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Influence of Recycled Asphalt Shingles on Asphalt Binder Content, Mixture Stiffness, and Laboratory Rutting Performance

Joshua David King
University of Arkansas, Fayetteville

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By

Joshua David King
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Abstract:

Recycled asphalt shingles (RAS) is a technology in which pavement costs can be reduced significantly and pavement properties may be enhanced. Also, incorporating shingles into pavements reduces the impacts of waste shingles in landfills, preserving our environment. However, for this new technology to be practical for implementation, a better understanding of how the ground shingles affect the properties of the asphalt is necessary. The purpose of this research was to examine the effects of recycled asphalt shingles on asphalt binder content, mixture stiffness, and laboratory rutting performance

For this project, shingles were added to hot mix asphalt mixtures at 2.5, 5, and 10 percent by weight of the total mix. This study showed that incorporating shingles into mixes is sometimes complex due to the interaction of a number of factors such as nominal maximum aggregate size, binder grade, aggregate type, and percent RAS. In spite of the complex behavior of these mixes, a few conclusions could be drawn. First, properties of mixes with RAS were not vastly different from their control counterparts. Second, the manufacturing waste shingles are expected to contribute more than 85 percent of their available binder to a mix. Finally, asphalt with shingles incorporated produced in industry will likely be stiffer than traditional HMA resulting in less rutting and stripping.

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Dr. Stacy Williams

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Introduction:

Asphalt shingles are one of the largest wastes generated from construction with an estimated 11 million tons of waste shingles each year (Grodinsky et al. 2002). Relieving the landfills and becoming environmentally friendly has become a large concern. Including shingles in asphalt mixtures provides a method of reducing the amount of shingle wastes in landfills. The inclusion of RAS also reduces costs of asphalt while also bettering certain material properties of the pavement. For example, aged shingles have stiff liquid asphalt which leads to a greater rutting resistance. Currently, many (21) states provide specifications allowing for the use of shingles in asphalt, but AHTD only allows for the use of 3 percent shingles as a special provision (Hall 2010). Arkansas' climate covers seven ecoregions which provides a range of soils and precipitation levels. If RAS provides positive results for asphalt in Arkansas' climate, provisions for the design, verification, and construction of RAS will contribute to the pavement engineering community greatly.

Recycled asphalt shingles (RAS) is a technology that holds promise for reduced impacts on landfills, reducing asphalt costs, and enhancing pavement performance. However, how the shingles influence certain properties of the asphalt is not well understood at this time. By adding RAS, the binder content, volumetric properties, rutting susceptibility, and stiffness are all expected to change. The binder contribution is the most appealing part of this research in that it provides the potential for a large savings. The shingles' ability to release binder depends on factors such as mixing temperature, point within the plant at which RAS is introduced to the mix, and most importantly shingle grind size. In order to provide specifications, the influence of RAS on asphalt properties must be investigated.

Background:

Asphalt shingles are one of the largest wastes generated from construction with an estimated 11 million tons of waste shingles each year (Grodinsky et al. 2002). Of these 11 million tons, one million tons of pre-consumer wastes are generated as a byproduct from the manufacturing plants. Approximately 10 million tons come from post-consumer shingles called “tear-offs” (Marks and Petermeier 1997). These shingles are aged and as a result often have a stiffer binder and less mineral aggregate. These tear-off shingles, if manufactured before 1980, have approximately 25 percent granular material and 75 percent binder material. The shingle binder material consists of 70 percent asphalt and 30 percent limestone filler. The resulting liquid asphalt binder is 52.5 percent (Brock 1987). In 1980, shingles began to be manufactured differently. Shingles manufactured after 1980 typically consist of 25 to 35 percent asphalt, 25 percent fiberglass and up to 50 percent granular/filler material (Brock 1987, Newcomb et al. 1993). According to Brock (1987), it is estimated that the amount of liquid asphalt being landfilled is 2,275,000 tons per year with an additional 20,000 tons coming from tabs cut from shingles, and 20,000 tons coming from shingles not meeting quality assurance/quality control (QA/QC). The results of one study suggested that if a shingle content of five percent were used in all asphalt mixtures, at least 600,000 tons of shingles could be used annually (Hanson et al. 1997). This large amount of waste clearly shows the impact of shingles on our environment. Landfills are being burdened with shingles that have up to, and in many cases more than, 30 percent asphalt by weight (rotochopper.com). This material, if reclaimed, can reduce the costs of pavements by three to five dollars per ton (Krivit 2010). Conservatively reclaiming 5 percent shingle material can produce savings of more than one dollar per ton

(Hanson 1997). From these data, it is very simple to see how the reduction of waste shingles is imperative.

As with many recycling projects, there are numerous challenges that have risen in the field of RAS. Grodinsky et al. (2002) conducted several case-studies with tear-offs incorporated and provides information pertaining to the problems the shingles inflict. Grodinsky concluded the main problem of using RAS is contamination such as wood, metal flashing, cans, paper, nails, agglomeration, and possible asbestos. The threat of asbestos has become less of a problem in recent years because shingles manufactured after 1980 should have no threat of asbestos (Brock 1987, Newcomb 1993). It is apparent that extensive QA/QC should be provided on all projects incorporating shingles.

Effects of Asphalt Binder

In the Superpave system (Arkansas' current asphalt mixture design procedures), asphalt binder is chosen based on climatic conditions of the project location. For each year, the hottest seven day period is selected and the maximum average air temperature is calculated. A mean and standard deviation are calculated for the years recorded. For the cold temperatures, the temperature for the coldest day for each year is recorded and the mean and standard deviation are recorded. Based on these data, the reliability desired, and the amount of projected loads, the binder performance grade (PG) is chosen which describes the quality of the asphalt binder – primarily its ability to perform at the given range of temperatures. The quality and quantity of binder used in an asphalt mixture greatly affects the mixture's properties. If the mixture has too much binder, the mixture will be susceptible to permanent deformation. If the mixture has too little binder however, complications could arise during construction and the pavement could be brittle, adversely affecting pavement performance. Adding to the concerns about the binder, the amount of oxidation binder has undergone is a concern in an asphalt mixture design. Oxygen reacts with the binder changing the composition of the molecules yielding more brittle asphalt. Older tear-off shingles have undergone oxidation to a great extent, especially in warm climates. Oxidized asphalt binders demonstrate excessive stiffness and when added to an asphalt mixture, are capable of making the pavement more susceptible to cracking. The excessive stiffness, however, can aid the rutting resistance of the pavement. When incorporating waste shingles into asphalt pavements, the shingles have the ability to release their aged binder to the mixture. When adding a small amount of RAS, a small amount of aged binder is added to the asphalt mixture. When a larger amount of binder is added however, the shingles will contribute a larger amount of aged binder.

Incorporating waste shingles into asphalt pavements can yield positive results on PG graded binders. The components of shingles are commonly used as ingredients of asphalt. Shingles contain mineral aggregate, binder, and a fibrous mat made of organic felt or fiberglass that can also be valuable to some asphalt mixtures (Turley and Krivit 2007). Along with this, Krivit (2010) shows how the high temperature grade of the virgin asphalt binder is improved by adding shingles to a mixture, but the low temperature grade is reduced. The change of grades found by Krivit can be summed up as added resistance to rutting, but lower resistance to low temperature cracking. This change in material properties would be valuable where the low temperature grade is conservative and the high temperature grade is not.

American Association of State Highway and Transportation Officials (AASHTO) Recommendations

The American Association of State Highway and Transportation Officials (AASHTO) is an international leader in setting technical standards for all phases of highway system development. The committees, composed of leading state DOT personnel, represent the highest standard of transportation expertise and address virtually every element of planning, design, constructing, and maintaining services. Every state implementing RAS are recommended to follow the AASHTO guidelines and specifications. AASHTO has adopted provisional specifications for the requirements of using RAS (AASHTO MP15 "Use of Reclaimed Asphalt Shingles as an Additive in Hot Mix Asphalt"). AASHTO provides information pertaining to gradation, addition rates, deleterious substances, and methods of sampling. The AASHTO specifications are slightly incomplete though, and do not address other pavement applications such as hot in place, cold patch, or cold recycled. AASHTO has, however, adopted a companion recommended practice to provide additional guidance for designing new HMA which incorporates RAS (AASHTO PP53-09 "Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in New Hot Mix Asphalt (HMA)"). Specific considerations include: shingle aggregate gradation, binder contribution, and performance grade.

Gradation and Specific Gravity According to AASHTO

The shingle aggregate gradation is needed in order to know if the virgin aggregate composition should be altered so that the mixture meets gradation requirements. To determine the aggregate gradation, AASHTO recommends that the fibers present in the shingles be removed prior to testing. According to AASHTO, deleterious substances shall not exceed 3 percent by mass on material retained on the 4.75 mm sieve. Light weight material (paper, wood, and plastic) shall not exceed 1.5 percent by mass of material retained on the 4.57 mm sieve. Table 1 provides a standard gradation given by AASHTO which may be used in lieu of determining the shingle gradation. Determining the shingle maximum theoretical specific gravity is to be done according to T 209. In this method a fine mist spray of alcohol may be used to reduce surface tension and allow fine particles to sink. Because the absorption of most shingle aggregate is minimal, the bulk specific gravity is assumed to be the same as the apparent specific gravity. These can be calculated after calculating the effective specific gravity.

Table 1: Standard Shingle Aggregate Gradation Provided by AASHTO

Shingle Aggregate Gradation	
Sieve Size (mm)	Percent Passing by Weight
9.5	100
4.75	95
2.36	85
1.18	70
0.6	50
0.3	45
0.15	35
0.075	25

Asphalt Binder Contribution of Shingles According to PP 53-09

In addition to the change of the PG, the shingle size affects the percentage of binder contribution. For example, shingles ground to a maximum particle size of 0.5 inches (maximum allowed by AASHTO MP 15-09) are expected to contribute 20 percent-40 percent of the available asphalt binder, and shingles ground to 0.25 inches are expected to contribute as much as 95 percent available asphalt binder (PP53-09). AASHTO provides an equation yielding an initial estimate of the percentage of asphalt binder (F_c) that is released from the shingles (equation 1). Because equation 1 is believed to be an underestimated value, a corrected value is given in equation 2.

Eq. 1	$F_c = \frac{P_{bv} - P_{bvr}}{(p_{sr})(P_{br})}$
Eq. 2	$F = 100\left(\frac{1 + F_c}{2}\right)$

Where:

F_c is the initial estimated shingle asphalt binder available (percent)

P_{bv} is the design asphalt binder content of a mix without shingles

P_{bvr} is the design asphalt binder content of a mix containing shingles (percent)

P_{sr} is the percentage of shingles in the HMA (decimal)

P_{br} is the percentage of binder in the RAS (decimal),

F is the shingle asphalt binder availability factor (percent)

In asphalt industries, AASHTO recommends adding RAS at ambient temperature to the heated aggregates prior to the addition of the heated virgin asphalt binder. In the blending procedure, the calculated value of the percentage of shingle asphalt binder in the final blended binder (P_{brf}) will be less than the true value. P_{brf} can be estimated using equation 3.

Eq. 3	$P_{brf} = \frac{F(P_{sr})(P_{br})}{P_{bbf}}$

Where:

P_{brf} is the percentage of shingle asphalt binder in the final blended binder

P_{bbf} is the percentage of the final blended binder in the new HMA (decimal)

Performance Grade According to AASHTO

The shingle asphalt will mix with the virgin asphalt binder to produce a final blended binder. The shingle asphalt binder grade is often significantly different than that of virgin binder. According to AASHTO, if the quantity of virgin asphalt binder is less than 70 percent by mass of the total binder, the PG of the blended binder may be significantly different and shall be further investigated (PP 53-09, MP 15-09). For most specifications, which limit RAS to approximately 5 percent, the binder replacement will comprise less than 30 percent. However, if significant portions of RAP are used also, then the binder replacement may exceed 30 percent, necessitating further testing.

ASTM International Recommendations

ASTM International, formerly known as the American Society for Testing and Materials (ASTM), is a recognized global leader of consensus standards. To date, ASTM International has published a document pertaining to the use of shingles in asphalt (Special Technical Publication 1193). This publication (edited by Waller) is a compilation of papers presented at the symposium on "A Critical Look at the Use of Waste Materials in Hot-Mix Asphalt" in Miami, Florida, held in December 1992. Waller compiles two papers relating to the use of waste shingles: "Properties of Dense-Graded and Stone-Mastic Asphalt Mixtures Containing Roofing Shingles" and "Recycled Asphalt Roofing Materials – A Multi-Functional, Low Cost Hot-Mix Asphalt Pavement Additive". Currently, ASTM

International is developing the draft “New Specification for Specifications for Recycled Asphalt Shingles (RAS) Derived from tear-off roofing scrap”.

Acceptance of RAS

It is apparent that most states implementing RAS are conservative by allowing 5 percent manufacturer’s waste into the mixture. Some states are becoming pioneers in the field of RAS by allowing up to 10 percent shingles. Table 2 summarizes each state’s acceptance of RAS according to the Construction Materials Recycling Association (CMRA). The CMRA is committed to reporting feasible ways to recycle shingles on the www.shinglerecycling.org website.

Table 2: State Acceptance of RAS

State	HMA Specification	Comments
DE	Beneficial Use Determination Policy	
FL	5% Manufacturing Wastes only	
GA	5%	
IA	2-5%	Depends on RAP Content
IN	5% Manufacturing Wastes only	Looking into tear-offs
IL	No Spec	
MA	5% Manufacturing Wastes only	
MD	5% Manufacturing Wastes only	
ME	No Spec	Manufacturing Wastes only
MI	5% Manufacturing Wastes only	
MN	5% Manufacturing Wastes only	
MO	7%	
NC	5% Manufacturing Wastes only	
NJ	5% Manufacturing Wastes only	
NH	No Spec	
OH	"Certain Percent"	Manufacturing Wastes only
PA	5% Manufacturing Wastes only	
SC	3-8%	Special Provisions
TX	5% (Surface), 10% MFS (Base)	Manufacturing Wastes only
VA	5% Manufacturing Wastes only	Special provisions
WI	Replace up to 30% binder	

The CMRA also supplies a “Best Practices Guide” for the use of tear-off shingles in HMA by Turley and Krivit (2007). Three major best practice strategies are given in this report and are listed below.

- Recyclers handling tear-off shingles should carefully plan and implement a supply QA/QC system.
- Tear-off shingle recyclers should optimize their operations to produce a RAS product that meets or exceeds specifications of their end markets.
- Tear-off shingle recyclers should develop a comprehensive marketing plan based on multiple outlets.

During the start up of a recycling facility it is recommended to accept only residential tear-offs . The Environmental Protection Agency (EPA) considers residential homes as “non-regulated facilities”. Implementing this recommendation will allow more experience to workers with the recycling venture.

Future Scope

Departments of transportation are urged by many associations to incorporate RAS into pavements. As a temporary means to demonstrate the feasibility of use of tear-off RAS into HMA, county departments of transportation should consider designing demonstration projects that specify the use of tear-off derived HMA. Counties are also encouraged to wave tipping fees at landfills for roofing contractors that provide de-nailed shredded shingles to the landfill which can then be used by the county on roads. Krivit and Associates (2008) advised counties consider enacting legislation if “reasonable” progress is not achieved (Krivit and Associates 2008).

Literature Review:

The use of RAS dates back as early as the 1980's but has never become widely accepted until recent years. To date, many states have conducted research, demonstrating the benefits and potential problems of RAS. Long-term pavement performance data are available, however; the data are limited to only a few sites. The information available has been documented in order to establish the features of the mixtures.

Binder Contribution of RAS

The quantity of binder used in an asphalt mixture greatly affects the mixture's volumetric properties. A large amount of binder can yield in "pumping" of the asphalt leading to permanent deformation. A binder deficient mixture will experience complications during construction as well as the life of the pavement will be affected. This is a concern when using waste shingles in asphalt pavements due to the shingles' ability to release binder to the mixture. Newcomb et al. (1993) prepared mixtures containing 2.5, 5, and 7.5 percent felt-backed shingles and then prepared the mixtures with fiberglass shingles in place of the felt-backed shingles in a dense graded asphalt mixture. The mixtures were verified by the Marshall method using penetration grade binders of 85/100 and 120/150. RAS was added at ambient temperatures as recommended by AASHTO procedures. It was concluded that the volumetric properties of the mixture containing 2.5 percent shingles were not significantly different than the control mixtures containing 0 percent shingles (negating the need for extensive testing on mixtures containing 2.5 percent RAS). There was generally no reduction in required asphalt binder when any levels of felt backed shingles were incorporated. The fiberglass shingles however, reduced the need for virgin binder by 12 percent at 5 percent RAS to 25 percent at 7.5 percent RAS. Each mixture yielded similar amounts of total air voids at 75 blows of the Marshall hammer. There was little change in air voids at low blow counts for the mixtures containing 5 and 7.5 percent fiberglass shingles. The difference in percent air voids was about 0.8 percent at 15 blows and 0.4 at 50 blows for the mixtures containing 5 and 7.5 percent fiberglass shingles. There was a substantial difference between both levels of shingles and the control. This indicates that the fiberglass shingles tend to compact more easily. From the extractions performed, it was found that incorporating 2.5 percent and 7.5 percent wastes gained about 1.5 and 2.5 percent total asphalt respectively. A stone mastic asphalt (SMA) mixture was verified as well and accepted 0.3 percent cellulose fibers (included for stiffness) and 10 percent felt backed shingles and then 10 percent fiberglass shingles. The fiberglass shingles were seen to contribute to the binder content very well. At 50 blows, the air voids were 1 percent and the control had 3 percent air voids. The SMA mixture had a substantially lower stability and higher flows than the dense graded mixture. This was most likely due to the increased binder content and higher amounts of RAS.

The results found by Newcomb et al. were similar to the results given by Button et al. (1995). Button conducted research on manufacturing waste shingles and tear-off shingles incorporated into a dense graded and also, a coarse matrix high binder (CMHB) mixture. Two different sizes (-4.75 and -12.5 mm) of the tear-off shingles were used in this study. The manufacturing waste shingles were not sized. Unlike Newcomb et al. (1993), the shingles were heated in the oven with the aggregate prior to mixing with virgin binder. When shingles were incorporated into the mixtures, it was determined that an equal weight of the finest graded material in the mixture be removed. Preliminary testing was conducted on the shingles where shingles were heated to 121, 135, and 143 degrees Celsius (typical of HMA plants) and rodded into molds in order to determine the malleability of heated shingles. Testing revealed heating the shingles to 135 degrees C provides a malleable and compactable material under slight hand pressure and very soft at 143 degrees Celsius. The stiffer asphalt in shingles made initial incorporation unsuccessful (high air voids). The additional 14 degrees C heating achieved required specifications, however control specimens were not heated with the extra 14 degrees. The optimum binder content for the dense graded mixture was 6.2 percent and 5.2 percent for the CMHB mixture. At 5 percent manufacturing waste, the optimum binder content was reduced 0.5 percent for the dense graded mixture and 0.2 percent for the CMHB mixture. At 10 percent manufacturing wastes, an additional reduction of 0.7 percent from the dense graded mixture containing 5 percent shingles was seen. For the CMHB mixture, the optimum binder content was the same for the mixtures containing 5 percent and 10 percent shingles. The consumer wastes reduced the optimum binder content for the dense graded mixture by 0.2 percent by incorporating 5 percent shingles and at 10 percent shingles the binder content was reduced 0.4 percent. For the CMHB mixture, the optimum binder content was not reduced for the mixture incorporating 5 percent tear offs but was reduced 0.1 percent for the mixture containing 10 percent tear-offs.

Maupin researched the effects of RAS in 2010 for the Virginia DOT. In his research, samples of recycled shingles were split and tested by solvent extraction method and the ignition furnace method. Two samples were tested by solvent yielding 24.3 percent and the companion samples yielded 29.2 percent by the ignition furnace method. A similar determination by South Carolina found that the difference between extraction and ignition testing was 2 percent for its shingles (Maupin 2010). From the limited data, equation 4 is recommended for use with the ignition oven as a correction factor (CF).

Eq. 4	$CF = \frac{(\%\ shingles * \%\ difference\ between\ binder\ determined\ by\ extraction\ and\ ignition\ furnace)}{100}$

After verifying mixtures, binder was recovered by extraction (AASHTO T164 Method A) and Abson recovery (AASHTO T170) and recovered binder was graded according to AASHTO M320.

The volumetric properties of asphalt will change with the incorporation of wastes shingles due to the additional binder, fines, and backing. In 2000 Mallick et al. provided the Massachusetts Department of Transportation (MassDOT) with an evaluation of RAS with respect to volumetric properties. A control mixture was established containing 0 percent recycled material and afterward, manufacturing wastes shingles were incorporated at 3, 5 and 7 percent. The testing results indicated the effects of RAS on volumetric properties to not be significantly different from conventional mixtures not containing RAS. The mixes were tested to find the theoretical maximum density (TMD) and bulk specific gravity. With these results, other material properties were determined. Finally, the rutting susceptibility of the mixtures was evaluated by use of the asphalt pavement analyzer (APA) wheel tracking device. The shingles (containing about 20 percent asphalt binder) were found to contribute very well to the mixtures reducing the virgin binder content from 5.2 to 4.6, 4.2, and 3.8 for the mixtures containing 0, 3, 5, and 7 percent shingles.

Upon completion of the project, the highway department in Massachusetts did not allow the use of shingles in HMA due to concerns about consistency of asphalt in waste shingles. The effects of different RAS contents with a range of properties were unknown to the Department of Transportation. Since 2000, the state DOT has incorporated into its specifications the allowance of up to 5 percent manufacturing waste shingles.

Influence of Waste Shingles on Binder Performance Grade

Because the asphalt binder in shingles is stiffer than virgin asphalt binder, the asphalt binder grade is expected to change with the incorporation of shingles. If the change is significant, additional design verification may need to be conducted on mixtures. In 2007 McGraw et al. conducted a joint research project for Minnesota and Missouri for the use of tear-offs in RAS. In Minnesota, a single binder grade (PG 58-28) was used for different percentages of RAS and reclaimed asphalt pavements (RAP) in the HMA. First, a control mixture containing 20 percent RAP and 0 percent RAS was established. Afterward, 5 percent RAP was replaced with manufacturing waste shingles and then with 5 percent tear-off shingles. Deleterious material in Minnesota was not acceptable. The PG grading results for the control mixture averaged 64.2 and -29.2 degrees Celsius with a standard deviation of 0.3 and 0.9 respectively. Incorporating the manufacturing wastes shingles yielded an average PG grading of 70.9 and -26.2 degrees Celsius with a standard deviation of 0.4 and 0.2 respectively. The tear-off shingles incorporated showed an average PG grading of 73.2 and -28.8 with a standard deviation of 0.2 and 2.4 respectively. In summary, the mixtures containing 5 percent manufacturing wastes and 5 percent tear-off wastes showed a positive change of 1 grade and 1.5 grades for the high PG grade respectively and a change of one half grades and no significant change for the low temperature PG grade respectively. The high standard deviation pertaining to the tear-off shingles indicated a difference in shingles.

In Missouri two different binder grades (PG 58-28 and PG 64-22) were used with a single source of RAP, a single source of tear-off shingles, and 0.25 percent anti-strip additive (Pave Bond Lite). First, a mixture was verified containing 20 percent RAP using each type of binder. Next, for each mix, 5 percent RAP was replaced with the tear-off shingles. Up to 3 percent deleterious substances were accepted but limited to 1.5 percent for wood. Mixture stiffness was measured in accordance to AASHTO TP9-96: *Standard Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device* at -10, -20, and -30 degrees Celsius. The results of the testing revealed that the addition of shingles increased the stiffness of the mixture significantly at the two lowest testing temperatures. For the mixture containing PG 64-22, the stiffness changed from 12 and 19.5 to 34.4 and 34.7 GPa at -20 and -30 degrees Celsius respectively. For the mixture containing a PG 58-28 binder, the increase was not significant changing from 17.3 to 21.4 GPa at -30 degrees Celsius. The tensile strength was also measured for these mixtures by the direct tension tests and showed a slight increase (less than 0.3 MPa) in tensile strength. These results indicate that for a mixture containing a PG 64-22 binder, and at temperatures below -10 degrees Celsius, the addition of shingles would result in thermal stresses developing in the pavement. Comparing these results to those found in Minnesota, the stiffness of the asphalt (RAP+RAS) prepared in Minnesota was lower than that which was prepared in Missouri, indicating a difference in tear off shingles (McGraw et al. 2007).

Scholtz (2010) found that there seemed to be a linear trend between critical temperatures and the amounts of RAP/RAS used. In this study Scholtz compared results to McGraw et al.'s study (2007) for the Missouri's Department of Transportation (MODOT) and verified the linear trend. Mixtures were investigated containing 5 percent RAS and different amounts of RAP (10 percent increments up to 50 percent). The mixtures containing 40 and 50 percent RAP were mixed with PG 70-28 binder. The critical temperature appeared to increase for both high and low temperatures. The maximum increase in high critical temperature using a PG 64-22 binder occurred in the mixture containing 5 percent RAS and 30 percent RAP which had an increase of 18.5 degrees Celsius. The minimum increase of high critical temperature occurred in the control mixture containing no recycled material which had a decrease in critical temperature of 4.5 degrees Celsius. Similarly, the critical low temperature raised a maximum of 14.0 degrees Celsius and occurred in the mixture containing 40 percent RAP and 5 percent RAS with the PG 70-28 binder. 10 percent RAP and 5 percent RAS yielded the least deviation from original ("as received") properties. The high critical temperature decreased 0.5 degrees C while the low critical temperature increased 2.5 degrees C. It was concluded that the addition of RAS with no RAP had a significant effect on the high temperature grade (16.5 degrees C) and a moderate effect on the low temperature grade (10.5 degrees C). It was possible that errors were introduced: for example, when extracting the binder, the method for recovering involved using solvents that possibly broke down fines creating biased results. This would lead to problems in the RAS (i.e., dissolving the backing). Also, Scholtz expected a bias to be introduced in that all binder may not have been recovered from the samples. The unrecovered binder would be harder with a higher critical temperature.

Maupin (2010) recovered field samples from six different projects using virgin PG 64-22 binder and found the PG grade of the binder. Of the six different projects, 3 sections contained 4 percent shingles in a 25.0 mm nominal maximum aggregate size, two projects contained 5 percent shingles in a 12.5 nominal maximum aggregate size mixture (one using WMA technology), one project contained 2 percent shingles and 18 percent RAP. The 3 sections containing 4 percent shingles were found to have a PG of 83-18, 81-19, and 81-20. The sections containing 5 percent shingles had a PG of 74-20 (using HMA technology) and 74-21 (using WMA technology). The final mixture containing 2 percent shingles and 18 percent RAP had a PG of 74-25. In summary, the high temperature grade was increased one grade on three of the projects, two grades on two of the projects, and three grades on one project. The low temperature grade deteriorated one grade on five of the cases and stayed the same on the sixth case. These results were enforced by Bonaquist's report given at the 4th Asphalt Shingle Recycling Forum in Chicago where he stated that the replacement of 25 percent virgin binder with shingle binder improves the high-temperature grade two levels and degrades the low-temperature grade one level.

Grzybowski (1993) evaluated the efficacy of RAS and also hypothesized improved pavement features. The viscosity was measured before and after aging the pavements and the control specimen having no shingles was measured to be 0.9 and 0.95 centipoise respectively. Incorporating 28.4 percent shingles increased the viscosity to 1.4 and 1.95 centipoise for the un-aged and aged mixtures respectively. This data demonstrates the ability of shingles to increase the viscosity of virgin binders.

In 1994 and 1995, two field test sections were constructed using five percent manufacturing wastes from a plant in Maryland. Shingles were shredded to achieve a maximum particle size of 0.5 inches at the plant in Maryland and shipped in boxes back to Georgia. Lab samples were first constructed verifying a 12.5 mm and a 19.0 mm mix. Testing revealed that the mixtures modified with recycled shingles yielded similar or slightly improved material properties. The viscosity for the modified 12.5mm mix increased, while the viscosity for the modified 19.0mm mix decreased. Testing error was blamed for the difference in results. Results of the increased viscosity indicated the modified mix hardened faster. The roadways constructed were visually inspected by Watson et al. in 1998 and were said to have little distress and were very comparable to control sections having zero percent recycled material. At the time of inspection, Georgia Department of Transportation had no plans to allow for the use of more than 5 percent waste shingles. Also, standard HMA design and QA/QC procedures were deemed satisfactory at that time.

Influence of Waste Shingles on Resilient Modulus

Because the asphalt binder in shingles is stiffer than virgin asphalt binder, the asphalt stiffness is expected to change with the incorporation of shingles. Most research demonstrates a point at which returns are diminished, especially for tear-off shingles. The use of much more than 5 percent tear-off shingles by weight could be problematic. The resilient modulus indicates the fatigue and thermal cracking susceptibility of a pavement. Newcomb et al. (1993) provided temperature dependent testing after verifying mixtures. The resilient modulus was measured at 1, 25, and 40 degrees Celsius. The resilient modulus versus temperature curves revealed control mixtures with 0 percent RAS to have a significantly greater resilient modulus than the mixtures containing manufacturing wastes in the dense graded mixtures. The control's resilient modulus was 5133 and 5420 MPa for the 120/150 and 85/100 penetration grade binders respectively at 1 degree Celsius. At 40 degrees Celsius, the resilient modulus reduced to 1223 (120/150 binder) and 1390 (85/100 binder) There appeared to be a trend, in that the more manufacturing shingles incorporated, the greater the reduction of the resilient modulus (possibly due to the increased fines). The reduction was more significant for the felt backed shingles than the fiberglass shingles. The mixture containing 7.5 percent felt backed shingles yielded a resilient modulus of 2411 and 2669 MPa at 1 degree Celsius and 591 and 968 MPa at 40 degrees Celsius for the 120/150 and 85/100 penetration grade binders respectively. The mixture containing 7.5 percent fiberglass backed shingles yielded a resilient modulus of 4070 and 3556 MPa at 1 degree Celsius and 871 and 744 MPa at 40 degrees Celsius for the 120/150 and 85/100 penetration grade binders respectively. A reduction was not the case for the tear-off shingles however. This was due to the aged binder and fewer fines contained in the shingles. The mixture containing 7.5 percent re-roof shingles yielded a resilient modulus of 5349 and 4149 MPa at 1 degree Celsius and 1119 and 1239 MPa at 40 degrees Celsius for the 120/150 and 85/100 penetration grade binders respectively. The SMA mixture revealed different results. Incorporating 10 percent RAS did not have a significant impact on the resilient modulus. The control mixture had a resilient modulus of 7063 and 935 MPa at 1 and 40 degrees Celsius respectively. Incorporating the felt backed shingles did not reduce the modulus significantly (6927 and 894 MPa at 1 and 40 degrees respectively), the fiberglass shingles, however; show a significant change. At 1 degree Celsius, the modulus was 6681 MPa and at 40 degrees, the modulus was 1300 MPa. This rise at higher temperatures can be attributed to the aggregates from the shingles stiffening the mixture and creating a more dense material.

Button et al. (1996) quantified the resilient modulus of mixtures at 4, 25, and 40 degrees Celsius and had significantly different results than Newcomb. The results indicated that the addition of roofing wastes did not have a significant effect on the resilient modulus of the dense graded mixture. The control mixture had an average resilient modulus of 12174, 3396, and 363 MPa at 0, 25, and 40 degrees Celsius respectively. The incorporation of 5 percent manufacturing shingles yielded an average resilient modulus of 12740, 3206, and 290 MPa at the respective temperatures. The incorporation of 10 percent manufacturing shingles yielded an average resilient modulus of 11752, 3322, and 432 MPa at the respective temperatures. The incorporation of 5 percent tear-off shingles yielded an average resilient modulus of 12878, 3862, and 294 MPa at the respective temperatures. The incorporation of 10 percent tear-off shingles yielded an average resilient modulus of 11573, 4060, and 366 MPa at the respective temperatures. By adding tear-off shingles, the resilient modulus was affected slightly more than by adding manufacturing wastes. Incorporating roofing wastes into the CMHB mixture yielded higher resilient moduli at 40 degrees Celsius than the control mixture, but a lower resilient modulus at 0 degrees Celsius. The control mixture yielded an average resilient modulus of 15567, 3620, and 313 MPa at respective temperatures. Incorporating manufacturing wastes at 5 percent showed resilient moduli of 10748, 3275, and 368 MPa and at 10 percent showed 13663, 3035, and 382 MPa at the respective temperatures. Incorporating fine tear-off wastes at 5 percent showed resilient moduli of 11938, 3717, and 474 MPa and at 10 percent showed 11610, 3689, and 668 MPa at the respective temperatures. It was expected that the dispersion of fibrous materials from the backing of the shingles was responsible for the increase at high temperatures and decrease at low temperatures. Differences between Newcomb and Buttons' results can be attributed primarily to the shingles used.

The study of RAS has expanded into Canada as well. In 2008 Tighe et al. at the University of Waterloo's Centre for Pavement and Transportation Technology (CPATT) presented their report at the Annual Conference of the Transportation Association of Canada. The research conducted contained four verified mixtures. The first mixture was a control mixture having no recycled material. One mixture contained 20 percent RAP only and one mixture contained 3 percent shingles only. Two of the mixtures contained 20 percent RAP, but differed in shingle content (1.4 percent and 3 percent). The resilient modulus was measured at 25 degrees Celsius and the mixture containing shingles only was nearly a third of the control. The control mixture yielded a mean resilient modulus of 1500 MPa and the mixture containing shingles only yielded 617 MPa. For the mixtures containing RAP, the results were 1330, 1339, and 816 MPa for the RAP only, RAP plus 1.4 percent shingles, and RAP with 3 percent shingles mixtures respectively. Overall, there is a significant decrease in resilient modulus when adding recycled material. Other literature available suggests that the decrease should not be this significant. Differences in results should be attributed to the difference in shingles manufactured.

Influence of Waste Shingles on Dynamic Modulus

The dynamic modulus is a representation of the elastic properties of a material. The dynamic modulus is found by subjecting an asphalt sample to a sinusoidal loading at different temperatures and frequencies. A high dynamic modulus indicates an overall "good" mixture. At high temperatures, a high dynamic modulus indicates a rutting resistant mixture. At low temperatures, however; a high dynamic modulus indicates a cracking resistant mixture. Tighe et al. (2008) investigates the dynamic modulus of each test mixture. At low temperatures, the mixtures containing RAP only had the highest dynamic modulus. At -10 degrees Celsius and a frequency of 25 Hz, the dynamic modulus was 24203 MPa which is significantly higher than the control (23166 MPa). Incorporating shingles into the mix with RAP yielded 17624 MPa and 13971 MPa for the mixtures containing 1.4 and 3 percent shingles respectively. The mixture containing shingles only had the lowest resilient modulus at 11012 MPa. At high temperatures, the results were very similar.

Influence of Waste Shingles on Tensile Strength

The tensile strength of asphalt is attributed to the asphalt binder in the mixture. A person could expect a polymer modified mixture to have a larger tensile strength than an unmodified mixture. Incorporating shingles with a stiffer binder could result in a mixture that will not strain due to the stiffness, but could produce a higher tensile strength. Newcomb et al. (1993) provided tensile strength results at -18 degrees Celsius. The general assumption employed was that higher strains at peak stress at cold temperatures could indicate deformation prior to thermal cracking. For the dense graded mixture with 120/150 penetration grade binder, the addition of RAS resulted in a lower cold temperature tensile strength. The control mixture's tensile strength was measured to be 2653 kPa and had a strain of 0.001727 in/in. Incorporating felt backed shingles decreased the tensile strength to 2308 and 1523 kPa for 5 and 7.5 percent shingles respectively. The corresponding strains were 0.001571 and 0.001685 in/in. For fiberglass shingles, the amount of reduction in strain did not appear to be dependent upon the RAS percentage but the reduction was consistently significant. At 5 percent, the tensile strength was 1971 kPa with a corresponding strain of 0.00109 in/in and at 7.5 percent, 1826 kPa with a corresponding strain of 0.001156 in/in. Tear off shingles resulted in a decrease in tensile strength and corresponding strain. At 5 percent the strength was reduced to 2415 kPa and at 7.5 percent the strength was 1537 kPa. The amount of strain appeared to be dependent on the amount of tear-offs incorporated. The corresponding strains were given to be 0.001219 and 0.000852 in/in for the 5 and 7.5 percent shingles. The dense graded mixture using 85/100 penetration grade binder yielded similar results. The cold tensile strengths for the SMA mixtures were similar to the dense graded mixtures. The control specimens yielded a strength of 2755 kPa and a corresponding strain of 0.001749 in/in. Incorporating shingles decreased the tensile strength to 2206 kPa for felt shingles (0.001605 in/in strain) and increased the tensile strength to 3268 kPa (strain of 0.001145 in/in) for the fiberglass shingles. The reduction in the ability of the mixtures containing shingles to strain appears to be caused by the shingles, however; it is also plausible that the inability to strain was caused by the reduction of asphalt binder.

Button measured tensile strength through ASTM D 4867 (indirect tension tests) at 25 degrees Celsius. When incorporating shingles into the dense graded mixture, the tensile strength was reduced significantly. The control specimens had a tensile strength of 1683 kPa with a strain of 0.000331 in/in. Incorporating manufacturing wastes at 5 percent showed a strength of 1387 kPa (0.000382 in/in strain) and at 10 percent showed a strength of 1339 kPa (strain of 0.000147 in/in). Incorporating tear-off wastes at 5 percent showed a strength of 1562 kPa (strain of 0.00103 in/in) and at 10 percent showed a strength of 1601 kPa (strain of 0.00193 in/in). For the CMHB mixtures, there was an increase in tensile strength of the mixtures containing tear-off shingles but a decrease for the mixtures containing manufacturing wastes. The control specimens had a tensile strength of 1100 kPa with a strain of 0.000111 in/in. Incorporating manufacturing wastes at 5 percent showed an average strength of 874 kPa (0.000252 in/in strain) and at 10 percent showed a strength of 899 kPa (strain of 0.000418 in/in). Incorporating tear-off wastes at 5 percent showed an average strength of 1303 kPa (0.000347 in/in strain) and at 10 percent showed a strength of 1356 kPa (strain of 0.000559 in/in). After tensile strengths were measured the effects that shingles had on the moisture susceptibility of the asphalt mixture were determined through Tex-531-C (which is very similar to AASHTO T283). The tensile strength ratios (TSR) were calculated based on indirect tensile strengths before and after moisture conditioning. For the dense graded mixtures, the TSR of the control mixture was 0.58. Incorporating manufacturing waste at 5 and 10 percent yielded a TSR of 0.56 and 0.72 respectively. Incorporating tear-off waste at 5 and 10 percent yielded a TSR of 0.71 and 0.72 respectively. For the CMHB mixtures, the TSR of the control mixture was 0.86. Incorporating manufacturing waste at 5 and 10 percent yielded a TSR of 0.96 and 0.80 respectively. Incorporating tear-off waste at 5 and 10 percent yielded a TSR of 0.78.

Maupin (2010) conducted indirect tension tests at 20 degrees Celsius and used results to estimate how well the binder of the shingles combined with the virgin binder. When mixed at 250 degrees Fahrenheit, the tensile strengths were 155, 165, 168, 173 and 190 psi for mixtures containing 0, 2, 3, 4, and 5 percent shingles respectively. When mixed at 300 degrees Fahrenheit, the tensile strengths were 183, 210, 220, 240, and 245 psi for mixtures containing 0, 2, 3, 4, and 5 percent shingles respectively.

Tighe et al. (2008) measured tensile strength on each of their verified mixtures. The mixture containing 20 percent RAP and 1.4 percent shingles yielded the highest tensile strength which was 556.8 kPa. The control mixture and the RAP only mixture had the next highest tensile strength of 507.3 and 454.2 kPa . The mixtures containing 3 percent shingles showed the worst tensile strength (341.9 kPa with RAP and 288.1 kPa for the mixture with shingles only).

Rutting Test Studies

The French wheel rutting test was used by Tighe et al. (2008) in order to investigate the rutting susceptibility of each of their mixtures. Each mixture showed similar results with the best performance yielding approximately 3.2 percent rut depth at 10,000 cycles and 4.27 percent at 30,000 cycles and the worst performance was 5.08 percent at 10,000 cycles and 3.95 percent at 30,000 cycles. Overall, it was concluded that incorporating shingles at small amounts can reduce the rutting susceptibility, but at greater cycles the permanent deformation can be larger. This can be attributed to the possibility that the shingles are causing the binder to strip from the aggregate.

The Georgia Loaded Wheel Tester was used by Grzybowski to evaluate the rutting susceptibility of a verified mixture with 10 percent RAS and a control mixture with no RAS. The mixture with 10 percent RAS showed a significant decrease of rutting susceptibility. At 1,000 cycles the control showed a rut depth of 2.1 mm and the mixture with RAS showed a depth of 0.8 mm. At 8,000 cycles the mixtures exhibited a permanent deformation of 5.1 mm and 1.7 mm for the control and 10 percent RAS mixtures respectively.

The Asphalt Pavement Analyzer (APA) was selected by Mallick (2000) to analyze the rutting susceptibility of verified mixtures. The APA is essentially the same as the Georgia loaded wheel tester. In the controlled temperature and moisture environment, the temperature was chosen to be 60 degrees Celsius. The control mixture was first tested and had a mean rut depth of 4.915 mm. The mixtures containing shingles showed a permanent deformation of 1.917 mm and 1.41 mm for 5 and 7 percent shingles respectively. This research further verifies the results found by Grzybowski and Tighe et al.

Maupin et al. (2010) conducted fatigue tests using the APA machine as well. Maupin performed testing on asphalt beams in accordance with Virginia Test Method 110 at 49 degrees Celsius with a pressure of 827 kPa. Maupin analyzed the mixtures by manually measuring the rut depth after 8,000 cycles and the rutting depths were said to be comparable to those reported for a conventional Virginia DOT surface mixture containing PG 70-22 binder. The mixtures gave an average rut depth of 1.4 mm when 4 percent shingles were incorporated, 0.9 mm when 5 percent shingles were incorporated (using WMA and HMA technology) and 1.3 mm for the mixture containing 2 percent shingles and 18 percent RAP.

Cold Patch Asphalt

Due to the deleterious material often found in wastes shingles, research incorporating shingles into the binder that is an emulsion is very limited. Grodinsky et al. (2002) incorporated RAS into three separate projects of cold patch asphalt. The cold patch mix design incorporated 14 percent shingles, 6 percent liquid binder, and 80 percent aggregate. The cold patch was heated to 180 degrees Fahrenheit. The RAS cold patch asphalt was “dryer and harder”, which resulted in difficulties for machine and handworking of the pavement. Along with this, concerns about long term cracking and loss of adhesion were expressed.

Rural Road Studies

The components of shingles make it a viable option for rural roads. Incorporating the shingles as an aggregate and uniformly grading the materials could provide a gravel road that performs better than a conventional unpaved road. Grodinsky et al. (2002) incorporated waste shingles into three different rural roads as an aggregate. The projects incorporating RAS as an aggregate began by shredding the shingles to a maximum of 3/8 inches, dumping, spreading, and grading the shingles with 1.5 inch maximum aggregate size gravel. The RAS/gravel mix was de-nailed on a conveyor with a drum magnet. Grodinsky reported that the community was very pleased with the material. The second project incorporated RAS/RAP/gravel into a rural road. The section did not report being better or worse than good quality gravel, but was less muddy with less drainage problems. An additional section of RAS/RAP/gravel had positive reviews of being in great condition. One resident however complained of scattered nails along the road. This complaint further reinforces the need for appropriate QA/QC testing of shingle sources used for roadway applications.

Marks and Petermeier studied the effects of consumer waste shingles in an Iowa DOT rural gravel road in 1997. Wood particles were not removed from the shingles because a contractor believed the wood could facilitate the grinding process. Nails were removed using a magnetic roller. It was the intent to add enough shingles to limestone gravel to create a one to one ratio. A grader bladed the crushed stone and ground shingles back and forth until the mixture appeared to be uniform. This mixture was approximately

2.5 inches thick. After implementation, the lighter particles of wood were displaced to the edge of the roadway by traffic. Positive results were reported in that the waste shingles provided a dust free granular surfaced roadway for at least two years. There were a few flat tires due to nails reported, but this problem appeared to no longer be present.

Summary

It is apparent that the use of shingles in asphalt is growing rapidly. The organizations involved are making great strides in the studies of the performance of RAS. As noted before, literature will continue to be searched and reviewed as it becomes available. It is apparent that the compositions and properties of RAS are well documented particularly for manufacturing scrap shingles. To date, the following list can be concluded.

- Important properties of shingles include asphalt stiffness, asphalt content, and gradation.
- Shingles made after 1980 do not contain asbestos materials and are considered safe for processing.
- RAS addition rates have varied from 3 to 10 percent by weight of the total mixture
- Studies have found an improvement in HMA properties when small amounts of RAS, such as 5 percent and less, are incorporated.
- Studies have found an improvement in rutting and cracking resistance when shingles are incorporated into the asphalt mixture.
- The amount of research on warm-mix/RAS and cold patch/RAS is limited.
- Shingles have been successfully implemented into rural roads serving as a superior product to gravel.

Research Objectives:

The overall objective of this research was to assess the use of RAS for asphalt pavements in Arkansas. Specific objectives are as follows.

- Validate existing mixture design procedures associated with RAS. The asphalt binder contribution was a primary concern in this objective. Different mixtures containing a range of RAS from 0 to 10 percent were designed according to AASHTO M323, PP 53 and MP 15. Two aggregate/manufacturing waste sources were used in order to determine whether significant differences exist. Two different nominal maximum aggregate sizes (NMAS) were selected in order to evaluate the effects RAS on different asphalt courses. Finally, two different asphalt binder grades were chosen to assess the asphalt performance sensitivity with RAS to binder grade. Volumetric properties were established and the binder contribution determined using AASHTO PP 53-09 and MP 15-09. The process of adding RAS to the asphalt was investigated as well. The shingles were added at ambient temperatures, as recommended by AASHTO, and compared to mixtures where the RAS has been heated and added as an aggregate.
- Evaluate the performance of mixtures containing RAS. After each specimen was verified and compared to see how the addition of RAS had affected the volumetric properties, each mixture's performance was compared. Specific performance tests evaluated compactability, rutting resistance, moisture damage susceptibility, and dynamic modulus.
- Determine the maximum shingle percentage and grind size that should be used. Based on the performance data obtained, a maximum shingle content was established. After establishing the maximum shingle content to use, various shingle grind sizes were

implemented. Finer ground shingles cost more to grind but may contribute to the mixture's asphalt binder better, reducing the requirement for virgin binder. In order to determine the optimum shingle grind size, tear-off shingles were used. First, certain mixes were established where manufacturing wastes shingles were replaced with tear-off shingles. Next, the shingles were sieved into two different fractions (retained on the #4 sieve and passing the #4 sieve). Each fraction was introduced to new asphalt separately and analyzed for binder contribution. Finally, the effects of agglomeration were assessed using manufacturing wastes shingles. The optimal grind size of shingles was determined based on the benefits in conjunction with the costs.

Scope:

This research consisted of the following tasks:

Task 1: Create mixture designs covering a range of properties. These properties included nominal maximum aggregate size (NMAS), binder grade (modified and unmodified), and aggregate source (limestone and river gravel). Each mixture was designed according to AASHTO procedures MP15 and PP53. After the mixture designs were established, shingles were incorporated to each control mixture at 2.5, 5, and 10 percent by weight of the total mix and re-established.

A total of eight control mixture designs were established and then adjusted for a range of shingle contents. This task only used manufacturing waste shingles. Table 3 summarizes parameters for the mixture designs.

Table 3: Summary of Parameters for Mixture Designs

Parameter	**Value**
Nominal Maximum Aggregate Size (NMAS)	12.5 mm, 25.0 mm
Binder Grade	PG 64-22, PG 70-22
Aggregate Source	Limestone, River Gravel
Shingle Content (%)	0, 2.5, 5, 10

The shingles were burned alone in order to verify the shingle aggregate gradation. The shingle aggregate gradation was needed in order to know if the virgin aggregate composition should be altered so that the mixture meets gradation requirements. To determine the aggregate gradation, clumps of fibers present in the shingles were removed prior to testing. Table 4 provides a standard gradation given by AASHTO which may be used in lieu of determining the shingle gradation and the shingle gradations used in this research. Analyses of shingles were compared to table 4 in order to determine the acceptability of the AASHTO standard gradation. Determining the shingle maximum theoretical specific gravity was done according to T 209.

Table 4: Shingle Aggregate Gradations

Shingle Aggregate Gradations					
Sieve Size (mm)	AASHTO	Source 1	Source 2	Source 1 TO	Source 2 TO
	Percent Passing by Weight				
9.5	100	100	100	100	100
4.75	95	98.6	98.6	98.6	99.1
2.36	85	97.5	97.5	96.3	98.0
1.18	70	83.6	83.6	80.4	80.2
0.6	50	60.9	60.9	61.7	59.5
0.3	45	51.0	51.0	50.5	53.1
0.15	35	43.2	43.1	39.6	45.8
0.075	25	31.5	31.5	32.6	36.7

Task 2: To investigate asphalt binder contribution. AASHTO provides an equation yielding an initial estimate of the percentage of asphalt binder (F_c) that is released from the shingles (equation 2 given in the background section of this research). Because equation 1 is an underestimated value, a corrected value is given in equation 2. After the binder contribution was found for each mix, the estimated costs and savings were determined and compared.

Task 3: To estimate performance parameters, including rutting resistance, moisture damage susceptibility, and dynamic modulus. The Evaluator of Rutting and Stripping in Asphalt (ERSA) test was performed to evaluate rutting and stripping susceptibility. Each of the 32 verified mixture designs covering a range of properties was evaluated in ERSA. Moisture is often used to aid the process of grinding, and because of shingles' ability to retain moisture there is concern that the shingle product will not be dry during RAS processing. This moisture could cause the mixture to be prone to failure by moisture damage or rutting, therefore additional tests for moisture damage were conducted according to AASHTO T 283. Based on the performance data obtained from ERSA, select samples were selected for this test. The selected samples covered a range of shingle contents and be compared to ERSA results. Finally, the dynamic modulus was quantified to see the effect of the shingles' binder on the stiffness of the asphalt. The shingle binder was expected to be stiffer than the asphalt binder due to the ageing and oxidation of shingles, and the blended binder could have exhibited excessive stiffness resulting in premature fatigue cracking. The investigation of dynamic modulus was limited to the surface mixtures. Differences in results were attributed primarily to the addition of RAS. These differences were expected to show a trend with respect to the amount of shingles added. Statistical analyses were performed on each of the eight mixture designs with ranging shingle contents in order to determine whether there was a significant difference in mixtures containing different amounts of RAS. The statistical analyses were used to determine the optimum percentage of RAS to use in asphalt mixtures. Upon completion of this task, a statistically supported decision was made regarding the maximum percentage of shingles to be allowed in HMA. The data obtained from this task was also used to develop recommendations for the inclusion of RAS in AHTD Standard Specifications.

Task 4: To evaluate mixtures containing tear-off shingles and compare to mixtures containing manufacturing wastes. Gradation and ignition oven testing of tear-off shingles was first compared to that of manufacturing wastes and also to AASHTO standard gradations. Next, several designs were selected covering a range of properties and the manufacturing waste shingle content was replaced with tear-off shingles. Where volumetric properties were significantly different, performance testing was conducted and compared directly to the results of mixtures containing manufacturing wastes. The effects of shingle grind size and agglomeration were also investigated in this task. Many factors affect binder contribution of shingles. Such factors include location in the manufacturing process where the RAS is added to the new HMA, the temperature of the aggregates, the temperature of the virgin asphalt binder, and the length of the mixing time (AASHTO PP 53-09). The shingle size however, is most likely the greatest factor affecting binder contribution (AASHTO PP53-09). As the shingle size is decreased, the ability to be incorporated into HMA becomes better. In other words, as the grind size decreases, the quantity of available binder from the shingles increases. This contribution labels RAS as a sustainable recycled material. An experiment was conducted to investigate the effects of binder contribution and its relationship to grind size. In this experiment the binder content of the shingles was found through testing in the ignition oven. Next, various fractions of ground shingles were incorporated into an established mix design at a prescribed rate, and the resulting air voids assisted in developing the relationship of grind size to effective binder contribution (Williams 2010).

Task 5: To evaluate the feasibility of using RAS with WMA. This task was limited to one WMA technology. 2 mix designs were selected for use with Evotherm 3G and 5 percent manufacturing wastes shingles. The mix designs covered 2 aggregates (syenite and limestone), 1 NMAS (12.5mm), and 2 binder grades (PG 64-22 and PG 70-22). For this task, only the binder contribution was evaluated and ERSA data was obtained and used to assess the feasibility of using RAS to enhance asphalt using WMA technology.

Statistical Analyses Conducted

For each of these analyses, ANOVA or t-tests were conducted using JMP software. A list of the objective questions and correlating data sets used for each statistical analysis are shown below along with summary tables for each analysis.

- Analysis #1: Did a change in RAS content significantly affect the properties of the mixture?
  - Experimental factors: NMAS, aggregate type, binder grade, and percent RAS
  - Responses: %AV (percent air voids), VMA (voids in the mineral aggregate), VFA (voids filled with asphalt), height at N_{des}, and $\%G_{mm}$ at N_{ini} (compaction at N_{ini})
- Analysis #2: Which factors significantly affected the amount of binder contribution?
  - Experimental factors: NMAS, aggregate type, binder grade, and percent RAS
  - Responses: Percent Binder Contributed
- Analysis #3: Did the RAS content significantly affect the rutting and stripping performance of the mixture?
  - Experimental factors: NMAS, aggregate type, binder grade, and percent RAS
  - Responses: rut depth at 10,000 cycles, rut depth at 20,000 cycles, rutting slope, stripping slope, SIP (stripping inflection point) (This data came from ERSA, the Evaluator of Rutting and Stripping in Asphalt) and the max load (obtained from the T283 test). A paired t-test was conducted on the tensile strength ratio (TSR) data obtained from the T283 test to determine if the TSR value was significantly affected by the addition of 5 percent RAS.
- Analysis #4: Did the RAS content significantly affect the dynamic modulus of the mixture?

- Experimental factors: aggregate type, binder grade, and percent RAS
- Responses: dynamic modulus (at 40, 70, and 100 degrees) and phase angle

- Analysis #5: Did the replacement of manufacturing wastes RAS with tear-off RAS (screened and unscreened) or amount of agglomeration significantly affect the amount of air voids?
  - For Analyses 5, paired t-tests were conducted with the air voids of mixtures containing 5 percent RAS being the response values.
- Analysis #6: Did the inclusion of RAS to mixes incorporating WMA technology practically affect the performance of the mixes.

Data and Analyses:

The purpose of this research was to better understand how recycled asphalt shingles affect the properties and performance of asphalt pavements. Data was generated to answer the following questions.

- Analysis #1: How sensitive were various mixture properties to changes in manufacturing shingle content?
- Analysis #2: How well did the shingles contribute binder to the asphalt mixture?
- Analysis #3: Were any of the mixtures containing manufacturing shingles more susceptible to rutting or stripping than the hot mix asphalt mixtures using ERSA and AASHTO T283?
- Analysis #4: How sensitive was dynamic modulus to changes in manufacturing shingle content?
- Analysis #5: How sensitive were various mixture properties to change in tear off shingle content, shingle grind size, and agglomeration?
- Analysis #6: How sensitive were various mixture properties to changes in shingle content when warm mix technology was incorporated?

For each of these investigations, the data were examined using statistical analyses. The statistical analyses conducted in this research included t-tests and multifactor ANOVA tests. The assumptions of normality, independence, and constant variance were verified for each analysis. An alpha value of 0.05, which corresponds to a 95% level of significance, was used.

Hot Mix Asphalt Mixture Designs

For this project, a limestone from northwest Arkansas and crushed river gravel from southwest Arkansas were used to create asphalt mixes representing aggregate sources typically found in Arkansas. These particular sources were chosen because they have differing mineral composition, density, and absorptive capacity, and were located in relative proximity to shingle manufacturers, making these sources likely candidates for future use in mixtures containing RAS. Nominal maximum aggregate sizes (NMAS) of 12.5mm and 25mm were selected in order to evaluate the effects RAS on different asphalt courses. Finally, PG 64-22 and 70-22 asphalt binder grades were chosen. The mix designs used for this project are summarized in Tables 5 and 6.

Table 5: Limestone Mix Designs

Northwest Arkansas' Limestone				
NMAS	**12.5mm**	**12.5mm**	**25.0mm**	**25.0mm**
Binder Grade	**PG 64-22**	**PG 70-22**	**PG 64-22**	**PG 70-22**
N_{des}	75	100	75	100
Job Mix Formula (%)				
1-1/2" Limestone	0	0	14	14
½" Sandstone	30	30	0	0
5/8" Limestone	11	11	35	35
½" Fine	11	11	20	20
½" Minus	11	11	20	20
Man. Sand	37	37	11	11
Blend Gradation				
% Passing				
1-1/2"	100.0	100.0	100.0	100.0
1"	100.0	100.0	91.7	91.7
¾"	100.0	100.0	87.4	87.4
½"	99.3	99.3	82.4	82.4
3/8"	89.0	89.0	66.1	66.1
No. 4	48.7	48.7	28.5	28.5
No. 8	28.0	28.0	19.1	19.1
No. 16	16.9	16.9	12.6	12.6
No. 30	10.0	10.0	8.9	8.9
No. 50	5.9	5.9	6.7	6.7
No. 100	4.1	4.1	5.0	5.0
No. 200	3.0	3.0	4.2	4.2
Virgin Binder Content	6.2	6.2	4.5	4.6
Air Voids (%)	4.6	4.5	4.7	4.5
VMA (%)	15	15	13.3	13
VFA (%)	72.1	73.1	64.7	69
Gsb	2.549	2.549	2.605	2.619
Gse	2.653	2.657	2.676	2.688
G_{mm}	2.416	2.419	2.496	2.501
F/A	0.7	0.6	1.2	1.2
Pbe (%)	4.4	4.663	3.496	3.6
Gb	1.0255	1.0235	1.0255	1.0235
G_{mm} at N_{ini} (%)	83.3	83.9	83.4	83.8
Mix Temp. (F)	315	320	315	320
Compaction Temp. (F)	293	312	293	312

Table 6: River Gravel Mix Designs

	Southwest Arkansas River Gravel			
NMAS	**12.5mm**	**12.5mm**	**25.0mm**	**25.0mm**
Binder Grade	**PG 64-22**	**PG 70-22**	**PG 64-22**	**PG 70-22**
N_{des}	75	100	75	100
Job Mix Formula (%)				
B	0	0	40	40
C	25	25	0	0
D	20	20	0	0
Screenings	25	25	25	25
Sand	20	20	20	20
½ CR	10	10	15	15
Blend Gradation				
% Passing				
1-1/2”	100	100	100	100
1”	100	100	100	100
¾”	99.6	99.6	86.5	86.5
½”	89.5	89.5	69	69
3/8”	76.3	76.3	60.6	60.6
No. 4	59.2	59.2	50.7	50.7
No. 8	46	46	43.9	43.9
No. 16	34	34	33.7	33.7
No. 30	25.2	25.2	25.4	25.4
No. 50	17.5	17.5	17.8	17.8
No. 100	7.6	7.6	7.8	7.8
No. 200	3.0	3.0	3.2	3.2
Virgin Binder Content (%)	5	4.8	4.6	4.3
Air Voids (%)	4.4	4.4	4.6	4.6
VMA (%)	14.4	14	14.2	13.9
VFA (%)	69.8	68.6	71.5	66.9
Gsb	2.584	2.584	2.596	2.596
Gse	2.624	2.627	2.631	2.635
G_{mm}	2.434	2.444	2.455	2.465
F/A	0.7	0.7	0.8	0.8
Pbe (%)	4.495	4.288	4.1	3.742
Gb	1.026	1.024	1.026	1.024
G_{mm} at N_{ini} (%)	88.8	88.4	88.8	88.4
Mix Temp. (F)	315	320	315	320
Compaction Temp. (F)	293	312	293	312

Analysis #1: Evaluation of Recycled Asphalt Shingle Mixture Designs

The first objective was to evaluate the effects of recycled shingles on hot mix asphalt mixture designs. For this analysis, the binder contribution was calculated in accordance with AASHTO MP 15. The experimental factors included nominal maximum aggregate size (NMAS), aggregate type (limestone and river gravel), binder grade/compaction level (PG 64-22 with N_{des}=75 and PG 70-22 with N_{des}=100), and shingle content. The responses included optimum binder content (P_b) percent air voids (%AV), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and percent compaction at N_{ini} (%G_{mm} at N_{ini}). This experimental setup is summarized in Table 7.

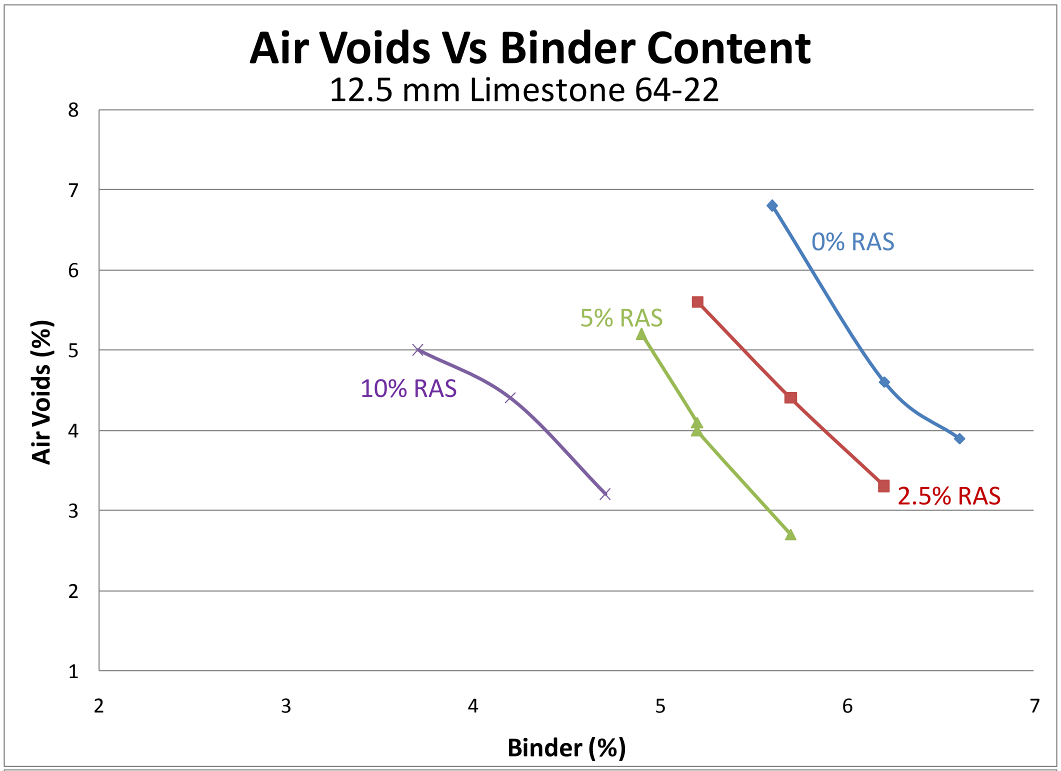
Table 7: Analysis #1 Experimental Setup

Does change in shingle content significantly affect the mixture properties?		
factors:	levels:	responses:
Aggregate type	Limestone Crushed River Gravel	Binder Content %AV VMA VFA %G_{mm} at N_{ini}
Binder Grade/Compaction level	PG 64-22 / N_{des}=75 PG 70-22 / N_{des}=100	
NMAS	12.5 mm 25.0 mm	
Shingle Content	0% 2.5% 5% 10%	

The purpose of this analysis was to determine how the addition of shingles affected the volumetric properties of the hot mix asphalt. It is important for the pavement community to know how the responses were affected, because certain mixes may be able to incorporate more RAS than others. For example, if the VMA is raised by incorporating

RAS, then the mixes with a low VMA can incorporate more than the mixes with a high VMA. Due to the amount of fines present in shingles, it was expected that the responses would change slightly. A reduction in the need for virgin asphalt binder was also expected to be the most significant change, which could in turn affect the other responses.

The first step of this analysis was to establish hot mix controls for each mix design by determining a gradation and optimum virgin binder content, then producing two samples for G_{mm} testing and two samples for G_{mb} testing at the design virgin optimum binder content. Next, the samples were produced with heated shingles which were incorporated at prescribed rates, and the "new" mixtures with RAS were verified. As expected, the virgin optimum binder content (at 4.5% air voids) changed the most when incorporating shingles. The reduction of required virgin binder makes RAS an appealing technology. Plots of the virgin binder content against air voids are shown in Figure 1.



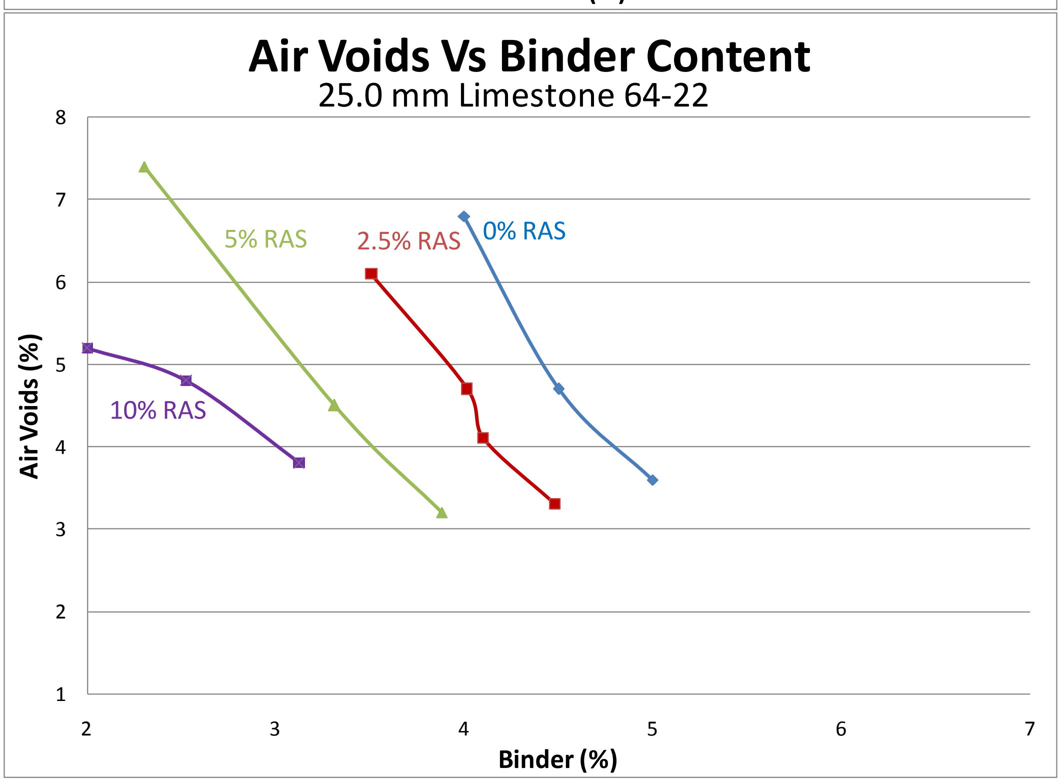


Figure 1a: Air Voids Vs. Virgin Binder Content for Limestone Mixes (PG 64-22)

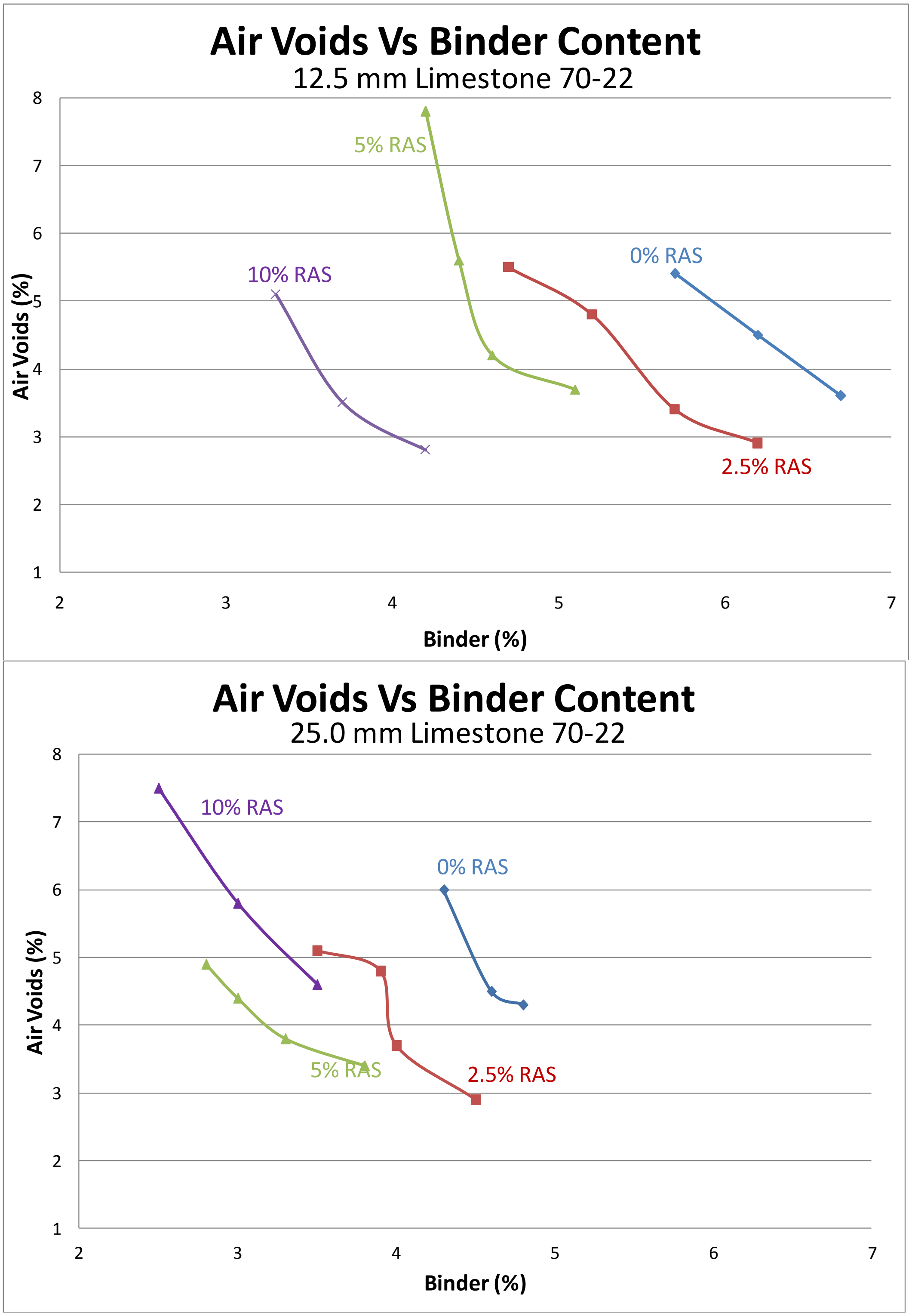
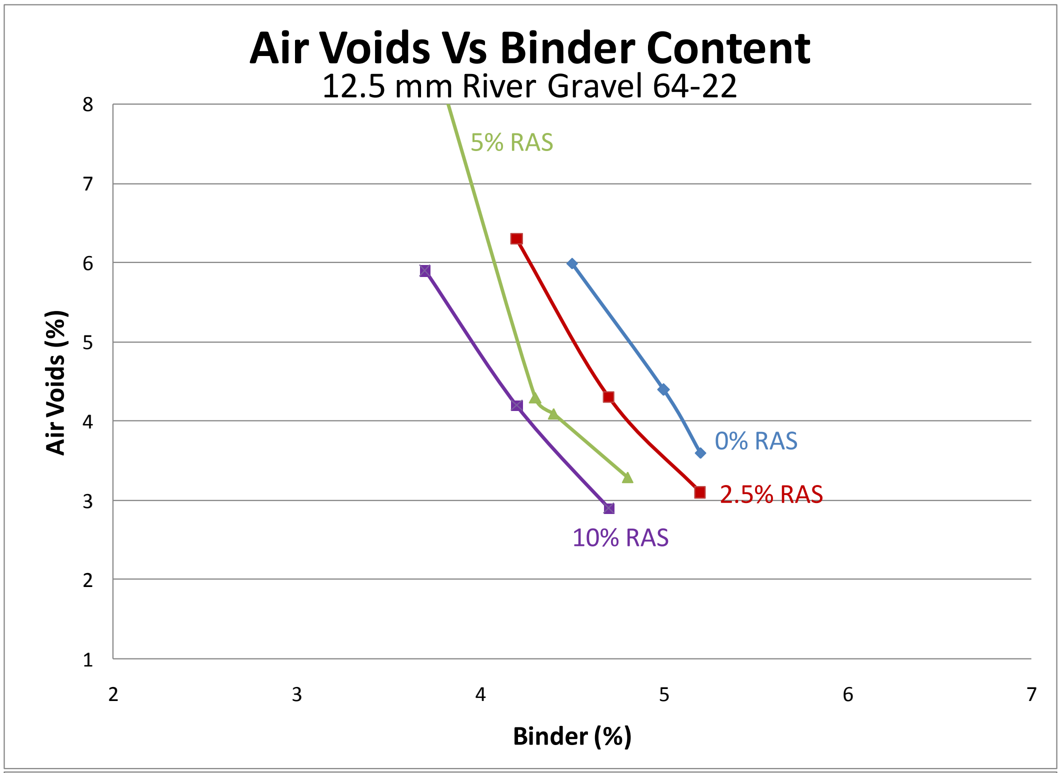


Figure 1b: Air Voids Vs. Virgin Binder Content for Limestone Mixes (PG 70-22)



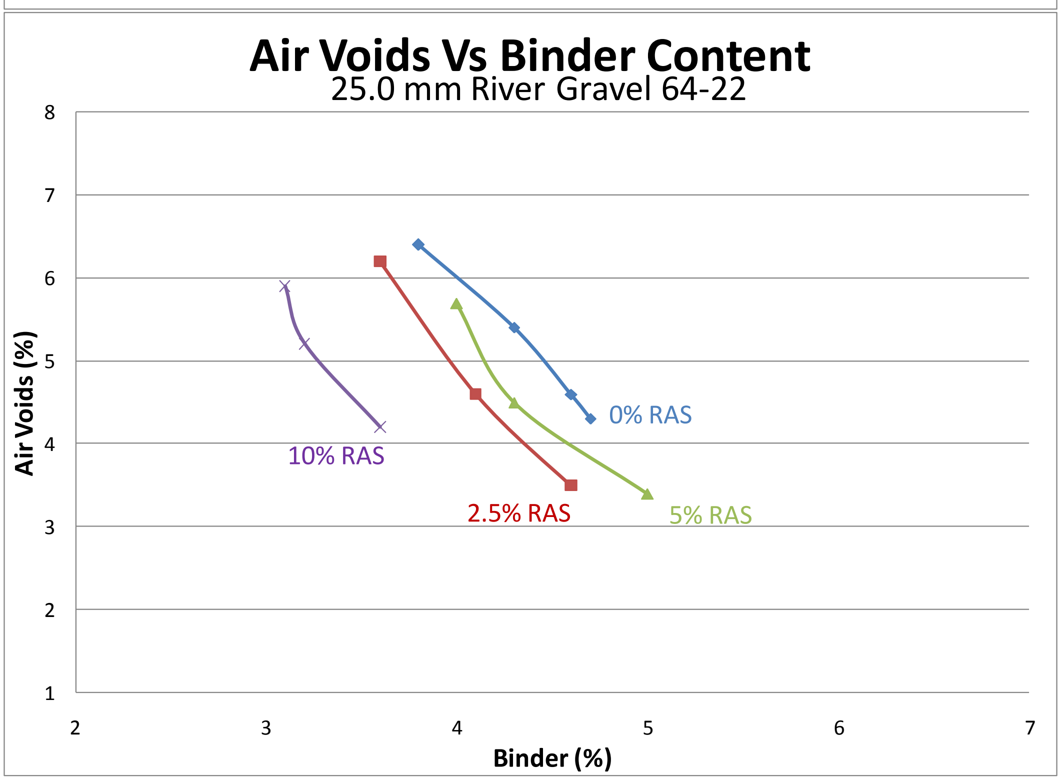
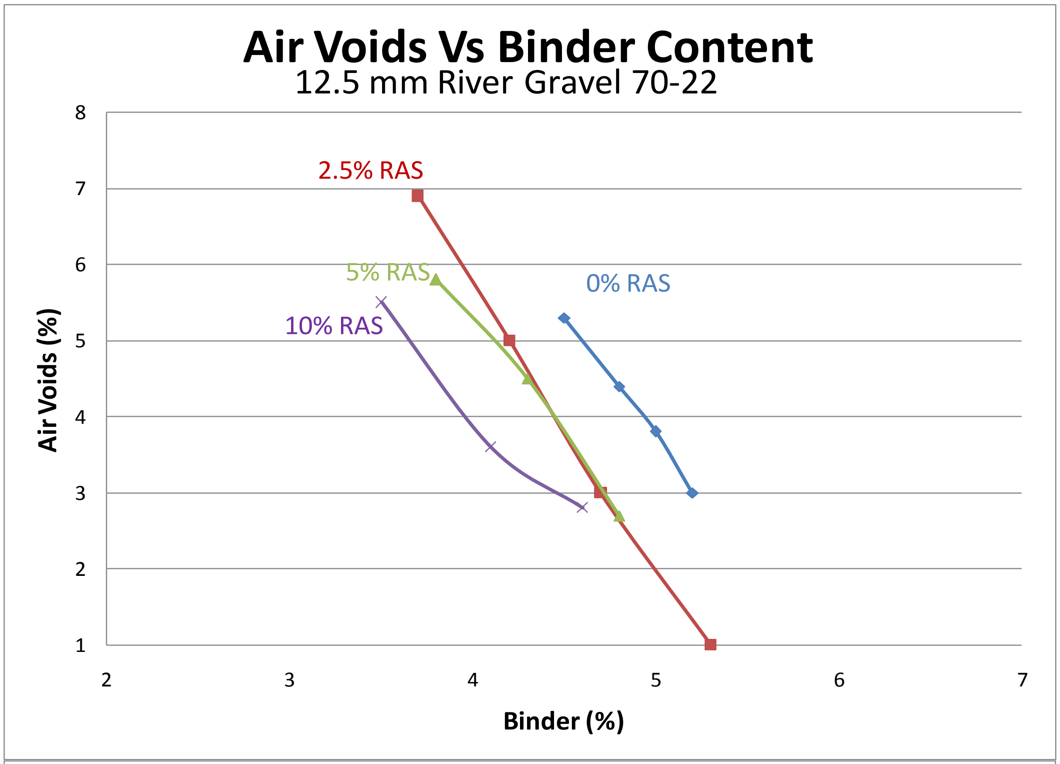


Figure 1c: Air Voids Vs. Virgin Binder Content for River Gravel Mixes (PG 64-22)



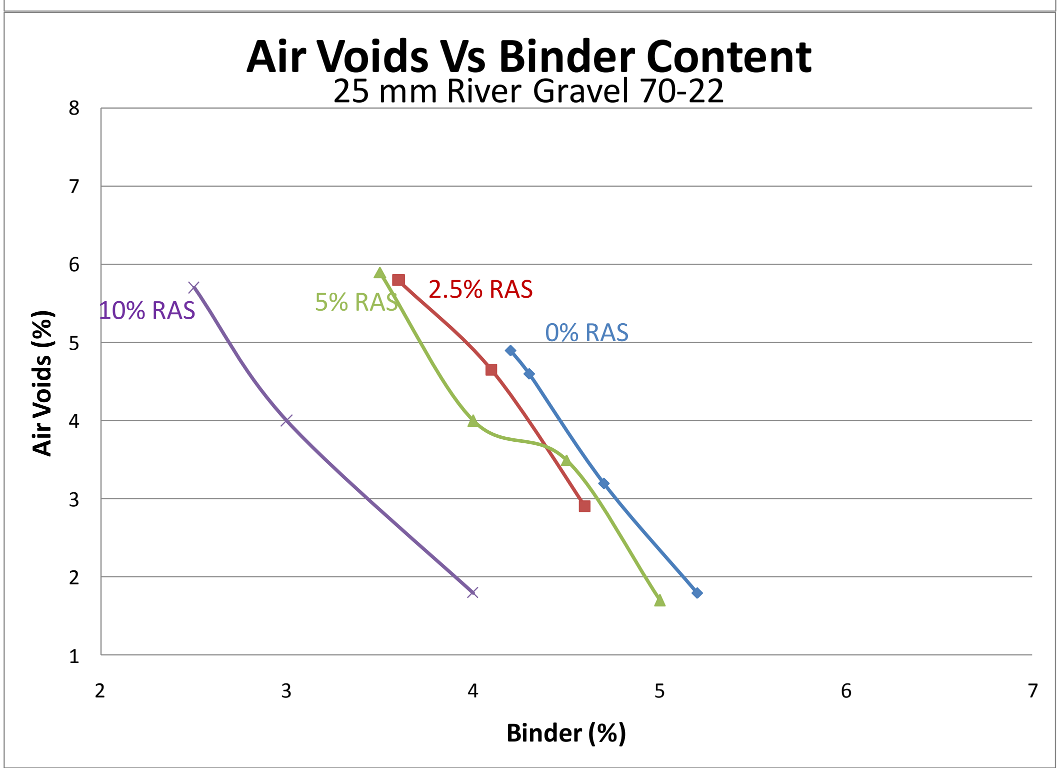


Figure 1d: Air Voids Vs. Virgin Binder Content for River Gravel Mixes (PG 70-22)

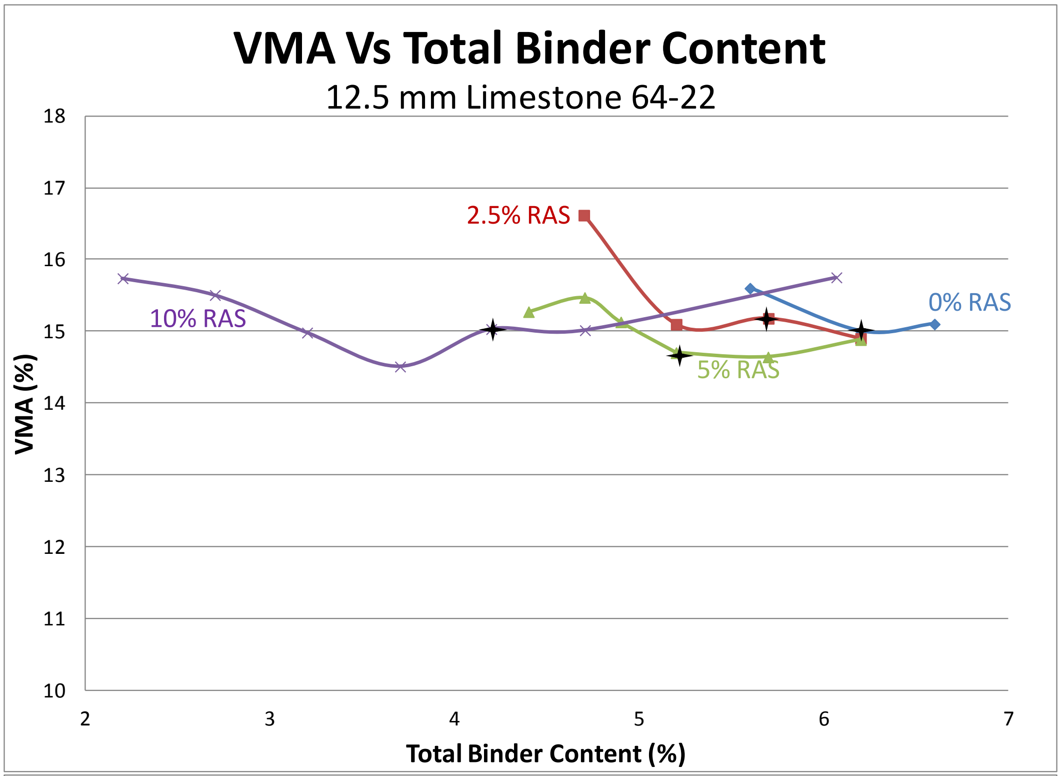
From Figure1, it was seen that the required virgin binder was reduced for each mix when RAS was incorporated but not always in the expected order. The limestone mixtures showed a large reduction of virgin binder when RAS was incorporated (approximately 0.6% reduction for every 2.5% RAS incorporated). The RAS in the 12.5mm river gravel with PG 64-22 showed a contribution of approximately 0.3% binder for every 2.5% RAS. The 12.5mm river gravel mix with PG 70-22 showed a 0.5% binder reduction when using 2.5% RAS but only 0.4% binder reduction for 5% RAS. The amount of air voids in the 25.0mm river gravel mixes with PG 70-22 binder did not show a practical difference between the mixes with 2.5% RAS and 5% RAS; however, greater reductions in virgin binder content were generated for the 10% RAS mixes.

The volumetric properties were found and compared to the control mixtures. The average values of two samples at virgin optimum binder contents were obtained for the volumetric properties with various shingle contents and are shown in Table 8.

Table 8: Average Values for Responses with Different Shingle Content

			Average Values for Responses			
Mix Design	% RAS	Virgin Pb	%AV	VMA	VFA	%G_{mm} at N_{ini}
12.5 mm PG 64-22 Limestone	0	6.2	4.7	15.2	66.4	83.3
	2.5	5.7	4.4	15.2	70.8	84.1
	5.1	5.2	4.1	14.7	72.2	83.9
	10	4.2	4.5	14.3	68.8	84.6
25.0 mm PG 64-22 Limestone	0	4.5	4.8	13.3	64.4	83.4
	2.5	4	4.7	13.3	63.0	83.5
	5	3.3	4.6	12.8	64.1	84.4
	10	2.5	4.5	12.6	61.6	80.8
12.5 mm PG 70-22 Limestone	0	6.2	4.5	15.0	69.9	83.9
	2.5	5.3	4.5	15.2	70.1	83.4
	5	4.5	4.6	14.6	68.2	83.8
	10	3.6	4.4	14.2	69.2	84.4
25.0 mm PG 70-22 Limestone	0	4.6	4.3	13.2	67.7	83.8
	2.5	3.9	4.4	13.1	66.5	83.7
	5	3.5	4.4	12.6	65.0	84.2
	10	3.5	4.6	11.9	61.3	85.1
12.5 mm PG 64-22 River Gravel	0	5	4.4	15.1	70.8	88.8
	2.5	4.7	4.3	15.0	71.4	88.8
	5	4.3	4.3	14.3	70.2	88.8
	10	4.1	4.4	14.7	70.1	88.2
25.0 mm PG 64-22 River Gravel	0	4.6	4.6	13.5	66.2	88.8
	2.5	4.1	4.5	13.7	67.6	89.2
	5	4.4	4.4	12.7	64.7	88.4
	10	3.7	4.2	13.8	69.5	88.8
12.5 mm PG 70-22 River Gravel	0	4.8	4.4	14.3	69.0	88.4
	2.5	4.2	4.8	14.6	67.7	88.5
	5	4.3	4.5	14.4	68.8	88.2
	10	4	4.7	15.0	68.6	87.8
25.0 mm PG 70-22 River Gravel	0	4.3	4.5	13.5	66.3	88.4
	2.5	4.1	4.7	14.2	67.4	88.4
	5	4	4.6	14.3	68.1	88.2
	10	3.8	4.7	15.1	69.0	88.1

Figures 2 through 5 show the data in Table 12 more clearly



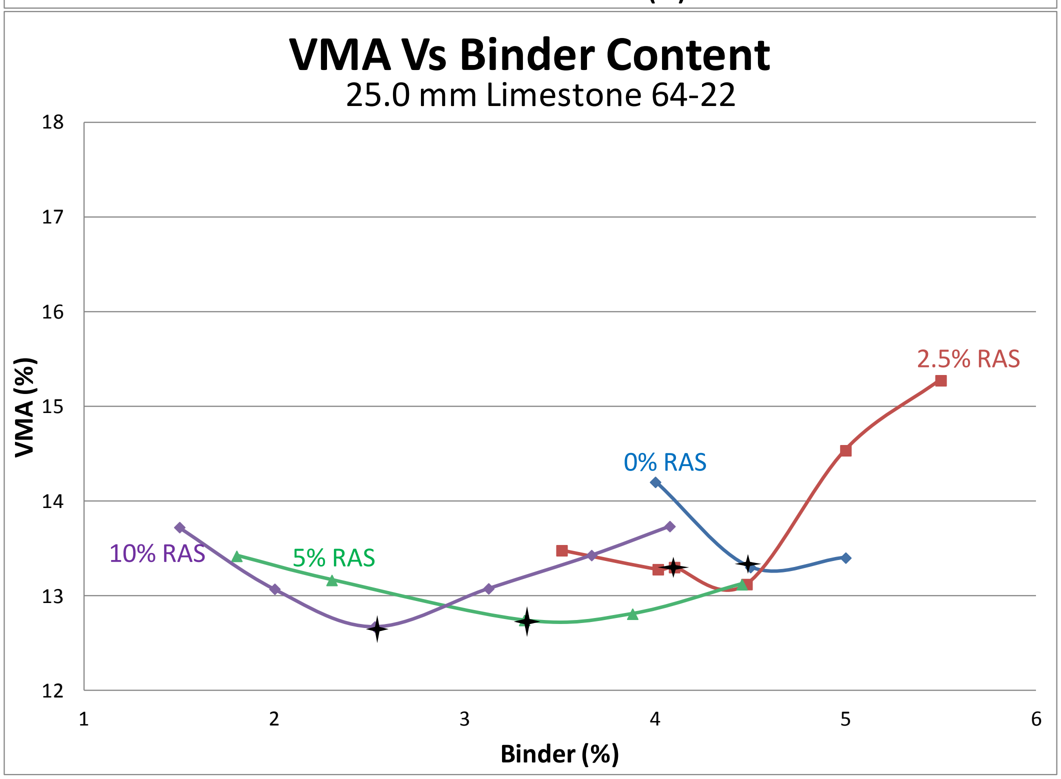
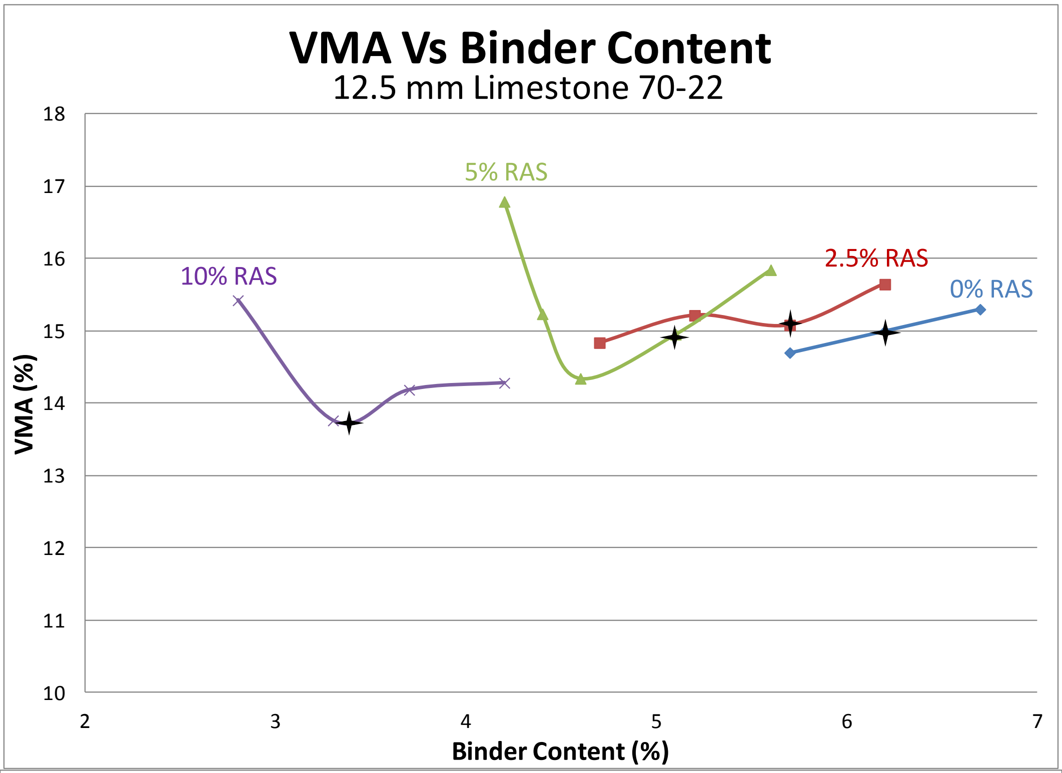


Figure 2a: Total VMA Vs. Virgin Binder Content in Limestone Mixes (PG 64-22)



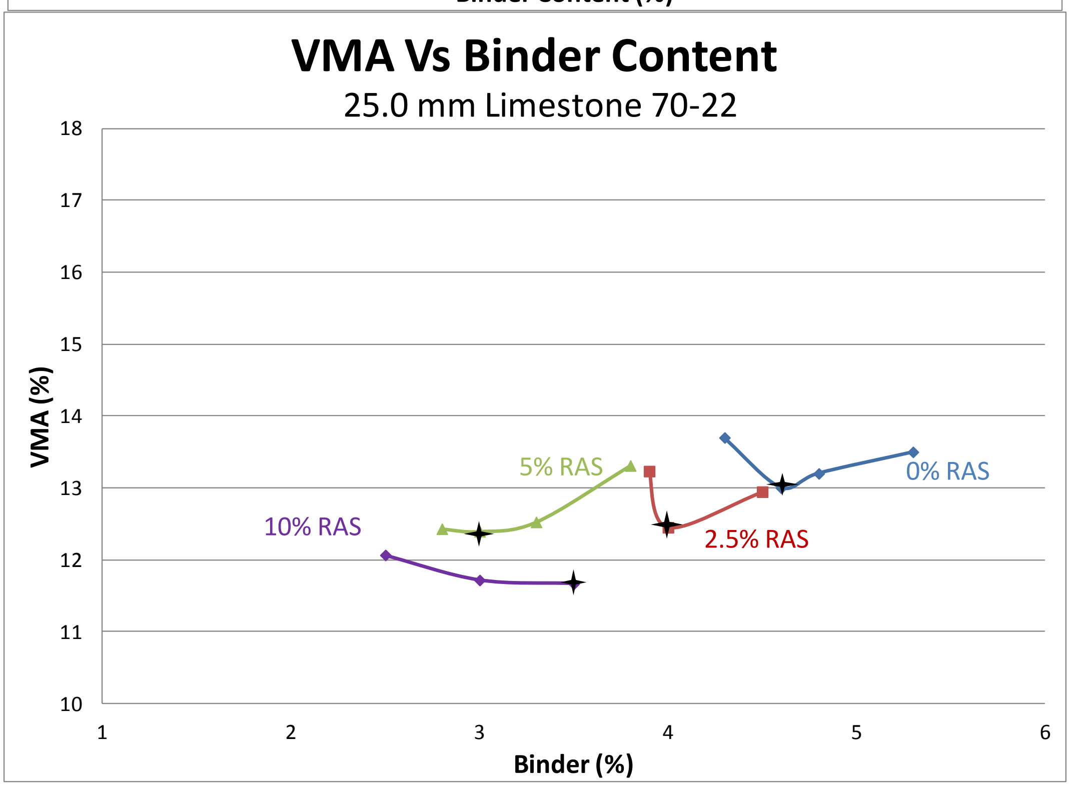
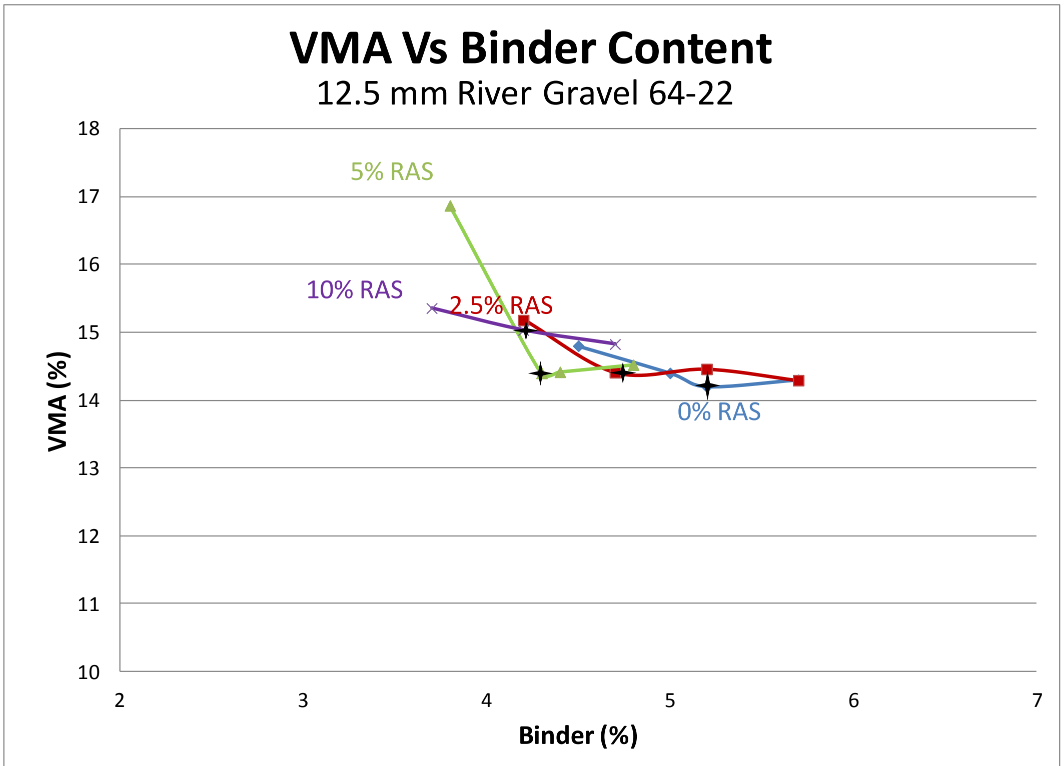


Figure 2b: Total VMA Vs. Virgin Binder Content in Limestone Mixes (PG 70-22)

The VMA in each of the limestone mixes generally decreased at the optimum binder content by incorporating RAS, and this decrease appeared more significant for the 25.0mm mixes than the 12.5mm mixes. The VMA appeared to be less sensitive to the RAS content in the PG 64-22 binder than in the PG70-22 binder. The VMA in the mixes with PG70-22 binder decreased 0.8 and 1.3 percent by adding 10 percent RAS to the 12.5 and 25.0mm mixes respectively.



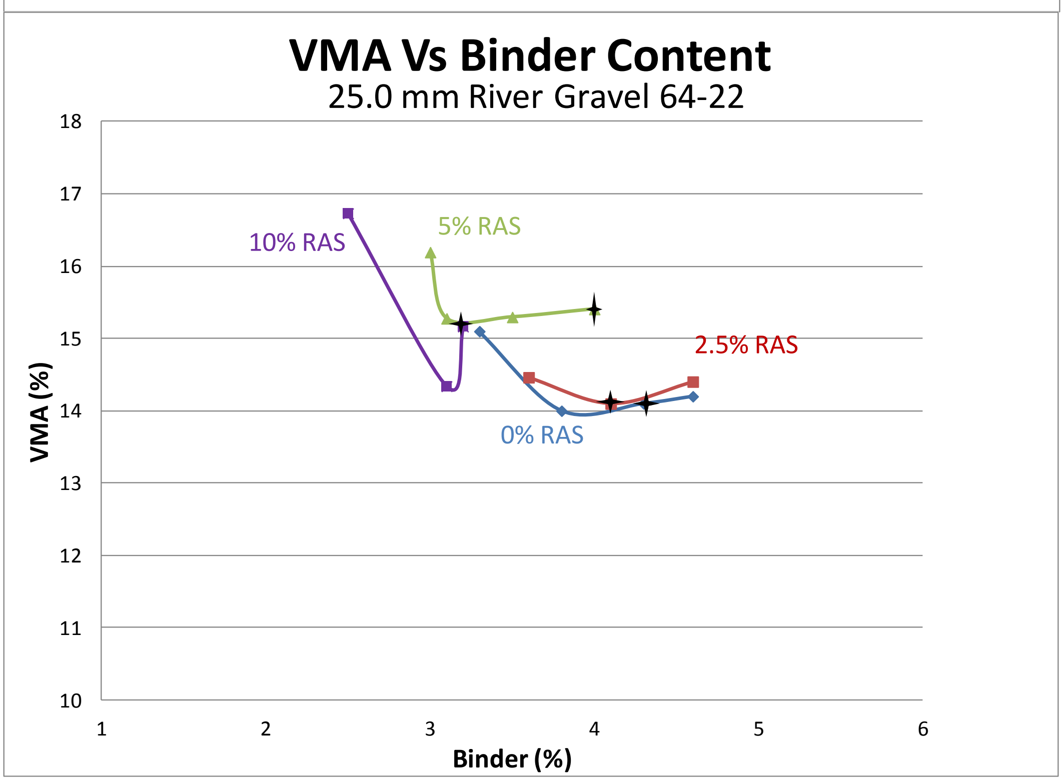


Figure 3a: Total VMA Vs. Virgin Binder Content in River Gravel Mixes (PG64-22)

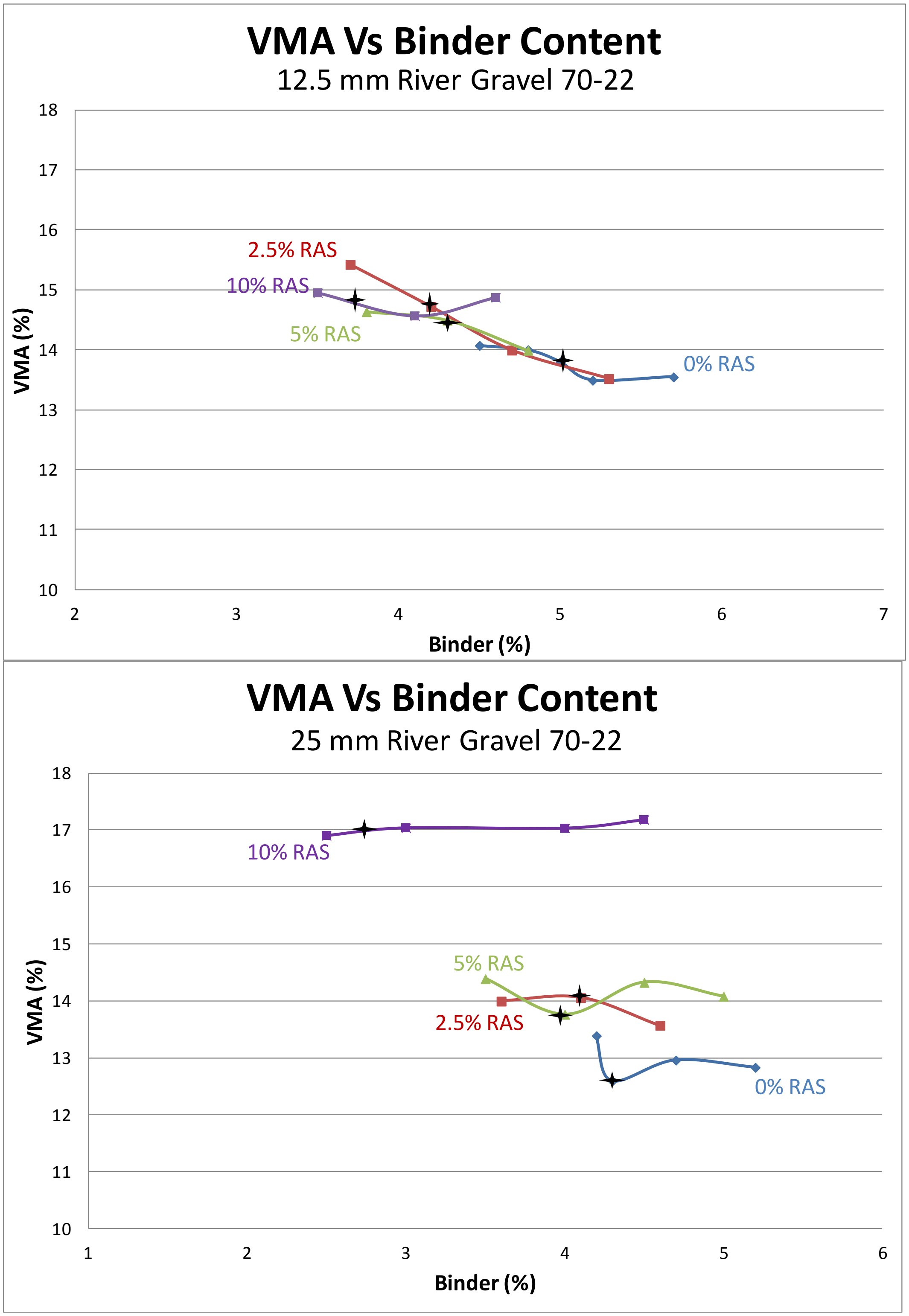
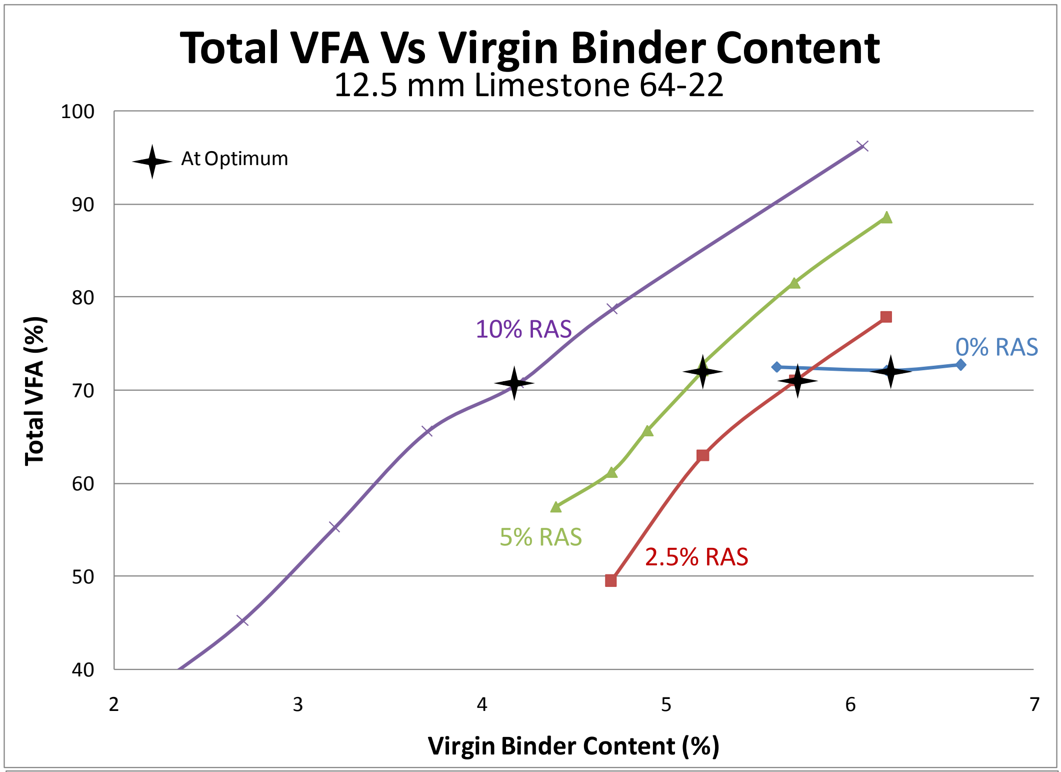


Figure 3b: Total VMA Vs. Virgin Binder Content in River Gravel Mixes (PG70-22)

Unlike the limestone mixes, RAS generally caused an increase in VMA for the river gravel mixes. Similarly to the limestone mixes, the mixes containing PG 64-22 binder showed less sensitivity to RAS content than the mixes with PG 70-22 binder. The mixes with PG 70-22 binder showed an increase in VMA when RAS was included. When 10 percent RAS was used with PG 70-22 grade binder the VMA increased 0.7 and 1.6 percent for the 12.5 and 25.0mm mixes respectively.

The changes in VMA with the incorporation of RAS differed with aggregate type. It is also noted that the river gravel mixes had a higher percentage of VMA in the control mixes than did the limestone mixes, suggesting that the limestone mixes tend to have VMA contents at the low end of the specification range, while the VMA of the river gravel mixes may be nearer to upper specification limits. Based on these results, it appears that for mixes prone to low VMA, the addition of RAS may exacerbate this problem. Mixes that trend toward higher VMA may see additional increases with the addition of RAS.



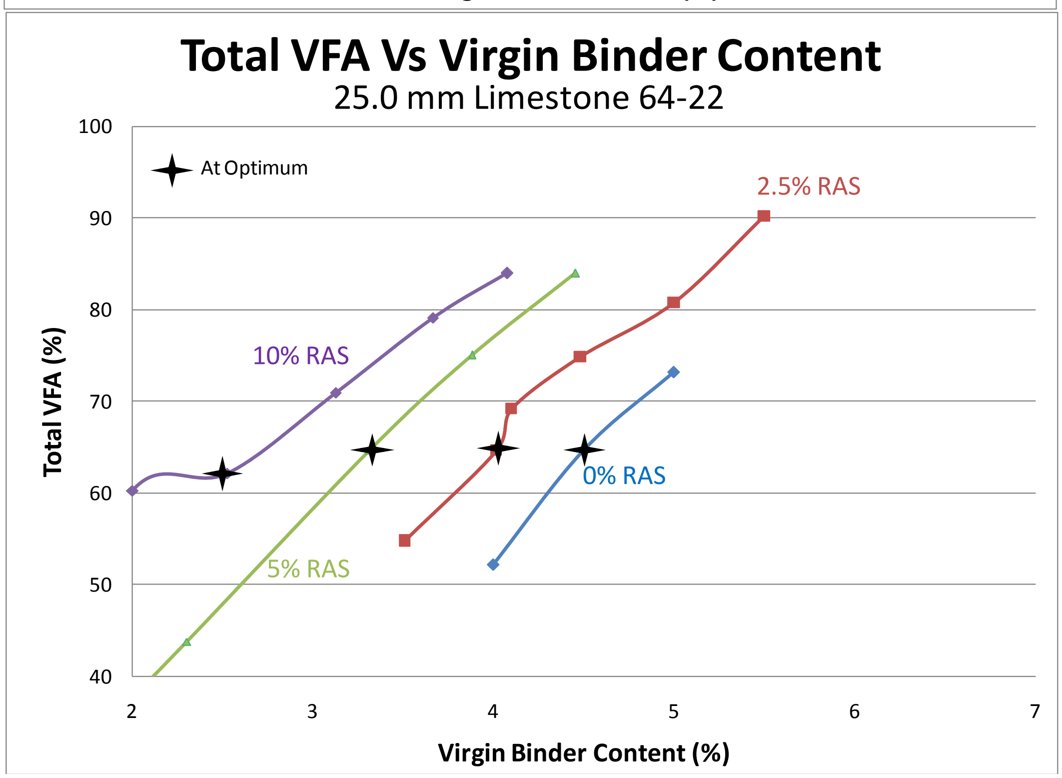
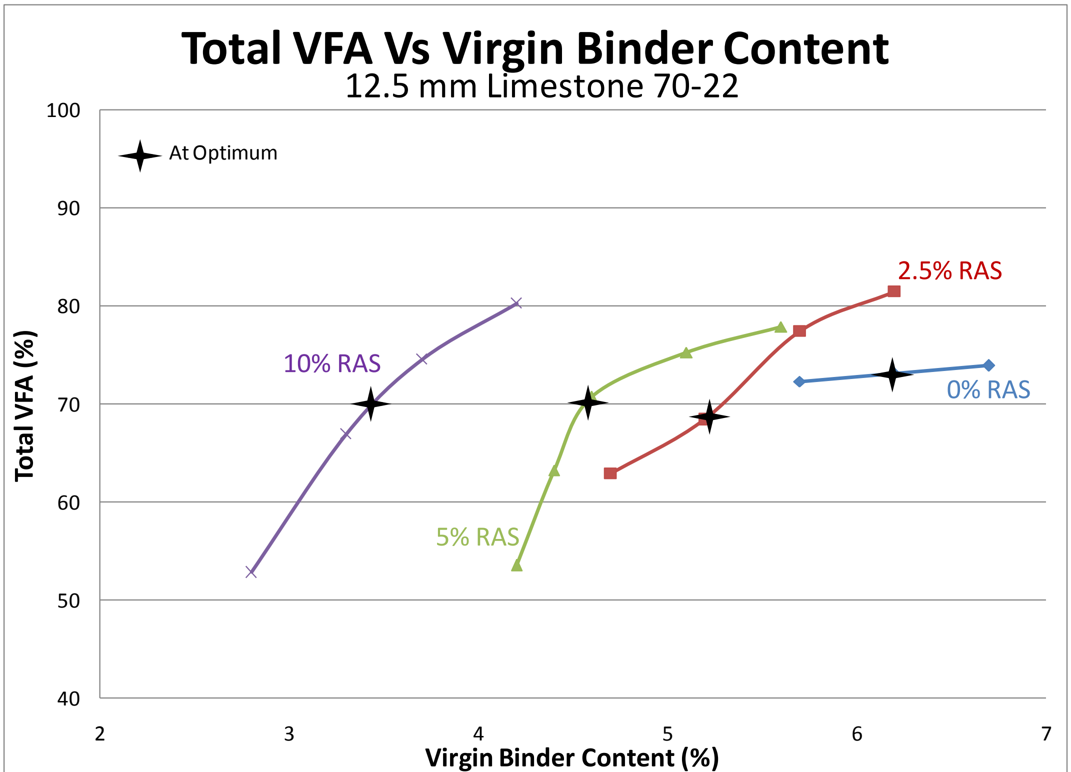


Figure 4a: VFA Vs Binder Content for Limestone (PG64-22)



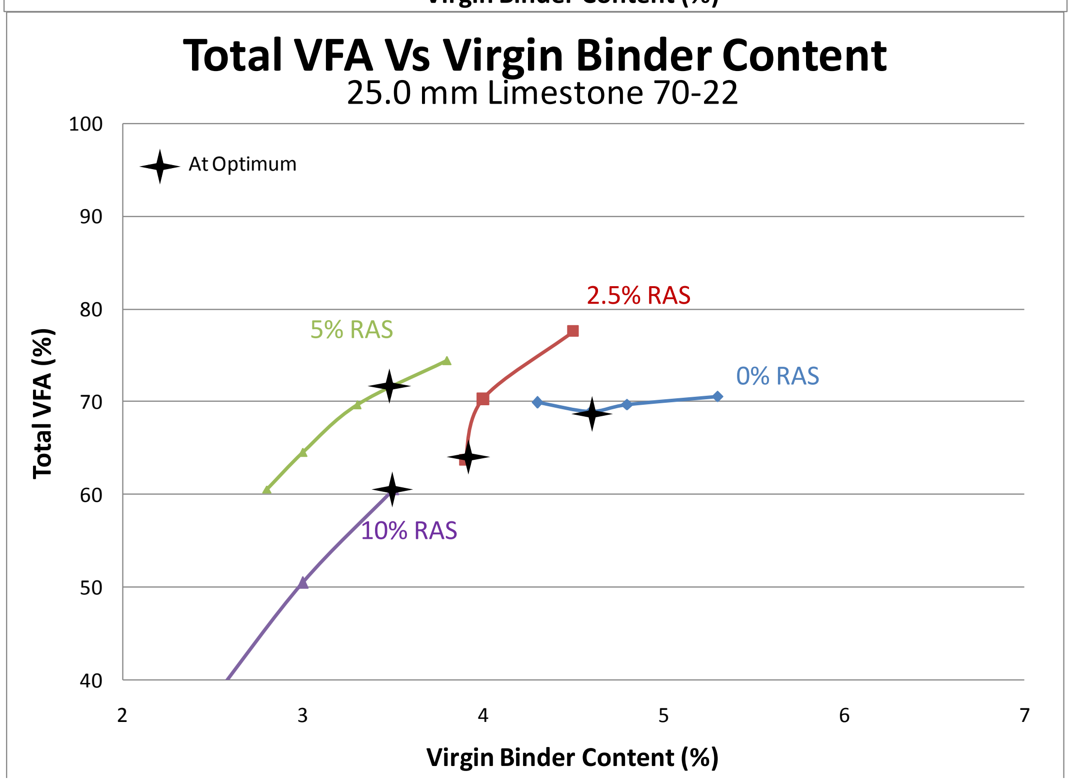
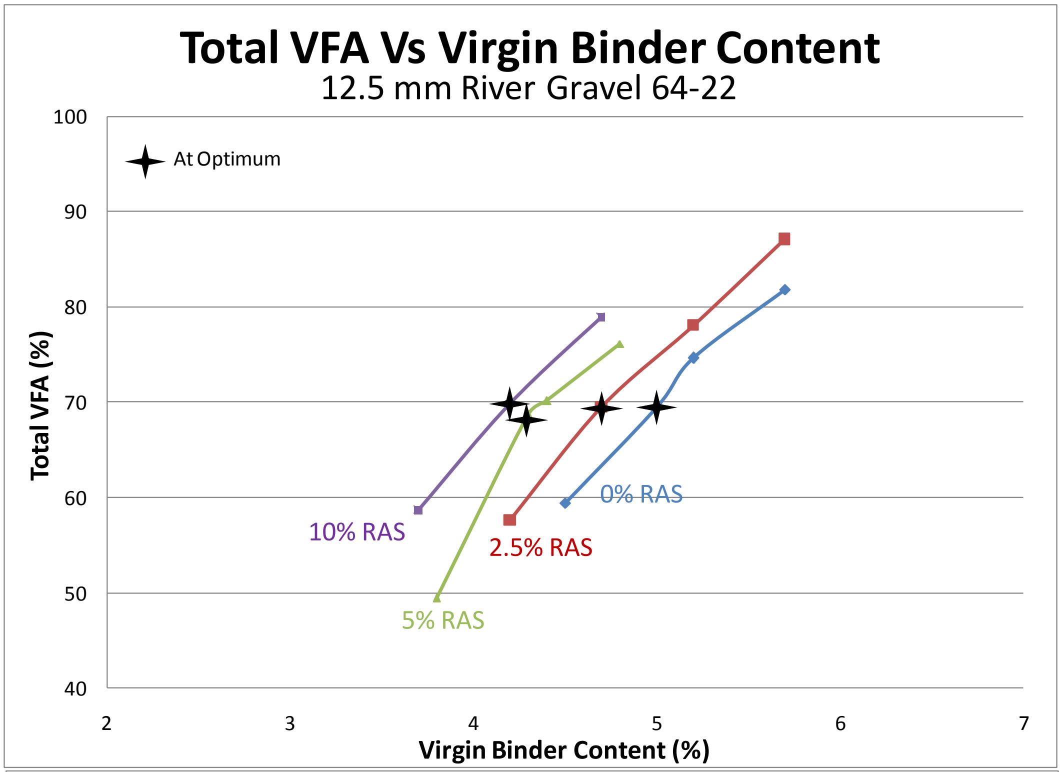


Figure 4b: VFA Vs Binder Content for Limestone Mixes (PG70-22)



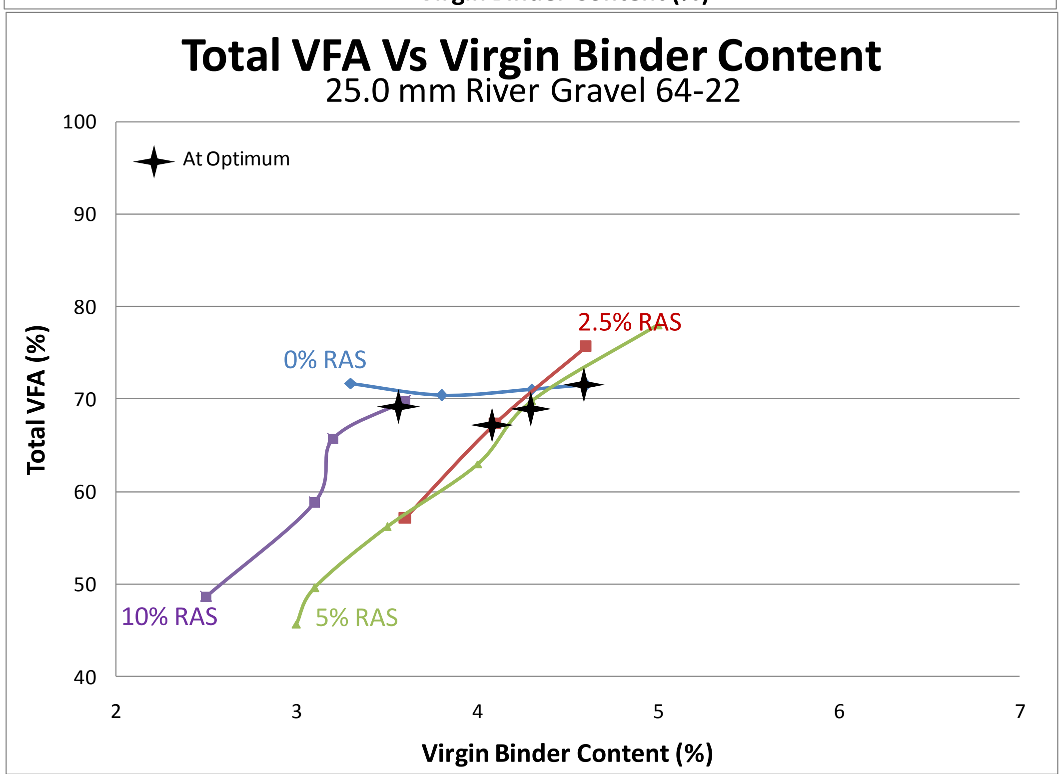
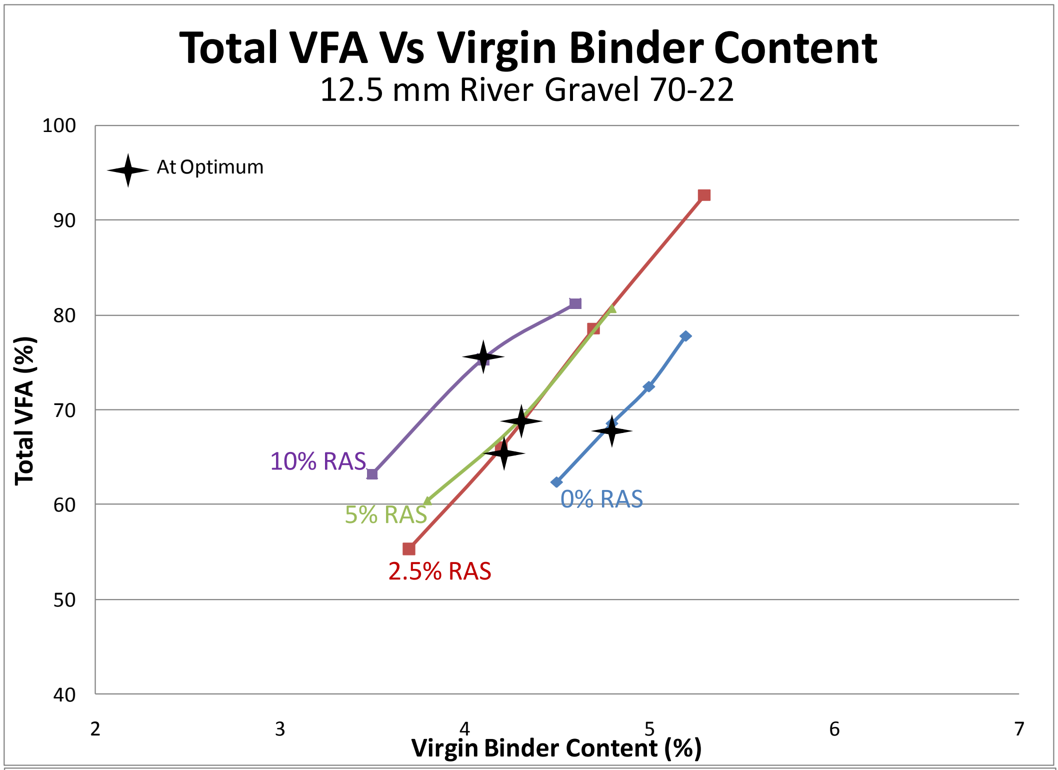


Figure 4c: VFA Vs Binder Content for River Gravel Mixes (PG64-22)



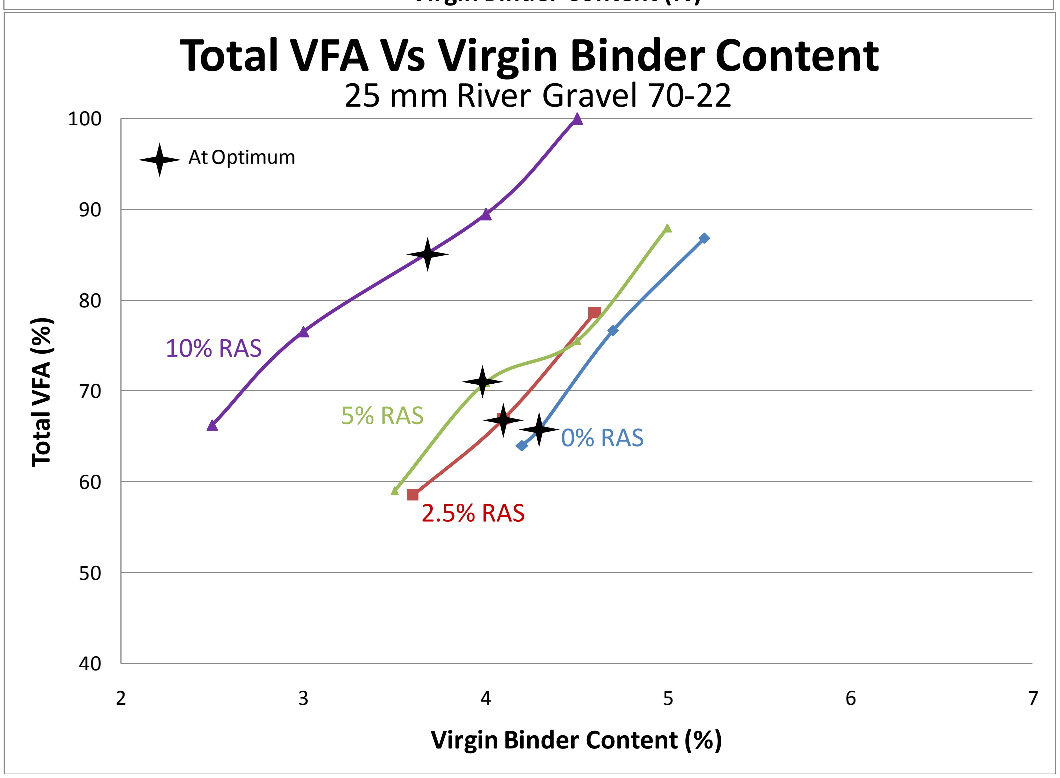
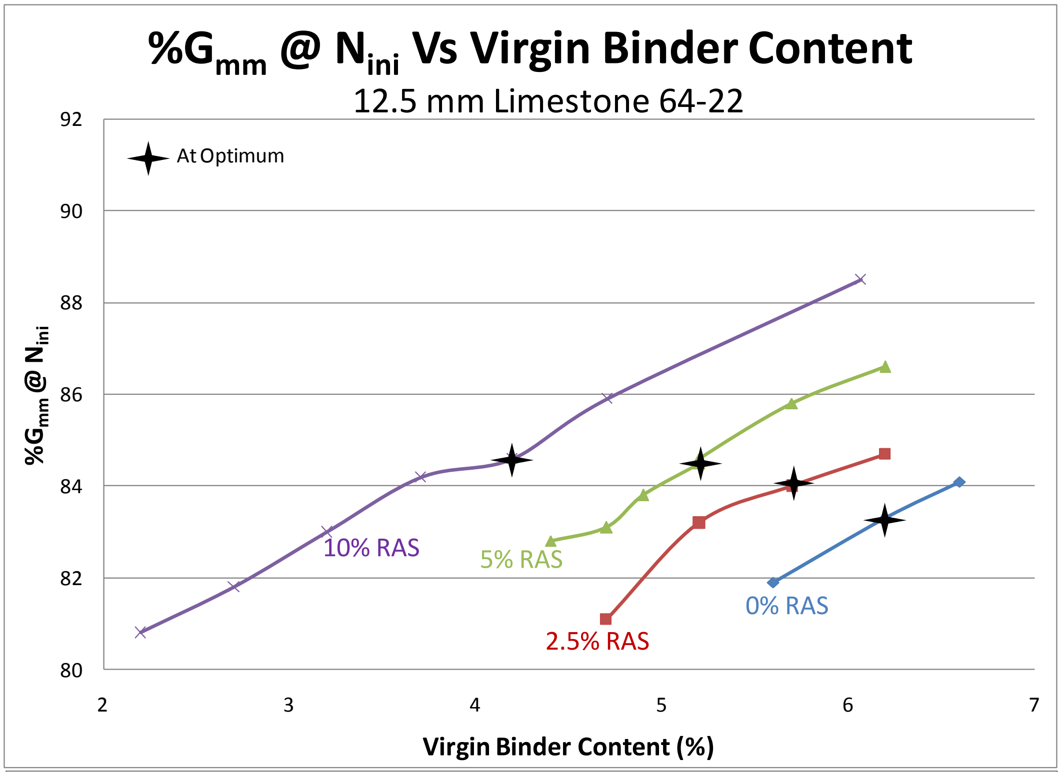


Figure 4d: VFA Vs Binder Content for River Gravel Mixes (PG70-22)

In general, the VFA did not appear to be sensitive to the amount of RAS in a mixture. In each of the limestone mixes, the VFA at optimum virgin binder content was not practically affected by the RAS content. Each of the differences observed for the VFA generally did not show a practical change from the control mixes at optimum virgin binder contents. The 25.0mm river gravel mix with PG 70-22 did however; appear to be sensitive to the RAS present. For this mix, the VFA consistently increased when RAS was incorporated (2.7 percent when 10 percent RAS was incorporated).



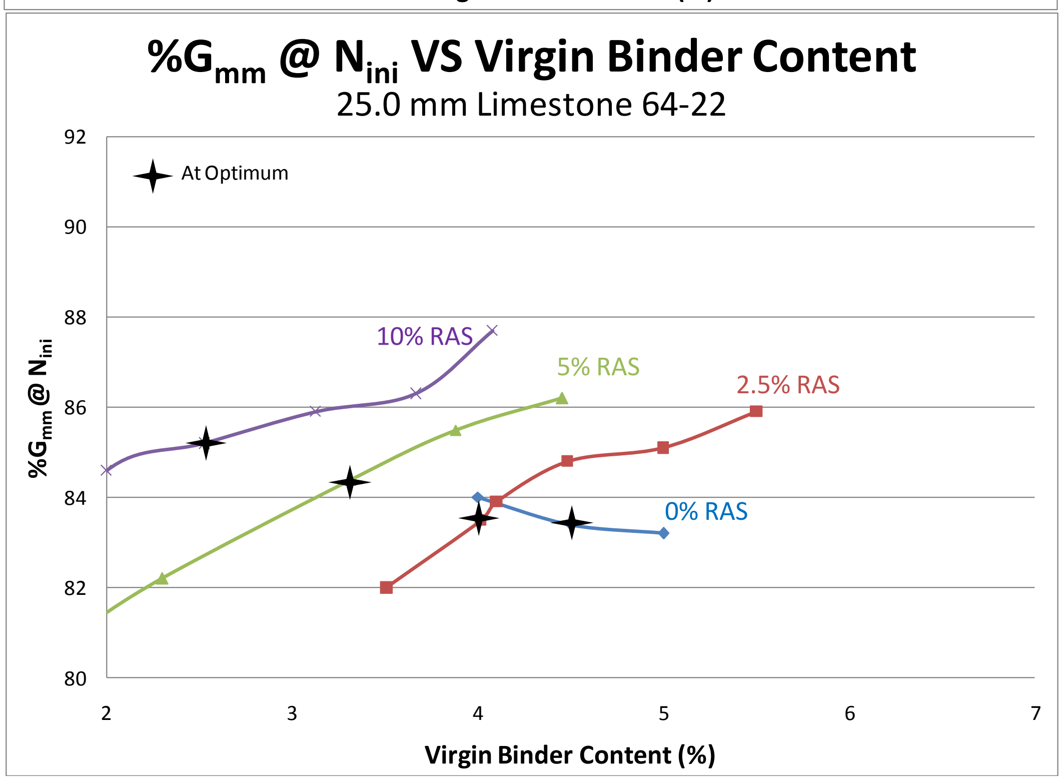
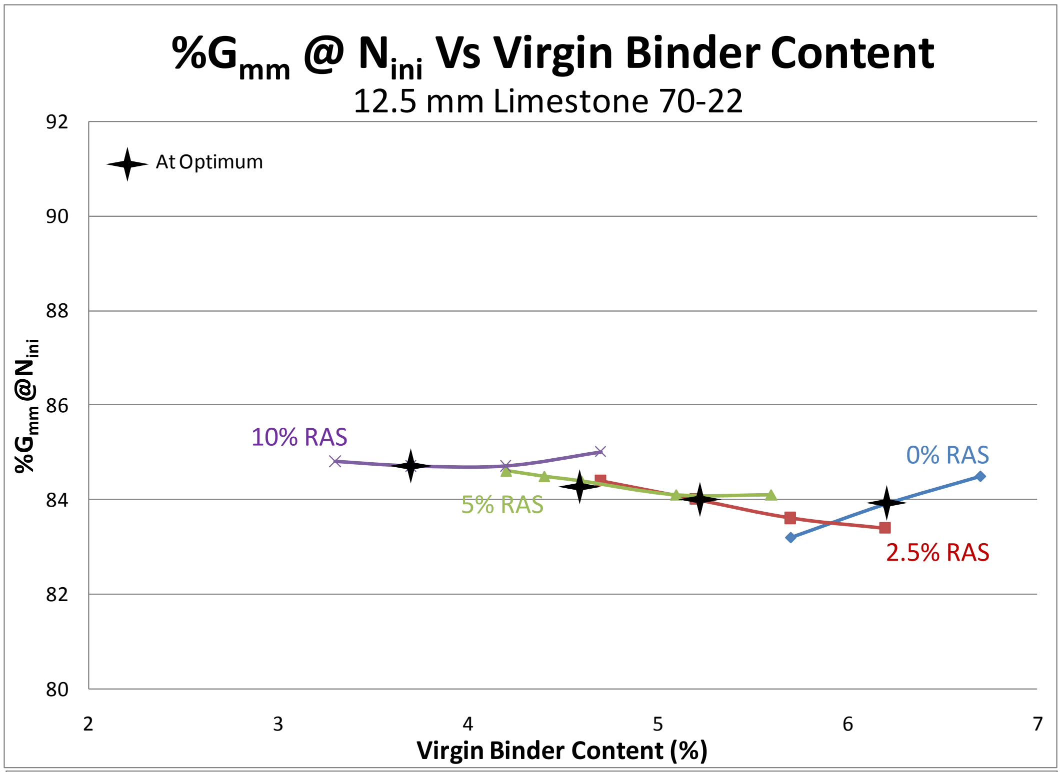


Figure 5a: %Gmm Vs. Binder Content in Limestone Mixes (PG 64-22)



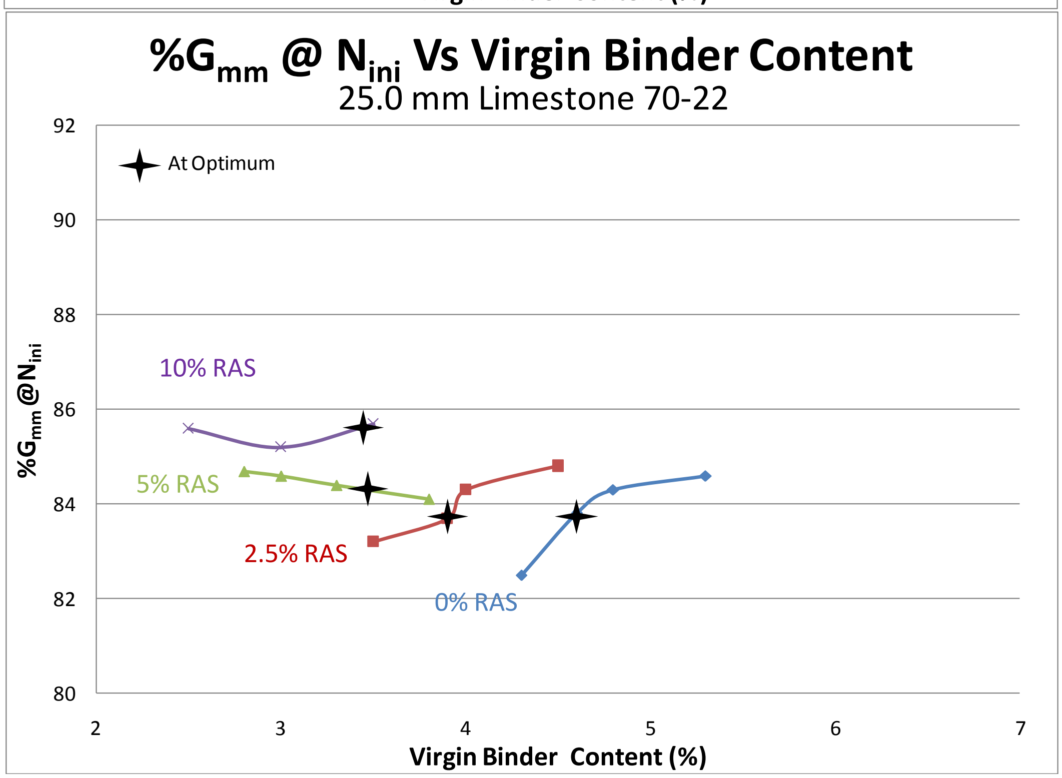


Figure 5b: %Gmm Vs. Binder Content in Limestone Mixes (PG 70-22)

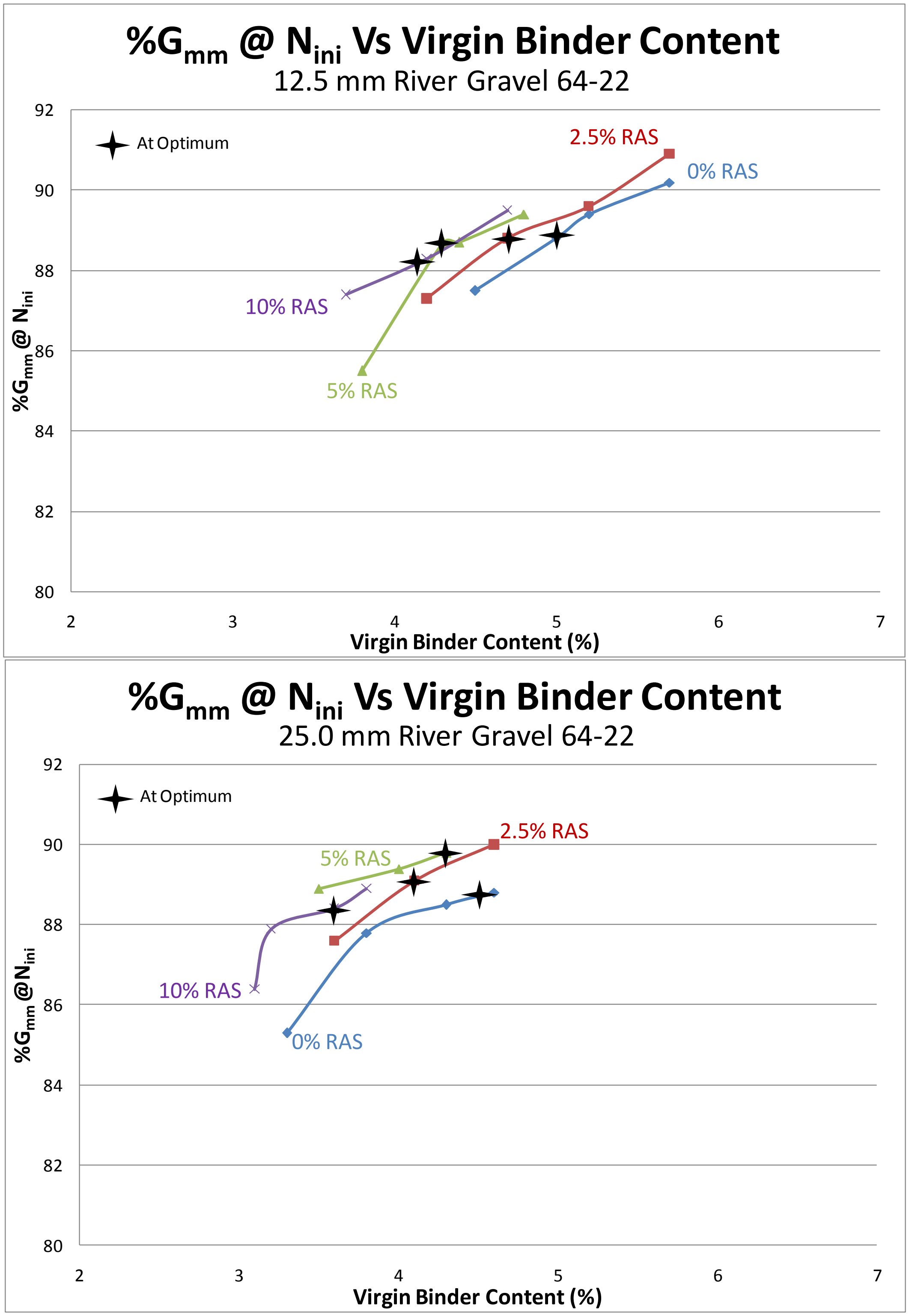
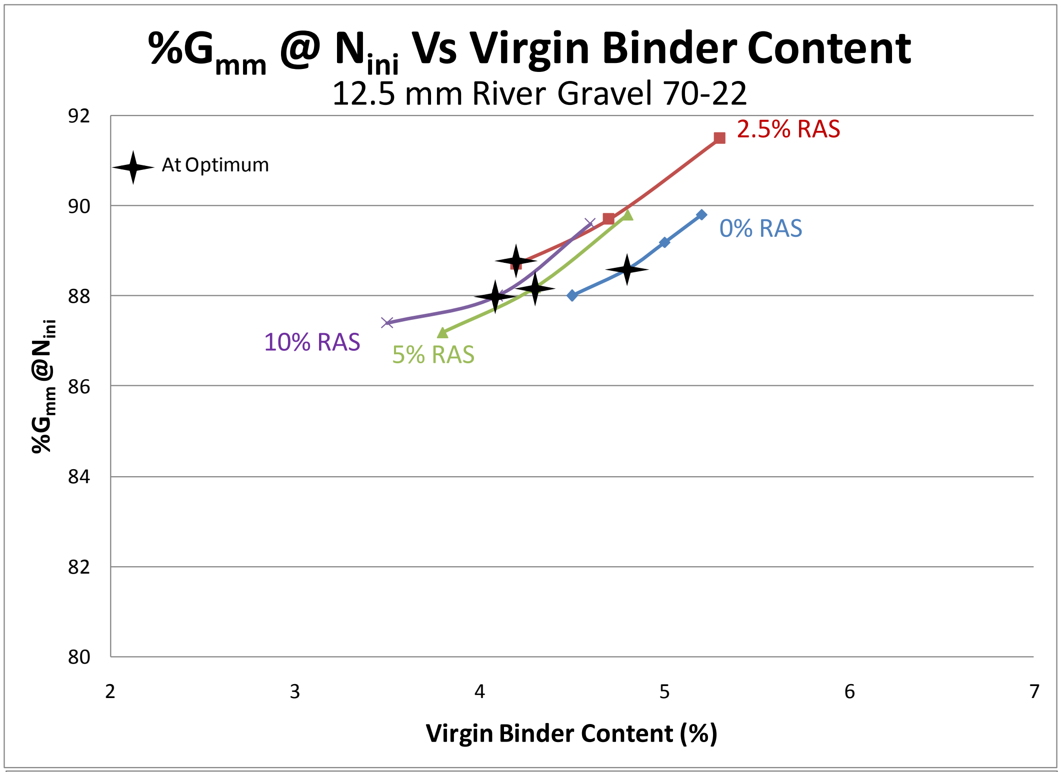


Figure 5c: %Gmm Vs. Binder Content in River Gravel Mixes (PG 64-22)



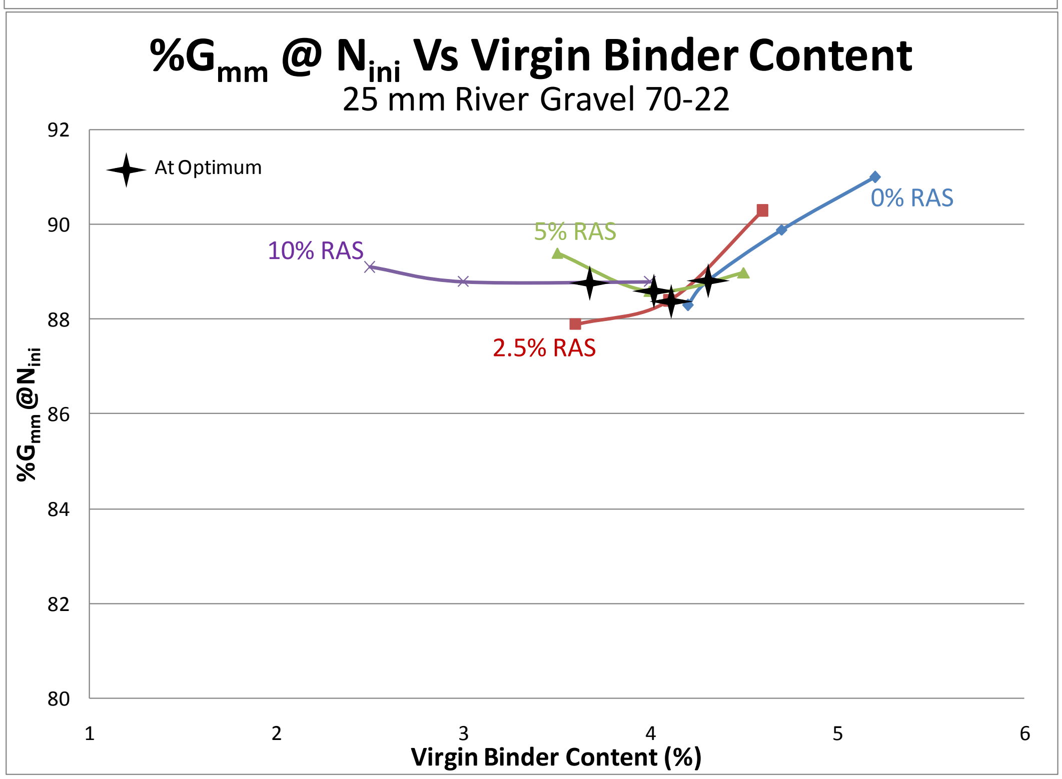


Figure 5c: %Gmm Vs. Binder Content in River Gravel Mixes (PG 70-22)

Figure 5 shows the percent of initial compaction. For the limestone mixes the percent G_{mm} @ N_{ini} appeared to increase for each of the mixes at their respective virgin optimum binder contents. This was more evident in the mixes using PG 64-22 binder. The river gravel mixes however, did not appear to be sensitive to the RAS content. This means that the incorporation of RAS at any amount may or may not affect the early compaction of the asphalt. It appears that the percent initial compaction is much more dependent on the aggregate type than RAS content. The limestone mixes had an average initial compaction of 83.8 percent and the river gravel mixes had an average of 88.5 percent.

Statistical Analysis for Volumetric Properties:

A statistical analysis (multi-factor ANOVA) was performed for each volumetric property of interest. The p-values obtained from the ANOVA tests are shown for each factor and combination of factors in Table 9. Significant factors and interactions are highlighted. Each property with significant factor interactions was investigated separately.

Table 9: P-values for Factors and Interactions of Factors

Factors/Interactions	P-values for Responses			
	%AV	VMA	VFA	$\%G_{mm}$ at N_{ini}
NMAS	0.2974	<0.0001	<0.0001	0.9011
PG	0.1802	0.5830	0.4283	0.0688
NMAS*PG	0.1632	0.0095	0.0011	0.2525
Agg	0.9588	<0.0001	0.0046	<0.0001
NMAS*Agg	0.7334	<0.0001	0.0001	0.8987
PG*Agg	0.0336	0.0109	0.1236	0.4900
NMAS*PG*Agg	0.3496	0.0050	0.8678	0.9211
%RAS	0.6908	0.0594	0.3209	0.5049
NMAS*%RAS	0.8654	0.1647	0.8297	0.4844
PG*%RAS	0.0529	0.0166	0.4186	0.2542
NMAS*PG*%RAS	0.3859	0.8127	0.3890	0.3665
Agg*%RAS	0.6214	<0.0001	0.0042	0.5964
NMAS*Agg*%RAS	0.2417	0.0626	0.0024	0.5920
PG*Agg*%RAS	0.9802	0.0021	0.1659	0.5959
NMAS*PG*Agg*%RAS	0.7706	0.3202	0.6132	0.5071

Statistical Results for Change of Air Voids:

For percent air voids, only one significant interaction was significant. The performance grade and aggregate type interacted significantly (p = 0.0336). Thus, the effect of the relationship between performance grade and aggregate type on air voids was not consistent for the mixtures and the individual effect of one factor could not be analyzed without considering the other factor.

For change in percent air voids, the binder grade was adjusted to the virgin optimum percent. For this analysis there should have been no difference in change in air voids because the air voids were designed to be 4.5 percent. However, the performance grade and the aggregate type displayed a significant interaction (p=0.0336). Figure 6 describes the two-factor interaction.

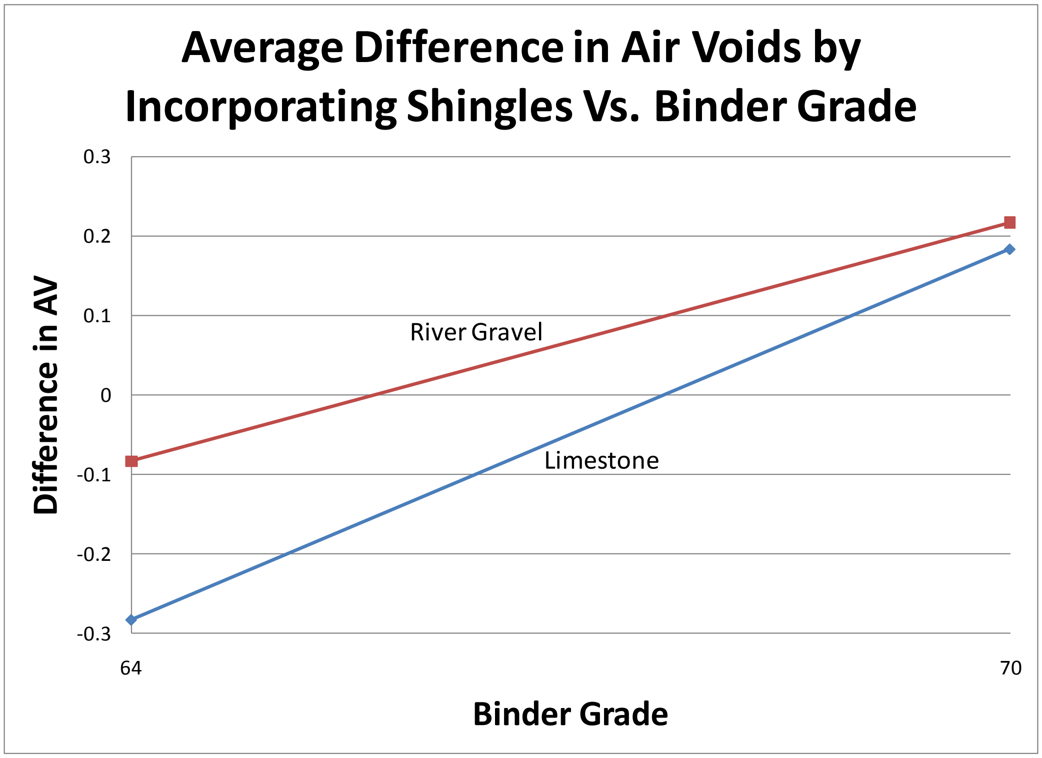


Figure 6: Interaction of Binder Grade for the Change in %AV

The air voids were consistently increased by the use of 70-22 binder over the 64-22 performance grade binder. However, the mixes were designed so that 4.5 percent air voids would be reached at the design binder content. In other words, increasing the binder content would yield lower air voids. Thus, the difference in air voids does not have practical significance.

Figure 6 shows the river gravel combined with shingles increased 0.3 percent between 64-22 and 70-22 grade binders and the limestone combined with shingles increased 0.48 percent when increasing binder grades. This demonstrates that the percent air voids in the limestone mixes were more sensitive to binder grade than the percent air voids in the river gravel mixes. The sensitivity of the change in air voids should intrigue contractors in that the reduction of air voids results in reduced virgin optimum binder content. The reduction of virgin binder will provide savings as the binder is the most expensive component of asphalt.

Statistical Results for VMA:

For VMA, three of the factors (performance grade, aggregate source, and percent shingles) interacted significantly (p = 0.0021). In other words, the volumetric properties were changed significantly by changing the aggregate type, binder grade, and amount of shingles incorporated into a mix. Because the three-way interaction was significant, lower order interactions and main effects could not be considered separately. Figures 7 and 8 describe this interaction in further detail. The VMA was also significantly affected by the NMAS. This was expected due to the nature of the design process.

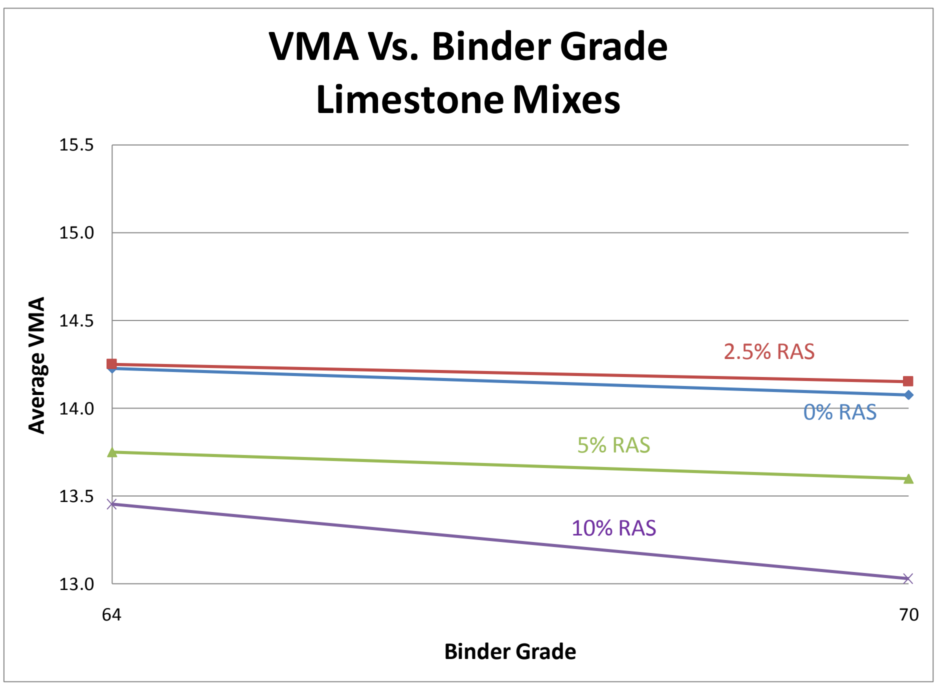


Figure 7: Interaction of Binder Grade and Shingles for the Change in VMA for Limestone Mixes

The average VMA slightly decreased in the limestone mixtures when increasing the binder performance grade and with increasing RAS content. The VMA for the mix with 2.5 percent shingles did not appear to be significantly different than the control mix but VMA values for 5 and 10 percent RAS were much lower. The control mix and the mix with 2.5 percent RAS showed an average VMA of 14.25 at PG 64-22 and decreased slightly when increasing binder grades to 14.05 for the control mix and 14.1 with 2.5 percent RAS. When 5 percent RAS was used, the average VMA decreased 0.2 percent when changing from PG 64-22 binder to PG 70-22 binder. The mix with 10 percent RAS showed the largest drop in VMA. When PG 64-22 binder was used the VMA was 13.45 and when PG 70-22 binder was used the VMA was 13.0. From the data above, the VMA for limestone mixtures is sensitive to the binder grade and amount of RAS incorporated.

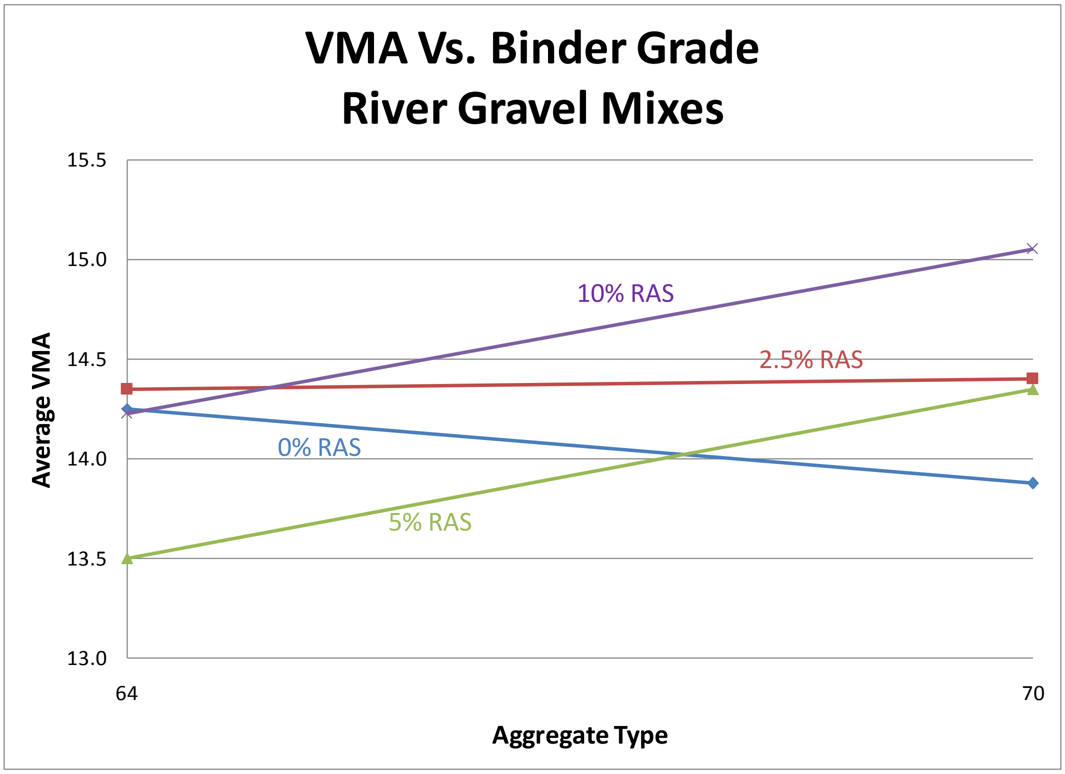
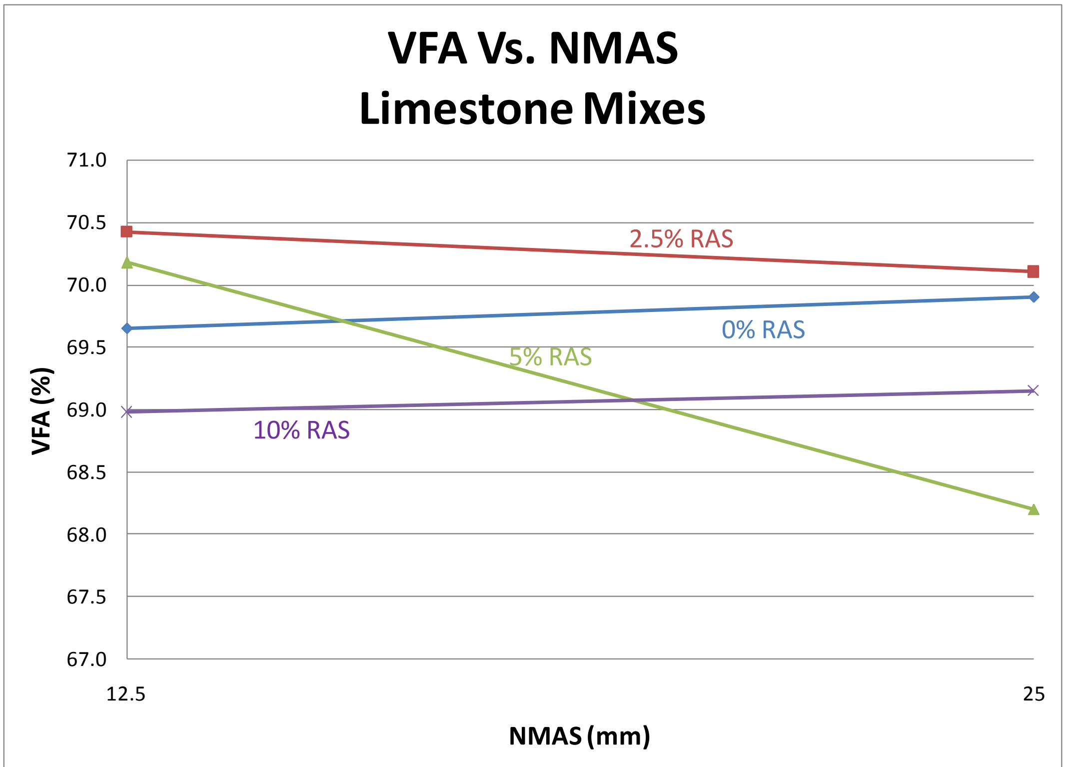


Figure 8: Interaction of Aggregate Type and Shingle Content for the Average VMA for River Gravel Mixes

For PG 64-22 binder, the incorporation of 2.5 and 10 percent shingles to the river gravel mix did not appear to significantly affect the VMA when compared to the control mix; yet a decrease was noted for the samples containing 5 percent RAS. However, when the binder grade was increased and RAS incorporated, the average VMA increased significantly. The control mixture showed a slight decrease in VMA from PG 64-22 binder to PG 70-22 binder but showed an increase when shingles were incorporated. This increase was most prominent for the higher shingle contents. The decrease in VMA in the control mixture was limited to 0.1 percent. The mixtures containing 2.5 and 5 percent shingles showed an increase of 0.1 and 0.8 percent respectively. The mixture with 10 percent shingles showed an increase in of 0.8 percent. From the above data, higher amounts of RAS appear to have a greater effect on VMA when changing the binder grade.

Statistical Results for VFA:

The VFA had multiple factors interacting. The NMAS, aggregate type, and percent shingles interacted significantly (p = 0.0024). Figure 9 describes this interaction in further detail.



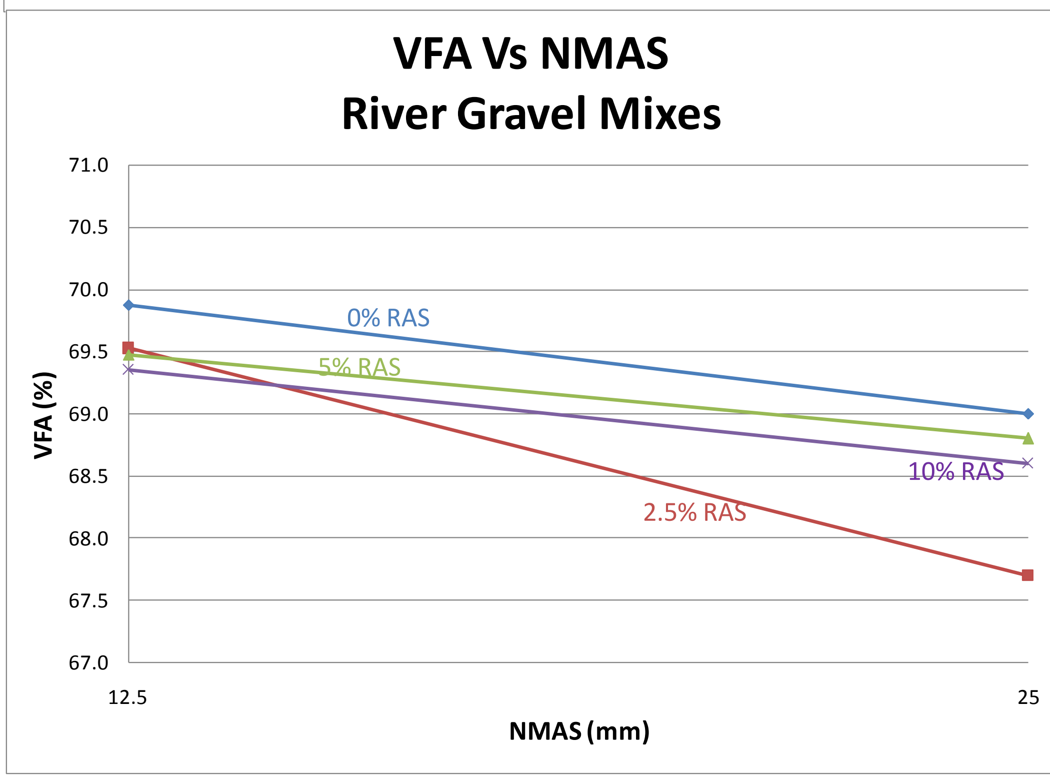


Figure 9: VFA Vs. NMAS for Limestone and River Gravel Mixes

The VFA for the limestone mixes did not appear to be sensitive to the NMAS for the various RAS percentages, with the exception of the 5 percent RAS mixture. For 5 percent RAS, VFA decreased with increasing NMAS. In the 12.5mm mix with 5 percent RAS, the VFA was 70.2 percent and in the 25.0mm mix the VFA was 68.1 percent. The mixes with 2.5 and 10 percent RAS had no practical change when changing the NMAS. The river gravel mixes showed similar results in that the increasing RAS content lowered the VFA. The mix with 2.5 percent shingles showed the largest decrease in VFA from 69.5 to 67.7 in the 12.5mm mix and 25.0mm mixes respectively. From Figure 9, it can be concluded that the VFA may decrease when increasing the percent RAS and this decrease may be more evident when the NMAS is larger.

Statistical Results for G_{mm} at N_{ini}:

No significant interactions of factors were observed for G_{mm} at N_{ini} however, the aggregate type affected the value significantly ($p = <0.0001$). The mean value for the limestone aggregate was 83.9 percent (standard deviation of 0.3) and the mean value for the river gravel was 88.5 percent (standard deviation of 0.3). Thus, the percent initial compaction was sensitive to the aggregate type and not to other factors. Thus, no changes are recommended with respect to early compaction for mixes containing RAS.

Conclusions from Analysis of Change in Volumetric Properties:

Based on the results of this analysis, the following conclusions can be drawn:

- Incorporating shingles into mixtures will reduce the air voids by introducing binder and thus, reduce the amount of virgin binder required. This reduction in virgin binder required results in a large savings for contractors. By incorporating 5 percent RAS, a contractor may see an average reduction of 0.5 percent virgin binder content required. The amount of reduction of air voids may be dependent on the aggregate type. The limestone mixes showed a large decrease in air voids (0.6 percent air for every 2.5 percent RAS) and the river gravel mixes showed only a slight decrease in air voids (0.3 percent air for every 2.5 percent RAS). A reduction of air voids of approximately 1 percent can reduce the required virgin binder by 0.5 percent. The difference in air void reduction could have also been attributed to the shingle source. The decrease in air voids is very attractive to contractors in that it provides savings by reducing virgin binder content.

- Incorporating shingles can significantly affect the VMA of a mixture, especially when incorporated at levels above 5 percent by weight of the mix. For the limestone mixes, the VMA was decreased significantly when incorporating RAS. At 5 percent RAS, the limestone mixes showed a decrease of a full percent in VMA at both binder grades. The limestone mixes with 10 percent RAS showed a decrease in VMA of 1.3 and 2 percent when using PG 64-22 and 70-22 respectively. The river gravel mixes showed an increase in VMA when PG 70-22 binder was used. When 2.5 and 5 percent RAS was used in the river gravel mixes, the VMA was increased approximately 1 percent and when 10 percent RAS was used the VMA was increased over 2 percent. Thus, the effects of RAS on VMA are considered to be mixture dependent. In some cases, the sensitivity of the VMA to RAS content in mixes may be appealing to contractors having trouble with VMA requirements.
- When incorporating shingles, changing the binder grade may significantly change the VFA of the mixture. The limestone mixes with 5 and 10 percent RAS showed

decreases in VFA (over 0.8 percent) but the mix with 2.5 percent RAS showed a slight increase. The river gravel mixes showed a significant decrease in VFA when PG 70-22 grade binder was used. The VFA decreased 0.7 percent when using 5 and 10 percent RAS and decreased 1.8 percent when using 2.5 percent RAS.

- The shingle content did not affect the amount of early compaction in each of the mixes. There were no factor interactions for the initial compaction but the aggregate type showed significant differences. The limestone mixes were more resistant to early compaction than river gravel.
- Shingles can effectively be incorporated into a mix up to 10 percent by weight of the mix. Mixes incorporating 2.5 percent RAS, in general, were not significantly different than the control mixtures. When using higher RAS contents, the VMA are expected to be practically different than the control mixture. The effects of RAS on VMA were mixture dependent and appeared to depend on aggregate type. For limestone mixes, the VMA was decreased by incorporating RAS and for the river gravel mixes; the VMA was increased by incorporating RAS. In other words, higher RAS contents may exaggerate difficulties with VMA.

Analysis #2: Examination of Percent Binder Contribution:

One of the most important considerations in investigating the effects of RAS on a mixture is the amount of binder contribution expected. Virgin binder is the most expensive ingredient of asphalt and thus, the binder contribution is extremely appealing to contractors in that it provides a means of reducing the virgin binder content and providing savings. In order to determine the amount of binder contribution, AASHTO PP53 was used.

For this analysis, the binder content of the shingles was found using the ignition oven. In order to establish a correction factor, aggregate was burned with known binder content. Next, a lab produced field sample containing the same aggregates with 9% RAP and 3% RAS was burned. Thus, a correction factor for the aggregate was established first, and a correction factor for the combined effects of the RAP and RAS was calculated. It was assumed that correction factor for the RAS was ¼ of the total correction factor corresponding to the proportion by weight of the recycled material. However, it was noted that the algebraic equations (equations 1 and 2) given by AASHTO PP53 are not sensitive to the correction factor.

The RAS from the limestone aggregate source yielded 21.18% binder and the RAS from the river gravel aggregate source yielded 15.09% binder by method of the ignition oven. Next, the binder contribution and percent binder availability were found according to AASHTO PP 53, which essentially considers the change in virgin optimum binder content for a given mixture when produced with and without RAS. It was assumed (as recommended by AASHTO) that only the binder contained in shingles reduced the air voids and that the fines and other ingredients contained in the shingles did not affect the air voids. This assumption can be made because the virgin optimum binder content is determined to be at a given level of air voids. Of course, the fines and other ingredients may reduce the air voids but this effect is generalized to be "shingle binder available". Whether the total reduction is from binder only or from binder and fines, the amount of required virgin binder will be the same. The percent binder contribution was found by selecting the virgin optimum virgin binder content (at 4.5% air voids). Tables 10 and 11 show the virgin optimum binder contents obtained for each mixture produced during this analysis along with the percent binder available from the shingles found using AASHTO PP53.

Table 10: Virgin Optimum Binder Contents and Binder Available for Limestone Mixes

Mix Design	% RAS	P_b	% Binder Available
12.5 mm PG 64-22 Limestone	0	6.2	
	2.5	5.7	97.2
	5.1	5.2	97.2
	10	4.2	97.2
25.0 mm PG 64-22 Limestone	0	4.5	
	2.5	4	97.2
	5	3.3	100
	10	2.5	97.2
12.5 mm PG 70-22 Limestone	0	6.2	
	2.5	5.3	100
	5	4.5	100
	10	3.6	100
25.0 mm PG 70-22 Limestone	0	4.6	
	2.5	3.9	100
	5	3.5	100
	10	3.5	76.0

Table 11: Virgin Optimum Binder Contents and Binder Available for River Gravel Mixes

Mix Design	% RAS	P_b	% Binder Available
12.5 mm PG 64-22 River Gravel	0	5	
	2.5	4.7	89.8
	5	4.3	96.4
	10	4.1	79.8
25.0 mm PG 64-22 River Gravel	0	4.6	
	2.5	4.1	100
	5	4.4	63.3
	10	3.7	83.1
12.5 mm PG 70-22 River Gravel	0	4.8	
	2.5	4.2	100
	5	4.3	83.1
	10	4	76.5
25.0 mm PG 70-22 River Gravel	0	4.3	
	2.5	4.1	76.5
	5	4	69.9
	10	3.8	96.4

Tables 10 and 11 show the optimum binder contents to be reduced with the incorporation of shingles. For each of the mixes, the binder contribution was seen to be very close to 100 percent which means we can expect most manufacturing shingles to contribute most of their binder. The limestone mixes saw a better binder contribution than the river gravel mixes which could be a result of the shingle's source. The fines in the shingles most likely aided the reduction of air voids and appeared as though additional binder was being contributed. A savings estimate was done based on the data above. Table 12 illustrates the typical costs associated with asphalt and the expected savings for the above mixtures and Table 13 gives the calculated costs of the asphalt developed at the University of Arkansas.

Table 12: Typical Costs Associated with Asphalt

Material	**Costs ($/Ton)**
PG 64-22 Asphalt	550
PG 70-22 Asphalt	650
12.5mm Agg	70
25.0mm Agg	60
RAS Shredding	19
RAS Disposal Fees	35 (-)

Table 13: Price Per Unit Ton of Asphalt of Mixes Developed

Mix Design	% RAS	Price of Asphalt ($/ton)
12.5 mm PG 64-22 Limestone	0	99.76
	2.5	96.96
	5.1	64.16
	10	88.56
25.0 mm PG 64-22 Limestone	0	82.05
	2.5	79.20
	5	75.37
	10	70.65
12.5 mm PG 70-22 Limestone	0	105.96
	2.5	100.34
	5	95.3
	10	89.28
25.0 mm PG 70-22 Limestone	0	87.14
	2.5	82.61
	5	79.85
	10	79.05
12.5 mm PG 64-22 River Gravel	0	94.00
	2.5	92.16
	5	89.84
	10	88.08
25.0 mm PG 64-22 River Gravel	0	82.54
	2.5	79.69
	5	80.76
	10	76.53
12.5 mm PG 70-22 River Gravel	0	97.84
	2.5	93.96
	5	94.14
	10	91.60
25.0 mm PG 70-22 River Gravel	0	85.37
	2.5	83.79
	5	82.80
	10	80.82

Figure 10 demonstrate the amount of binder reduction and savings more plainly.

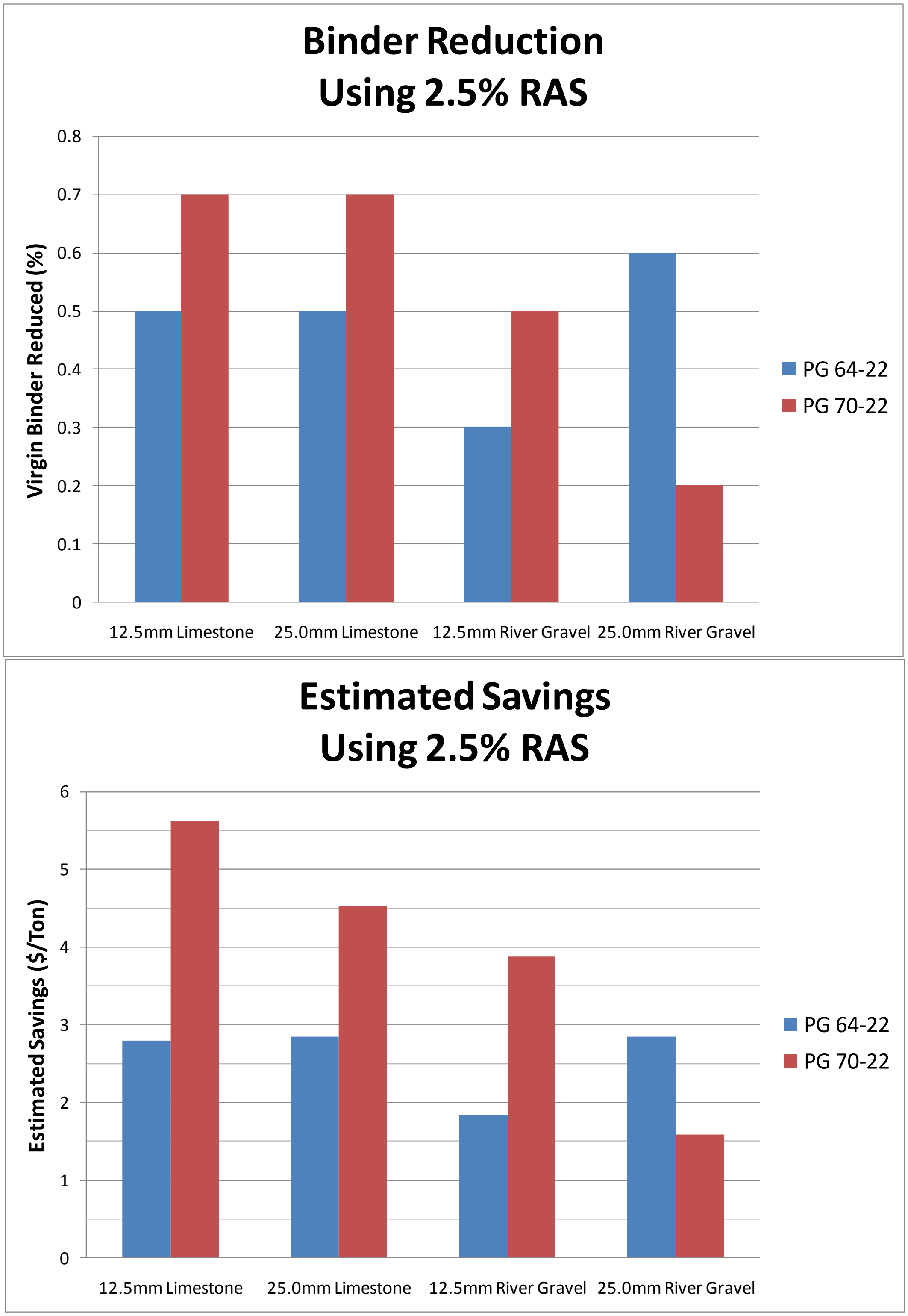
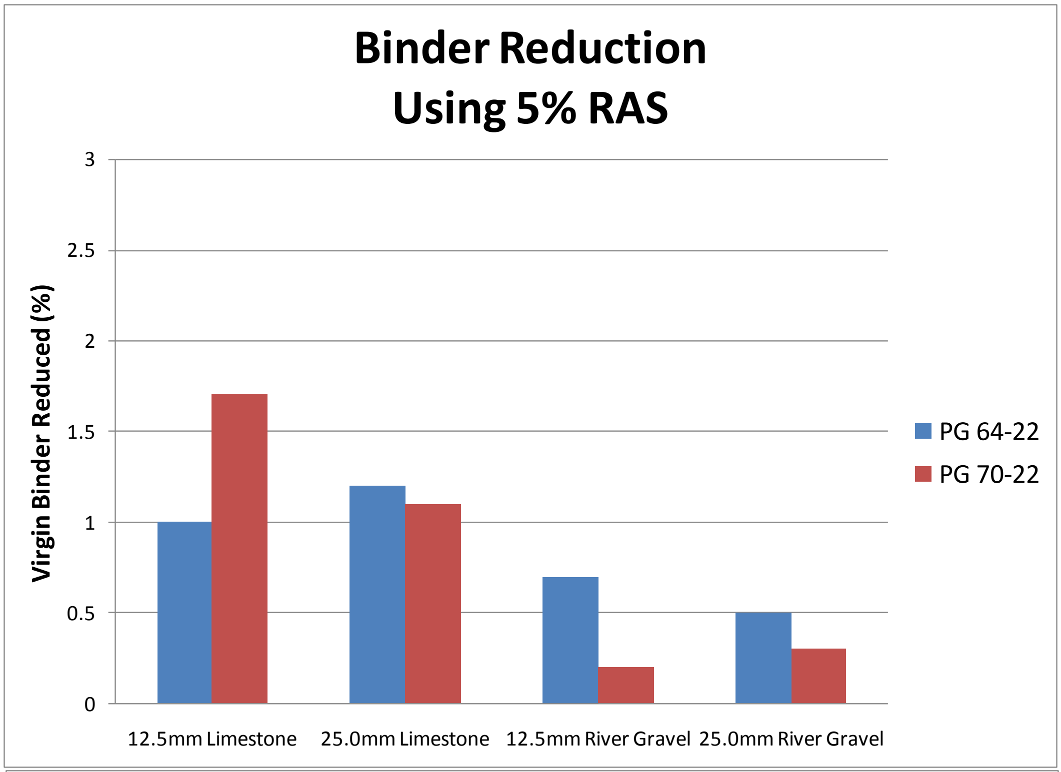


Figure 10a: Amount of Binder Reduction and Savings for Mixes Developed (2.5 percent RAS)



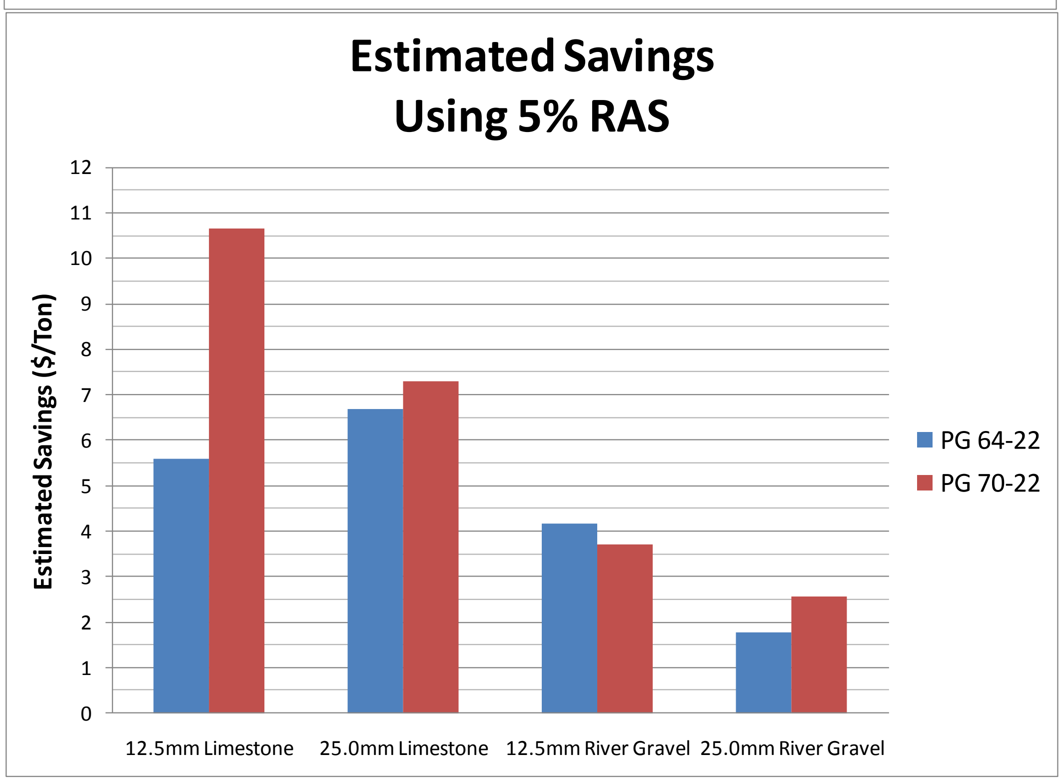
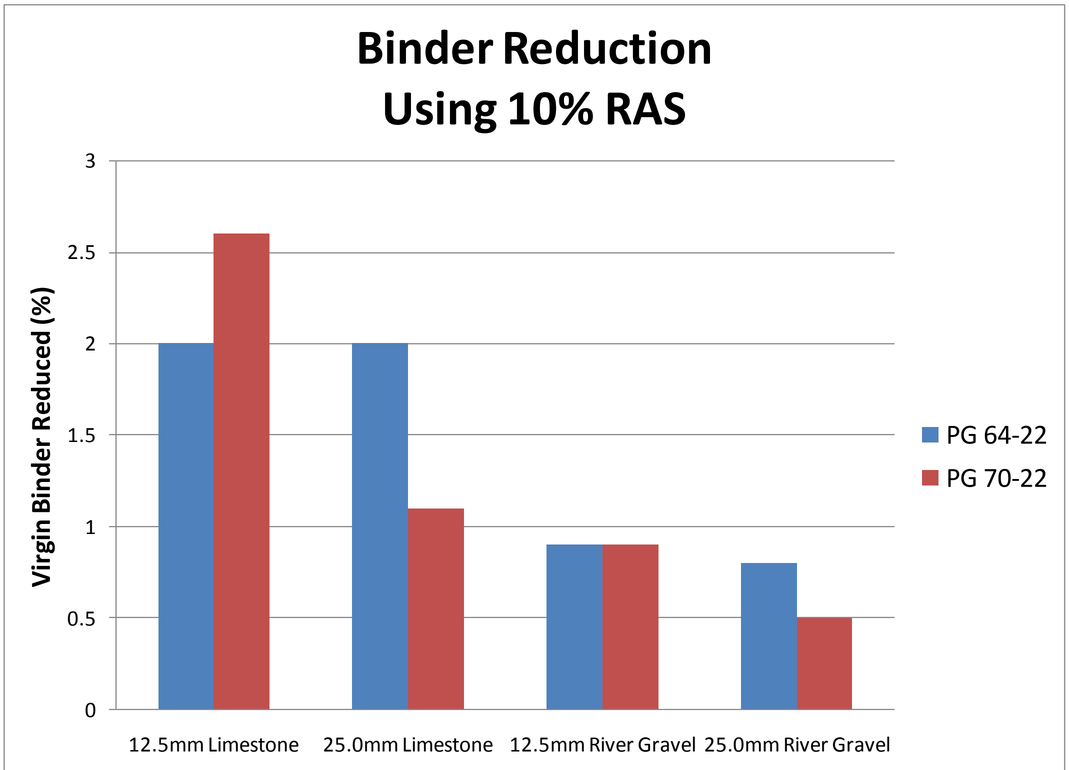


Figure 10b: Amount of Binder Reduction and Savings for Mixes Developed (5 percent RAS)



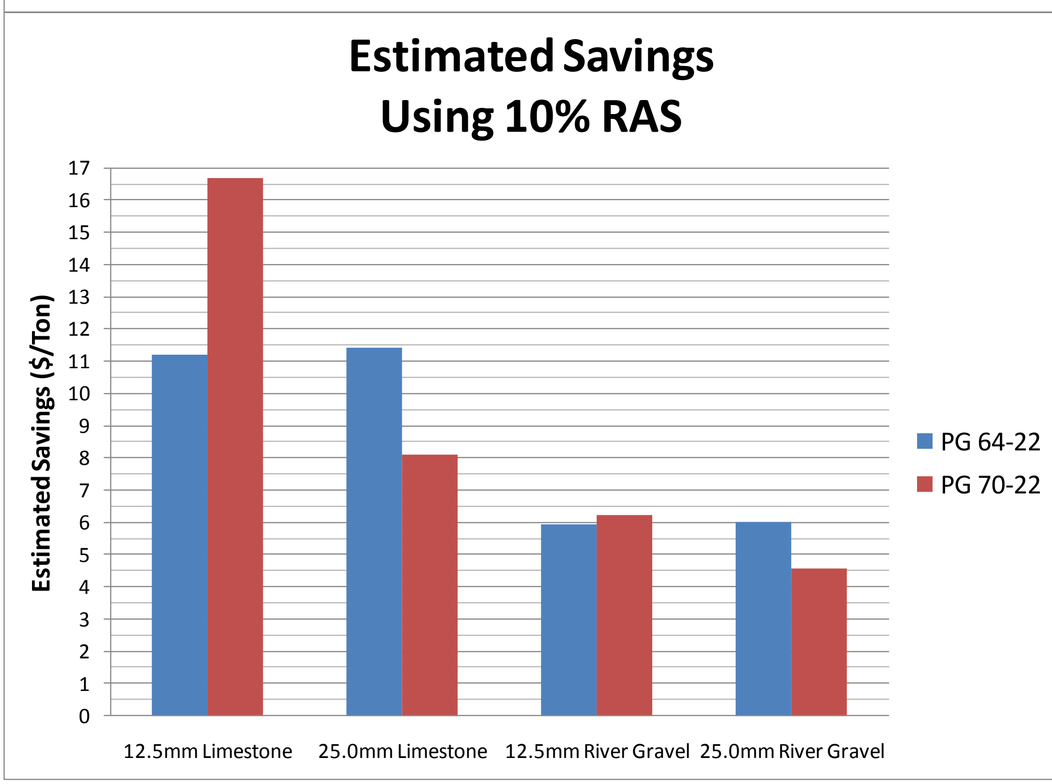


Figure 10c: Amount of Binder Reduction and Savings for Mixes Developed (10 percent RAS)

Figure 10 shows the potential savings from using shingles in asphalt. For the limestone mixtures, the savings is much larger than for the river gravel mixtures. At any amount of shingle incorporation, there is a savings.

Statistical Analysis for Binder Contribution:

A statistical analysis was performed for the binder contribution. Table 14 describes the setup of the factors for the statistical analysis.

Table 14: ANOVA Setup of Factors and Responses for Analysis #2

factors:	levels:	response:
NMAS	12.5 mm	Binder Contribution
	25.0 mm	
Binder Grade	64-22	
	70-22	
Aggregate Type	Limestone	
	River Gravel	
Shingle Content	2.5	
	5	
	10	

The p-values obtained from the ANOVA tests are shown for each factor and interactions of factors in Table 15. There were no significant interactions of factors observed for the binder contribution however, the aggregate type affected the value significantly ($p = 0.0220$). The mean value for the limestone aggregate was 96.8 % (standard deviation of 6.7) and the mean value for the river gravel was 84.6 percent (standard deviation of 12.1). It is likely that the different shingle sources used for these aggregate types behaved differently causing the aggregate type to be the significant factor.

Table 15: P-values for Factors and Interactions of Factors

Factors/Interactions	P-values for Response
NMAS	0.2996
PG	0.7116
NMAS*PG	0.6534
Agg	0.0220
NMAS*Agg	0.7753
PG*Agg	0.9996
NMAS*PG*Agg	0.5833
%RAS	0.2873
NMAS*%RAS	0.6470
PG*%RAS	0.9682
NMAS*PG*%RAS	0.6893
Agg*%RAS	0.9029
NMAS*Agg*%RAS	0.1197
PG*Agg*%RAS	0.2767
NMAS*PG*Agg*%RAS	0.1432

Conclusions from Analysis of Binder Contribution:

Based on the results of this analysis, the following conclusions can be drawn:

- The aggregate and shingle source should be expected to affect the shingle binder contribution significantly. The limestone mixes saw an average of over 96 percent binder contribution while the river gravel mixes saw over 84 percent binder contribution.
- Fines within the shingles are also expected to reduce air voids appearing as if the shingles are contributing additional binder. In some instances, the binder contribution may be calculated as over 100 percent. If this is the result, the binder contribution should be read as 100 percent (it is not feasible to assume more than 100).
- Shingles can be expected to contribute binder to a mixture significantly reducing the need for virgin binder content. The reduction of virgin binder results in savings. The

limestone mixes saw a savings of approximately $2.75 per ton when using 2.5 percent RAS, $6.00 per ton when using 5 percent, and $11.25 per ton when using 10 percent RAS. The river gravel mixes saw savings of approximately $2.30 per ton, $2.30 per ton, and $5.25 per ton when using 2.5, 5, and 10 percent RAS respectively.

- It is recommended that provisions for RAS be incorporated into specifications due to the amount of savings available.

Analysis #3: Rutting and Stripping Susceptibility of Mixture Designs

Rutting and stripping are major concerns for asphalt mixtures and are frequent modes of failure. It was hypothesized that adding shingles to mixtures could aid the mix in terms of rutting resistance due to the stiffer binder in the shingles. For the analyses of rutting and stripping susceptibility, each control mix established in Analysis #1 was tested using 2.5, 5, and 10 percent manufacturing wastes shingles in the Evaluator of Rutting and Stripping of Asphalt (ERSA). The control mixes, having 0 percent shingles, were compared directly to the similar mixes having shingles. After conducting the ERSA tests, certain mixtures were selected for further analysis and comparison using AASHTO T283 (moisture damage) tests.

The Evaluator of Rutting and Stripping of Asphalt (ERSA) machine was developed at the University of Arkansas and is similar to the Hamburg wheel test. It uses a loaded 2-inch steel wheel (132 pounds) cycling 20,000 times over 2 cores submerged in water at 50 degrees Celsius. As the samples rutted, the rut depth was measured using an LVDT connected to the loaded steel wheel. The test specimens were prepared at the virgin optimum binder content and compacted to a height of 75 mm with 7 ± 1 percent air voids. Replicate ERSA tests were run for each mix type. The rut depth was plotted against the cycle number in order to determine the initial consolidation, rut depth at 10,000 cycles, rut depth at 20,000 cycles, rutting slope, stripping slope, and stripping inflection point. These values were used to compare each sample directly to the others and evaluate rutting and stripping susceptibility.

The following data from ERSA were collected and used to conduct a series of multi-factor ANOVA tests: initial deformation, rutting slope, stripping slope, stripping inflection point (SIP), rut depth at 10,000 cycles, and rut depth at 20,000 cycles. The experimental setup is shown in Table 16.

Table 16: ANOVA Setup for Analysis #2- ERSA Results

factors:	levels:	responses:
Shingle content (%)	0	rut depth at 10,000 cycles
	2.5	rut depth at 20,000 cycles
	5	rutting slope
	10	stripping slope
Aggregate type	Limestone	SIP (stripping inflection point)
	River Gravel	
Binder grade/ compaction level	PG 64-22/N_{des}=75	
	PG 70-22/N_{des}=100	
NMAS (nom. max. agg. size)	12.5mm	
	25mm	

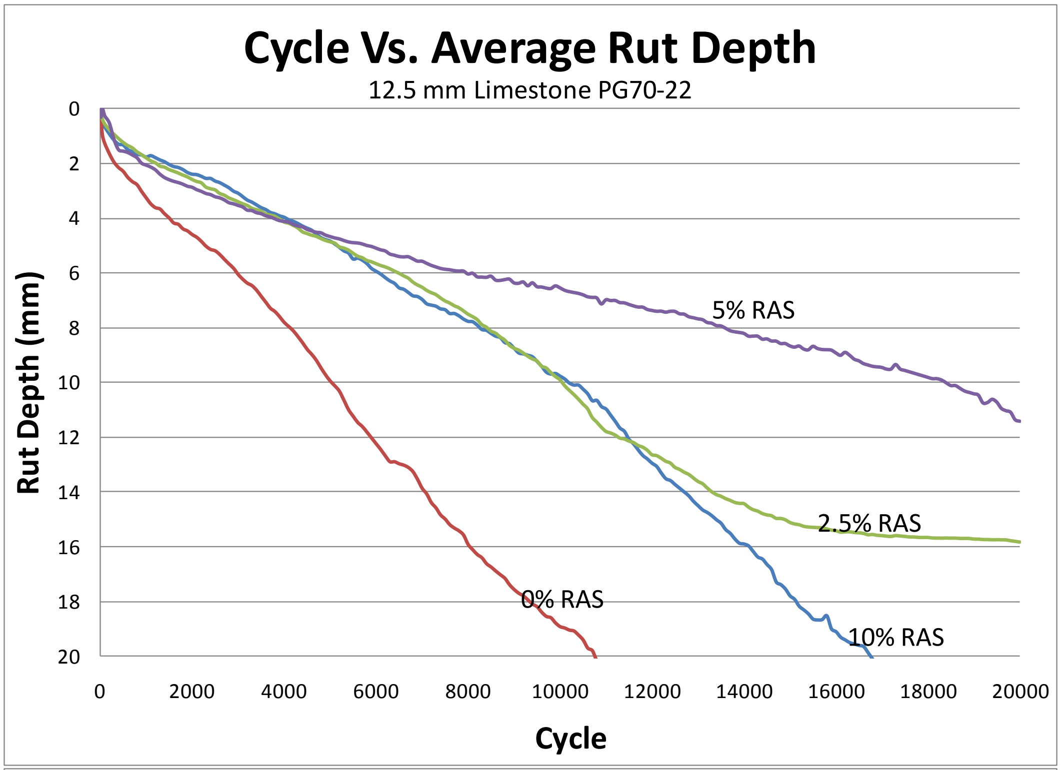
Performance of Mixtures in ERSA:

Table 17 shows average response data obtained from ERSA. The following figures (11-14) show the results obtained from each mix design when tested using ERSA. Each series in each of these figures shows the rut depth versus number of cycles for the average of two sets of samples tested for each mix design.

Table 17: Average Response Data from ERSA

Mix Design	Shingle Content (%)	Values for Responses Initial Deformation (mm)	Rut Depth @ 10,000 Cycles (mm)	Rut Depth @ 20,000 Cycles (mm)	Rutting Slope (cyc/mm)	Striping Slope (cyc/mm)	SIP* (Cycles)
12.5 mm Limestone 64-22	0	3.3	20	20	545	545	NS
	2.5	2.5	19.8	20	394	394	3750
	5	1.6	20	20	565	565	NS
	10	0.9	8.7	18.9	660	660	13000
25.0 mm Limestone 64-22	0	2.7	17.4	20	496	496	NS
	2.5	2.9	8.1	14.8	1368	1368	16000
	5	2.2	7.5	18.9	811	811	10100
	10	1.6	5.3	8.7	2861	2861	NS
12.5 mm Limestone 70-22	0	1.2	18.6	20	509	509	3200
	2.5	3.7	10.3	15.9	559	559	9800
	5	0.9	6.4	11.1	1699	1699	NS
	10	1.2	9.7	20	862	862	9200
25.0 mm Limestone 70-22	0	0.7	5.1	8.7	3102	3102	NS
	2.5	1.9	6.9	14.6	1904	1904	NS
	5	0.5	10.4	16.2	568	568	6600
	10	0.6	9.3	16.4	2288	775	7300
12.5 mm River Gravel 64-22	0	0.9	3.9	6.6	5380	5380	NS
	2.5	1.1	6	10.9	908	908	17300
	5	0.4	4.3	8.4	2582	2582	NS
	10	2.7	3.8	6.2	3021	3021	NS
25.0 mm River Gravel 64-22	0	0.7	4.7	8.1	2949	2949	NS
	2.5	1.2	4.1	7.9	2490	2490	19800
	5	1	8	10.7	2667	2667	NS
	10	0.3	3.4	8.7	3914	3914	NS
12.5 mm River Gravel 70-22	0	0.7	3.2	4.8	2797	2797	NS
	2.5	1.1	4.9	7.7	2217	2217	NS
	5	2.8	6.3	9.9	2721	2721	NS
	10	1.1	3.8	6.2	3701	3701	NS
25.0 mm River Gravel 70-22	0	2.1	4.8	10.9	4933	4933	NS
	2.5	2	7.7	11.4	1740	1740	NS
	5	2.2	8.6	11.2	1320	1320	8500
	10	1.5	4.6	6.8	5159	5159	NS

Note* - NS = No Stripping



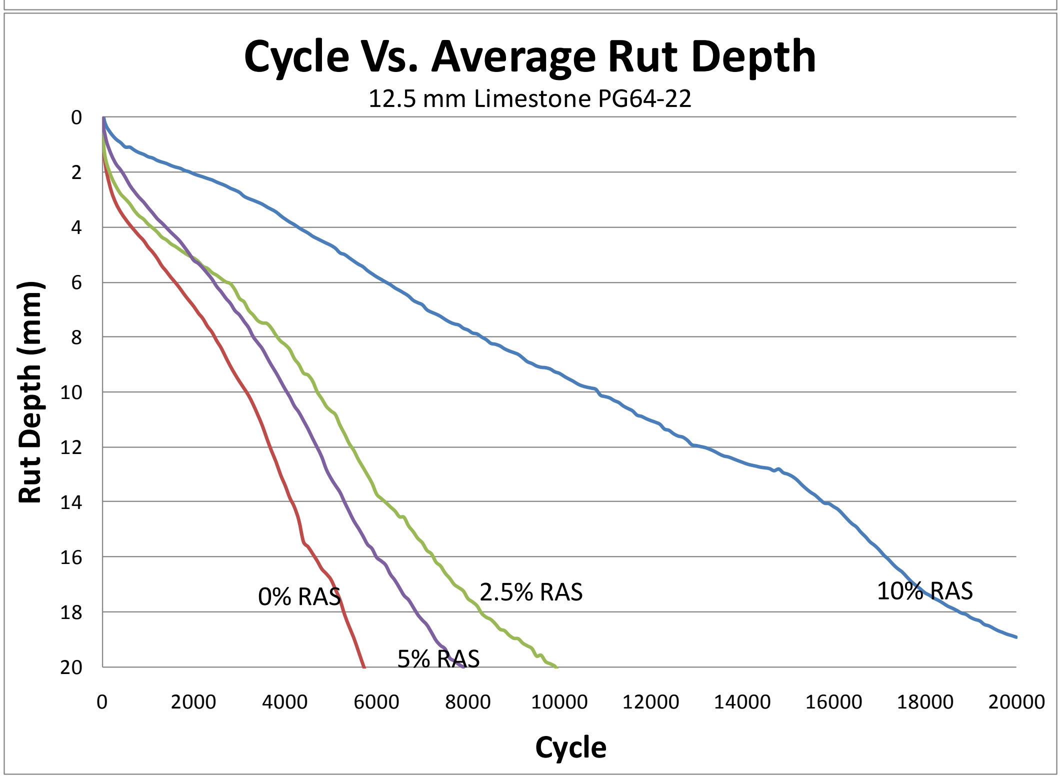


Figure 11: Average ERSA Results for all Limestone 12.5 mm Mixes

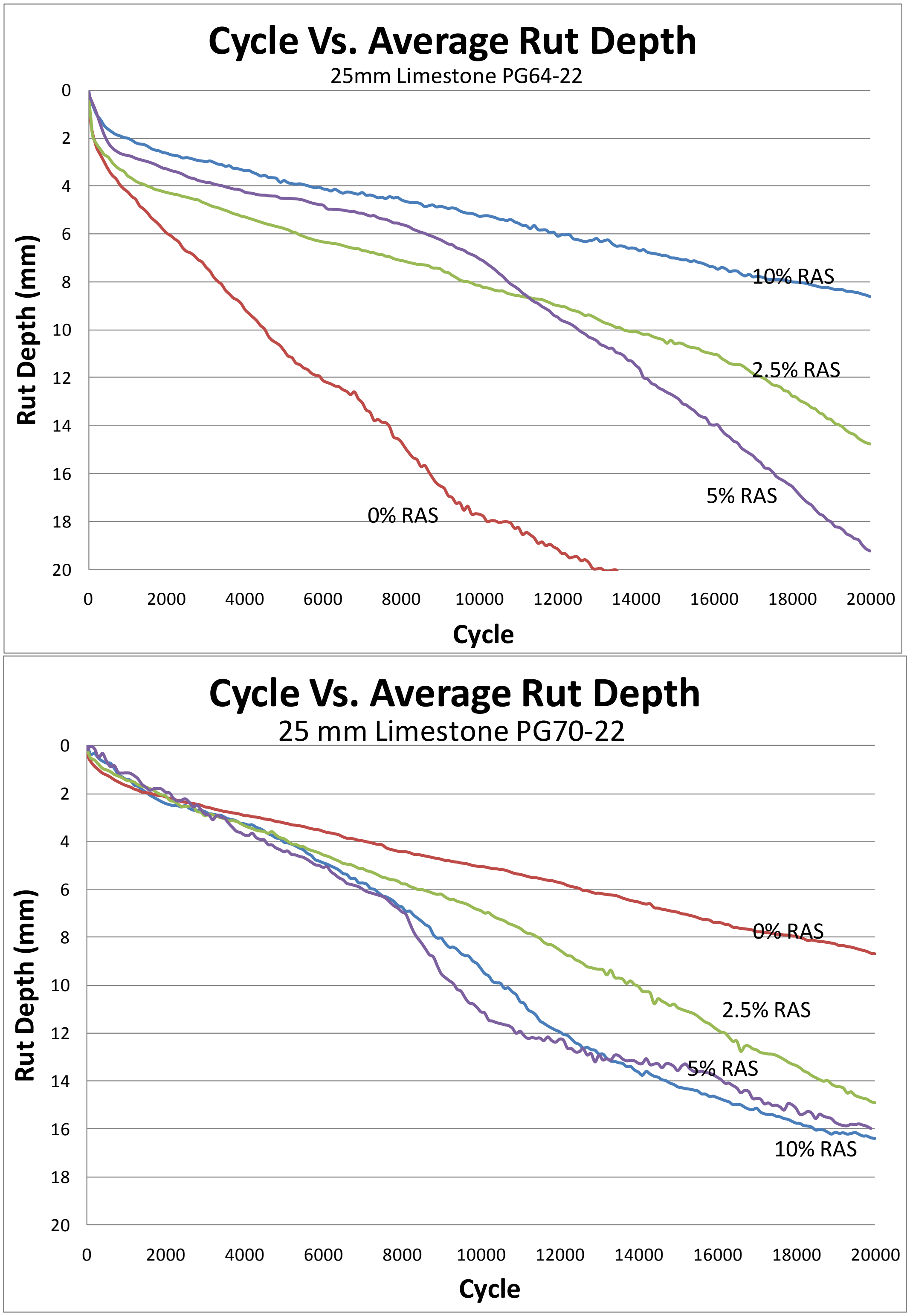
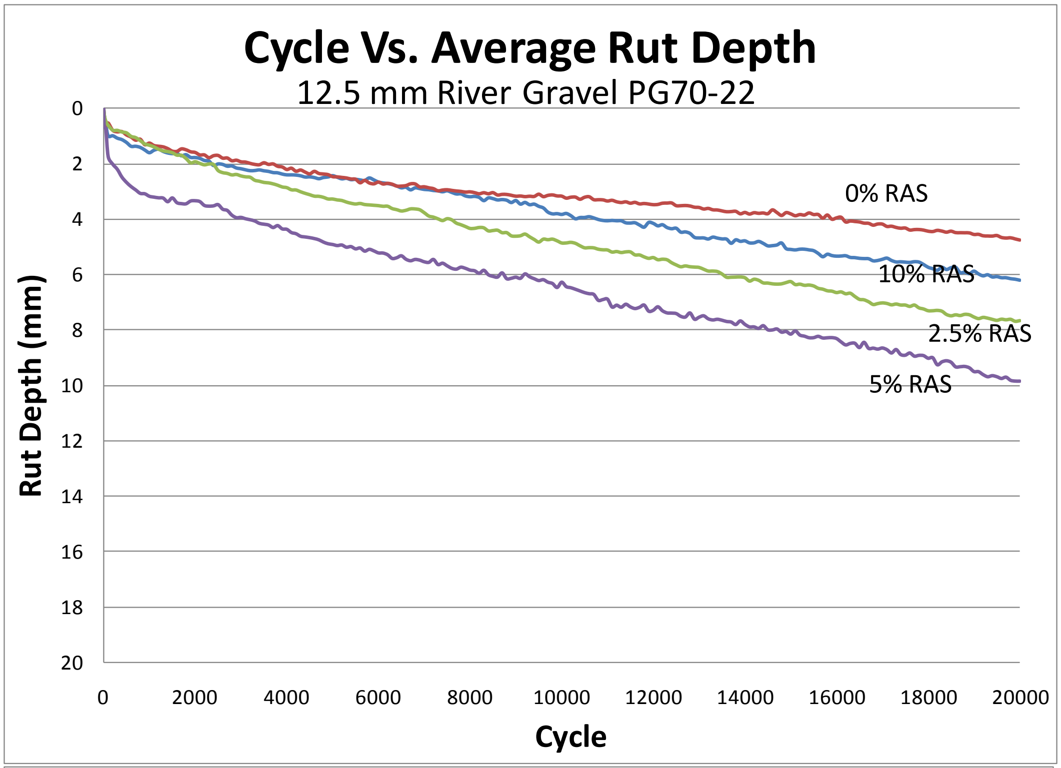


Figure 12: Average ERSA Results for all Limestone 25.0 mm Mixes



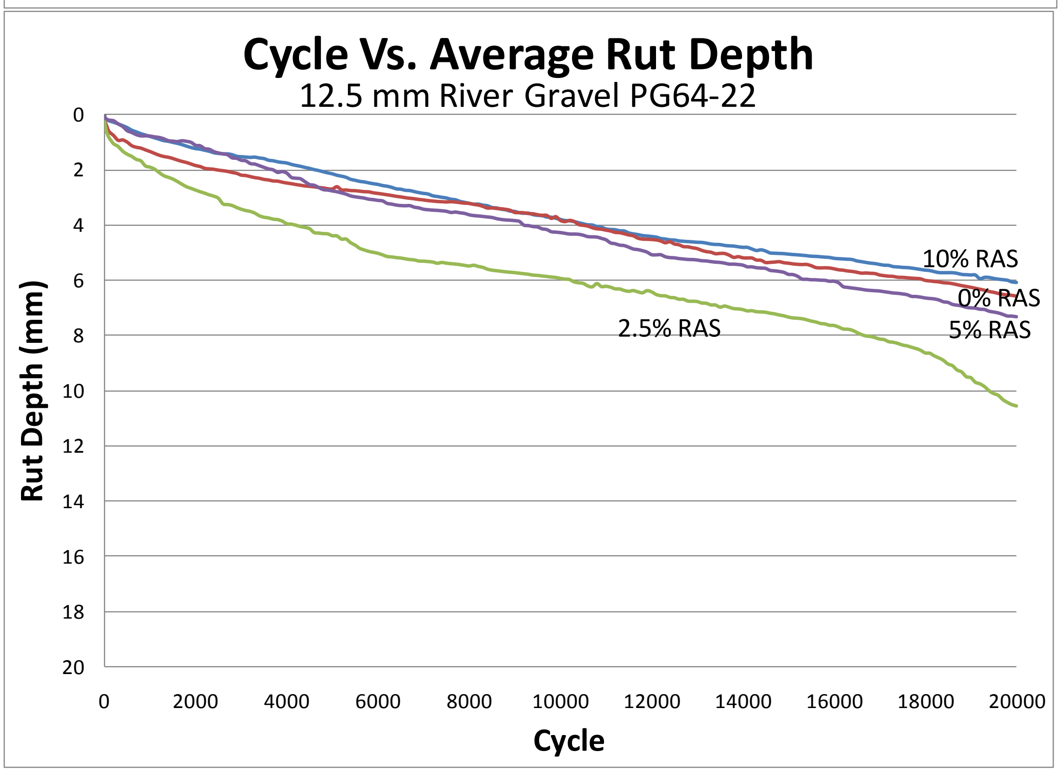
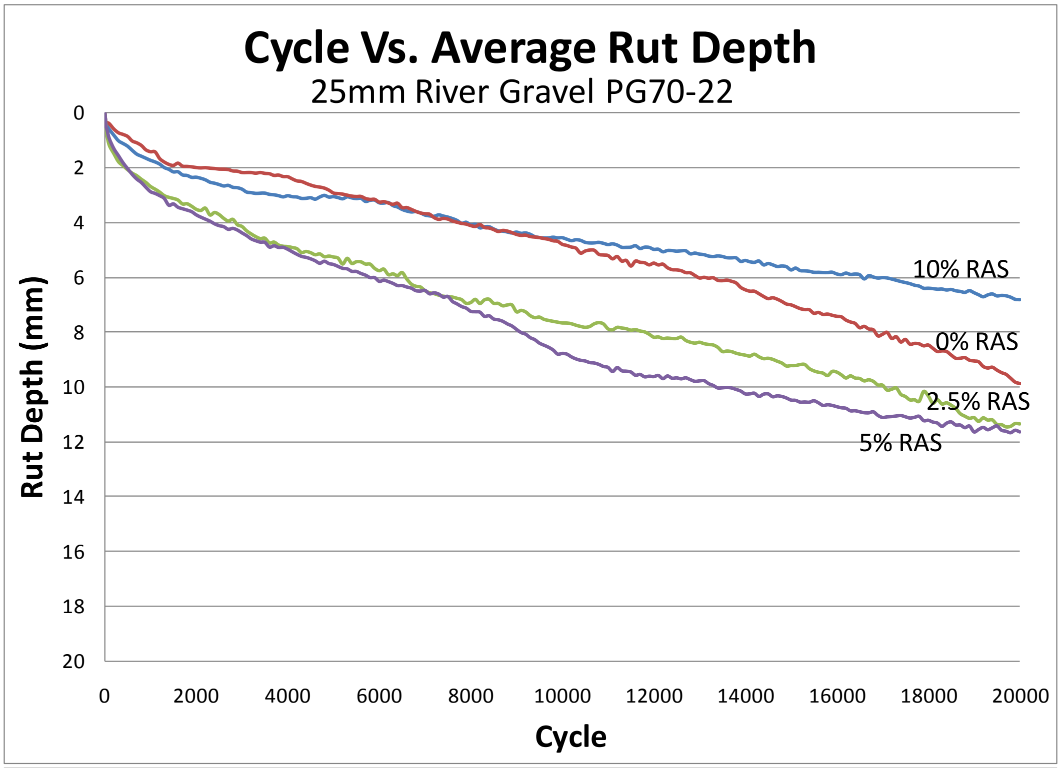


Figure 13: Average ERSA Results for all River Gravel 12.5 mm Mixes



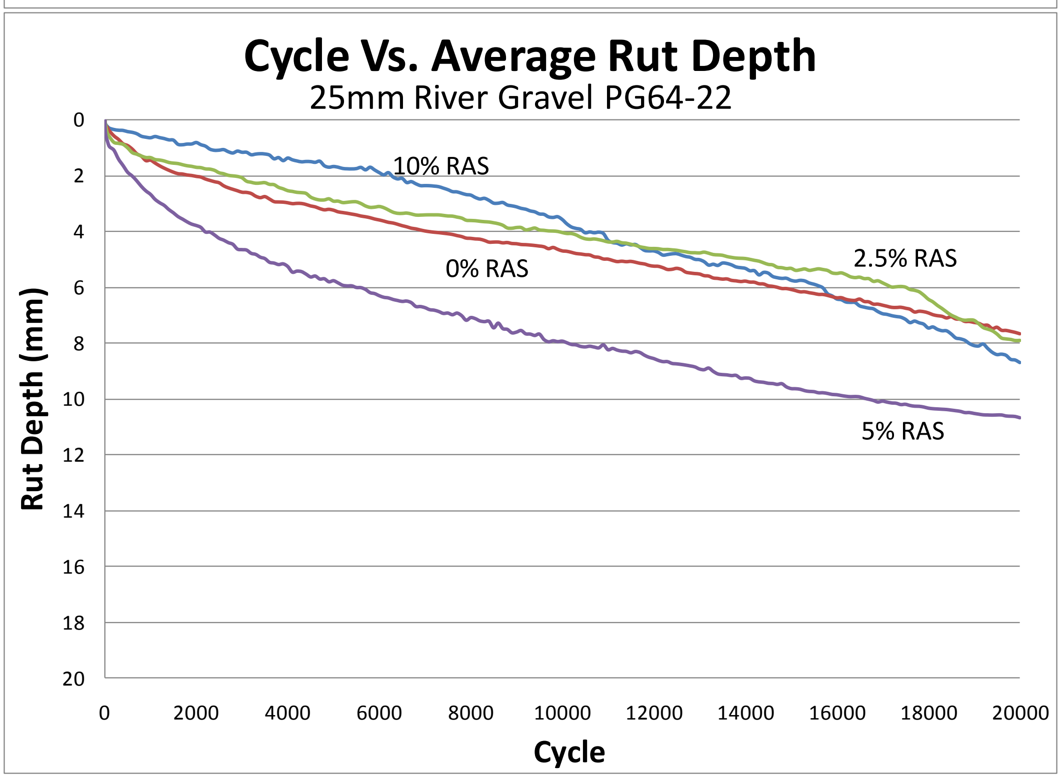


Figure 14: Average ERSA Results for all River Gravel 25.0 mm Mixes

Figures 11 through 14 show that the incorporation of shingles into mixtures in small amounts can affect the rutting and stripping susceptibility of a mixture. For each limestone mixture, the rutting resistance is aided by the incorporation of shingles, with the exception of the 25.0 mm mixture with PG 70-22 binder. The incorporation of small amounts of shingles into river gravel mixtures however, yielded a slight increase in rutting susceptibility. It is likely that the river gravel control mixtures were relatively stiff so that the incorporation of shingles did not stiffen the mixture significantly.

From the figures above, it appears that the mixtures containing 2.5 percent RAS are not significantly different than the mixtures containing 5 percent RAS with respect to rutting slope and stripping slope. This assumption was validated using a 4 factor ANOVA analysis with data from Table 22. The only instance where a significant difference existed between mixtures containing 2.5 and 5 percent shingles was in the 12.5 mm limestone with PG 70-22 binder. In this case, the mixture containing 5 percent shingles was much stiffer than the mix containing 2.5 percent shingles.

Statistical Analyses:

Table 18 shows a summary of the results from the ANOVA tests. This table lists the p-values for each factor and interaction of factors, and the values that are significant are highlighted.

Table 18: P-values for Factors and Interactions from ANOVAs

factors/interactions	P-values for Responses				
	rut depth at 10,000 cycles	rut depth at 20,000 cycles	rutting slope	stripping slope	SIP
NMAS	0.0027	0.2610	0.0783	0.1529	0.7546
PG	0.0270	0.1296	0.8885	0.5912	0.8776
NMAS*PG	0.0442	0.2256	0.4619	0.8650	0.3178
AGG	<0.0001	<0.0001	<0.0001	<0.0001	0.0007
NMAS*AGG	<0.0001	0.0004	0.0886	0.4408	0.6640
PG*AGG	0.0017	0.0806	0.2972	0.7706	0.4170
NMAS*PG*AGG	0.2892	0.7851	0.3369	0.6836	0.9252
RAS	0.0005	0.3047	0.2695	0.5035	0.3395
NMAS*RAS	0.1094	0.4968	0.3501	0.7131	0.2948
PG*RAS	0.0093	0.0429	0.9887	0.5901	0.4474
NMAS*PG*RAS	0.1826	0.3442	0.1192	0.0543	0.0888
AGG*RAS	0.0023	0.9910	0.5549	0.7088	0.1379
NMAS*AGG*RAS	0.0525	0.9753	0.4095	0.4390	0.4831
PG*AGG*RAS	0.0206	0.0078	0.0498	0.0966	0.9884
NMAS*PG*AGG*RAS	0.1056	0.0033	0.7040	0.5521	0.0659

Each of the responses, except for the stripping slope and the stripping inflection point, showed a significant interaction of factors. Tables 19 and 20 show the mean values for the levels of each factor for the responses that did not have significant factor interactions, meaning that the factor could be analyzed individually. In general, the aggregate type significantly affected each response. This means that similar results for each response could not be expected when changing aggregate types. The stripping slope and stripping inflection point were also affected significantly by the aggregate type. This makes sense because the binder could adhere better to one type of aggregate and not strip off as easily compared to the other aggregate. The binder grade, NMAS, and RAS content did not show a significant difference for the responses relating to the stripping which indicates a mix containing RAS may be as stripping susceptible/resistant as a similar mix without RAS. Figure 15 shows an example of the amount of visual stripping in a completed ERSA limestone specimen.

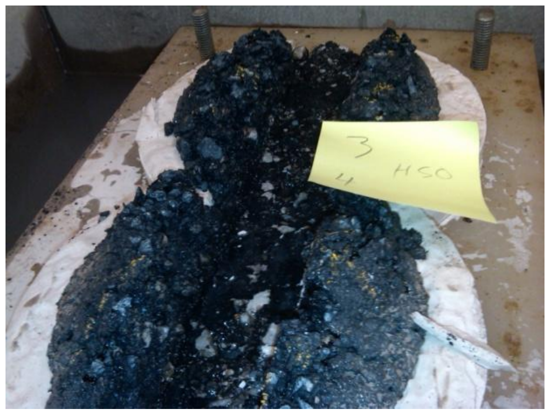


Figure 15: Completed Limestone ERSA Specimens

Table 19: Mean Values of Stripping Slope for Factor Levels

Factor	Stripping Slope			
NMAS	12.5mm	25mm		
	1820	2316		
Agg	Limestone	River Gravel		
	1040	3031		
Binder	PG 64-22	PG 70-22		
	1976	2160		
% RAS	0	2.5	5	10
	2589	1448	1617	2619

Table 19 shows a large difference in stripping slope between aggregate types. The 25mm NMAS and polymer modified binder however both showed similar (and slightly worse) performance. The addition of shingles in small quantities showed large adverse effects in the stripping slope but at large quantities showed similar results to the controls; however, none of these differences were statistically significant.

Table 20: Mean Values of Stripping Inflection point for Factor Levels

Factor	Stripping Inflection Point			
NMAS	12.5mm	25mm		
	30622	31631		
Agg	Limestone	River Gravel		
	23800	36966		
Binder	PG 64-22	PG 70-22		
	31375	30878		
% RAS	0	2.5	5	10
	37700	26088	30119	30600

Table 20 is similar to Table 19 in that the NMAS and binder grade showed little effect on the performance of the asphalt mixture, but the aggregate type caused a large difference in stripping inflection point.

Statistical Results for Rut Depth at 10,000 cycles:

For rut depth at 10,000 cycles, three factors showed significant interaction (PG, aggregate type, and percent RAS, p=0.0206). Figures 16 and 17 describe this interaction in detail followed by discussion.

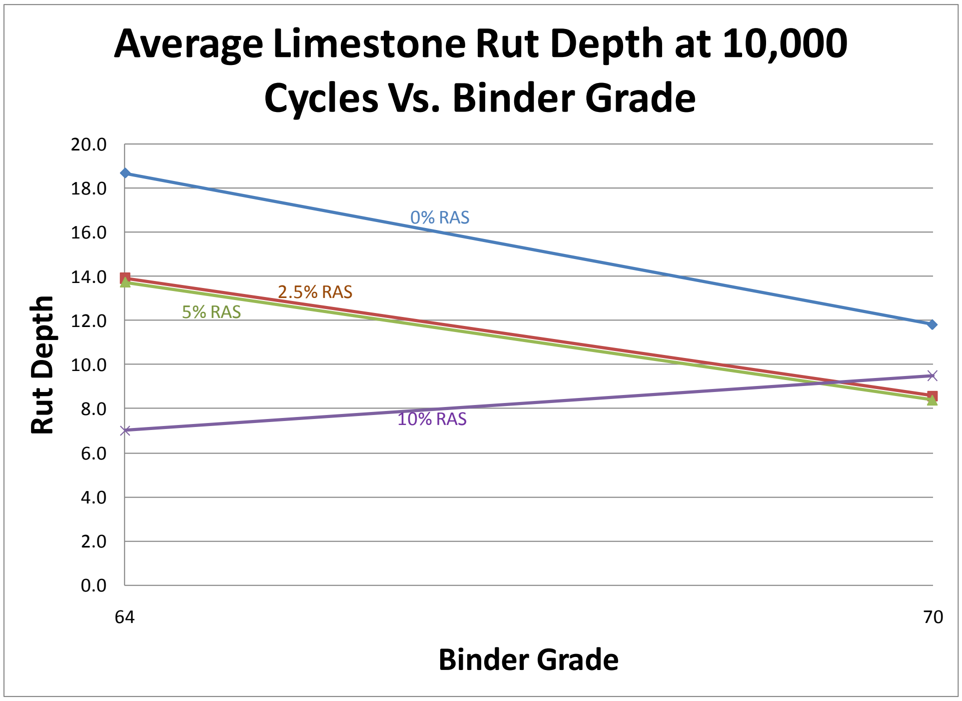


Figure 16: Average Rut Depth at 10,000 cycles Vs. Binder Grade for Limestone Mixes

The average rut depth at 10,000 cycles decreased significantly when the binder grade increased. This was expected due to the nature of the binders. For the 64-22 grade binder, the mixtures were sensitive to the amount of RAS incorporated into the mix. Specifically, as the amount of RAS increased, the rutting resistance increased. The 70-22 grade binder mixes did not show as much sensitivity to the RAS content but showed a slight increase in rutting resistance (approximately 3mm improvement at each level of RAS).

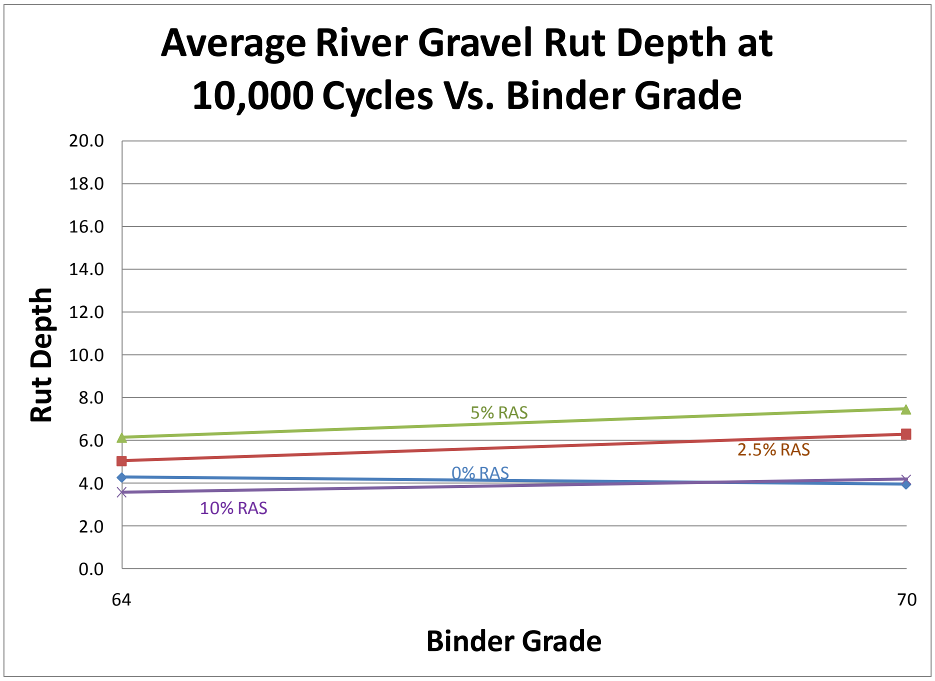


Figure 17: Average Rut Depth at 10,000 cycles Vs. Binder Grade for River Gravel Mixes

The average rut depth decreased significantly when changing aggregate types from limestone to river gravel. For the 70-22 grade mix at small amounts of RAS, the rut depth increased but with larger amounts of RAS, the rut depth decreased and became similar to the control mixture. Also, because the lines on the interaction graph are relatively parallel, the interaction between PG grade and RAS content that was shown for limestone is not evident for the river gravel.

Statistical Results for Rut Depth at 20,000 cycles:

For rut depth at 20,000 cycles, each of the factors showed significant interaction (p=0.0033). This interaction is not informative. At 20,000 cycles, enough samples had reached a maximum rutting depth of 20mm to cause difficulties in interpreting data. For example, one mix may have reached a maximum rut depth at 9,000 cycles and another may have reached a max rut depth at 19,950 cycles. Each of these samples show a 20mm rut depth at 20,000 cycles making it appear as if both perform equally at 20,000 cycles which is not true. The mix reaching 20mm at 9,000 cycles is the poorer performing mix, but this will not appear in this response. For this reason, the statistical significance was not pursued any further.

Statistical Results for Rutting Slope:

For the rut slope, three factors showed marginal interaction (PG grade, aggregate type, and percent RAS, p=0.0498). Figures 18 and 19 describe this interaction in detail followed by discussion.

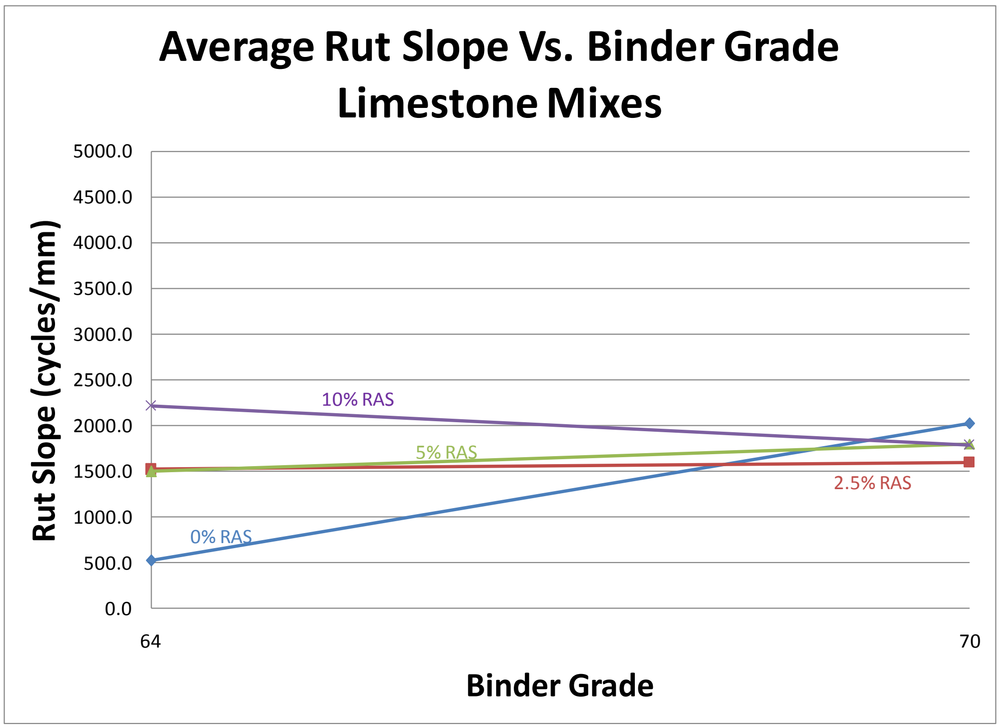


Figure 18: Average Rut Slope Vs. Binder Grade for Limestone Mixes

In the limestone mixes, the PG 70-22 binder did not appear to be sensitive to the RAS content. The PG 64-22 binder however, was sensitive to the RAS content and positively affected. From Figure 18, the 64-22 binder had an increase in rut slope from approximately 500 cyc/mm to 1500 cyc/mm when incorporating RAS at 2.5 and 5 percent.

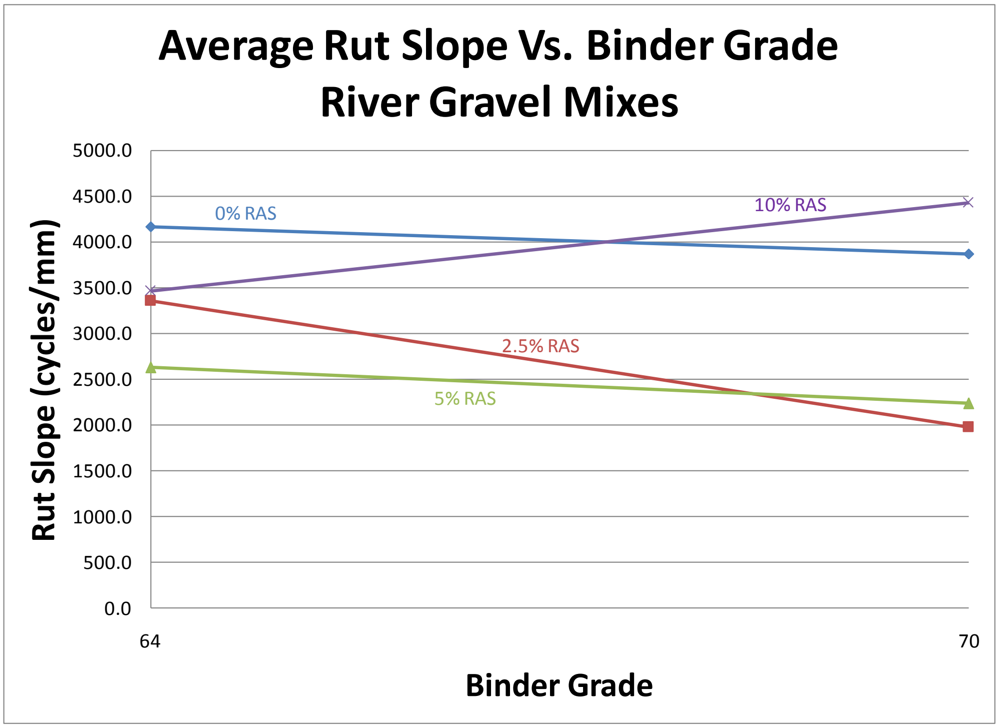


Figure 19: Average Rut Slope Vs. Binder Grade for River Gravel Mixes

The average rut slope increased significantly when changing aggregate types from limestone to river gravel. For the river gravel mix, the control mix and the mix with 5 percent RAS appeared to act similar and be predictable. The mixes with 2.5 and 10 percent RAS however, were not. From Figure 19, no practical conclusions can be drawn.

General Conclusions from ANOVA tests for ERSA:

The results of the data collected from ERSA and analyzed using ANOVA statistics showed that the use of RAS will generally aid the rutting resistance of a mix. In order to determine the virgin optimum amount of shingles to add, the mix must be thoroughly investigated. The addition of a given amount of shingles affected each mixture differently but showed the potential for performance similar to or better than the control mixture. For stripping performance, factors such as binder grade, nominal maximum aggregate size, aggregate type, and shingle content did not interact to cause unique results.

From the results of the ERSA analysis, the following conclusions can be made:

- The incorporation of shingles into extremely poor performing mixtures may aid the rutting and stripping resistance greatly but may not improve control mixes that already perform well. However, this may also be dependent on the shingle source. Each of the river gravel control mixes survived the ERSA test and with the incorporation of the RAS did not see a practical increase in performance. The limestone mixtures however, used a different source of RAS and had a practical increase in performance when any amount of RAS was incorporated.

- The samples containing RAS performed as well as the control mixes for some mix designs but not for all mix designs. Signs of excessive rutting and stripping were observed for only a few of the mixes when RAS was incorporated.

- Control mixtures that failed before 20,000 cycles showed improved performance when shingles were incorporated. However, control mixes not reaching failure throughout the entire test were generally adversely affected by the incorporation of shingles.

Comparison of Select Mixes to AASHTO T283 (Moisture Damage)

After conducting the ERSA tests, certain mixtures were selected for further analysis and comparison using AASHTO T283 (moisture damage) tests. Each control mix design was tested and compared to mixtures containing 5 percent shingles. It was thought that this information would aid the pavement engineering community greatly due to the increasing number of agencies allowing up to 5 percent RAS in pavements. Also, the 12.5 mm limestone mix containing 10 percent shingles was selected for testing due to the enhanced performance over the control mixture shown in the ERSA data. This selection encompasses a range of performance based on ERSA results. Specimen subsets were selected for conditioning, and then each test specimen was broken to determine its maximum load. In addition, each specimen was visually rated on a scale from 1 to 5. The tensile strength ratio (TSR) was calculated by dividing the average maximum load of the conditioned specimen by the average maximum load of the unconditioned specimen. The TSR is informative because it quickly describes the amount of moisture induced damage. The results of the moisture damage tests are presented in Table 21.

Table 21: Results from Moisture Damage Tests

Mixture	Shingle Content	Conditioned Visual Rating	Unconditioned Visual Rating	Conditioned Load	Unconditioned Load	TSR
12.5mm Limestone 64-22	0	4	2	3353	3777	0.89
	5	3	2	4533	5180	0.88
	10	2	2	5127	7362	0.70
12.5 mm Limestone 70-22	0	3	2	3827	4674	0.82
	5	2	2	6107	6456	0.95
25.0 mm Limestone 64-22	0	3.5	3	2673	3397	0.79
	5	2	2	4147	5327	0.78
25.0 mm Limestone 70-22	0	3	2	3204	4178	0.77
	5	3	2.5	4265	5174	0.82
12.5mm River Gravel 64-22	0	2	2	6207	5727	1.08
	5	3	3	5860	6310	0.93
12.5 mm River Gravel 70-22	0	2	3	7287	6722	1.08
	5	3	3	6520	6999	0.93
25.0 mm River Gravel 64-22	0	2	2.5	5981	5740	1.04
	5	2	3	5157	5982	0.86
25.0 mm River Gravel 70-22	0	3	3	5960	6355	0.94
	5	2	2	6500	6434	1.01

Details on the results for each of these mixes are given in the following sections.

Results for 12.5mm Limestone 64-22 Mixes:

According to ERSA results, the 12.5mm limestone mixture containing PG 64-22 binder performed extremely poorly without RAS and was by far the worst performing sample with respect to rutting. Near the edge of the unconditioned samples, the aggregate cracked showing a weak aggregate. As seen in the left column of Figure 20, the center of the specimen is mostly black due to the aggregate being fully coated with binder. At the edges of the samples, however; the specimen displays a number of white spots which were caused by broken aggregate. According to the TSR test results, the addition of RAS aided the performance of the mixture. With 5 percent RAS, fewer signs of stripping were present. The moisture damage results agreed with the ERSA results for this sample fairly well. The addition of RAS produced a sample capable of enduring higher loads and reduced the amount of stripping present in each conditioned sample. The change in performance with respect to RAS can be seen in Figure 20 which shows the control mixture samples and samples with RAS incorporated.

	Non-Conditioned	Conditioned
0% RAS		
5% RAS		
10% RAS		

Figure 20: Conditioned and Non-conditioned 12.5mm Limestone Samples PG 64-22

Results for 12.5mm Limestone 70-22 Mixes:

According to the ERSA results, the 12.5mm limestone mixture with PG 70-22 binder performed similarly, somewhat improved, to the 12.5mm limestone mixture with PG 64-22 binder. The addition of 5 percent RAS aided the mixture far more than any other amount of RAS. The moisture damage results appear to agree very closely with the ERSA results. The addition of 5 percent RAS helped the conditioned load greatly and increased the TSR to 0.95 from 0.82 with no RAS. Figure 21 show the broken samples with and without RAS.

	Non-Conditioned	Conditioned
0% RAS		
5% RAS		

Figure 21: Conditioned and Non-conditioned 12.5mm Limestone Samples PG 70-22

Results for 25.0mm Limestone 64-22 Mixes:

According to the ERSA results, the 25mm limestone mixtures with PG 64-22 binder performed similar to the 12.5 mm limestone mixes with PG 64-22 binder. The only difference was that the 25.0 mm samples did not rut as badly. The incorporation of shingles at any amount showed a very large increase in rutting and stripping resistance. The moisture damage results agreed with the ERSA results for this mix. The loads were increased significantly when shingles were introduced at 5 percent and the visual rating was also significantly improved. Figure 22 shows the samples broken with and without RAS incorporated.

<table>
<tr><th></th><th>Non-Conditioned</th><th>Conditioned</th></tr>
<tr><td>0% RAS</td><td></td><td></td></tr>
<tr><td>5% RAS</td><td></td><td></td></tr>
</table>

Figure 22: Conditioned and Non-conditioned 25.0mm Limestone Samples PG 64-22

Results for 25.0mm Limestone 70-22 Mixes:

The ERSA results showed the 25.0mm limestone mix with PG 70-22 binder to be the only limestone mixture to be adversely affected by the incorporation of shingles. When tested in ERSA, the mixture was more susceptible to rutting and stripping when any amount of RAS was incorporated. The moisture damage tests did agree with these results. The moisture damage testing revealed the mix to be similar to the 25.0mm limestone mix with PG 64-22 binder when 5 percent RAS was present. When compared to the control mix, the difference was not substantial. This leads to the assumption that neither of the tests reported incorrect values. The ERSA results show the mix as being adversely affected when RAS was incorporated and the sample was submerged at 50 degrees C. The moisture damage tests showed that a conditioned sample containing RAS was similar to a conditioned sample without RAS. Figure 23 shows the samples broken with and without RAS incorporated.

	Non-Conditioned	Conditioned
0% RAS		
5% RAS		

Figure 23: Conditioned and Non-conditioned 25.0mm Limestone Samples PG 70-22

Results for 12.5mm River Gravel 64-22 Mixes:

The 12.5mm river gravel mixtures with PG 64-22 binder did not show any stripping and only gradual rutting. According to ERSA, this mix was ranked relative to the others and determined to be the best overall performing mix. The moisture damage results closely agree with the ERSA results. The moisture damage results showed only a very small average increase in load. Figure 24 shows the samples broken with and without RAS incorporated.

	Non-Conditioned	Conditioned
0% RAS		
5% RAS		

Figure 24: Conditioned and Non-conditioned 12.5mm River Gravel Samples PG 64-22

Results for 12.5mm River Gravel 70-22 Mixes:

The ERSA results for the 12.5mm river gravel mix with PG 70-22 binder showed the mix to be extremely stiff and with the incorporation of shingles the mix was less stiff. Even with the addition of RAS, the mix still performed very well with no visible signs of stripping and very minor rutting. The ERSA results mostly agree with the moisture damage results. The addition of RAS in the moisture damage testing showed a very slight increase in maximum load but when variability was considered, the increase was not determined to be a practically significant difference. Figure 25 shows the samples broken with and without RAS incorporated.

	Non-Conditioned	Conditioned
0% RAS		
5% RAS		

Figure 25: Conditioned and Non-conditioned 12.5mm River Gravel Samples PG 70-22

Results for 25.0mm River Gravel 64-22 Mixes:

The moisture damage results for the 25.0mm river gravel mix with PG 64-22 binder were closely related to the ERSA results. ERSA showed the mix to not be greatly affected by the addition of the RAS. Similar to the 12.5mm river gravel mixes, the samples rutted slowly and showed almost no visible signs of stripping. The moisture damage results show the samples to only be slightly better when shingles were incorporated. The moisture damage samples were seen to somewhat agree to the ERSA results. Figure 26 shows the samples broken with and without RAS incorporated.

	Non-Conditioned	Conditioned
0% RAS		
5% RAS		

Figure 26: Conditioned and Non-conditioned 25.0mm River Gravel Samples PG 64-22

Results for 25.0mm River Gravel 70-22 Mixes:

ERSA showed the 25.0mm river gravel mixes with PG 70-22 binder to be very similar to the 25.0mm river gravel mixes with PG 64-22 binder. The mixture was very stiff and as a result did not show visible signs of stripping and displayed minimal rutting. Moisture damage testing results agreed with the ERSA results in that the incorporation of RAS did not greatly affect the mixture. A very slight increase was seen in the mean load for the moisture damage specimens and the ERSA results show a very slight decrease in performance at 5 percent shingles. Variability between samples is likely to be the reason for disagreements. Figure 27 shows the samples broken with and without RAS incorporated.

	Non-Conditioned	Conditioned
0% RAS		
5% RAS		

Figure 27: Conditioned and Non-conditioned 25.0mm River Gravel Samples PG 70-22

The mix designs were ranked from best performance (1) to worst performance (8) based on the results from the moisture damage and ERSA tests. These rankings are shown in Tables 22 and 23.

Table 22: Performance Ratings for Mixtures based on MD Responses

MD Rankings for Mixes Without RAS						
	Conditioned Visual Rating	Unconditioned Visual Rating	Conditioned Load	Unconditioned Load	TSR	Avg rating for MD
12.5 mm River Gravel 70-22	3	8	1	1	1	1
25.0 mm River Gravel 70-22	3	4	2	2	3	2
12.5 mm River Gravel 64-22	3	4	3	3	1	3
25.0 mm River Gravel 64-22	1	7	4	4	4	4
12.5 mm Limestone 70-22	3	1	5	5	5	5
12.5 mm Limestone 64-22	2	1	6	6	6	6
25.0 mm Limestone 70-22	8	3	7	7	7	7
25.0 mm Limestone 64-22	7	4	8	8	8	8
MD Rankings for Mixes With 5% RAS						
	Conditioned Visual Rating	Unconditioned Visual Rating	Conditioned Load	Unconditioned Load	TSR	Avg rating for MD
25.0 mm River Gravel 70-22	1	1	2	2	1	1
12.5 mm Limestone 70-22	1	1	3	3	2	2
12.5 mm River Gravel 70-22	5	6	1	1	3	3
12.5 mm River Gravel 64-22	5	6	4	4	3	4
25.0 mm River Gravel 64-22	1	6	5	5	6	5
12.5 mm Limestone 64-22	5	1	6	7	5	6
25.0 mm Limestone 64-22	1	1	8	6	8	7
25.0 mm Limestone 70-22	5	5	7	8	7	8

Table 23: Performance Ratings for Mixtures based on ERSA Responses

ERSA Rankings for Mixes Without RAS						
	Rut depth at 10,000 cycles	Rut depth at 20,000 cycles	Rutting slope	Stripping slope	SIP	Avg rating for ERSA
12.5 mm River Gravel 70-22	3	3	2	2	2	1
12.5 mm River Gravel 64-22	1	2	3	3	3	1
25.0 mm River Gravel 64-22	2	1	4	4	1	1
25.0 mm River Gravel 70-22	4	4	1	1	4	4
25.0 mm Limestone 70-22	5	5	5	5	6	5
12.5 mm Limestone 70-22	6	6	6	6	5	6
25.0 mm Limestone 64-22	7	7	7	7	8	7
12.5 mm Limestone 64-22	8	8	8	8	7	8
ERSA Rankings for Mixes With 5% RAS						
	Rut depth at 10,000 cycles	Rut depth at 20,000 cycles	Rutting slope	Stripping slope	SIP	Avg rating for ERSA
12.5 mm River Gravel 70-22	2	2	1	1	1	1
12.5 mm River Gravel 64-22	1	1	3	3	1	2
25.0 mm River Gravel 64-22	5	3	2	2	1	3
12.5 mm Limestone 70-22	3	4	4	4	1	4
25.0 mm River Gravel 70-22	6	5	5	5	7	5
25.0 mm Limestone 64-	4	7	6	6	7	6
12.5 mm Limestone 64-22	8	8	8	8	1	7
25.0 mm Limestone 70-22	7	6	7	7	8	8

Tables 22 and 23 show that results obtained from the moisture damage test were similar to the results obtained from ERSA. In both tests, the limestone mixtures were the poorer performers when RAS was not used. The differences in the ratings can be attributed to the variability in data for the poor performers. The river gravel mixtures were very stiff and provided data that indicated similar rankings, though individual indicators may have been ranked differently. For example, the 12.5mm river gravel samples with PG 70-22 binder performed the best for the TSR but had the worst unconditioned visual rating (3). It can be concluded that the ERSA tests results were similar to the moisture damage tests revealing the 12.5mm river gravel mixtures to be of the best, followed by the 25mm river gravel mixtures, and each of the limestone mixtures without RAS performed poorly. For the mixtures with RAS, the limestone mixtures were enhanced much more than the river gravel mixtures. The T283 data showed the 12.5mm limestone mix with PG 70-22 binder as jumping to the second best performing mix and the ERSA data showed the same mix to jump to the fourth best performing mix.

Statistical Analyses for Moisture Damage Results:

Two statistical analyses were conducted on the data obtained from the moisture damage testing. A paired t-test was conducted to determine if the TSR value was significantly affected by the addition of 5 percent RAS, and an ANOVA test was conducted to determine what factors significantly affected the maximum loads. Table 21 above shows the values used, and Table 24 shows the results of the t-test.

Table 24: Results of t-Test

Effect	t calc	t crit	P-value	Significant Difference from Control?
RAS	0.7624	1.8946	0.2354	No

These results verified the figures above which showed no significant differences in TSR between the control specimens and the specimens with 5 percent RAS.

Next, an ANOVA analysis was conducted to determine which factors affected the max load. The primary focus of this analysis was to determine if the incorporation of 5 percent RAS had a significant effect on the amount of moisture induced damage. Aggregate type was taken as a blocking factor. Table 25 shows the experimental setup, Table 21 above shows the average of the values used, and Table 26 shows the results of the ANOVA analysis.

Table 25: Experimental Setup

Does change in shingle content significantly affect the maximum load?		
factors:	levels:	responses:
Conditioning Present	Yes	Max Load
	No	
Binder Grade/Compaction level	PG 64-22/N_{des}=75	
	PG 70-22/N_{des}=100	
Aggregate	Limestone	
	River Gravel	
NMAS	12.5 mm	
	25.0 mm	
Shingle Content	0%	
	5%	

Table 26: Results of the ANOVA Analysis

Factors/Interactions	P-values for Response
NMAS	0.0144
PG	0.0020
NMAS*PG	0.2505
Agg	<0.0001
%RAS	0.0007
NMAS*%RAS	0.8291
PG*%RAS	0.9363
NMAS*PG*%RAS	0.8766
Conditioning	0.0339
NMAS* Conditioning	0.6371
PG* Conditioning	0.8007
NMAS*PG* Conditioning	0.9314
%RAS* Conditioning	0.2701
NMAS* Conditioning *%RAS	0.6814
PG* Conditioning*%RAS	0.2578
NMAS*PG* Conditioning *%RAS	0.9440

Table 26 shows the NMAS, PG, percent RAS, and conditioning each showed significance, but no interactions were seen. Increasing the PG grade from 64-22 to 70-22 had the largest impact on the max load (increased from averages of 4942 to 5682 respectively). The percent RAS increased the max load by an average of 4957 at 0 percent to an average of 5684 at 5 percent. At 12.5mm NMAS the average load was 5682 and at 25.0mm the average load was 5029. Finally, the conditioning showed an average decrease in strength from average values of 5529 (not conditioned) to 5040. The primary focus here was to determine the effects of RAS on the max load endured which was seen to improve the max load endured by 15 percent.

From the results of the AASHTO T283 analysis, the following conclusions can be made:

- The results from AASHTO T283 closely agreed with the results from ERSA; this strengthens the findings from both tests.
- The incorporation of shingles into poorly performing mixtures may aid the max load endured. At 5 percent RAS, mixes yielded an average load of 5684 and the control mixes yielded an average load of 4957.

Conclusions from Analysis #3, Rutting and Moisture Susceptibility

For Analysis #3, samples were tested for laboratory rutting and stripping performance using ERSA, the Evaluator of Rutting and Stripping of Asphalt machine, which is similar to the Hamburg Wheel test and mixes were also tested according to AASHTO T283 moisture damage testing. The results from these tests were examined for each mix design, and the results were statistically analyzed using ANOVA analyses. Based on the results of Analysis #3, the following conclusions can be made:

- In, general, the incorporation of shingles into mixtures may aid the rutting and stripping resistance greatly. The limestone mixes had an improved performance for each response tested in analysis #3. However, the improved performance is not always the case as evidenced by the few mixes that performed poorly with the incorporation of RAS.
- For properties relating to stripping performance, the factors typically did not interact. Because the shingle content did not interact with other factors, changes in other factors such as aggregate type affected the mixes in the same way as the control mixes.

- From above data, the maximum percent RAS allowed in HMA should conservatively be 5 percent. The rut depth at 10,000 cycles, 20,000 cycles, and the rutting slope each saw a statistical significant interaction involving the amount of RAS. At 10,000 cycles, the rut depth was improved significantly in the limestone mixes by incorporating RAS but the rutting slope was decreased slightly in the river gravel mixes.
- It is recommended that a mix design should be tested for rutting and stripping susceptibility before use in industry. Inclusion of RAS into mixes may guard against approving a mix that exhibits excessive rutting and stripping.

Analysis #4: Dynamic Modulus

Analyses #1 through #3 demonstrated the potential of using RAS as it proved successful in reducing the virgin binder content and rutting susceptibility. In other words, the mixes were generally cheaper and stiffer when RAS was incorporated into the mix. When rutting susceptibility decreases, the potential for failure due to cracking may increase. Thus, it was necessary to further test the mixes to ensure that the addition of RAS did not cause the stiffness to be excessive. For Analysis #4, all 12.5mm mixtures were selected for further analysis and comparison using AASHTO TP-62 (dynamic modulus) tests. Each 12.5 mm NMAS control mix design was tested along with corresponding mixtures containing 5 percent manufacturing wastes shingles. Only 12.5 mm mixtures were tested due to the greater potential for failure due to cracking and because of the potential use of RAS in overlays. Also, the 12.5 mm limestone mix containing PG 64-22 and 10 percent shingles was selected for testing due to the significant increase in rutting performance over the control mixture as shown in the moisture susceptibility data. The selection of mixes tested for dynamic modulus encompassed a range of performance based on ERSA and moisture damage results.

The dynamic modulus value can be used to evaluate the rutting and cracking potential of an asphalt mixture. At a high temperature, the asphalt binder is less viscous and will rut easily. At low temperatures, however, mixtures can be excessively stiff. The dynamic modulus predicts the mode of failure and potential by measuring the stiffness at low to high temperatures. The stiffer a mixture is at high temperatures, the less likely the mixture is to fail by rutting. If a mixture is excessively stiff, however, the mixture is more likely to fail by cracking. For this analysis, master curves were developed for control mixes and compared directly to similar mixes containing RAS.

The dynamic modulus test was performed using a continuous sinusoidal compressive stress with a MTS testing machine and an apparatus holding 4 LVDTs measuring the strain which lagged behind the stress. The lag time between peak stress and strain was measured as the phase angle. The apparatus was assembled at the University of Arkansas and is shown in Figure 28. The test was performed on 3 samples of each mixture at three different temperatures and six different loading frequencies. According to TP-62, five different temperatures should be used; however, Bennert and Williams (2009) suggested the highest and lowest temperatures have a large variance in data; thus, those two temperatures were omitted from this testing regimen. For each combination of temperature and frequency, one dynamic modulus (E^*) and one phase angle (φ) were calculated for each specimen using the DYNMOD program developed at the University of Arkansas (Nam 2005).

Figure 28: Testing Apparatus assembled at the University of Arkansas

Results of Dynamic Modulus Testing:

The results of the dynamic modulus tests are presented in Tables 27 through 30.

Table 27: Dynamic Modulus Values for Limestone Mixtures

	HZ	E^* (ksi)		
		40F	70F	100F
12.5 mm Limestone 64-22 0% RAS	0.1	555.7	201.912	75.949
	0.5	820.2	308.519	100.264
	1	982.9	371.780	109.902
	5	1217.0	547.1	163.6
	10	1472.4	646.9	196.7
	25	1864.1	1074.7	288.1
12.5 mm Limestone 64-22 5% RAS	0.1	683.0	253.8	94.3
	0.5	974.0	380.6	128.7
	1	1072.0	426.8	144.0
	5	1362.3	599.0	214.6
	10	2006.5	778.5	255.9
	25	2498.4	1221.6	344.7
12.5 mm Limestone 64-22 10% RAS	0.1	636.9	276.2	125.9
	0.5	852.4	378.6	164.7
	1	913.8	459.7	202.8
	5	1002.8	589.4	262.0
	10	1203.3	803.0	316.3
	25	1706.1	1237.4	472.1
12.5 mm Limestone 70-22 0% RAS	0.1	556.1	191.9	085.3
	0.5	786.3	283.4	103.4
	1	881.3	346.1	115.7
	5	1265.4	552.6	160.7
	10	1402.1	697.9	197.3
	25	1573.5	1380.5	426.0
12.5 mm Limestone 70-22 5% RAS	0.1	730.9	289.1	103.4
	0.5	952.5	414.5	133.6
	1	1103.5	481.6	152.5
	5	1311.7	656.4	220.3
	10	1550.5	881.1	257.1
	25	1974.5	939.0	395.3

Table 28: Dynamic Modulus Values for River Gravel Mixtures

	HZ	E^* (ksi)		
		40F	70F	100F
12.5 mm River Gravel 64-22 0% RAS	0.1	727.7	166.9	56.6
	0.5	1252.6	286.8	76.8
	1	1422.8	312.2	80.4
	5	1759.4	495.3	126.9
	10	2077.8	617.9	161.4
	25	2377.0	1020.2	219.3
12.5 mm River Gravel 64-22 5% RAS	0.1	595.6	159.4	58.7
	0.5	865.8	248.8	62.9
	1	988.7	278.4	70.7
	5	1631.0	432.9	116.3
	10	1765.8	518.8	154.0
	25	2167.7	854.0	196.0
12.5 mm River Gravel 70-22 0% RAS	0.1	495.1	216.8	69.6
	0.5	779.4	326.8	92.2
	1	890.7	393.7	104.8
	5	1175.6	520.0	156.6
	10	1152.7	672.3	197.8
	25	1441.5	822.5	256.5
12.5 mm River Gravel 70-22 5% RAS	0.1	508.3	248.8	85.2
	0.5	710.5	380.8	113.1
	1	760.8	452.9	130.5
	5	1009.7	687.2	189.5
	10	1358.2	856.9	234.9
	25	1635.2	943.8	328.0

Table 29: Phase Angle Values for Limestone Mixtures

	HZ	Φ		
		40F	70F	100F
12.5 mm Limestone 64-22 0% RAS	0.1	19.2	23.6	14.2
	0.5	13.3	24.9	19.9
	1	14.0	24.1	21.8
	5	10.8	23.4	27.5
	10	10.0	16.3	29.3
	25	15.2	22.1	34.4
12.5 mm Limestone 64-22 5% RAS	0.1	17.7	22.2	18.1
	0.5	13.2	24.2	22.4
	1	12.1	22.6	23.6
	5	14.4	18.6	26.7
	10	10.2	19.3	27.2
	25	17.3	19.7	26.6
12.5 mm Limestone 64-22 10% RAS	0.1	16.2	23.2	19.9
	0.5	13.0	19.7	21.6
	1	12.2	16.8	22.0
	5	9.2	17.0	23.1
	10	12.4	23.5	25.3
	25	24.7	20.7	25.7
12.5 mm Limestone 70-22 0% RAS	0.1	19.9	23.7	13.7
	0.5	18.5	25.1	17.8
	1	14.9	24.6	19.9
	5	15.9	25.7	25.2
	10	18.7	24.5	28.0
	25	12.0	25.1	30.7
12.5 mm Limestone 70-22 5% RAS	0.1	19.5	22.9	18.5
	0.5	15.7	19.5	20.9
	1	13.4	18.8	21.7
	5	17.3	18.7	23.4
	10	15.1	18.0	24.7
	25	16.5	21.1	22.3

Table 30: Phase Angle Values for River Gravel Mixtures

	HZ	Φ		
		40F	70F	100F
12.5 mm River Gravel 64-22 0% RAS	0.1	19.4	26.0	14.9
	0.5	16.4	26.7	18.9
	1	13.0	24.4	20.4
	5	13.4	22.5	28.1
	10	20.0	23.7	30.9
	25	17.6	19.3	35.2
12.5 mm River Gravel 64-22 5% RAS	0.1	15.8	25.5	14.0
	0.5	12.9	25.9	17.5
	1	14.3	20.3	20.0
	5	12.6	24.8	25.9
	10	11.1	23.9	29.2
	25	22.8	25.3	32.4
12.5 mm River Gravel 70-22 0% RAS	0.1	19.9	23.4	16.3
	0.5	17.1	23.2	20.9
	1	16.5	22.4	22.9
	5	13.5	19.6	27.6
	10	12.9	21.5	29.7
	25	16.4	24.6	30.4
12.5 mm River Gravel 70-22 5% RAS	0.1	18.2	24.1	18.1
	0.5	14.5	22.8	21.1
	1	11.7	22.0	22.3
	5	8.8	24.8	24.8
	10	14.1	19.5	26.7
	25	16.0	21.1	28.0

From Tables 27 through 30, it is seen that the lowest value for each mix is at the lowest loading rate and highest temperature. This is expected because the mixtures were less stiff at high temperatures and endured a longer load at the lowest frequency. At the lowest temperature and the highest frequency it was seen that the dynamic modulus was the highest for each mixture. This portion of the analysis will only cover the extreme conditions.

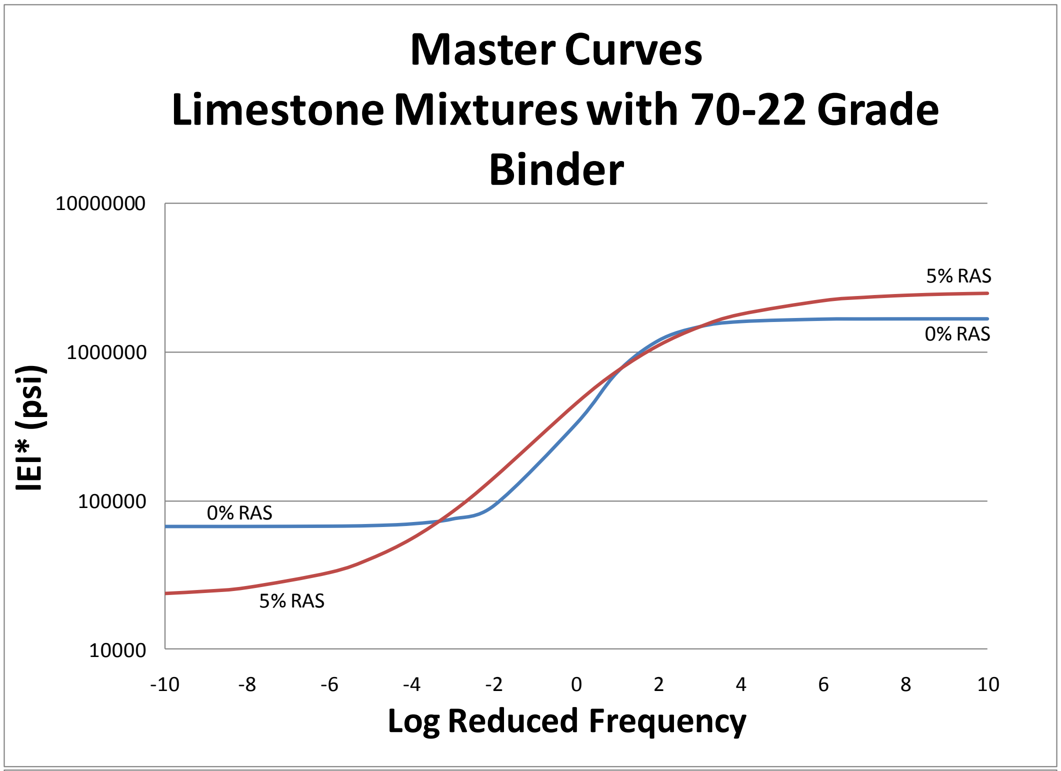
From Table 27, the limestone control mixture with 64-22 binder grade changed drastically when RAS was incorporated at 5 percent; however, adding 10 percent RAS did not show a large difference from the control mixture. The control mixture showed a modulus of 1,864.1 ksi and at 5 percent RAS showed 2,498.4. The mixture containing 5 percent RAS could be considered at risk for cracking susceptibility. The limestone mixture with PG 70-22 binder had an increase in modulus when 5 percent RAS is incorporated (1,573.5 to 1,974.5 respectively).

From Table 28 the river gravel control mixture with PG 64-22 binder yielded a large modulus but the mixture incorporating 5 percent RAS was lower (2,377.0 to 2,167.7 respectively). The difference here was not of practical significance. The river gravel control mixture with PG 70-22 binder showed an increase in modulus when incorporating the RAS (1,441.5 to 1,635.2 respectively). This is likely due to the stiffness of the shingle binder contributing to the mixture.

Development of Master Curves:

The dynamic modulus data collected at different test temperatures can be shifted relative to the frequency to form a single master curve. The master curve describes the frequency and temperature dependent properties of asphalt under viscoelastic conditions. By shifting the data, the dynamic modulus can be determined for a broad range of temperatures and loading rates. After the shift, the single dynamic modulus value is plotted against the shifted frequency termed as log reduced frequency. Also, the master curves allow a specimen to be easily compared to another specimen. The fitted master curves were developed using the Excel Spreadsheet for Master Curve developed by Dougan et al.

at the University of Connecticut's Connecticut Transportation Institute. Figures 29 and 30 show the master curves developed with explanation following.



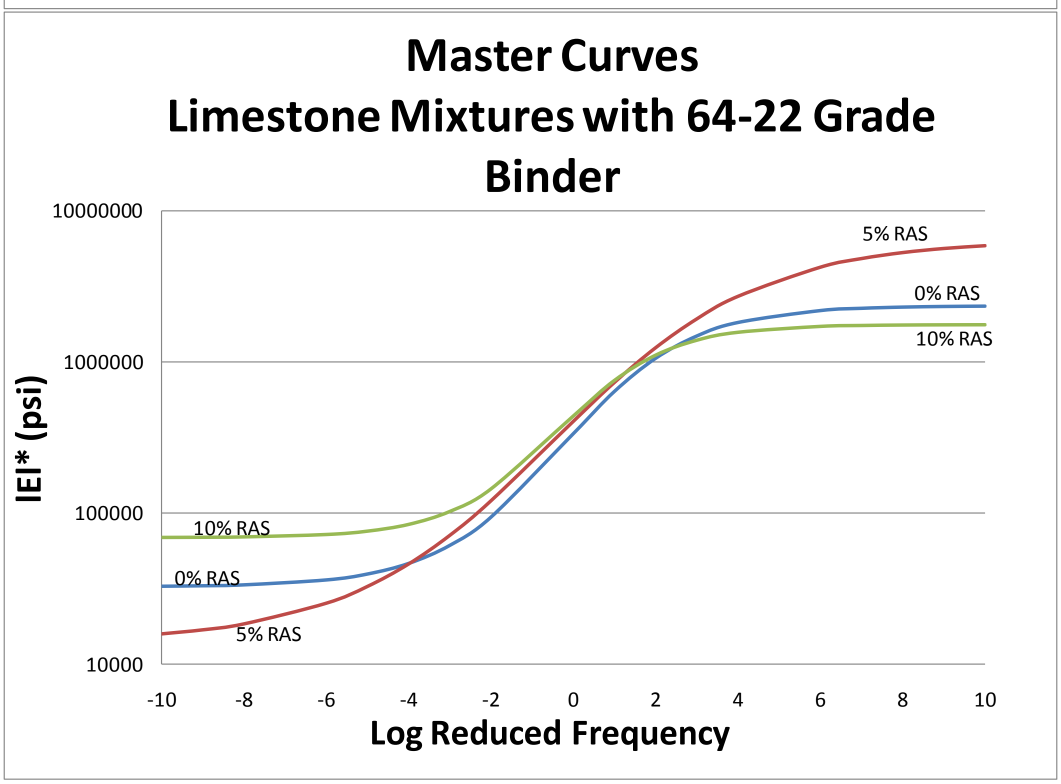
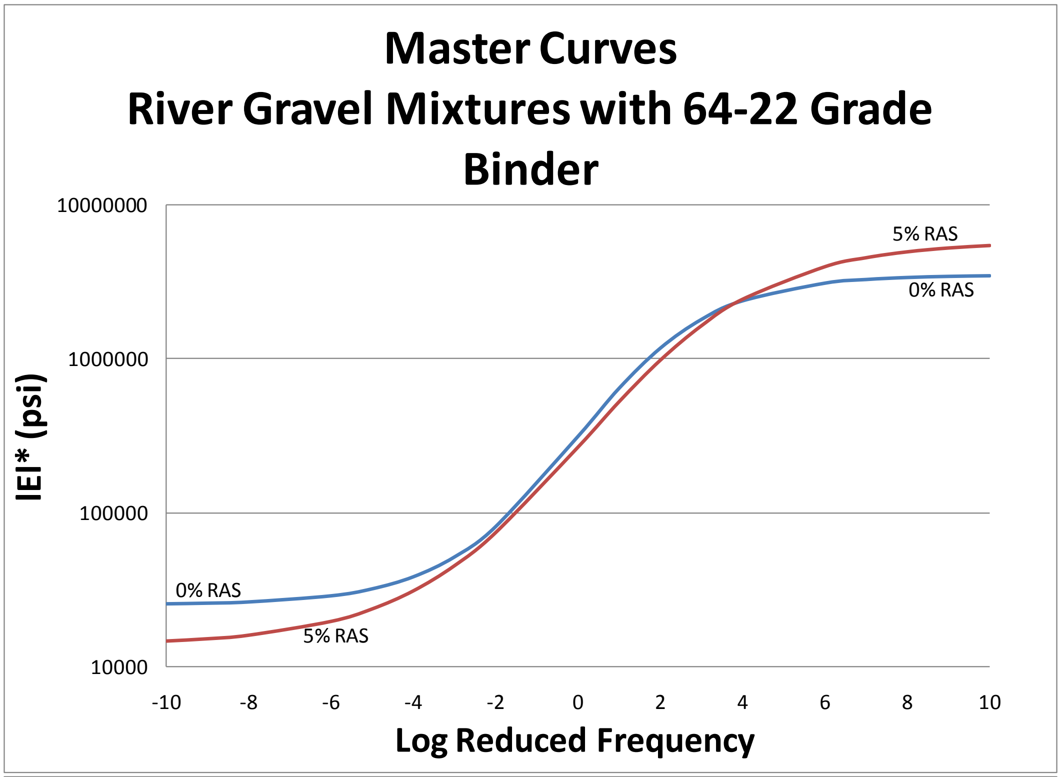


Figure 29: Master Curves for Limestone Mixtures

As seen in Figure 29 incorporating shingles at a small percent may increase the dynamic modulus at low temperatures significantly. This is a concern in areas where the temperatures are extremely low or fluctuate rapidly. At lower temperatures, the mixture containing 5 percent RAS was stiffer than the control mixture but at 10 percent RAS the mix was less stiff. At intermediate temperatures, the mixtures containing RAS yielded slightly stiffer properties, reinforcing the data obtained from ERSA and the moisture damage testing.



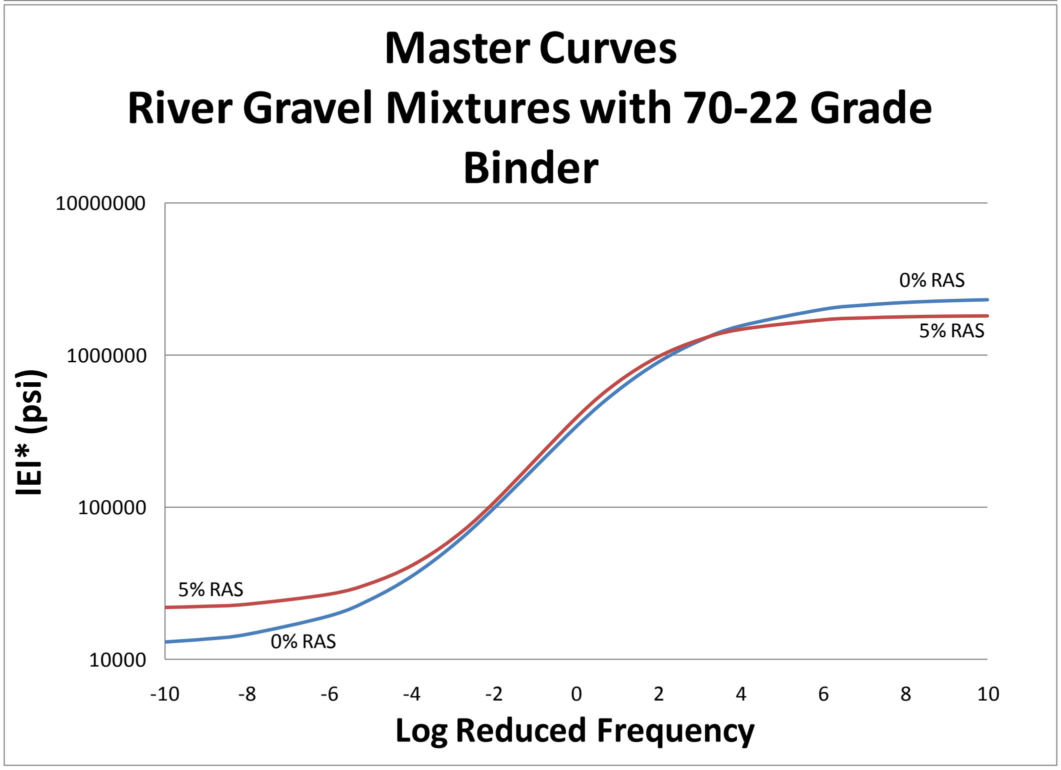


Figure30: Master Curves for River Gravel Mixtures

Figure 30 shows that the incorporation of RAS may slightly increase the stiffness at very low temperatures when PG 64-22 binder is used and may slightly decrease the stiffness at very low temperatures when using PG 70-22 binder. The data shown indicates that the incorporation of RAS at small amounts does not significantly affect the mixtures containing river gravel. This was also seen in the ERSA and moisture damage data.

Statistical Analyses:

Tables 31 through 33 show a summary of the results from the ANOVA tests. This table lists the p-values for each factor and interaction of factors, and the values that are significant are highlighted.

Table 31: P-values for Factors and Interactions from ANOVA at 100F

			P-values for Responses					
		PG	Agg	PG*AGG	RAS	PG*RAS	AGG*RAS	PG*AGG*RAS
0.1	DM	0.0729	0.0020	0.2854	0.0121	0.9151	0.3009	0.4210
	Φ	0.0057	0.1023	0.0161	<0.0001	0.0189	0.0017	0.7529
0.5	DM	0.0629	0.0015	0.1229	0.0164	0.5187	0.1165	0.3687
	Φ	0.5978	0.3241	0.0354	0.0911	0.2333	0.1629	0.4713
1	DM	0.0345	0.0009	0.0419	0.0051	0.5743	0.0769	0.2261
	Φ	0.6345	0.3374	0.0024	0.5469	0.3318	0.1092	0.5294
5	DM	0.0648	0.0014	0.0567	0.0096	0.3939	0.0509	0.4002
	Φ	0.0039	0.1228	0.1157	0.0001	0.9224	0.5879	0.6453
10	DM	0.1296	0.0139	0.0884	0.0160	0.5474	0.1550	0.4919
	Φ	<0.0001	0.0001	0.9354	<0.0001	0.0758	0.7747	0.9797
25	DM	0.9082	0.0399	0.3126	0.7840	0.6931	0.6620	0.8884
	Φ	0.0103	0.0723	0.8424	0.0059	0.4998	0.2538	0.4783

Table 32: P-values for Factors and Interactions from ANOVA at 70F

		P-values for Responses						
		PG	Agg	PG*AGG	RAS	PG*RAS	AGG*RAS	PG*AGG*RAS
0.1	DM	0.0009	0.0010	0.0417	0.0009	0.0263	0.0214	0.6368
	Φ	0.3497	0.1163	0.4191	0.7409	0.9350	0.7519	0.6031
0.5	DM	0.1347	0.0634	0.0690	0.0109	0.2847	0.0473	0.4989
	Φ	0.0033	0.0162	0.4047	0.0018	0.2786	0.0178	0.2365
1	DM	0.0097	0.0610	0.0521	0.0146	0.0612	0.1268	0.9822
	Φ	0.3008	0.5245	0.2108	<0.0001	0.9115	0.0531	0.0379
5	DM	0.0040	0.0598	0.0538	0.0523	0.0138	0.7456	0.1828
	Φ	0.8863	0.0557	0.4885	0.1818	0.6532	0.0009	0.1446
10	DM	0.1118	0.0318	0.0789	0.3068	0.0481	0.7380	0.7402
	Φ	0.3894	0.5016	0.5668	0.4116	0.0672	0.9092	0.1802
25	DM	0.6860	0.0677	0.7196	0.2693	0.3557	0.5243	0.0538
	Φ	0.9432	0.6663	0.6529	0.8216	0.2450	0.4507	0.5467

Table 33: P-values for Factors and Interactions from ANOVA at 40F

		P-values for Responses						
		PG	Agg	PG*AGG	RAS	PG*RAS	AGG*RAS	PG*AGG*RAS
0.1	DM	0.8232	0.1208	0.0488	0.3686	0.1120	0.0763	0.9503
	Φ	0.2256	0.0777	0.8719	0.0300	0.2899	0.3994	0.8030
0.5	DM	0.1696	0.7583	0.0485	0.3646	0.0690	0.0125	0.4868
	Φ	0.8983	0.0248	0.3254	0.2250	0.2951	0.5544	0.3348
1	DM	0.1530	0.5927	0.0348	0.2727	0.0572	0.0146	0.8682
	Φ	0.8596	0.9101	0.5124	0.2591	0.9623	0.1589	0.2163
5	DM	0.0638	0.3826	0.0169	0.6433	0.9603	0.4538	0.8512
	Φ	0.5682	0.7136	0.2310	0.2496	0.6114	0.4598	0.9643
10	DM	0.1114	0.4824	0.2565	0.3608	0.4331	0.3181	0.7184
	Φ	0.6903	0.1276	0.2550	0.2277	0.4080	0.5997	0.0645
25	DM	0.1793	0.9230	0.4238	0.7674	0.3740	0.7454	0.9401
	Φ	0.4412	0.6091	0.2861	0.6430	0.8098	0.7450	0.4335

As seen in Table 33, the dynamic modulus at low temperatures was not affected by the incorporation of RAS to the extent that the higher temperatures are. At 40 degrees, the RAS had a significant effect on the dynamic modulus for 2 loading frequencies. At 40 degrees, the 0.5 frequency had a mean dynamic modulus of 909.6 for the control mix and

875.7 for the mix with 5 percent RAS. At 40 degrees, when the frequency was 1 the dynamic modulus was 1044.4 for the control and was 981.3 with 5 percent RAS. At 70 and 100 degrees, 5 out of the 6 loading frequencies showed the RAS as having a significant effect on the dynamic modulus. Figure 31 displays the mean dynamic modulus values for each frequency at 70 and 100 degrees.

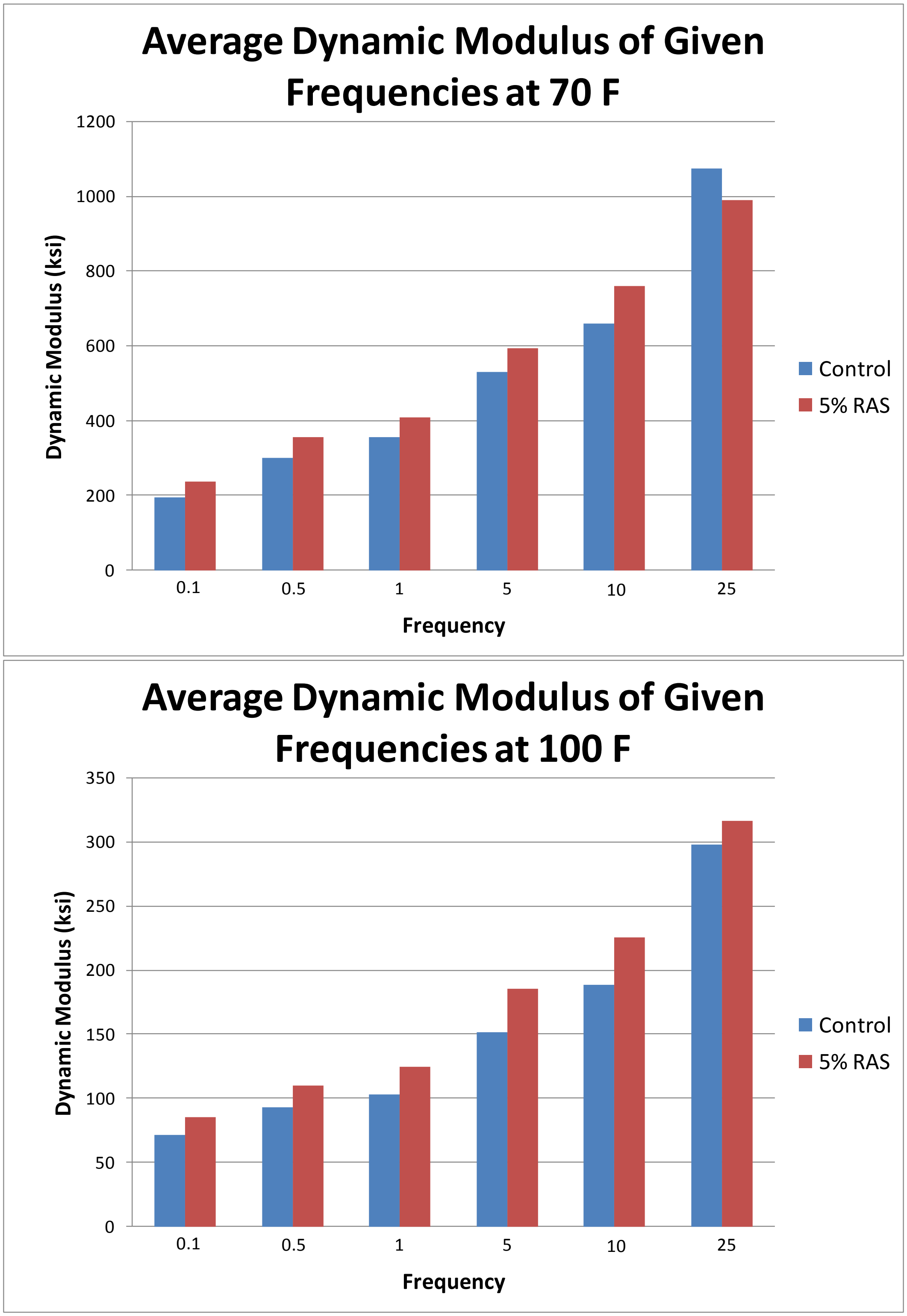


Figure 31: Mean Dynamic Modulus of Given Frequencies at 70 and 100 degrees

Figure 31, in general, demonstrates that the incorporation of RAS creates stiffer asphalts at higher temperatures. This is true for every frequency except at 25 Hz in the 70 degree chart. In this instance, the incorporation of RAS lowered the dynamic modulus. In the 100 degree chart each of the frequencies were shown to be significantly different when RAS was incorporated except for the 25 Hz where there was no significant difference when incorporating RAS.

The phase angle was seen to have similar statistics. At 40 degrees, the RAS had a significant effect on the phase angle for 1 loading frequency. At 70 degrees, the phase angle was significantly affected by the RAS for 3 frequencies and at 100 degrees, 4 frequencies showed significance. This information verifies the statements above regarding the stiffness of asphalt when RAS is incorporated into the mixture.

Conclusions from Analysis #4, Dynamic Modulus Testing Using AASHTO TP-62

For Analysis #4, samples were tested using AASHTO TP-62 to measure the dynamic modulus and phase angle. The results from this test were examined for select mix designs, and the results were statistically analyzed using ANOVA. Based on the results of Analysis #4, the following conclusions can be made:

- For values relating to high temperature performance, a couple of factors were significant, including RAS and aggregate type. The samples containing RAS performed similarly to the control mixes at very cold temperatures. The binder grade and aggregate type show significant interaction and the RAS only showed a significant effect at the uppermost region of the master curves.

- At intermediate temperatures, the inclusion of RAS may slightly aid the rutting resistance of the mixtures as mentioned in Analysis #3. The inclusion of RAS at intermediate temperatures should not practically affect the cracking susceptibility of mixtures.

- At lower temperatures, the inclusion of RAS may not affect the stiffness of the asphalt mix significantly. The limestone mixture with PG 64-22 binder was the only mixture to have an extremely affected stiffness at low temperatures by the inclusion of RAS and saw an increase in the dynamic modulus.

- From the data above, the increase in performance at high temperatures (i.e., increased rutting resistance) appears to outweigh the potential for a decrease in performance at low temperatures (i.e., increased cracking)

Analysis #5: How Sensitive were Various Mixture Properties to Tear-Off Shingles, Particle Size, and Agglomeration?

Analysis #5 was conducted to examine the changes in volumetric properties from select mixtures containing manufacturing wastes and tear-off RAS, as well as the effects of manufacturing wastes that had agglomerated. There were four different parts of this analysis in which two different sources of tear-off shingles were selected. First, differences were analyzed between control mixtures and mixes containing tear-off shingles. Second, differences were analyzed between mixes containing tear-off shingles and mixes containing tear-off shingles that were screened to pass the #4 sieve. Next, differences were analyzed between mixes with agglomerated shingles and non-agglomerated shingles. Finally, the performance data of select mixes with tear-off shingles was obtained. The limestone aggregates were used in the comparisons of tear-off shingles, while the mixtures containing river gravel were used to assess the influence of manufacturing wastes agglomeration.

Analysis of Mixes with Unscreened Tear-Off RAS

First, the differences were analyzed between control mixtures and mixes containing tear-off shingles. The ignition oven was used to establish the amount of available binder in each shingle source. Shingle Source 1 yielded a binder content of 7.62 percent and Source 2 yielded 23.36 percent. The binder contribution to each mix was established in accordance with AASHTO PP53. The virgin optimum binder content of each mix was found and compared directly to the control mix with 0 percent RAS to calculate the binder contribution of each mix. Table 34 shows the virgin optimum binder contents and the binder contribution for each mix.

Table 34: Virgin Optimum Binder Contents and % Contribution

Mix Design	% RAS	Opt Binder	% Binder Contribution
12.5 mm PG 64-22 Limestone	0	6.2	
	5 (MFR)	5.1	97.17
	5 (Source 1)	10.5	No Contribution
	5 (Source 2)	5.8	84.55
25.0 mm PG 64-22 Limestone	0	4.5	
	5 (MFR)	3.4	100
	5 (Source 1)	4.6	37.23
	5 (Source 2)	4	93.20

From Table 34, it was seen that the incorporation of tear-off shingles did not contribute binder nearly as well as manufacturing wastes. When compared to the control mixes, the virgin optimum binder content increased when using tear-offs from source 1 but decreased when using source 2 which means the shingle source has a large impact on the amount of binder contribution. This is consistent with the large difference in shingle binder content of the two sources.

Statistical Analysis for Tear-Offs Grind Size Binder Contribution

Several paired t-tests were conducted in this analysis to determine the impacts of tear-off shingles. The first paired t-test was conducted to determine whether tear-offs and manufacturing wastes created significant differences in air void contents. The response values used for each of the analyses were the air void contents at the design binder content. The 12.5mm mixes response values were 7.7 percent for the tear-off shingles and 4.6 percent for the manufacturing wastes shingles. The 25.0mm response values were 6.6 and 4.5 percent for the tear-offs and manufacturing wastes shingles respectively. Table 35 shows the results of the t-tests.

Table 35: T-Test Results for Source #1 Shingles

Effect	t calc	t crit	P-value	Significant Difference?
RAS	7	6.3138	0.0452	Yes

Table 35 shows the significant difference between the RAS binder contribution for tear-offs from source 1 and manufacturing wastes. When using the tear-offs, the air voids were increased significantly (p= 0.0452). The 12.5mm mix had a larger difference in air voids. By using tear-offs, the air voids were increased by 3.1 percent and in the 25.0mm mix the air voids increased by 2.1 percent.

The second paired t-test was conducted to compare manufacturing wastes to the second tear-off source with respect to air void content. The 12.5mm mixes response values were 7.1 percent air voids for the tear-off shingles and 4.6 percent for the manufacturing wastes shingles. The 25.0mm response values were 6.5 and 4.5 percent for the tear-offs and manufacturing wastes shingles respectively. Table 36 shows the results of the t-tests.

Table 36: T-Test Results for Source #2 Shingles

Effect	t calc	t crit	P-value	Significant Difference between MFR and Tear-offs?
RAS	5.4444	6.3138	0.0578	Marginal

Table 36 shows the marginal significant difference between the RAS binder contribution for tear-offs from source 2 and manufacturing wastes (p=0.0578). For this statistic, the significance is likely masked by the small sample size (n=2). The 12.5mm mix had a larger difference in air voids. By using tear-offs, the air voids were increased by 2.5 percent and in the 25.0mm mix the air voids increased by 2 percent. While these differences were only marginally significant according to the paired t-test, they clearly exhibit a practically significant difference. This change in air voids translates to a difference in binder content that is of equal practical significance, such that the manufacturer's wastes generate the greater savings in needed virgin binder content for a particular mixture.

Analysis of Mixes with Unscreened and Screened Tear-Off RAS

Next, specimens were created containing tear-off shingles which passed the #4 sieve only. The shingle size was varied because shingles that are ground to a particle size of 1/4 inch or smaller were expected to contribute asphalt binder much better than shingles ground to a maximum size of 1/2 inch. Figure 32 shows a gradation of the tear-off shingles used for this part of the analysis and Table 37 shows the virgin optimum binder contents and binder contribution for the mixes.

Table 37: Virgin Optimum Binder Contents and % Contribution

Mix Design	% RAS	Opt Binder	% Binder Contribution
12.5 mm PG 64-22 Limestone	0	6.2	
	5 (MFR)	5.1	97.17
	5 (Source 1)	10.5	No Contribution
	5 (-#4) (Source 1)	6.5	30.12
	5 (Source 2)	5.8	84.55
	5 (-#4) (Source 2)	6.3	43.37
25.0 mm PG 64-22 Limestone	0	4.5	
	5 (MFR)	3.4	100
	5 (Source 1)	4.6	37.23
	5 (-#4) (Source 1)	4.4	56.63
	5 (Source 2)	4	93.20
	5 (-#4) (Source 2)	3.9	89.76

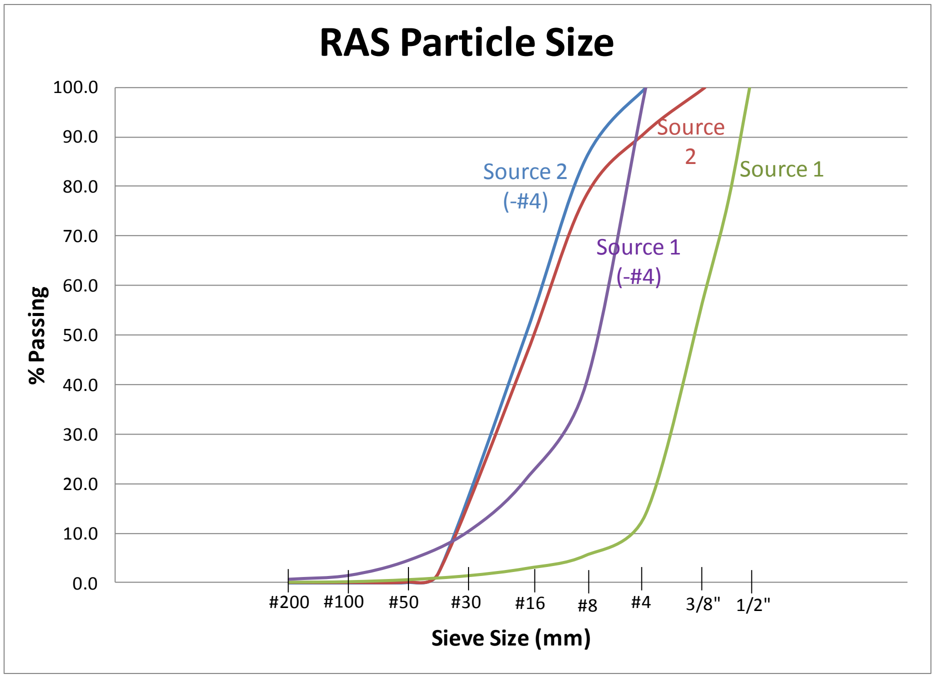


Figure 32: Tear-Off Shingle Gradation

Visual inspection of shingle source 2 revealed the material to be in general very fine and mostly passing the #4 sieve. Because the material has been ground very well prior to lab testing, the subtraction of material retained on the #4 sieve resulted in only a very small amount of material being withheld from the mix as seen in Figure 32. Therefore, the differences in specimens containing the entire gradation of RAS particles and those containing only the RAS particles passing the #4 sieve were not expected to exhibit large differences.

The shingle size was shown to have significance in the 12.5mm mix for the RAS from source 1. Without fractioning the shingles, the virgin optimum binder content was 10.5 percent and when using only shingles that passed the #4 sieve, the virgin optimum binder content was 6.5 percent. The virgin optimum binder content for the control mixture (0 percent RAS) was 6.2 which meant that the tear-off shingles from source 1 did not contribute binder, and the larger particles actually caused the mixture to require significantly more binder. A possible cause for the tear-offs absorbing binder may have been the presence of fibers in the RAS absorbing binder.

The 25.0mm mix showed a slight difference in binder content when the shingles were ground to minus #4 for both shingle sources. From source 1, the binder content was 4.6 percent when using 5 percent RAS and 4.4 percent when using minus #4 shingles. The 25.0mm control mix (0 percent RAS) had a virgin optimum binder content of 4.5 percent which means the tear-off shingles from source 1 again did not contribute binder to the mix and the tear-offs from source 2 did not show a practical contribution. In each case, it appears as though the tear-off shingles are extremely stiff, reducing the amount of binder contribution.

Statistical Analysis for Tear-Offs Grind Size Binder Contribution

Several paired t-tests were conducted in this analysis to determine the impacts of tear-off shingles and significance of shingle particle size. The first paired t-test was conducted to determine if the differences in air voids for different maximum shingle particle sizes (i.e., screened and unscreened shingles) from source 1 was significant. The response values used for each of the analyses were the air void contents at the design binder content. The 12.5mm mixes response values were 7.7 percent for the unscreened shingles and 7.3 percent for the screened shingles. The 25.0mm response values were 6.6 and 6.3 percent for the unscreened and screened shingles respectively. Table 38 shows the results of the t-tests.

Table 38: T-Test Results for Source #1 Shingles

Effect	t calc	t crit	P-value	Significant Difference between RAS Size?
RAS Size	7	6.3138	0.0452	Yes

Table 38 shows the significant difference between the RAS particle sizes for source 1. When only using RAS that was minus #4 sieve, the air voids were reduced significantly (p= 0.0368). The 12.5mm mix had a larger difference in air voids when the RAS particle size was changed. By using shingles that passed the #4 sieve, the air voids were decreased by 0.4 percent and in the 25.0mm mix the air voids decreased by 0.3 percent.

The second paired t-test was conducted to determine if the differences between the shingle grind sizes was significant for source #2 shingles. The 12.5mm mixes response values were 6.6 and 7.5 percent for the unscreened and screened shingles respectively. The 25.0mm mixes had response values of 6.5 percent for the unscreened shingles and 5.6 percent for the screened shingles. Table 39 shows the results of the t-tests.

Table 39: T-Test Results for Source #2 Shingles

Effect	t calc	t crit	P-value	Significant Difference between RAS Size?
RAS Size	0	6.3138	0.5	No

Table 39 shows no significant difference between the RAS particle sizes for source 2 (p=0.3351). By using shingles that passed the #4 sieve, the air voids were increased 2.7 percent and in the 25.0mm mix the air voids decreased 0.7 percent. This reinforces the statement above that visual inspection of shingle source 2 revealed the material to be in general "very fine and mostly passing the #4 sieve". Because the material has been ground very well prior to lab testing, the subtraction of material retained on the #4 sieve resulted in only a very small amount of material being withheld from the mix. Therefore, the replacement of this very small amount of RAS had only a very minor effect on the mixtures.

Analysis of Mixes with Agglomerated Manufacturing Wastes RAS

Finally, the effects of agglomeration were also investigated due to the potential for agglomeration as the shingles lay in the asphalt plant for long periods of time. Figure 33 shows a gradation of the agglomerated shingles and shingles not agglomerated used for this part of the analysis and Table 40 shows the virgin optimum binder contents and binder contribution for the mixes.

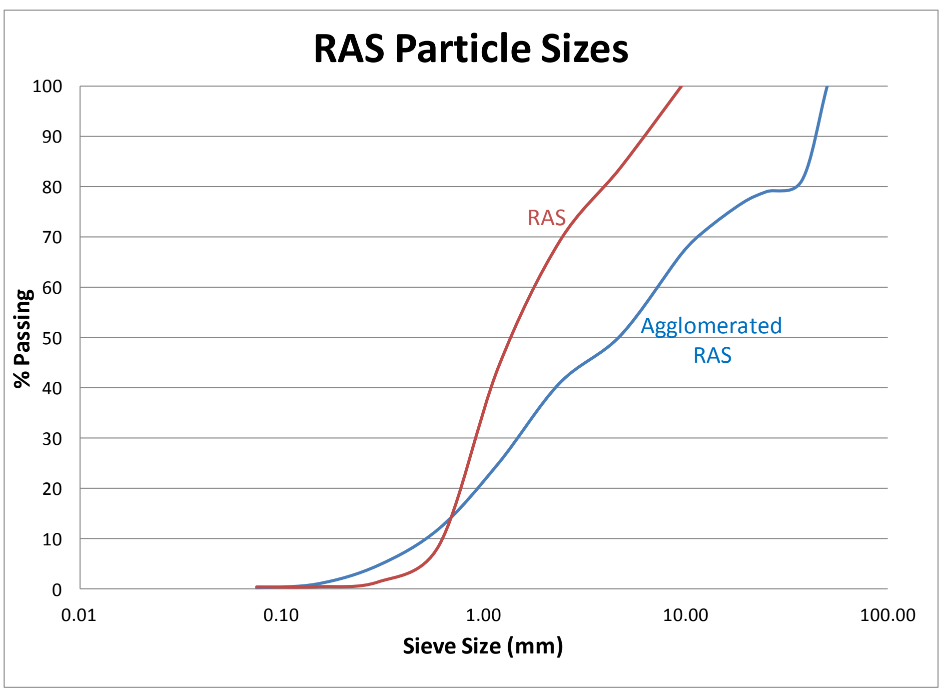


Figure 33: Agglomerated and Non-Agglomerated Shingle Gradation

Table 40: Virgin Optimum Binder Contents and % Contribution

Agglomerated RAS			
12.5 mm PG 64-22 River Gravel	2.5	4.7	89.2
	2.5 (Agglomerated)	5	50.0
	5	4.4	95.8
	5 (Agglomerated)	4.4	95.8

The effects of agglomeration appear to be marginally significant. When incorporated at 2.5 percent, the RAS contributed 50 percent of the available binder when agglomerated and when not agglomerated the RAS contributed 89.2 percent of the available binder. The binder contribution in the agglomerated mix was offset by the agglomerated shingles absorbing binder. When using 5 percent RAS, the effects of agglomeration were not seen. The effects of the agglomeration in the mix with 5 percent RAS were masked by the small sample size. The binder contribution was 95.8 percent when agglomerated and not agglomerated. From the above data, agglomeration and shingle particle size may be a large concern when particles and clumps are excessive in size.

Statistical Analysis for Agglomeration Binder Contribution

The final paired t-test was conducted to determine if the differences between the shingle agglomeration sizes was significant. The response values used for this analysis were the air void contents at the design binder content. The mix with 2.5 percent RAS response values were 4.3 percent for the non-agglomerated shingles and 4.8 percent for the agglomerated shingles. The mix with 5 percent RAS response values were 4.3 percent and 4.6 percent for the non-agglomerated and agglomerated shingles respectively. Table 41 shows the results of the t-tests.

Table 41: T-Test Results for Agglomerated Shingles

Effect	t calc	t crit	P-value	Significant Difference in Agglomeration?
RAS Size	4	6.3138	0.0780	Marginal

Table 41 shows marginal significant difference between the agglomerated RAS and non-agglomerated RAS (p=0.0780). There was a practical significant difference in air voids, but for this statistic the significance is masked by the small sample size (n=2). By using shingles that were agglomerated, the air voids were increased 0.5 percent in the mix with 2.5 percent RAS and 0.3 percent in the mix with 5 percent RAS. From the above data, the effects of agglomeration and shingle particle size may be a large concern to contractors.

Tear-Off Performance Data

This part of the analysis compares performance data of mixes with tear-off RAS. The first source of tear-offs showed a negative binder contribution at the optimum compaction and therefore, additional testing was negated. The second source of tear-offs was tested in ERSA to evaluate the rutting and stripping susceptibility and was compared to the mix containing manufacturing wastes. Figure 34 shows the ERSA output of each mixture.

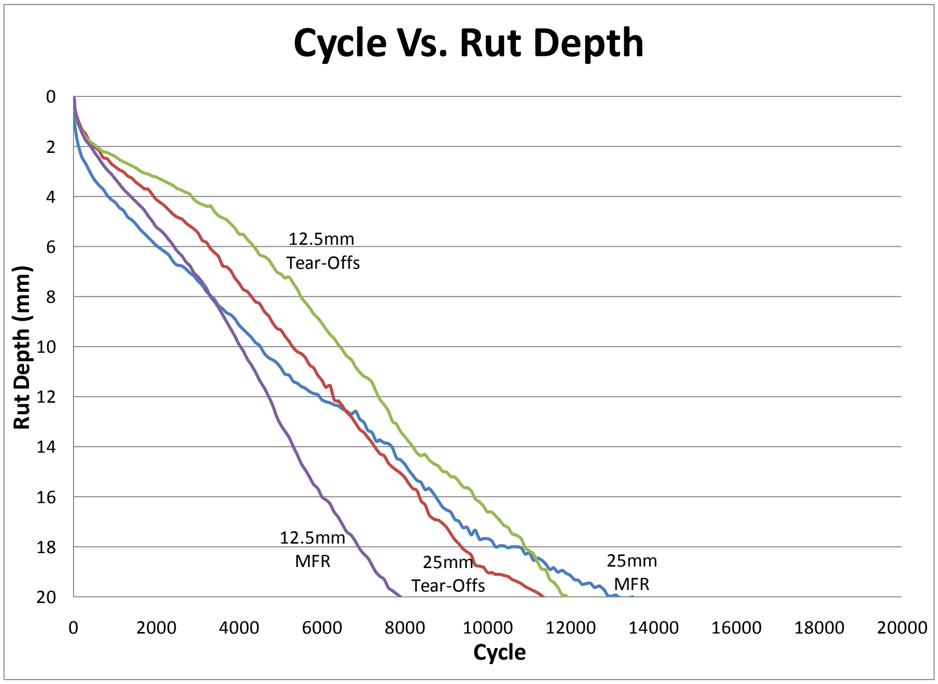


Figure 34: ERSA Results for Limestone Mixtures Containing 5 Percent Shingles

Figure 34 shows how replacing the manufacturing waste with tear-off shingles affects the pavement. The 12.5mm mixture had an increase in rutting resistance and appears to not have a practical significant difference in stripping susceptibility. The stiffness of the tear-off shingles contributed to the increased rutting resistance of the 12.5mm mix. The 25.0mm mixture appeared to behave the same whether the mixture had manufacturing wastes or tear-off shingles incorporated.

From the results of Analysis #5, the following conclusions can be made:

- Tear-off shingles do not appear to contribute binder nearly as well as the manufacturing wastes. This is a large concern for contractors in that the cost is proportional to the virgin optimum binder content. A given pavement with RAS will most likely be cheaper if the RAS is made up of manufacturing wastes rather than tear-off shingles.

- Tear-off shingles do not appear to adversely affect a pavement's performance. In the case of the 12.5mm mix, the pavement showed an increased rutting resistance and the life of the pavement increased from 8,000 cycles to 12,000 cycles. In some cases, the tear-off shingles are expected to absorb virgin binder and show a negative binder contribution. In the event that tear-off shingles are incorporated, the mixture is expected to perform equal or better to a similar mix containing manufacturing wastes shingles. Ultimately, however, the economic advantages may not be present.
- When using tear-off RAS sources, the effects of agglomeration did generate air void increases of practical significance. Thus, agglomeration is a valid concern and contractors should make every effort to prohibit RAS agglomeration. Field data would be beneficial in further establishing the effects of agglomeration.

Analysis #6-How sensitive were various mixture properties to changes in shingle content when warm mix technology was incorporated?

The final analysis incorporated a limited study of combining manufacturing wastes with warm mix technology. Research conducted at the University of Arkansas on warm mix technology yielded concerns relating to the rutting and stripping susceptibility (Porter 2011). If the stiffness of shingles were to aid the rutting resistance of a WMA mixture, the pavement community would benefit greatly. For this analysis, two 12.5mm NMAS mix designs were selected which were previously developed at the University of Arkansas. The first was a limestone mix with 70-22 grade binder. The second mix selected was a syenite mixture with grade 64-22 binder. Analysis #6 was conducted to compare the two mixtures using warm mix technology to two identical mixtures incorporating 5 percent manufacturing wastes shingles. The mix designs used for this project are summarized in Table 42.

Table 42: WMA Mix Designs Used for RAS Incorporation

	Syenite	Limestone
NMAS	**12.5mm**	**12.5mm**
Binder Grade	**PG 64-22**	**PG 70-22**
N_{des}	75	100
Job Mix Formula (%)		
¾" Syenite	50	
½" Syenite	25	
Industrial Sand	15	
Donna Fill	10	
¾" Sandstone		31
½" Limestone		22
Coarse Lime		15
Avoca Lime		12
Asphalt Grit		20
Blend Gradation		
% Passing		
1-1/2"	100	100
1"	100	100
¾"	100	100
½"	97	91
3/8"	89	75
No. 4	69	47
No. 8	48	28
No. 16	34	18
No. 30	25	12
No. 50	16	9
No. 100	10	7
No. 200	4.9	5.0
Binder Content (%)	4.9	5.6
Air Voids (%)	4.5	4.5
VMA (%)	14.8	14.6
VFA (%)	68.9	69.2
Gsb	2.596	2.523
Gse	2.618	2.596
G_{mm}	2.434	2.390
F/A	1.07	1.11
Pbe (%)	4.4	4.0
Gb	1.031	1.023
G_{mm} at N_{ini} (%)	87.4	84.1
Mixing Temp	232	245
Compaction Temp	245	255

Mixture Temperature and Additive:

A chemical additive named Evotherm 3G (formula J-1) was selected for this analysis. The additive was mixed into the binder which was heated until pourable (266°F). The Evotherm 3G was added to the binder at a rate of 0.5% by weight of the binder using a pipette. Then, the container of binder was placed on a heating element and an overhead drill press with paint paddle was used to stir the binder for 30 minutes. After stirring, the binder was cooled to room temperature and stored until needed. The treated binder was heated to the same temperature as the aggregates and used similarly to hot mix asphalt binder. The samples were aged in the oven for two hours before compacting.

Determination Binder Contribution:

The first step of this analysis was to produce the established mix designs with heated manufacturing shingles incorporated and the binder content reduced such that the air voids were 4.5 percent. The amount of binder contribution was determined according to AASHTO PP 53 and the virgin optimum binder content was found and compared to the control mixtures. The average values obtained for the virgin optimum binder contents with shingles are shown in Table 43.

Table 43: Average Values Obtained for Virgin Optimum Binder Content

		Average Values for Responses	
Mix Design	% RAS	Opt Binder	% Binder Contribution
PG 64-22 Syenite	0	4.9	
	5	5	45.28
PG 70-22 Limestone	0	5.6	
	5	4.6	97.21

Table 43 illustrates the effects of shingles when warm mix technology was incorporated in the mixtures. The syenite at 232 degrees showed no binder contribution, and in fact, the design virgin binder content increased from the original warm mix design. The limestone mix at 245 degrees showed a large binder contribution (97.21 percent). The mixing temperature appeared to be the critical factor for the binder contribution. 245 degrees appeared to be hot enough to activate and release the binder in the RAS, whereas 232 degrees did not.

Performance Data Using WMA:

The second part of this analysis compared performance data for the above mixes. The Syenite mix showed a slight increase in virgin optimum binder content when RAS was incorporated; however, testing was conducted to determine the possibility of RAS stiffening the mix. The mixes were tested in ERSA to evaluate the rutting and stripping susceptibility and were compared to the control mixes with and without Evotherm 3G. Figures 35 and 36 show the ERSA outputs for each of the mixes.

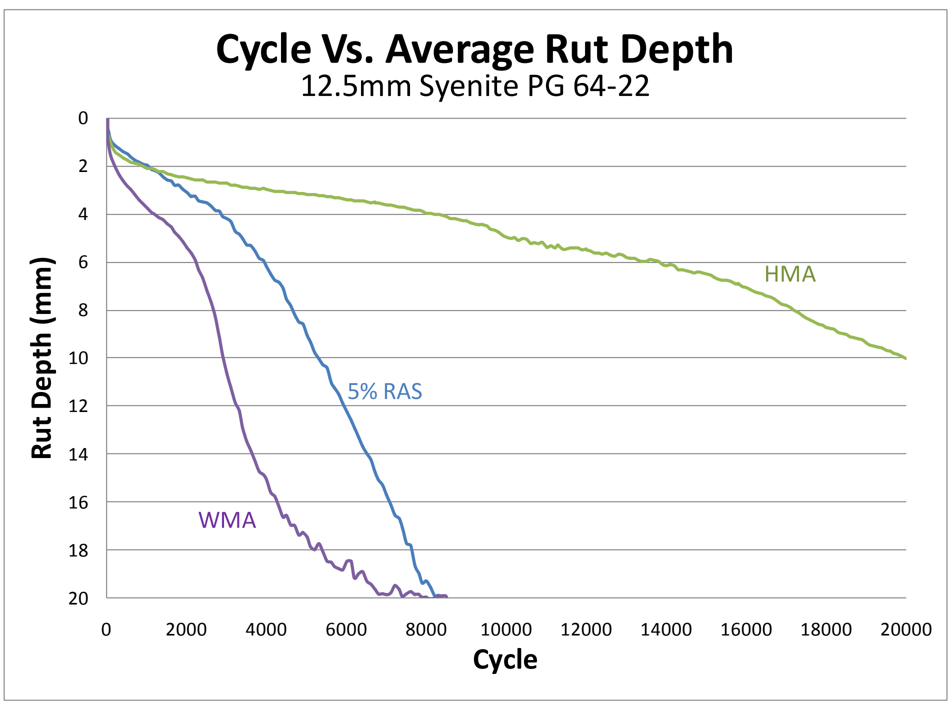


Figure 35: ERSA Results for Limestone Mixtures Containing 5 Percent Shingles

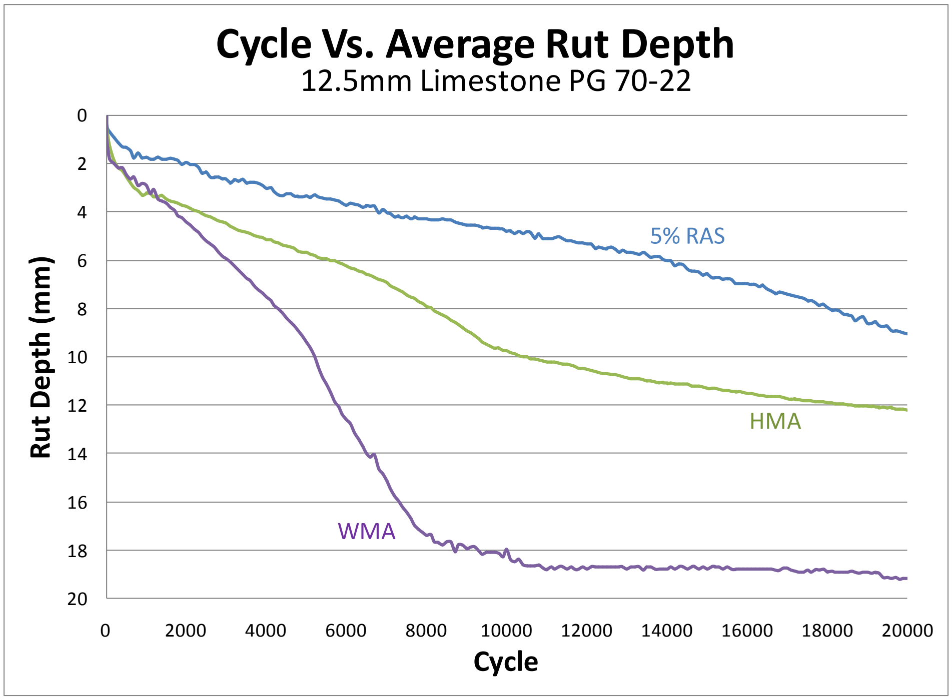


Figure 36: ERSA Results for Limestone Mixtures Containing 5 Percent Shingles

Figures 35 and 36 show how incorporating manufacturing RAS with WMA technology may significantly improve the pavement. The syenite mix did not show a large difference in the life of the pavement in ERSA (less than 8000 cycles) but the stripping slope was decreased from 116cyc/mm to 263cyc/mm. The limestone mix showed a very large difference in data when RAS was incorporated. When RAS was incorporated with WMA technology, the resulting mix performed much better than the HMA control mix. The resulting mix showed no signs of stripping and had a rutting slope of 3379cyc/mm. When WMA was used without RAS the rutting slope was 538cyc/mm with a stripping slope of 311cyc/mm. The HMA control mix showed a rutting slope of 1756cyc/mm.

From the results of Analysis #6, the following conclusions can be made:

- The extent to which RAS contributes binder to a mix may be dependent upon the Temperature. The RAS within the syenite mix at 232 degrees did not contribute binder to the mix but the limestone mix at 245 degrees saw a binder contribution of 97.21 percent.
- Incorporating RAS into approved mixes with WMA technology has shown to provide equal or better lab performance. In the ERSA samples tested, the syenite mix was seen to perform slightly better (rutting slope improved 147cyc/mm) and the limestone mix was seen to perform much better (rutting slope improved 2839cyc/mm). In the case of the limestone mix, the WMA/RAS combination outperformed the HMA control mix.
- The results of this limited testing warrant further laboratory studies of WMA and RAS combinations.

Conclusions and Recommendations:

This research found that the inclusion of RAS into pavements may yield cheaper pavements and better performance. The stiffness may be increased and the binder in the shingles will be released reducing the required virgin binder content. This translates as a savings to contractors and departments of transportation. This study found that the incorporation of 5 percent RAS into a mix will yield a savings between $1.75/ton and $6.60/ton with an average of $4.50/ton when using PG 64-22 binder. For the PG 70-22 binder, this study found savings between $2.55/ton and $10.65/ton with an average of $6.05/ton. This amount of savings can strengthen the infrastructure by freeing funds to produce more roads.

Pavements that are rutting/stripping susceptible may see enhanced performance when RAS is added. ERSA testing yielded the control mixtures to be positively affected in most cases when RAS was incorporated. The addition of a given amount of shingles affected each mixture differently but showed potential for performance similar to or better than the control mixture. The shingles' ability to enhance the performance of the asphalt may be dependent upon the source of shingles. The dynamic moduli measured in this study revealed the increase in performance at high temperatures to outweigh the potential for a decrease in performance at low temperatures. It is recommended that a mix design should be tested for rutting and stripping susceptibility before use in industry. Including RAS into these mixes will help guard against approving a mix that fails prematurely.

This study found the potential for RAS to be incorporated with WMA technology. One of the mixes had far better performance than the HMA control mix and WMA mix.

However, the ability of RAS to contribute binder to a mix may depend on the temperature. For projects incorporating WMA technology, the temperature should be closely monitored to ensure the RAS contributes appropriately.

Incorporating tear-off shingles into mixes showed similar performance to mixes incorporating manufacturing wastes however, the tear-offs did not contribute binder nearly as well as the manufacturing wastes. This means that a given pavement with RAS will most likely be cheaper using manufacturing wastes. The agglomeration and shingle particle size affected the binder contribution significantly in this study. In order to produce a consistent asphalt pavement, the agglomeration should be kept to a minimum and the shingle particle size should be consistently less than ¼ inch.

AASHTO PP53 and MP15 were used in this study to verify and characterize the mixes containing RAS. The only deviation from these documents was that this study added hot shingles to the asphalt mixes where AASHTO recommends adding the RAS at ambient temperatures, however; specimens were created and compared with shingles added at ambient temperatures and hot temperatures and found to be nearly identical.

The inclusion of RAS into asphalt pavements may exaggerate difficulties with certain mixture properties. For example, mixes with a low VMA may see a lower value when RAS in incorporated and mixes with a high may have a higher value when RAS is incorporated. Due to the exaggerated difficulties with certain mixture properties, it is imperative that appropriate QA/QC be maintained on jobs incorporating RAS. The shingle particle size and amount of agglomeration should also be monitored closely as this study found significant effects on the binder contribution.

For the reasons listed above, the following recommendations are made regarding the inclusion of RAS into asphalt pavements.

- Manufacturing waste RAS should be incorporated into mixes using PG 64-22 and PG 70-22 binders. This study showed the positive effects on the pavement performance and binder contribution. The binder contribution of the RAS reduces the costs of the pavement and frees funds that can aid the infrastructure.

- The use of RAS with WMA technology should be permitted where the RAS is manufacturing wastes. This study found the incorporation of RAS to enhance the performance of the mixes with the product Evotherm 3G. Additional research should be conducted on other WMA products to ensure that RAS improves the performance of all mixes with WMA technology.

- Incorporating tear-off shingles into mixes should be limited. Tear-offs exhibit excessive agglomeration which reduces the surface area of the shingles and hinders the ability to contribute binder.

- The maximum shingle grind size should be investigated more thoroughly. Data may suggest that the grind size be limited to ¼ inch in all mixes. This may allow for maximum binder contribution by having a large surface area. This may produce a consistent product where larger shingles may not produce a consistent binder contribution.

- Due to exacerbated difficulties with volumetric properties, the inclusion of RAS should be conservatively limited to 5 percent by weight of the mix. Also, if agglomeration and shingle grind size are not monitored closely, the binder contribution may not be consistent. This means that each lot of asphalt may differ in air voids producing a road that does not meet specifications. For a mix with 5 percent RAS, the change in air voids will be limited but when using more RAS, the change in air voids may be exaggerated.

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