2010

An investigative look at the effects of post consumer recycled asphalt shingles on soils and flexible pavements

Blake Anthony Michael Rubino
Iowa State University

An investigative look at the effects of post consumer recycled asphalt shingles on soils and flexible pavements

by

Blake Anthony Michael Rubino

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Civil Engineering Materials)

Program of Study Committee:
R. Christopher Williams, Major Professor
Jeramy C. Ashlock, Co-Major Professor
Vernon R. Schaefer
Mervyn G. Marasinghe

Iowa State University

Ames, Iowa

2010

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ACKNOWLEDGEMENTS

This thesis would not have been possible without the guidance and support from my family, friends, and faculty members. I am grateful to my parents Michael and DeeAnna Rubino for their guidance and support throughout my entire education. I would also like to thanks my fiancée Megan for her love and support. I need to thank my friend Owen Berg. If not for his help throughout these last 5 years I would not have been able to achieve this educational feat. Finally I need to thank my major professors Chris Williams, and Jeremy Ashlock. Their help, guidance, and expertise have been instrumental to my graduate level success.

CHAPTER 1: INTRODUCTION

This thesis describes a preliminary investigation into the potential beneficial re-use of Recycled Asphalt Shingles (RAS) in soil stabilization and hot mix asphalt (HMA) design.

Two soil types; western Iowa loess and green foundry sand, were chosen based upon their composition and local need for amendment. Loess is a common soil type encountered in western Iowa that may benefit from the addition of RAS as a stabilization treatment. Stabilization of loess by increasing its shear strength and cohesion while reducing collapsibility and swelling potential would improve its usefulness in foundation and pavement applications. Foundry sand was chosen as the second material because of its common re-use in highway construction and the need to identify additional potential applications for recycling this material. This study examined whether the addition of RAS to spent foundry sand could result in a beneficial construction material. To evaluate the performance of the RAS-soil mixtures, several commonly used geotechnical tests were performed.

The addition of waste materials to asphalt has been increasing in popularity with the increasing amount of information available. The amount of binder available in shingles for use in asphalt mixes makes this material an interesting and valuable commodity for use in HMA design. The Superpave design process, dynamic modulus testing, and flow number testing are all commonly used procedures and tests in today's asphalt design technology that were utilized in this preliminary research.

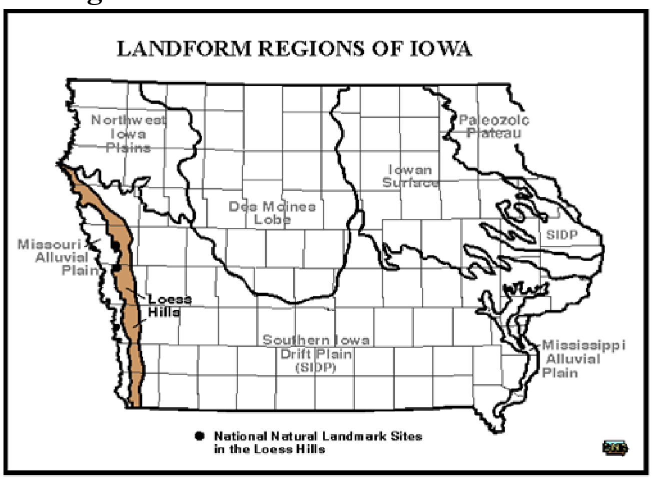
The contents of the thesis include a background description of materials used, two journal articles detailing laboratory investigations on the behavior of RAS with loess and foundry sand, respectively, and a third journal article on the effects of RAS in the application of hot mix asphalt (HMA) gradation and performance. The final chapter summarizes the findings of the investigation and offers recommendations for future research.

CHAPTER 2: MATERIALS BACKGROUND

Loess Soil

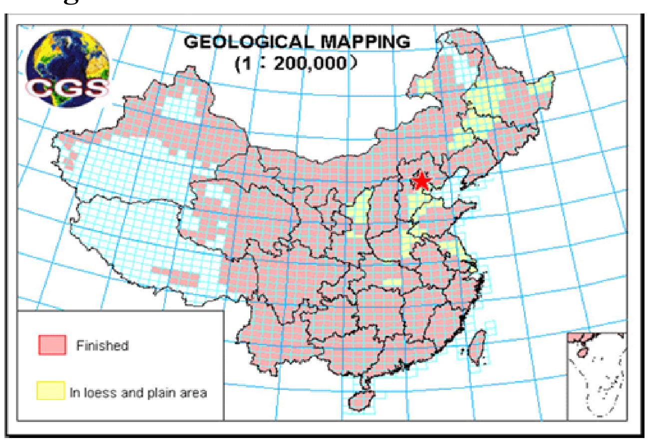
Loess, *pronounced "luss",* is German for loose or crumbly. The USGS defines Loess as a gritty, lightweight, porous material composed of tightly packed grains of quartz, feldspar, mica, and other minerals. Loess is a source of rich agricultural soil, and is common in the U.S. and around the world. Western Iowa's loess hills are unusual in that the strata can reach up to 200 feet in thickness. Shaanxi, China is the only other location in the world where loess layers exceed this depth. *(1)*

Figure 2.1: Location of Iowa Loess Hills



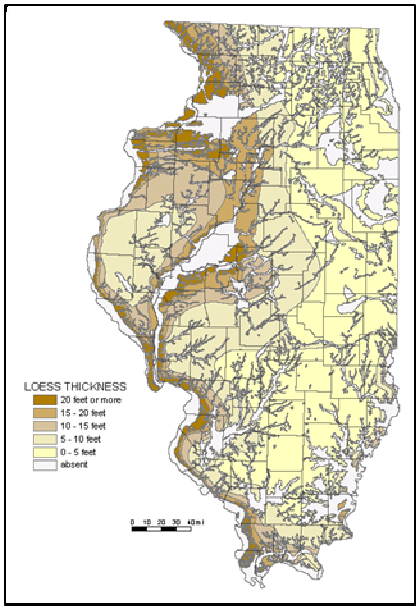
Source: Iowa Department of Natural Resources (2)

Figure 2.2: Location of Shaanxi Loess Hills



Source: Chinese Geological Survey *(3)*

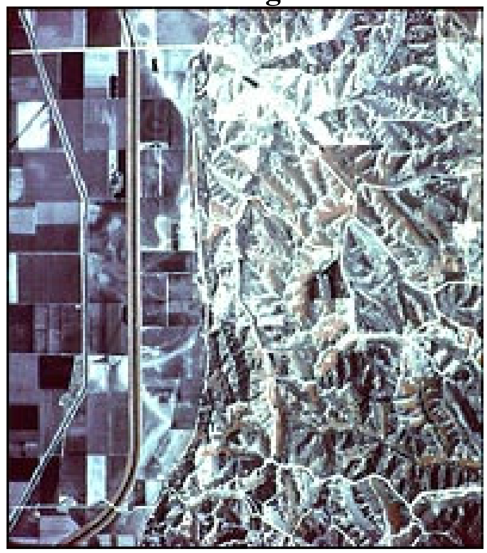
Figure 2.3 Illinois loess thickness



Source: Illinois State Geological Survey *(4)*

The Iowa loess deposits are aeolian in origin, created by wind transporting silt particles which were formed by the grinding advances of glaciers. After the glacial ice melted, water transported the silt through the river valley, where the silty mud dried and was carried away by strong winds creating loess deposits. Figure 2.3 illustrates the loess deposits carried across Iowa and into Illinois. Most of the material around the Missouri River Valley was deposited within 10 miles of the river, resulting in the deep formations known as the Iowa Loess Hills as shown in Figure 2.4 *(2)*.

Figure 2.4: Infrared Image of Iowa Loess Hills



Source: Geological Survey Bureau,
Iowa Department of Natural Resources *(1)*

Areas of loess are dynamic and rapidly changing. When loess is dry it forms stable surfaces often with steep or vertical cleavage, while wet loess is very susceptible to collapse and erosion due to a lack of clay particles. The loess hills of Iowa are extremely fragile and have among the highest rates of erosion in the U.S., at approximately 40 tons/acre/year. Consequently, the evolution of gullies poses serious problems in loess landscapes. Gullies can be very wide and deep, and upon widening can cause the collapse of bridges and roads *(1)*.

Foundry Sand

The first step in metal casting begins with the formation of a mold into which molten metal will be poured. The materials used to form the mold depend upon the type of metal being used and the desired product shape, with sand being the primary molding material for casting metals. Currently, 85% of foundries use green sand, which is composed of silica sand, bentonite clay, sea coal, and water *(5)*. The sand molds are typically used only once, with most of the sand capable of being reused for future molds. Sand mixtures are often used to create cores that fit within the mold to form detailed internal portions. Resins or chemical binders are usually added to ensure that these cores are strong and capable of withstanding the heat of molten metal.

Foundry sand is the largest by-product generated by the foundry industry. For most foundries, sand waste accounts for 55% to 90% of the total waste stream *(5)*. The composition of the foundry waste produced is directly related to the metals used, the furnace type, and the molding technology. Green sand is commonly reused after the metal product is removed from the mold. The repeated use of sand creates fines that are too small to be effectively reused and which must be disposed of. The fines are removed through a screening process, with additional sand added to ensure a uniform gradation. Sand that is chemically bonded to make cores or shell molds is more difficult to reuse, and is typically land-filled after a single use. Sand waste from brass and bronze factories contains hazardous residual metals such as lead, copper, nickel, and zinc which may require treatment before disposal.

Four commonly used methods of recovering sand are attrition reclamation, dry sand reclamation, water (wet) reclamation, and thermal sand reclamation. After the sand becomes "unsuitable" it may be recycled for use in several common applications. If the sand is not hazardous it may be used in concrete, asphalt, bricks and tiles, flowable fill, geotechnical and roadway fill, daily landfill cover, and manufactured topsoil composting *(6)*.

In 2002, the USDA Agricultural Research Service along with Pennsylvania State University, The Ohio State University, Purdue University, and the USEPA concluded that the beneficial use of non-olivine foundry molding sands from iron, steel, and aluminum foundries in soil applications presents no significant risk to human health or the environment. The majority of sand generated by iron, steel, and aluminum foundry processing is nonhazardous and has a very low leaching potential for heavy metals and organics. The US EPA estimates that only 2% of the foundry sand generated in the US exceeds hazardous waste characteristics for toxicity *(5)*.

Iowa's foundry sand policy specifies two categories for reuse; one for which no authorization is required and the second for beneficial uses for which applications are required. Foundry sand can be beneficially reused if it meets a criteria of 90% of federal

RCRA TCLP leachate concentration limits and has a pH between 5.0 and 10.0 as evaluated by EPA method 9045.

The following foundry sand applications do not require authorization in Iowa:

- Raw material in the manufacture of asphalt products
- Raw material in the manufacture of cement or concrete products
- Leachate control drainage material at a sanitary landfill
- Subbase for hard-surface road construction
- Fill material
- Emergency flood control use for sandbags
- Alternative cover material at a sanitary landfill

For all other beneficial purposes, a permit must be obtained through the Iowa Department of Natural Resources.

A foundry sand management plan must be recorded by all foundries recycling their sand waste in Iowa. The plan must contain a description of compliance assurance, sampling procedures, records of quarterly sampling for the first year followed by annual sampling thereafter, identification of storage site management controls, and an annual summary of how the spent sand was used. The annual report must be completed by March 1st of each year and kept onsite for at least five years *(7)*.

The Illinois foundry sand reuse policy differs slightly from that of Iowa, in that all wastes are managed by the Illinois EPA. Foundry waste is classified into one of four categories: beneficially usable waste, potentially usable waste, low risk waste, and chemical waste. The beneficially usable waste classification category is the only one which qualifies foundry sand for reuse, and material falling under any of the other classifications must be sent to an appropriate landfill site.

The Illinois foundry sand beneficial reuse program is a self-implementing program, in that the IEPA will not inspect a reuse location unless they receive complaints from the public. Once a foundry determines that the sand meets the "beneficially reusable" classification criteria, the foundry may pursue any reuse alternative that will not adversely affect human health or the environment, without notification of the IEPA. The IEPA standard for determining if a foundry sand is "beneficially usable" is based upon twenty-five parameter limits from the federal national primary drinking water standard with an additional seven parameters based on the federal national secondary drinking water standards *(7)*.

Recycled Asphalt Shingles (RAS)

Typical asphalt shingles are rectangular in shape and approximately 12-18 inches wide by 36-40 inches long. Asphalt shingles are produced by sequentially adding other components to a base layer of organic fibers or fiberglass felt. As outlined in Table 2.1, asphalt shingles are comprised primarily of materials used in hot-mix asphalt, including 20 to 30% asphalt cement (binder) by weight *(8)*. Numerous characteristics are monitored throughout the production of shingles according to ASTM specifications D 225 *(9)* and D3462 *(10)*, which identify a wide range of shingle products that are commonly used in the U.S. Approximately 11 million tons of waste asphalt roofing shingles are generated in the U.S. each year. Re-roofing jobs account for 10 million tons, while manufacturing scrap produces another 1 million tons *(11)*.

Table 2.1: Composition of asphalt shingles

Component	Fraction
Fiberglass or cellulose backing	2-15%
Asphalt cement from partial refinement of petroleum	19-36%
Ceramic-coated, sand-sized natural aggregate	20-38%
Mineral filler / stabilizer (limestone, dolomite, silica)	8-40%

Post-consumer shingle material is first ground up by crushers, hammer mills, or rotary shredders. The shingles are often passed though the shredding process twice to achieve the desired size reduction, then segregated from metal and wood debris by magnetic or mechanical techniques. Water is sometimes added during the shredding process to cool the material and prevent dust accumulation. Tear-off shingles vary in composition due to the combination of different manufactured products and contaminated debris from the shingle removal process *(11)*.

In a study by Asphalt Reclamation Industries, LLC more than 3,000 samples of asphalt shingles and tarpaper were analyzed in accordance with USEPA method 600/R-93/116. A total of 0.3% of the samples analyzed tested positive for asbestos levels greater than 1%, with an additional 0.5% of samples containing trace amounts (less than 1%) of asbestos. Similar findings of infrequent asbestos detection have been reported in a study by Central C&D Recycling in Des Moines, Iowa involving testing of 3,000 demolition samples, all of which were found to contain less than 1% asbestos by weight *(12)*.

The Use of RAS in HMA

Several states have conducted or funded laboratory and field studies on portions of highways and trails pertaining to the feasibility of using RAS in HMA pavement design. The following states currently allow the use of manufacturer's scrap shingles to be used in a certain percentage of HMA pavements *(13)*:

- Delaware
- Florida
- Illinois
- Indiana
- Maine
- Maryland
- Massachusetts
- Michigan
- New Jersey
- North Carolina
- Ohio
- Pennsylvania

The following states currently allow the use of both manufacturer's scrap and Post-Consumer shingle scrap in certain percentages of HMA pavements *(13)*:

- Minnesota
- Iowa
- Missouri
- Texas
- Alabama
- Wisconsin
- Georgia
- South Carolina
- Virginia
- New Hampshire

Washington's WSDOT has stated that asphalt single recycling presents a possible opportunity. The State Materials Lab is in the process of working with King County as they build a test RAS asphalt project, and will be monitoring its performance over time *(14)*.

Wisconsin's WisDOT just approved a rule change in 2009 allowing for up to 5% recycled shingles to be used as part of their state road projects *(15)*.

The MoDOT has a general provision and supplemental specification that states their local policy on the use of RAS in asphalt pavements. Some of Missouri's key guidelines are: a maximum of 7% shingles for PG 64-22 binders, PG 52-28 or PG 58-22 binders must be used for ratios of virgin binders to total binders being less than 70%, all shingles must be ground to ½ in. minus, post-consumer shingles must not contain 1.5% wood by weight or contain more than 3.0% total deleterious material by weight, and post-consumer shingles must be certified to contain less than the maximum allowable amount of asbestos by national or local standards. Mix designs must also be made on the following shingle aggregation *(16)*:

Table 2.2: MoDOT Approved Shingle Aggregate Gradation for Mix Design[1]

Shingle Aggregate Gradation	
Sieve Size	**Percent Passing by Weight**
3/8 in. (9.5 mm)	100
No. 4 (4.75 mm)	95
No. 8 (2.36 mm)	85
No. 16 (1.18 mm)	70
No. 30 (600 µm)	50
No. 50 (300 µm)	45
No. 100 (150 µm)	35
No. 200 (75 µm)	25

[1]section 403.2.6.2 Recycled Asphalt Shingles.

The IDOT has established specification DS-09038, allowing 2%-5% RAS by aggregate weight to be used in mixes. This percentage of RAS is to be part of the allowable RAP quantities used. Iowa uses the same shingle aggregate gradation assumptions for mix design as Missouri, which is shown in Table 2.2 *(17)*.

The MnDOT has a specification of Tear-Off (or Post-Consumer), shingles for use in asphalt mixtures. Similar to MoDOT, Minnesota has specifications for the addition of shingles to their asphalt mixes, whereby only 5% shingles may be used by weight. The addition of shingles is considered in the maximum allowable RAP percentage. The ratio of virgin binder to total binder must be 70% or greater. All shingles must pass a ½ in. sieve with 90% passing a #4 sieve. Finally, similar to MoDOT's gradation, MnDOT has approved the aggregate gradation shown in Table 2.3 for use in asphalt mix design *(18)*.

Table 2.3: MnDOT approved shingle aggregate gradation for mix design

Shingle Aggregate Gradation	
Sieve Size	**Percent Passing by Weight**
3/8 in. (9.5 mm)	100
No. 4 (4.75 mm)	97
No. 8 (2.36 mm)	95
No. 16 (1.18 mm)	80
No. 30 (600 µm)	60
No. 50 (300 µm)	50
No. 100 (150 µm)	40
No. 200 (75 µm)	30

Dust Control Usage

In a project entitled "Let Me Shingle Your Roadway", the Iowa DOT mixed 500 tons of ground shingles with crushed limestone granular surfacing across 0.3 miles of roadway creating a shingle-limestone mixture approximately 2.5 inches thick. Marks and Petermeier *(19)* concluded that the use of RAS was an effective dust control technique and cost effective recycling method, which also provided improved lateral control and a smoother quieter roadway.

Recent Recycling Policy

The United States Environmental Protection Agency (EPA) of Region VII in Kansas City issued a letter in early 1996 in response to an inquiry from an Iowa firm which was planning on recycling waste shingles. The letter noted that the National Emission Standards for Hazardous Air Pollutants (NESHAP) regulation identifies and controls asbestos containing materials (ACM). The EPA stated that asphalt shingles coming from residential buildings having four or fewer dwelling units would be exempt from NESHAP and would not require asbestos analysis before being used in roadway projects. This exception is for waste coming from the renovation or demolition of structures which do not constitute a "facility" (i.e., residential buildings having four or fewer dwelling units). The EPA also stated that asphalt shingles from a "facility" require sampling and analysis for asbestos content. Any material containing greater than 1% asbestos cannot be used for roadways *(19)*.

Influence of RAS on Asphalt Mixtures

Newcomb *(20)* performed a 1993 study of RAS in ACC mixtures. Among his findings were that the use of shingles tends to increase the resistance of pavement to cracking due to the reinforcing provided by the fibers in shingles with the rutting resistance improved due to the combination of fibers and hardness of the asphalt in shingles. Incorporation of shingles can reduce the optimum binder content and enhance the mixture's ability to densify under compaction. The addition of 5% shingles caused a substantial decrease in temperature susceptibility at cold temperatures while shingle percentages greater than 5% resulted in an overall decrease in mixture stiffness over a wide range of temperatures. The use of felt shingles did not appear to influence the moisture sensitivity of the mixture. The use of fiberglass shingles increased tensile strengths for conditioned samples and had little impact on unconditioned samples, with a uniform reduction in cold tensile strengths *(20).*

According to Hanson, Foo, and Lynn from the National Center for Asphalt Technology, the potential capacity for using recycled asphalt shingle (RAS) in HMA far exceeds the amount of material generated. The use of 5% shingles in all the HMA produced in North Carolina would consume 600,000 tons of shingles. Those shingles consumed would allow approximately one third of all HMA plants to eliminate the landfilling of shingles in that state. However, not all facilities can handle the recycled material due to equipment costs and production volume *(21)*.

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CHAPTER 3. EFFECTS OF RECYCLED ASPHALT SHINGLES ON MECHANICAL PROPERTIES OF LOESS

Modified from a paper published in the Compendium of Papers from the 89th Annual Meeting of the Transportation Research Board

Blake Rubino, Jeramy C. Ashlock, R. Christopher Williams

ABSTRACT

An investigation was carried out to evaluate the effects of post-consumer recycled asphalt shingles (RAS) on various mechanical properties of a loess soil. Compaction, unconfined compression, split-cylinder indirect tensile-strength, and California Bearing Ratio tests were conducted for a range of RAS contents. Increasing the percentage of RAS by dry unit weight caused a decrease in the optimum moisture content (OMC) and maximum dry unit weight of the soil-RAS mixture. Samples compacted and tested at or below OMC generally experienced a decrease in tensile strength and unconfined compressive strength. However, mixtures compacted wet of optimum with RAS contents of 10 and 20% experienced slight increases in unconfined compressive strength compared to the unaltered soil. California Bearing Ratios from uncured and un-soaked samples consistently decreased with increasing RAS content. Although addition of the recycled shingles did not result in an increase in strength properties for the particular soil type tested, the effect of decreasing the unit weight accompanied by only a moderate loss of compressive strength may make it useful as a recycled lightweight fill material. The reduction in strength properties of the loess with the addition of RAS results in it not being acceptable for use in soil modification for pavement systems.

INTRODUCTION AND BACKGROUND

It is currently estimated that 10 million tons of post-consumer asphalt shingles are disposed of in landfills each year. As outlined in Table 3.1, asphalt shingles are comprised of the same four basic materials used in hot-mix asphalt, including 20 to 30% asphalt cement (binder) by weight (*1*). A number of performance and environmental issues pertaining to the use of recycled asphalt shingles (RAS) as a construction material are presently being studied in the US, predominantly in relation to hot-mix asphalts. Recent advancements in specialized grinding and sorting processes produce more consistent RAS than could be achieved in recent years. Additionally, shingle recyclers are increasingly following asbestos testing protocols and QA/QC standards to ensure removal of non-asphalt construction debris such as wood, nails and felt. With such improved production techniques, clear economic and environmental benefits are being realized through a reduction in the volume of waste shingles sent to landfills and decreased greenhouse gas emissions associated with the production of virgin asphalt. Amendment of soils is done for several reasons, but mostly for increasing the performance of the soil through strength parameters and/or for producing a lighter weight material. Although the use of asphalt as a soil stabilization material has received some attention in previous years (e.g. *2, 3*), only limited laboratory testing has been performed on the use of recycled asphalt shingles for soil stabilization (e.g. *4, 5*). Additional economic and environment benefits stand to be realized by the identification of new geotechnical applications for recycled asphalt shingles.

Table 3.1: Composition of asphalt shingles

Component	**Fraction**
Fiberglass or cellulose backing	2-15%
Asphalt cement from partial refinement of petroleum	19-36%
Ceramic-coated, sand-sized natural aggregate	20-38%
Mineral filler / stabilizer (limestone, dolomite, silica)	8-40%

EXPERIMENTAL PROCEDURES

A series of preliminary strength and compaction tests were conducted using a Western Iowa loess to examine the potential usefulness of RAS in soil stabilization or soil modification applications. The specific loess tested has a USCS classification of ML (AASHTO classification A-4), with a liquid limit of 32 and a plasticity index of 6. Laboratory tests performed include standard and modified Proctor (ASTM D 698-11a and ASTM D1557-02), unconfined compression (ASTM D 2166-00), California Bearing Ratio (ASTM D 1883-99), and indirect tensile-strength tests (ASTM D6921-07). Recycled asphalt shingles with a maximum size of 3/8” and 95% passing the #4 sieve were used at 0%, 10%, 20%, and 30% by air dried mass for amendment of the loess soil.

Batches of air-dry loess and RAS were combined with water necessary to achieve the desired moisture content and mixed for five minutes using a HOBART 110 volt, ½ HP mechanical mixer to prepare the test specimens.

RESULTS, STATISTICAL ANALYSIS, AND DISCUSSION

Compaction Tests

Proctor tests in this study were performed using a Soil Test International mechanical soil compactor immediately after mixing. Due to the lower specific gravity of the recycled asphalt shingles (average G_s=1.6) compared to that of loess (G_s=2.7), it was anticipated that addition of RAS to the soil would result in a decrease in the maximum dry unit weights. As shown in Figures 3.1 and 2.2, the expected trend was confirmed for both standard and modified Proctor tests. The maximum dry unit weight of 110.5 lb/ft^3 and optimum moisture content (OMC) of 14.8% for the virgin loess were decreased to 100.5 lb/ft^3 and 13.8%, respectively, for standard compaction of the sample containing 30% RAS. Similar trends were observed for modified compaction effort, although with slight irregularities just dry of the peak values of unit weight. Values of OMC and maximum dry unit weight obtained in the compaction tests are summarized in Table 3.2.

Table 3.2: Optimum moisture contents and maximum dry densities from Standard and Modified Proctor tests

	Standard		Modified	
% RAS	Optimum moisture content	Max. dry density (lb/ft^3)	Optimum moisture content	Max. dry density (lb/ft^3)
0	14.8%	110.5	12.0%	119.0
10	14.5%	105.0	11.0%	116.0
20	14.0%	104.0	10.8%	114.5
30	13.8%	100.5	11.5%	110.0

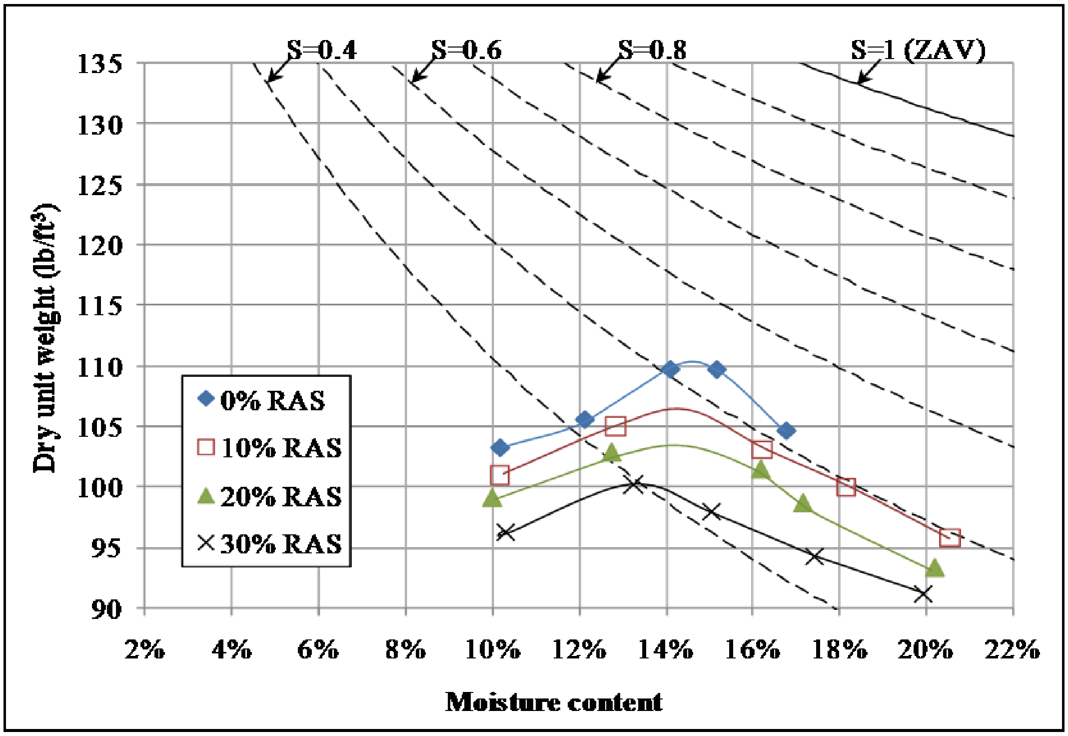

Figure 3.1: Standard Proctor test compaction curves for soil-RAS mixtures

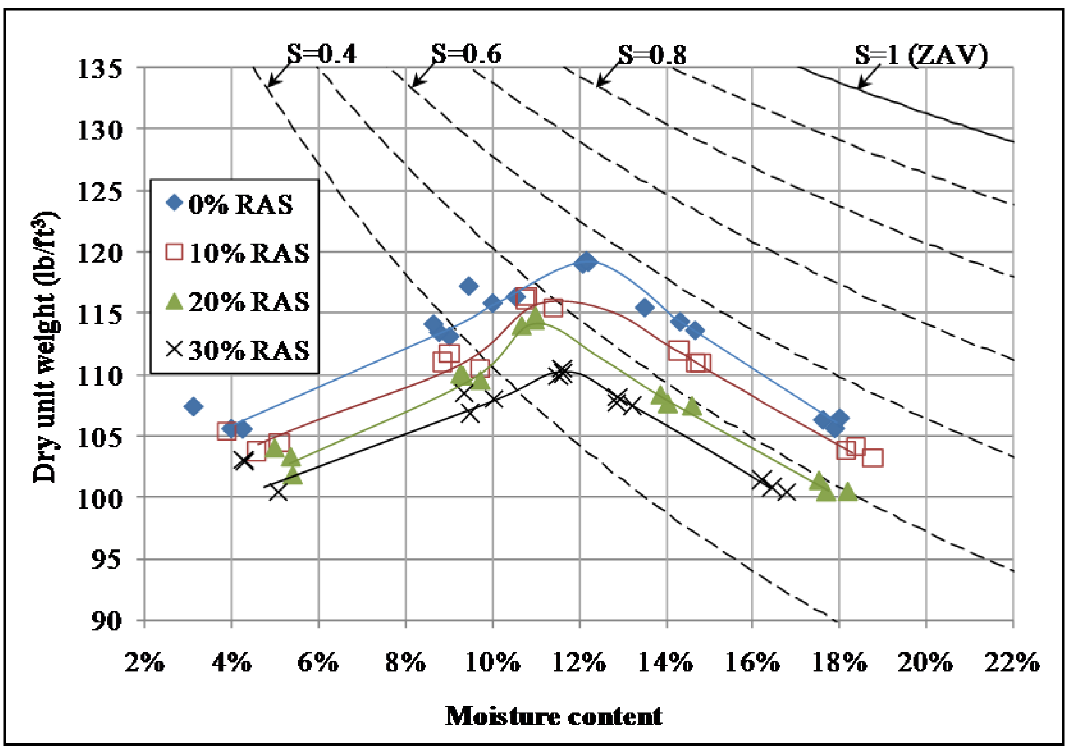

Figure 3.2: Modified Proctor test compaction curves for soil-RAS mixtures

Unconfined Compressive Strength

Cylindrical unconfined compression test specimens of 2.8" diameter by 5.6" height were compacted to within 5% of their standard Proctor densities at three different targeted moisture contents of OMC±2% using an Iowa State compaction apparatus (*6*). All unconfined compression, CBR, and indirect tensile-strength tests were performed using a digitally controlled servo-pneumatic IPC Global UTM-5P/14P Universal Testing Machine with a maximum load capability of 14 kN. An axial strain rate of 1% was used for all unconfined compressive strength tests. The test configurations for unconfined compression and indirect tensile strength tests are shown in Figure 3.3. As shown in Figure 3.4, the dry unit weights and moisture contents obtained using the hand-operated Iowa State compaction apparatus closely followed those obtained with the mechanical soil compactor (Figure 3.1). A representative sample illustrating the failure mode is shown in Figure 3.5. The unconfined compressive strength is plotted against moisture content in Figure 3.6, indicating that the addition of RAS generally decreases the unconfined compressive strength with the exception of the data points wet of optimum. Relations between compressive strength, moisture content and dry unit weights of the soil-RAS mixtures are shown in Figures 3.7 and 3.8 and summarized in Table 3.3.

Table 3.3: Unconfined compressive strengths for samples compacted to within 5% of standard Proctor density at target moisture contents of OMC±2%

% RAS	Moisture content (**Dry**)	Dry unit weight (lb/ft^3)	Compressive strength (psi)	Moisture content (**Opt.**)	Dry unit weight (lb/ft^3)	Compressive strength (psi)	Moisture content (**Wet**)	Dry unit weight (lb/ft^3)	Compressive strength (psi)
0	12.3%	103.9	41.0	15.1%	108.8	47.1	18.5%	103.2	17.1
	12.5%	103.8	41.3	14.9%	108.8	46.7	18.6%	102.9	17.0
	12.3%	104.3	42.7	14.9%	108.7	42.5	18.5%	103.3	18.4
10	11.8%	102.5	41.9	15.0%	104.8	32.5	16.9%	101.8	23.0
	12.0%	102.5	39.4	15.3%	104.3	32.5	16.8%	102.0	22.4
	12.0%	102.5	41.2	15.1%	104.8	33.3	16.8%	102.0	22.7
20	12.0%	100.5	39.3	13.7%	104.3	39.1	16.6%	99.5	21.2
	11.7%	100.5	39.5	13.6%	103.7	42.5	16.4%	100.1	21.8
	11.6%	101.2	38.1	13.8%	103.5	42.5	16.2%	100.0	21.9
30	11.5%	98.5	31.5	14.0%	99.0	30.8	17.1%	95.4	10.6
	11.2%	98.9	31.6	13.5%	99.3	32.2	17.0%	95.6	11.2
	11.3%	98.9	31.1	13.7%	99.7	31.0	17.0%	96.6	13.5

(a) Servo-pneumatic test set-up

(b) Specimen orientation

Figure 3.3: Servo-pneumatic test configuration and specimen orientation for unconfined compression and indirect tensile strength tests

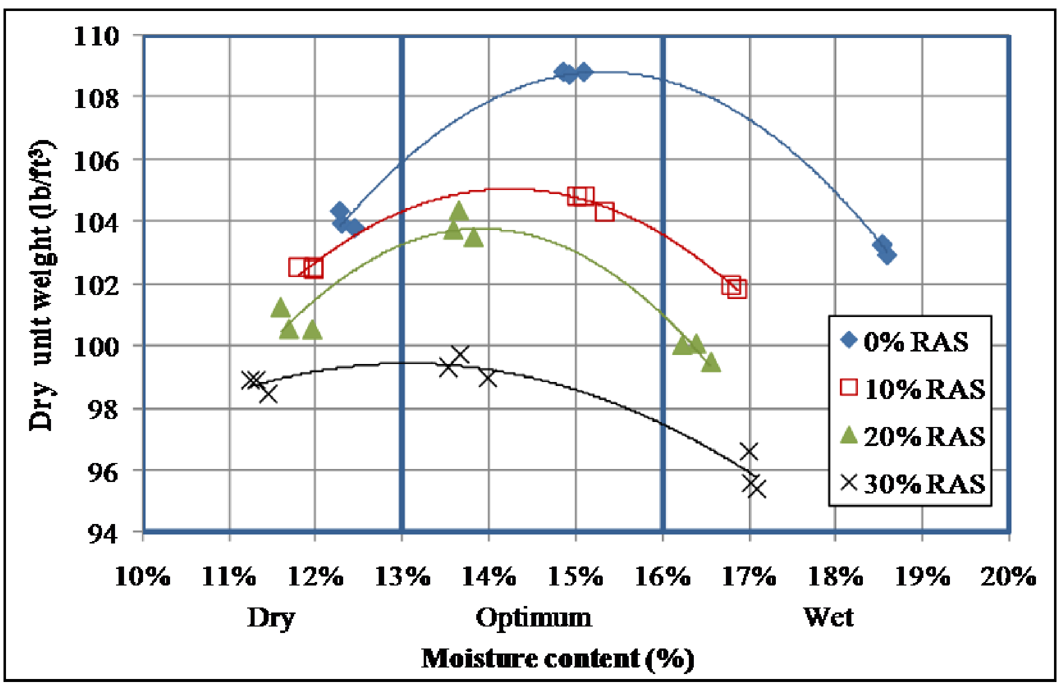

Figure 3.4: Dry unit weights within 5% of Standard Proctor density achieved for unconfined compression samples using the Iowa State compaction device

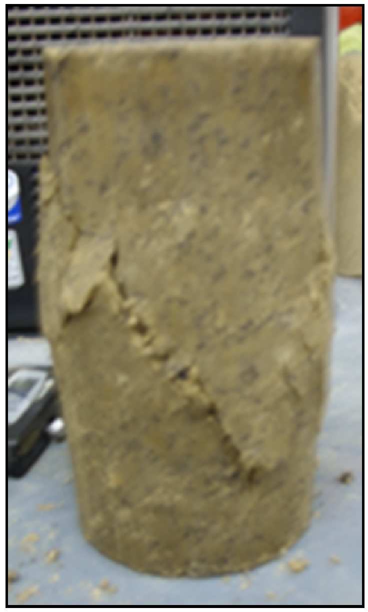

Figure 3.5: Failure mode of an unconfined compression test specimen with RAS

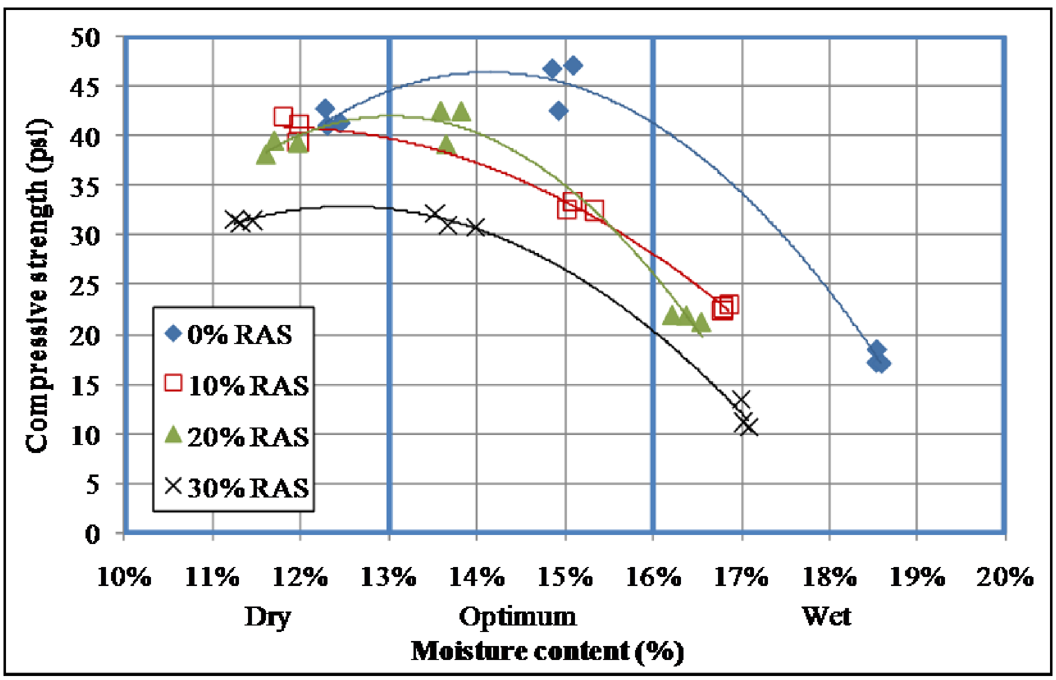

Figure 3.6: Unconfined compressive strength vs. moisture content for samples compacted to within 5% of Standard Proctor density

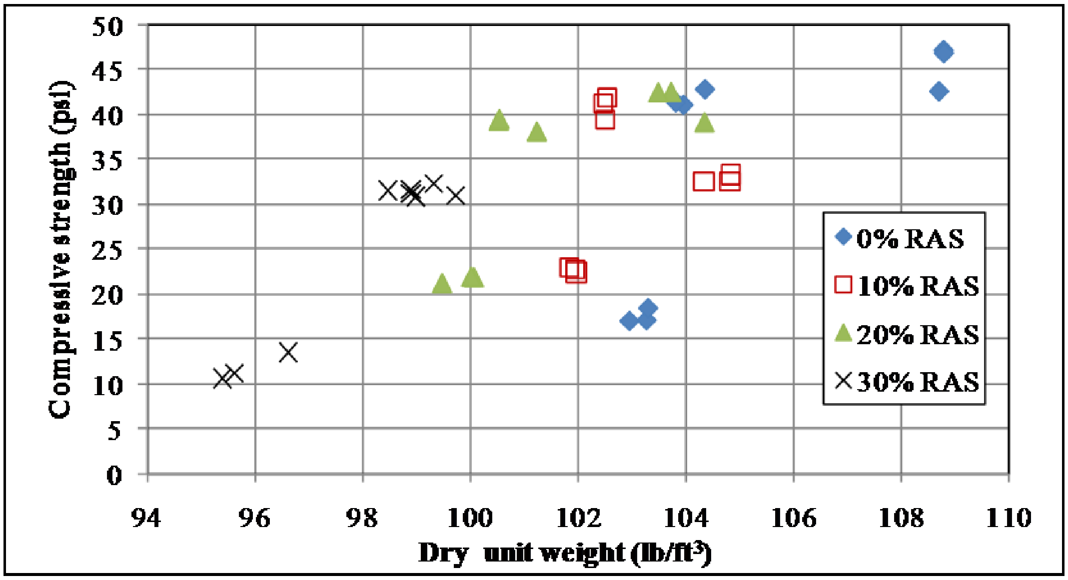

Figure 3.7: Unconfined compressive strength vs. dry unit weight for samples compacted to within 5% of Standard Proctor density

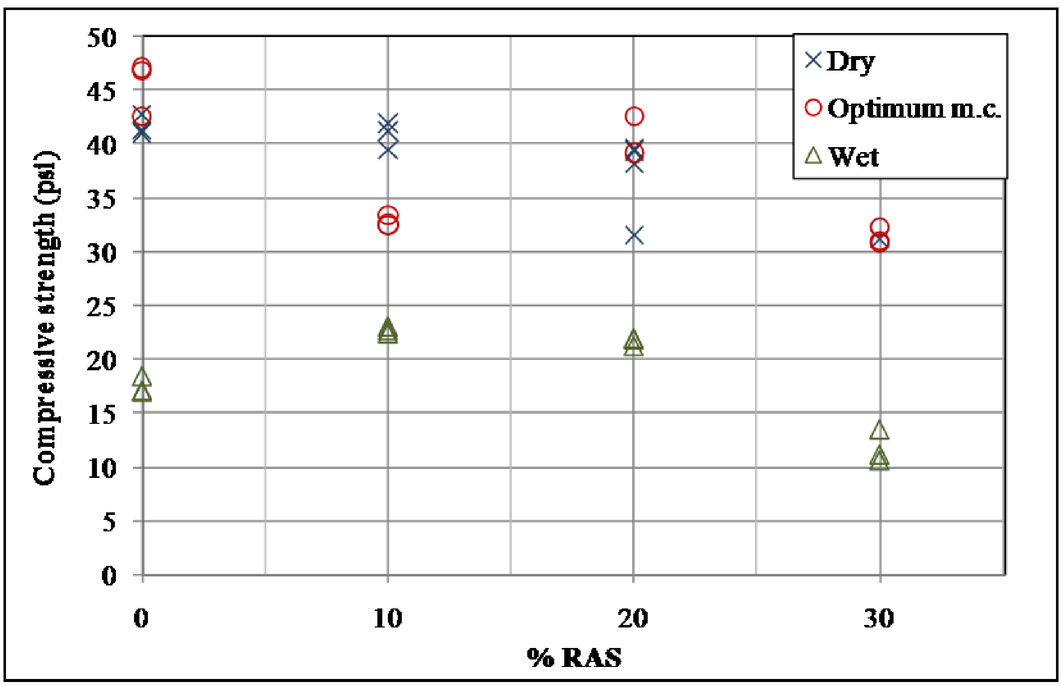

FIGURE 3.8 Unconfined compressive strength vs. RAS content for samples compacted to within 5% of Standard Proctor density

Statistical analyses were performed on the unconfined compressive strength data sets with the results shown in Table 3.4. The initial statistical model did not conform to a priori expectations, namely that an increase in shingle content would lead to an increase in unconfined compressive strength. The initial model had a large intercept value, which led to a positive coefficient for the shingle content (% RAS), contrary to the observed trends. It is important to point out that the shingle content does affect the dry unit weight and thus there is some statistical confounding between these two "independent" variables. A reduced model with a zero intercept resulted in an improvement in the overall R^2_{adj} value, from 0.951 to 0.957. All of the independent parameters were judged to be statistically significant if their p-value was below the threshold value of 0.10. To utilize the reduced model for unconfined compressive strength in a predictive manner, for example, one may choose the inputs to the model from the interpolated relations between dry density and moisture content shown in Figure 3.4. The resulting predicted unconfined compressive strength will then exhibit a nonlinear dependence on moisture content, similar to that shown in Figure 3.6.

Means testing was performed on the unconfined compressive strength data using the paired t-test at optimum moisture contents for the four RAS contents (0, 10, 20, and 30%). A threshold p-value of 0.10 or a 90% level of confidence was used to determine if the means were statistically different. The means of the unconfined compressive strength values that were statistically different for the various shingle contents are highlighted in bold italics in Table 3.5. The means of the unconfined compression strengths are statistically the same when comparing 0 and 20% RAS as well as when 10 and 30% are compared.

Table 3.4: Summary of unconfined compressive strength regression analysis

Unconfined Compressive Strength, σ_{uc}		
Model	**F-Statistic**	**$R^2_{adj.}$**
σ_{uc} = -187.4 + 18.2 * (Shingle Content) - 312.5 * (Moisture Content) + 2.6 * (Dry Unit Wt)	228.9	0.951
Parameter	**t-Statistic**	**p-value**
Intercept	-7.5	<0.001
Shingle Content	2.7	0.01
Moisture Content	-16.7	<0.001
Dry Unit Wt	11.4	<0.001
Reduced Model	**F-Statistic**	**$R^2_{adj.}$**
σ_{uc} = -24.8 * (Shingle Content) - 376.1 * (Moisture Content) + 0.9 * (Dry Unit Wt)	888.2	0.957
Parameter	**t-Statistic**	**p-value**
Shingle Content	-4.5	<0.001
Moisture Content	-13.8	<0.001
Dry Unit Wt	218	<0.001

Table 3.5: Summary of unconfined compressive strength paired t-tests at optimum moisture content

t values for means testing				
Shingle Content (%)	0	10	20	30
0	-	***0.019***	0.219	***0.009***
10	-	-	***0.014***	0.151
20	-	-	-	***0.009***

Indirect Tensile-Strength

Tensile strength is an important parameter that affects the performance of clay liners and controls the creation and propagation of tensile cracks which can cause landslides or progressive erosion of structures such as highway embankments, dams and excavations (*7*). Split-cylinder indirect tension tests were used to examine whether the fibrous and asphalt components of RAS can produce an increase in tensile strength of the soil-RAS mixtures. The mechanical soil compactor was used to prepare 4" diameter samples at modified Proctor density and OMC. The samples were then tested at a displacement-rate of 50 mm/min in the IPC testing machine, with force and displacement data sampled at a rate of 100 Hz to ensure that the peak strength was captured. The failure mode of a representative sample is exhibited in Figure 3.9.

Figure 3.9: Failure mode of an indirect tensile test specimen with RAS

As shown in Figure 3.10, the addition of 20% RAS resulted in a noticeable increase in tensile strength dry of optimum, but all three RAS contents tested typically produced a decrease in tensile strength near the optimum moisture content. Results wet of optimum were less conclusive due to the range of strength values obtained with 0% RAS.

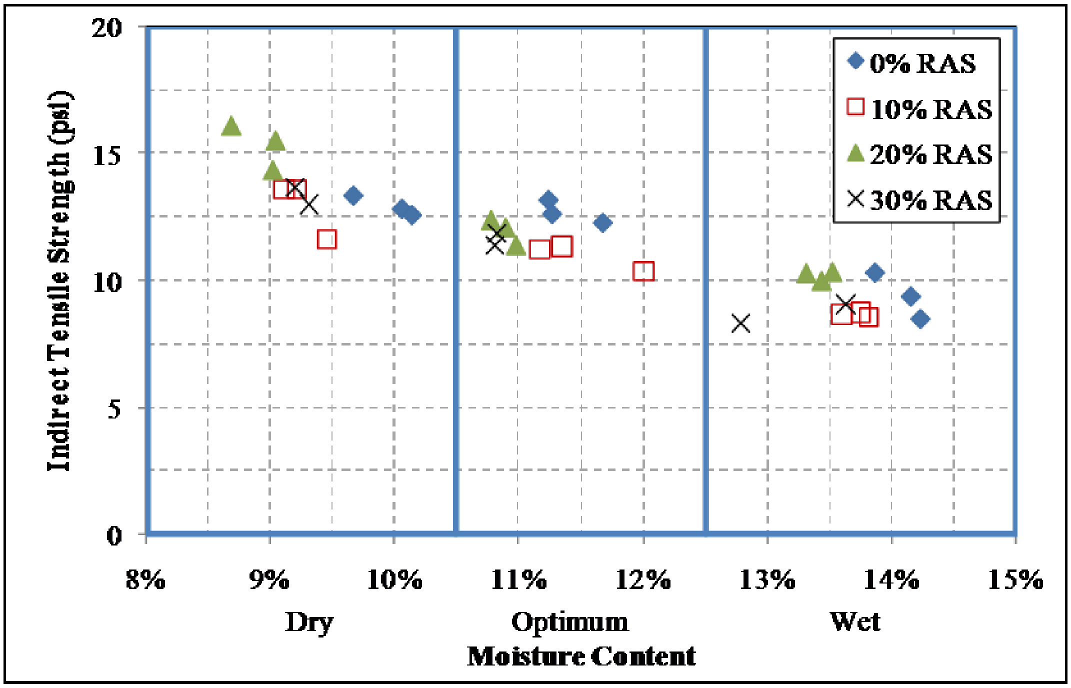

Figure 3.10: Indirect tensile strength of soil-RAS mixtures compacted to within 5% of Standard Proctor density

A statistical analysis was performed on the indirect tensile strength data sets, similar to the analysis described above for unconfined compressive strength. The analysis of the indirect tensile strength data was performed to determine whether shingle content and moisture content had statistically significant effects. Both the shingle and moisture content parameters were found to have statistically significant effects on tensile strength, with a p-value threshold of 0.10, or a 90% level of confidence. Overall, the model has an R^2_{adj} value of 0.826, indicating a very good correlation or quality of fit. Results of this analysis are shown in Table 3.6 below. Means testing was also performed on the indirect tensile strength data using the paired t-test at the optimum moisture contents for the four RAS contents. A threshold p-value of 0.10 or a 90% level of confidence was used to determine if the means were statistically different. The means of the indirect tensile strength values that were statistically different for the various shingle contents are highlighted in bold italics in Table 3.7. As shown in this table, none of the shingle contents resulted in a tensile strength that was statistically the same as the unmodified loess. However, regardless of the shingle content, the indirect tensile strength was statistically invariant.

Table 3.6: Summary of indirect tensile strength regression analysis

Indirect Tensile Strength, σ_{IDT}		
Model	**F-Statistic**	**$R^2_{adj.}$**
σ_{IDT} = 23.9 - 2.4 * (Shingle Content) - 105.5 * (Moisture Content)	84.3	0.826
Parameter	**t-Statistic**	**p-value**
Intercept	24.3	<0.001
Shingle Content	-1.9	0.069
Moisture Content	-13	<0.001

Table 3.7: Summary of indirect tensile strength paired t-tests at optimum moisture content

t values for means tests				
Shingle Content (%)	0	10	20	30
0	-	***0.099***	***0.026***	***0.026***
10	-	-	0.231	0.246
20	-	-	-	0.184

California Bearing Ratio

To investigate the potential use of RAS in improving the classification of loess as a sub-grade for pavement foundations, unsoaked California Bearing Ratio (CBR) tests with a surcharge load of 10 lbs were conducted using the IPC testing machine. CBR samples were prepared using 25, 56, and 76 blows per layer using the mechanical soil compactor, with target moisture contents equal to the standard compaction OMCs given in Table 3.2. As shown in Table 3.8, increasing RAS contents caused a decrease in the CBR for all three compactive efforts. Research has shown that CBR values less than 10 can cause excessive deflections and deterioration of pavements (*8*). As shown in the summarized CBR results of Table 3.8, all RAS contents tested resulted in a CBR below 10 for a compactive effort of 25 blows per layer. However, the observed CBR values remained above 10 for all RAS contents for compactive efforts greater than or equal to 56 blows per layer. Some of the results required a zero-correction by projecting the initial linear portion of the stress vs. penetration curve to the x-axis to determine the corrected origin, as outlined in ASTM D 1883-99. Figure 3.11 shows a typical test result that was slightly modified using this technique prior to determining the CBR value.

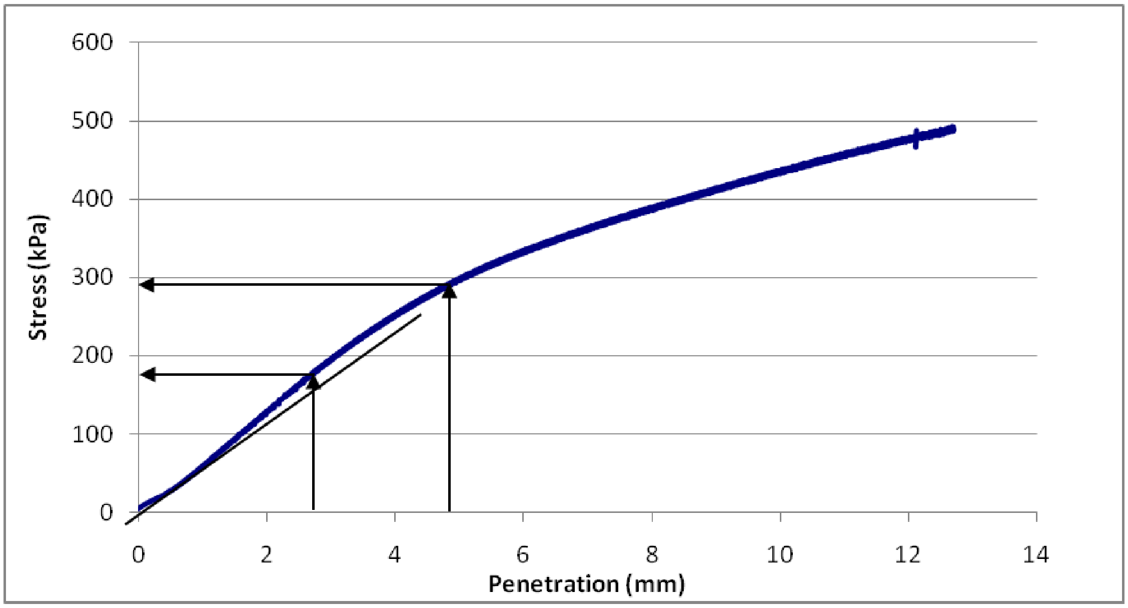

Figure 3.11: Typical CBR data curve

Table 3.8: California Bearing Ratios for RAS-soil mixtures

% RAS	Compaction Effort (blows/layer)	Dry Density (lb/ft^3)	Moisture Content	CBR
0	25	98.2	15.3%	8.3
	56	106.6	15.2%	20.4
	76	110.0	15.4%	22.0
10	25	95.3	14.8%	8.2
	56	104.1	14.9%	15.4
	76	108.2	14.8%	20.7
20	25	96.3	14.7%	7.5
	56	103.8	14.3%	13.7
	76	105.8	14.3%	18.0
30	25	93.2	14.0%	6.2
	56	102.6	13.7%	12.7
	76	105.0	13.6%	13.1

Additional CBR samples were prepared and soaked in water for 4 days. Samples compacted using 25 blows/layer and 56 blows/layer were tested for their CBR value after soaking. Table 3.9 shows the results of these tests. Unfortunately, the addition of RAS did not significantly improve the soaked CBR values of the loess. A third set of samples were compacted to within 95% of Standard Proctor density and soaked in water to measure their swell potential. The resulting swell data is shown in Figure 3.12.

Table 3.9: Soaked CBR results

% RAS	Compaction Effort (blows/layer)	Dry Density Before Soaking (lb/ft^3)	Soaked CBR Value
0	25	102.0	4.5
	56	109.6	8.0
10	25	100.3	5.1
	56	107.0	6.0
20	25	96.7	4.8
	56	105.2	6.9
30	25	95.7	4.3
	56	102.1	6.2

The results of the swell tests illustrate that as the RAS content increases, the amount of resulting swell decreases. Since the RAS is comprised of materials with low swelling potential these results are as expected for the loess-RAS mixtures.

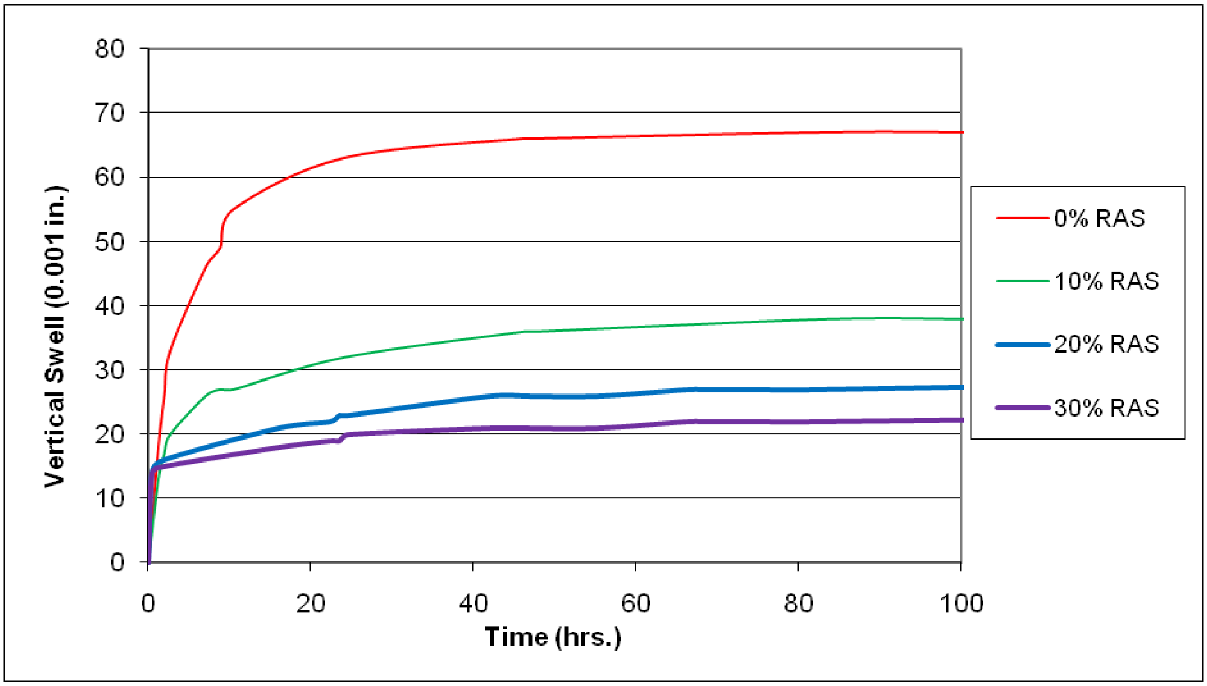

Figure 3.12: Soaked CBR swell observations

CONCLUSIONS

In this study, a preliminary investigation was carried out to examine the strength and compaction characteristics of a Western Iowa loess combined with post-consumer recycled asphalt shingles. The loess was prepared with 10, 20 and 30% RAS by dry unit weight and tested in compaction, unconfined compression, indirect tensile strength, and California Bearing Ratio tests. The following was determined:

- The addition of RAS resulted in decreases in maximum dry density and optimum moisture content.
- The addition of RAS resulted in a decreased swelling potential.
- The addition of RAS generally yielded lower indirect tensile strength and unconfined compressive strength values of the loess studied. However, a slight increase in indirect tensile strength was noted for the 20% RAS mixture compacted dry of optimum.

- In most cases, there was not a statistically significant difference in the indirect tensile strength and unconfined compressive strength values of the loess when blended with 10, 20 and 30% RAS at optimum moisture content.

The results of this research indicate that RAS can potentially be used to achieve a reduction in borrow materials and produce a lightweight fill for certain applications. The possible economic and environment benefits of using post-consumer recycled asphalt shingles in geo-materials warrants further study for different soil types and applications, and an improved understanding of their behavior under varying curing conditions as well as in-situ settings.

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CHAPTER 4. PHYSICAL AND MECHANICAL PROPERTIES OF MIXTURES CONTAINING FOUNDRY SAND AND POST-CONSUMER RECYCLED ASPHALT SHINGLES

A paper to be submitted to the ASCE Journal of Geotechnical and Geoenvironmental Engineering, ASTM Geotechnical Testing Journal or Transportation Research Record

Blake Rubino, Jeramy C. Ashlock, R. Christopher Williams

ABSTRACT

In this study, the effects of post-consumer recycled asphalt shingles (RAS) on the physical and mechanical properties of foundry sand are examined. By optimizing the combination of these two recycled materials to maximize the beneficial properties of each, an improved construction material is sought to provide a "green", sustainable, and economical option for use in geotechnical applications. Laboratory tests were performed to measure selected strength, compaction and permeability characteristics of foundry sand-RAS mixtures. The tests demonstrated that increasing the RAS content caused a decrease in the composite dry unit weight with little effect on the optimum moisture content. Falling head tests indicated that an increase in RAS content generally increased the permeability. Direct shear tests showed no apparent change in friction angle or cohesion under increasing RAS contents for air dried states, but exhibited a decrease in friction angle and increase in cohesion for mixtures tested at their optimum moisture content. California Bearing Ratios from uncured and un-soaked samples consistently decreased with increasing RAS content. To realize potential economic and environmental benefits, it is recommended that the beneficial use of RAS with other soil types and applications be examined.

INTRODUCTION AND BACKGROUND

Industrial byproducts historically disposed in landfills are increasingly being considered for beneficial use as pavement and geotechnical construction materials to reduce carbon footprints, minimize consumption of virgin materials, and boost economic profits. Foundry sand from iron, steel, and aluminum production are prime candidates for such beneficial uses. Approximately 9–10 million tons of sand is discarded by foundries each year in the United States. The foundry industry estimates that approximately 28% of this sand is currently directed towards beneficial use such as embankments, site development fills, and road bases *(1)*. However, the American Foundry Society has set a goal to increase this figure to 50% beneficial use by the year 2015*(2)*. Concurrently, approximately 10 million tons of post-consumer asphalt shingles are disposed of in landfills each year. Recent technological advances in recycling processes can deliver a consistent recycled asphalt shingle (RAS) product composed of materials commonly used in hot mix asphalt, including lime dust, high quality aggregate, fibers, and 20 to 30% percent asphalt binder*(3)*. The goal of this study is to perform a preliminary characterization of selected physical and mechanical properties of foundry sand-RAS mixtures to determine their suitability for beneficial use as construction materials.

EXPERIMENTAL PROCEDURES

For this investigation, a series of preliminary classification, strength, compaction and permeability tests were conducted using foundry sand from a foundry located in Bettendorf, Iowa to examine the potential usefulness of RAS-foundry sand blends in soil stabilization or soil modification applications. The foundry sand used is derived from the production of carbon, low alloy, armor, austenitic manganese, and stainless steel alloys by shell, green sand, and no-bake molding technologies supported by a vibratory sand reclamation system *(4)*. The RAS was collected by a shingle recycler in Minnesota and ground up using a conveyer fed grinder. The shingle material was passed through the grinding process multiple times to achieve the end gradation that was used in this research, see Table 4.1 for shingle gradation. Laboratory tests performed included Specific Gravity (ASTM D854) *(5)*, Absorption (ASTM C128) *(6)*, Standard Proctor (ASTM D 698-11a) *(7)*, California Bearing Ratio (ASTM D 1883-99) *(8)*, Permeability *(9)*, and Direct Shear (ASTM D3080-04) *(10).*

Recycled asphalt shingles with a maximum size of 3/8” and 95% passing the #4 sieve were used at treatment levels of 0%, 10%, 20%, and 30% by mass for the amendment of the foundry sand. Batches of foundry sand and RAS were combined with water necessary to achieve the desired moisture content and mixed manually by hand to prepare the test specimens which were immediately tested. Experimental procedures were similar to those described in a preliminary study of a mixture of RAS and Western Iowa Loess *(11)*. Figures 4.1 and 4.2 illustrate the appearance of the foundry sand and RAS materials.

Figure 4.1: Foundry sand

Figure 4.11: Recycled asphalt shingles

RESULTS, STATISTICAL ANALYSIS, AND DISCUSSION

Gradation Analysis

Sieve analysis results for the foundry sand and the RAS are shown in Table 4.1, with particle size distribution curves shown in Figure 4.3. The spent foundry sand was gap-graded due to residual metals from the casting process with approximately 80% of the material passing between 9.5 mm and 0.075 mm (No. 4 and No. 200) sieve sizes. Particles larger than 9.5 mm tended to be waste metals and spent welding sticks, with a small portion consisting of aggregate minerals. The foundry sand particle shape was typically round to slightly angular. The RAS material was uniformly graded with almost all the material passing between 9.5 mm and 0.075 mm (No. 4 and No. 200) sieve sizes and a uniformity coefficient of approximately 7.5. The RAS contained portions of slightly bituminous-covered sand particles to clumps of bituminous material with pieces of fabric or paper dispersed throughout the mixture. As the RAS was mixed with the foundry sand, the uniformity of the mixture gradation was observed to increased. The measured adsorption of the foundry sand alone was approximately 2.55%. When the RAS was added, the adsorption of the resulting mixture ranged from 1.87% to 1.75% for all three RAS treatment levels. The specific gravity of the foundry sand was determined to be 2.79, while the specific gravity of asphalt shingles is approximately 1.9. As RAS was added to the foundry sand, the specific gravity of the mixture therefore decreased as expected.

Table 4.1: Sieve analysis results

	Foundry Sand	RAS
Sieve Size	Percent Passing	Percent Passing
1 1/2"	100.0%	100.0
1"	92.5%	100.0
3/4"	91.0%	100.0
#4	83.9%	93.5
#8	80.2%	52.9
#16	74.9%	35.0
#30	67.5%	16.9
#50	37.0%	6.6
#100	5.5%	1.5
#200	3.6%	0.9

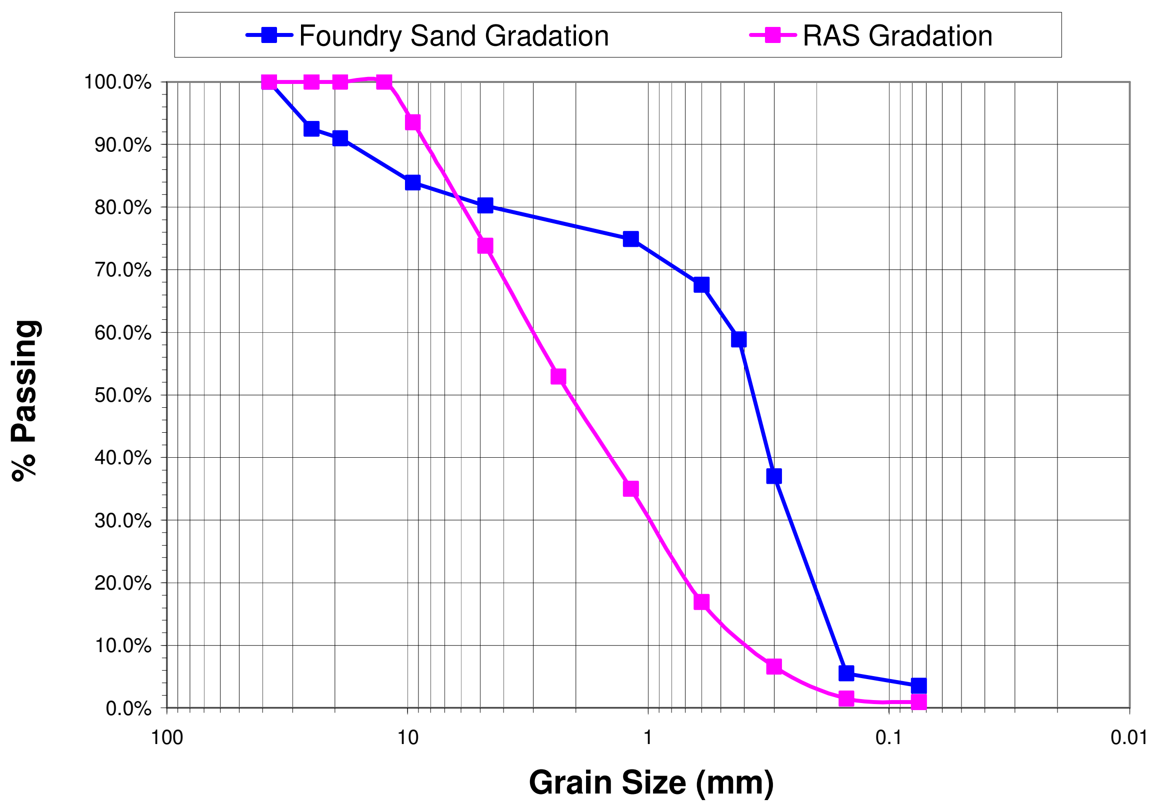

Figure 4.3: Foundry sand and RAS particle distribution

Standard Proctor Tests

Figure 4.4 illustrates the standard proctor compaction curves for the foundry sand with 0%, 10%, 20%, and 30% RAS content by dry mass. Relative density tests were not performed due to the cohesive nature of the material. As shown in Figure 4.4, the lower specific gravity of the RAS results in a decrease in dry unit weight of the mixture with increasing RAS content, but the optimal moisture content is relatively constant.

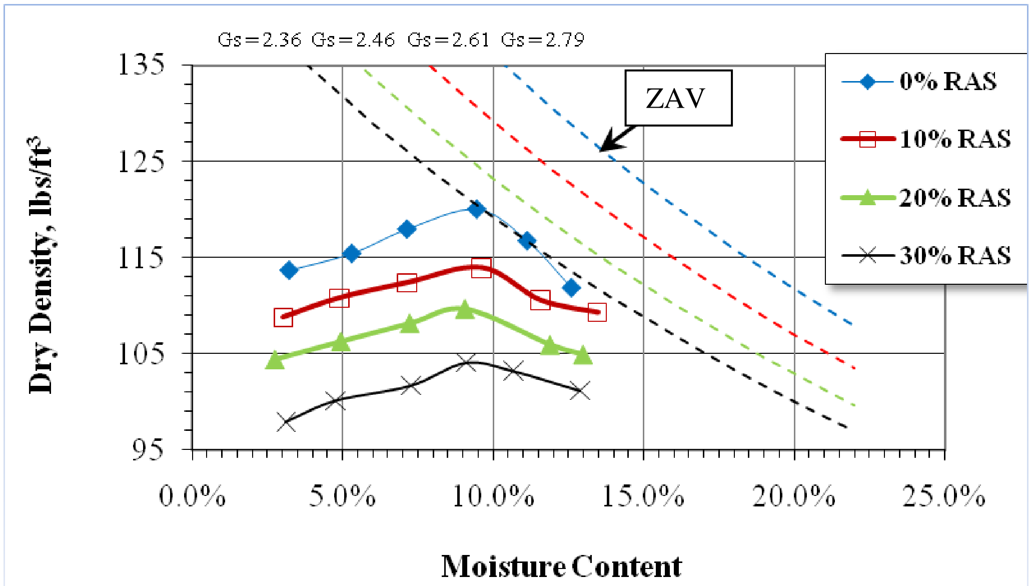

Figure 4.4: Foundry sand dry density-optimum moisture content curves

Table 4.2: Optimum moisture contents and maximum dry unit weights from Standard Proctor tests

% RAS	Optimum Moisture Content	Max. Dry Unit Weight (lb/ft^3)
0	9.5%	120.0
10	9.5%	114.0
20	9.5%	110.0
30	9.5%	104.0

All test samples were compacted within plus or minus 5% of the maximum dry unit weight reported in Table 4.2. For subsequent statistical analyses, it will be assumed that every RAS content corresponds to a unique maximum dry unit weight as indicated in

Table 4.2, which will result in a perfect correlation between these two variables. Therefore, only one of the variables will be treated as independent. The default independent variable will be the RAS content, as the focus of this paper is to characterize the properties of the soil mixture in terms of RAS content.

Permeability Tests

Falling head tests were used based upon foundry sand literature showing a large variability in permeability with a low coefficient value of 10^{-6} cm/s *(1)*. The test setup is shown in Figure 4.5 and test results are shown in Table 4.3. The addition of RAS to the foundry sand increased the permeability by an order of magnitude, the permeability reaching a maximum at 20% RAS and decreasing slightly at 30% RAS. Although the permeability of the 30% RAS mixture was significantly greater than that of the foundry sand, it is apparent that the water resistant properties of the asphalt binder may contribute to a reduction of permeability beyond an optimum RAS content. As the RAS is classified as a coarse-grained material with little fines, the eventual decrease in permeability may be related to the contribution of the RAS towards a more uniform gradation of the mixture. A statistical analysis of the permeability testing data set was performed to model the observed behavior in Table 4.3, and to test the mean similarities of the coefficients of permeability for the soil-RAS mixtures.

Figure 4.5: ELE International, Inc. model 25-0618 (K-610A) permeameter

Table 4.3: Summary of permeability results for RAS contents

% RAS	Mean Permeability (cm/sec)	Number of Trials	Std. Dev.	COV
0	1.80×10^{-4}	6	$6.89*10^{-6}$	3.8%
10	4.01×10^{-4}	6	$6.18*10^{-6}$	1.5%
20	1.35×10^{-3}	6	$1.15*10^{-5}$	0.85%
30	1.08×10^{-3}	6	$4.23*10^{-5}$	3.91%

The permeability model was designed as a polynomial function to illustrate the dimensionality of the test. The test can be divided into 3 dimensions, with the 3 dimensions representing the path the water takes through the cross section and height of sample. The model has a large F-statistic indicating statistical significance, a large $R^2_{adj.}$ value indicating a good fit, and parameters with low p- values indicating their statistical significance within the model. Table 4.5 shows a statistical difference in mean permeability's between the four different levels of RAS

Table 4.4: Permeability statistical model

Permeability Model		
Model	**F-Statistic**	**$R^2_{adj.}$**
(Permeability) = $6.39*10^{-4} + 1.03*10^{-4} * (\%RAS) + 1.23*10\text{-}6 * (\%RAS)^2 + 3.24*10\text{-}7 * (\%RAS)^3$	3755.23	0.998
Parameter Estimates	**t - Ratio**	**p - Value**
Intercept	-28.15	< 0.0001
(%RAS)	71.79	< 0.0001
$(\%RAS)^2$	-27.2	< 0.0001
$(\%RAS)^3$	-48.31	< 0.0001

Table 4.5: Means similarity test of permeabilities[2]

		RAS Content			
		0	10	20	30
RAS Content	0	-2.6585E-05	1.9392E-04	1.1428E-03	6.5259E-04
	10	-	-2.6585E-05	9.2226E-04	6.5259E-04
	20	-	-	-2.6585E-05	2.4309E-04
	30	-	-	-	-2.6585E-05

[2]Shows the difference in treatment means minus LSD, therefore positive values indicate pairs of means that are significantly different

Direct Shear Tests

Direct shear tests were conducted to determine the drained strength parameters of the foundry sand and foundry sand-RAS mixtures using the GeoTAC DigiShear device (Figure 4.6). All samples were tested at air dried as well as optimum moisture contents, with compaction by tamping to within plus or minus 5% of maximum dry unit weight. Each specimen was sheared at a rate of 0.004 in/min. This shearing rate was used to allow for dissipation of pore pressures and to establish a smooth curve. Samples were tested under normal stresses of 5, 15, 30, 75, and 120 psi, representative of typical loading conditions in pavements *(11).* A statistical analysis of the direct shear data was performed to determine the quality of fit of the regression analysis on the shear data. The results of the direct shear testing are shown in Figures 4.7 through 4.15 and Table 4.6.

Figure 4.6: GeoTAC DigiShear direct shear apparatus

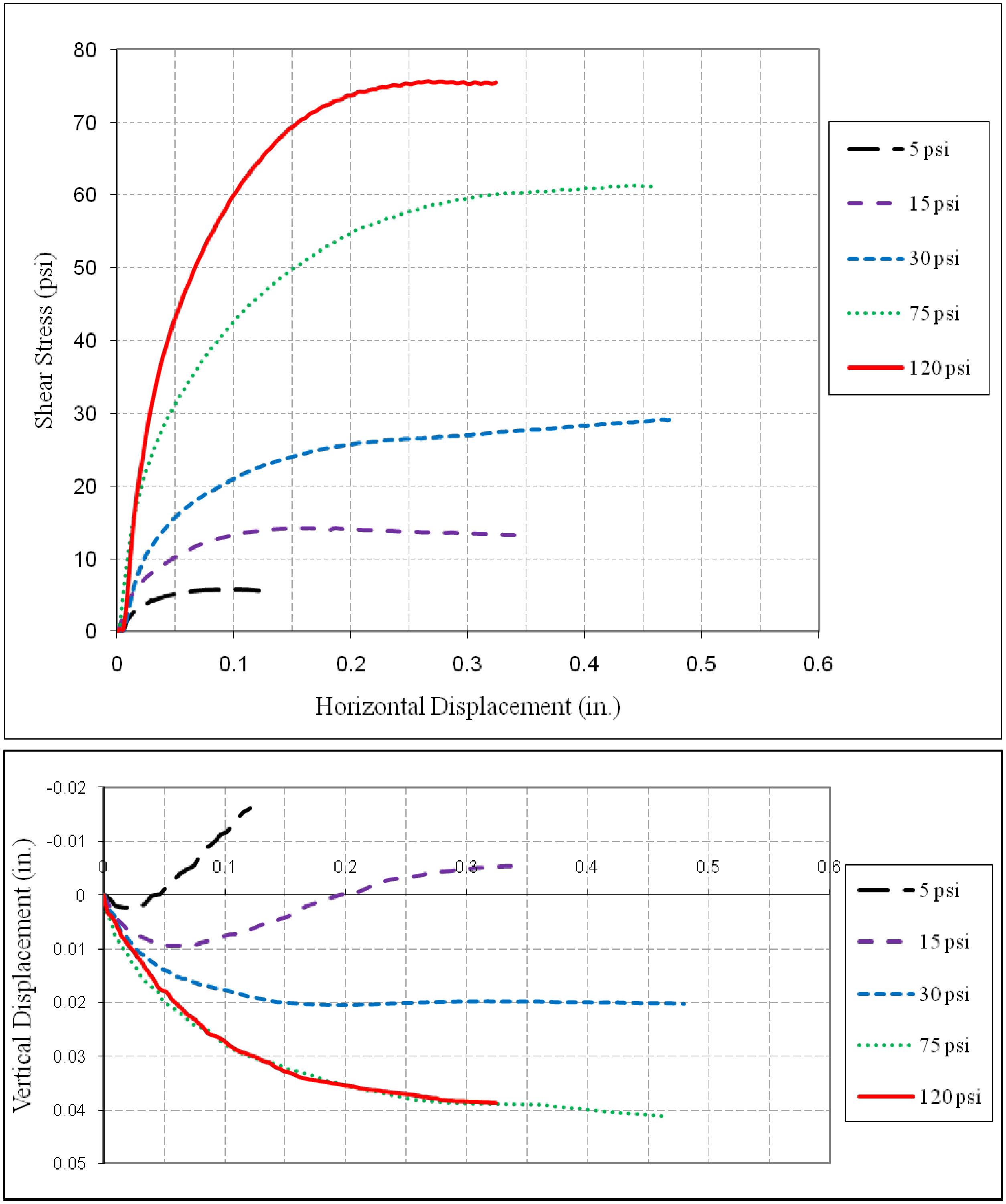

Figure 4.7: Typical direct shear test results for OMC foundry sand-RAS mixtures at RAS content of 30%

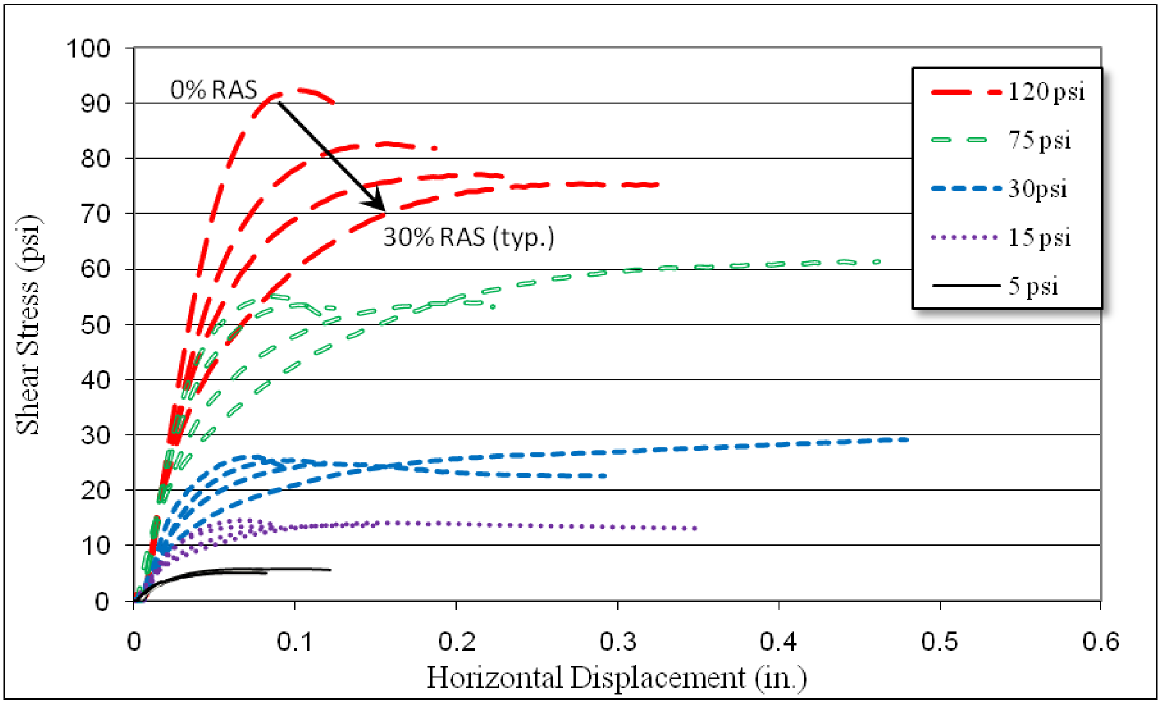

Figure 4.8: Typical shear stress vs. displacement results for foundry sand-RAS mixtures at OMC

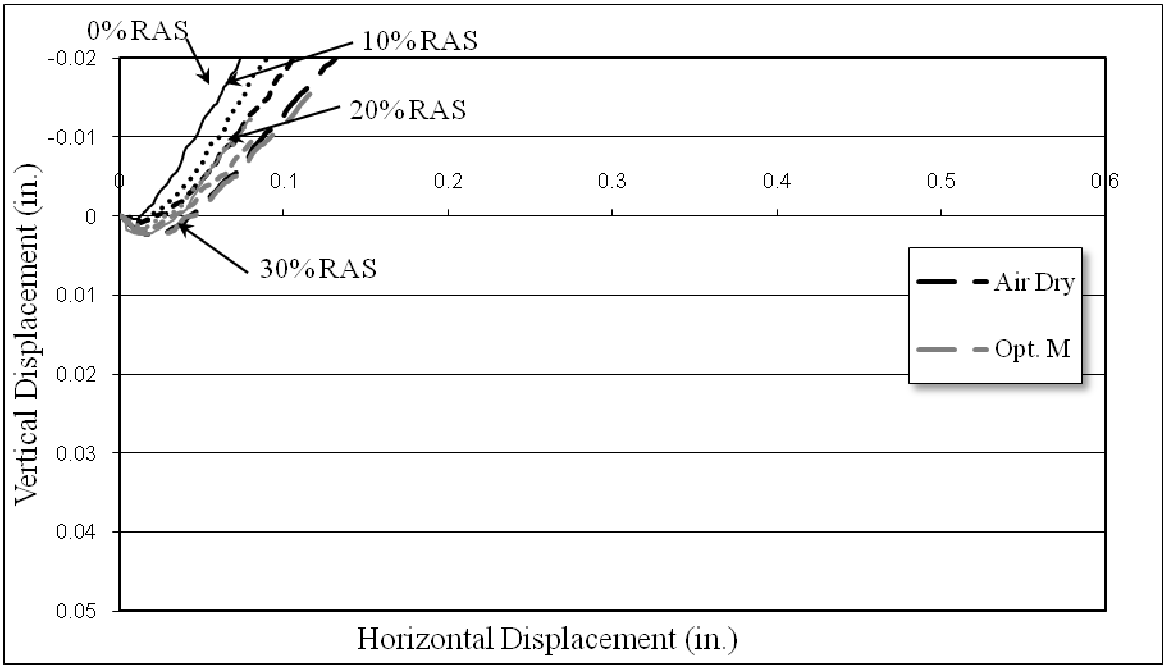

Figure 4.9: Vertical vs. horizontal displacement for all RAS contents at air-dry and optimum moisture contents (5 psi normal stress)

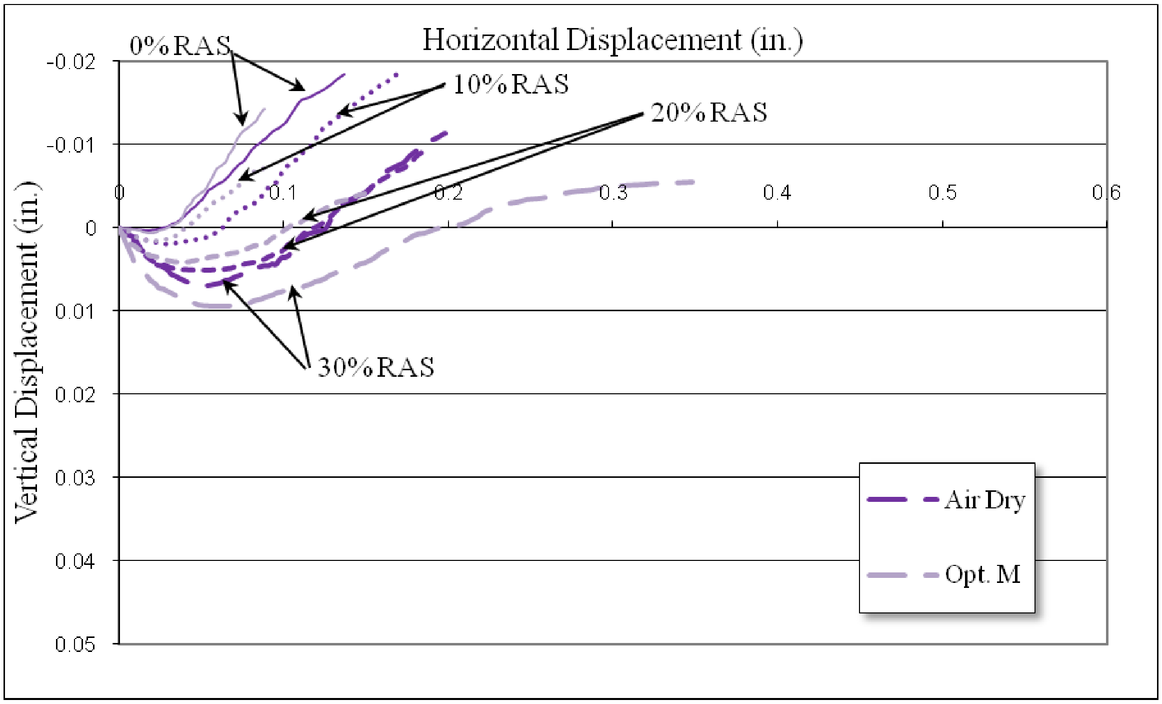

Figure 4.10: Vertical vs. horizontal displacement for all RAS contents at air-dry and optimum moisture contents (15 psi Normal Stress)

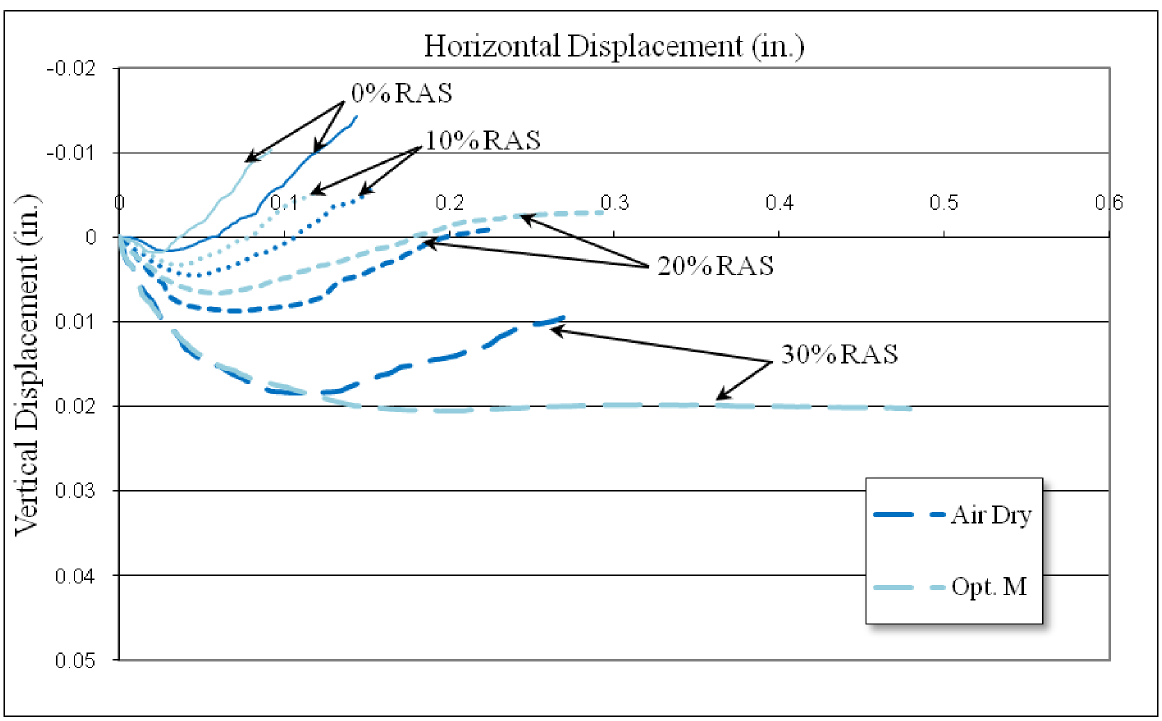

Figure 4.11: Vertical vs. horizontal displacement for all RAS contents at air-dry and optimum moisture contents (30 psi Normal Stress)

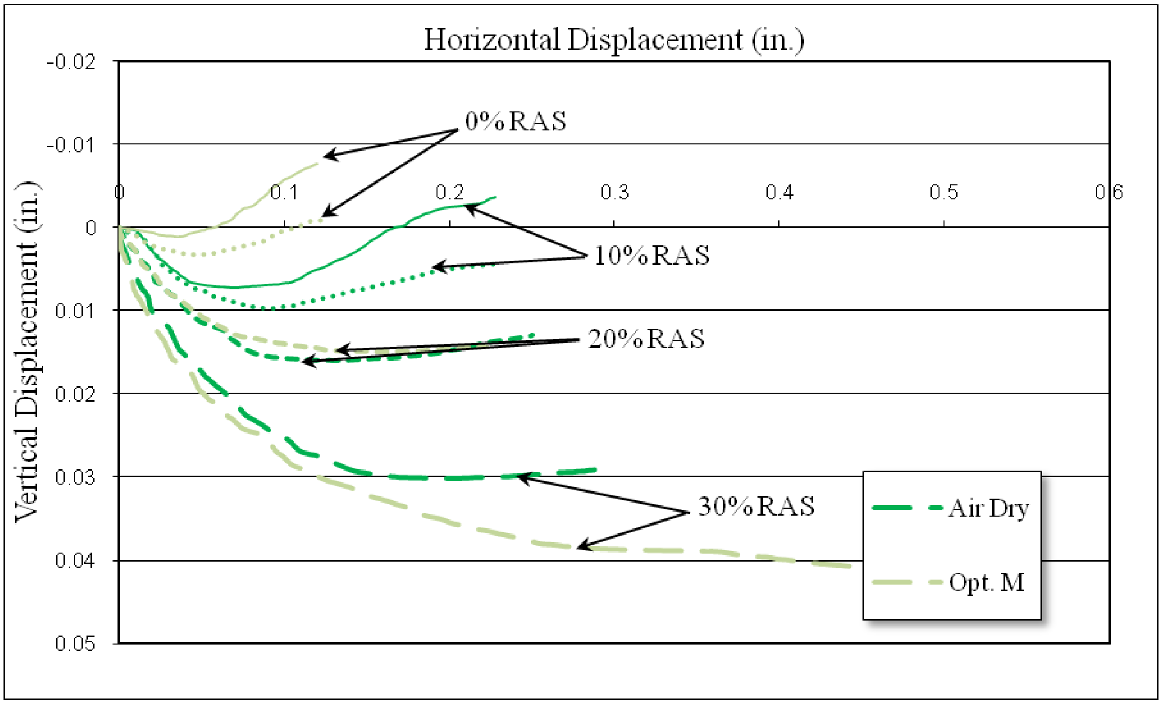

Figure 4.12: Vertical vs. horizontal displacement for all RAS contents at air-dry and optimum moisture contents (75 psi Normal Stress)

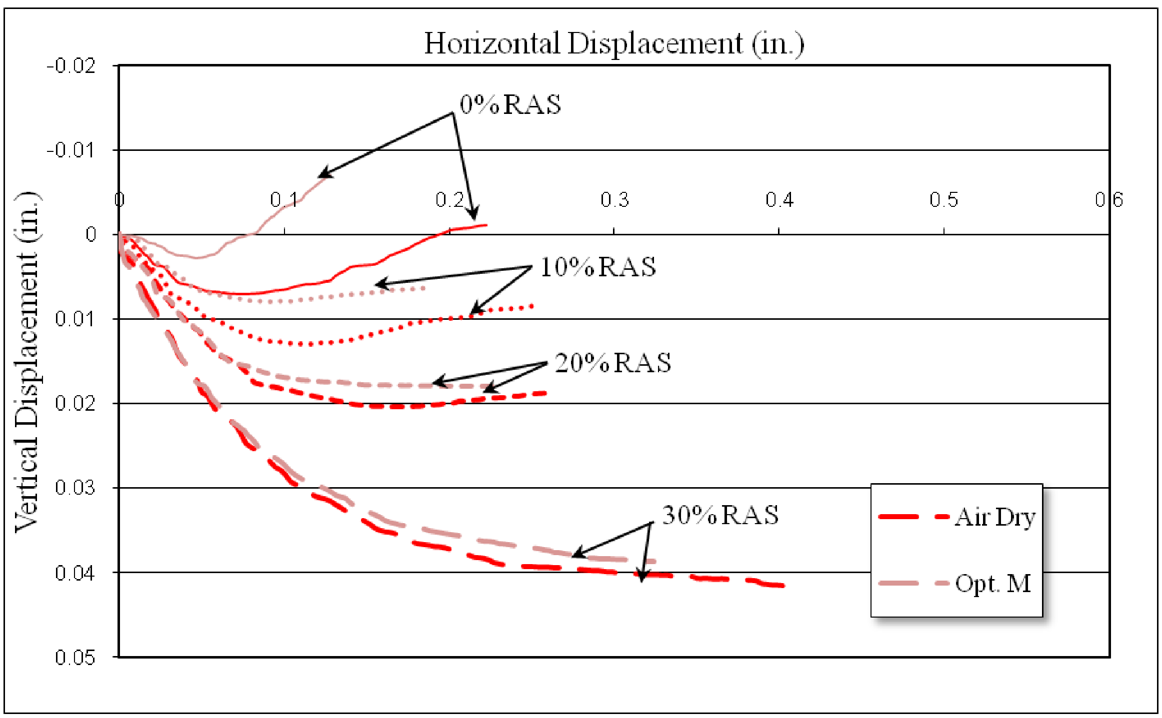

Figure 4.13: Vertical vs. horizontal displacement for all RAS contents at air-dry and optimum moisture contents (120 psi Normal Stress)

Table 4.6: Summary of direct shear results

% RAS	Air Dry		Opt. Moisture	
	ϕ	c (psi)	ϕ	c (psi)
0	36.7°	5.15	36.4°	2.71
10	36.3°	4.17	33.5°	3.78
20	36.1°	4.87	31.9°	4.48
30	37.7°	5.58	31.7°	7.00

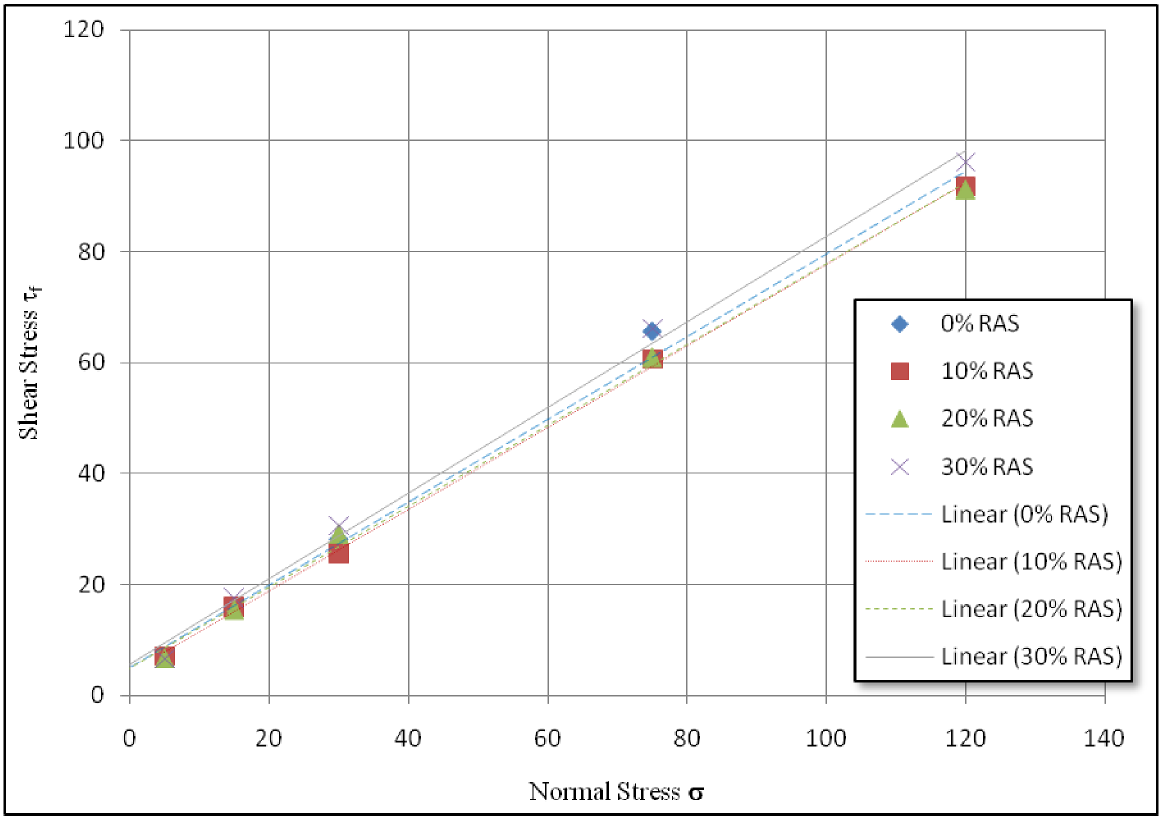

Figure 4.14: Air dry direct shear Mohr-Coulomb envelopes

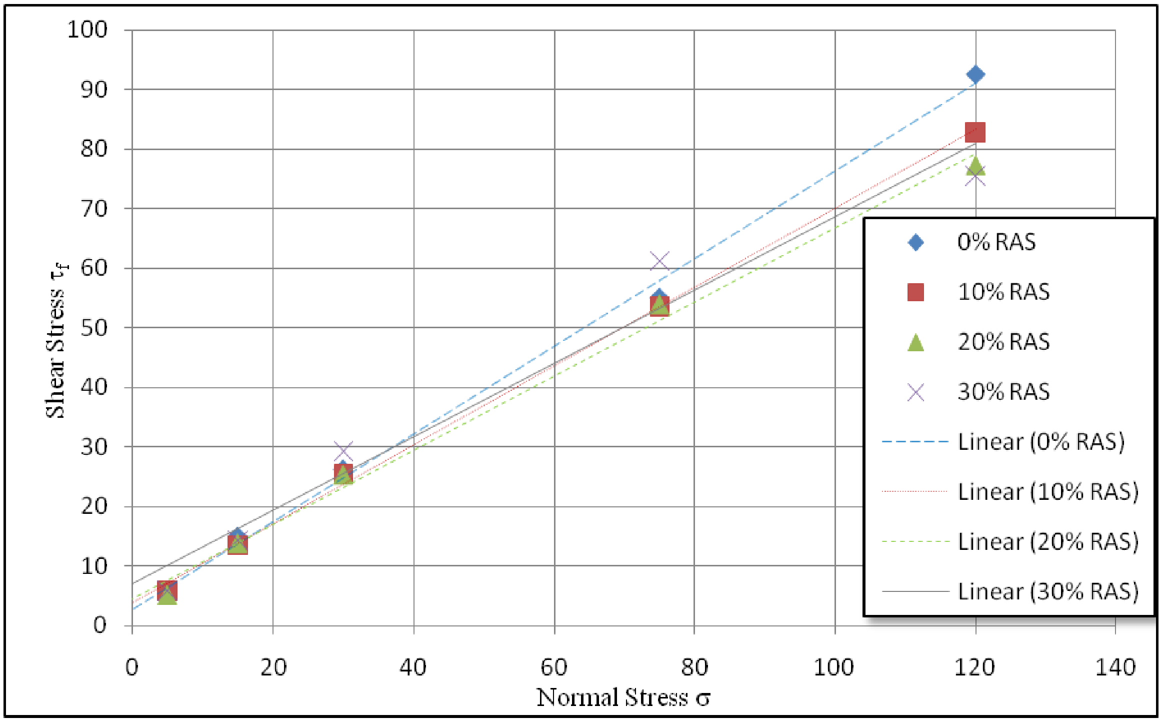

Figure 4.15: Optimum moisture direct shear Mohr-Coulomb envelopes

The shear stress vs. shear displament results of Figure 4.6 indicate that as the RAS content increases, the behavior transitions from brittle to ductile failure, or from that of a dense to a loose sand. Figures 4.7 to 4.11 also illustrate a systematic transition from contractive to dilative behavior with increasing RAS content. The control sample without RAS behaves like a dense sand, exhibiting dilation for the range of normal stresses examined. The transition to a contractive behavior similar to that of a loose sand is likely due the RAS initially creating greater separation of the sand grains prior to shearing, after which the compressibility of the RAS leads to contraction of the sand grains during the shearing phase. Tables 4.7 and 4.8 summarize the statistical analysis of the direct shear test results (τ_f) for the air dried and optimum moisture conditions and RAS, respectively. The Mohr-Coulomb strength parameters, ϕ and c, are derived from statistical analysis of the direct shear test data and are summarized in Table 4.6.

Table 4.7: Summary of direct shear regression analysis for mixtures at air dried moisture contents

Air Dry 0% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.7448 * \sigma_n + 5.1468$	426.93	0.993
Air Dry 10% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.7359 * \sigma_n + 4.1671$	4064.81	0.999
Air Dry 20% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.7305 * \sigma_n + 4.8668$	1172.55	0.997
Air Dry 30% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.7718 * \sigma_n + 5.5755$	701.01	0.995

Table 4.8: Summary of direct shear regression analysis for mixtures at optimum moisture contents

Opt. Moisture 0% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.7362 * \sigma_n + 2.7082$	996.18	0.996
Opt. Moisture 10% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.6621 * \sigma_n + 3.7808$	2528.55	0.998
Opt. Moisture 20% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.6226 * \sigma_n + 4.4797$	488.23	0.993
Opt. Moisture 30% RAS		
Model	**F-Statistic**	**$R^2_{adj.}$**
$\tau_f = 0.6167 * \sigma_n + 7.0027$	81.22	0.964

Tables 4.7 and 4.8 define the linear regression model for each sand-RAS mixture for the air dry and optimum moisture conditions, respectively. Each model has a large F-statistic indicating the model's statistical significance, and high $R^2_{adj.}$ values indicating a good fit. These models were used to obtain the values of cohesion and friction angle shown in Table 4.8. There does not appear to be a clear trend among air dried friction angles and cohesions with increasing RAS content. However, samples tested under optimum

moisture conditions exhibited a decrease in friction angle and an observed increase in cohesion with increasing RAS content.

Table 4.9: Direct Shear Statistical Model

Model	**F-Statistic**	**$R^2_{adj.}$**
τ_{max} (psi) = $7.05 + w\,\beta + 0.700\,\sigma$	1240.37	0.985
Parameters	**t - Ratio**	**p - Value**
Intercept	6.40	< 0.0001
Moisture Content, *w*	-3.86	0.0004
Normal Stress, σ	49.66	< 0.0001

Air dry: $\beta = 0$, Optimum moisture content: $\beta = -4.68$

The direct shear statistical model was designed to estimate the shear strength as a function of moisture content and normal stress, as the latter are the two statistically significant variables.

California Bearing Ratio Test

To investigate the potential use of foundry sand-RAS mixtures as a sub-grade for pavement foundations, unsoaked California Bearing Ratio (CBR) tests with a surcharge load of 10 lbs were conducted using a UTM-25 servo-hydraulic testing machine as shown in Figure 4.14. CBR samples were prepared in 3 layers with 35 blows per layer using a mechanical soil compactor, with target moisture contents and dry unit weights equal to the optimum Standard Proctor values given in Table 4.2. A statistical analysis of the CBR data was performed to establish predictive models to determine the relationship between dry unit weights and CBR, and the relationship between CBR and RAS contents.

Figure 4.16: CBR Test setup in IPC Global UTM-25 Universal Testing Machine

The test data summarized in Table 4.10 indicate that an increasing RAS content results in an exponential decrease of CBR value, which is also illustrated in Figure 4.16. All RAS contents tested resulted in a CBR below 10 for the compactive effort of 35 blows per layer. As shown in Figure 4.15, the CBR tends to have a strong correlation to dry unit weight.

Table 4.10: Summary of CBR results

% RAS	Dry Unit Weight (lb/ft^3)	Moisture Content	CBR
0	122.6	8.9%	18.5
	119.8	9.6%	21.1
10	114.5	9.1%	9.6
	115.0	8.5%	9.2
20	105.6	9.3%	5.2
	106.1	9.4%	5.4
30	99.4	8.4%	3.7
	101.0	8.9%	3.3

The statistically significant variable when determining the CBR value was RAS content, which may be correlated to the dry unit weight. Two models were developed using exponential relationships. Table 4.11 illustrates the modeled relationship between CBR and dry unit weight, and Table 4.12 illustrates the CBR dependency upon the RAS content, which can be correlated to dry unit weight. As shown in Table 4.12 and Figure 4.16, CBR values were seen to exhibit an exponential dependence on RAS content (or alternatively, dry unit weight).

Table 4.11: Summary of CBR-dry unit weight regression analysis

Model	**F-Statistic**	**$R^2_{adj.}$**
$(CBR) = \dfrac{e^{0.11\gamma d}}{30375}$	224.31	0.974
Parameter Estimates	**t - Ratio**	**p – Value**
Intercept	-12.49	< 0.0001
Dry Unit Wt., γ_d	14.98	< 0.0001

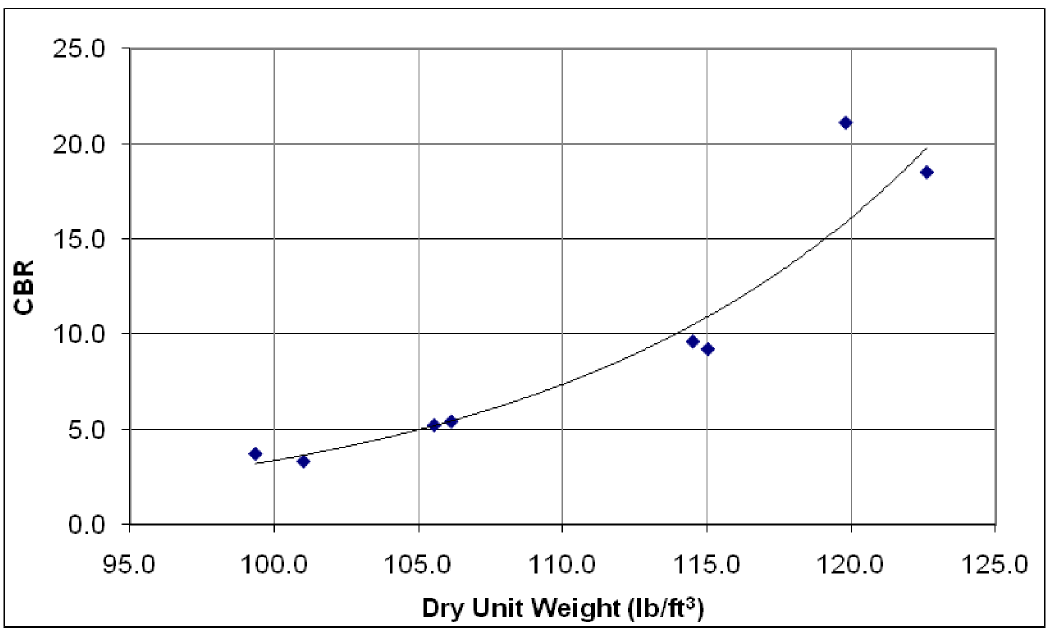

Figure 4.17: Relationship between CBR and dry unit weight

Table 4.12: Summary of CBR-RAS content regression analysis

Model	**F-Statistic**	**$R^2_{adj.}$**
$(CBR) = 18.17\ e^{-0.058*(\%RAS)}$	284.68	0.976
Parameter Estimates	**t - Ratio**	**p – Value**
Intercept	45.35	< 0.0001
(%RAS)	-16.87	< 0.0001

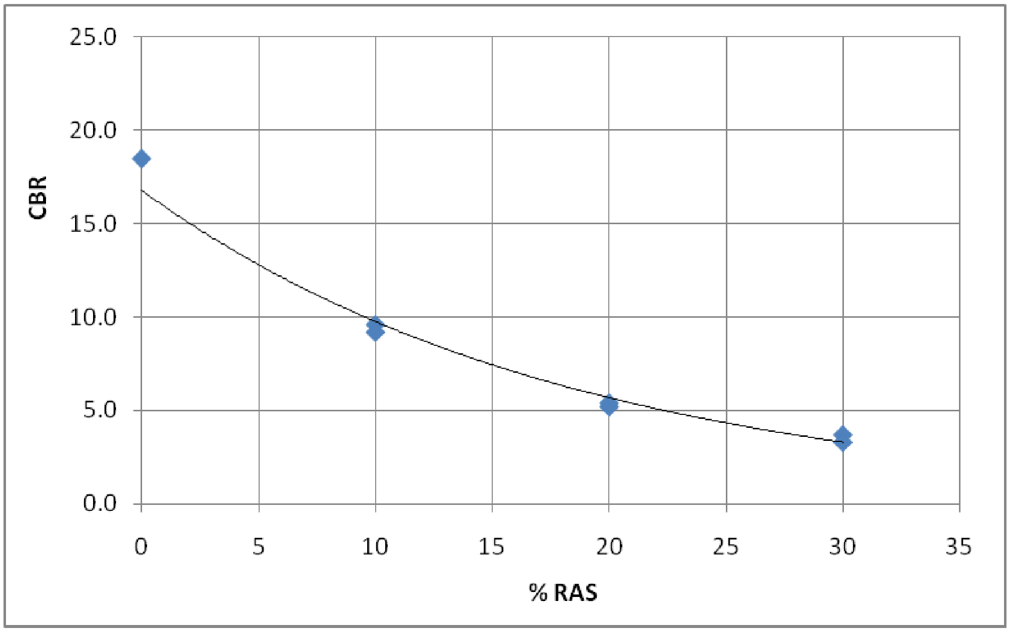

Figure 4.18: Dependence of CBR values on RAS content

CONCLUSIONS

In this study, a preliminary investigation was carried out to examine the effects of post-consumer recycled asphalt shingles on the physical and mechanical properties of foundry sand for use in geotechnical applications. When determining how the foundry sand and RAS materials may be used in geotechnical applications, three main criteria should be considered:

1. Are the materials technically advantageous to use?
2. Are they safe?
3. Are they economical?

The particle size distributions indicate that an increase in RAS content will lead to a more uniformly graded material. The increase of RAS also causes a decrease in dry unit weight and adsorption. Falling head tests showed that permeability increased with an increase in RAS, with a maximum value observed near a RAS concentration of 20%. Increasing the RAS content was also seen to cause a transition from a dilative to a contractive behavior under shearing, likely due to the compressibility of RAS. CBR test results imply that an increase in RAS content decreases the soil mixture's suitability for subgrade, subbase, and base course applications. The CBR value appears to have a strong dependence on dry unit weight. Further testing is recommended to evaluate the appropriateness of the material for specific applications.

Many states have independent criteria and specifications pertaining to the reuse of foundry sand and RAS. Although approximately 80% of spent foundry sand passes the TCLP standard *(13)*, it may not be acceptable for all applications. Standardized testing and regulations need to be developed for use nationwide to determine the acceptability of these materials, and particular approved uses for geotechnical applications.

The potential economical and environmental impacts of the use of foundry sand-RAS mixtures are not yet fully understood. Many variables should be addressed when considering their beneficial use, such as the distance the materials must be transported, the costs of natural aggregates and virgin binders, the relative performance in engineering applications, the public's interest and perception, environmental safety, and the engineer's/contractor's design and construction abilities.

The results of this research indicate that the use of RAS and foundry sand in geotechnical applications could possibly provide economic and environment benefits. Further investigation of clean sand as well as other soil types is recommended, as well as studies of the behavior of RAS under varying mixing temperatures and curing methods. Cyclic testing and freeze-thaw studies would also be useful for evaluation of the long-term performance as a sub-base or subgrade material. Due to somewhat mixed results between the direct shear and CBR data, it is recommended that resilient modulus, triaxial and in-situ testing be investigated for the mixtures of foundry sand and recycled asphalt shingles.

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CHAPTER 5. THE EFFECTS OF POST CONSUMER RECYCLED ASPHALT SHINGLES ON HMA AND ITS PERFORMANCE

A paper to be submitted to the T&DI Green Highway Conference, 2010, Denver, CO.

Blake Rubino, R. Christopher Williams, Jeramy C. Ashlock

ABSTRACT

In recent decades, the use of post-consumer recycled asphalt shingles (RAS) in hot mix asphalt (HMA) has gained acceptance and become an increasingly common practice. To date, however, relatively little research has been done to quantify the effects of RAS on the volumetric properties of HMA. To address this knowledge gap, an investigation was carried out to evaluate the effects of RAS on aggregate gradation and performance of HMA. Three mix designs containing five percent RAS and three control mix designs without RAS were designed with different aggregate gradations containing limestone, gravel, and concrete sand. Laboratory samples were prepared for dynamic modulus and flow number testing, with the results evaluated using statistical methods. The tests indicate that all of the mixes containing RAS achieved a reduction in the amount of virgin binder required, with minimal overall effects on the performance measures evaluated. One of the key findings is that the influence of RAS on the volumetric properties of HMA can vary depending upon the type of HMA gradation, suggesting not only that the binder in RAS can replace a portion of the virgin binder, but also that the other components of RAS can act as fillers, further reducing the amount of virgin binder required.

INTRODUCTION AND BACKGROUND

It is currently estimated that 10 million tons of post-consumer asphalt shingles are disposed of in landfills each year. Asphalt shingles are comprised of the same four basic materials used in hot-mix asphalt, including fiberglass or cellulose backings (for stone mastic asphalt mixes), lime dust (often used as an anti-stripping agent in HMA), granules/sand and 20 to 30% asphalt cement (binder) by weight (Northeast Recycling

Council 2007). Recent advancements in specialized grinding and sorting processes are enabling the production of more consistent RAS than could be achieved in recent years. Additionally, shingle recyclers are increasingly following asbestos testing protocols and QA/QC standards to ensure removal of non-asphalt construction debris such as wood, nails and felt. Many states now allow the beneficial re-use of waste shingles from manufactured scrap and post consumer waste sources in pavement and geotechnical applications.

Clear economic and environmental benefits are being realized through a reduction in the volume of waste shingles sent to landfills and decreased use of virgin asphalt (McGraw et al 2010, Scholz 2010). The addition of waste materials to pavements is not a new idea. Recycled asphalt pavement (RAP), and shredded tires have both been used in HMA design to reduce costs both environmentally and monetarily. A substantial impetus in using RAS in HMA is the higher prices of asphalt binder, reaching $700/ton in 2008, as compared to historical prices. Further, the processing of RAS through industrial grinders has greatly improved in the past 10 years, primarily through the utilization of hammermill type grinding technologies.

Some of the earliest published literature on the use of post-manufacturer recycled shingles in HMA was done by Emery and MacKay (1991), who accurately identified the limiting factors to utilizing RAS in pavement construction today: material variability; collection, storage and processing costs; lack of technical guidance and specifications; environmental constraints; and agency conservatism. Research completed on post-manufacturer recycled shingles has demonstrated that the material can perform as well as or better than standard HMA mixes (Watson et al 1998; Foo et al, 1999; Reed 1999; Amirkhanian and Vaughan 2001).

Button et al (1996) and Abdulshafi et al (1997) found that a finer grind produces a more consistent and better performing mix. Button et al (1996) also found that a finer ground post consumer RAS would increase the tensile strength of the mix more than a coarser grind. More recently, McGraw et al (2010) found that a finer grind size will activate higher percentages of asphalt binder from the RAS, while eliminating the likelihood of nails being found in the mix.

EXPERIMENTAL PROCEDURES

Figure 5.1 illustrates the RAS gradation as received from a supplier of post consumer RAS. The RAS used in this study had a G_{mb} of 1.9, and binder content of 28.4%. Three mix designs were prepared using limestone, river gravel, and concrete sand. The gradations of these three mixes were designed to allow an evaluation of the effect of RAS on fine, intermediate, and coarse gradations (see Figure 5.2). The Superpave mix design manual recommends that the aggregate gradation passes below the restricted zone as in gradations 2 and 3. This is not a requirement with gradations being allowed to be above or even through the restricted zone by some owner/agencies (The Asphalt Institute 2001). Limestone, river gravel, and concrete sand were chosen as the aggregates because they are readily available and commonly used for asphalt mix design in the Midwest portion of the United States. The binder used to make the samples was a PG 64 – 22. The 64 -22 performance grade is commonly used in the central portion of the United States. A level of 5% RAS is typically allowed in the asphalt design within states currently pursuing this technology. Five samples of the three gradations were generated with and without RAS for a total of 30 samples.

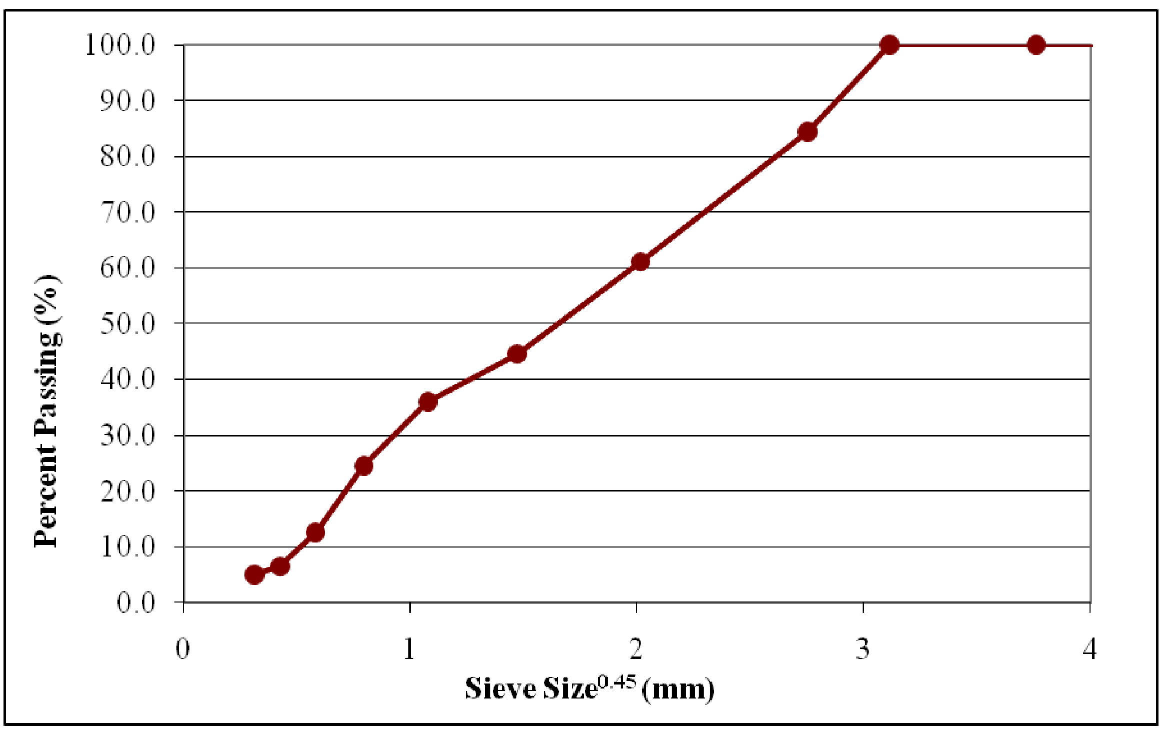

Figure 5.1: As-received RAS gradation

Aggregate was prepared by placing it in an oven overnight at 150° Celsius. The RAS was oven dried for 2-3 minutes before mixing, added to the heated aggregate at 5% by mass, then mixed and allowed to rest in the oven for 1-2 minutes before the virgin binder was added. After mixing, the samples were placed in an oven at 130 ° Celsius and allowed to cure for 2 hours where they were turned after the first hour. Varying asphalt contents were mixed and compacted at 100 gyrations using a gyratory compactor. Mix designs were done and the asphalt content at 4.0% air voids was determined as the optimum virgin binder content which is summarized in Figure 5.3.

Dynamic modulus and flow number samples were prepared in a similar fashion, with a target compacted air void content of 7.0%, as this is a commonly accepted value for newly constructed HMA pavements. All samples were compacted to within 7%+/-1% air voids as shown in Table 5.1.

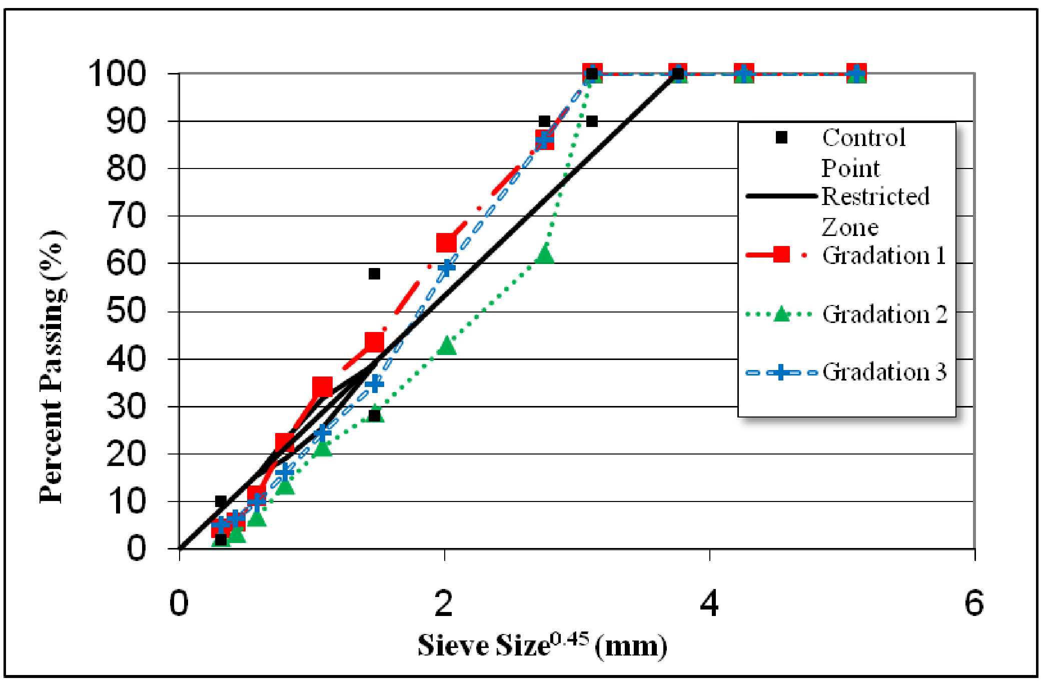

Figure 5.2: Sieve gradations of mix designs evaluated

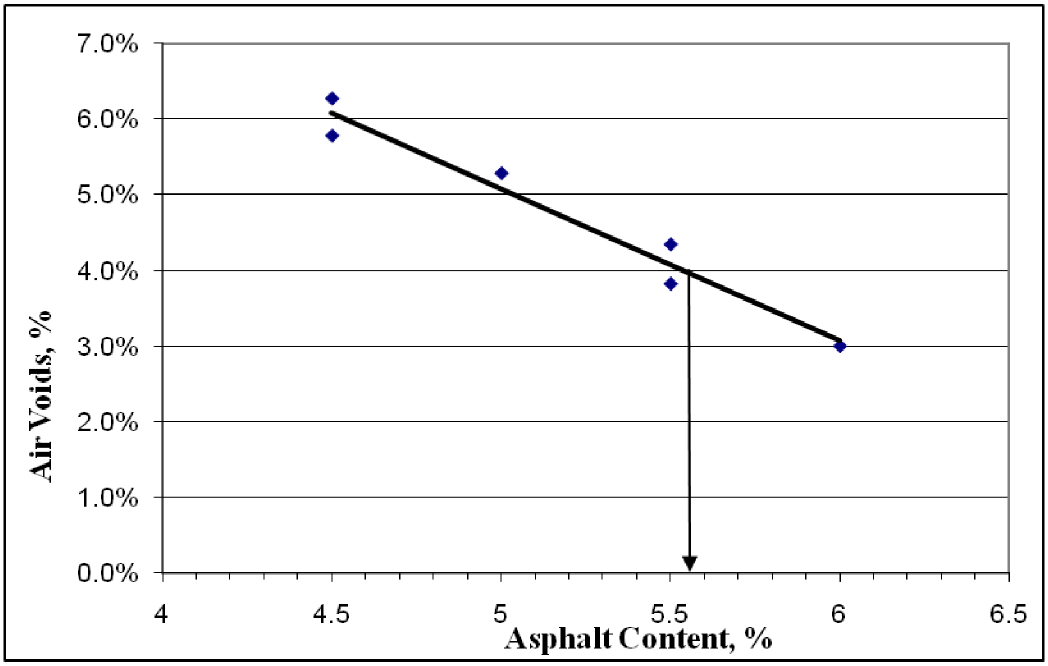

Figure 5.3: Example of optimum asphalt content determination

Table 5.1: Compacted air voids values for dynamic modulus and flow number samples

Gradation	1	1 + R	2	2 + R	3	3 + R
Sample A	7.49%	7.92%	7.90%	7.67%	7.28%	6.32%
Sample B	6.76%	7.58%	7.46%	7.16%	7.28%	6.80%
Sample C	6.90%	7.53%	7.28%	7.52%	7.27%	6.72%
Sample D	7.38%	7.22%	7.34%	7.70%	7.48%	6.93%
Sample E	7.59%	6.87%	7.56%	7.37%	7.36%	7.24%
Average	7.22%	7.42%	7.51%	7.48%	7.33%	6.8%

RESULTS, STATISTICAL ANALYSIS AND DISCUSSION

The volumetrics and asphalt requirements of each gradation with and without RAS are shown in Table 5.2. Gradation 2 utilized the largest amount of asphalt from the shingles, producing a 2.20% reduction in virgin binder. Gradation 1 had a reduction of 1.97% and Gradation 3 had a reduction of only 10% virgin asphalt binder. These results indicate that a finer blend (e.g. Gradation 2), will lead to the greatest reduction in virgin asphalt binder required for HMA design. It should also be noted that the addition of RAS reduced the voids in mineral aggregate (VMA) of the samples. Gradations 1, 2, and 3 resulted in VMA reductions of 3.2%, 0.8%, and 1.9%, respectively. The voids filled with asphalt (VFA) values are also presented in Table 5.2. A negligible 1.0% change in VFA was observed between samples containing RAS and those without. A typical minimum VMA value for 12.5 mm nominal aggregate size is 14.0%. The VMA values of the three gradations were all less than 14.0%. For reference, typical Superpave design VFA values range from 65% to 80%.

Table 5.2: Mix design binder content contrast

Gradation	Shingle Content	Optimum Virgin Binder Content	VMA	Δ Virgin Binder Content	Δ VMA	VFA	Δ VFA
1	0.0%	6.45%	12.5%	-1.98%	-0.4%	66.0%	+1.0%
1R	5.0%	4.48%	12.1%			67.0%	
2	0.0%	5.55%	12.9%	-2.20%	-0.1%	69.0%	0.0%
2R	5.0%	3.35%	12.8%			69.0%	
3	0.0%	5.30%	11.5%	-0.53%	-0.2%	64.0%	+1.0%
3R	5.0%	4.77%	11.3%			65.0%	

There is a maximum of 1.4% usable asphalt binder in the 5% RAS, (28.4% * 5% = 1.4%) added to the asphalt mix. However, Gradations 1 and 2 had changes in virgin binder contents greater than 1.4%. The RAS is thus potentially acting as a filler and/or it is reducing the internal friction of Gradations 1 and 2 during compaction. Gradation 3 had a reduction in virgin binder content of less than 1.4%. In fact the binder utilization from the RAS for Gradiation 3 is quite low at 0.53% compared to the other two gradations. In other words, only 37% of the possible 1.4% asphalt binder available is used for Gradation 3. In contrast, previous research has shown that the average useable binder from studied RAS mixes is typically 60% or more (Marasteanu et al 2007).

Dynamic Modulus Testing

The dynamic modulus test results are represented in the form of a sigmoidal function master curve. Each specimen was tested at temperatures of 4^{o}, 21^{o}, and 37^{o} Celsius. The resulting data is empirically modified using a non-linear least squares regression method to create shift factors that allow the sigmoidal master curve to be correlated to the different test temperatures. The sigmoidal function asymptotes at low and high frequencies represent the limiting mix stiffness at high and low temperatures, respectively (Witczak 2002, Bonaquist et al 2003, Williams and Breakah 2010).

Figures 5.4 through 5.6 contrast the samples containing RAS with the control samples. As mentioned above, the lower frequencies represent the samples at high temperatures while the higher frequencies represent the samples at low temperatures. Figures 5.4 through 5.6 illustrate a similarity between the samples with and without RAS at mid to high frequencies, while the differences at low frequencies for all gradations show a definite increase in stiffness for all mixtures containing RAS.

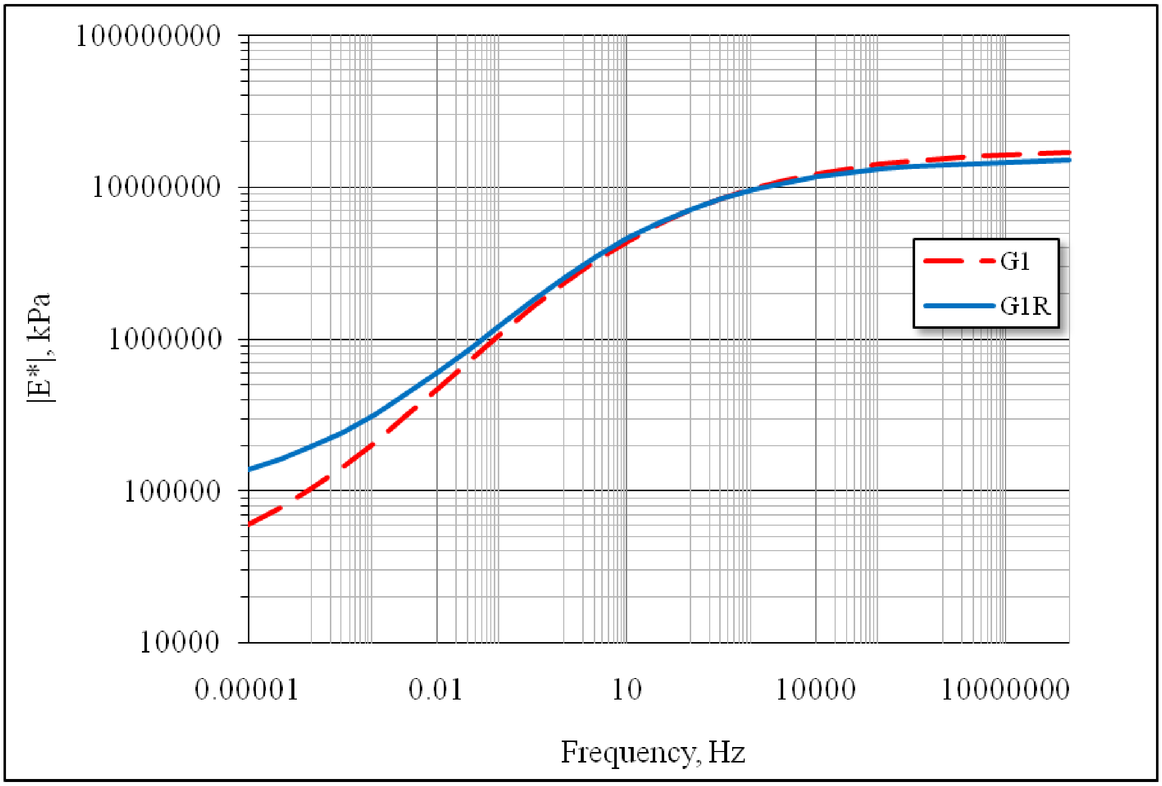

Figure 5.4: Gradations 1 and 1R dynamic modulus master curve comparison

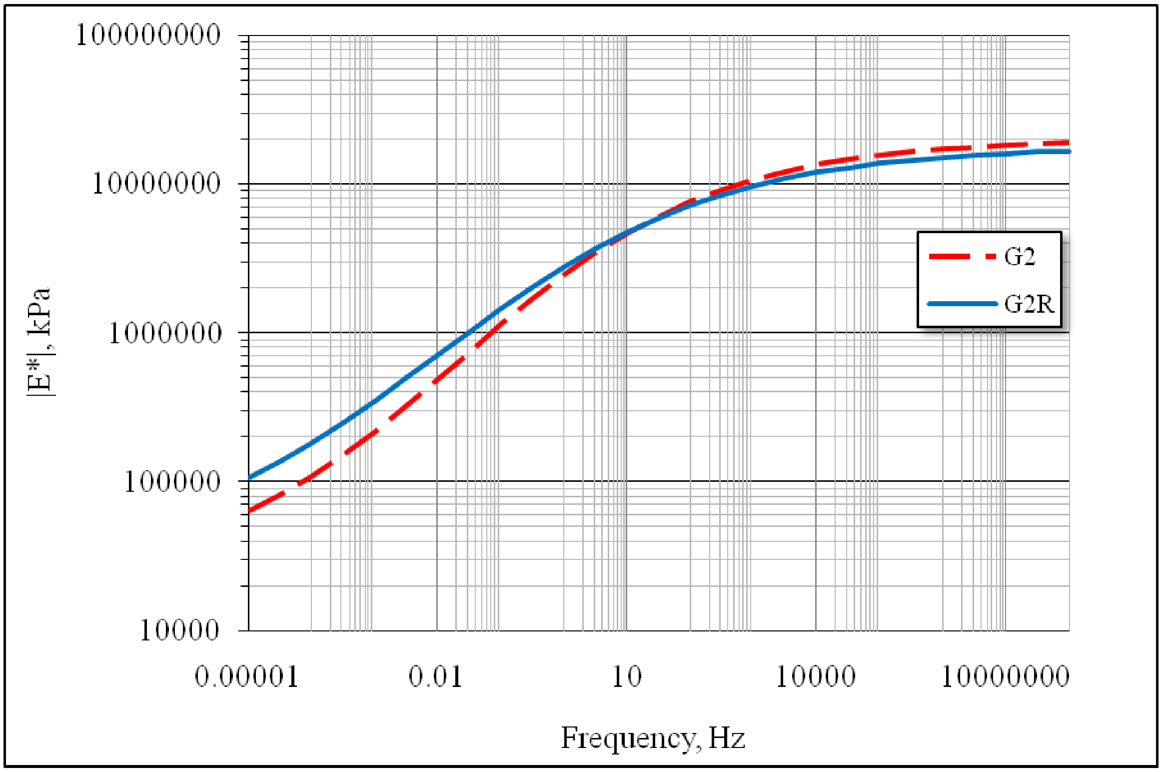

Figure 5.5: Gradations 2 and 2R dynamic modulus master curve comparison

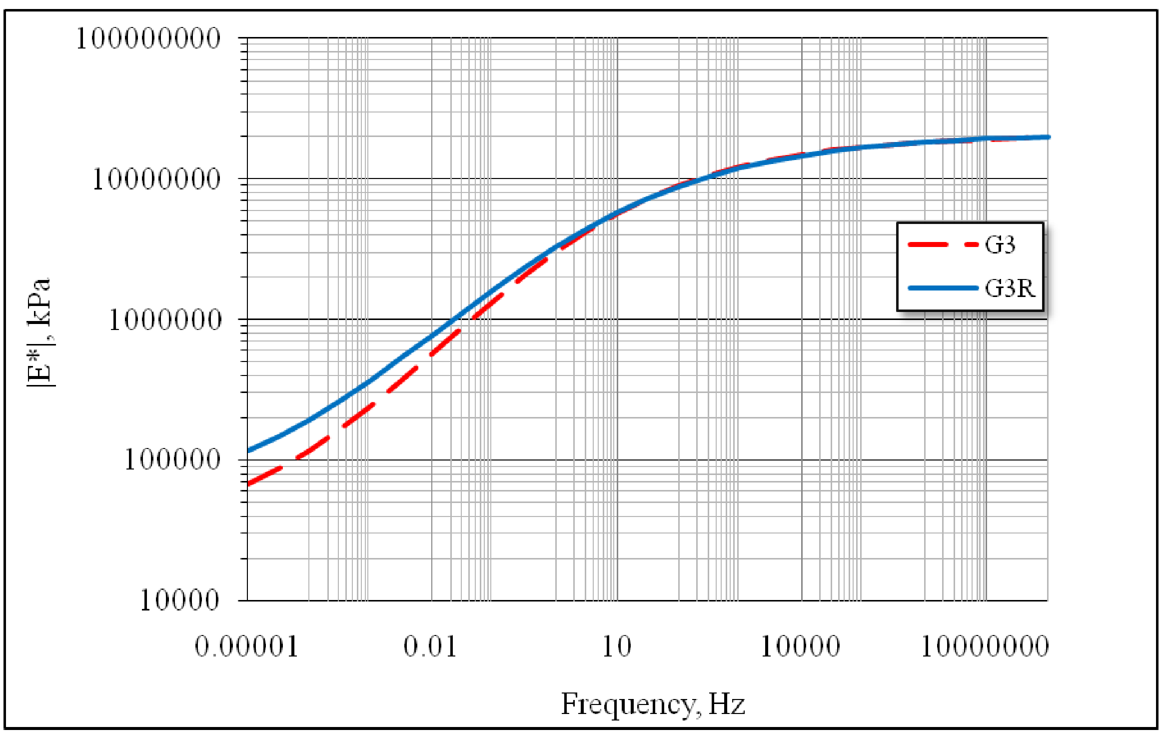

Figure 5.6: Gradations 3 and 3R dynamic modulus master curve comparison

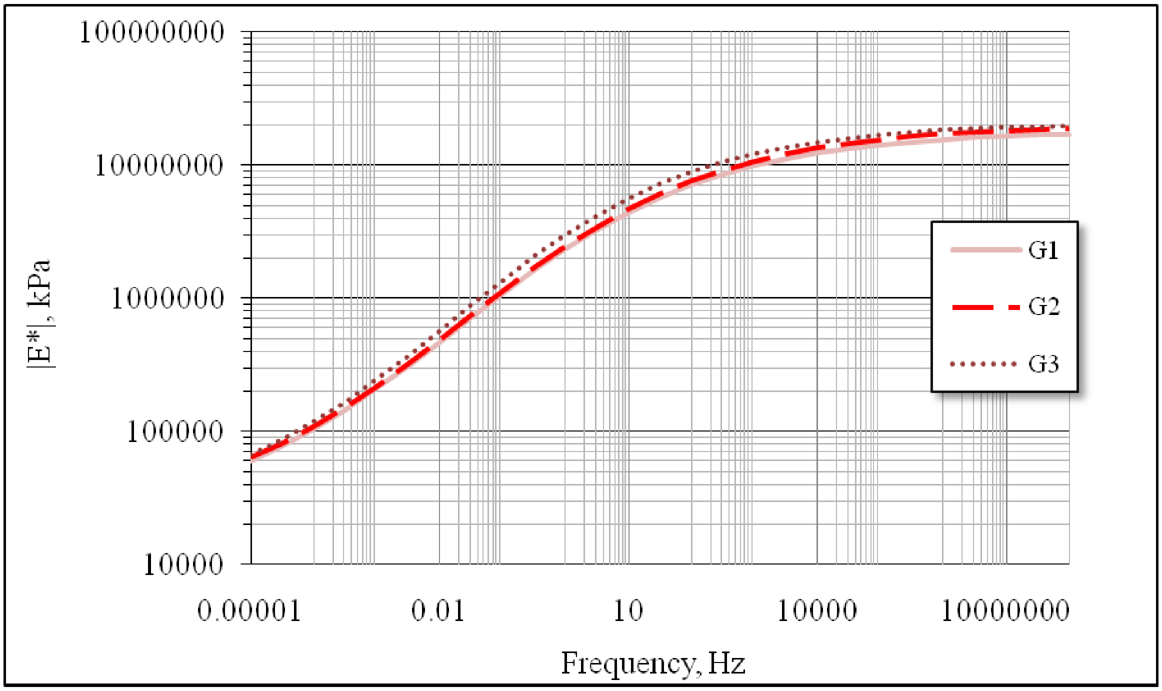

Figure 5.7: Dynamic modulus master curves for samples without RAS

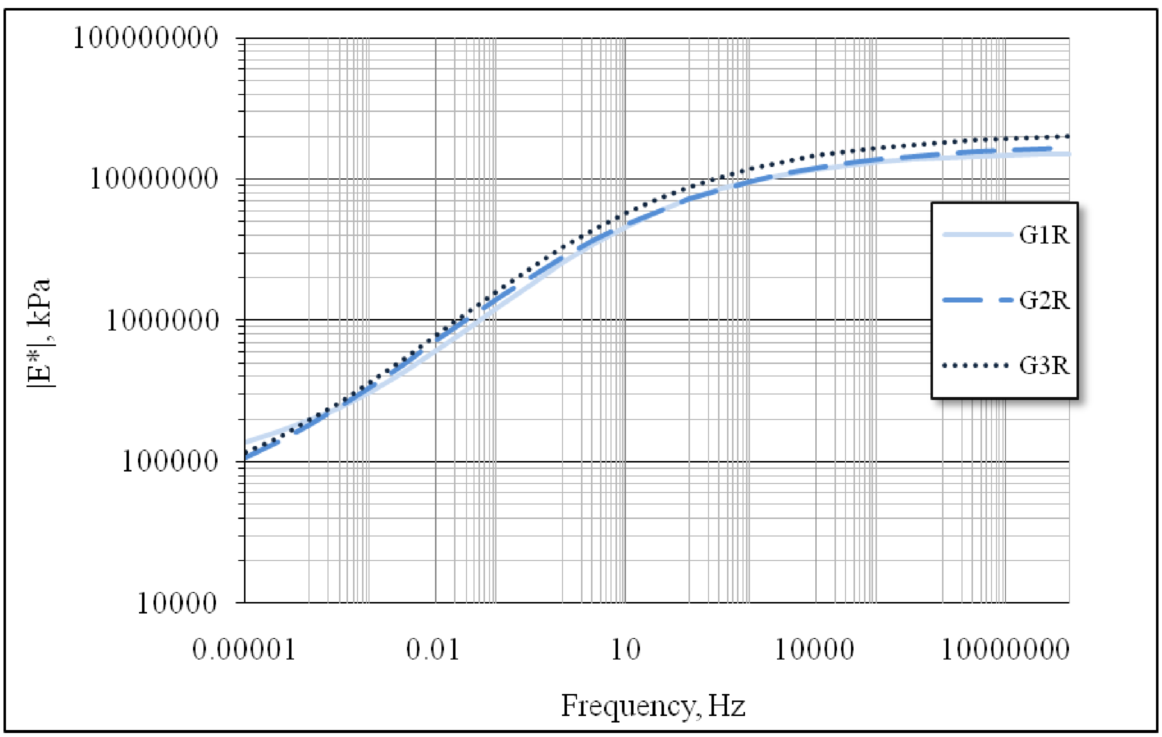

Figure 5.8: Dynamic modulus master curves for samples containing RAS

Flow Number

The flow number is evaluated by the cyclic loading and unloading of an asphalt sample. The permanent deformation is measured in percent strain with increasing cycles until the sample reaches 5.5% strain. Figure 5.9 shows the primary, secondary, and tertiary flow states of one of the tested samples. The flow number is evaluated at the intersection of the secondary and tertiary flow regions. The flow number is calculated as the number of cycles where the minimum average strain rate is recorded, as illustrated in Figure 5.10 (Witczak 2002, Bonaquist et al 2003). Figure 5.11 illustrates the difference in flow numbers between each gradation and their counterpart containing RAS. Each mix containing RAS resulted in a larger flow number than the corresponding mixes without RAS. Figure 5.12 illustrates the difference in cycles to reach 3% strain. Again, every mix containing RAS resulted in a larger cyclic value to reach 3% strain when compared to its counterpart containing RAS. Tables 5.3 through 5.5 show the flow number values and number of cycles to reach 3% strain for each gradation with their corresponding mean, standard deviation, and covariance.

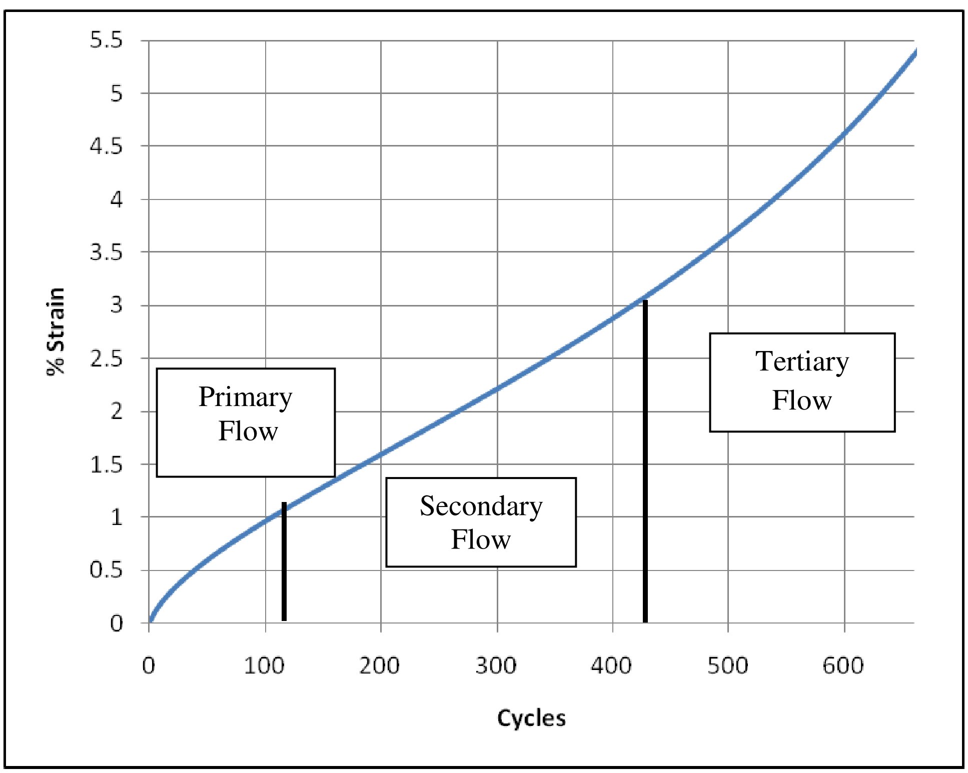

Figure 5.9: Accumulated % strain vs. cycles for sample G1_A

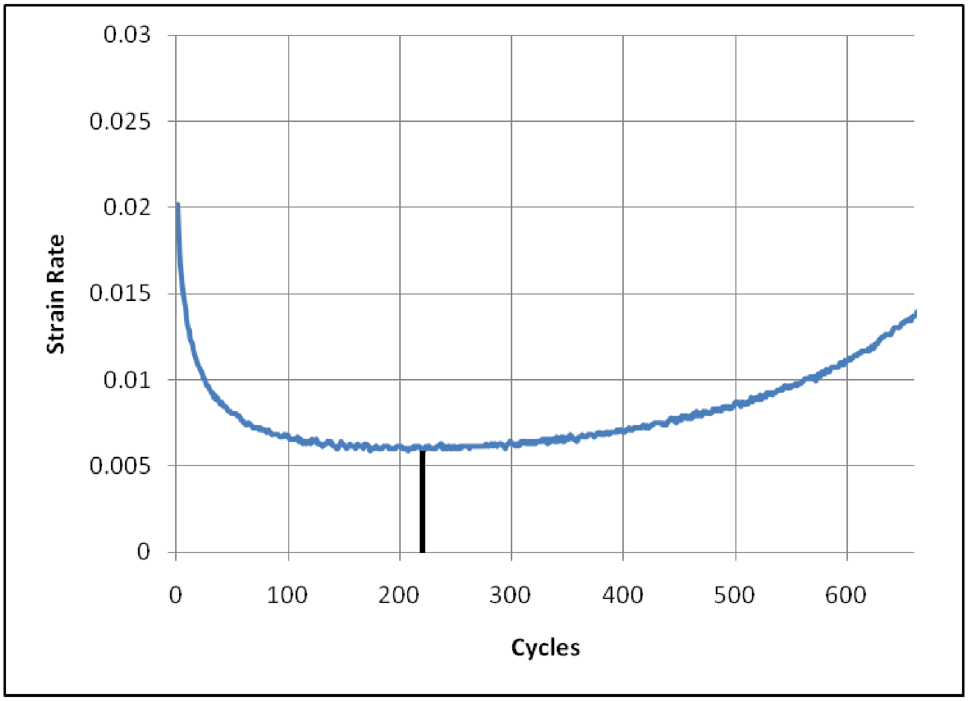

Figure 5.10: Average strain rate vs. cycles for Sample G1_A

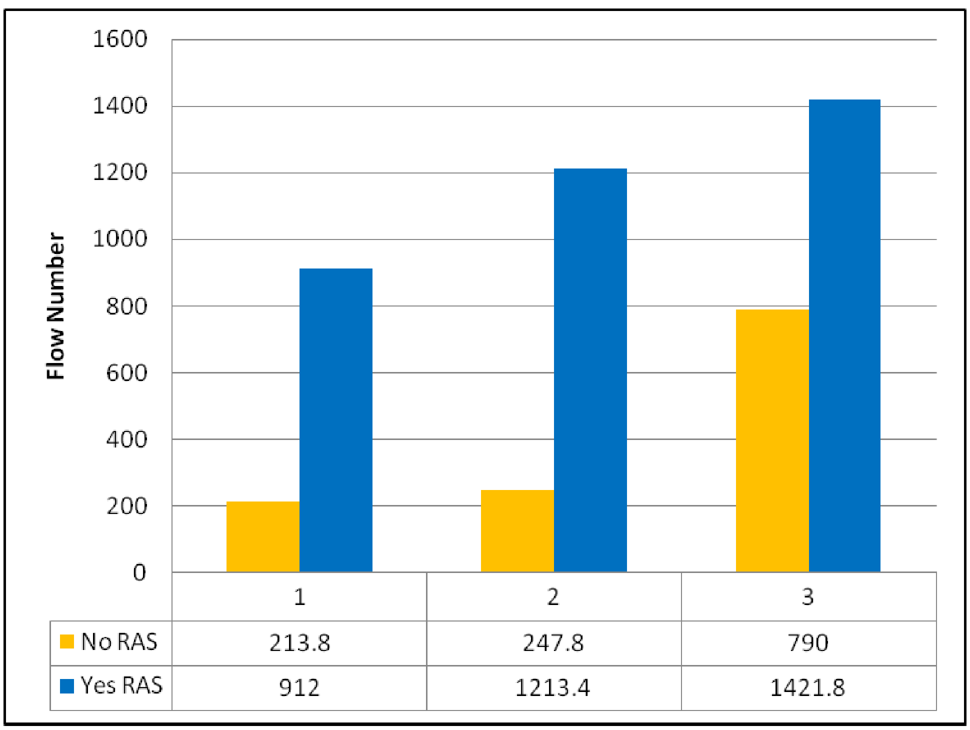

Figure 5.11: Flow number comparison mixes with RAS and without RAS

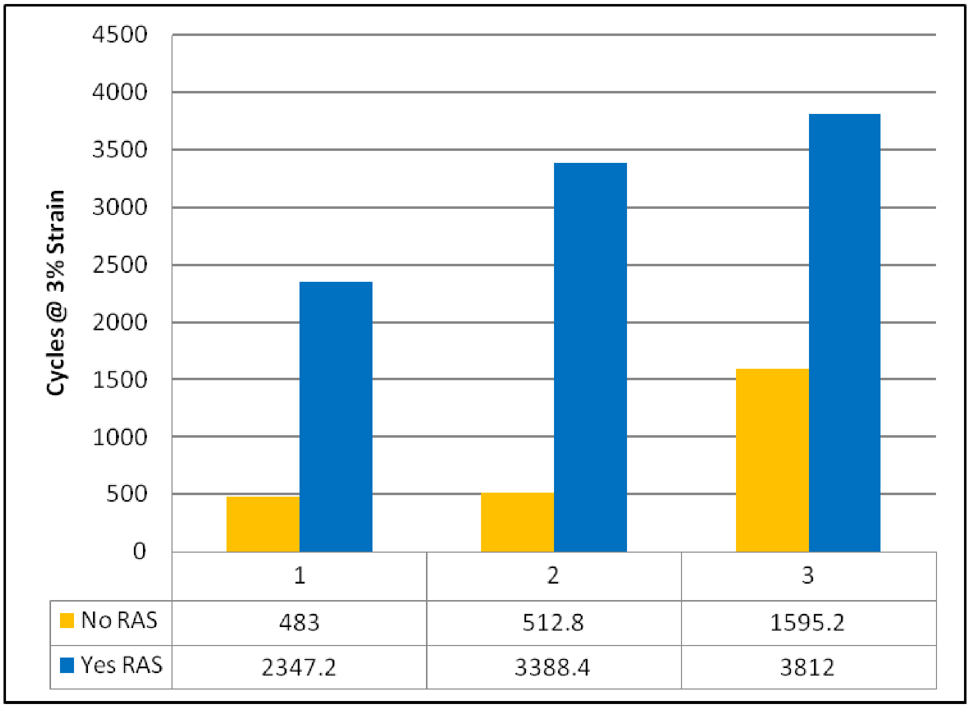

Figure 5.12: Number of cycles to 3% strain for mixes with RAS and without RAS

Table 5.3: Flow number test data results for gradation 1

Gradation	Sample	Shingles	Flow Number	Cycles to 3% Strain
1	A	N	221	417
	B	N	179	494
	C	N	227	534
	D	N	221	485
	E	N	221	485
Average			*214*	*483*
Std. Dev.			*19.63*	*42.09*
C.O.V.			*9.0%*	*9.0%*
1R	A	Y	858	1588
	B	Y	1063	2148
	C	Y	1057	2953
	D	Y	866	2176
	E	Y	716	2871
Average			*912*	*2347*
Std. Dev.			*147.71*	*567.17*
C.O.V., %			*16.0%*	*24.0%*

Table 5.4: Flow number test data results for gradation 2

Gradation	Sample	Shingles	Flow Number	Cycles to 3% Strain
2	A	N	172	357
	B	N	259	681
	C	N	283	640
	D	N	233	319
	E	N	292	567
Average			*248*	*513*
Std. Dev.			*48.17*	*165.26*
C.O.V., %			*19.0%*	*32.0%*
2R	A	Y	1206	2874
	B	Y	1146	4194
	C	Y	1526	4187
	D	Y	1293	3483
	E	Y	896	2204
Average			*1213*	*3388*
Std. Dev.			*228.80*	*860.68*
C.O.V., %			*19.0%*	*25.0%*

Table 5.5: Flow number test data results for gradation 3

Gradation	Sample	Shingles	Flow Number	Cycles to 3% Strain
3	A	N	913	1492
	B	N	629	1313
	C	N	851	1833
	D	N	862	1414
	E	N	695	1924
Average			*790*	*1595*
Std. Dev.			*121.43*	*268.23*
C.O.V.			*15.0%*	*17.0%*
3R	A	Y	1365	3382
	B	Y	1395	2902
	C	Y	1357	5409
	D	Y	1440	2577
	E	Y	1552	4790
Average			*1422*	*3812*
Std. Dev.			*79.73*	*1229.34*
C.O.V., %			*6.0%*	*32.0%*

The coefficient of variance within flow numbers is much smaller than those compared to cycles to 3% strain. The largest COV for flow numbers is 19.0% and the largest COV for cycles to 3% strain is 32.0%. The large variance seen in the data calculating cycles to 3% strain may result in this evaluation of the flow number test to be inadequate.

Table 5.6 was developed using paired t-tests to determine if the means of the flow numbers were significantly different. SAS, a statistical software package was used to conduct the analysis (SAS 2008). The results show that there is a significant difference in flow number means between respective samples with and without RAS. The results also showed that Gradations 1 and 2 without RAS, and Gradations 1R and 3 did not have significantly different means flow number values at an α–level of 0.05.

Table 5.6: Gradation flow number means comparison

	G1	G1R	G2	G2R	G3	G3R
G1	-	531.4	***-132.8***	832.8	409.4	1041.2
G1R	-	-	497.4	134.6	***-44.8***	343.0
G2	-	-	-	798.8	375.4	1007.2
G2R	-	-	-	-	256.6	134.6
G3	-	-	-	-	-	465.0
G3R	-	-	-	-	-	-

[1]Positive values show pairs of means that are significantly different
[2] t = 2.06 with a = 0.05

CONCLUSIONS

This investigation was carried out to determine the effects of post-consumer recycled asphalt shingles on the mix design volumetrics and performance of different asphalt gradations. To examine these effects, three gradations were designed with and without RAS. The following conclusions were determined from mix volumetrics, dynamic modulus testing, and flow number testing.

- All gradations with RAS required less virgin binder than their counterpart mixes without RAS,
- The finer blend (Gradation 2) had the largest reduction in virgin asphalt binder (2.2%) with the addition of 5% RAS as compared to its non-RAS mix,
- Gradations 1 and 2 experienced a larger decrease in optimum binder than available in the RAS material,

- The RAS may be acting as a filler and/or reducing the internal friction of Gradations 1 and 2 during compaction,
- The dense gradation "utilized" the least amount of binder available in the RAS,
- All gradations with RAS had a reduced VMA as compared to the non-RAS mixes,
- The addition of RAS caused an increase in VFA of 0.0% to 1.0%,
- At low frequencies, the mixtures with RAS tested as a stiffer material,
- The flow number values for mixes containing RAS were larger than those without RAS, and
- The number of cycles to reach 3% strain increased with the addition of RAS to the mixes.

The results of this research identified that the aggregate gradation has an effect on mix design when adding RAS. The possible economic and environmental benefits of using RAS in HMA design warrants further study for different aggregates, percentages of RAS, and RAS particle size. The examination of binder replacement as compared to void filler/reduced mix stiffness during compaction is another point of interest that requires additional research. Further, low temperature fracture testing should be done to confirm the dynamic modulus test results at high frequencies (low temperatures). Moisture susceptibility testing also needs to be done on mixes containing RAS to ensure performance measures are met for freeze/thaw cycles.

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CHAPTER 6. CONCLUSIONS AND RECCOMENDATIONS

This thesis detailed a study of the mechanical properties and performance of RAS in geotechnical and asphalt pavement applications. Laboratory tests were performed to study the feasibility and performance of RAS in geotechnical applications involving loess and foundry sand, and the volumetric and performance effects of using RAS in hot mix asphalt (HMA) with varying gradations.

The investigation of the loess-RAS mixtures resulted in the following conclusions (Chapter 3):

- The addition of RAS resulted in decreases in maximum dry density and optimum moisture content.
- The addition of RAS resulted in a decreased swelling potential.
- The addition of RAS generally yielded lower indirect tensile strength and unconfined compressive strength values for the particular loess studied. However, a slight increase in indirect tensile strength was noted for the 20% RAS mixture compacted dry of optimum.
- In most cases, there was not a statistically significant difference in the indirect tensile strength and unconfined compressive strength values of the loess when blended with 10, 20 and 30% RAS at optimum moisture content.

It is recommended that further research be performed on the economic and environmental benefits of using post-consumer recycled asphalt shingles in geo-materials for different soil types and applications. It is also recommended that further studies be carried out on the long term effects of RAS-stabilized soil, such as creep behavior and freeze-thaw susceptibility. Finally, it is advised to research an optimized curing and placement method for the use of soil-RAS modification.

The investigation of foundry sand-RAS mixtures resulted in the following conclusions (Chapter 4):

- Based on the particle size distributions of foundry sand and RAS, it is expected that the gradation of the foundry sand-RAS mixtures will increase in uniformity with the addition of RAS. This assumption was verified visually upon mixing the laboratory samples,
- The maximum dry density decreased with increasing RAS content,
- The permeability of the foundry sand-RAS mixture generally increased with RAS content, with a maximum permeability occurring at 20% RAS,
- The direct shear behavior transitioned from a brittle failure with dilation (i.e. the foundry sand alone in a dense state) to an increasingly ductile and contractive nature (like that of a loose sand) for increasing RAS percentages or confining pressures, and
- The CBR value decreased along with the dry unit weight with increasing RAS content.

It is recommended that further triaxial, cyclic, and freeze-thaw tests be conducted to better quantify the behavior and long-term performance of this material. Additionally, the curing and placement method for the use of RAS in soil modification should be investigated.

The investigation of RAS in HMA with varying aggregate gradations resulted in the following conclusions (Chapter 5):

- All gradations with RAS required less virgin binder than their counterpart mixes without RAS,
- The finer blend, gradation 2, had the largest reduction in virgin asphalt binder (2.2%) with the addition of 5% RAS as compared to its non-RAS mix,
- Gradations 1 (Fine) and 2 (Coarse) had larger decreases in optimum binder content than available in the RAS material,
- Based on evaluation of the test results, it is hypothesized that the RAS may be acting as a filler and/or reducing the internal friction of gradations 1 and 2 during compaction,

- The dense gradation utilized the least amount of binder available in the RAS,
- All gradations with RAS had a reduced VMA as compared to the non-RAS mixes,
- The addition of RAS resulted in an increase in VFA of 0.0% to 1.0%,
- At low frequencies, the mixtures with RAS behaved as stiffer materials,
- The flow numbers for mixes containing RAS were larger than those without RAS, and
- The number of cycles to reach 3% strain increased with the addition of RAS.

The possible economic and environmental benefits of using RAS in HMA design warrants further study for different aggregates, RAS contents, and RAS particle sizes. The examination of binder replacement as compared to void filler/reduced mix stiffness during compaction is another point of interest that requires additional research. Further, low temperature fracture testing should be done to confirm the dynamic modulus test results at high frequencies (i.e. low temperatures). Moisture susceptibility testing on mixes containing RAS should be carried out to verify that performance measures can be met under the action of freeze-thaw cycles.

The results of these investigations indicate that RAS can potentially be added to soils to achieve a reduction in borrow materials while producing a lightweight fill for certain applications, thus offering economic and environmental benefits from the recycling of this material. The study of RAS in HMA also identified that the aggregate gradation has an important effect on mix design.