratio (CBR) Test. This test has been used for many years to provide an indication of the structural capacity provided by a granular pavement layer. The CBR test was developed by the California Highway Department in 1929 for use in an empirical flexible pavement design procedure (27). Results from the CBR test provide an index of strength. The test involves pushing a 3 sq. in. piston into a sample at a specified rate of 0.05 in/min. The unit load is recorded at each 0.1 in. of penetration up to a total deformation of 0.5 in. Deformations at 0.1 and 0.2 in. are then compared with loads needed to cause equal deformation into a standard, well-graded crushed stone containing ¾ in. maximum sized particles. The CBR test is run in accordance with AASHTO T193.

Saeed et al (24) identified shear strength of the granular materials as the single most important property that governs unbound layer performance. In order to measure shear strength, Saeed et al (24) recommended the triaxial shear test. This test was recommended because: 1) the test is universally accepted for measuring shear strength; 2) most state DOTs have the capability to run the test; 3) the test method can allow testing at different stress states; 4) the test method includes repetitive loadings similar to the actions of traffic; 5) the test provides an indication of both resilient and permanent strains; and 6) the test method can allow for varying moisture content. A method of test was provided by Saeed et al (24) at the conclusion of NCHRP Project 4-23. The method is very similar to triaxial shear tests conducted on soils in that a sample is confined and a deviator stress is applied. However, the method recommended by Saeed et al (24) differs in that the method recommends a cyclic loading following a haversine waveform.

2.3.3.6 Fundamental Properties

A fundamental property that can be determined for granular materials is the resilient modulus. The resilient modulus is useful in characterizing the stiffness of a granular material and provides the amount of recoverable strain due to a specific stress state. Similar to the shear strength test described above, the resilient modulus test is a triaxial test in that a confining stress is used to confine the sample and a deviator stress is applied to cause deformation. Unlike the shear strength test, the sample is not loaded to failure. Rather, relatively small strains are induced in order to determine the magnitude of recoverable strain for various stress states. Defined, the resilient modulus is the ratio of a deviator stress to the amount of recoverable strain (27). Resilient modulus is a required input for all granular and fine-grained pavement layers within the new Mechanistic-Empirical Pavement Design Guide.

2.3.3.7 Durability Tests

The most common tests to evaluate the durability, especially freeze/thaw, of granular base materials are the sodium and magnesium sulfate tests. These tests have also been shown related to degradation due to the actions of wetting and drying. Sulfate soundness tests are conducted in accordance with AASHTO T104, Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate. The test is conducted by preparing a sample per specification depending upon if the material is a coarse or fine aggregate. Samples are then soaked in a saturated solution of either sodium or magnesium sulfate for 16 to 18 hours. The samples are then drained and oven dried to a constant mass. Typically, samples are subjected to five cycles of wetting and drying. After the final cycle, the sample is rinsed to remove the sulfate solution and dried back to constant mass. The weighted averaged of aggregate loss is then determined. There is some concern in the literature that these tests may not be applicable for RCA materials. It is hypothesized that the sulfate ions can attack the cement mortar surrounding aggregate particles which can lead to severe mass loss in samples (11).

Another method to evaluate the freeze/thaw characteristics of granular materials was developed by Senior and Rogers (26). This method is similar to the sulfate soundness test in that the test evaluates durability; however, the method is slightly different in that samples are subjected to actual freezing temperatures instead of the simulated freezing in the sulfate soundness test. Individual size fractions retained on the 0.530 in., 3/8 in. and No. 4 sieves (13.2, 9.5 and 4.75mm) are placed in separate 1 liter jars. The samples are soaked in a 3 percent sodium chloride (NaCl) solution for 24 hours. After soaking, the samples are drained and sealed prior to being placed in a freezer for 16 hours. Freezing is followed by thawing at room temperature for 8 hours. The freezing and thawing defines one cycle of conditioning. Conditioning is repeated for a total of five cycles. A weighted average of mass loss is then determined based upon the samples gradation.

The New York State Department of Transportation has adopted a test similar to the method proposed by Senior and Rogers (26). This test method is documented in Test Method NY 703-09, Standard Test Method for Resistance of Coarse Aggregates to Freezing and Thawing. The primary difference between the New York method and the Senior and Rogers (26) method is that the New York method requires 25 freeze/thaw cycles.

Both the Los Angeles Abrasion and Impact and Micro-Deval tests have been used as indicators of durability. In fact, a reasonable correlation has been developed between the magnesium sulfate soundness test and the Micro-Deval test (25, 26)

A study conducted by the Ohio Department of Transportation used a concrete freeze/thaw machine manufactured by ScienTemp to compare the durability of RCA to a gravel and limestone aggregate (28). Each aggregate sample (3 RCA sources and a single source of limestone and gravel) were prepared by fractionating the samples on the 1 in., ¾ in., No. 4 and No. 30 (25mm, 19mm, 4.75mm and 0.60mm) sieves. Each fraction was then covered with ½ in. (12.5mm) of water and subjected to 54 freeze/thaw cycles. After the freeze/thaw condition, the percent loss was determined for each fraction. This process continued to determine the cumulative percent loss after a total of 100 and 160 freeze/thaw cycles had been accumulated.

Based upon the results of this testing, Mulligan (28) concluded that the RCA materials were not as durable as the natural (virgin) aggregates. This was based upon an increased amount of aggregate loss observed for the RCA materials. This observation was generally true for each fraction size evaluated.

2.4 Materials Specifications for Recycled Concrete

Chesner (29) has prepared a white paper and specification for the use of RCA in unbound pavement layers. This reference provides an excellent overview of the specification developed for using RCA in unbound layers (which was adopted as AASHTO M 319-02, Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course) by providing narrative discussions on each section of the specification.

Within the Chesner specification are several "Notes" that are related to the construction and performance of RCA in unbound granular layers. The first Note discusses the compaction of RCA materials in the field. Chesner indicates that the proper compaction of these materials "… is critical to the performance…" of the granular layer. The author also indicated that the water absorption characteristics of RCA materials are generally higher than typical aggregates and, therefore, RCA materials will likely have a higher optimum moisture content. Chesner (29) also indicates that the control of compaction in the field can be difficult. This is primarily caused by variations in specific gravity of the RCA materials. An appendix presented within the specification presents an alternative method (alternative to Proctor and field density testing) of controlling layer density. This method basically entails rolling the granular layer until refusal.

Another note within the specification (29) indicates that engineers should be aware that pore water within and passing through RCA layers may be highly alkaline in nature. Water emerging from a RCA layer may have a pH of approximately 11 to 12 which indicates that it may be corrosive to metal culverts and rodent guards on drainage system outlets.

The specification (29) also notes that the use of RCA should be minimized, when possible, over a geotextile drainage layer, gravel drain fields, drain field piping or soil lined stormwater retention/detention facilities. Soluble minerals can precipitate and be transported from the RCA materials and deposited within drainage systems. The precipitants are sometimes referred to as tufa-like or portlandite deposits.

Chesner (29) indicates that layers of RCA materials can be expected to gain strength over time. The gain in strength is due to re-cementing of the RCA fines. The note indicates that if the RCA materials are to be utilized in a drainage layer, the fine portion of the RCA should be removed to reduce the potential for re-cementation and resultant loss in permeability.

The fifth Note states that RCA materials will typically yield high sulfate soundness loss values in the lab. Chesner (29) indicates this can happen with "… conventional sulfate soundness …" which suggests that high loss values may occur with either sodium or magnesium sulfate soundness solutions.

The final Note contained within the specification recommended by Chesner (29) indicates that engineers should be cautioned to ensure that RCA materials are not contaminated with extraneous solid waste or hazardous materials. The White Paper indicates that there is more potential for solid waste or hazardous materials when the RCA materials are obtained from building demolition.

A typical material that is contained within recycled Portland cement concrete pavements is hot mix asphalt. Rigid pavements are routinely overlaid with hot mix asphalt. Even when milling the hot mix asphalt layer off a Portland cement concrete pavement, hot mix asphalt materials will still likely be included when recycling the rigid pavement. The Minnesota DOT allows up to 3 percent asphalt binder within a RCA sample, by weight (9). With this specification, milling the asphalt layer may not always be necessary, thus, reducing construction time and cost. Other states limit the amount of recycled asphalt pavement to values as low as 2 percent (30).

The White Paper provided by Chesner (29) discusses gradation requirements and proportioning within the specification. The authors state that there is no evidence that the gradation requirements for RCA should be any different than virgin aggregates used for granular aggregates. The authors recommend the requirements set forth in AASHTO M147, Materials for Aggregate and Soil-Aggregate Subbase, Base and Surface Courses, and ASTM D 2940, Graded Aggregate Materials for Bases or Subbases for Highways and Airports, or the specifying agency for gradation requirements. Other materials, e.g. natural aggregates, can be successfully combined with RCA in order to meet gradation requirements.

Physical properties within the specification includes a general description of RCA as materials consisting of crushed concrete and natural aggregate that has been derived from the crushing of Portland cement concrete that are hard, durable fragments of stone, gravel, slag, crushed concrete and/or sand. Requirements for RCA are included for the amount of plastic soils using Atterberg liquid limits, plasticity index and sand equivalency, Los Angeles Abrasion and soundness.

The specification also states that RCA materials should not have more than 5 percent hot mix asphalt or masonry materials.

CHAPTER 3 – RESEARCH APPROACH

3.1 Introduction

In order to accomplish the objectives of this research study, five tasks were required. The following sections describe the activities within each of these five tasks.

3.1.1 Task 1 – Literature Review

Task 1 of this project involved conducting a review of available literature on the use of RCA in pavement systems. Chapter 2 presented the literature review. The literature review included published papers as well as reports and articles on the use of RCA. Information obtained within the literature review was helpful in identifying the current state of practice related to the specifying of RCA materials.

3.1.2 Task 2 – Identification of RCA and Limestone Sources

Task 2 of this project involved identifying seven sources of RCA and three sources of crushed limestone. The intent in selection of the seven RCA sources was to select sources that should provide a wide range of performance. Crushed limestone meeting the MDOT requirements for No. 610, No. 825 B, and ¾ inch and down were used for comparison purposes.

3.1.3 Perform Laboratory Testing of Granular Materials

All ten of the granular materials (seven RCA and three limestone) were subjected to the same classification and strength tests. Classification tests conducted on the ten materials included: particle size analyses, Atterberg limits, coarse and fine aggregate specific gravity and absorption, micro-Deval loss, Los Angeles Abrasion loss, coarse aggregate angularity and fine aggregate angularity. Strength tests included standard Proctor, modified Proctor, California Bearing Ratio (CBR), and resilient modulus. The CBR and resilient modulus testing were conducted on samples prepared at a target of 99 percent of standard and modified Proctor maximum dry density.

3.1.4 Prepare Final Report

A draft final report that documents the work of the entire research effort was prepared. The draft final report provides conclusions and recommendations formed to answer the project objectives. The draft final report was prepared in accordance with MDOT requirements.

CHAPTER 4 - MATERIALS AND TEST METHODS

4.1 Introduction

This chapter provides information on the RCA materials utilized during the research effort along with descriptions of each laboratory test used during the project.

4.2 Materials

A total of ten materials were utilized within this research project. Seven of the ten were RCA materials obtained from Mississippi suppliers. The remaining three were limestone materials obtained from Mississippi suppliers. Of the three limestone materials, one met the MDOT requirements for No. 610, one met the requirements for No. 825 B, and one met the requirement for ¾ inch and down. Requirements for these limestone sizes are provided within Section 703.04 of the Mississippi Standard Specifications for Road and Bridge Construction (2004).

The seven RCA materials were selected in a manner to provide a range of properties. Two the RCA materials were recycled from MDOT rigid pavements. Four of the RCA materials were construction debris, and the final RCA material was recycled prestressed concrete. Table 8 provides general comments on the seven RCA materials based upon source information and visual observations.

Table 8: Descriptions of RCA Materials

Material I.D.	Comments
RCA1	Recycled MDOT Interstate rigid pavement
RCA2	Construction debris, soil added, possibly contains concrete wash-out
RCA3	Residential construction debris, clayey/silty sand added
RCA4	Construction debris, with small amounts of asphalt, granite countertops and other non concrete materials
RCA5	Recycled prestressed concrete, possible addition of soil
RCA6	Construction debris, soil added
RCA7	Recycled MDOT US Highway rigid pavement

4.3 Test Methods

The following sections describe each of the tests conducted on the RCA materials.

4.3.1 Particle Size Analysis (AASHTO T27)

All states set gradation limits for materials that are to be used as granular base course layers under pavements. The gradation of a material is an indicator of other properties such as permeability, frost susceptibility, and shear strength. This routine test consists of shaking a sample of known mass through a stack of sieves in descending sizes. The standard procedure of this method is outlined in AASHTO T27, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.

4.3.2 Atterberg Limits (AASHTO T89 & T90)

The plasticity of the minus No. 40 (0.425mm) sieve size material was evaluated using Atterberg Limits. Plastic limits are used to identify the moisture content at which a material begins to exhibit plastic behavior. The liquid limit is used to define when the material behaves as a viscous liquid. The numerical difference between the two limits is called the Plasticity Index (PI) which indicates the magnitude of the range of moisture contents a material will remain in a plastic state. This test is used by many DOT's as another means to measure the cleanliness of a granular material.

4.3.3 Moisture/Density Relationship; Proctors (AASHTO T99 and T180)

Field compaction of granular layers is very important to the life of both flexible and rigid pavement structures. Proper compaction of a given material increases the shear strength and stiffness and decreases the permeability. Laboratory compaction typically is used to establish a relationship between moisture content and dry density, which is then used to determine an estimated optimum moisture content and maximum dry density. To do this, a representative sample is compacted into a mold, of known volume, through a range of moisture contents and the resulting calculated dry densities are plotted versus the moisture contents. This graph is used to estimate the maximum density and corresponding moisture content. Standard Proctors following the procedure set forth by AASHTO T99, Moisture-Density Relations of Soils Using a 2.5-kg Rammer and a 305-mm Drop, to define optimum moisture and maximum dry density was used for the RCA materials. This test is typically termed the "Standard Proctor Test." Proctors following the procedure set forth by AASHTO T180, Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop, was also utilized to define the relationship between moisture and density.

4.3.4 Flat and/or Elongated Particles (ASTM D4791)

The shape characteristics of coarse RCA particles (retained on the No. 4 (4.75mm) sieve) were evaluated using ASTM D4791, Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate. The percentage determined from this procedure helps make inferences about the amount of breakdown that may occur during compaction of the material. Breakdown of particles during field work changes the overall gradation of the aggregate, which may affect performance. The test method proportionally quantifies an aggregate's dimensions in order to define its shape. Representative samples of RCA were measured with a proportional caliper using three ratios of 5:1, 3:1, and 2:1. Length is defined as the maximum dimension of the particle and width is the largest dimension perpendicular to the length. Thickness is defined as being the dimension perpendicular to both the width and length. Particles were classified into two groups: Flat and Elongated and Flat or Elongated. Particles are classified as Flat and Elongated if the ratio of length to thickness is larger than the ratio being used to measure. Flat or Elongated particles are those that fail the definitions of flat or elongated.

4.3.5 Uncompacted Void Content of Coarse Aggregate (AASHTO T326)

In addition to the particle size distribution and particle shape, the shear strength of granular materials is greatly influenced by the angularity of the particles. In order to evaluate the angularity characteristics of the coarse RCA materials, AASHTO TP56, Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture and Grading), was conducted. This test method entails allowing a graded sample of coarse aggregate to fall freely from a specified height into a calibrated cylinder. Using the bulk specific gravity of the materials, the percentage of air voids between the particles within the calibrated cylinder is determined. Results from this test are expressed as the percent voids between the particles.

4.3.6 Specific Gravity and Absorption (AASHTO T85/T84)

Specific gravity is the ratio of the weight of a given volume of material to the weight of a similar volume of water. Or stated another way in terms of an aggregate, specific gravity is a numerical value showing the number of times heavier an aggregate particle is when it is compared to an equal volume of water. Most naturally occurring aggregates have a specific gravity of 2.6 to 2.7, although values as low as 2.4 or as high as 3.0 have been encountered. Specific gravity of an aggregate is not an indication of the quality of the aggregate itself; however, it can be an indication of potential problems and is needed for computations involving volume and mass. Another property derived from the specific gravity test is water absorption. Absorption has been used as an indicator of aggregate durability as related to freezing and thawing. High absorption has been used as a sign of unsound aggregates. AASHTO test methods T 84, Specific Gravity and Absorption of Fine Aggregates, and T85, Specific Gravity and Absorption of Coarse Aggregates, were used to determine the specific gravity and absorption of the fine and coarse grained particles of RCA, respectively.

4.3.7 Uncompacted Void Content of Fine Aggregate (AASHTO T304)

Uncompacted Void Content of fine aggregate or fine aggregate angularity (FAA) is an index that is a function of particle shape, angularity, and surface texture, which could provide an indicator of the potential for resisting permanent deformation. This test is performed by filling a 100mL cylindrical measure by allowing the fine aggregate to freely flow through a funnel from a fixed height into the measure. The aggregate is struck off the top of the measure and the mass is determined. The uncompacted void content is calculated based on the absolute volume of the fine aggregate and the volume of the measure and expressed as the percent air voids.

4.3.8 Los Angles Abrasion and Impact (AASHTO T96)

The Los Angles Abrasion and Impact Test simulates the amount of breakdown that an aggregate may experience during processing, handling, and placement. This is important because as the aggregate degrades the gradation changes, which, as stated earlier, is an indicator of several other aggregate properties. Testing was conducted according to AASHTO T96, Los Angles Abrasion and Impact by placing a sample graded according to the nominal maximum aggregate size in a rotating steel drum with steel spheres. After 500 revolutions, the sample was washed over a sieve coarser than the No.12 sieve, and the retained material dried to determine the percentage of loss.

4.3.9 Micro-Deval Abrasion Loss for Coarse Aggregates (AASHTO T 327)

Unlike the LA Abrasion and Impact Test, Micro-Deval abrasion loss is used to determine abrasion loss with minimal to no impact. Also, this test can be used as an indicator of the soundness of coarse particles. All six samples were tested in accordance with AASHTO T 327. Two replicate samples of each material were graded based on the nominal maximum aggregate size. The composite sample was then placed in a stainless steel jar along with 5000g of steel charge and 2 liters of water and allowed to soak for at least 1 hour. The jar was then rotated at 100 ± 5 rpm for 2 hours or 105 minutes allowing the aggregate particles to abrade with the steel charges. After the specified time, the sample was removed from the jar and washed over a No. 4 and No. 16 (4.75mm and 1.18mm) sieve. The retained material was then dried back to a constant mass and the percent weight loss was determined to the nearest tenth.

4.3.10 Magnesium Sulfate Soundness of Aggregates (AASHTO T104)

Soundness testing gives insight to the amount of degradation that an aggregate may experience caused by environmental factors, particularly freeze/thaw. The RCA was tested in accordance to AASHTO T104, which calls for a graded sample to be immersed into a sodium sulfate solution for 15 hours followed by 8 hours of oven drying. During the drying process the dissolved salts crystallize within the permeable pores of the aggregate particles causing expansive forces similar to the expansion of water when freezing. The samples were subjected to 5 cycles of soaking and drying before being washed thoroughly over a No. 8 (2.36mm) sieve. The material retained was then dried to a constant mass and the percent loss calculated.

4.3.11 California Bearing Ratio (AASHTO T193)

The California Bearing Ratio (CBR) has been a widely accepted test procedure for determining a soil or soil-aggregate mixture’s strength for use in pavement design calculations.

This procedure measures the resistance exhibited by a laboratory compacted sample when it is subjected to strain controlled load. The measured resistance is expressed as a percent of that of a solid limestone rock, which is given the value of 100. Samples can be tested after a saturation period (this produces a worst case situation for mixtures containing clays), or they can be tested unsoaked to yield a maximum value under favorable conditions. The RCA samples in this study were tested after the prescribed soaking period.

4.3.12 Determining the Resilient Modulus of Soils and Aggregate Materials

Stiffness is a characteristic used as an aid in pavement structural design, as well as an indicator to material performance within the pavement system. Resilient modulus testing of each sample was conducted in accordance with the method recommended by NCHRP Project 1-28A. This procedure simulates the stresses at various depths within a pavement structure caused by passing wheel loads by using a triaxial pressure chamber and a servo-controlled hydraulic actuator, as shown in Figure 3. The amount of recoverable axial deformation that was exhibited by the specimens was measured using internal platen to platen displacement transducers. The specimens used in this test are fashioned in the same manner as those used in the Repeated Load Shear Test. Specimens were subjected to a 1,000 repetition preconditioning stage prior to testing. After the preconditioning stage the sample was tested under a combination of varying confining pressures and cyclic stresses ranging from 1.5 psi (10kPa) to 140 psi (965kPa) in a 30 sequence test. Each sequence consisted of a single confining stress and cyclic stress of 100 load repetitions. The amount of axial deformation and the corresponding loads were measured during the last 6 load cycles of each sequence.

Figure 3: Resilient Modulus Testing Apparatus

CHAPTER 5 – TEST RESULTS AND ANALYSIS

5.1 Introduction

This Chapter presents the results and analyses obtained from the testing performed on the materials selected for this study. After presenting the test results, analyses of the data are provided to accomplish the project objectives.

5.2 Test Results

The following sections present results of all testing conducted on the seven RCA materials and three limestone materials. Test results are divided into two categories: classification testing and strength testing. Appendix A provides all test results.

5.2.1 Classification Tests

As highlighted within Chapter 4, a number of classification tests were conducted on the ten materials. Classification tests included particle size analyses, Atterberg limits, coarse and fine aggregate specific gravity and absorption, micro-Deval loss, Los Angeles Abrasion loss, coarse aggregate angularity and fine aggregate angularity.

Table 9 presents the results of the particle size analyses conducted on the ten materials. Figures 4 through 6 illustrate the RCA gradations compared to the MDOT Standard Specification gradation requirements for No. 610, Size 825 B and ¾ inch and Down. Recall that Special Provision No. 907-703-10, dated June 6, 2012, states that RCA materials meet the gradation requirements of Size 825 B (Figure 5) with the exception that the percent passing the No. 200 sieve shall be between 2 and 18.

Based upon the gradation requirements provided within Special Provision 907-703-10, three of the seven RCA materials did not explicitly meet the requirements; however, the three not meeting requirements were very close. RCA1 did not meet requirements on the 1 in. and ½ in. sieves being 2 and 0.7 percent too fine, respectively. RCA5 was 0.2 percent too fine on the 1 in. sieve. Finally, RCA7 was 1.7 percent too fine on the 1 in. sieve.

Table 9: Particle Size Test Results for All Ten Materials

Sieve Size (US)	Materials									
	RCA1	RCA2	RCA3	RCA4	RCA5	RCA6	RCA7	No. 610	825 B	3/4 Down
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	98.3	100.0	100.0	100.0	100.0
1 in.	100.0	95.2	97.5	97.1	98.2	96.0	99.7	96.3	95.8	100.0
3/4 in.	96.5	88.8	89.9	92.5	94.5	91.2	88.9	88.0	78.3	99.3
1/2 in.	85.7	77.5	75.2	80.3	83.4	84.1	69.9	74.8	61.9	84.0
3/8 in.	76.2	64.9	63.8	71.9	72.8	78.4	60.2	69.9	55.1	77.8
No. 4	55.7	47.4	45.2	54.5	51.4	62.0	43.3	56.1	43.4	61.5
No. 8	44.6	37.5	37.7	45.0	39.5	49.6	34.1	42.2	32.6	46.7
No. 10	42.0	35.9	35.9	43.0	37.2	45.0	30.0	39.8	30.6	34.8
No. 16	36.5	30.1	32.0	37.9	32.1	41.6	26.8	32.3	23.9	25.2
No. 40	24.6	16.2	21.6	28.1	21.5	27.9	13.7	20.6	15.4	17.9
No. 50	18.9	9.9	17.3	22.2	16.2	21.8	9.1	17.4	13.2	14.2
No. 200	7.4	4.0	6.8	6.9	6.6	13.0	2.5	10.5	8.6	10.3

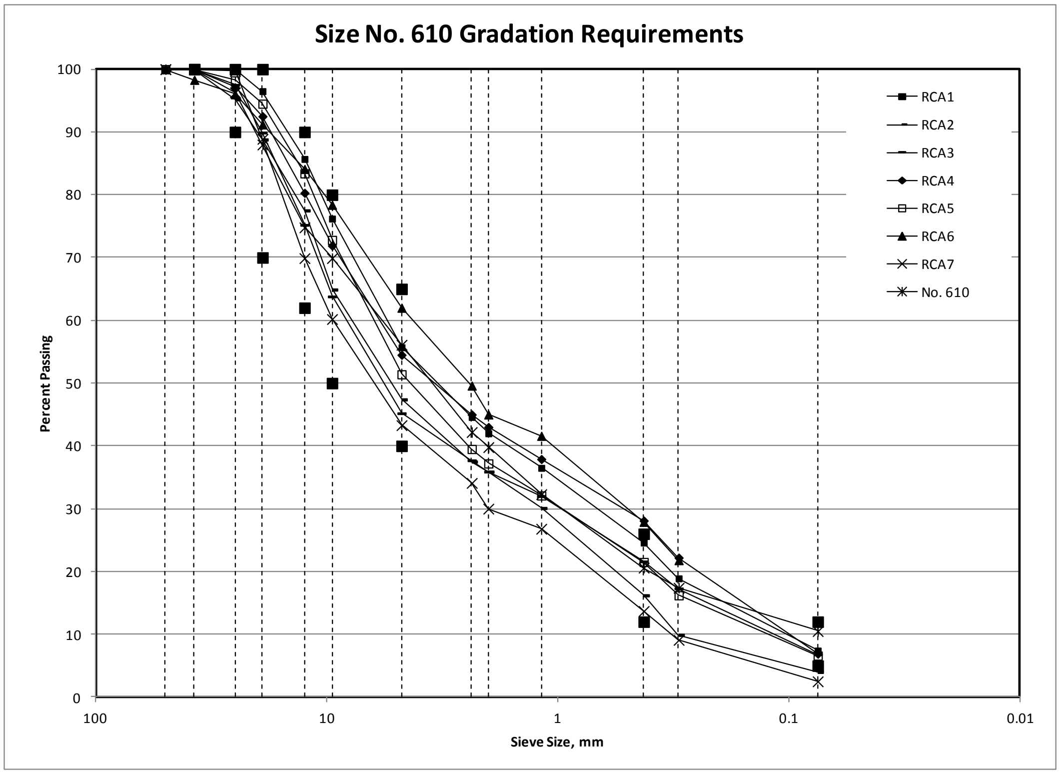

Figure 4: RCA Gradations Compared to No. 610 Requirements

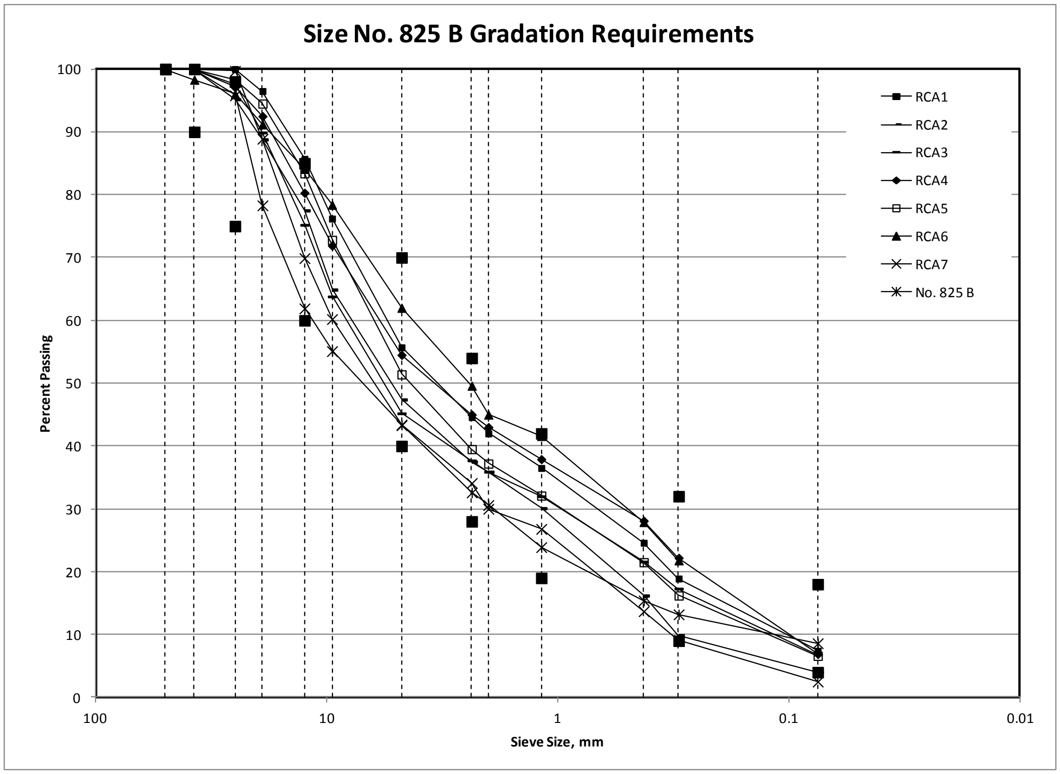

Figure 5: RCA Gradations Compared to No. 825 B Requirements

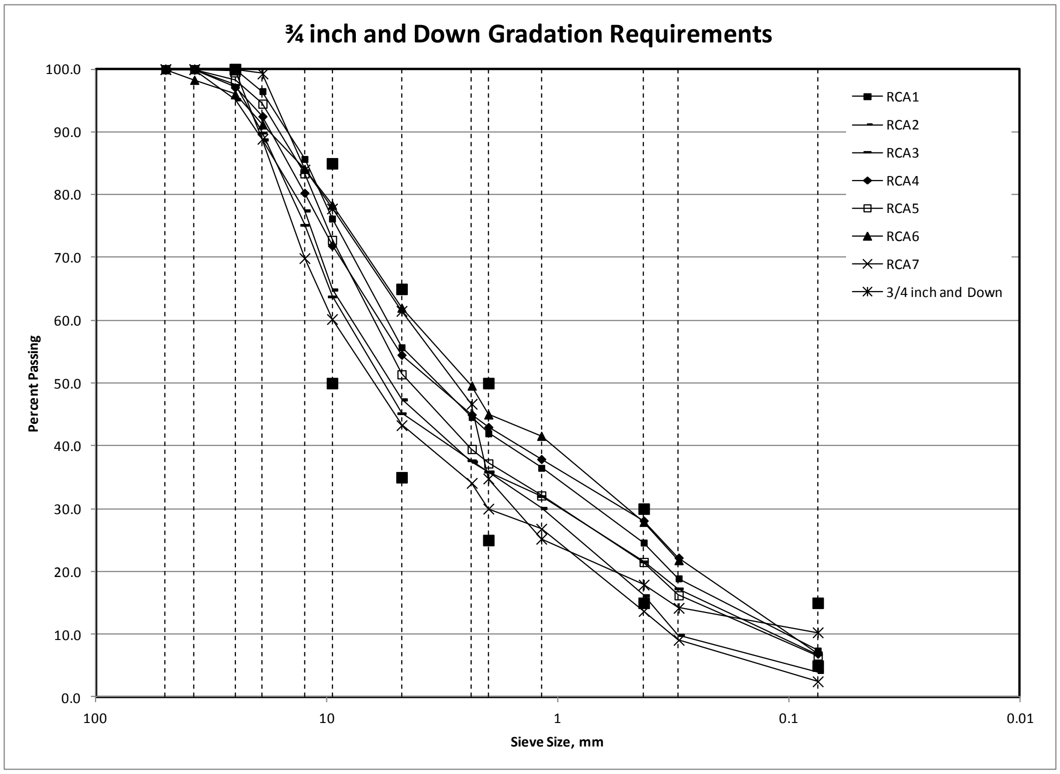

Figure 6: RCA Gradations Compared to 3/4 Down Requirements

Table 10 presents the test results for the remaining tests that are characterized as classification tests. Los Angeles Abrasion loss values ranged from a low of 22 percent for the ¾ inch and Down material to a high of 32 percent for RCA6 and RCA7. The range in loss values for the ten materials was 10 percent. On average, the Los Angeles Abrasion loss values for the RCA materials were slightly higher than for the limestone materials. According to the Mississippi Standard Specification for Road and Bridge Construction (2004), coarse aggregates used for crushed stone courses shall have a Los Angeles Abrasion loss value of 45 percent or below. Therefore, all ten materials meet current MDOT requirements.

Micro-Deval loss values ranged from a low of 10 percent to a high of 20 percent, or a range of 10 percent. Interestingly, this range is identical to that of the Los Angeles Abrasion loss test results. Six of the seven RCA materials had micro-Deval loss values of 16 or above. The lone RCA material having a micro-Deval loss less than 16 percent was RCA1 which had 10 percent loss. Interestingly, RCA1 was a recycled MDOT Interstate pavement. The three limestone materials had micro-Deval loss values ranging from 14 to 20 percent loss. On average, the percent loss for the RCA and limestone materials was similar.

Table 10: Classification Test Results

Properties	Materials									
	RCA1	RCA2	RCA3	RCA4	RCA5	RCA6	RCA7	No. 610	825 B	3/4 Down
L.A. Abrasion (% loss)	28	28	29	27	29	32	32	24	25	22
Micro-Deval (% loss)	10	20	20	19	17	16	16	16	20	14
Mg. Sulf. Soundness (% loss)	2	11	1	2	5	2	1	1	17	1
Fine Agg. Flow (% voids)	43	39	46	47	43	46	43	43	46	43
Coarse Agg. Flow (% voids)	45	42	45	47	44	46	48	46	48	48
Liquid Limit (%)	20	37	30	19	26	26	NP	NP	NP	NP
Plastic Limit (%)	NP	NP	29	NP	NP	23	NP	NP	NP	NP
Plasticity Index (%)	NP	NP	1	NP	NP	3	NP	NP	NP	NP
App. Specific Gravity	2.599	2.590	2.575	2.567	2.580	2.573	2.607	2.716	2.699	2.703
Bulk Specific Gravity	2.276	2.057	2.166	2.267	2.141	2.195	2.284	2.553	2.618	2.549
Bulk SSD Spec. Gravity	2.400	2.264	2.325	2.383	2.312	2.343	2.408	2.614	2.648	2.606
Water Absorption	5.5	10.0	7.3	5.2	7.9	6.7	5.4	2.3	1.2	2.2

Magnesium sulfate soundness values ranged from a low of 1 percent loss to a high of 17 percent loss. Interestingly, the highest percent loss was for the Size 825 B limestone material. Sulfate soundness loss values for the RCA materials ranged from 1 to 11 percent. RCA2 had the highest percent loss. Recall from Table 8 that this source was the only source that potentially included wash-out. According to the Mississippi Standard Specification for Road and Bridge Construction (2004), the percentage of soundness loss cannot exceed 20 percent. Therefore, all ten materials meet this requirement.

Fine aggregate angularity (FAA) values ranged from a low of 39 percent to a high of 47 percent for the ten materials. RCA2 had the lowest FAA value. Recall this source potentially included wash-out. Of the other six RCA materials, the FAA ranged from 43 to 47 percent. The three limestone materials had FAA values ranging from 43 to 47 percent. Therefore, all of the RCA materials, except RCA2, had a similar FAA to the limestone materials.

Coarse aggregate angularity (CAA) values ranged from 42 to 48 percent. Again, the RCA2 source had the lowest angularity result. All of the remaining RCA materials and the limestone materials had similar CAA results.

Results of Atterberg limit tests indicated that eight of the ten materials were non-plastic. The Mississippi Standard Specifications for Road and Bridge Construction states that aggregates used for crushed stone courses should be non-plastic. RCA3 and RCA6 were the only two materials with a plasticity index. RCA3 had a plasticity index of 1 while RCA6 had a plasticity index of 3. For both of these RCA materials, the visible appearance of the materials suggested that soils had been added, likely to provide material finer than the No. 200 sieve.

Apparent specific gravity values for the seven RCA materials were all similar ranging from 2.567 to 2.607. However, the bulk specific gravity of the different RCA materials varied greatly ranging from 2.057 to 2.284. Likewise, the water absorption of the different RCA materials varied greatly ranging from 5.2 percent to 10.0 percent. The specific gravities and absorption of the three limestone materials were somewhat similar.

5.2.2 Strength/Stiffness

Two strength related tests were conducted on the ten materials. California Bearing Ratio tests were conducted at six different densities. The different densities were created by using both a Standard Proctor hammer and a Modified Proctor hammer. With each hammer, samples were prepared using 25, 56, and 80 blows per layer. Table 11 presents the results of CBR values at these resulting densities. Samples prepared with the Standard Proctor hammer had CBR values ranging from 19 to 88. As would be expected, the CBR values generally increased as the blows/lift used to create the samples increased (higher density). Collectively, the CBR values for the three limestone materials were generally higher than those for the RCA materials. Samples prepared with the Modified Proctor hammer had CBR values ranging from 53 to 208. Similar to the Standard Proctor results, the CBR values generally increased as the blows/lift increased. Comparison between the limestone and RCA materials were somewhat mixed in that the different RCA materials had CBR values above and below the limestone materials.

Resilient modulus testing was conducted at two different target densities. Target densities for the resilient modulus test samples were 98 percent of both the Standard and Modified Proctor maximum dry density. Resilient modulus values are dependent upon the stress state at which the samples are tested. To normalize the results, resilient modulus results are presented as the regression coefficients of the constitutive model for resilient modulus (Equation 1). Table 12 presents the regression coefficients for the ten materials tested at the two different target densities. For reporting purposes, NCHRP 1-28A suggests that resilient modulus test results for base/subbase materials be presented at a bulk stress of 30 psi and an octahedral stress of 7.1 psi. Table 13 presents the results of the resilient modulus tests at this stress state. Resilient modulus values for materials compacted with a density related to the standard compactive effort ranged from a low of roughly 20.1 ksi to a high of 29.5 ksi. Resilient modulus values for the materials targeted at 98 percent of the modified compactive effort ranged from 23.5 ksi to a high of 32.2 ksi. In all cases, the samples fabricated to 98 percent of the modified compactive effort had a higher resilient modulus indicating that the increase in density resulted in higher resilient modulus values.

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

Where:

M_R = Resilient Modulus

θ = Bulk Stress:

$$\theta = \sigma_1 + \sigma_2 + \sigma_3$$

τ_{oct} = Octahedral Shear Stress:

$$\tau_{oct} = \frac{1}{3} * \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$$

$\sigma_1, \sigma_2, \sigma_3$ = Principal Stresses

p_a =atmospheric pressure (14.7 psi)

k_i = regression constants

Table 11: Results of California Bearing Ratio Testing

Compaction Effort	Blows/lift	Materials									
		RCA1	RCA2	RCA3	RCA4	RCA5	RCA6	RCA7	No. 610	825B	3/4 Down
Standard	25	37	19	33	20	28	48	43	44	43	40
	56	87	35	64	35	51	35	70	57	63	59
	80	88	51	80	46	68	50	84	65	73	76
Modified	25	80	56	80	53	73	73	72	134	84	105
	56	195	112	134	80	117	118	120	167	127	141
	80	168	208	202	98	133	142	122	164	140	140

Table 12: Regression Coefficients for Constitutive Model for Each Material

Compaction Effort	Coeff.	Materials									
		RCA1	RCA2	RCA3	RCA4	RCA5	RCA6	RCA7	No. 610	825B	3/4 Down
Standard	K_1	1,108.9	840.3	910.2	1,203.1	1,142.7	911.1	1,130.1	1,285.8	1,223.9	1,152.0
	K_2	0.995	0.998	1.036	1.055	1.056	1.000	1.021	1.013	1.033	0.994
	K_3	-0.598	-0.564	-0.682	-0.885	-0.855	-0.608	-0.704	-0.699	-0.686	-0.556
Modified	K_1	1,083.2	1,045.9	1,132.3	1,311.7	1,178.4	1,265.7	1,401.7	1,349.1	1,412.4	1,367.1
	K_2	0.974	0.974	1.009	1.024	1.006	0.939	1.011	0.994	0.974	0.999
	K_3	-0.508	-0.685	-0.716	-0.844	-0.707	-0.644	-0.763	-0.622	-0.645	-0.688

Table 13: Resilient Modulus Values at Standard Stress State for Each Material

Compaction Effort	Materials, Resilient Modulus (psi)									
	RCA1	RCA2	RCA3	RCA4	RCA5	RCA6	RCA7	No. 610	825B	3/4 Down
Standard	26,189	20,156	21,414	26,485	25,473	21,510	26,077	29,559	28,687	27,641
Modified	26,112	23,514	25,783	28,704	26,871	28,206	31,377	31,540	32,258	31,251

Prior to providing analyses of the test results, a discussion on the preparation of the strength/stiffness test specimens is warranted. The first step in preparing the test samples was to conduct Proctor testing for establishing the maximum dry density and optimum moisture content. Initially, approximately 5 percent moisture was placed into a sample and stored in a sealable plastic bag overnight prior to Proctor testing. After the materials were held overnight, Proctor testing was accomplished. Strength/stiffness test specimens were prepared in a similar manner.

This method of preparing test specimens worked for RCA1; however, very erratic Proctor results were observed for RCA2. Because of the erratic Proctor results, the collective data was evaluated to determine a possible reason. Of the different data available, the one that seemed to provide an answer was water absorption. Table 10 showed that the water absorption for RCA1 was 5.5 percent. This is very close to the percentage of water that was added to the sample prior to storage overnight. However, RCA2 had a water absorption of 10 percent. The 5 percent water added to RCA 2 was half of the actual water absorption. It is hypothesized that moisture added after the overnight storage and prior to actual Proctor testing acted in one of two ways: 1) added water was absorbed by the RCA material or 2) added water remained on the surface of the RCA material and acted as free water. Depending upon how long the RCA material sat prior to the actual Proctor compaction in the mold determined how much of the added water was absorbed and how much acted as free water. Based upon this hypothesis, it was believed that the variation in free water caused the erratic Proctor results.

Based upon the above discussion, a new protocol was developed for preparation of Proctor and strength/stiffness test specimens. First, the specific gravity and absorption values were determined for the coarse and fine fractions of an RCA material. These specific gravity and absorption values for the coarse and fine fractions were then used to calculate a combined water absorption volumetrically for the RCA material. Water was added to the RCA material at a percentage equal to the combined water absorption and placed into a sealable bag. The bag was sealed and allowed to sit overnight prior to preparing Proctor and strength/stiffness specimens. This methodology resulted in more realistic and repeatable test specimens.

5.3 Analysis of Test Results

This project had two primary objectives. The first objective was to determine whether materials meeting current MDOT requirements for RCA materials will perform their intended purposes within a granular course. Secondly, this project was to determine whether RCA materials provide the same structural value as comparable crushed limestone granular courses. The following sections present analyses conducted to accomplish these project objectives.

5.3.1 Evaluation of RCA Characterization Testing Results

As described previously, the use of RCA as aggregate for crushed stone courses is governed through Special Provisions. Within Special Provision No. 907-703-10, dated June 6, 2012, RCA is defined as "… recycled concrete pavement, structural concrete, or other sources that can be crushed to meet the gradation requirements for Size 825 B… In no case shall waste from concrete production (wash-out) be used as a crushed stone base." This Special Provision also states, "If crushed concrete is used, the crushed material shall meet the gradation requirements of Size 825 B with the exception that the percent passing, by weight, of the No. 200 sieve shall be 2-18 percent."

Besides the language described above, RCA must also meet other materials properties in accordance with the Mississippi Standard Specifications for Road and Bridge Construction. Coarse aggregate portions (coarser than No. 8 sieve) must have a Los Angeles Abrasion percent loss of less than 45 and a minimum dry-rodded unit weight greater than 70 pcf. For the fine aggregate portion (materials finer than No. 8 sieve), the material must be non-plastic.

The first step in the analysis of the laboratory data was to compare the characteristics of the various RCA materials and then compare these RCA characteristics to the limestone materials. The characteristics of the RCA materials were determined using the classification tests described in Chapter 4. Results of classification testing were presented within Table 10.

Figure 7 compares the results of Los Angeles Abrasion loss and Micro-Deval loss for the ten materials. This figure shows no relationship in the test results between the two test methods; therefore, even though they are abrasion tests, they don't measure similar characteristics. On average, the Los Angeles Abrasion results for the seven RCA materials are slightly higher than the three limestone materials (29 percent to 24 percent loss, respectively). The RCA and limestone materials both had an average Micro-Deval percent loss of 17 percent. None of the ten materials (RCA and limestone) had Los Angeles Abrasion loss values near MDOT's requirement of less than 45 percent.

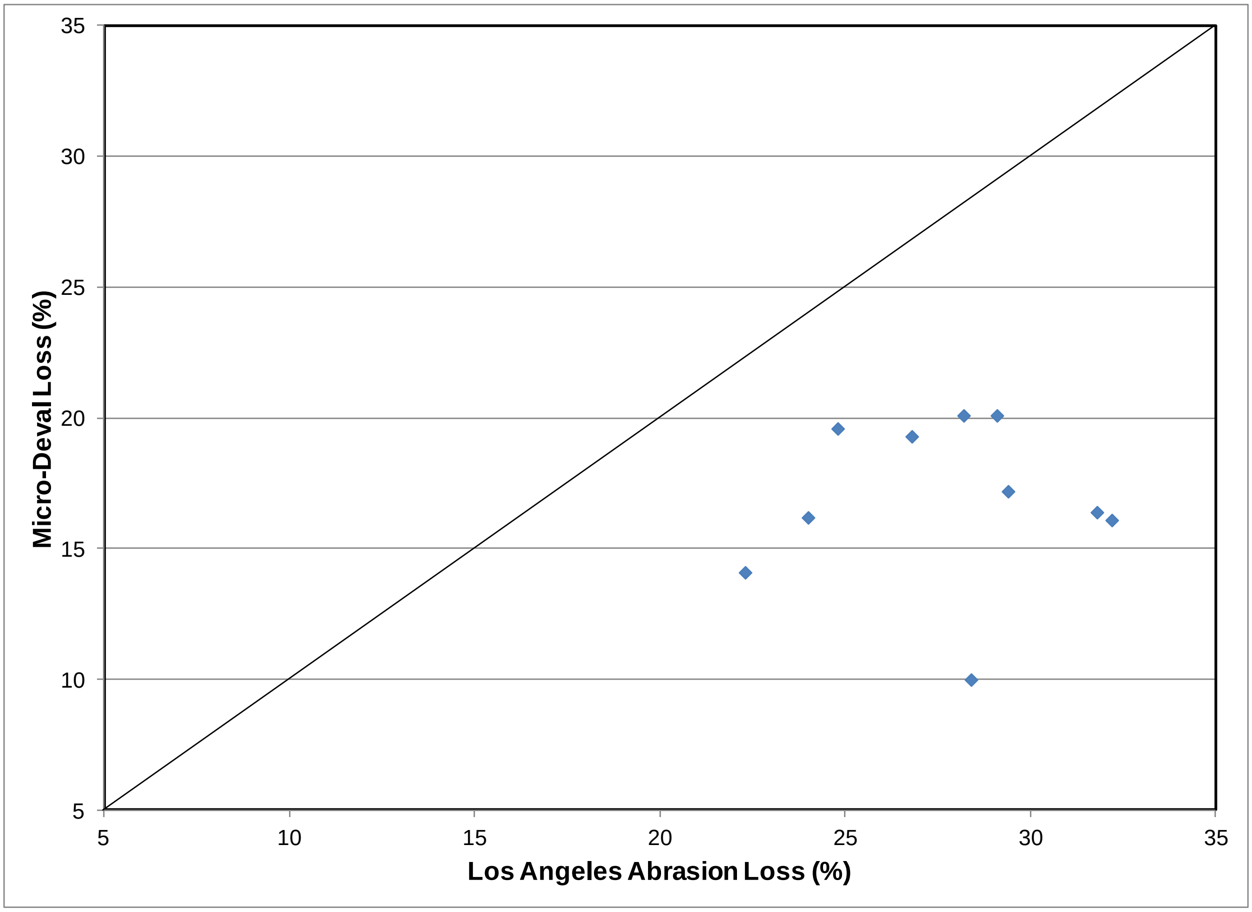

Figure 7: Comparison of Los Angeles Abrasion and Micro-Deval Test Results

The Micro-Deval test is not specified by MDOT; however, some research has shown that this test is more related to the performance of granular base layers than the Los Angeles Abrasion test. Senior and Rogers (26) suggested that a Micro-Deval loss of 40 percent generally differentiates between a granular material that performs well or poor in pavement base applications based upon research in Canada. None of the ten materials tested in this study approached a Micro-Deval loss of 40 percent.

Figure 8 illustrates a comparison between Los Angeles Abrasion loss values and magnesium sulfate soundness (MSS) loss values. Similar to Figure 7, no discernible trend is observed between the results of the two characterization tests. Interestingly, the average MSS loss of the seven RCA materials was less than the average loss of the three limestone materials (3 percent compared to 6 percent, respectively). However, the limestone average loss was greatly affected by the MSS loss of 17 percent for the 825 B material. This 825 B material was the only source that approached MDOTs specification for MSS of a maximum loss of 20 percent.

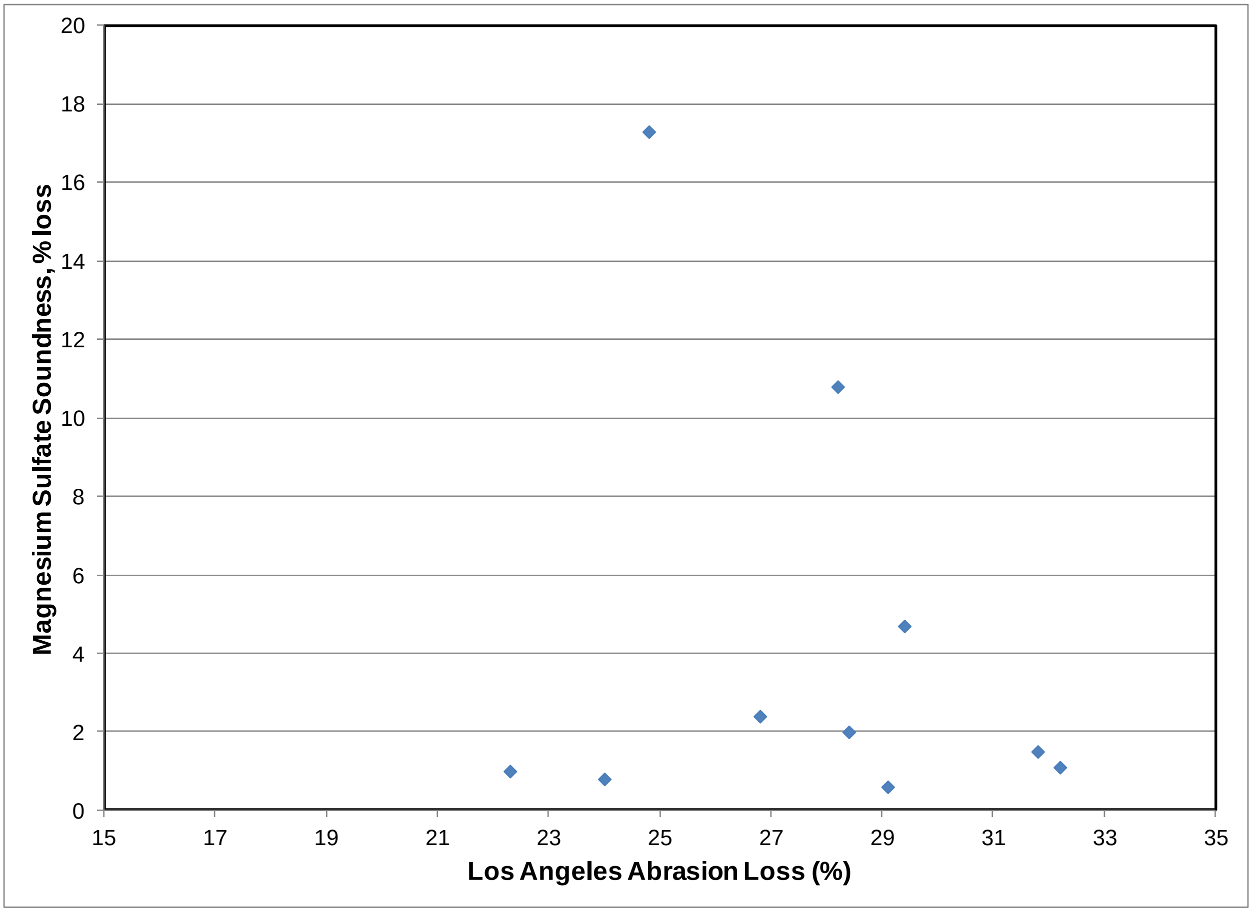

Figure 8: Comparison of Los Angeles Abrasion and Magnesium Sulfate Soundness Loss Results

A comparison between the MSS loss and Micro-Deval loss is presented in Figure 9. Senior and Rogers (27) have shown a strong relationship between these two properties using a large sample size (R^2=0.72, n=106). Data within Figure 9 are not as strongly correlated with a coefficient of determination (R^2) of 0.12. However, an interesting observation from Figure 9 is that a Micro-Deval loss value of 18 percent does appear to differentiate between low MSS values and higher MSS loss values. In context, “higher” MSS loss values did not fail MDOT specification requirements; rather, the values are generally higher when Micro-Deval loss values are above 18 percent. The value of 18 percent is also interesting because Kandhal and Parker (34) identified this value as differentiating good and poor performing aggregates for hot mix asphalt. As shown on Figure 9, four materials had a Micro-Deval loss of greater than 18 percent. Three of the four were RCA materials (RCA2, RCA3 and RCA4). All three of these RCA materials were from the demolition of construction debris (Table 8). The fourth material having a Micro-Deval loss of greater than 18 was the 825 B limestone. This sample had the highest percent loss of the three limestones and also had the highest MSS loss of all ten materials.

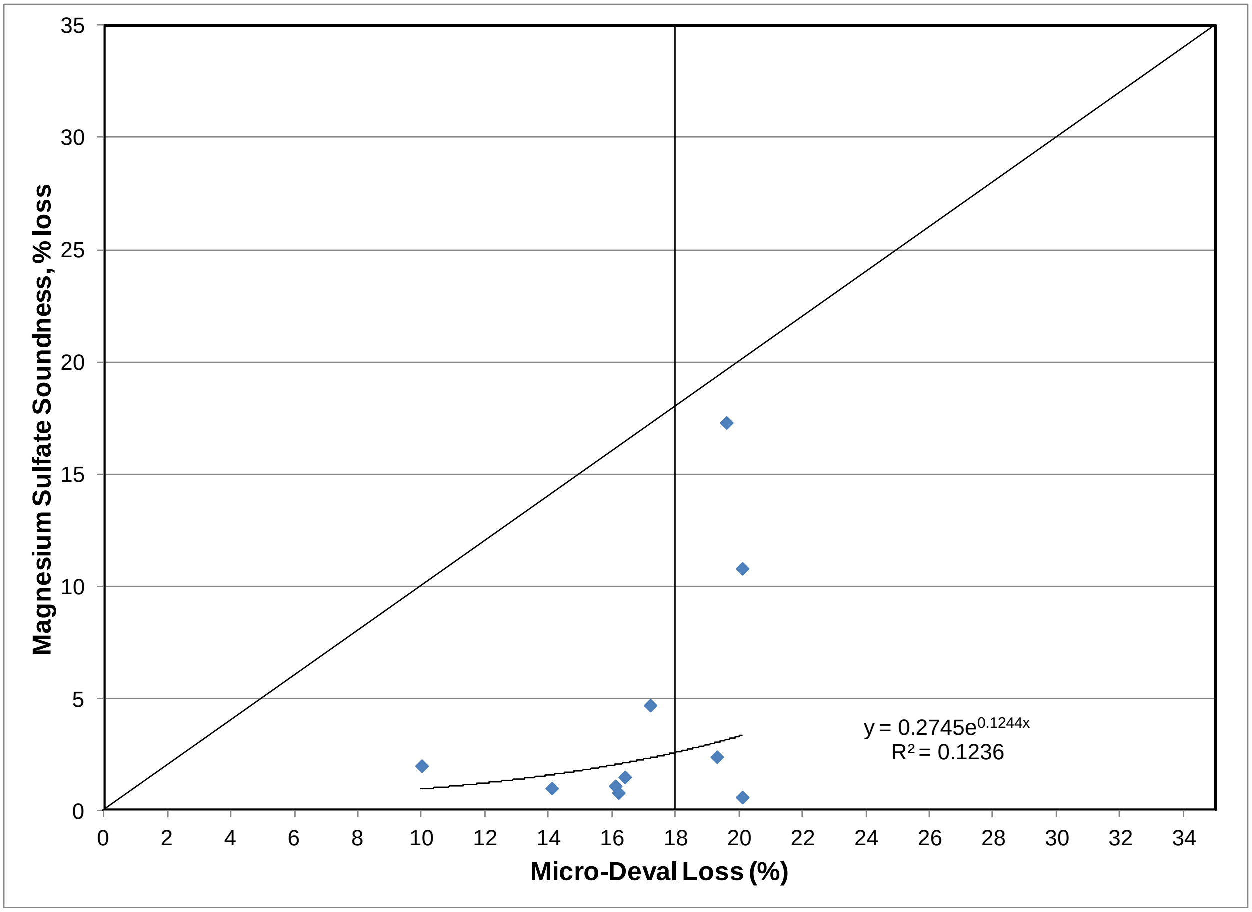

Figure 9: Comparison of Micro-Deval and Magnesium Sulfate Soundness Loss Results

Figure 10 compares the results of Los Angeles Abrasion loss and water absorption. This figure shows a reasonably strong relationship between these two characteristics (R^2=0.56). Los Angeles Abrasion loss increased as water absorption increased. This relationship suggests that as the amount of water permeable voids increase, the abrasion resistance of the material also increases. On average, the RCA materials had water absorptions much higher than the limestone materials (6.8 percent compared to 1.9 percent).

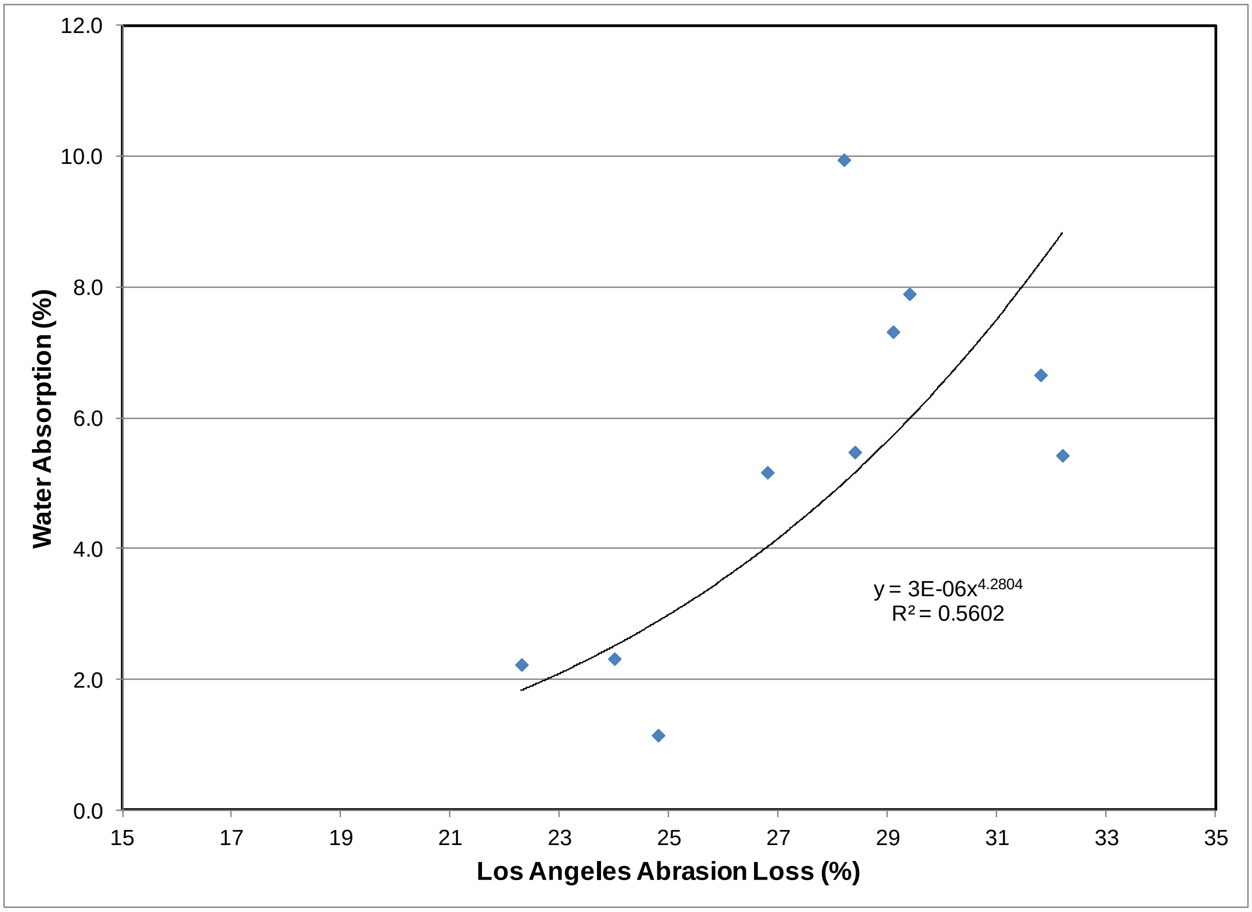

Figure 10: Comparison of Los Angeles Abrasion loss and Water Absorption

Figure 11 presents a similar comparison to Figure 10 between Micro-Deval loss and water absorption. As shown on this figure, no relationship is discernible between these two characteristics. Therefore, unlike the Los Angeles Abrasion loss, Micro-Deval loss does not appear to be influenced by the amount of water permeable voids within the sample. This finding is somewhat surprising because water is utilized within the Micro-Deval test while it is not used during the Los Angeles Abrasion test.

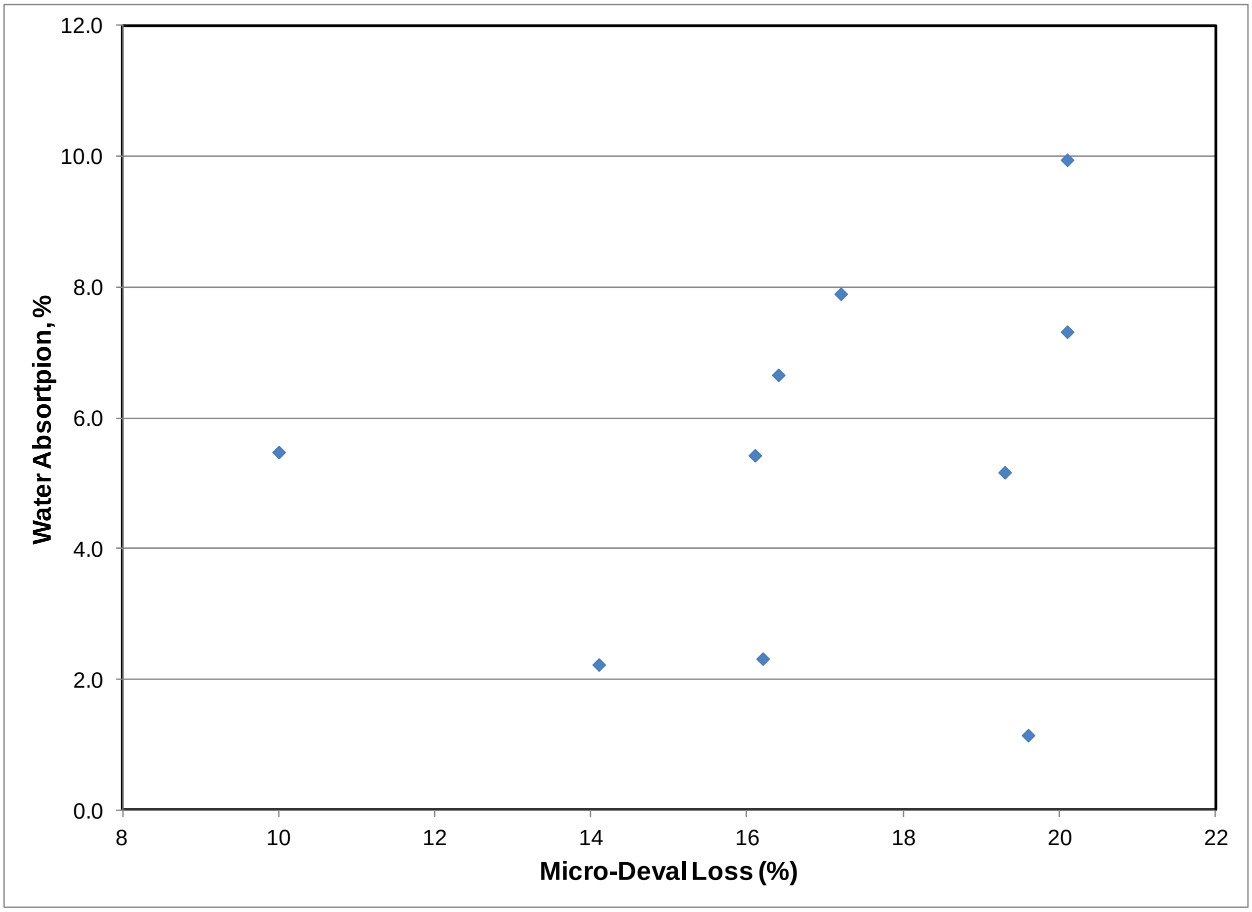

Figure 11: Comparison Between Micro-Deval Loss and Water Absorption

A comparison between MSS loss and water absorption is presented within Figure 12. For all ten data points, there is no discernible trend between the two characterization tests (R^2=0.014). However, one data point appears to influence the strength of the relationship. Limestone material 825 B had a MSS loss of 17 percent and water absorption of 1.2 percent. If this lone data point is neglected, the relationship strengthens (Figure 13) with a coefficient of determination of 0.47. A relationship between the results of these two characterization tests intuitively makes sense. Water absorption is a measure of the water permeable voids within the individual particles. As the amount of permeable voids increase, more of the magnesium sulfate solution can infiltrate into the particles. The increased amount of magnesium sulfate solution within the particles potentially allows more degradation through the freeze-thaw process.

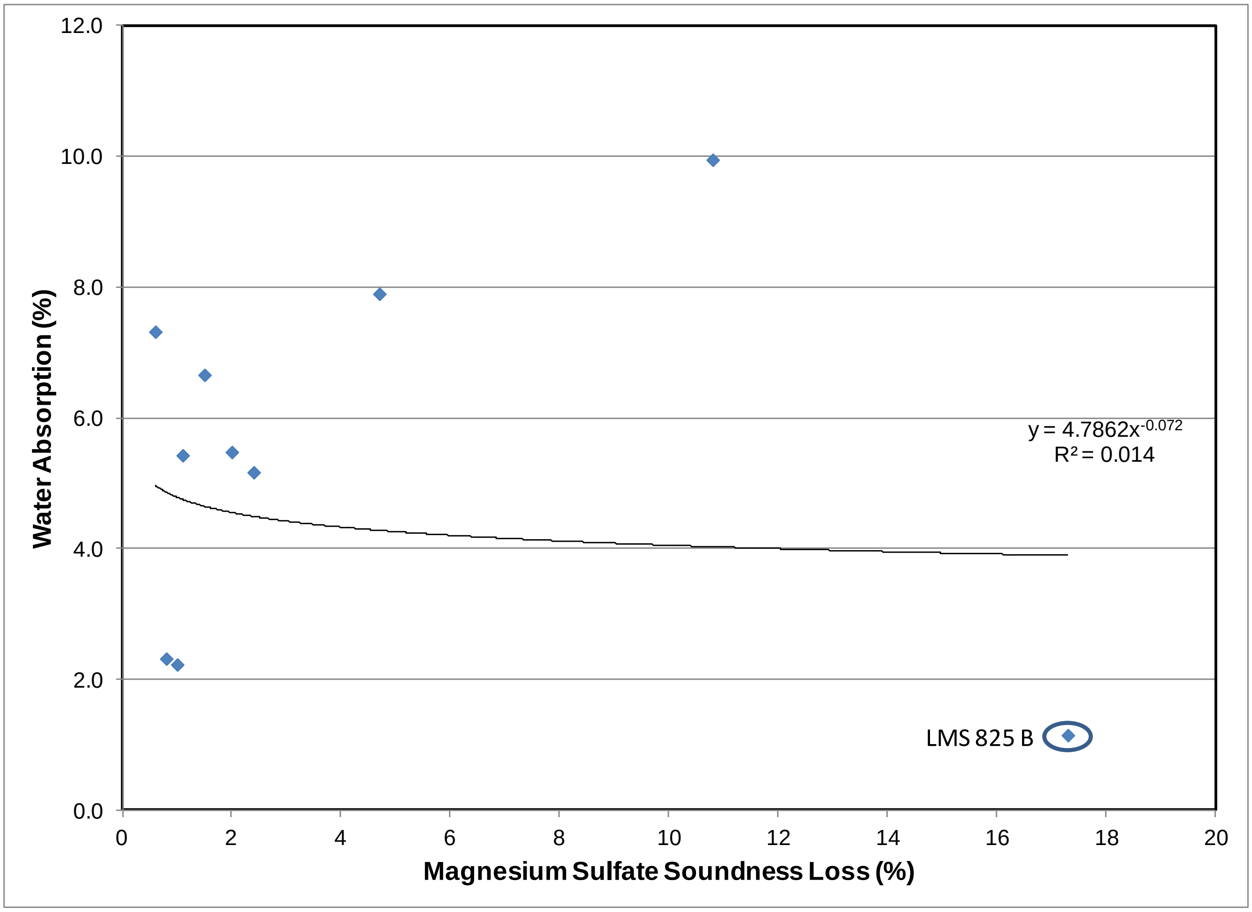

Figure 12: Comparison Between Magnesium Sulfate Soundness Loss and Water Absorption

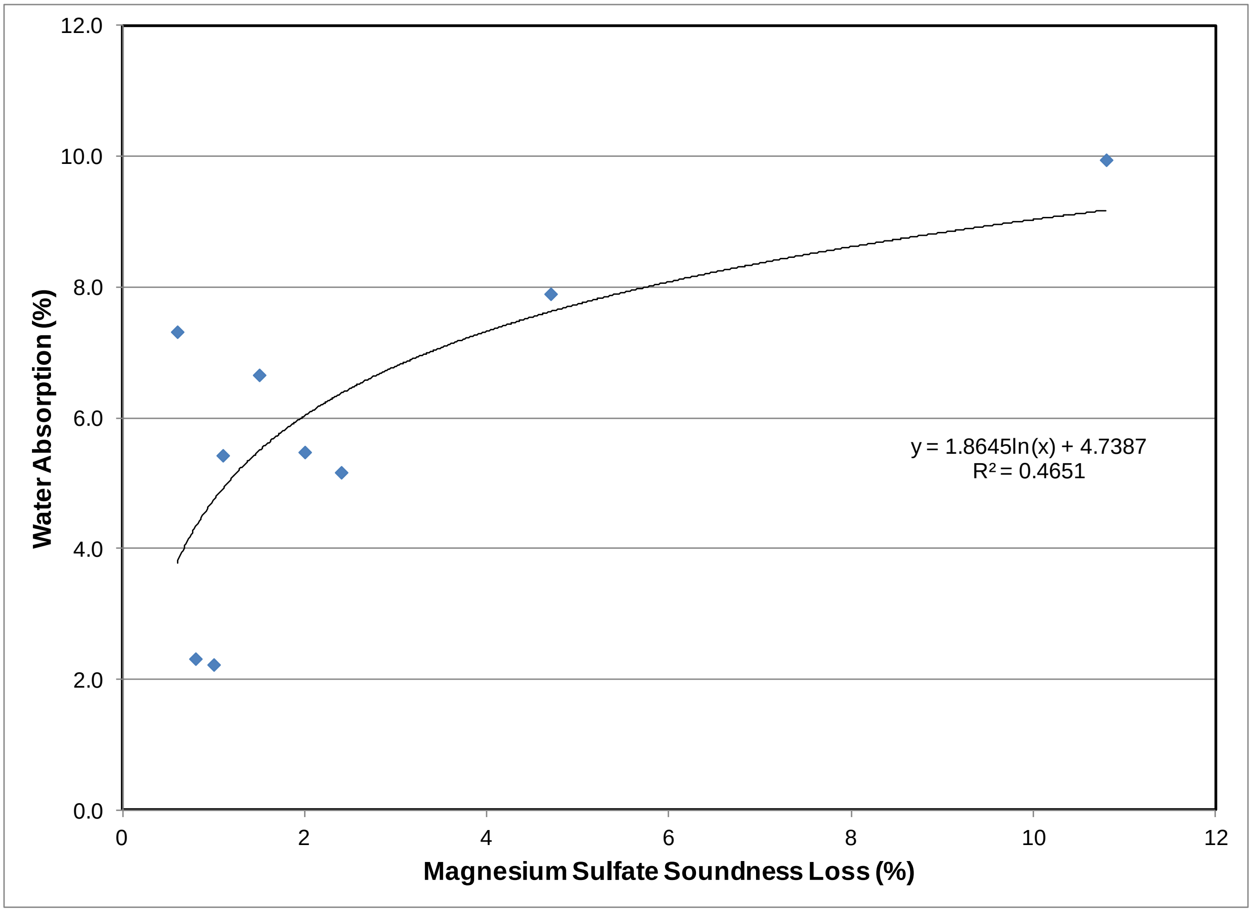

Figure 13: Comparison Between Magnesium Sulfate Soundness and Water Absorption with 825 B Limestone Removed

5.3.2 Evaluation of Strength/Stiffness Testing Results

The California Bearing Ratio (CBR) test was conducted to evaluate the strength of each of the ten materials. Recall that CBR tests were conducted on samples compacted to 25, 56 and 80 blows per lift using both a Standard and Modified compactive effort. Table 11 presented the results of CBR testing for all of the materials at each of the compaction efforts and blows per lift.

Because the method of compaction for each CBR test sample was conducted to standardized compactive efforts (blows per lift), the resulting densities were the result of the compactive effort and not a target density. The MDOT requires that granular layers be compacted to an average of 99 percent of maximum dry density with no individual density value below 95 percent. In order to compare each material at a given density, the relationship between CBR and dry density had to be determined for each material. Figure 14 illustrates how the CBR was determined at the MDOT critical densities. The critical densities were deemed to be 99 percent and 95 percent of Standard Proctor maximum dry weight and 100 percent of the Modified Proctor maximum dry density. The 100 percent of Modified Proctor maximum dry density was selected to compare to the “standard” CBR value of 100 used by the Corps of Engineers.

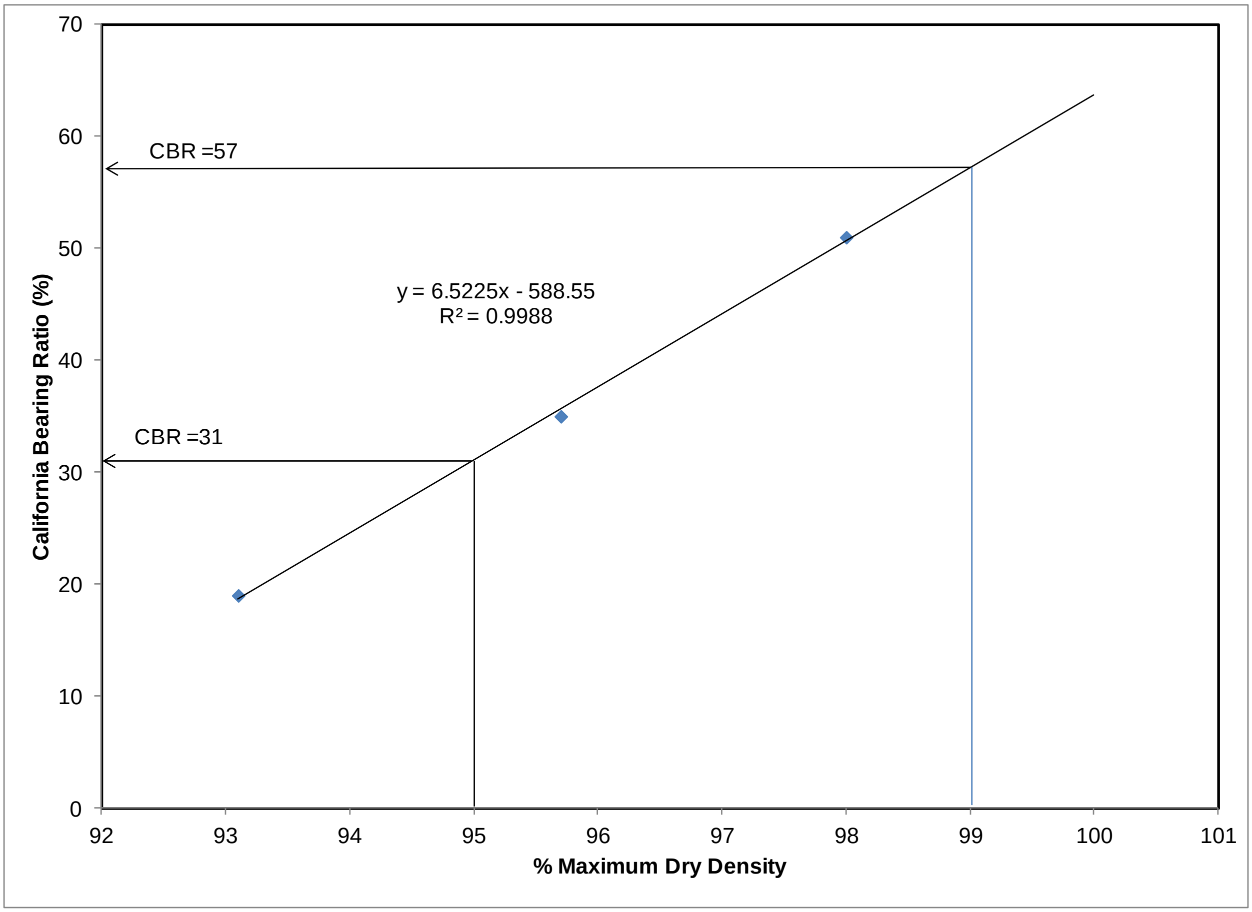

Figure 14: Determination of CBR Values for RCA2

The stiffness of the different materials was evaluated using the resilient modulus test. Test specimens were prepared and tested at a target density of 98 percent of maximum dry density for both a Standard and Modified compactive effort.

Similar to the evaluation of the characterization tests, analysis of the data entailed developing relationships between the different characterization test data and the strength/stiffness measures. Figure 15 illustrates the relationship between the CBR strength at 99 percent Standard compactive effort and Los Angeles Abrasion loss. As shown in this figure, there was no relationship between the CBR strength and Los Angeles Abrasion loss results. A similar lack of relationship was found for all of the characterization tests except magnesium sulfate soundness loss and the results of CBR strength testing at both 99 and 95 percent of Standard maximum dry density. Figure 16 illustrates the relationship between MSS loss and CBR strength at 99 percent of Standard maximum dry density. This figure shows a very slight trend of decreasing CBR values with increasing MSS loss values. No discernible trends were observed for the CBR samples prepared at 100 percent Modified maximum dry density.

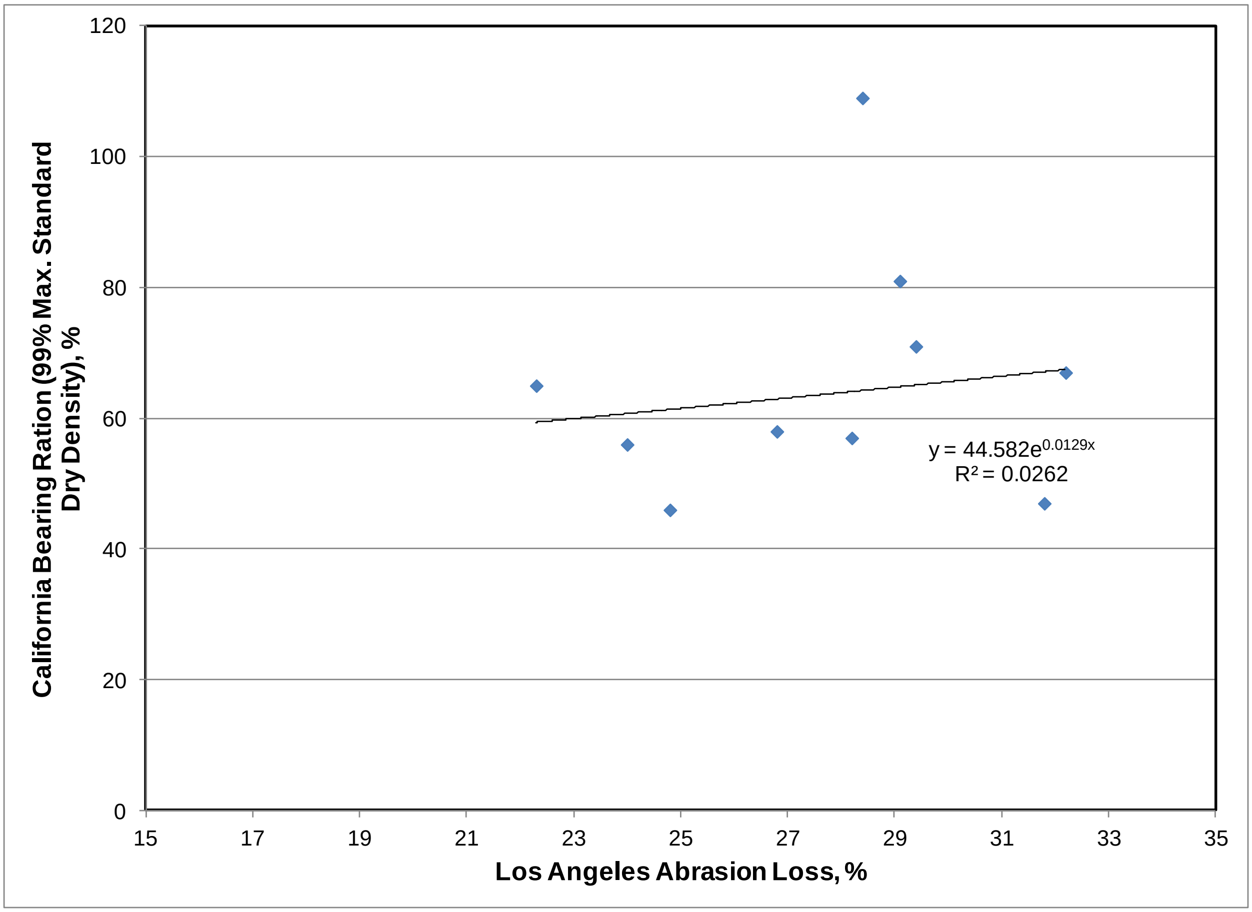

Figure 15: Relationship Between CBR Strength and Los Angeles Abrasion Loss

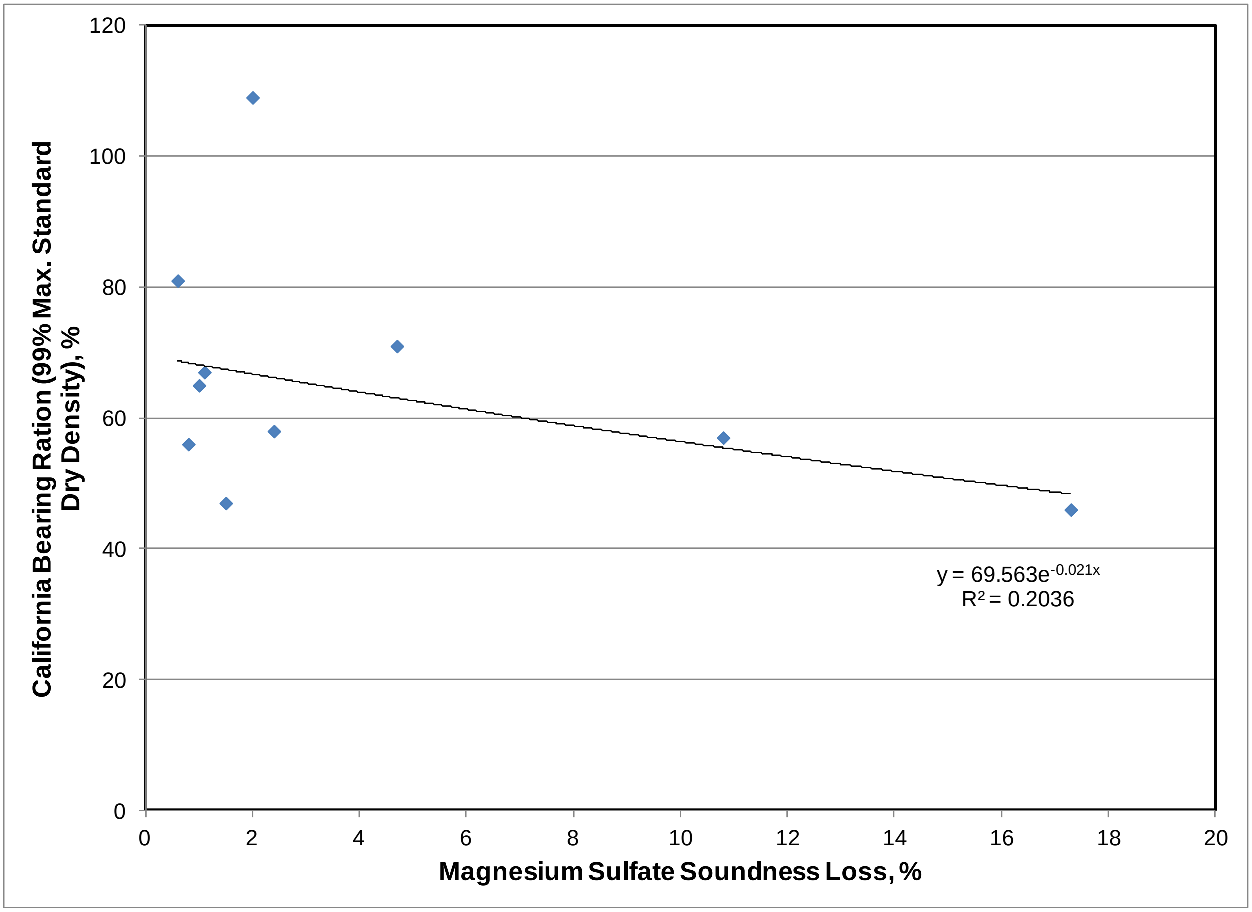

Figure 16: Comparison of Magnesium Sulfate Soundness and CBR Strength

Stiffness measurements were conducted using the resilient modulus (M_r) test on samples prepared at 98 percent maximum dry density using both a Standard compactive effort and Modified compactive effort. Unlike the CBR data, some interesting trends were observed between the resilient modulus results and the characterization tests.

Figure 17 illustrates the relationship between M_r and Los Angeles Abrasion loss. This figure shows M_r results for both the Standard and Modified compactive efforts. As shown on the figure, the trends are not strong; however, both trends show that M_r decreased as the Los Angeles Abrasion loss increased. This suggests that materials that are more prone to degradation through abrasion will have a lower stiffness within the pavement structure. Unlike the results from the Los Angeles Abrasion loss, the results from the Micro-Deval tests showed no relationship to the M_r results. Likewise, no relationships were observed between the results of MSS loss and M_r stiffness.

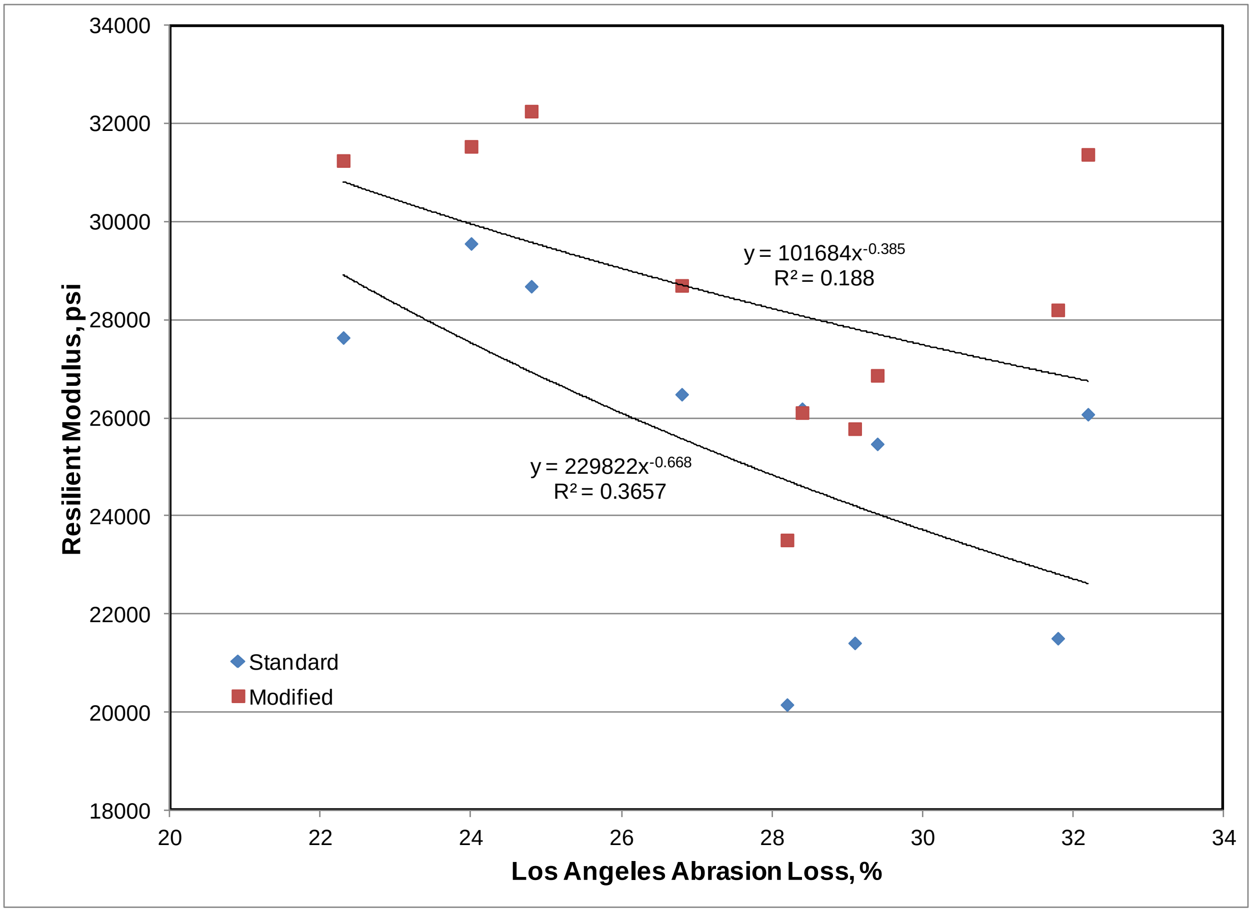

Figure 17: Relationship Between Resilient Modulus and Los Angeles Abrasion Loss

The relationship between coarse aggregate angularity (CAA) and M_r results are illustrated within Figure 18. This figure shows a slight trend between the results of CAA and M_r testing conducted on specimens compacted to 98 percent of Standard maximum dry density (R^2=0.39). However, the relationship between the CAA results and M_r were much stronger for specimens compacted to 98 percent of Modified maximum dry density (R^2=0.77). For both relationships, the trend shows that the stiffness of the materials increased as the CAA increased. This suggests that higher CAA values improve the structural capacity of a granular layer. Unfortunately, no trends could be found for either M_r results when compared to the fine aggregate angularity results.

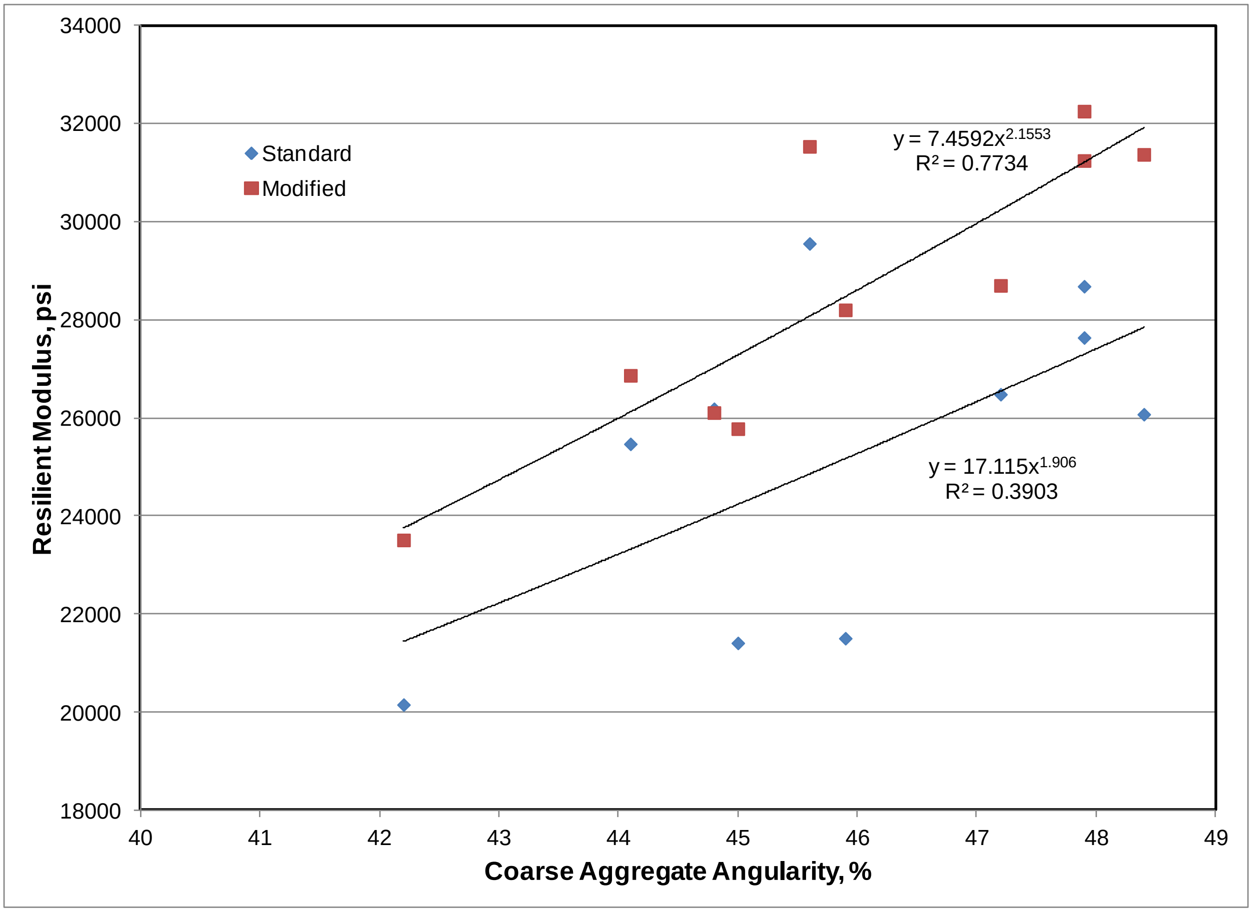

Figure 18: Relationship Between Resilient Modulus and Coarse Aggregate Angularity

Interestingly, reasonably strong relationships were obtained between water absorption and both measures (Standard and Modified) of M_r. These relationships are illustrated within Figure 19. For both relationships, the coefficient of determination was above 0.60. As shown within Figure 19, the stiffness of the materials decreased as the water absorption increased.

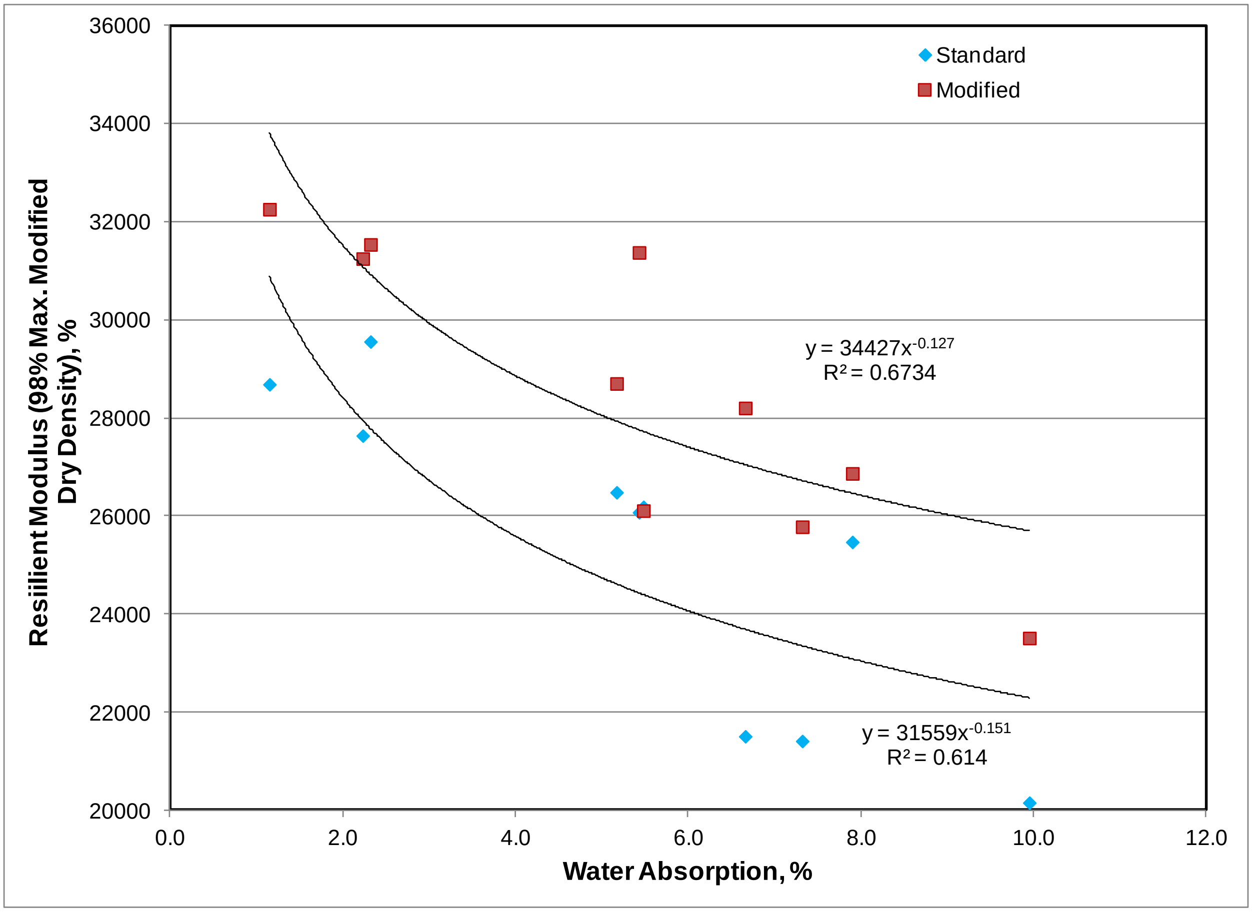

Figure 19: Relationship Between Resilient Modulus and Water Absorption

5.5.3 General Analysis

As described within Section 4.2 and detailed within Table 8, four of the seven RCA materials were the result of crushing demolition debris. The remaining three RCA sources were derived from concrete fabricated to specific specifications. These three "controlled" sources included two recycled MDOT rigid pavements and a recycled prestressed concrete source. An evaluation of the characterization and strength/stiffness data was conducted comparing average values from three categories: 1) controlled concrete sources; 2) construction demolition sources; and 3) limestone sources.

Of the characterization tests conducted, comparing the average test results from the three categories indicated slight differences in Los Angeles Abrasion loss, Micro-Deval loss, and water absorption. These comparisons are illustrated in Figures 20 through 22, respectively. Figure 20 shows that, on average, the RCA materials had a higher Los Angeles Abrasion loss than did the limestone materials. Also, on average, the controlled concrete sources had a slightly higher average Los Angeles Abrasion loss than the construction demolition sources.

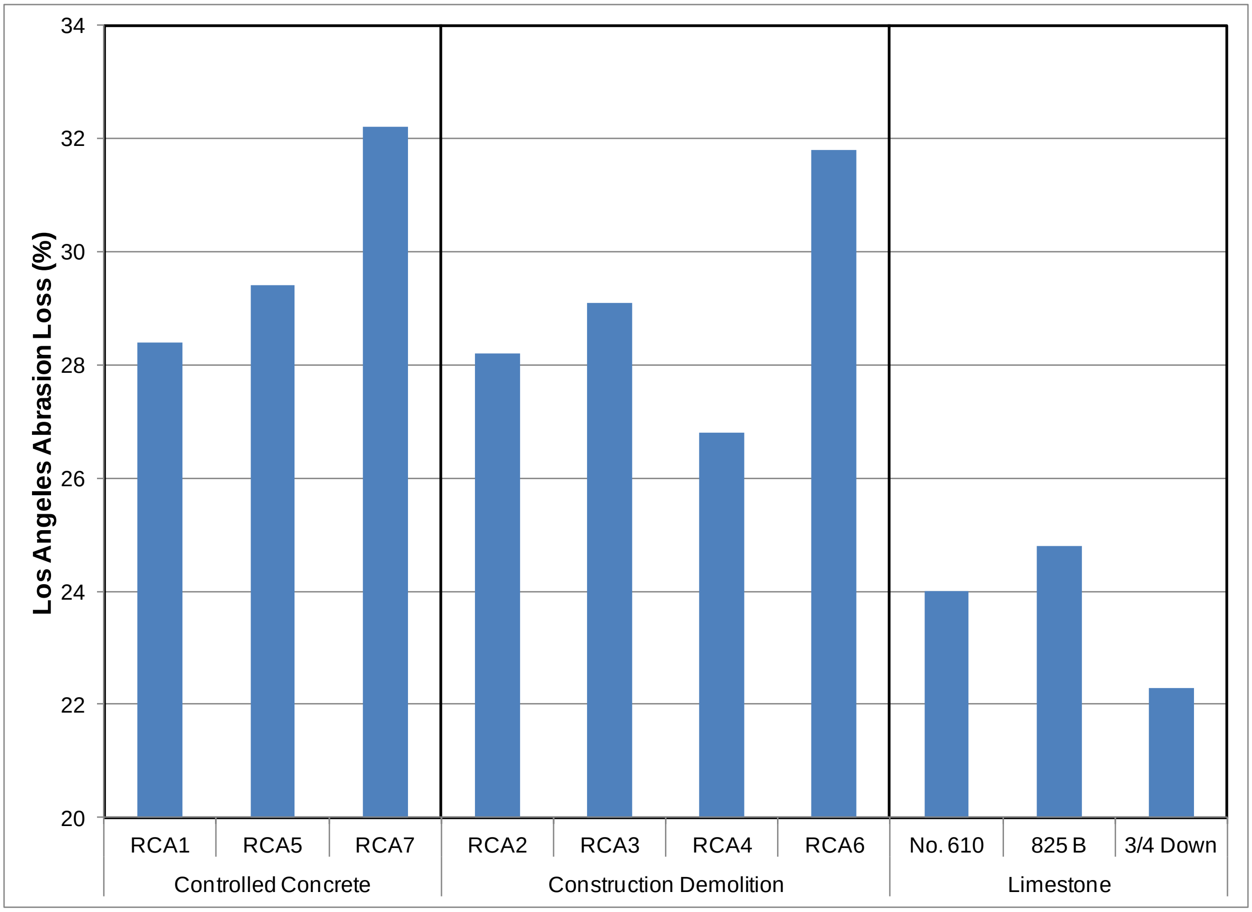

Figure 20: Los Angeles Abrasion Loss Values by Category

Figure 21 shows that the Micro-Deval loss for the construction demolition and limestone sources was similar. However, the average Micro-Deval loss for the controlled concrete sources was, on average, lower. Similar to the Los Angeles Abrasion loss data, Figure 22 shows that the water absorption values for the limestone sources were less than the two RCA categories. On average, the water absorption for the controlled concrete sources was about 1.0 percent less than the construction demolition sources. Additionally, the water absorption variability appears to be less within the controlled concrete sources. Interestingly, the water absorption values for RCA1 and RCA7 were almost identical. Recall from Table 8 that these two sources were both recycled MDOT rigid pavements. RCA1 was from Central Mississippi while RCA7 was from North Mississippi.

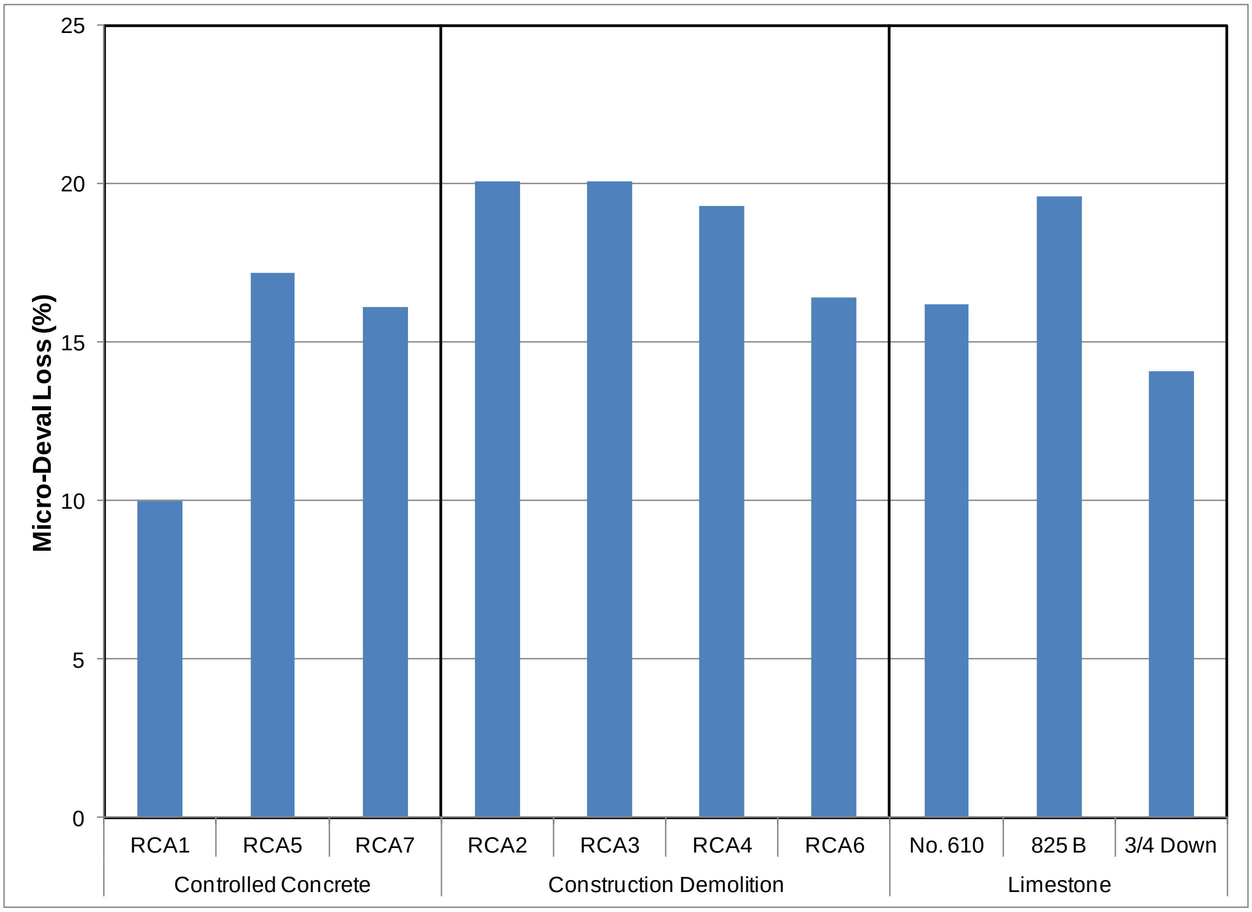

Figure 21: Micro-Deval loss by Category

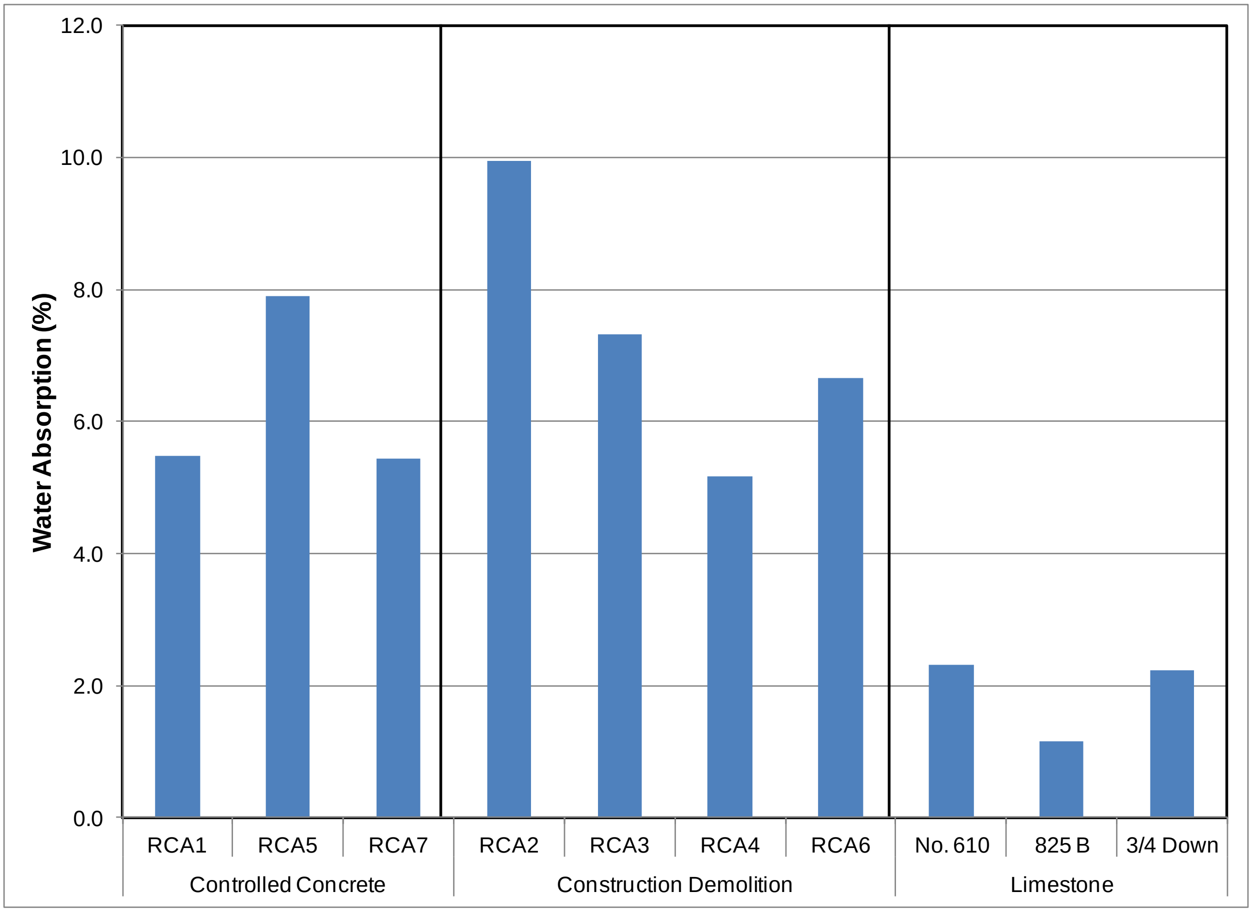

Figure 22: Water Absorption Values by Category

Similar analyses were conducted using the strength/stiffness data. Figures 23 and 24 illustrate the CBR data at 99 percent Standard maximum dry density and 100 percent of Modified maximum dry density, respectively. Figure 23 shows that, on average, the controlled concrete sources had the highest CBR value of the three categories at 99 percent of Standard maximum dry density. Also, on average, the RCA materials from the construction demolition category had a slightly higher average CBR than did the limestone materials.

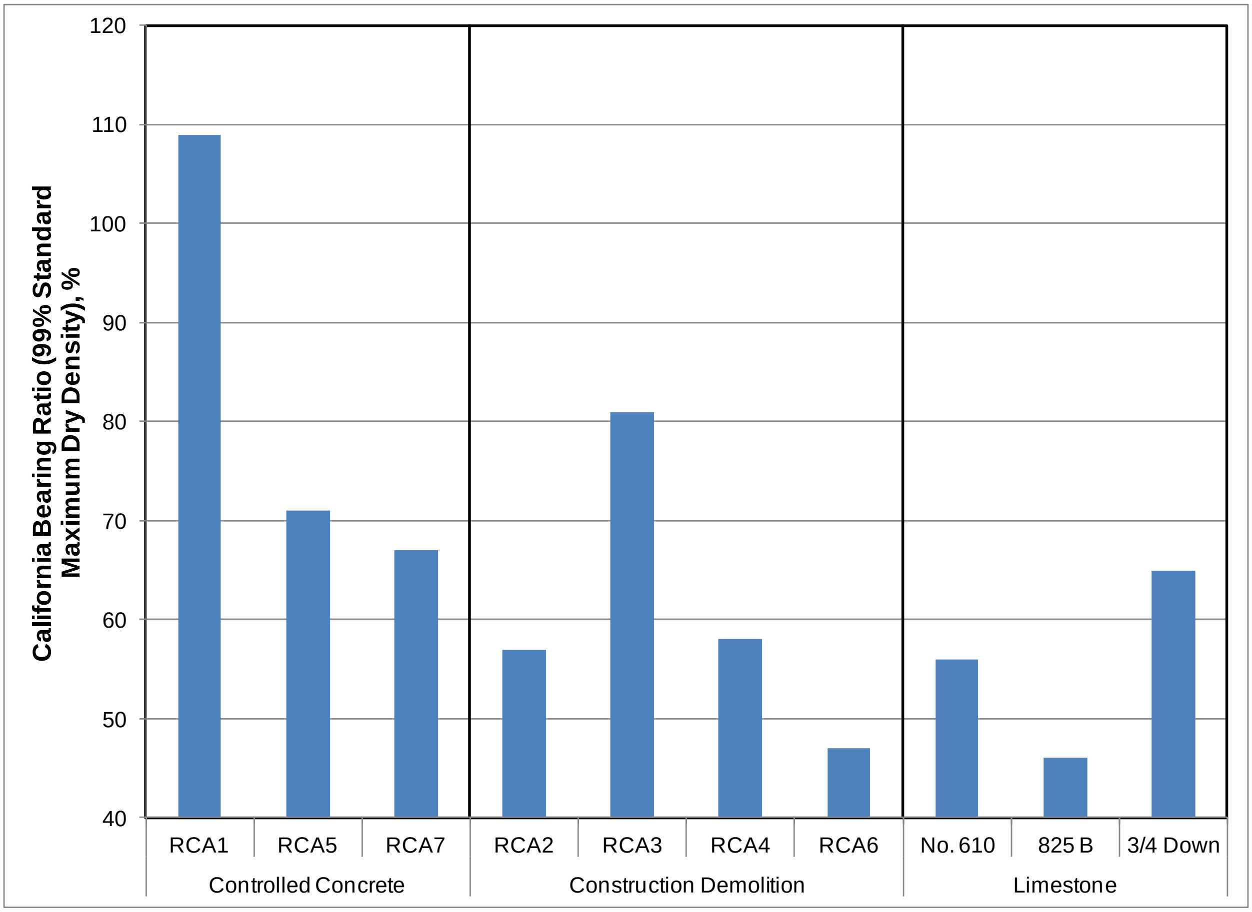

Figure 23: California Bearing Ratio at Standard Compactive Effort by Category

Figure 24 shows that the average CBR at 100 percent Modified maximum dry density for the controlled concrete category sources again had the highest value. For the Modified compactive effort, the limestone materials average was similar to the controlled concrete category average. The construction demolition category had the lowest average CBR.

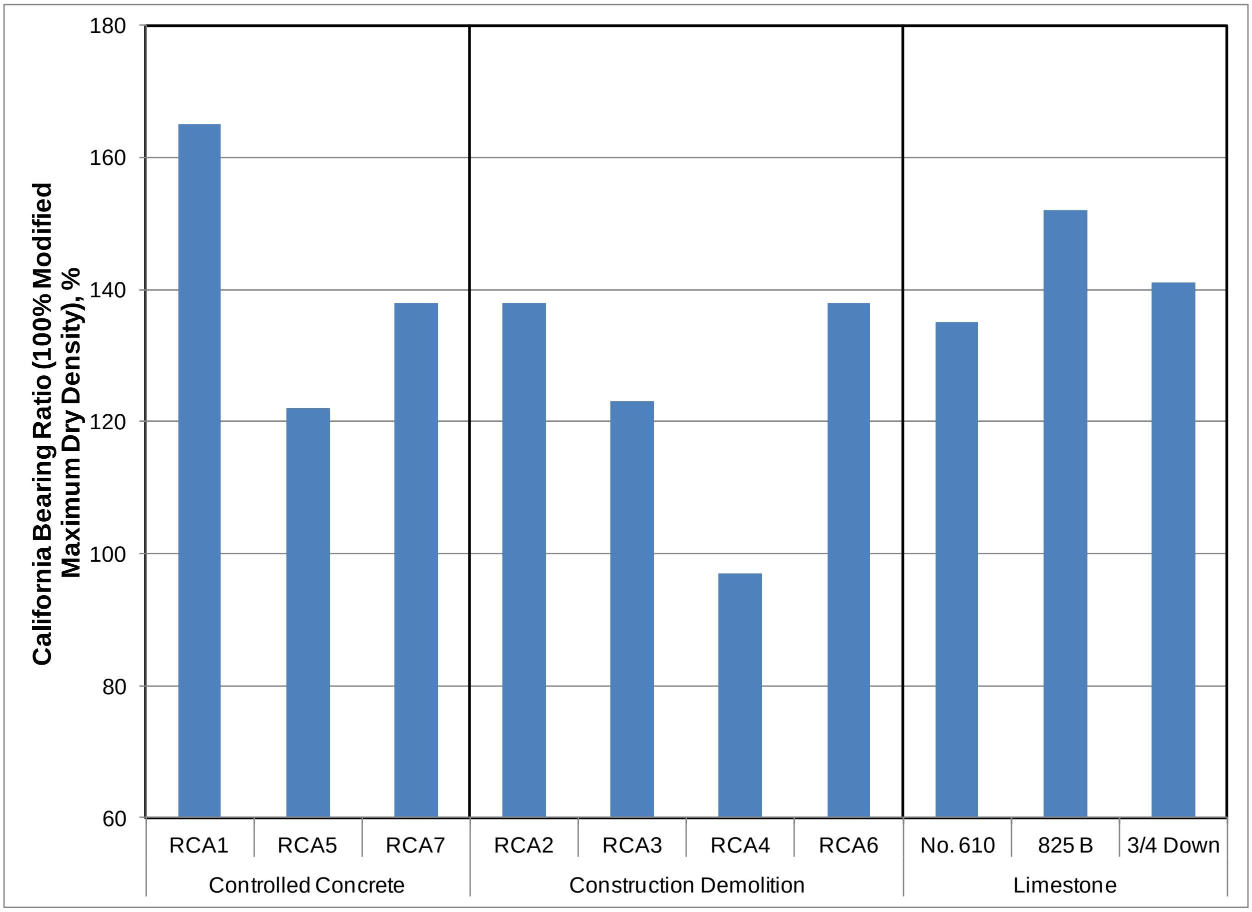

Figure 24: California Bearing Ratio for Modified Compactive Effort by Category

Figures 25 and 26 present the resilient modulus data by category. Figure 25 shows the resilient modulus results for specimens compacted to 98 percent of Standard maximum dry density. At this compactive effort, the limestone materials had the highest average resilient modulus. Of the two RCA categories, the controlled concrete category had the highest average resilient modulus.

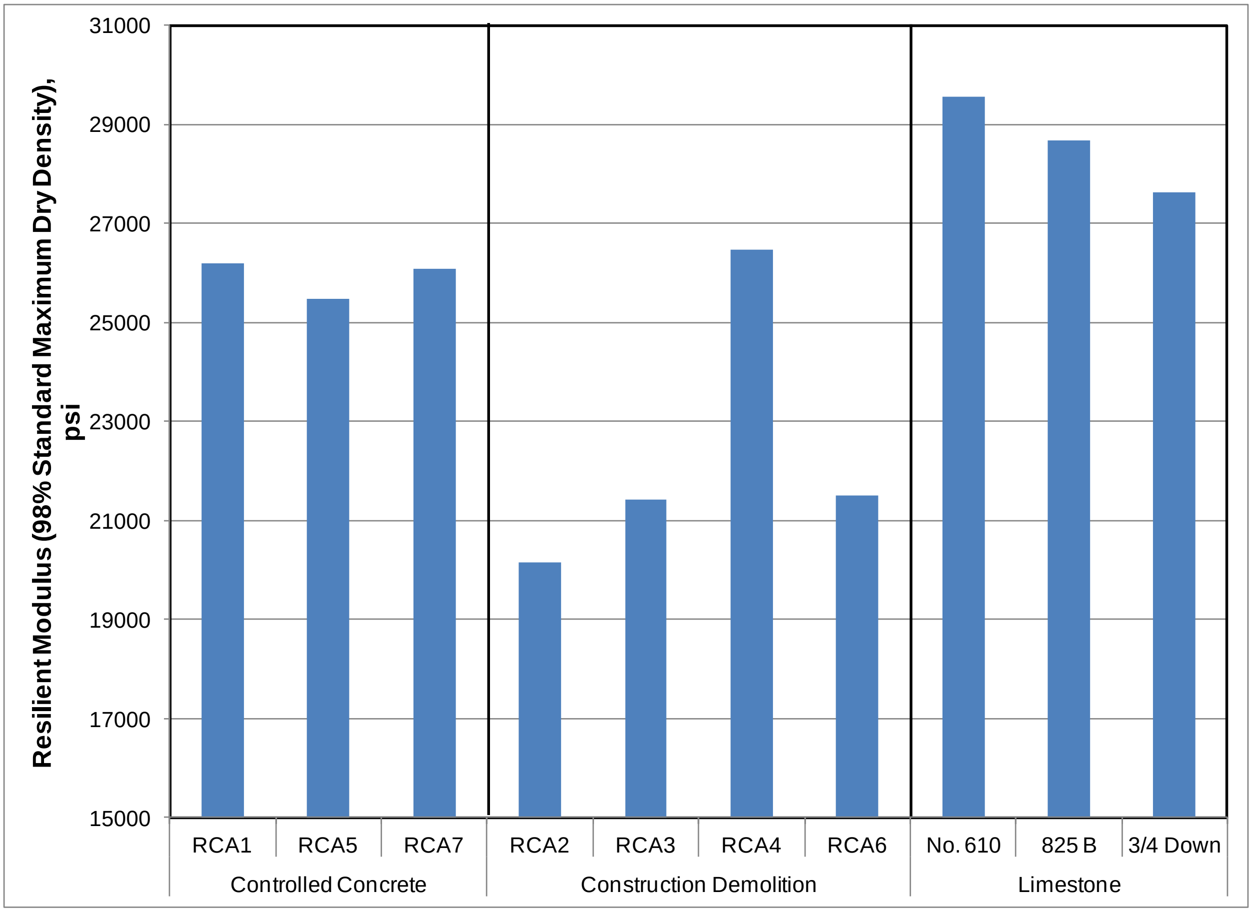

Figure 25: Resilient Modulus Values for Standard Compactive Effort by Category

Figure 26 illustrates the resilient modulus results for specimens compacted to 98 percent of Modified maximum dry density. Similar to the resilient modulus data for the Standard compactive effort, the limestone sources had the highest average resilient modulus followed by the controlled concrete sources. Again, the construction demolition category had the lowest average resilient modulus.

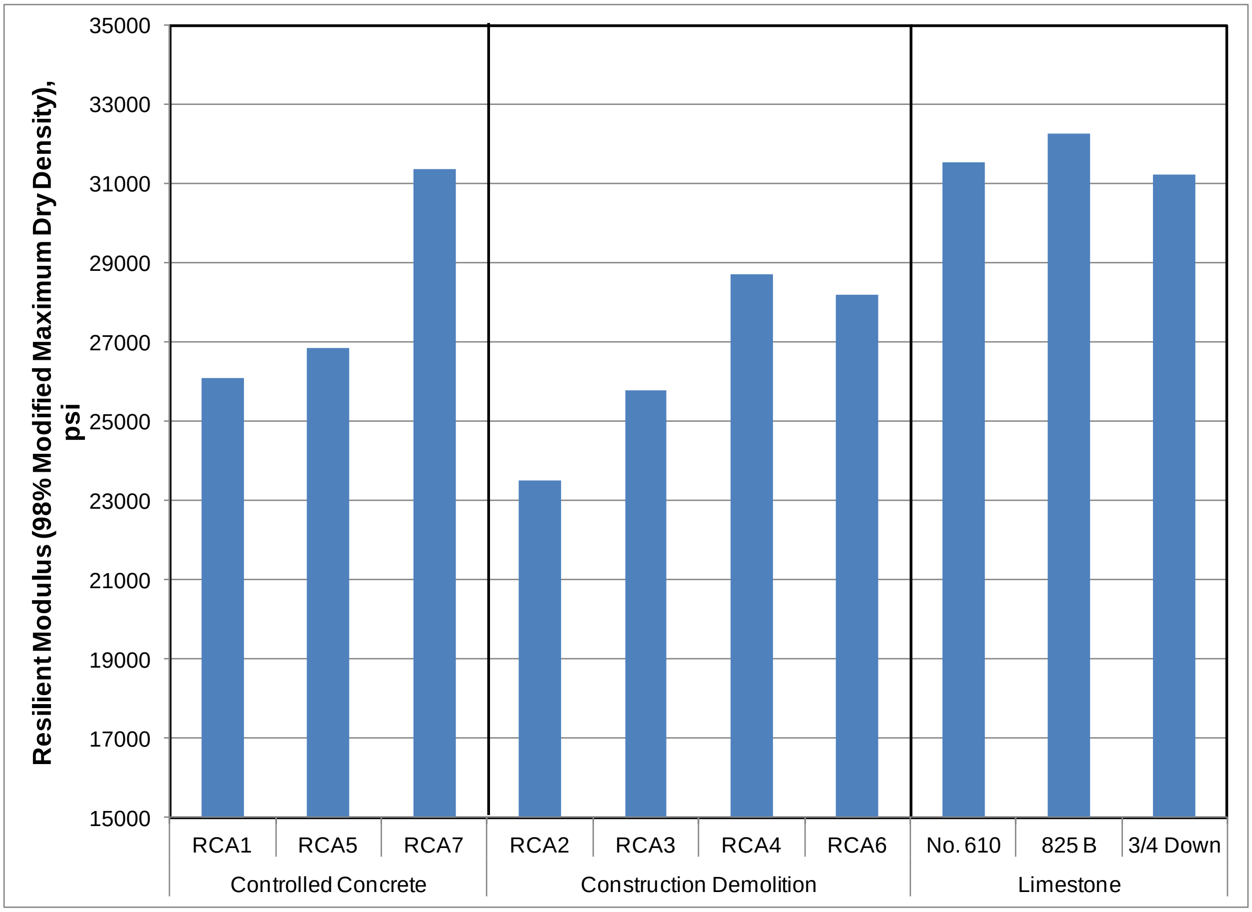

Figure 26: Resilient Modulus Values for Modified Compactive Effort by Category

One data intuitive in a number of the figures previously presented that included CBR values is that CBR values increased as the percent density increased. Figure 27 illustrates the results of CBR values at 95 and 99 percent of Standard maximum dry density for all ten materials. As shown within this figure, on average, the CBR increased by 24 when the percent Standard density increased from 95 to 99 percent. An increase in CBR of 24 is a significant improvement in the structural capacity of a pavement granular layer.

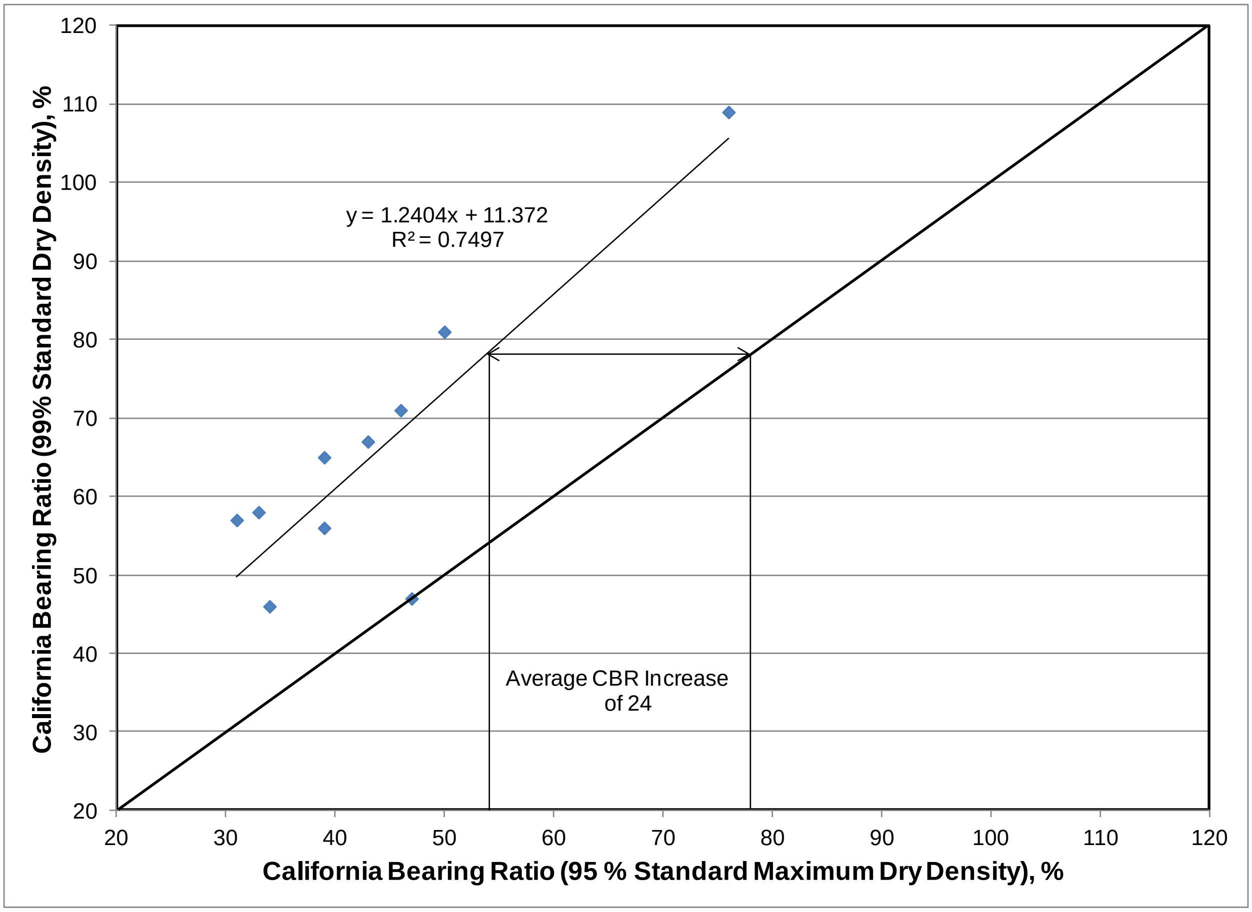

Figure 27: Comparison of California Bearing Ratio Values at 95 and 99 Percent Standard Density

Figures 23 through 26 presented strength and stiffness data for the seven RCA and three limestone materials tested during this study. This data was used to develop typical pavement design information that could be utilized during pavement design. Two properties were deemed important for assisting in pavement design: structural layer coefficient and resilient modulus. Structural layer coefficients are currently utilized by MDOT for designing pavement structures, while, in the future, a mechanistic-empirical pavement design method will be used for designing pavement structures. The mechanistic-empirical method will require a resilient modulus value for RCA materials.

The 1993 American Association of State Highway and Transportation pavement design guide (32) provides guidance for selection of granular base layer structural coefficients based upon CBR or resilient modulus values. Using the average CBR or resilient modulus values for the materials within each of the three categories shown within Figures 23 through 26, a representative base layer coefficient was developed. Because both CBR and resilient modulus are dependent upon the percent density at which the material is compacted, base layer coefficients are provided at differing minimum allowable density levels. Table 14 presents the representative base layer coefficients for the three material categories based upon minimum allowable density.

Table 14: Base Layer Structural Coefficients for Granular Materials Tested

Material Category	Minimum Allowable Layer Density		
	95% Standard	99% Standard	100% Modified
Controlled RCA	0.12	0.13	0.14
Construction Demolition RCA	0.10	0.12	0.14
Limestone	0.10	0.12	0.14

During MDOT State Study 170 (33), Burns Cooley Dennis, Inc. conducted resilient modulus testing on three limestone granular base materials: ¾” Down, No. 610, and 825-B. Based upon the resilient modulus results from State Study 170, recommended resilient modulus values were provided for these three designations (34). Different limestone materials meeting the requirements of these three designations were also tested during this study. Therefore, in addition to typical resilient modulus values for RCA materials (by category), updated resilient modulus values for limestone materials are also provided. Table 15 presents estimates of resilient modulus values for the three categories of materials.

Table 15: Estimates of Resilient Modulus Values for Granular Base Materials

Material Category/Classification	Estimated Resilient Modulus, psi
Controlled RCA	24,000
Construction Demolition RCA	20,000
LMS ¾” Down	24,500
LMS No. 610	22,000
LMS 825-B	30,000

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

This research project was conducted with two primary objectives, which include: 1) determine whether materials meeting current MDOT requirements for RCA materials will perform their intended purpose within a granular course; and 2) determine whether RCA materials provide the same structural value as comparable crushed limestone granular courses. In order to accomplish these objectives, seven RCA materials were obtained from Mississippi suppliers for testing and evaluation. For comparison purposes, three limestone samples were also obtained and subjected to the same testing regimen. These ten materials were subjected to typical laboratory characterization tests in order to evaluate each material. Additionally, California Bearing Ratio and resilient modulus testing was conducted in order to compare the strength and stiffness of the various materials.

6.2 CONCLUSIONS

Based upon the research approach undertaken for the ten selected materials for this project, the following conclusions are provided.

- The reliability and repeatability of Proctor and strength/stiffness test specimens greatly increased when RCA materials were soaked overnight at a moisture content equal to the combined (coarse and fine fractions combined volumetrically) water absorption.
- Three of the seven RCA materials did not explicitly meet MDOT's gradation requirements; however, the three not meeting requirements were very close with a maximum of 2.0 percent deviation on the 1.0 in. sieve.
- None of the ten materials failed MDOT requirements of a maximum of 40 percent loss when tested in accordance with the Los Angeles Abrasion test.
- None of the ten materials failed MDOT requirements of a maximum of 20 percent loss when tested in accordance with magnesium sulfate soundness test.
- Two of the seven RCA materials failed MDOT's requirement of being non-plastic.
- Los Angeles Abrasion loss and Micro-Deval loss do not measure similar characteristics even though both tests are abrasion tests.
- A Micro-Deval loss of 18 percent appeared to differentiate RCA sources with higher magnesium sulfate soundness values. "Higher" meaning in magnitude because none of the RCA materials failed MDOT magnesium sulfate soundness requirements.
- Los Angeles Abrasion loss and water absorption were related. As water absorption increased, Los Angeles Abrasion loss also increased.
- Magnesium sulfate soundness loss and water absorption were related. As water absorption increased, the magnesium sulfate soundness loss also increased.

- No reasonable relationships were observed between California Bearing Ratio results and the characterization test results.
- A reasonable relationship was observed between Los Angeles Abrasion loss and resilient modulus results for both Standard and Modified compactive efforts. As the Los Angeles Abrasion loss increased, resilient modulus decreased.
- Reasonable relationships were observed between coarse aggregate angularity and resilient modulus results for both Standard and Modified compactive efforts. As the coarse aggregate angularity increased, resilient modulus increased.
- Reasonably strong relationships were observed between water absorption and resilient modulus results for both Standard and Modified compactive efforts. As water absorption increased, the stiffness of the materials decreased.
- Collectively, Los Angeles Abrasion loss was less for limestone materials when compared to the RCA materials.
- For Micro-Deval loss, RCA materials that were fabricated from controlled concrete had the lowest values of loss.
- RCA materials fabricated from controlled concrete resulted in the highest CBR values for test specimens prepared at 99 percent of Standard maximum dry density. For test specimens prepared at 100 percent of Modified maximum dry density, the CBR values for RCA materials fabricated from controlled concrete and limestone materials were essentially the same.
- RCA materials fabricated from controlled concrete sources and limestone materials resulted in higher resilient modulus values than RCA materials fabricated from construction debris. This was true for resilient modulus results from test samples fabricated using both a Standard and Modified compactive effort.
- California Bearing Ratio and resilient modulus values increased as the percent maximum dry density increased.

6.3 RECOMMENDATIONS

Based upon the conclusions provided above, the following recommendations are provided for consideration.

- Recycled concrete aggregates meeting all MDOT current requirements should be allowed for use in granular pavement layers. However, RCA materials meeting all MDOT current requirements that are produced from controlled concrete crushing would be preferable over construction demolition for high volume roadways, such as interstates and high truck volume highways.
- The protocol for preparing Proctor and strength/stiffness test specimens is recommended. This protocol includes determining the specific gravity and water absorption for both the coarse and fine fraction of RCA specimens during the characterization portion of testing.

Proctor and strength/stiffness test specimens should be soaked overnight in a sealable container (plastic bags work well) at a moisture content equal to the combined water absorption. The combined water absorption is calculated volumetrically using the gradation of the material and the specific gravities of the coarse and fine fractions of the material.

- Because RCA materials can have excessive absorption, RCA stockpiles should be maintained in the field at a moisture content representative of a saturated surface dry condition. Maintaining this moisture content will reduce variability in construction densities related to the amount of free water available within the stockpile.
- Consideration should be given to requiring a minimum fine aggregate angularity, as measured with the fine aggregate flow test, of 40 percent. The fine aggregate angularity of the lone source that potentially included wash-out material had a fine aggregate angularity of 39 percent.
- Recycled concrete aggregates meeting all applicable, current MDOT requirements can be blended with natural <u>crushed</u> aggregates also meeting all applicable MDOT requirements. Though this type of blending was not conducted in this study, the literature states that this practice has been successful.
- Compaction requirements for granular pavement layers should be a minimum 99 percent of Standard maximum dry density.
- Table 14 provides recommended granular base structural coefficients for the RCA and limestone materials based upon the minimum allowable percent compaction.
- Table 15 provides recommended typical resilient modulus values for use as default values within the upcoming MDOT mechanistic-empirical pavement design method.

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APPENDIX A

Data for All RCA and Limestone Materials

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 1

AASHTO: A-1-a

USCS: SP-SM

District: ______

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	100.0
3/4 in.	96.5
1/2 in.	85.7
3/8 in.	76.2
No. 4	55.7
No. 8	44.6
No. 10	42.0
No. 16	36.5
No. 40	24.6
No. 50	18.9
No. 200	7.4

Standard Proctor*	
γ_d, pcf	MC, %
116.7	6.2
119.4	8.0
121.8	10.8
120.0	11.9
γ_{dmax}, pcf	122.0
Opt. MC	10.3

* Rock Corrected

Modified Proctor*	
γ_d, pcf	MC, %
116.5	6.3
119.2	7.9
123.3	9.2
122.2	10.6
γ_{dmax}, pcf	123.5
Opt. MC	9.6

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.605
Bulk	2.317
Bulk SSD	2.427
Water Abs.	4.80

Specific Gravity FA	
Type	Value
Apparent	2.595
Bulk	2.244
Bulk SSD	2.379
Water Abs.	6.03

Mg Sulfate Soundness	
% Loss	2.0

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5002.5
+ #12 Mass after wash	3582.4
% Loss	28.4

Micro-Deval	
Property	Value
Grading	19 mm
Original Mass, g	1501.4
+ #12 Mass after wash	1350.6
% Loss	10.0

Comb. Sp. Grav.	
Type	Value
Apparent	2.599
Bulk	2.276
Bulk SSD	2.400
Water Abs.	5.48

Atterberg Limits	
LL	20
PL	NP
PI	NP

Angularity	
FA Flow	42.8
CA Flow	44.8

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	10.4	91.0	37
56	10.5	94.7	87
80	9.1	97.4	88

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	9.6	96.3	80
56	9.4	99.0	195
80	9.4	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 1 AASHTO: A-1-a USCS: SP-SM District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	88.8	72.4	77.5	85.0	81.6	83.1	82.1
3/8 in.	79.0	60.0	60.5	72.1	68.0	69.9	67.9
No. 4	57.7	41.6	39.7	50.6	49.4	48.9	43.2
No. 8	46.2	33.3	31.1	39.4	39.6	38.9	31.7
No. 16	37.8	29.1	26.7	33.4	34.1	33.3	26.7
No. 40	25.5	19.7	18.2	22.6	23.4	23.0	17.8
No. 50	19.6	14.6	13.8	17.0	17.6	17.7	13.8
No. 200	7.7	5.8	5.8	7.4	7.3	7.8	6.6

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 1 AASHTO: A-1-a USCS: SP-SM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	14999	13170	14442	13189	14548	13381	14663	13246	2.02	0.88
2	23614	24046	23613	24253	22238	23398	23155	23899	3.43	1.87
3	35473	37558	35532	38085	32612	35435	34539	37026	4.83	3.79
4	51212	53040	51811	54014	46728	48898	49917	51984	5.57	5.23
5	68917	67192	70088	68628	62744	61059	67250	65627	5.87	6.13
6	15312	14367	15282	14404	15381	14526	15325	14432	0.33	0.58
7	24658	25830	25241	26080	24369	25077	24756	25662	1.79	2.04
8	37798	39455	38529	40046	35898	37228	37408	38909	3.63	3.82
9	55374	54119	56547	55396	51449	50357	54457	53291	4.9	4.92
10	72370	67484	74432	68968	67174	61778	71325	66077	5.24	5.75
11	16894	16608	17275	16683	17416	16662	17195	16651	1.57	0.23
12	28090	28997	29054	29329	28361	28108	28502	28811	1.74	2.19
13	43665	42875	44882	43551	42281	40566	43609	42331	2.98	3.7
14	61794	57084	63169	58063	57549	53269	60837	56139	4.82	4.51
15	71687	69140	73338	70732	66605	63944	70543	67939	4.97	5.22
16	18200	18326	18667	18501	18710	18561	18526	18463	1.53	0.66
17	30361	31855	31141	32265	30197	30758	30566	31626	1.65	2.46
18	46040	45639	46428	46479	43223	43454	45230	45191	3.87	3.46
19	60975	59861	61511	60937	55376	56034	59287	58944	5.73	4.37
20	70735	71322	71601	73050	65080	66405	69139	70259	5.12	4.91
21	20076	22065	20381	22516	20081	22081	20179	22221	0.87	1.15
22	33254	36783	33896	37341	32088	35425	33079	36516	2.77	2.7
23	47235	50643	47846	51693	43551	47905	46211	50080	5.03	3.9
24	60589	64954	61719	66499	55919	61236	59409	64229	5.18	4.21
25	73020	76047	75107	78200	68042	71529	72056	75258	5.04	4.52
26	20425	25287	21063	25547	20608	24930	20699	25255	1.59	1.23
27	34468	40941	35580	41669	33663	39380	34570	40663	2.78	2.88
28	48746	55763	50051	56987	46009	53080	48269	55277	4.27	3.62
29	60601	69678	62805	71486	58692	66041	60699	69068	3.39	4.02
30	0	0	0	0	0	0	0	0	0	0
K_1	1109.2		1113.2		1104.3		1108.9			
K_2	1.017		1.029		0.940		0.995			
K_3	-0.626		-0.630		-0.539		-0.598			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 1 AASHTO: A-1-a USCS: SP-SM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	14393	12898	14302	12901	14342	13491	14346	13097	0.32	2.61
2	21573	22580	22144	23020	23839	24750	22519	23450	5.23	4.89
3	31598	34326	33530	35454	36368	38831	33832	36204	7.09	6.48
4	45971	47652	48115	49672	52947	55084	49011	50803	7.29	7.56
5	62681	59842	64257	62725	71176	70049	66038	64206	6.84	8.2
6	15081	14050	14815	14076	15516	14745	15137	14290	2.34	2.76
7	23447	24371	23771	24841	25883	26605	24367	25272	5.43	4.66
8	34740	36500	36382	37571	39797	40970	36973	38347	6.98	6.09
9	50951	49830	52784	51706	58048	56793	53928	52776	6.83	6.83
10	67842	61663	68818	64211	75409	70811	70690	65562	5.82	7.2
11	16893	16223	16591	16291	17723	17104	17069	16539	3.43	2.96
12	26997	27613	27816	28181	30302	30096	28372	28630	6.07	4.54
13	40632	40456	42593	41526	46406	44815	43210	42266	6.79	5.38
14	57802	54028	59288	55641	64549	60187	60546	56619	5.86	5.64
15	69420	65683	69992	67773	75955	73273	71789	68910	5.04	5.69
16	18275	18247	18035	18353	19334	19221	18548	18607	3.73	2.87
17	29441	30609	30141	31152	32777	33217	30786	31659	5.71	4.35
18	43210	44052	45295	45069	48456	48264	45654	45795	5.79	4.8
19	58240	57912	59811	59380	63596	63501	60549	60264	4.55	4.81
20	68837	69733	69526	71485	73895	76202	70753	72473	3.88	4.62
21	20321	21880	20816	22047	21465	23186	20867	22371	2.75	3.18
22	32494	35892	34043	36453	35435	38659	33991	37001	4.33	3.95
23	45543	49857	47698	50764	49691	53719	47644	51447	4.35	3.93
24	59347	65198	62021	66342	64150	69719	61839	67086	3.89	3.5
25	73618	77655	75220	78875	78468	82559	75769	79696	3.26	3.2
26	20748	24939	22050	25094	22033	26373	21610	25469	3.46	3.09
27	34450	40578	36653	41090	37166	43306	36090	41658	4	3.48
28	48487	56305	51445	57028	52227	59633	50720	57655	3.89	3.04
29	63956	71994	66311	72739	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1052.2		1064.1		1133.3		1083.2			
K_2	0.933		0.968		1.022		0.974			
K_3	-0.438		-0.493		-0.594		-0.508			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 2

AASHTO: A-1-a

USCS: GP-GM

District: __________

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	95.2
3/4 in.	88.8
1/2 in.	77.5
3/8 in.	64.9
No. 4	47.4
No. 8	37.5
No. 10	35.9
No. 16	30.1
No. 40	16.2
No. 50	9.9
No. 200	4.0

Standard Proctor*	
γ_d, pcf	MC, %
110.1	11.0
107.1	13.1
109.7	14.6
112.0	14.8
106.8	16.8
γ_{dmax}, pcf	114.0
Opt. MC	15.4

* Rock Corrected

Modified Proctor*	
γ_d, pcf	MC, %
110.9	9.8
113.3	10.4
116.4	12.7
116.4	13.1
γ_{dmax}, pcf	116.4
Opt. MC	12.6

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.570
Bulk	2.171
Bulk SSD	2.326
Water Abs.	7.18

Specific Gravity FA	
Type	Value
Apparent	2.612
Bulk	1.943
Bulk SSD	2.199
Water Abs.	13.20

Mg Sulfate Soundness	
% Loss	10.8

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5000.3
+ #12 Mass after wash	3590.4
% Loss	28.2

Micro-Deval	
Property	Value
Grading	19 mm
Original Mass, g	1501.5
+ #12 Mass after wash	1200.3
% Loss	20.1

Comb. Sp. Grav.	
Type	Value
Apparent	2.590
Bulk	2.057
Bulk SSD	2.264
Water Abs.	9.95

Atterberg Limits	
LL	37
PL	NP
PI	NP

Angularity	
FA Flow	38.5
CA Flow	42.2

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	15.4	93.1	19
56	15.8	95.7	35
80	15.4	98.0	51

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	13.1	93.6	56
56	13.2	98.0	112
80	13.0	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 2 AASHTO: A-1-a USCS: GP-GM District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	N/A	N/A	N/A	N/A	N/A	N/A
1 1/2 in.	100.0	N/A	N/A	N/A	N/A	N/A	N/A
1 in.	95.2	N/A	N/A	N/A	N/A	N/A	N/A
3/4 in.	88.8	N/A	N/A	N/A	N/A	N/A	N/A
1/2 in.	77.5	N/A	N/A	N/A	N/A	N/A	N/A
3/8 in.	64.9	N/A	N/A	N/A	N/A	N/A	N/A
No. 4	47.4	N/A	N/A	N/A	N/A	N/A	N/A
No. 8	37.5	N/A	N/A	N/A	N/A	N/A	N/A
No. 10	35.9	N/A	N/A	N/A	N/A	N/A	N/A
No. 16	30.1	N/A	N/A	N/A	N/A	N/A	N/A
No. 40	16.2	N/A	N/A	N/A	N/A	N/A	N/A
No. 50	9.9	N/A	N/A	N/A	N/A	N/A	N/A
No. 200	4.0	N/A	N/A	N/A	N/A	N/A	N/A

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 2 AASHTO: A-1-a USCS: GP-GM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	10971	10114	10055	9432	11647	10654	10891	10067	7.34	6.08
2	17714	18920	15052	16776	18687	19057	17151	18251	10.97	7.01
3	28696	29960	23425	25782	27963	29338	26695	28360	10.7	7.95
4	42597	42870	35187	36069	40016	40999	39267	39979	9.58	8.79
5	56383	54816	47241	45489	52672	51593	52099	50633	8.83	9.36
6	11564	11073	10772	10289	12108	11597	11481	10987	5.85	5.99
7	18862	20343	16831	18107	19700	20457	18464	19636	7.99	6.75
8	30133	31583	26236	27339	29583	30827	28651	29916	7.36	7.57
9	44657	44094	38563	37570	42149	42147	41790	41270	7.33	8.12
10	58809	55235	51553	46673	55388	52059	55250	51323	6.57	8.43
11	13420	12880	12645	11706	13720	13363	13262	12650	4.18	6.74
12	22314	22976	20629	20550	22598	22948	21847	22158	4.87	6.29
13	35143	34497	31876	30225	34380	33573	33800	32765	5.06	6.86
14	49504	46563	43986	40506	47466	44483	46985	43851	5.94	7.02
15	61363	56859	52715	49367	57625	53672	57234	53300	7.58	7.05
16	15139	14558	13831	13363	15083	14770	14684	14230	5.04	5.33
17	25108	25407	22469	22726	24208	25201	23928	24445	5.61	6.1
18	37455	37106	32792	32866	35772	36021	35340	35331	6.68	6.23
19	47525	48998	41158	43310	45414	46605	44699	46304	7.26	6.17
20	57858	58909	49699	52176	55896	55613	54484	55566	7.82	6.06
21	17100	17593	15744	16239	16592	17705	16479	17179	4.16	4.75
22	26332	29628	24194	26799	26305	29158	25610	28528	4.79	5.31
23	0	0	30655	37115	35035	39833	0	0	0	0
24	0	0	0	0	44412	51014	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	856.7		776.3		888.0		840.3			
K_2	1.052		0.962		0.980		0.998			
K_3	-0.632		-0.481		-0.578		-0.564			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 2 AASHTO: A-1-a USCS: GP-GM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	14610	12299	14888	12521	14269	12093	14589	12304	2.13	1.74
2	22190	22373	21986	22089	21940	21564	22039	22009	0.6	1.86
3	32606	34188	32183	33517	31658	32884	32149	33530	1.48	1.94
4	46370	47392	45434	46137	44197	45495	45334	46341	2.4	2.08
5	60971	59198	59578	57284	57701	56737	59417	57739	2.76	2.24
6	14734	13653	14762	13538	14046	13180	14514	13457	2.79	1.83
7	22700	23853	22290	23436	22070	22964	22353	23418	1.43	1.9
8	33662	35564	32580	34651	32558	34153	32933	34790	1.92	2.06
9	48152	48063	45897	46374	45783	46045	46611	46827	2.87	2.31
10	63102	58768	59886	56270	59628	56191	60872	57076	3.18	2.57
11	16044	15619	15786	15404	15352	15057	15727	15360	2.22	1.85
12	25507	26436	24622	25792	24697	25399	24942	25876	1.97	2.02
13	38385	38061	36659	36627	36893	36452	37312	37047	2.51	2.38
14	53341	49433	50620	47183	50898	47374	51620	47996	2.9	2.6
15	64290	59043	60977	55584	61133	56238	62133	56955	3.01	3.23
16	16962	17404	16653	17029	16196	16758	16604	17063	2.32	1.9
17	27151	28720	26087	27774	26153	27545	26464	28013	2.25	2.22
18	39615	40248	37678	38355	37933	38439	38409	39014	2.74	2.74
19	50802	51237	47833	48152	48497	48791	49044	49393	3.18	3.3
20	62248	59993	58381	55739	59261	56963	59963	57565	3.38	3.8
21	17991	20500	17566	19996	17228	19697	17595	20064	2.17	2.02
22	28600	32566	27396	31126	27605	31168	27867	31620	2.31	2.59
23	38877	43605	36678	40983	37557	41544	37704	42044	2.94	3.28
24	50535	54403	47342	50195	47972	51564	48616	52054	3.48	4.12
25	64027	62528	60712	56952	60383	59100	61707	59527	3.27	4.72
26	18448	23044	18108	22311	17390	22104	17982	22486	3	2.2
27	30017	35800	29032	33856	28550	34194	29200	34617	2.56	3
28	40732	47090	39351	43643	39055	44719	39713	45151	2.25	3.91
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1058.1		1056.8		1022.9		1045.9			
K_2	0.977		0.971		0.975		0.974			
K_3	-0.661		-0.721		-0.672		-0.685			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 3

AASHTO: A-1-a

USCS: GW-GM

District: __________

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	97.5
3/4 in.	89.9
1/2 in.	75.2
3/8 in.	63.8
No. 4	45.2
No. 8	37.7
No. 10	35.9
No. 16	32.0
No. 40	21.6
No. 50	17.3
No. 200	6.8

Standard Proctor*	
γ_d, pcf	MC, %
113.8	10.3
115.1	11.1
116.3	13.0
115.5	13.7
γ_{dmax}, pcf	116.5
Opt. MC	12.5

* Rock Corrected

Modified Proctor*	
γ_d, pcf	MC, %
115.6	10.2
118.0	11.8
115.9	13.5
γ_{dmax}, pcf	118.0
Opt. MC	11.8

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.582
Bulk	2.213
Bulk SSD	2.356
Water Abs.	6.45

Specific Gravity FA	
Type	Value
Apparent	2.567
Bulk	2.112
Bulk SSD	2.289
Water Abs.	8.40

Mg Sulfate Soundness	
% Loss	0.6

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5002.2
+ #12 Mass after wash	3547.1
% Loss	29.1

Micro-Deval	
Property	Value
Grading	19 mm
Original Mass, g	1501.9
+ #12 Mass after wash	1199.4
% Loss	20.1

Comb. Sp. Grav.	
Type	Value
Apparent	2.575
Bulk	2.166
Bulk SSD	2.325
Water Abs.	7.32

Atterberg Limits	
LL	30
PL	29
PI	1

Angularity	
FA Flow	45.6
CA Flow	45.0

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	13.7	92.7	33
56	13.3	97.1	64
80	12.8	98.7	80

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	11.3	97.6	80
56	12.0	101.2	134
80	12.2	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 3	AASHTO: A-1-a	USCS: GW-GM	District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	83.6	83.5	86.3	88.5	87.3	87.6	86.1
3/8 in.	71.0	68.8	73.9	76.7	75.4	74.1	75.0
No. 4	50.3	46.2	51.2	56.0	51.9	48.7	53.7
No. 8	41.9	35.6	39.6	44.3	40.5	35.6	43.2
No. 16	35.6	29.9	32.8	36.6	34.3	30.2	36.5
No. 40	24.0	20.3	22.3	24.6	24.0	21.0	24.7
No. 50	19.2	16.5	18.2	19.9	19.8	17.2	20.2
No. 200	7.6	7.5	8.2	9.0	8.7	7.7	9.8

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 3 AASHTO: A-1-a USCS: GW-GM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	10980	9860	13546	11736	11978	10552	12168	10716	10.63	8.85
2	17817	18278	20966	21554	18908	19342	19230	19725	8.32	8.47
3	27420	28837	31832	33721	28268	30267	29173	30942	8.03	8.11
4	40124	40996	46195	47683	41346	42763	42555	43814	7.55	7.91
5	53556	52129	62046	60351	55046	54152	56883	55544	7.97	7.71
6	11453	10765	13738	12788	12311	11504	12501	11686	9.23	8.76
7	18602	19613	21773	22806	19917	20735	20097	21051	7.93	7.7
8	28595	30165	33383	35210	30222	31651	30733	32342	7.92	8.02
9	41888	41775	48745	48437	43956	43385	44863	44532	7.84	7.81
10	55364	51954	64763	59942	58499	54023	59542	55306	8.04	7.5
11	12898	12511	15237	14748	13724	13281	13953	13513	8.5	8.41
12	21501	22006	24999	25740	22746	23191	23082	23646	7.68	8.07
13	33250	32596	38668	37869	35158	34186	35692	34884	7.7	7.75
14	46783	43488	54085	49965	49311	45416	50060	46290	7.41	7.18
15	56812	52591	65499	60334	59528	54753	60613	55893	7.33	7.15
16	14121	14013	16374	16484	14780	14912	15092	15136	7.68	8.27
17	23378	24079	27050	28114	24389	25390	24939	25861	7.61	7.96
18	34709	34725	39954	40207	35965	36425	36876	37119	7.43	7.56
19	44558	45081	51433	51950	46665	47247	47552	48093	7.41	7.3
20	53371	53775	61781	61417	55931	55885	57028	57026	7.56	6.92
21	15413	16794	17556	19729	15998	17613	16322	18045	6.79	8.39
22	24873	27740	28421	32143	25634	29203	26309	29695	7.1	7.55
23	33688	38094	39069	43796	34626	39932	35794	40608	8.03	7.17
24	42974	48577	50447	55431	44630	50737	46017	51581	8.53	6.79
25	53842	56650	62455	64271	0	0	0	0	0	0
26	16237	19114	17633	22282	0	0	0	0	0	0
27	26022	30884	27153	35331	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	839.1		997.7		893.8		910.2			
K_2	1.047		1.033		1.027		1.036			
K_3	-0.685		-0.694		-0.667		-0.682			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 3 AASHTO: A-1-a USCS: GW-GM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	15192	13138	15870	13445	15467	13421	15510	13335	2.2	1.28
2	23003	23691	24667	24484	23830	24120	23833	24099	3.49	1.65
3	34449	36302	36488	37994	35267	37131	35401	37142	2.9	2.28
4	49744	51118	51682	53162	50124	51841	50517	52040	2.03	1.99
5	66243	64183	68473	66674	66728	65021	67148	65293	1.75	1.94
6	15493	14272	15788	14586	15590	14576	15624	14478	0.96	1.23
7	23922	25284	24874	26009	24568	25744	24455	25679	1.99	1.43
8	36107	38061	36965	39219	36638	38679	36570	38653	1.18	1.5
9	52298	51801	52977	53203	52900	52582	52725	52529	0.71	1.34
10	68534	63605	69386	65079	69392	64524	69104	64403	0.71	1.16
11	17000	16374	17130	16685	17386	16717	17172	16592	1.14	1.14
12	27364	28109	27582	28626	27879	28581	27608	28439	0.94	1.01
13	41587	40736	41737	41346	42239	41201	41854	41094	0.82	0.78
14	57891	53402	58254	53770	58776	54274	58307	53815	0.76	0.81
15	67818	63742	68888	63660	69280	64795	68662	64066	1.1	0.99
16	17992	18287	18032	18574	18304	18602	18109	18488	0.94	0.94
17	28943	30525	29183	30893	29673	31094	29266	30837	1.27	0.94
18	42519	43077	42684	43181	43468	43845	42890	43368	1.18	0.96
19	55118	55108	55028	54630	56121	56093	55422	55277	1.09	1.35
20	65858	64671	65501	63422	66694	65822	66018	64638	0.93	1.86
21	19228	21608	18822	21552	19479	22050	19176	21737	1.73	1.25
22	30773	34665	30394	34612	31348	35330	30838	34869	1.56	1.15
23	42458	46652	41782	45977	43083	47533	42441	46721	1.53	1.67
24	54473	58455	53072	56550	54928	59562	54158	58189	1.79	2.62
25	67649	67339	65468	64223	68016	68667	67044	66743	2.05	3.42
26	19238	24342	18622	24425	19349	24791	19070	24520	2.05	0.97
27	31804	38067	30771	37624	32086	38842	31554	38178	2.19	1.62
28	44631	50465	42962	48834	45032	51470	44208	50256	2.48	2.65
29	0	0	53301	58492	55956	62856	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1111.3		1152.8		1132.9		1132.3			
K_2	1.003		1.028		0.997		1.009			
K_3	-0.687		-0.784		-0.677		-0.716			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 4 AASHTO: A-1-a USCS: SP-SM District: ______

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	97.1
3/4 in.	92.5
1/2 in.	80.3
3/8 in.	71.9
No. 4	54.5
No. 8	45.0
No. 10	43.0
No. 16	37.9
No. 40	28.1
No. 50	22.2
No. 200	6.9

Standard Proctor*	
γ_d, pcf	MC, %
113.8	6.8
116.5	8.0
119.1	9.0
118.1	10.4
γ_{dmax}, pcf	119.4
Opt. MC	9.4

* Rock Corrected

Modified Proctor*	
γ_d, pcf	MC, %
117.3	6.3
119.0	8.2
120.6	9.8
119.7	11.5
γ_{dmax}, pcf	120.7
Opt. MC	10.0

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.574
Bulk	2.295
Bulk SSD	2.403
Water Abs.	4.74

Specific Gravity FA	
Type	Value
Apparent	2.561
Bulk	2.244
Bulk SSD	2.367
Water Abs.	5.52

Mg Sulfate Soundness	
% Loss	2.4

Atterberg Limits	
LL	19
PL	NP
PI	NP

Angularity	
FA Flow	46.8
CA Flow	47.2

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5000.7
+ #12 Mass after wash	3658.7
% Loss	26.8

Micro-Deval		Comb. Sp. Grav.	
Property	Value	Type	Value
Grading	19 mm	Apparent	2.567
Original Mass, g	1503.2	Bulk	2.267
+ #12 Mass after wash	1212.6	Bulk SSD	2.383
% Loss	19.3	Water Abs.	5.17

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	9.9	92.8	20
56	9.6	95.5	35
80	9.8	96.9	46

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	10.5	97.3	53
56	10.3	101.0	80
80	10.2	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 4	AASHTO: A-1-a	USCS: SP-SM	District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	86.8	89.2	93.0	94.0	89.9	89.6	91.8
3/8 in.	77.7	79.0	86.1	85.6	80.3	81.6	83.2
No. 4	58.9	62.2	68.3	65.4	62.2	63.0	66.2
No. 8	48.6	51.9	57.4	53.8	51.8	51.9	55.2
No. 16	40.9	45.0	49.1	45.5	44.5	44.2	47.8
No. 40	30.4	31.8	34.5	33.1	32.1	31.6	33.8
No. 50	24.0	23.9	25.9	25.6	24.5	24.3	25.5
No. 200	7.5	6.7	7.9	9.0	7.5	8.0	7.5

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 4 AASHTO: A-1-a USCS: SP-SM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	16440	14640	15885	13770	15179	13094	15835	13835	3.99	5.6
2	26734	26300	25522	25248	25241	24825	25832	25458	3.07	2.98
3	38772	40317	37492	39296	38052	39556	38105	39723	1.68	1.34
4	53315	55772	52733	55002	54080	56314	53376	55696	1.27	1.18
5	68611	69315	69256	68913	70643	71313	69503	69847	1.49	1.84
6	16797	15814	16134	14918	15535	14233	16155	14988	3.91	5.29
7	27438	27752	26126	26708	25724	26283	26429	26914	3.39	2.81
8	40034	41236	38676	40244	39197	40439	39302	40640	1.74	1.29
9	55704	55162	55106	54455	56384	55456	55731	55024	1.15	0.94
10	70564	66723	71123	66379	71987	68118	71225	67073	1.01	1.37
11	18409	17946	17419	17014	16585	16318	17471	17093	5.23	4.78
12	29992	30191	28528	29173	28071	28735	28864	29366	3.48	2.54
13	44049	42803	42492	41918	42908	41941	43150	42221	1.87	1.2
14	59024	54696	58301	54099	59073	54632	58799	54476	0.74	0.6
15	68085	63846	69045	63568	69806	64482	68979	63965	1.25	0.73
16	19395	19838	18340	18884	17362	18180	18366	18967	5.54	4.39
17	31054	32251	29646	31267	29322	30805	30007	31441	3.07	2.35
18	43735	44142	42307	43310	42816	43220	42953	43557	1.68	1.17
19	54496	54719	54145	54218	54400	54410	54347	54449	0.33	0.46
20	64436	62532	65020	62347	65119	62724	64858	62534	0.57	0.3
21	20034	23013	19229	21777	18336	21326	19200	22039	4.42	3.96
22	31026	35286	29808	34614	29700	34061	30178	34654	2.44	1.77
23	39784	46120	38278	45441	39384	45105	39149	45555	1.99	1.14
24	49971	55317	49630	54984	50925	54690	50175	54997	1.34	0.57
25	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1260.3		1193.9		1155.0		1203.1			
K_2	1.012		1.046		1.107		1.055			
K_3	-0.845		-0.865		-0.946		-0.885			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 4 AASHTO: A-1-a USCS: SP-SM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	17172	14821	17253	15079	18432	15741	17619	15214	4.00	3.12
2	26815	27097	27458	27455	27870	28040	27381	27531	1.94	1.73
3	39971	42064	40477	42532	40538	42741	40329	42446	0.77	0.82
4	56827	58734	56710	59349	56770	58893	56769	58992	0.10	0.54
5	72896	73480	74650	74233	74038	72995	73861	73570	1.21	0.85
6	17534	16042	17687	16330	18518	16992	17913	16455	2.96	2.96
7	27792	28623	28422	29057	28683	29596	28299	29092	1.62	1.67
8	41792	43015	42109	43625	41947	43753	41949	43464	0.38	0.91
9	59374	58005	60029	58910	59514	58392	59639	58436	0.58	0.78
10	75122	70516	76512	71710	75725	70549	75786	70925	0.92	0.96
11	18940	18266	19223	18616	19972	19266	19378	18716	2.75	2.71
12	30639	31188	31346	31771	31442	32217	31142	31725	1.41	1.63
13	45916	44375	46784	45559	46429	45539	46376	45158	0.94	1.50
14	62653	57394	63528	58540	62768	58119	62983	58018	0.75	1.00
15	71562	67234	73413	69089	72231	67844	72402	68056	1.29	1.39
16	19630	20242	19926	20275	20674	21222	20077	20580	2.68	2.70
17	31562	33354	32298	34086	32446	34440	32102	33960	1.47	1.63
18	45478	46019	46345	47189	46024	47038	45949	46749	0.95	1.36
19	57789	57330	59729	59091	58953	58310	58824	58244	1.66	1.51
20	68230	65701	70402	68005	69799	66676	69477	66794	1.61	1.73
21	20123	23567	20718	24112	21149	24681	20663	24120	2.49	2.31
22	31497	36765	32735	37780	32894	37988	32375	37511	2.36	1.74
23	41983	48060	43919	49654	43985	49285	43296	49000	2.63	1.70
24	53839	57847	57019	60206	57049	59205	55969	59086	3.30	2.00
25	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1286.1		1301.1		1348.0		1311.7			
K_2	1.043		1.033		0.996		1.024			
K_3	-0.878		-0.838		-0.817		-0.844			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 5

AASHTO: A-1-a

USCS: SP-SM

District: ______

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	98.2
3/4 in.	94.5
1/2 in.	83.4
3/8 in.	72.8
No. 4	51.4
No. 8	39.5
No. 10	37.2
No. 16	32.1
No. 40	21.5
No. 50	16.2
No. 200	6.6

Atterberg Limits	
LL	26
PL	NP
PI	NP

Angularity	
FA Flow	42.7
CA Flow	44.1

Standard Proctor*	
γ_d, pcf	MC, %
108.7	11.8
110.7	12.7
111.5	13.7
108.3	15.7
γ_{dmax}, pcf	111.5
Opt. MC	13.7

* Rock Corrected

Modified Proctor*	
γ_d, pcf	MC, %
111.8	10.2
112.8	12.9
113.9	14.4
112.8	15.2
γ_{dmax}, pcf	114.0
Opt. MC	14.2

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.590
Bulk	2.231
Bulk SSD	2.370
Water Abs.	6.21
Specific Gravity FA	
Type	Value
Apparent	2.570
Bulk	2.062
Bulk SSD	2.260
Water Abs.	9.60

Mg Sulfate Soundness	
% Loss	4.7

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5001.9
+ #12 Mass after wash	3531.4
% Loss	29.4

Micro-Deval		Comb. Sp. Grav.	
Property	Value	Type	Value
Grading	19 mm	Apparent	2.580
Original Mass, g	1501.8	Bulk	2.141
+ #12 Mass after wash	1243.6	Bulk SSD	2.312
% Loss	17.2	Water Abs.	7.90

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	14.1	92.1	28
56	13.9	96.9	51
80	13.9	97.5	68

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	15.0	95.8	73
56	14.8	100.7	117
80	15.5	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 5 AASHTO: A-1-a USCS: SP-SM District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	88.3	82.5	85.7	85.1	88.5	88.6	89.1
3/8 in.	77.0	67.9	71.8	70.9	77.1	76.8	77.4
No. 4	54.4	45.1	50.6	49.4	56.4	55.8	57.4
No. 8	41.8	34.2	39.5	38.4	44.3	44.1	46.5
No. 16	34.0	27.8	33.1	31.7	36.3	36.5	38.9
No. 40	22.8	17.2	21.1	20.1	23.2	24.5	26.3
No. 50	17.1	12.4	15.5	14.6	17.1	18.3	19.8
No. 200	7.0	4.6	6.3	5.7	6.9	7.6	8.5

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 5 AASHTO: A-1-a USCS: SP-SM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	14981	12650	14651	12926	15032	12843	14888	12806	1.39	1.10
2	22992	22910	23346	23429	23157	23216	23165	23185	0.76	1.12
3	33558	35434	35007	36272	34338	35850	34301	35852	2.11	1.17
4	47930	49485	48751	50712	48777	49995	48486	50064	0.99	1.23
5	63461	62052	64359	63640	63778	62623	63866	62772	0.71	1.28
6	14933	13724	14904	14031	14941	13927	14926	13894	0.13	1.12
7	23265	24363	24276	24940	23571	24672	23704	24658	2.19	1.17
8	34592	36662	35889	37585	35295	37036	35259	37094	1.84	1.25
9	49903	49703	50913	51037	50260	50160	50359	50300	1.02	1.35
10	65348	60810	66416	62531	65167	61302	65644	61548	1.03	1.44
11	16177	15703	16652	16070	16444	15921	16424	15898	1.45	1.16
12	26001	26869	27356	27594	26500	27177	26619	27213	2.57	1.34
13	39102	38822	40846	39879	39765	39164	39904	39288	2.21	1.37
14	54846	50513	55939	52037	54739	50894	55175	51148	1.20	1.55
15	66114	59914	66560	61843	65468	60267	66047	60675	0.83	1.69
16	17134	17432	17622	17915	17302	17718	17353	17689	1.43	1.37
17	27540	29053	28798	29839	27895	29356	28078	29416	2.31	1.35
18	40345	40657	41801	41892	40544	40985	40897	41178	1.93	1.55
19	51523	51538	52861	53237	51347	51846	51910	52207	1.60	1.73
20	61569	59996	63417	62113	62430	60258	62472	60789	1.48	1.90
21	17608	20606	18381	21094	18145	20801	18045	20834	2.20	1.18
22	28403	32662	29781	33634	29035	32947	29073	33081	2.37	1.51
23	38652	43512	40403	44936	39298	43783	39451	44077	2.24	1.72
24	48564	53731	50930	55707	49527	53924	49674	54454	2.40	2.00
25	60539	61237	63129	63664	61887	61358	61852	62086	2.09	2.20
26	17197	23093	17883	23686	17666	23300	17582	23360	1.99	1.29
27	28526	35655	29621	36572	29010	35937	29052	36054	1.89	1.30
28	38637	46441	40999	48095	39292	46637	39643	47057	3.08	1.92
29	0	0	50509	58092	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1079.3		1193.9		1155.0		1142.7			
K_2	1.016		1.046		1.107		1.056			
K_3	-0.753		-0.865		-0.946		-0.855			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 5 AASHTO: A-1-a USCS: SP-SM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	15246	13432	17388	14531	15673	13725	16102	13896	7.04	4.10
2	24089	24521	25482	25978	24196	24672	24589	25057	3.15	3.20
3	36035	38147	37555	39805	35863	38063	36484	38672	2.55	2.54
4	52010	53516	53364	55206	51237	53203	52204	53975	2.06	2.00
5	69060	67296	71488	68879	68635	66885	69728	67687	2.21	1.56
6	15747	14589	17188	15741	16002	14925	16312	15085	4.71	3.93
7	24943	26100	26450	27603	25414	26403	25602	26702	3.01	2.98
8	37515	39493	39075	41190	38111	39813	38234	40165	2.06	2.25
9	54126	53767	55633	55512	54934	54292	54898	54523	1.37	1.64
10	70536	65967	72639	67664	71988	66826	71721	66819	1.50	1.27
11	17499	16724	18733	17897	17825	17159	18019	17260	3.55	3.43
12	28504	28827	29740	30407	28934	29451	29059	29562	2.16	2.69
13	42883	41864	44359	43605	43814	42917	43685	42795	1.71	2.05
14	59070	54675	61294	56507	60888	56543	60417	55908	1.96	1.91
15	69684	65009	72475	66843	72321	67858	71493	66570	2.19	2.17
16	18512	18655	19227	19910	18945	19203	18895	19256	1.91	3.27
17	29812	31208	30846	32852	30767	32176	30475	32078	1.89	2.58
18	43427	43899	44990	45719	45194	45687	44537	45102	2.17	2.31
19	55606	55823	57902	57717	58971	58832	57493	57458	2.99	2.65
20	66572	65127	69633	67057	70405	69496	68870	67227	2.94	3.26
21	19323	21980	19924	23416	20199	22782	19815	22726	2.26	3.17
22	30768	35120	32075	36863	32639	36822	31827	36269	3.02	2.74
23	42087	47003	44483	48925	45430	49955	44000	48628	3.92	3.08
24	53835	58272	57347	60246	58430	63229	56537	60582	4.25	4.12
25	66498	66542	70578	68583	71248	73500	69441	69542	3.70	5.14
26	19227	24687	19668	26164	20057	25656	19651	25502	2.11	2.94
27	31159	38326	32756	40173	33444	40695	32453	39732	3.61	3.13
28	43276	50258	46302	52223	47502	54517	45693	52333	4.77	4.07
29	53414	60818	58585	62805	60307	67816	57435	63813	6.25	5.65
30	0	0	0	0	0	0	0	0	0	0
K_1	1149.3		1232.5		1153.4		1178.4			
K_2	1.030		0.993		0.994		1.006			
K_3	-0.761		-0.723		-0.638		-0.707			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 6 AASHTO: A-1-a USCS: SM District: ________

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	98.3
1 in.	96.0
3/4 in.	91.2
1/2 in.	84.1
3/8 in.	78.4
No. 4	62.0
No. 8	49.6
No. 10	45.0
No. 16	41.6
No. 40	27.9
No. 50	21.8
No. 200	13.0

Atterberg Limits	
LL	26
PL	23
PI	3

Angularity	
FA Flow	45.5
CA Flow	45.9

Standard Proctor*	
γ_d, pcf	MC, %
111.8	9.9
115.8	11.6
117.0	13.8
115.8	14.7
γ_{dmax}, pcf	117.2
Opt. MC	13.2

* Rock Corrected

Mg Sulfate Soundness	
% Loss	1.5

Modified Proctor*	
γ_d, pcf	MC, %
119.4	7.9
123.7	10.3
121.2	11.9
118.6	13.3
γ_{dmax}, pcf	123.7
Opt. MC	10.2

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.559
Bulk	2.280
Bulk SSD	2.390
Water Abs.	4.78

Specific Gravity FA	
Type	Value
Apparent	2.582
Bulk	2.146
Bulk SSD	2.315
Water Abs.	7.86

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5003.3
+ #12 Mass after wash	3414
% Loss	31.8

Micro-Deval		Comb. Sp. Grav.	
Property	Value	Type	Value
Grading	19 mm	Apparent	2.573
Original Mass, g	1502.5	Bulk	2.195
+ #12 Mass after wash	1256.55	Bulk SSD	2.343
% Loss	16.4	Water Abs.	6.66

CBR, Standard Proctor			
Blows/Lift	MC, %	$\%\gamma_{dmax}$	CBR
25	14.2	99.7	48
56	14.3	102	35
80	14.2	103	50

CBR, Modified Proctor			
Blows/Lift	MC, %	$\%\gamma_{dmax}$	CBR
25	11.3	94.8	73
56	11.5	98.3	118
80	11.0	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 6 AASHTO: A-1-a USCS: SM District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	92.2	86.3	86.3	82.0	89.7	88.5	87.7
3/8 in.	86.0	74.5	75.5	70.8	79.2	78.5	74.6
No. 4	68.0	52.8	55.4	49.9	57.4	58.7	52.2
No. 8	54.3	41.2	43.6	38.9	45.2	46.6	41.1
No. 16	45.6	34.2	36.8	31.9	38.4	39.3	34.6
No. 40	30.6	23.6	25.5	21.0	26.1	26.7	23.5
No. 50	23.9	18.8	20.4	16.6	20.3	21.0	18.5
No. 200	14.3	11.3	12.6	10.0	12.2	12.6	11.3

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 6 AASHTO: A-1-a USCS: SM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	12622	10974	11886	10613	12212	11007	12240	10865	3.01	2.01
2	19791	19795	18416	19118	19664	20039	19290	19651	3.94	2.43
3	28937	30645	27678	29572	29588	31237	28734	30485	3.38	2.77
4	41525	42989	40287	41465	42777	44054	41530	42836	3.00	3.04
5	55717	54215	53804	52283	56970	55765	55497	54088	2.87	3.23
6	12796	11953	12207	11560	12629	12005	12544	11839	2.42	2.06
7	20382	21241	19539	20520	20440	21528	20120	21097	2.51	2.46
8	30395	32151	29483	31073	31155	32831	30344	32018	2.76	2.77
9	44166	44071	42956	42548	45575	45204	44232	43941	2.96	3.03
10	58687	54501	56687	52622	59979	56075	58451	54399	2.84	3.18
11	14088	13782	13760	13330	14253	13875	14034	13662	1.79	2.13
12	23105	23806	22635	23010	23788	24174	23176	23663	2.50	2.51
13	35387	34922	34826	33754	36833	35681	35682	34785	2.90	2.79
14	50070	46328	48694	44794	51362	47537	50042	46220	2.67	2.97
15	60557	55867	57099	54041	61414	57531	59690	55813	3.83	3.13
16	15181	15465	14952	14960	15621	15598	15251	15341	2.23	2.20
17	25047	26118	24670	25258	25995	26601	25237	25992	2.71	2.62
18	37241	37360	36478	36165	38313	38244	37344	37257	2.47	2.80
19	48252	48541	46795	46975	48897	49842	47981	48453	2.24	2.96
20	57720	57651	54203	55843	58440	59412	56788	57635	3.99	3.10
21	16470	18433	16337	17882	17193	18694	16667	18336	2.76	2.26
22	27146	30132	26572	29137	28030	30690	27249	29986	2.70	2.62
23	37625	41226	36511	39913	38130	42229	37422	41123	2.21	2.82
24	48808	52673	47026	51078	49280	54232	48371	52661	2.46	2.99
25	59155	61618	0	0	61113	63500	0	0	0	0
26	0	0	0	0	17856	21162	0	0	0	0
27	0	0	0	0	29525	34177	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	919.7		888.3		925.4		911.1			
K_2	0.996		0.993		1.012		1.000			
K_3	-0.608		-0.600		-0.616		-0.608			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 6 AASHTO: A-1-a USCS: SM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	17104	13799	17829	14672	20221	16388	18385	14953	8.87	8.81
2	25628	24954	26172	25711	29053	28289	26951	26318	6.83	6.64
3	36878	37968	37372	38909	40458	41599	38236	39492	5.07	4.77
4	51214	52457	52103	53565	55231	55918	52849	53980	3.99	3.27
5	67867	65350	69142	66624	70759	68350	69256	66775	2.09	2.25
6	16680	15300	17330	15890	19909	18002	17973	16397	9.50	8.66
7	25345	26578	26183	27408	28624	29903	26717	27963	6.38	6.19
8	36864	39486	37912	40528	40079	42924	38285	40979	4.28	4.30
9	52891	53149	54342	54490	55922	56280	54385	54640	2.79	2.87
10	69333	64815	71200	66408	71903	67337	70812	66187	1.88	1.93
11	17493	17473	18287	18143	20377	20297	18719	18638	7.96	7.92
12	27545	29407	28751	30379	30497	32671	28931	30819	5.13	5.44
13	41712	42156	43304	43502	44387	45298	43134	43652	3.12	3.61
14	59083	54765	60871	56484	61692	57324	60549	56191	2.20	2.32
15	69709	65015	72141	67138	71319	66799	71056	66317	1.74	1.72
16	18402	19444	19284	20189	21016	22281	19567	20638	6.80	7.13
17	29527	31903	30873	33014	32250	35070	30883	33329	4.41	4.82
18	44112	44493	45742	46060	46925	47347	45593	45967	3.10	3.11
19	58743	56534	59835	58549	61276	58565	59951	57882	2.12	2.02
20	68417	66001	70695	68509	70122	67143	69745	67218	1.70	1.87
21	19685	22852	20632	23741	22062	25824	20793	24139	5.76	6.32
22	32222	36093	33505	37435	34833	38985	33520	37504	3.89	3.86
23	46057	48111	47126	50021	48982	50428	47388	49520	3.12	2.50
24	59061	59844	60011	62415	62209	61058	60427	61106	2.67	2.11
25	71619	68691	72402	71899	75498	68809	73173	69800	2.80	2.61
26	20035	25504	20580	26517	22232	28477	20949	26833	5.46	5.63
27	33484	39526	34237	41147	35980	42196	34567	40956	3.70	3.28
28	48557	51939	49556	54225	51919	53657	50011	53273	3.45	2.23
29	60459	62968	61902	66039	65048	63445	62470	64151	3.76	2.58
30	70182	71623	0	0	75736	70863	0	0	0	0
K_1	1185.2		1223.6		1388.3		1265.7			
K_2	0.968		0.952		0.896		0.939			
K_3	-0.661		-0.624		-0.647		-0.644			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 7

AASHTO: A-1-a

USCS: GP

District: ______

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	99.7
3/4 in.	88.9
1/2 in.	69.9
3/8 in.	60.2
No. 4	43.3
No. 8	34.1
No. 10	
No. 16	26.8
No. 40	13.7
No. 50	9.1
No. 200	2.5

Atterberg Limits	
LL	NP
PL	NP
PI	NP

Angularity	
FA Flow	42.9
CA Flow	48.4

Standard Proctor*	
γ_d, pcf	MC, %
113.9	9.6
117.0	10.7
118.0	12.4
116.5	13.4
γ_{dmax}, pcf	118.2
Opt. MC	11.8

* Rock Corrected

Mg Sulfate Soundness	
% Loss	1.1

Modified Proctor*	
γ_d, pcf	MC, %
121.9	8.2
123.0	10.0
124.5	11.3
123.1	13.1
γ_{dmax}, pcf	124.5
Opt. MC	11.5

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.632
Bulk	2.342
Bulk SSD	2.452
Water Abs.	4.71

Specific Gravity FA	
Type	Value
Apparent	2.576
Bulk	2.213
Bulk SSD	2.353
Water Abs.	6.38

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5002.6
+ #12 Mass after wash	3392.5
% Loss	32.2

Micro-Deval		Comb. Sp. Grav.	
Property	Value	Type	Value
Grading	19 mm	Apparent	2.607
Original Mass, g	1500.1	Bulk	2.284
+ #12 Mass after wash	1258.6	Bulk SSD	2.408
% Loss	16.1	Water Abs.	5.43

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	13.0	95.0	43
56	12.2	99.6	70
80	12.0	101.6	84

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	11.4	95.6	72
56	11.6	98.6	120
80	12.2	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 7 AASHTO: A-1-a USCS: GP District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	78.6	83.9	83.0	84.0	87.6	89.7	86.7
3/8 in.	67.7	74.2	72.5	74.6	78.1	81.1	75.8
No. 4	48.7	55.1	54.9	57.3	60.2	62.4	57.9
No. 8	38.4	42.9	43.6	46.5	47.6	50.5	47.0
No. 16	30.1	34.8	36.7	39.2	38.4	41.5	38.9
No. 40	15.4	19.1	21.2	23.2	21.7	24.5	23.9
No. 50	10.2	13.5	15.3	16.5	15.6	17.9	17.9
No. 200	2.8	4.4	5.9	6.1	6.2	7.1	8.0

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No.: 7	AASHTO: A-1-a	USCS: GP	District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	15492	13750	15376	13761	13729	12394	14866	13302	6.63	5.91
2	24249	25142	24332	24939	21304	22622	23295	24234	7.40	5.78
3	36583	39188	36602	38666	32403	35260	35196	37705	6.87	5.66
4	52899	55091	52445	54201	48137	49633	51160	52975	5.14	5.53
5	70554	69411	69416	68220	64704	62651	68225	66761	4.55	5.40
6	15962	14949	15899	14964	14500	13493	15454	14469	5.35	5.84
7	25534	26809	25340	26647	22809	24196	24561	25884	6.19	5.66
8	39155	40680	38276	40308	35139	36787	37523	39258	5.63	5.47
9	56838	55549	55271	55007	51659	50413	54589	53656	4.87	5.26
10	73885	68331	72325	67707	67997	62208	71402	66082	4.27	5.10
11	17954	17169	17798	17126	16558	15536	17437	16610	4.39	5.61
12	29581	29750	29174	29637	26574	26954	28443	28780	5.74	5.50
13	45266	43320	44534	43205	40916	39486	43572	42004	5.35	5.19
14	62551	56805	62470	56834	57206	52134	60742	55258	5.04	4.90
15	70314	67800	72481	68037	66214	62568	69670	66135	4.57	4.67
16	19042	19184	19271	19170	17688	17402	18667	18585	4.58	5.51
17	31125	32288	31649	32290	28399	29406	30391	31328	5.74	5.31
18	45614	45597	46614	45751	41516	41859	44581	44402	6.06	4.96
19	58437	58297	59362	58782	53335	53960	57045	57013	5.69	4.66
20	67764	68284	67265	69170	62882	63676	65970	67043	4.07	4.40
21	20146	22726	20307	22839	18854	20712	19769	22092	4.03	5.42
22	32470	36463	32468	36771	29480	33558	31473	35597	5.48	4.98
23	44407	49108	43860	49708	39011	45555	42426	48124	7.00	4.66
24	56139	61284	55344	62564	50218	57561	53900	60470	5.96	4.30
25	70169	70371	68311	72338	0	0	0	0	0	0
26	20513	25624	20534	25763	0	0	0	0	0	0
27	33539	39921	33385	40440	0	0	0	0	0	0
28	46640	52865	46376	53950	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1173.9		1164.9		1051.6		1130.1			
K_2	1.030		1.011		1.023		1.021			
K_3	-0.739		-0.684		-0.689		-0.704			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 7 AASHTO: A-1-a USCS: GP District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	17975	15861	20373	17581	18283	15833	18877	16425	6.91	6.10
2	27860	28958	30848	31236	28110	28670	28939	29621	5.73	4.74
3	42067	45044	44601	47582	41540	44305	42736	45643	3.83	3.77
4	61174	63165	63457	65615	59795	61586	61475	63455	3.01	3.20
5	81506	79369	83746	81462	78698	77619	81317	79483	3.11	2.42
6	18348	16847	20445	19001	18536	17178	19110	17675	6.07	6.56
7	29410	30803	31727	33065	29202	30490	30113	31453	4.65	4.47
8	44897	46582	46899	48974	43992	45879	45263	47145	3.29	3.44
9	65928	63361	67255	65522	63829	62201	65671	63694	2.63	2.65
10	82482	77668	84180	79370	81485	76094	82716	77710	1.65	2.11
11	20472	19651	22155	21595	20237	19655	20955	20300	4.99	5.52
12	33689	34030	35487	36185	32894	33631	34023	34615	3.90	3.97
13	51754	49286	53343	51426	49822	48569	51640	49760	3.41	2.99
14	69773	64286	71425	65954	69286	63227	70161	64489	1.60	2.13
15	75989	76298	78505	77402	77419	75002	77304	76234	1.63	1.58
16	21230	21923	23013	23841	21224	21821	21822	22528	4.73	5.05
17	34878	36747	36963	38868	34616	36369	35486	37328	3.62	3.61
18	52466	51602	54195	53447	51280	50922	52647	51991	2.78	2.51
19	66887	65551	68194	66795	66625	64571	67235	65639	1.25	1.70
20	76935	76400	77589	76867	74694	75174	76406	76147	1.99	1.15
21	22659	25949	24220	27850	22365	25436	23081	26412	4.32	4.82
22	37524	41311	39379	43227	36600	40896	37834	41811	3.74	2.97
23	54796	55182	55858	56610	51493	54490	54049	55427	4.21	1.95
24	70015	68239	71167	68782	64670	67334	68617	68118	5.05	1.07
25	84624	78174	85050	77745	77220	76889	82298	77602	5.35	0.84
26	23215	28944	24215	30951	22068	28809	23166	29568	4.64	4.06
27	39186	45060	40353	46722	36809	44511	38783	45431	4.66	2.53
28	58032	59085	58742	59914	52611	58372	56462	59124	5.94	1.31
29	71591	71361	73825	71133	63495	70310	69637	70935	7.80	0.78
30	84952	80456	87223	79291	0	0	0	0	0	0
K_1	1358.8		1495.8		1350.6		1401.7			
K_2	1.031		0.987		1.016		1.011			
K_3	-0.772		-0.766		-0.751		-0.763			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 8   AASHTO: A-1-a   USCS: GW-GM   District: ______

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	95.8
3/4 in.	78.3
1/2 in.	61.9
3/8 in.	55.1
No. 4	43.4
No. 8	32.6
No. 10	30.6
No. 16	23.9
No. 40	15.4
No. 50	13.2
No. 200	8.6

Standard Proctor*	
γ_d, pcf	MC, %
134.5	3.7
141.5	5.1
139.6	6.7
γ_{dmax}, pcf	142.0
Opt. MC	5.5

* Rock Corrected

Modified Proctor*	
γ_d, pcf	MC, %
143.1	3.8
147.0	5.0
144.5	6.0
142.9	7.5
γ_{dmax}, pcf	147.0
Opt. MC	5.0

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.720
Bulk	2.644
Bulk SSD	2.672
Water Abs.	1.08

Specific Gravity FA	
Type	Value
Apparent	2.672
Bulk	2.584
Bulk SSD	2.617
Water Abs.	1.29

Mg Sulfate Soundness	
% Loss	17.3

Atterberg Limits	
LL	NP
PL	NP
PI	NP

Angularity	
FA Flow	45.9
CA Flow	47.9

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5006.7
+ #12 Mass after wash	3763.2
% Loss	24.8

Micro-Deval		Comb. Sp. Grav.	
Property	Value	Type	Value
Grading	19 mm	Apparent	2.699
Original Mass, g	1500.5	Bulk	2.618
+ #12 Mass after wash	1205.9	Bulk SSD	2.648
% Loss	19.6	Water Abs.	1.15

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	7.4	95.9	43
56	7.5	101.4	63
80	6.9	102.1	73

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	6.3	97.6	84
56	6.8	99.6	127
80	6.5	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 8 AASHTO: A-1-a USCS: GW-GM District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	79.1	90.7	90.3	90.0	91.7	90.4	91.8
3/8 in.	70.4	83.3	82.2	82.3	86.0	83.4	86.5
No. 4	55.4	69.1	65.2	68.1	71.4	69.9	72.4
No. 8	41.6	51.7	48.0	52.3	55.0	54.6	57.1
No. 16	30.5	37.6	35.4	39.0	41.8	41.6	43.6
No. 40	19.7	23.7	23.2	25.3	27.3	27.3	29.0
No. 50	16.9	20.3	20.0	21.7	23.4	23.6	25.1
No. 200	11.0	13.3	13.3	14.6	15.3	15.8	16.9

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 8 AASHTO: A-1-a USCS: GW-GM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	17979	16111	16946	15028	15719	14340	16881	15160	6.70	5.89
2	27966	28963	26659	27654	24523	25849	26383	27489	6.59	5.69
3	42191	44608	40207	43261	36920	39959	39773	42609	6.69	5.61
4	60121	62170	58955	61061	54287	55938	57788	59723	5.34	5.57
5	79061	77903	78741	77086	72425	70396	76742	75129	4.88	5.48
6	18622	17486	17655	16349	16752	15600	17676	16478	5.29	5.76
7	29612	30868	28317	29492	26531	27670	28153	29343	5.50	5.47
8	44605	46320	43057	44922	40319	41801	42660	44348	5.09	5.22
9	64083	62853	63193	61492	58855	57068	62044	60471	4.51	5.00
10	81486	76990	80967	75754	75769	70327	79407	74357	3.98	4.77
11	20912	20028	19676	18794	19060	17946	19883	18923	4.74	5.53
12	34148	34182	32587	32730	30870	30878	32535	32597	5.04	5.08
13	51557	49420	50093	47770	46933	45072	49528	47421	4.77	4.63
14	70324	64550	68651	62792	64382	59454	67786	62265	4.52	4.16
15	80726	76826	77737	74992	73303	71421	77255	74413	4.83	3.69
16	21879	21929	20549	20944	19894	20025	20774	20966	4.87	4.54
17	35590	37101	33779	35522	32130	33746	33833	35456	5.12	4.73
18	51724	52098	50185	50274	47108	47991	49672	50121	4.73	4.11
19	67599	66395	66089	64379	62707	61898	65465	64224	3.83	3.51
20	76772	77698	74600	75465	72814	73205	74729	75456	2.65	2.98
21	23415	26387	22053	24917	21848	23916	22439	25073	3.80	4.96
22	37422	41988	35645	40176	34786	38677	35951	40280	3.74	4.12
23	52447	56301	50593	54305	48972	52770	50671	54459	3.43	3.25
24	67326	70497	67064	68081	64093	67285	66161	68621	2.71	2.44
25	83898	81347	83117	77846	79765	77839	82260	79011	2.67	2.56
26	23305	29541	22831	28003	22862	26677	22999	28074	1.15	5.11
27	38056	46040	37482	44073	36763	42880	37434	44331	1.73	3.60
28	56388	62054	57237	59722	54804	59189	56143	60322	2.20	2.53
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1363.6		1287.3		1206.4		1285.8			
K_2	0.999		1.042		0.998		1.013			
K_3	-0.699		-0.755		-0.642		-0.699			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 8 AASHTO: A-1-a USCS: GW-GM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	17092	15548	17484	16073	18379	16605	17652	16075	3.74	3.29
2	25930	28186	25807	28440	28503	30175	26747	28934	5.69	3.74
3	40673	43774	39847	43458	43271	46873	41264	44702	4.33	4.22
4	61009	61529	59794	60419	64177	65793	61660	62580	3.67	4.53
5	80909	77675	80000	75792	85377	82891	82095	78786	3.51	4.67
6	17959	16937	18603	17482	19357	18061	18640	17493	3.75	3.21
7	28252	30226	28527	30536	30677	32243	29152	31002	4.55	3.50
8	44154	45898	43975	45775	47129	48851	45086	46842	3.93	3.72
9	65656	62945	64637	62310	69062	66736	66452	63997	3.49	3.74
10	83337	77838	82967	76790	88699	82201	85001	78943	3.77	3.63
11	20506	19531	21244	19696	21773	20766	21174	19998	3.01	3.35
12	33239	33893	33586	34333	35322	35861	34049	34696	3.28	2.98
13	51052	49680	51014	49932	54390	52375	52152	50663	3.72	2.94
14	70902	65872	70643	66027	74316	68900	71954	66933	2.85	2.55
15	79909	79477	82091	79621	83616	82299	81872	80466	2.28	1.98
16	22154	21915	23026	22469	23147	23153	22776	22512	2.38	2.76
17	35673	37079	36222	37383	37309	39070	36401	37844	2.29	2.83
18	52640	53069	52996	53687	55723	55408	53786	54055	3.14	2.24
19	69968	68911	70759	69673	72076	71203	70934	69929	1.50	1.67
20	80213	81829	80331	82930	82768	83997	81104	82919	1.78	1.31
21	24792	25874	25432	26845	25225	27595	25150	26771	1.30	3.22
22	39291	42773	39700	43642	40704	44609	39898	43675	1.82	2.10
23	55020	59263	55367	59736	58643	60660	56343	59886	3.55	1.19
24	71900	75302	71622	76712	75206	76265	72909	76093	2.73	0.95
25	88957	87346	87433	91508	89678	87820	88689	88892	1.29	2.56
26	26101	29497	25307	30278	25356	30895	25588	30223	1.74	2.32
27	42872	48433	40625	48993	41506	49433	41668	48953	2.72	1.02
28	0	0	59526	67521	61806	67171	0	0	0	0
29	0	0	79209	84336	78007	80157	0	0	0	0
30	0	0	0	0	95589	91218	0	0	0	0
K_1	1308.0		1331.7		1407.7		1349.1			
K_2	1.006		0.960		1.016		0.994			
K_3	-0.631		-0.545		-0.691		-0.622			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 9

AASHTO: A-1-a

USCS: SP-SM

District: ______

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	96.3
3/4 in.	88.0
1/2 in.	74.8
3/8 in.	69.9
No. 4	56.1
No. 8	42.2
No. 10	39.8
No. 16	32.3
No. 40	20.6
No. 50	17.4
No. 200	10.5

Atterberg Limits	
LL	NP
PL	NP
PI	NP

Angularity	
FA Flow	43.0
CA Flow	45.6

Standard Proctor*	
γ_d, pcf	MC, %
128.9	3.6
135.7	5.0
139.4	6.6
136.3	8.4
γ_{dmax}, pcf	139.4
Opt. MC	6.7

* Rock Corrected

Mg Sulfate Soundness	
% Loss	0.8

Modified Proctor*	
γ_d, pcf	MC, %
137.6	3.0
145.3	4.7
142.5	6.6
140.3	7.4
γ_{dmax}, pcf	145.6
Opt. MC	5.0

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.727
Bulk	2.656
Bulk SSD	2.682
Water Abs.	1.00

Specific Gravity FA		
Type	Value	Combo
Apparent	2.707	2.716
Bulk	2.478	2.553
Bulk SSD	2.563	2.614
Water Abs.	3.41	
Combined Water Abs.	2.32	

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5003.7
+ #12 Mass after wash	3802.7
% Loss	24.0

Micro-Deval	
Property	Value
Grading	19 mm
Original Mass, g	1500.3
+ #12 Mass after wash	1256.7
% Loss	16.2

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	7.4	100.4	44
56	7.4	102.1	57
80	7.7	102.5	65

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	5.4	96.4	134
56	5.6	100.5	167
80	5.5	100.2	139

Smpl. No. 9 AASHTO: A-1-a USCS: SP-SM District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	85.0	83.2	85.1	88.9	91.6	87.7	87.7
3/8 in.	79.4	77.1	78.6	81.8	85.0	81.7	80.2
No. 4	63.8	60.7	62.8	67.3	71.4	67.4	63.9
No. 8	48.0	45.0	47.3	51.8	56.0	53.0	48.6
No. 16	36.7	33.7	35.5	39.0	42.4	40.1	37.0
No. 40	23.4	22.0	23.2	25.6	27.7	27.0	25.3
No. 50	19.8	18.9	20.0	22.0	23.7	23.4	22.1
No. 200	11.9	12.1	12.9	14.2	15.0	15.2	14.7

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 9 AASHTO: A-1-a USCS: SP-SM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	16373	14805	16745	15143	14442	12975	15853	14308	7.80	8.15
2	26057	27046	25883	27082	23850	25119	25263	26415	4.86	4.25
3	39314	42143	38770	41584	37320	40149	38468	41292	2.68	2.49
4	57503	59399	55706	57867	56476	57655	56562	58307	1.59	1.63
5	76022	74997	72823	72480	74648	73819	74498	73765	2.15	1.71
6	17229	16118	17471	16439	15236	14572	16645	15710	7.37	6.35
7	27606	28866	27768	28904	25665	27009	27013	28259	4.33	3.83
8	42548	44002	42193	43300	41058	42055	41933	43119	1.86	2.29
9	62023	60291	60803	58753	61165	58804	61330	59283	1.02	1.47
10	79924	74443	77211	72013	77881	73576	78339	73344	1.80	1.68
11	19593	18560	19925	18840	17306	16858	18941	18086	7.53	5.93
12	32312	32222	32521	32140	30211	30406	31681	31589	4.03	3.25
13	49197	47218	48701	46420	47739	45552	48546	46397	1.53	1.80
14	67847	62352	66435	60735	66081	61282	66788	61456	1.40	1.34
15	78509	74838	74870	72454	77422	74505	76934	73932	2.43	1.75
16	20895	20719	20990	20956	19118	18808	20334	20161	5.19	5.84
17	33605	35150	33654	34915	32805	33359	33355	34475	1.43	2.82
18	48805	50074	48603	49182	48523	48619	48644	49292	0.30	1.49
19	64816	64517	63950	62845	63968	63836	64245	63733	0.77	1.32
20	77379	76137	73715	73755	75754	76307	75616	75400	2.43	1.89
21	22388	24746	22235	24884	21488	23149	22037	24260	2.19	3.97
22	34461	40107	34280	39683	33587	38514	34109	39435	1.35	2.09
23	48532	54519	48121	53494	45658	53563	47437	53859	3.28	1.06
24	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1256.7		1274.8		1140.2		1223.9			
K_2	1.024		0.998		1.077		1.033			
K_3	-0.692		-0.664		-0.703		-0.686			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 9 AASHTO: A-1-a USCS: SP-SM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	19274	17622	18711	16790	18987	16102	18991	16838	1.48	4.52
2	29998	31347	28619	29760	27726	28578	28781	29895	3.98	4.65
3	44541	47844	42522	45406	40311	43720	42458	45657	4.98	4.54
4	64131	66271	60677	62889	58218	60778	61009	63313	4.87	4.38
5	83842	82615	79512	78532	79041	76186	80798	79111	3.28	4.11
6	20548	19087	19413	18208	19093	17500	19685	18265	3.88	4.35
7	32052	33267	30364	31747	29090	30617	30502	31877	4.87	4.17
8	48032	49625	45696	47327	43255	45875	45661	47609	5.23	3.97
9	69077	66813	65342	63898	64090	62315	66170	64342	3.92	3.55
10	86479	81396	83422	78148	84490	76650	84797	78731	1.83	3.08
11	23142	21784	21727	20835	20882	20106	21917	20908	5.21	4.03
12	37157	36762	35231	35224	33089	34228	35159	35405	5.79	3.61
13	55852	52704	53237	50718	51200	49756	53430	51059	4.36	2.94
14	74050	68270	72585	66161	72105	65480	72913	66637	1.39	2.18
15	82096	80842	81604	78829	81709	78673	81803	79448	0.32	1.52
16	23893	24220	22944	23147	21803	22497	22880	23288	4.57	3.74
17	38108	39765	36990	38260	35336	37478	36811	38501	3.79	3.02
18	55480	55328	53913	53697	53112	53169	54168	54065	2.22	2.08
19	70484	70007	69742	68529	70227	68633	70151	69056	0.54	1.19
20	81975	81697	78623	80372	80824	81359	80474	81142	2.12	0.85
21	25156	28474	24407	27437	23492	26767	24352	27559	3.42	3.12
22	40093	44867	39049	43596	38575	43112	39239	43859	1.98	2.07
23	56927	59677	54798	58592	56126	58797	55950	59022	1.92	0.98
24	74600	74372	69881	74022	72933	74969	72471	74454	3.30	0.64
25	90086	84333	85520	84653	87405	88280	87670	85755	2.62	2.56
26	25843	31648	24699	30675	23863	30154	24802	30826	4.01	2.46
27	42243	49351	40688	48115	39438	47996	40790	48487	3.45	1.55
28	64025	65460	61477	65180	60150	66821	61884	65821	3.18	1.33
29	83239	77266	0	0	77325	81468	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1488.8		1407.5		1340.9		1412.4			
K_2	0.983		0.972		0.968		0.974			
K_3	-0.704		-0.645		-0.586		-0.645			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 10 AASHTO: A-1-a USCS: SP-SM District: ____________

Gradation Data	
Sieve	% Passing
2 in.	100.0
1 1/2 in.	100.0
1 in.	100.0
3/4 in.	99.3
1/2 in.	84.0
3/8 in.	77.8
No. 4	61.5
No. 8	46.7
No. 10	34.8
No. 16	25.2
No. 40	17.9
No. 50	14.2
No. 200	10.3

Atterberg Limits	
LL	NP
PL	NP
PI	NP

Angularity	
FA Flow	42.8
CA Flow	47.9

Standard Proctor*	
γ_d, pcf	MC, %
132.3	4.7
141.3	6.5
134.7	9.3
γ_{dmax}, pcf	141.7
Opt. MC	7.0

* Rock Corrected

Mg Sulfate Soundness	
% Loss	1.0

Modified Proctor*	
γ_d, pcf	MC, %
135.5	2.2
144.2	4.9
141.4	7.1
138.5	7.6
γ_{dmax}, pcf	144.7
Opt. MC	5.6

*Rock Corrected

Specific Gravity CA	
Type	Value
Apparent	2.731
Bulk	2.662
Bulk SSD	2.687
Water Abs.	1.00

Specific Gravity FA		
Type	Value	Combo
Apparent	2.686	2.703
Bulk	2.483	2.549
Bulk SSD	2.558	2.606
Water Abs.	3.05	
Combined Water Abs.	2.23	

L. A. Abrasion	
Property	Value
Grading	B
Original Mass, g	5002.6
+ #12 Mass after wash	3885.1
% Loss	22.3

Micro-Deval	
Property	Value
Grading	19 mm
Original Mass, g	1501.6
+ #12 Mass after wash	1289.75
% Loss	14.1

CBR, Standard Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	6.9	95.2	40
56	7.1	99.4	59
80	7.2	99.2	76

CBR, Modified Proctor			
Blows/Lift	MC, %	%γ_{dmax}	CBR
25	5.1	97.0	105
56	5.6	99.5	141
80	5.5	100.2	139

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 10 AASHTO: A-1-a USCS: SP-SM District: 0

Original Gradation and Gradations after CBR Testing

Original Gradation		Standard Proctor			Modified Proctor		
Sieve	% Passing	25 Blows	56 Blows	80 Blows	25 Blows	56 Blows	80 Blows
2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 1/2 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	84.6	81.6	84.2	87.3	85.2	86.9	91.1
3/8 in.	78.3	73.7	76.8	80.0	77.7	79.8	85.1
No. 4	61.9	58.2	62.5	64.8	61.0	64.4	69.4
No. 8	47.0	42.9	47.7	49.0	44.9	49.5	53.2
No. 10	35.0	40.2	44.6	45.9	42.1	46.6	50.3
No. 16	25.4	31.6	35.6	36.2	32.9	37.6	40.8
No. 40	18.0	20.3	22.8	23.2	21.2	25.0	27.2
No. 50	14.3	17.5	19.6	19.9	18.4	21.7	23.7
No. 200	10.4	11.8	13.2	13.5	12.9	14.9	16.4

NOTE:
Original gradation reflects the +3/4 in. material scalped from the sample similar to the CBR samples. This allows a comparison of aggregate breakdown.

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 10 AASHTO: A-1-a USCS: SP-SM District: 0

Standard Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	14810	13320	15488	14409	14037	13419	14778	13716	4.91	4.39
2	20549	23828	24452	26480	21564	24356	22188	24888	9.13	5.64
3	31966	36943	39222	41519	35191	37966	35460	38809	10.25	6.19
4	51557	51564	58327	58756	53735	53658	54540	54659	6.34	6.77
5	70695	64970	75923	74486	71103	68135	72574	69197	4.01	7.00
6	15944	14858	16642	15716	15423	14667	16003	15080	3.82	3.71
7	23624	25971	27029	28401	24424	26298	25026	26890	7.11	4.90
8	37414	39242	42438	43441	38762	40196	39538	40960	6.58	5.37
9	57034	53800	62205	59962	57644	55715	58961	56492	4.79	5.58
10	74239	66754	78652	74356	75607	69505	76166	70205	2.97	5.48
11	18724	17108	19031	18080	18369	17023	18708	17404	1.77	3.38
12	29055	29495	31263	31793	29347	29854	29888	30381	4.01	4.07
13	44434	43417	47962	46963	45185	44356	45860	44912	4.05	4.09
14	62638	58074	66963	62476	63175	59702	64259	60084	3.67	3.70
15	73984	70794	76865	75386	75940	72905	75596	73028	1.95	3.15
16	20492	19277	20851	20403	20693	19216	20679	19632	0.87	3.40
17	31564	32687	33727	34833	32449	33012	32580	33510	3.34	3.45
18	45834	47205	49817	50077	47447	48147	47699	48476	4.20	3.02
19	62406	62177	66550	65081	63571	63565	64176	63608	3.33	2.28
20	72670	74905	75823	77315	74513	76682	74335	76301	2.13	1.64
21	22695	23291	23194	24474	23174	23273	23021	23679	1.23	2.91
22	32916	38344	36173	40072	33834	38678	34308	39031	4.89	2.35
23	46418	53502	50464	55109	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1118.4		1221.2		1116.4		1152.0			
K_2	0.953		1.031		0.999		0.994			
K_3	-0.467		-0.667		-0.533		-0.556			

Work Assignment No. BCD-MT 2010-02

State Study No. 238, "Evaluation of Crushed Concrete Base Strength"

Smpl. No. 10 AASHTO: A-1-a USCS: SP-SM District: 0

Modified Effort Resilient Modulus Results by Sequence

	Resilient Modulus									
	REP 1		REP 2		REP 3		Average		CV	
Sequence	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r	M_r	Pred M_r
1	17497	15463	18704	16650	18172	16395	18124	16170	3.34	3.86
2	27204	27894	28759	29886	27923	29444	27962	29075	2.78	3.60
3	40821	43137	42981	45911	42066	45351	41956	44800	2.58	3.27
4	58697	60383	61811	63773	61451	63259	60653	62472	2.81	2.92
5	78252	76014	80712	79646	80983	79374	79982	78344	1.88	2.58
6	18108	16821	19277	18038	19074	17809	18820	17556	3.32	3.69
7	28502	29851	30558	31737	29864	31440	29641	31009	3.53	3.27
8	43050	44754	45671	47442	45498	47275	44740	46490	3.28	3.24
9	62539	61569	65709	63984	66170	64238	64806	63263	3.05	2.33
10	80741	75866	82812	77962	84524	78856	82692	77562	2.29	1.98
11	19979	19347	21430	20588	21347	20348	20919	20094	3.90	3.28
12	32439	33294	34786	34921	34591	34934	33939	34383	3.84	2.74
13	49390	48588	52594	50105	52905	50670	51630	49788	3.77	2.16
14	68699	64062	70818	64904	72750	66426	70756	65131	2.86	1.84
15	81492	76865	78774	76709	82082	79374	80783	77649	2.18	1.93
16	21311	21585	22504	22883	22876	22819	22230	22429	3.68	3.26
17	34560	36370	36339	37687	36820	38033	35906	37363	3.32	2.35
18	50977	51695	53048	52408	54289	53652	52771	52585	3.17	1.88
19	68197	66579	67252	66131	69655	68724	68368	67145	1.77	2.06
20	78631	78699	75794	76734	78680	80803	77702	78745	2.13	2.58
21	23175	25409	23724	26875	24327	27040	23742	26441	2.43	3.39
22	37097	41609	37920	42274	38741	43348	37919	42410	2.17	2.07
23	52998	56479	53318	56035	54581	58410	53632	56975	1.56	2.22
24	69727	71568	68773	69040	70389	74096	69630	71568	1.17	3.53
25	86079	83531	83819	78619	85988	85277	85295	82476	1.50	4.19
26	24280	28676	23599	29942	24208	30059	24029	29559	1.56	2.59
27	40283	46073	38628	45808	39621	47723	39511	46535	2.11	2.23
28	59829	62054	58517	61396	59861	65678	59402	63043	1.29	3.66
29	79666	77211	0	0	76028	78674	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0
K_1	1302.1		1416.9		1382.3		1367.1			
K_2	1.000		1.002		0.995		0.999			
K_3	-0.648		-0.748		-0.668		-0.688			