EVALUATION OF RECYCLED ASPHALT SHINGLES FOR BENEFICIAL REUSE IN ROADWAY CONSTRUCTION

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1.0 Introduction

Approximately 11 million tons of reclaimed asphalt shingles (RAS) are disposed in landfills every year (Shingle Recycling Organization, 2005). Re-roofing jobs account for 10 million tons (referred as “tear-offs”), with another 1 million from manufacturing scrap. Previous research has demonstrated that these materials can be recycled into a variety of products. Currently, RAS is used primarily as an additive to hot-mix asphalt, however; this application constitutes a small percentage of the total disposed shingles. A widespread, large-scale recycling and reuse operation would utilize the remainder of an otherwise wasted resource while clearing landfill space and creating potential business opportunities.

Three potential reuse applications are the utilization of RAS in the aggregate base (AB) and subbase (ASB) layers of roadway pavements, as working platforms for pavement construction over soft subgrades, and as an embankment fill. RAS has the potential to act as an additive or substitute for the earth materials typically utilized in these applications. Recycled materials such as reclaimed pavement material, reclaimed asphalt pavement, glass, and fiberglass are already used in roadway pavement structures. The addition of RAS to this selection would offer opportunities for additional diversion of waste materials that would otherwise be placed in landfills.

The biggest impediment to the successful reuse of RAS in roadway applications is the lack of knowledge regarding recycling and re-processing protocol. There is, however; ample information regarding the regional availability of RAS for recycling applications. In a 2003 study characterizing the statewide distribution of municipal solid waste in Wisconsin, the Cascadia Consulting Group estimated that 285,000 tons of asphalt roof shingles were disposed annually in Wisconsin landfills.

Disposed shingles comprise 6% of the total municipal solid waste. As such, shingles constitute the third largest item by weight found in the waste characterization study. The 2003 figure does not include the shingles disposed in construction and demolition waste landfills. The Cascadia Group estimated that construction and demolition debris (~ 30% of materials landfilled) exist in sufficient quantity to offer significant opportunities for additional diversion and recycling of shingle waste.

As with any recycling activity, the proper regulatory and permitting requirements for the reuse of RAS must be addressed. The purpose of this study was to determine the technical specifications of RAS, the effect of fly ash stabilization on RAS strength, and the practicality of the widespread implementation of RAS in roadway applications. RAS, fly ash stabilized RAS (S-RAS), RAS-aggregate mixtures, and RAS-silt mixtures were evaluated for particle size characteristics, compaction characteristics, California Bearing Ratio (CBR), unconfined compressive strength, and resilient modulus.

2.0 Current Beneficial Reuse Practices

Currently, RAS is utilized primarily as an additive in hot-mix asphalt (HMA). Several state departments of transportation, including the Minnesota Department of Transportation (MNDOT), have implemented guidelines for the beneficial reuse of RAS in HMA. The guidelines put in place by MNDOT were developed through an extensive study conducted by the department. MNDOT initiated original research and development programs for the recycling and reuse of waste shingles as early as 1990. These investigations were supported by the Recycled Materials Resource Center (RMRC).

The projects focused on field-testing, market development and technology transfer of RAS as an additive in HMA. The projects also addressed the potential applications of RAS as a dust control supplement, and as an unbound aggregate supplement in base course construction, however; the primary objective was to develop guidelines for the addition of RAS into HMA. The research initiative concluded that HMA produced with 5% RAS maintained the bituminous engineering pavement properties essential to quality performance (Crivit, 2005).

Although MNDOT was successful in developing guidelines for the reuse of RAS in HMA, there was still a need for continued research and development in the applications of RAS as a dust control supplement, and additive to virgin aggregates in roadway construction. MNDOT began preliminary research for the development of secondary RAS applications (Crivit, 2005).

In the preliminary analysis, MNDOT identified several barriers to the successful implementation of the wide-spread reuse of RAS in roadway construction applications (dust inhibitor, and additive to virgin aggregates). First, there is a general lack of specifications and end-use demand for RAS in roadway applications. Second, the supply of RAS is limited. RAS is currently being reused as a 5% additive in HMA and there is sufficient source material for this application, however; an additional reuse initiative would heighten the demand for RAS and may deplete the current supply. Third, there is a lack of communication and outreach in regards to the technical, economic, and environmental benefits of shingle-derived products (Crivit, 2005).

In order to address the aforementioned challenges, MNDOT oversaw several independent research projects designed to assess the technical, environmental, and economical feasibility of RAS in roadway construction. In November, 2001, MNDOT oversaw a demonstration by Bituminous Roadways Inc., and SKB Environmental on the utilization of RAS cold-blended with virgin aggregates as a dust control measure. The RAS was blended at a 50:50 volume-to-volume ratio and compacted to specified density. Researchers working on a similar project for the Iowa DOT found that RAS tended to bind the aggregate and minimized dust in a construction environment (Marks and Petermier, 1997).

Additionally, the MNDOT in conjunction with RMRC, oversaw field tests of RAS blended with a traditional unbound aggregate for use as base course. The purpose of the study was to observe and quantify the performance of a Class 7 – BC (as defined by MNDOT specifications) aggregate containing a maximum of 10% RAS by volume. The project is underway, but has not yet been completed. At this time, only qualitative observations have been made in regards to RAS performance as an aggregate additive (Crivit, 2005).

3.0 Previous Studies

Other state DOTs have undertaken projects similar to those initiated by MNDOT, and many of these studies have indicated that RAS has a beneficial effect on some soils, but again; these observations were largely qualitative. Hooper and Marr (2004) cited the lack of quantitative evidence and sought to provide baseline quantitative data regarding the performance of RAS and RAS composite mixtures as base course. Hooper and Marr performed sieve analyses, Atterberg limits, modified Proctor compaction tests, and CBR tests on 25-mm minus RAS mixed with increasing amounts (0, 33, 50, 67 and 100% by volume) of crushed stone gravel. They also tested 25-mm minus RAS blended (33% by volume) with either a silty sand, a clean sand, or clay. The RAS used in this study was developed exclusively from pre-consumer, off-specification shingles obtained directly from shingle manufacturers. Although the RAS in this study was composed entirely of manufacturer scrap shingles, the authors expected the results to apply equally well to post-consumer, tear-off shingles provided wood, nails, plastic, and other residue material are removed prior to processing.

Hooper and Marr (2004) found that the CBR of the crushed stone gravel was 92% prior to RAS addition. CBR of 25-mm minus RAS was 6%. The addition of RAS at the specified intervals resulted in a diminishment in CBR of the crushed stone gravel. Hooper and Marr found that CBR of the silty sand was 33%, CBR of the clean sand was 21%, and CBR of clay was 8% prior to RAS addition. The addition of RAS resulted in a decrease in CBR for the silty sand and clean sand, but resulted in an increase in CBR for clay. A summary of the CBR results from Hooper and Marr's study of RAS, RAS-aggregate, and RAS-soil blends is presented in Table 1.

Hooper and Marr concluded that the addition of RAS to inherently strong materials such as crushed gravel and sand resulted in a decrease in CBR strength. The addition of RAS to inherently weak, plastic materials such as clay resulted in an increase in CBR strength. The authors suspected that where the highly angular particles of gravel and sand contributed to increased interparticle friction, the addition of RAS disrupts this phenomenon and thereby decreases material strength. Even so, the CBR results suggested that RAS-stone gravel blends can be used as a structural fill material and also potentially provide subbase support for pavements and light structures. The authors also suggested that when RAS is added to clay, the cohesion of the clay particles holds the RAS particles in place such that they do not "slip" as easily during CBR testing. Additionally, the introduction of RAS increases the amount of granular material in the clay and thereby increases shear strength during CBR loading.

Hooper and Marr did not investigate the influence of particle size on RAS stiffness. Also, the authors did not investigate the effect of cementing agents such as asphalt emulsion and self-cementing fly ash on RAS stiffness. Finally, they did not investigate RAS resilient modulus, a parameter essential for the empirical-mechanistic design of roadway pavement systems, or unconfined compressive strength. Additional research is needed to assess RAS performance in resilient modulus and unconfined compressive strength tests, the effect of particle size on RAS stiffness, and the effect of stabilizing agents as a means to improve RAS performance.

4.0 Materials

4.1 Reclaimed Asphalt Shingles

Asphalt roofing shingles consist of a thin cellulose or fiberglass foundation saturated with asphalt (19 to 36% by weight). The cellulose i.e. organic felt backing was used exclusively for many years until concerns over asbestos prompted the development of fiberglass backings. Ceramic-coated natural sand-size rock (20 to 38% by weight) and a mineral filler/stabilizer (8 to 40% by weight consisting of limestone, silica, dolomite, etc.) are added to the asphalt layer (Shingle Recycling Organization, 2005). Ninety percent of the mineral filler is smaller than 0.15-mm, and 70 % is smaller than 0.08 mm.

Waste shingles are classified either as manufacture scrap or tear-offs from demolitions or re-roofing projects. Roofing shingles are typically replaced every 10 to 30 years. Thus, the shingles taken from a housing demolition or re-roofing job can be anywhere from ten to thirty years in age, or older depending on the situation. As a result, most "tear-offs" are derived from shingles constructed with a cellulose felt backing. However, as more and more roofs are constructed with fiberglass materials, the presence of the cellulose backing in "tear-offs" will diminish. Scrap shingles taken from fabricated housing plants, construction companies, and shingle manufacturers are generally less than one year in age, and composed primarily of shingles constructed with a fiberglass backing (Crivit, 2005). Hooper and Marr (2004) suggested that tear-off derived RAS should exhibit similar performance to manufacturer scrap derived RAS provided all wood, nails, plastic and other residue materials are removed.

The Wisconsin Department of Natural Resources requires that shingles selected for recycling be free of asbestos (limited to 1%), wood, nails, plastic, styrofoam and other excess materials. These materials are removed by hand and discarded. The shingles are then ground, screened and graded to produce RAS. Recycling facilities utilize varying combinations of these steps to produce different gradations of RAS. RAS gradations typically are classified according to the maximum particle size present in the mix. Thus, a 19-mm minus RAS gradation contains particles 19-mm in diameter and smaller.

RAS samples utilized in this study were obtained from the Stratford Building Supply Co. (Stratford, WI) and the Bruce Landscaping Co. (Verona, WI). The Stratford Building Supply grinds waste shingles once over and then screens at three size intervals: 51-mm minus, 25-mm minus, and 19-mm minus. The Bruce Landscaping Co. uses a slightly different procedure. The waste shingles are ground once and then screened at 51-mm minus. They are then re-ground. Afterwards, the shingles are graded a second time using a finer screen to produce a final gradation of 10-mm minus. A 5-mm minus gradation was obtained by screening the 25-mm minus gradation through a 5-mm sieve.

The RAS obtained from the Stratford Building Supply Co. included tear-offs from construction jobs undertaken by the company, and manufacturer scrap from the nearby Wausau Housing Co. Based on visual inspection, the Stratford Building Supply Co. mixes contained mostly manufacturer scrap shingles, however; the exact ratio of tear-off to scrap material was unknown. The RAS obtained from the Bruce Co. included tear-offs from demolition and construction jobs undertaken by the company, as well as manufacturer scrap obtained from housing fabricators in the Madison area. Based on visual inspection, the Bruce Co. mix contained mostly tear-offs, however; the exact ratio of tear-off to scrap material was unknown.

4.2 Soil and Aggregate

The objective of this study was to qualify the functionality of RAS as an additive to or replacement for soils and aggregates typically used in aggregate base course (AB), subbase course (ASB), and working platform or embankment fill applications. Wisconsin Department of Transportation (WisDOT) Grade 2 granular backfill was selected as a representative base course aggregate and Boardman silt was selected as a representative embankment fill soil. The Grade 2 granular backfill and Boardman silt were used to create composite RAS-aggregate and RAS-soil blends. Additionally, these materials were tested without RAS for the purpose of comparison with pure RAS gradations.

Grade 2 granular backfill classifies as poorly graded gravel with some silt and sand (GP-GM) by the Unified Soil Classification System (USCS), and is recognized as a medium-sized aggregate by WisDOT specifications. Grade 2 granular backfill is most commonly used as base course in road construction. Boardman silt is a naturally occurring soil from the Columbia River region near Boardman, OR. Boardman silt is classified as sandy silt with a liquid limit of 22, plasticity index of 1 and a specific gravity of solids of 2.73. Boardman silt was chosen for this study because it represents a possible fine-grained fill material and was readily available for use at the University of Wisconsin-Madison Geotechnical Laboratory.

4.3 Fly Ash

Fly ash is a byproduct released during coal combustion and is composed of the inorganic, incombustible material present in coal. This material is fused into a glassy, amorphous structure during combustion and is suspended in the exhaust gases. Fly ash solidifies out of the exhaust and is collected by electrostatic precipitators or filter bags. Because the material solidifies while suspended in gas, fly ash particles are generally spherical in shape and range in size from 0.5 μm to 100 μm. Fly ash can react with water, calcium hydroxide, and alkali to form cementitious compounds and is often used as a high-performance filler in many concrete mixes. In recent years, fly ash has also been used as a stabilizing additive to road bases, structural fills, embankments, and soil foundations.

Fly ashes are classified as class C, class F, or non-specification according to the presence or absence of several different compounds as specified in ASTM C 618. A class C fly ash from the Columbia Power Plant near Portage, WI was selected for this study. The fly ash was used to create fly-ash stabilized RAS composite mixtures (S-RAS). The compositional properties of Columbia fly ash, Class C fly ash, and Class F fly ash are summarized in Table 2 (after Edil et al., 2006).

5.0 Results and Analysis

5.1 Pure RAS, RAS-Grade 2, and RAS-Silt Blends

5.1.1 Particle Size Analysis

The particle size characteristics of five RAS gradations (51-mm minus, 25-mm minus, 19-mm minus, 10-mm minus, and 5-mm minus) were evaluated in general accordance with ASTM D 422. Particle size curves for the five RAS gradations are plotted in Figure 1. The results of the particle size analysis are summarized in Table 3.

Each specimen was classified in general accordance with the Unified Soil Classification System (USCS) system outlined in ASTM D 2487, however; these classifications are idealized in every sense. The USCS system idealizes soil particles as spheres and classifies them according to diameter. RAS particles are not necessarily spherical in shape. Depending on the way the RAS gradations are prepared, the individual RAS particles may be spherical, or they may be flat and plate-like. Based on visual observation of the RAS gradations received from the Bruce Co. and the Stratford Building Supply Co., the majority of RAS particles are significantly longer than they are thick i.e. length to thickness aspect ratios of 25 to 50. As the RAS particles become smaller, this aspect ratio generally decreases. Additionally, RAS particles generally become more equidimensional when ground to sizes smaller than 1 mm. At sizes less than 1 mm, the shingle has been mostly separated into its constituent parts. These constituents i.e. sand and mineral particles, asphalt globules, etc., are more equidimensional in nature. The organic or fiberglass foundation is the constituent material contributing most significantly to the plate-like nature of larger RAS particles.

Based on the observations cited above, the USCS system may not be best suited to classify RAS gradations. However, a better means of classifying RAS mixes does not exist at this time. The development of a specialized RAS particle classification system would benefit future study. Parameters of interest might include length to thickness aspect ratio, maximum particle size, percentage of plate-like particles vs. spherical particles, etc. Additionally, the RAS gradations could be characterized according to the relative percentages of tear-off and scrap material present in the mix, as well as other qualifying indicators such as asphalt and sand content.

5.1.2 Standard Proctor Compaction

The compaction characteristics of five RAS gradations (51-mm minus, 25-mm minus, 19-mm minus, 10-mm minus, and 5-mm minus) were evaluated in general accordance with ASTM D 698 (standard Proctor effort). The compaction curves for the five RAS gradations are shown in Figure 2. The maximum dry unit weight and optimum water content for each specimen are summarized Table 4. The maximum dry unit weight and optimum moisture content of Grade 2 granular backfill and Boardman silt are included in Table 4 for reference.

The maximum dry unit weight of the five RAS gradations ranged from approximately 9 to 12.5 kN/m^3 (57 to 80 lb/ft^3). The optimum moisture content ranged from approximately 7 to 14 percent. The highest maximum dry unit weights were observed in the RAS gradations with the smallest maximum particle size (10-mm minus and 5-mm minus).

Compaction is a function of soil gradation (Holtz and Kovacs, 1981) in granular soils. In most situations, maximum dry unit weight increases with decreasing particle size uniformity. The differences in uniformity (C_u) between the five RAS gradations were minimal.

Compaction is also related to angularity and surface roughness of the individual particles. More angular particles and particles with rougher surfaces are typically more difficult to “pack” in a dense configuration as compared to more rounded, smoother particles. Based on visual observation of the five RAS gradations, particles larger than 10-mm are generally more plate-like, angular around the edges, and covered with rougher, sand-blasted surfaces. RAS particles smaller than 10-mm are generally more rounded, have smoother surfaces, and are more equidimensional. Thus, the differences in compactive behavior between the five RAS gradations appear to be more closely related to differences in particle shape (angular vs. rounded) and surface roughness (smooth vs. rough surfaces) as compared to particle size uniformity.

5.1.3 California Bearing Ratio

The penetrative resistance of five pure RAS gradations (51-mm minus, 25-mm minus, 19-mm minus, 10-mm minus, and 5-mm minus), compacted to 95% of standard maximum dry unit weight, was measured using the California Bearing Ratio (CBR) test in general accordance with AST D 1888. In addition, the 25-mm minus RAS gradation was blended with WisDOT Grade 2 granular backfill, and the 5-mm minus RAS gradation was blended with Boardman silt at a 50:50 mass-to-mass ratio, compacted to 95% of standard maximum dry unit weight, and tested for CBR. Pure samples of Grade 2 granular backfill and Boardman silt were also tested for CBR as a comparative reference. The results of these tests are summarized in Table 5. Suggested CBR for soils used in pavement structures are summarized in Table 6.

The CBR of pure RAS is comparable to that of a poor subgrade according to the guidelines outlined in Table 6. This indicates that pure RAS is susceptible to penetration and possible particle crushing under locally intense pressures. The 25-mm minus RAS-Grade 2 and the 5-mm minus RAS-silt blends exhibited slightly improved CBR compared to pure RAS. However, the CBR of 50:50 RAS-Grade 2 and RAS-Silt blends decreased significantly compared to the CBR of pure Grade 2 gravel and Boardman silt.

Although CBR is an indicator of the localized material strength, it is not a comprehensive measure of total material stiffness. CBR is best utilized as a supplement to resilient modulus and other material index properties. The results of CBR testing for RAS, RAS-Grade 2 granular backfill, and RAS-Boardman silt mixtures indicate that pure RAS and 50:50 RAS-Grade 2 and RAS-Silt blends are potentially susceptible to penetration and particle crushing under locally intense pressures.

5.1.4 Resilient Modulus

Resilient modulus tests were conducted on pure RAS samples to determine the particle size, gradation, and compaction characteristics necessary to maximize resilient modulus. Particle size analyses, compaction tests, and CBR tests established a distinct hierarchy of performance among the 5 RAS gradations selected for the study. To prevent redundancy and to streamline the testing process, the RAS gradations with the poorest performance in the aforementioned testing sequence were not tested for resilient modulus. The RAS gradations selected for resilient modulus testing were: 25-mm minus, 10-mm minus, and 5-mm minus. The 51-mm minus RAS gradation and the 25-mm minus RAS gradation exhibited nearly identical particle size, compaction and CBR characteristics. Therefore, resilient modulus tests were run solely on the 25-mm minus gradation to minimize the need for additional samples. The 19-mm minus RAS gradation exhibited the lowest fines percentage, lowest maximum dry unit weight, and lowest CBR of the five RAS gradations and was therefore not tested for resilient modulus.

The selected RAS gradations were compacted to 95% standard dry unit weight and tested for resilient modulus in general accordance with the NCHRP 1-28 A protocol for cohesive subgrades. RAS was generally classified as a coarse, granular material, and has been proposed as a supplement and/or replacement for granular fills used in base and subbase applicatons. Thus, according to NCHRP standards, RAS should then be tested using the 1-28 A protocol for base-subbase. However, the CBR test results indicated that the penetrative resistance of pure RAS was significantly less than typical granular backfill materials, and generally closer to the penetrative resistance of soft subgrade soil. As a result, the bulk stresses utilized in the NCHRP 1-28 A base-subbase protocol could potentially strain pure RAS specimens beyond the allowable limit. (The NCHRP 1-28 A procedure requires that no more than 5% total strain occur during resilient modulus testing.)

A preliminary resilient modulus test was conducted on a 10-mm minus RAS specimen using the base-subbase protocol to determine if more than 5% total strain could occur using the base-subbase protocol. The test specimen experienced 9% total strain during the resilient modulus test, which is in excess of the limit allowed by the NCHRP. Thus, pure RAS was tested for resilient modulus using the cohesive protocol rather than the NCHRP base-subbase protocol because the bulk stresses used in the base-subbase protocol strained the preliminary RAS specimen beyond the limits allowed by the NCHRP.

In addition to the pure RAS gradations, the 25-mm minus RAS gradation was blended with WisDOT Grade 2 granular backfill at a 50:50 mass-to-mass ratio, compacted to 95% of standard dry unit weight, and tested for resilient modulus according to the NCHRP 1-28 A protocol for cohesive subgrades. Pure specimens of Grade 2 granular backfill were also tested for resilient modulus according to the NCHRP 1-28 A protocol for cohesive subgrades. Although both pure Grade 2 granular backfill and the 50:50 RAS-Grade 2 blend were considered granular materials, they were tested using the cohesive protocol for the purposes of back comparison to pure RAS gradations.

The cohesive protocol consisted of 16 loading sequences. Each sequence featured a different combination of confining pressure and deviator stress. Deviator stress is equivalent to axial stress plus contact stress and is used to calculate octahedral shear stress. The deviator stress loads deforms the specimen axially whereas confining pressure provides lateral support and restrains axial compression. Resilient modulus varies with both confining pressure and deviator stress. Therefore, both the effect of confining pressure and deviator shear stress must be accounted for when determining resilient modulus.

Resilient modulus versus bulk stress for the three RAS gradations tested (25-mm minus, 10-mm minus, and 5-mm minus) is shown in Figure 3. Resilient modulus versus octahedral shear stress for the three RAS gradations tested is shown in Figure 4. Three specimens were tested for each gradation shown. Resilient modulus for a single gradation is reported as the average resilient modulus of the three specimens tested for that gradation.

Resilient modulus of pure RAS generally increased with increasing bulk stress and decreased with increasing octahedral shear stress. For the range of bulk stresses studied, the 10-mm minus RAS gradation exhibited the highest resilient modulus of the three RAS gradations. The 25-mm minus RAS gradation exhibited the lowest resilient modulus of the three RAS gradations.

Andrei et al. (2004) suggested that a deviator stress of 41 kPa, and a confining pressure of 14 kPa exemplify the typical stress state experienced by cohesive subgrades in flexible pavement systems. Additionally, the NCHRP 1-28 A protocol suggested that a deviator stress of 103 kPa, and a confining pressure of 35 kPa exemplify the typical stress state experienced by aggregate base course in flexible pavement systems. Resilient modulus for each of the three pure RAS gradations, the 50:50 RAS-Grade 2 blend, and the pure Grade 2 gradation was calculated for the stress states recommended by Andrei et al. and the NCHRP using the NCHRP 1-28 A revised power model (Eq. 1), which is defined as

The NCHRP 1-28A power model for resilient modulus is defined as

$$\boldsymbol{M_R = k_1 \rho_a \left(\frac{\theta - 3k_6}{\rho_a}\right)^{k_2} \left(\left(\frac{\tau_{oct}}{\rho_a}\right) + k_7\right)^{k_3}} \qquad \text{(Eq. 1)}$$

where M_r is resilient modulus, k_1, k_2, k_3, k_6, and k_7 are empirical constants, p_a is the atmospheric pressure, τ_{oct} is the octahedral shear stress, and θ is the bulk stress. The NCHRP 1-28A model effectively combines the influence of bulk stress and shear stress into a single equation. The results are summarized in Table 7.

NCHRP project 1-37 A recommends 75 MPa as a minimum resilient modulus for functional base course material. Pure RAS gradations did not meet this requirement, however; pure RAS may be suitable as a filter layer between fine-grained subgrades and granular bases or subbases. Pure RAS may also be suitable for use as a general fill or possibly as a high permeability drainage layer. The low penetrative resistance of pure RAS could potentially limit the use of RAS as a working platform application over soft subgrades. Further testing of RAS for shear strength and compressibility would be necessary to determine its feasibility as general fill material.

Pure RAS exhibited resilient modulus values significantly lower than WisDOT Grade 2 granular backfill; an aggregate commonly used in base course construction. One-to-one mixes of 25-mm minus RAS and Grade 2 granular backfill exhibited resilient modulus values on the lower end of the range specified by the NCHRP. Mixes of RAS and Grade 2 granular backfill composed of at least 50% gravel by mass may be suitable for use in base course, however; mixing Grade 2 granular backfill with RAS reduces resilient modulus proportionally.

5.2 Fly Ash Stabilized RAS (S-RAS)

5.2.1 Standard Proctor Compaction

A primary objective of this study was to determine whether pure (unstabilized) RAS was suitable as a replacement for virgin aggregates in base course construction. As evidenced by CBR and resilient modulus tests, pure RAS is unsuitable as base course material. Recent studies have shown that fly ash, a byproduct of coal combustion, can be used as a stabilizer for soft subgrades, weak subbase and base course aggregates, and embankment fills (Senol et al, 2002). Two RAS gradations (25-mm minus and 10-mm minus) were stabilized with class C fly ash (20% by dry mass of RAS) from Columbia Power Plant near Portage, WI and tested for compaction, CBR, resilient modulus, and unconfined compressive strength. The 25-mm minus and 10-mm minus RAS gradations were selected for testing because these gradations generally represented the upper and lower performance bounds observed in pure RAS gradations.

The compaction characteristics of fly ash stabilized RAS (S-RAS) were measured using the standard Proctor compaction method in general accordance with ASTM D 698. The standard Proctor compaction curves for S-RAS are presented in Figure 5. The results of the compaction testing are summarized in Table 8. In general, the addition of fly ash resulted in an approximately 10 to 14% increase in maximum dry unit weight.

5.2.2 California Bearing Ratio

The California Bearing Ratio (CBR) of S-RAS, compacted to 95% of the standard Proctor maximum dry unit weight and cured for 7 days in a 100% humidity room, was evaluated in general accordance with ASTM D 1888. The CBR test results are summarized in Table 9. Fly ash stabilization of pure RAS generally resulted in a two-fold increase in CBR. However, S-RAS is still considered unsuitable as subbase or base course material on the basis of CBR parameters outlined in Table 6.

As mentioned previously, CBR is an index property and is not necessarily indicative of the total stiffness of S-RAS. Further evaluation of resilient modulus and unconfined compressive strength are needed to fully to determine whether S-RAS is capable of supporting overburden and live traffic loads when protected by a surface pavement.

5.2.3 Resilient Modulus

S-RAS specimens (25-mm minus and 10-mm minus stabilized with Class C fly ash at a 20% dry weight ratio) tested for resilient modulus according to the NCHRP 1-28 A protocol for cohesive subgrades. Prior to testing, S-RAS specimens were compacted to a minimum of 95% of the standard Proctor maximum dry unit weight and cured in a 100% humidity room. Three specimens were prepared for each gradation and cured for a period of 7 days. An additional set of three specimens was prepared for the 10-mm minus gradation and cured for a period of 28 days to evaluate the effect of curing length on S-RAS resilient modulus.

Resilient modulus versus bulk stress for S-RAS and pure (unstablized) RAS are shown in Figure 6. Resilient modulus versus octahedral shear stress for S-RAS and pure RAS are shown in Figure 7. Resilient modulus for a single gradation was calculated as the average of the three specimens tested.

Resilient modulus of S-RAS and RAS were calculated for the stress state recommended by Andrei et al. for cohesive subgrades, and for the stress state recommended by the NCHRP for base and subbase course using the NCHRP 1-28 A revised power model (Eq. 1). The results are summarized in Table 9. In general, S-RAS specimens exhibited higher resilient modulus values compared to pure RAS specimens, however; the resilient modulus values of S-RAS were not sufficient to warrant the use of S-RAS in base course construction.

5.2.4 Unconfined Compressive Strength

S-RAS specimens were tested for unconfined compressive strength in general accordance with ASTM D 2166 after completion of resilient modulus testing. S-RAS specimens were compressed at a rate of 0.21% strain per minute until peak compressive strength was achieved.

The results of unconfined compressive strength testing are summarized in Table 10. Pure RAS specimens were generally classified as granular materials and were therefore assumed to have an unconfined compressive strength of zero.

Senol et al. (2002) performed unconfined compressive tests on fly ash-stabilized specimens of low-plasticity clay. The CBR of the unstabilized clay was similar to pure RAS (~1-2) gradations. Additionally, the clay was stabilized with Columbia Class C fly ash and cured for 7 days in the same manner as this study. Thus, the study by Senol et al. provides a reasonable comparison of unconfined compressive strength of S-RAS and a fly ash-stabilized soft subgrade.

Senol et al. observed that unconfined compressive strength of fly ash-stabilized clay specimens (20% fly ash by mass) increased by approximately 700 to 1100 kPa over unstabilized specimens. The quantity of improvement observed by Senol et al. is significantly greater than the improvement observed for S-RAS specimens in this study.

RAS does not appear to benefit nearly as much from fly ash stabilization as the soft clays studied by Senol et al. There are several potential explanations for this phenomenon. First, RAS contains significant quantities of asphalt, a highly organic material. In general, fly ash is able to bind more effectively when mixed with inorganic soils such as silts, clays, and sands. The organic materials present in RAS (asphalt, felt backing, etc.) may contribute to diminished pozzolanic activity as compared natural soil materials. Second, the specific gravity and optimum compaction characteristics of RAS are such that the compacted void ratio of RAS is much higher than that of a clay compacted at optimum water content and maximum dry unit weight. As the void ratio increases, the individual particles become less interconnected. The possibility exists that when RAS is mixed with fly ash, the fly ash adheres to and coats the individual particle surfaces, but is unable to adequately bond the RAS particles together because of the decreased interconnectedness between the individual RAS particles.

6.0 Conclusions

For the purposes of this study, the behavior of RAS was assumed to similar to that of a soil or aggregate. However, RAS is not a soil or aggregate, therefore; the assumptions built into the tests used in this study may not necessarily be applicable to RAS. For instance, the basic assumptions built in to the USCS classification system do not fit well with the particulate nature of RAS. In the future, RAS should be classified according to more appropriate parameters such as average particle aspect ratio, asphalt content, relative percentages of plate-like particles, mass ratio of fiberglass to cellulose, etc.

The particle size characteristics of RAS are dependent on the procedure used to manufacture RAS at a recycling facility. Different recycling facilities will undoubtedly use different processing techniques. Additionally, different facilities will produce RAS with varying quantities of tear-off and manufacturer scrap shingles. As such, the particle size and compositional characteristics of RAS are unique to the facility at which it is produced. In the future, it may be beneficial to standardize RAS production and classification procedures.

Large RAS particles are a combination of a cellulose or fiberglass backing, asphalt coating, imbedded sand grains, and mineral filler. Large RAS particles are typically angular in shape, flat, and generally plate-like. In smaller RAS particles, the individual constituents of the shingle tend to be broken down and separated out and the particles tend to become smoother, more rounded, and generally more equidimensional. As a result, RAS gradations composed primarily of particles less than 10 mm tend to pack better than RAS gradations composed primarily of particles larger than 10 mm. As a result, RAS gradations that are composed primarily of smaller particles (<10 mm) generally compact at a higher dry unit weight compared to RAS gradations composed of larger particles (>10 mm). RAS is not very sensitive to compaction moisture, which is a positive quality.

The localized penetrative resistance, or CBR, of RAS is minimal for all gradations studied. Penetrative resistance of RAS improves slightly with increasing dry unit weight, however; the improvement is not sufficient to prevent localized penetrative failure of compacted RAS. Due to low CBR, RAS is not suitable as a working platform for construction over soft subgrades.

According to resilient modulus test results, pure (unstabilized) RAS is considered unsuitable for use base course material although it could potentially be used as a filter layer between fine-grained subgrades and granular base, i.e., as a subbase course.. Additionally, RAS-Grade 2 granular backfill mixtures (minimum 50:50 mass-to-mass ratio) are suitable for use as subbase and are potentially suitable for use as base course in an unstabilized state (resilient modulus ~ 77 MPa). However, the resilient modulus of Grade 2 granular backfill decreases proportionally with increasing RAS content.

Fly ash stabilized (class C at 20% by dry mass of RAS) RAS is less susceptible to penetrative deformation than unstabilized RAS, however; S-RAS is still highly susceptible to penetrative deformation when unpaved (i.e., CBR < 10). S-RAS experienced measurable improvement in resilient modulus over unstabilized specimens however, the improvement does not render S-RAS to be suitable for use as a base course material. S-RAS resilient modulus increases with increasing curing time for time periods longer than 7 days, however; the overall stiffness gain is small (2-4 MPa).

Fly ash stabilization of RAS generally provides less improvement in stiffness compared to fly ash stabilized low-plasticity clays. This may be due to the high asphalt content of RAS particles and resulting diminishment in pozzolanic activity and/or the diminished particle interconnectedness for cementation.

7.0 Practical Implications

Based on the results of the resilient modulus, CBR, and unconfined compressive strength tests, RAS and S-RAS are not considered suitable for use in base course construction. However, RAS and S-RAS may be suitable for use as a subbase filter layer between fine grained subgrades and granular bases, i.e., as a subbase material. Similarly, RAS and S-RAS may be suitable as general fill material or drainage material. However, additional studies are necessary to further assess the practicality of using RAS, S-RAS, and RAS composite mixtures as filter, fill or drainage material. Shear strength, hydraulic conductivity, and compressibility studies would be the most applicable tests for such an evaluation.

S-RAS exhibited marginal improvement in CBR, resilient modulus, and unconfined compressive strength as compared to other soft subgrade materials. However, S-RAS exhibited less improvement compared to fly ash stabilized soft subgrade materials, possibly due to decreased pozzolanic activity and/or the diminished particle interconnectedness for cementation. However, other forms of stabilization i.e. cold asphalt emulsion, etc. might prove more effective in strengthening RAS. Further studies which evaluate alternative stabilization methods of RAS could prove whether the beneficial reuse of RAS as base course is indeed possible.

The recycling and reuse of waste materials as replacements for natural materials is a new field of research. In the future, more and more waste materials will be considered for reuse in geotechnical applications. Care must be taken when analyzing the behavior of new materials according to standardized tests designed for natural earth materials. Additional research of RAS and other potentially recyclable materials can only benefit society in its efforts to promote technically sound, environmentally conservative design initiatives.

Table 1 Material properties of RAS, RAS-crushed stone, and RAS-soil blends (after Hooper and Marr, 2004)

Material	**Compaction Dry Unit Weight (kN/m^3)**	**Compaction Water Content (%)**	**Plasticity Index**	**CBR**
25-mm minus RAS (100%)	13.7	8	NP	6
Crushed Stone Gravel (100%)	19	7	NP	92
67:33 CSG:RAS	16.5	11	NP	23
50:50 CSG:RAS	16.2	9	NP	20
33:67 CSG:RAS	15.1	11	NP	20
Silty Sand (100%)	16.5	12	NP	33
67:33 Silty Sand:RAS	16.6	9	NP	19
Clean sand (100%)	14.8	11	NP	21
67:33 Clean Sand:RAS	14.9	10	NP	13
Clay (100%)	16.6	12	13	8
67:33 Clay:RAS	16.2	11	12	20

Note: NP = non-plastic

Table 2 Compositional properties of Columbia, Class C, and Class F fly ashes (after Edil et al., 2006)

Fly Ash	Strength Activity @ 7 Days (%)	LOI (%)	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)
Columbia	87	0.7	22.3	31.1	18.3	6.1
Class C	75	6.00 Max.	-	$SiO_2+Al_2O_3+Fe_2O_3$ 50.0 min.		
Class F	75	6.00 Max.	-	$SiO_2+Al_2O_3+Fe_2O_3$ 70.0 min.		

Note: LOI = Loss on Ignition

Table 3 Particle size parameters and USCS classification of RAS

Material Type	**Maximum Particle size (mm)**	**D_{60} (mm)**	**D_{30} (mm)**	**D_{10} (mm)**	**C_u[1]**	**C_z[2]**	**Gravel[3] Fraction (%)**	**Sand[4] Fraction (%)**	**Fine[5] Fraction (%)**	**USCS Class**
RAS	51	2.9	0.9	0.3	10	1	35	64	1	SW
RAS	25	2.5	0.8	0.3	8	1	33	65	2	SW
RAS	19	2.7	1.2	0.5	5	1	25	74	1	SP
RAS	10	0.8	0.3	0.08	10	1	8	81	11	SW-SM
RAS	5	1.1	0.5	0.2	6	1	<1	96	3	SW

[1] C_u = Coefficient of Uniformity = D_{60} / D_{10} where D_x is the particle size corresponding to x% passing

[2] C_z = Coefficient of Curvature = D_{30}^2 / (D_{60} * D_{10})

[3] Retained on No. 4 sieve with mesh opening of 4.75-mm

[4] Passing No. 4 sieve but retained on No. 200 sieve

[5] Passing No. 200 sieve with mesh opening of 0.075-mm

Table 4 Standard Proctor compaction test results for RAS, Grade 2 granular backfill, and Boardman silt

Material Type	**RAS gradation (mm minus)**	**Optimum water content (%)**	**Maximum dry unit weight (kN/m^3)**
RAS	51	7.4	10.4
RAS	25	9.8	9.9
RAS	19	6.9	8.8
RAS	10	14.2	12.5
RAS	5	8.0	12.3
Grade 2	N/A	10.0	21.0
Boardman Silt	N/A	15.0	16.5

Table 5 California Bearing Ratio (CBR) of RAS, RAS-Grade 2, and RAS-silt blends

Material Type	RAS Gradation (mm minus)	CBR
RAS	51	2
RAS	25	2
RAS	19	1
RAS	10	3
RAS	5	3
Grade 2	N/A	58
Boardman silt	N/A	20
50:50 RAS-Grade 2	25	3
50:50 RAS-Silt	5	8

Table 6 Suggested CBR for soils used in pavement structures (from Hooper and Marr, 2003)

Pavement Course	Material	CBR
Base course	Good quality crushed rock	>80
	Good quality gravel	50 to 80
Subbase course	Good quality soil	30 to 50
	Very good	20 to 30
Subgrade	Good to fair	10 to 20
	Questionable to fair	5 to 10
	Poor	<5

Table 7 Resilient modulus of RAS according to NCHRP 1-28 A power model

Material Type	**RAS Gradation (mm minus)**	**Mean Resilient Modulus[1] (As Subgrade) (MPa)**	**C.O.V (%)[3] / Standard Deviation**	**Mean Resilient Modulus[2] (As Base-subbase) (MPa)**	**C.O.V. (%)[3] / Standard Deviation**
RAS	25	29	9.3 / 2.7	34	4.7 / 1.6
RAS	10	36	14.2 / 5.1	41	9.0 / 3.7
RAS	5	33	8.8 / 2.9	38	1.8 / 0.7
Grade 2	N/A	84	4.9 / 4.1	112	2.7 / 3.0
50:50 RAS-Grade 2	25	62	4.5 / 2.8	77	3.0 / 2.3

[1] Resilient modulus calculated using θ = 83 kPa, and τ_{oct} = 19.3 kPa (Andrei et al., 2004)

[2] Resilient modulus calculated using θ = 208 kPa, and τ_{oct} = 48.6 kPa (NCHRP, 2004)

[3] C.O.V. = coefficient of variance = (standard deviation / mean) * 100%

Table 8 Compaction test results for S-RAS and unstabilized RAS

Material Type	RAS Gradation (mm)	Fly Ash Content (%)	Dry Unit Weight (kN/m^3)	Optimum Water Content (%)
RAS	25	0	10.4	10
S-RAS	25	20	11.9	12
RAS	10	0	12.5	14
S-RAS	10	20	13.7	13

Table 9 Resilient modulus of RAS and S-RASaccording to NCHRP 1-28 A power model

Material Type	**RAS Gradation (mm minus)**	**Mean Resilient Modulus[1] (As Subgrade) (MPa)**	**C.O.V (%)[3] / Standard Deviation**	**Mean Resilient Modulus[2] (As Base-subbase) (MPa)**	**C.O.V. (%)[3] / Standard Deviation**
RAS	25	0	0	29	9.3 / 2.7
S-RAS (7 day cure)	25	20	7	38	2.9 / 1.1
RAS	10	0	0	36	14.2 / 5.1
S-RAS (7 day cure)	10	20	7	55	5.8 / 3.2
S-RAS (28 day cure)	10	20	28	60	0.8 / 0.5

[1] Resilient modulus calculated using θ = 83 kPa, and τ_{oct} = 19.3 kPa (Andrei et al., 2004)

[2] Resilient modulus calculated using θ = 208 kPa, and τ_{oct} = 48.6 kPa (NCHRP, 2004)

[3] C.O.V. = coefficient of variance = (standard deviation / mean) * 100%

Table 10 Unconfined compressive strength of S-RAS and RAS

Material Type	**RAS Gradation (mm)**	**Fly Ash Content (%)**	**Curing Time (days)**	**Unconfined Compressive Strength (kPa)**
RAS	25	0	0	~0
S-RAS (7 day cure)	25	20	7	212
RAS	10	0	0	~0
S-RAS (7 day cure)	10	20	7	214
S-RAS (28 day cure)	10	20	28	233

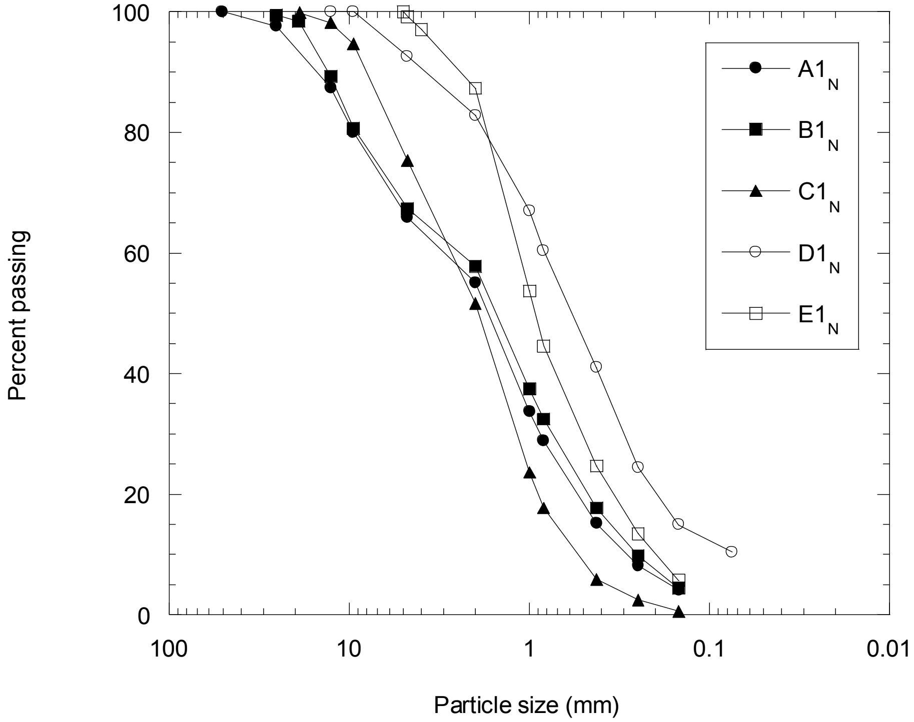

Figure 1 Particle size curves for 5 RAS gradations

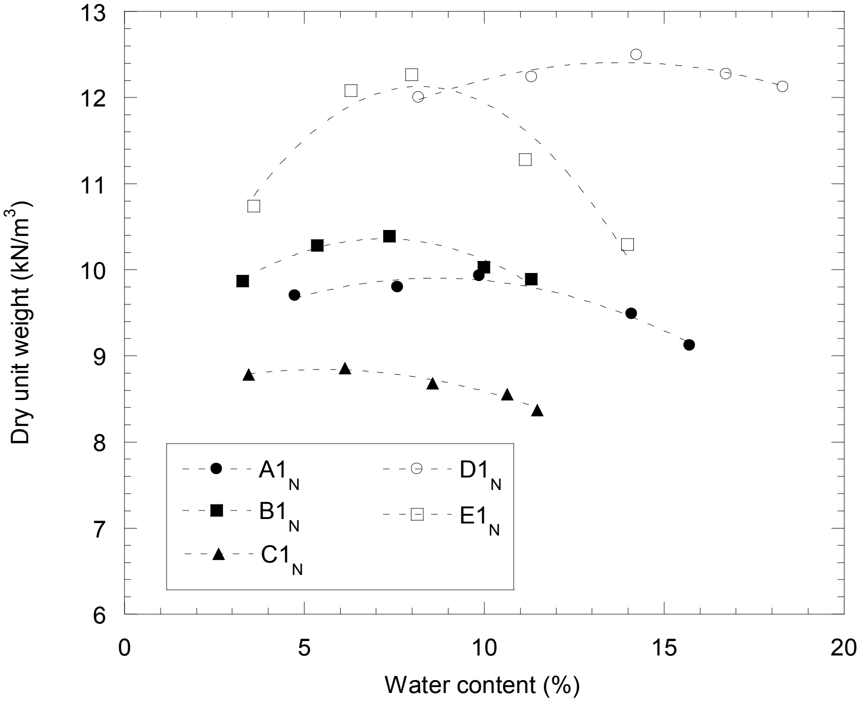

Figure 2 Standard Proctor compaction curves for 5 RAS gradations

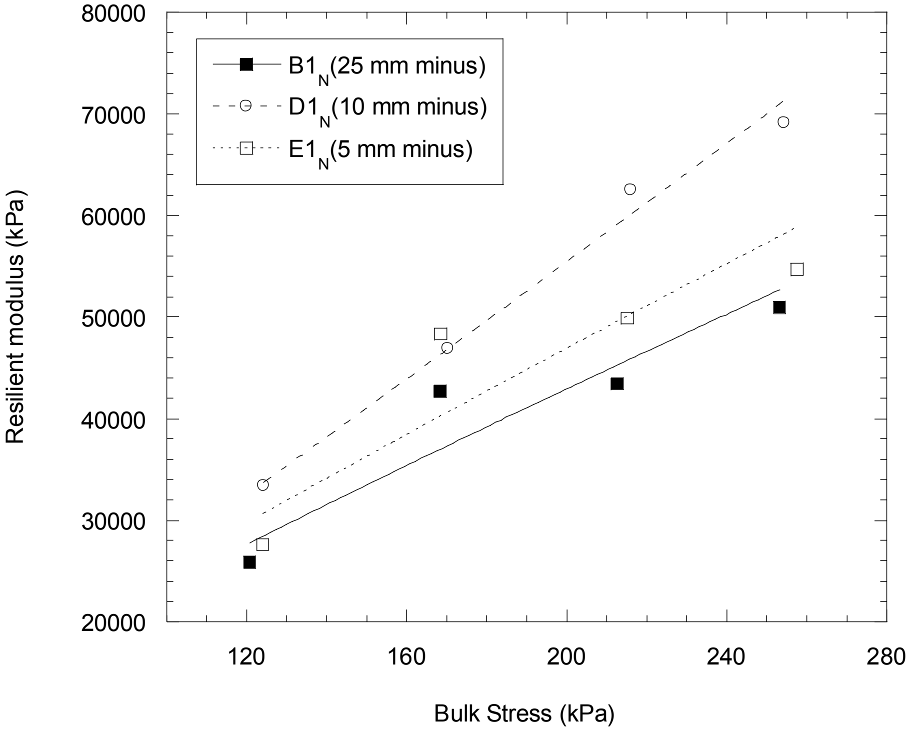

Figure 3 Resilient modulus versus bulk stress for 3 RAS gradations

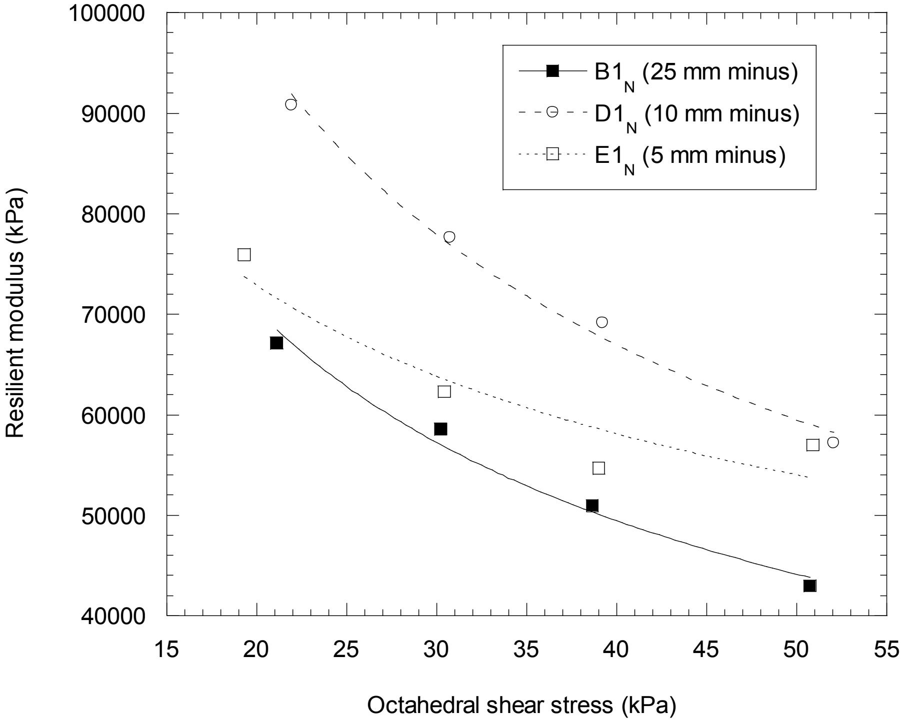

Figure 4 Resilient modulus versus octahedral shear stress for 3 RAS gradations

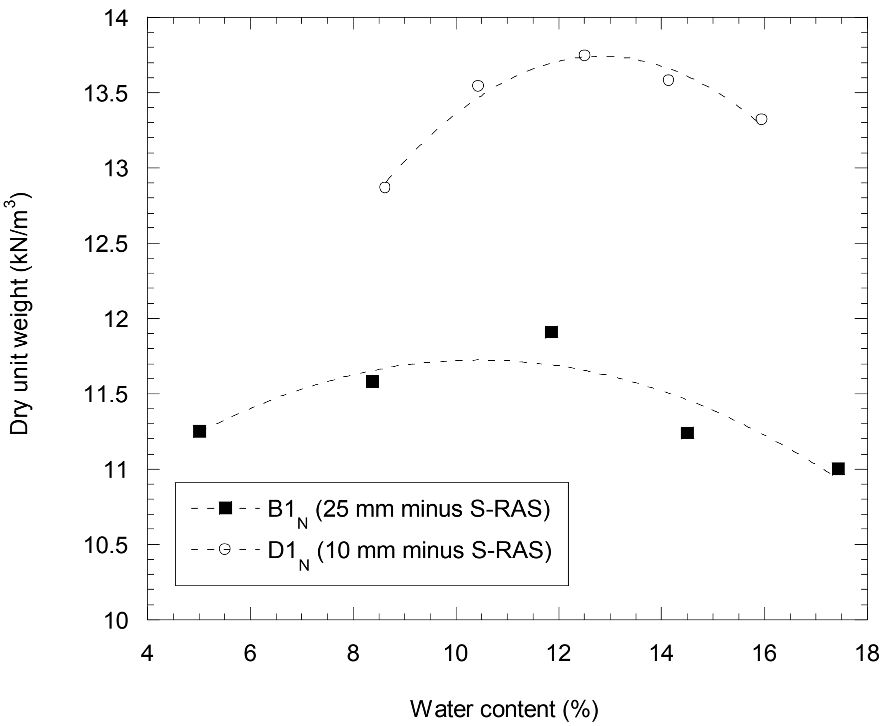

Figure 5 Standard Proctor compaction curves for S-RAS gradations stabilized with 20% class C fly ash

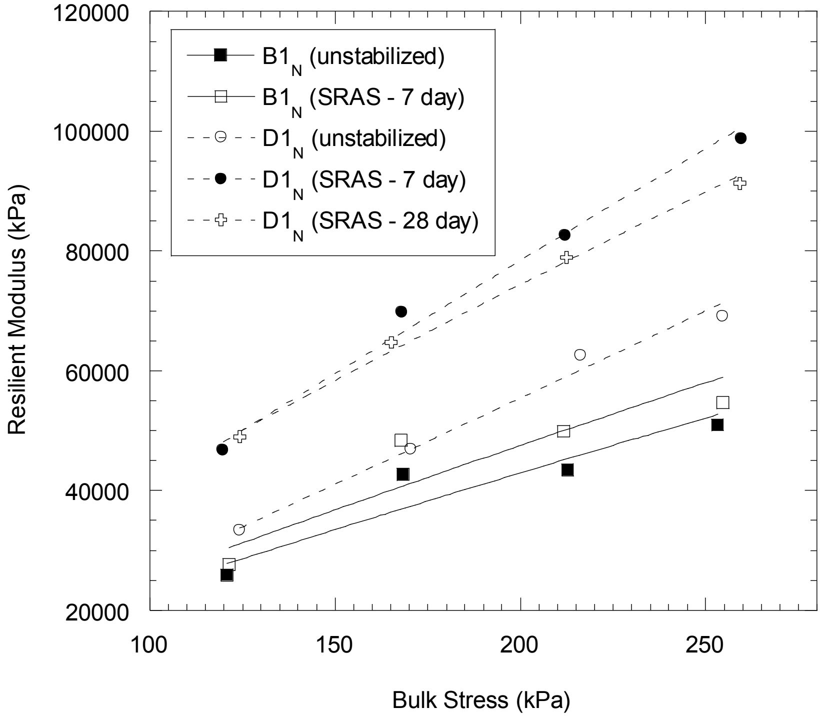

Figure 6 Resilient modulus versus bulk stress for S-RAS (7 and 28 day cure) and RAS

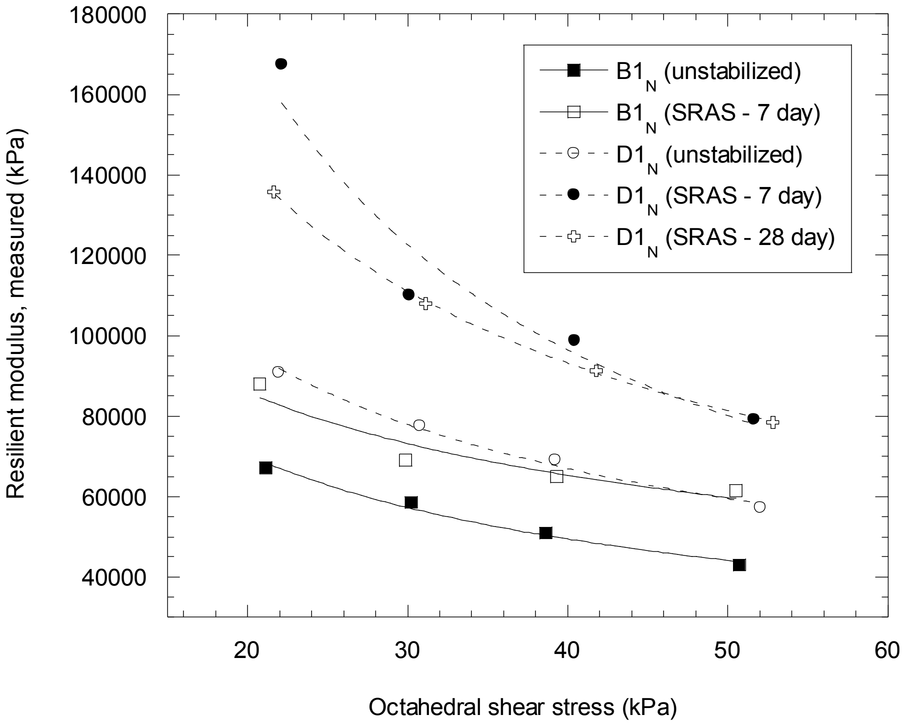

Figure 7 Resilient modulus versus octahedral shear stress for S-RAS (7 and 28 day cure) and RAS

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