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Effects of Residual Moisture and Zero Conditioning Time on Maximum Theoretical Specific Gravity

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ABSTRACT

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A critical issue in determining theoretical maximum specific gravity (G_{mm}) for Hot Mix Asphalt (HMA) mixtures appears when the aggregates used have high absorption. This high absorption in aggregates, like air cooled iron blast furnace slag, can greatly affect the G_{mm} values of the sample, which in turn affects the contractor's ability to accurately evaluate the volumetric properties of the asphalt concrete. WV Paving, the largest asphalt paving contractor in West Virginia, uses slag aggregates in many of their mixes. There is concern that the dry-back procedure used to determine G_{mm} of these mixtures is not producing reliable results. G_{mm} results from lab prepared mixes were observed to be different from plant prepared mixes. This is of concern to both the contractor and the West Virginia Division of Highways as G_{mm} is an important parameter in both mix design and quality control. Two hypotheses for the issue were identified that may affect the measured properties of the plant produced mixes; residual moisture and a short conditioning time. To test the effects of residual moisture samples of slag aggregate were saturated with water for a period of time then heated allowing some of the water to evaporate and then mixed with other aggregates and binder. Samples were also produced and tested without having the two hour conditioning time required in the AASHTO procedures. Findings indicated that a third of the residual moisture samples were significantly different from the control values, with seventy percent of those samples containing high slag contents. The conditioning time results showed that the lack of a conditioning period was significantly different than the controlled two hour conditioning at a 95% confidence level.

A related issue is a vacuum method for measuring G_{mm} has been developed and is in use by some contractors. The experimental design for this research compared the results of the standard test method to the vacuum method. There is a small, but consistent difference between the standard and vacuum methods. Further research should be conducted to see if a short conditioning time should be required for HMA mixtures containing highly absorptive aggregates.

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

In order to correctly evaluate asphalt concrete's volumetric properties the theoretical maximum specific gravity (G_{mm}) must be accurately measured. This has proven to be a problem when absorptive aggregates are used in a mixture. The dry-back procedure has been implemented for years in attempt to correct this issue; however this procedure is prone to errors. In more recent years a new device, the CoreLok, has been released as an alternative method for measuring specific gravity of asphalt mixes.

One of the significant problems with the use of certain aggregates is their absorptive properties. Once a sample of asphalt is mixed, the longer it conditions the more asphalt is absorbed into the aggregates until the voids are saturated with asphalt. This absorption greatly changes the G_{mm} value of the sample. This is then reflected in the values for air voids and makes it more difficult for a contractor to achieve their correct densities in the field while constructing a new pavement.

The need for improving specific gravity measurements is not unique to West Virginia. The FHWA (2010) reviewed methods for determining specific gravity and the associated impact on volumetric analysis of asphalt mixes. With respect to G_{mm} the FHWA report states:

> The current standard test methods for determination of G_{mm} for HMA mixtures containing aggregate with low absorption are satisfactory. However, the multilaboratory precision estimate for mixtures containing moderately to highly absorptive aggregate is so large that it is not valid to distinguish air voids results for split specimens conducted in two laboratories that differ by as much as 2.0 percent. Clearly, further work needs to be conducted to improve the reproducibility of the G_{mm} determination for such aggregate. Another important objective for further research should be to reduce the time to complete the test for mixes containing absorptive aggregate.

1.2 PROBLEM STATEMENT

The material issue evaluated in the research is from an asphalt plant in the southern part of West Virginia. West Virginia Paving, Dunbar, WV, has been having issues with theoretical maximum specific gravity test results between laboratory produced samples and samples taken from plant production. Plant produced samples have lower G_{mm} values compared to those created in the laboratory for mix design. Two main questions arose from discussions about this problem. Is there a small amount of water still inside the absorptive material after it exits the asphalt plant? In this case the water may evaporate out of the stone leaving small micro punctures in the asphalt coating. Second, plant samples are pulled straight from the plant and tested; is there sufficient time between mixing and testing to allow the asphalt to absorb into the voids of the slag?

In addition, a vacuum based procedure for measuring asphalt mix specific gravity has been developed and is being used by some contractors. This method uses the CoreLok system developed by Instrotek, Inc. The WVDOH has limited experience with the CoreLok method. To gain experience with this test method, samples were evaluated with the conventional (Rice) method, the CoreLok method and the dry-back process.

1.3 OBJECTIVE

The objectives for this research were all observed to aid in determining a quality answer for the theoretical maximum specific gravity. The three objectives are as followed:

- Is the Dry Back procedure necessary?
- Can the CoreLok replace the original Rice Test (AASHTO's T209)?
- Is there a difference between the plant and laboratory processes?

Null hypotheses were used to distinguish if there was any difference between the test methods and between the different sample variations described above.

1.4 ORGANIZATION OF THESIS

This thesis is organized into five chapters. Following the introduction, Chapter 2 contains background on the use of slag in hot mix asphalt pavements, brief history on the T209 and CoreLok test methods, and finally summaries of research conducted with the CoreLok. Chapter 3 discusses the research methodologies and test procedures that were used in the laboratory to conduct the research. Chapter 4 contains the analysis of the results from the laboratory findings. Finally in Chapter 5 conclusions and recommendations are presented. The Appendix includes the test results for each mixture.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

With the great quantities of waste products created each year there is a strong push to find better uses for them. The transportation sector has been a great recipient of these materials. Currently the Federal Highway Administration (FHWA) allows many different kinds of by-products to be used in the construction of asphalt pavements; the list below illustrates the wide span of materials.

Blast Furnace Slag	Nonferrous Slags
Coal Bottom Ash	Reclaimed Asphalt Pavement
Coal Boiler Slag	Roofing Shingle Scrap
Foundry Sand	Scrap Tires
Mineral Processing Wastes	Steel Slag
Municipal Solid Waste Combustor Ash	Waste Glass

While there are many allowable types of materials this research evaluated the use of Blast Furnace Slag, therefore the remaining materials will not be mentioned further in this report.

2.2 SLAG IN HMAC

Blast Furnace slag has become an important resource in many states for the use in road construction and rehabilitation. At least 17 states have adopted the use of blast furnace slag; several are located in the eastern United States. According to the US Geological Survey in 2006 nearly 41.3% of air-cooled blast furnace slag was used for road bases and surfaces, another 13.3% was used for asphaltic concrete (Van Oss, 2007).

Slag is a co-product of the production of iron and steel, along with other metals. For the production of iron and steel, iron ore, scrap iron and steel, fluxes (limestone and/or dolomite), and coke are placed in the blast furnace. The coke is then combusted to reduce the iron ore to a molten state. The slag which primarily consists of silicates, alumina-silicates, and calcium-alumina-silicates is less dense then iron therefore it floats on the molten iron and can be separated from the iron product and removed as a co-product. Although slag is less dense than iron slag’s density greatly depends on the residual iron content in the slag. Typical specific gravities range from 2.0 to 2.5 for air cooled slag (FHWA, 1997).

2.2.2 Different Types of Slag

Once the slag is formed in the blast furnace there are multiple ways to separate the slag, which creates different products. The main methods are Air-Cooling, Expanded or Formed, and Pelletized.

Air-cooled blast furnace slag (ACBFS) forms from the cooling of liquid slag that is poured into large beds and is allowed to cool slowly under normal conditions. This slow cooling allows the slag to form a hard crystalline structure. After the slag cools it is crushed into usable sized aggregates.

Expanded slag is cooled with the use of water, steam, or air. This process allows for an accelerated cooling which increases the size of the crystalline structure, leaving a lightweight product. Expanded slag has a much higher porosity and lower specific gravities if compared to air cooled slag.

Pelletized slag is formed when molten slag is quenched with water or air in a spinning drum. The process forms pellets which can be controlled by the speed of the quenching process. If the slag is rapidly cooled, less crystallization will occur and the slag will have a glassy appearance (FHWA, 1997).

Air-cooled blast furnace slag will be discussed from this point on since it was used for this experiment.

2.2.3 Benefits of ACBFS

The main benefits from the use of slag are some of its physical and mechanical properties. ACBFS is angular with a roughly cubical shape. ACBFS also has good frictional resistance, stripping resistance, and high stability. Slags high stability is due to its high internal angle of friction, which is 40 to 45 degrees. The rough, porous, angular surface and hardness (5 to 6) of slag all help contribute to a high frictional resistance. The slag used in West Virginia has been approved as a skid resistant aggregate suitable for use in wearing layers. Slag also has high polished stone values and an affinity to asphalt, not water, and therefore, slag has high stripping resistance (FHWA, 1997).

2.2.4 Drawbacks of ACBFS

The two main flaws with the use of slag is its high absorption from its porous surface, and the high variability in the material. The FHWA states that since there is variation in the production process of iron that variability continues into the slag, resulting in inconsistent results for gradations, specific gravities, absorptions, and angularity. This lack of consistency contributes to HMAC performance problems, like flushing, raveling, and high fines. Flushing is related to high binder content and raveling is related to low binder content which could be from the inconsistency in the absorption of ACBFS. Absorption is the other main drawback with slag. A high absorption requires more asphalt to be added to the mixture, which adds cost to the mixture. The FHWA says that this cost is usually offset by the high yield from using a slag mixture. The high yield is due to the lower density of the slag, therefore more volume for the same amount of weight (FHWA, 1997).

2.3 TEST METHODS

2.3.1 CoreLok

The CoreLok was developed by InstroTek Inc. located in Raleigh, North Carolina and was released in the late 1990's. InstroTek developed this vacuum sealing device to address the limitations of the previous test methods. The CoreLok is not only used for testing specific gravities for asphalt samples, it can test a wide variety of samples. This includes apparent specific gravity, absorption, and bulk specific gravity of aggregates using the AggPlus system. The CoreLok can also test for porosity of compacted asphalt samples and can be used to determine the percentage of asphalt in a mixture. Figure 1 illustrates the CoreLok and the additional AggPlus System (InstroTekCorelok Aggregate, 2011).

The basic procedure for using the machine is: the sample is weighed and placed in a sample or channel bag, for a G_{mm} sample ASTM requires at least 1500 grams be used. The sample size does not change with the nominal maximum aggregate size like AASHTO's T209. The sample and bag are then placed inside of a larger plastic bag and everything is placed into the CoreLok chamber, shown in Figure 2, 3, and 4. The vacuum is then applied, which is approximately 30 in. Hg (InstroTekCorelok Operations, 2011).

Figure 1 - The CoreLok Vacuum Machine with the Agg. Plus Device

Figure 2 - CoreLok Procedure Step A: 1500 g placed in the channel bag.

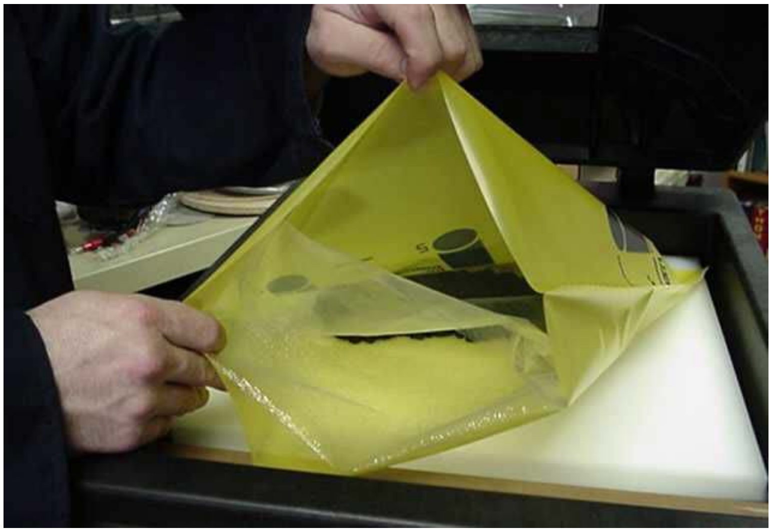

Figure 3 - CoreLok Procedure Step B: Channel bag placed inside larger bag.

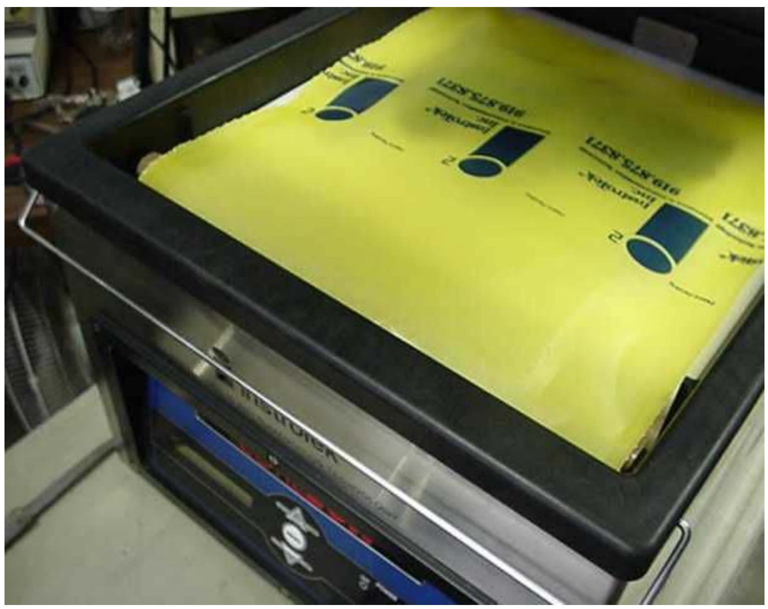

Figure 4 - CoreLok Procedure Step C: Both bags and sample are placed in the CoreLok, the lid is closed. After the vacuum and sealing processes are completed the bags can be removed.

After the vacuum is drawn it is maintained for a predetermined dwelling time depending on the type of sample tested. For a G_{mm} sample the dwelling time is five minutes. Following the dwelling time, the outer bag is sealed and the vacuum is released. The bag is removed from the chamber and transferred to a water bath, then depending on the test being performed the bag is cut open and water is allowed to saturate the sample.

Weights are recorded and used to calculate the desired value. InstroTek provides data sheets for individual tests along with a computer program that will return the desired value; Figure 5 is the data sheet for the G_{mm} procedure. There are other equipment and extra procedures if doing tests with the AggPlus system.

For the experiment presented herein, only G_{mm} samples were tested. For a G_{mm} sample the weights needed for the calculation are the dry weight, the weight of the bags (channel and large), and the weight submerged under water. The formula for calculating the G_{mm} value is (InstroTek, 2011):

$$G_{mm} = \frac{B}{(A + B - C) - (A/V_C)}$$

Where:
A=Bag weight
B = Weight of Sample in Air
C = Submerged Weight of Sample in Water
V_C = Density of Bags = 0.903 g/cm^3

InstroTek claims that when testing maximum specific gravity there is no need for the dry-back method because of the limited amount of time the sample is exposed to water. Also InstroTek designed the CoreLok so there was no need to vibrate the sample as it was drawing a vacuum; they say this vibrating will potentially strip the asphalt from the rocks.

2.3.2 Rice Method and Additional Dry-Back Procedures

The Rice method, AASHTO T 209, was developed by James Rice in 1964. This procedure is used to determine the theoretical maximum specific gravity of an uncompact asphalt sample, which resembles the specific gravity of the mix if compacted so it contained no air voids. In the early 1990’s an improved Rice method was developed and an additional dry-back procedure was added for highly absorbent aggregates. The full description of the procedure is found in the AASHTO’s Standard Specifications for Transportation Materials, Part 2A: Tests, T-209.

CoreLok™ Max/Apparent Gravity Data Collection Table

Sample #	A Bag Weight (grams)	B Weight of Rubber Sheets (grams) (put in 0 if not used)	C Weight of Sample in air (grams)	D Weight of Bags and Sample in Water (grams)	E (A+B+C) – D Total Volume	F A/Vc +B/Rc Bag and rubber sheet Volume	G E-F Sample Volume	H C/G Density

R_C = ______ g/cm3 (value written on rubber sheets)
V_C = 0.903 g/cm^3

Important

- Do not squeeze down on the bags, when spreading the sample.
- Before using the large bag, inspect the bag for holes or stress points. Do not use damaged bags.
- Use a large water tank for conducting this test.
- Use all three white filler plates.
- Remove the sliding plate.
- Place rough side of the channeled bag down inside the external bag.
- Immediately place the sealed sample in the water tank.
- To stop the possibility of air from getting into the bag, cut 1" (25mm) of the bag while at least 2" (50mm) under the water.
- Hold the bags open for 15 seconds to allow water to get in
- If you see a massive amount of bubbles (Like boiling water) coming out of the bag, repeat the test.
- While under water, place the sample in the weighing basket
- Use the alligator clip to keep the cut portion of the bag from floating out of water.
- Make sure the bag is not floating out of the water or touching the sides and bottom of the water tank.
- Use the rubber sheet if the material consistently punctures bags.

Figure 5 - Data Chart for CoreLok G_{mm} Test

The basic concept behind these procedures is to find the volume of the sample with no air voids. The sample is first weighed dry, and then transferred to the “bucket” where water is added to cover the sample completely. At this point a vacuum is applied to the sample under the water to rid the sample of air. The sample is then weighed under water to acquire the volume of the sample. If the sample is contains absorbent aggregates the additional dry-back procedure is required, which takes between one to two hours. This additional procedure establishes the saturated surface dry weight, which is needed in the calculation:

$$G_{mm} = \frac{A}{(B + D - E)}$$

Where:
A= Oven Dry Weight
B = Saturated Surface Dry Weight
D = Weight of Container in Water
E = Weight of Container + Sample in Water.

2.4 G_{MM} INVESTIGATIONS USING THE CORELOK

Several studies have investigated the use of the CoreLok to measure the bulk specific gravity of asphalt concrete. However, only two studies were found that investigated the use of the CoreLok for measuring the maximum theoretical specific gravity.

2.4.1 Florida DOT

The Florida Department of Transportation evaluated the CoreLok method for determining the bulk and maximum theoretical specific gravity of asphalt mixes and the bulk specific gravity of aggregates (Sholar et al., 2003). Only the G_{mm} research is reviewed herein. Results using the CoreLok method were compared to results obtained with the FDOT test procedure FM 1-T 209, similar to AASHTO T209. The test set-up for FM 1-T-209, as shown on Figure 6, requires the weigh in air method and two specimens are required for each test result. In addition, FM 1-T-209 requires measuring the saturated surface dry mass of the sample using the dry-back process. An interesting note in the test method is that in the event that final surface dry mass of the specimen is less than the original mass of the dry specimen, then the original dry mass is used in lieu of the saturated surface dry mass for the calculation of G_{mm}. Sholar et al. noted that the dry weight is less than the saturated surface dry weight when the amount of material lost during the test is greater than the amount of water in the voids of the sample. This was an issue with the RAP mixes as a high percent of the RAP was uncoated and fines were lost when the water was drained from the sample.

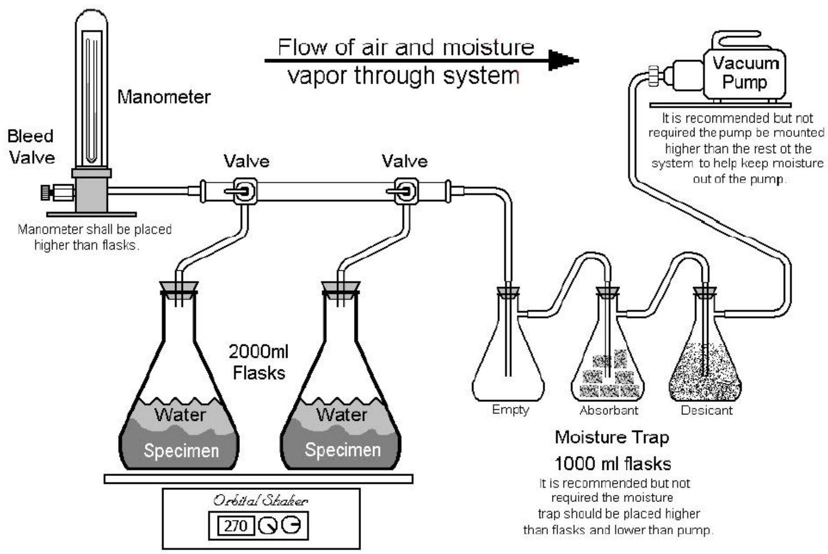

Figure 6- Test set up for FDOT test method FM 1-T209

Sholar et al. studied six different mixes with varying degrees of absorption, aggregate size, and material type. Ten replicate samples were tested for each material and test method. No slag was used in their experiment, but a highly absorptive limestone was used.

Table 1 presents the statistical analysis results of the FDOT study. Sholar et al. noted that the CoreLok G_{mm} values were greater than the conventional results for all six sample types. The hypothesis of equal means was not rejected for the sample with the lowest absorption, G-1. The hypothesis of equal means was also not rejected for the RAP sample with percent water absorption of 1 to 2 percent. However, the p-value was 0.09, indicating that if the confidence level for the statistical test was 90 percent rather than 95 percent, then the hypothesis of equal means would be rejected. Similarly, the t-test for limestone sample 2, LS-2, did not reject the hypothesis of equal means for a confidence level of 95 percent, but the p-value indicates the hypothesis would be rejected for a confidence level of less than 94 percent. The p-value for the highly absorptive aggregate, LS-4, indicates that there is virtually no chance that the results from the conventional and CoreLok methods are from the same population. The net conclusion was that the conventional and CoreLok methods produce different results for asphalt concrete made with moderate and highly absorptive aggregates.

Sholar et al. (2003) also compared the data they collected without using the dry-back procedures and found only one mixture showed significant difference from the CoreLok test method. They concluded that using the CoreLok with high absorptive aggregates results in higher G_{mm} values which would result in higher computed air voids in the mix. The reason for this was explained as the lack of a dry-back method with the CoreLok.

Table 1– FDOT t-test Results for G_{mm} Test Data for the CoreLok and FM 1-T 209

	Mixture Designation					
	G-1	LS-1	LS-2	LS-3	LS-4	RAP
t-statistic	0.54	4.32	2.01	2.52	23.86	1.80
t-critical	2.10	2.10	2.10	2.10	2.10	2.11
Significantly Different?	No	Yes	No	Yes	Yes	No
p-value	0.59	4.12E-04	0.06	0.02	4.47E-15	0.09
Percent water absorption	<1	2 to 3	2 to 3	2 to 3	5 to 6	1 to 2
Difference*	0.001	0.011	0.002	0.004	0.033	0.002

* CoreLok - Conventional

2.4.2 University of Cincinnati

Rajagopal and Crago (2007) evaluated the CoreLok relative to AASHTO test methods for both the bulk and maximum theoretical specific gravity. Only the G_{mm} results are reviewed in the following. The experimental design included a range of mix types and aggregate sources, including four mixes with slag aggregate, resulting in 33 samples. Although not explicitly stated, the paired t-test analysis method used to evaluate the data suggests that each sample was tested with both the AASHTO and CoreLok methods. The test results are presented in Table 2. The mean G_{mm} values for the test methods are equal with a value of 2.444. As would be expected the t-test did not identify a significant difference between the two methods. A regression analysis found a strong correlation between the two methods, with an r value of 0.53. However, the slope of the regression was 0.92 which indicates the results from the CoreLok are lower than T-209 for low G_{mm} values and vice versa for high G_{mm} values.

Table 2 - Comparison Data for AASHTO T-209 and CoreLok (Rajagopal and Crago 2007)

Mix type	AASHTO T-209	CoreLok
Dense Grade Heavy Gravel	2.447	2.393
Dense Grade Heavy Lime Stone	2.443	2.455
Dense Grade Heavy Gravel	2.445	2.443
Dense Grade Heavy Lime Stone	2.500	2.529
Dense Grade Heavy Gravel	2.422	2.410
Dense Grade Heavy Lime Stone	2.504	2.530
Dense Grade Heavy Lime Stone	2.486	2.461
Dense Grade Medium Gravel	2.447	2.446
Dense Grade Medium Lime Stone	2.491	2.508
Dense Grade Medium Gravel	2.466	2.459
Dense Grade Medium Lime Stone	2.450	2.457
Superpave Medium Slag	2.351	2.308
Superpave Medium Lime Stone	2.457	2.321
Superpave Medium Slag	2.379	2.409
Superpave Medium Lime Stone	2.475	2.478
Superpave Medium Slag	2.354	2.389
Superpave Medium Lime Stone	2.468	2.483
Superpave Heavy Lime Stone	2.465	2.511
Superpave Heavy Slag	2.437	2.410
Superpave Heavy Lime Stone	2.512	2.509
Superpave Heavy Slag	2.411	2.379
Superpave Heavy Lime Stone	2.462	2.457
SMA Heavy Lime Stone	2.452	2.451
SMA Heavy Lime Stone	2.360	2.442
SMA Heavy Lime Stone	2.384	2.387
SMA Heavy Lime Stone	2.427	2.398
302 Heavy Gravel	2.511	2.460
302 Medium Gravel	2.475	2.481
302 Medium Lime	2.498	2.561
302 Medium Slag	2.444	2.483
SMA Heavy Lime Stone	2.400	2.419
SMA Heavy Lime Stone	2.408	2.404
SMA Heavy Gravel	2.429	2.427
Averages	2.444	2.444

CHAPTER 3 RESEARCH METHODOLOGY

3.1 INTRODUCTION

The experimental plan was designed to evaluate differences in maximum theoretical specific gravity between lab produced and plant produced mixes with a blend of slag and limestone aggregates. Maximum theoretical gravity was measured using the conventional (Rice), dry-back, and CoreLok methods. The materials for this experiment were provided by West Virginia Paving. The asphalt cement was a PG 64-22. The three types of stones were limestone sand, a No. 8 slag, and a No. 8 limestone.

3.2 EXPERIMENTAL DESIGN

The factors and levels for the experiment are shown in Table 3. Three levels of slag content were used as increasing the slag content should increase the chance for residual moisture. The Superpave mix design method, using 80 gyrations for N_{design}, was used to establish the design binder content for each blend. Samples were prepared at the design binder content and at the design binder content plus 0.5 percent. The higher binder content was included in the experiment to test if better sealing of the voids in the slag, due to a greater binder film thickness, would alter the volumetric properties of the mix. One of the issues when comparing lab prepared mixes versus plant mixes is the potential for residual moisture on the aggregates of the plant mixture. An attempt was made to simulate this by saturating the aggregates and then only allowing them to dry until the target residual moisture content remained before blending the mix. Another issue for this comparison is the lack of a conditioning time for the plant samples; therefore two conditioning times were tested. Table 4 shows the data summary sheet.

Table 3 - Experimental Factors/Levels

Slag Content	12%, 27%, 42%
Asphalt Content	Design(dependent on the Mix), Design +0.5%
Moisture Content	0%MC, 2%MC
Conditioning Time	Design(2 hours), Zero conditioning time
Test Method	Rice, Rice with additional Dry-Back, CoreLok

Table 4 - Data Table

% Asphalt	Test Method	Trial	Gmm					
			% slag					
			12%		27%		42%	
			% Moisture					
			0	2	0	2	0	2
0.50%	CoreLok	1						
		2						
	Rice	1						
		2						
	Dry-Back	1						
		2						
Design	CoreLok	1						
		2						
	Rice	1						
		2						
	Dry-Back	1						
		2						
Zero Condition Time	CoreLok	1						
		2						
	Rice	1						
		2						
	Dry-Back	1						
		2						

3.3 MATERIAL

3.3.1 Asphalt Cement

The asphalt binder used was supplied by WV Paving. The binder is a performance grade, (PG) 64-22, sourced from Shelly Liquid Division located in Gallipolis, Ohio. This batch of binder had a mixing temperature range of 152 to 165°C and a compaction temperature of 140 to 146°C. The binder had a specific gravity of 1.021.

3.3.2 Aggregate Properties

Three aggregates were used for the entire project; they were limestone sand (L/S sand), a No. 8 limestone (L/S), and a No. 8 slag stone. All the aggregates were gathered from the Dunbar, WV plant owned by West Virginia Paving. Table 5shows the producer, the bulk specific gravity (G_{sb}), and the apparent specific gravity (G_{sa}) of each aggregate. The slag was an air cooled blast furnace steel slag.

Table 5 - Aggregate Properties

Material	**Producer**	**Location**	G_{sb}	G_{sa}
L/S Sand	Mulzer	Cape Sandy	2.619	2.736
L/S #8	Carmeuse	Maysville	2.643	2.735
Slag #8	Mountain	Greenup	2.553	2.664

3.3.3 Aggregate Preparation

The aggregates were air dried. Three samples of each aggregate type were randomly sampled for a washed gradation analysis. The gradations for each aggregate are shown in Table 6. The remaining materials was washed to remove the mineral filler, dried, sieved and each size-type combination was stored in a separate bin. Bag house fines were used in the mixtures as a substitute for the mineral filler lost when washing.

Table 6 – Aggregate Gradations

Sieve Size (US)	Sieve Size (mm)	#8 LS	#8 Slag	LS Sand
1	25	100.0	100.0	100.0
3/4	19	100.0	100.0	100.0
1/2	12.5	100.0	100.0	100.0
3/8	9.5	88.3	90.5	100.00
#4	4.75	26.1	32.0	95.88
#8	2.36	8.3	14.7	73.80
#16	1.18	5.2	11.0	48.28
#30	0.6	4.2	8.0	31.70
#50	0.3	3.5	5.5	19.61
#200	0.075	2.9	3.5	7.41

3.4 MIX DESIGN

For the experiment, three mix designs were completed each with increasing amounts of slag. Each mix was designed according to AASHTO specifications. G_{mb} samples were made and tested and the design binder content was selected for each mixture. The binder content for each mix was 6.2% for low slag, 6.5% for medium slag, and 7.0% for high slag content.

3.4.1 Aggregate Blends

The lower slag content mixture, 12 percent slag, represents a mix with less slag than used in production. The medium or 27 percent slag mix resembles a normal slag content production mix, and the higher 42 percent slag mixture resembles an extreme case where slag is the abundant material used. All three mixtures were 9.5 mm mixes and meet the gradation requirements, Table 7, for a Superpave mix design. Also listed in Table 7 are the combined gradations of each mixture along with the combined specific gravities. These mixes meet the Superpave definition of coarse mixes since the percent material passing the No. 8 (2.36mm) sieve is less than the criteria of 47 percent. Mixtures 1, 2, and 3 are low slag, medium slag, and high slag content respectively. The combined gradations of the three mixtures are shown on Figure 7. Care was taken to eliminate the factor of gradation in this experiment. The gradations are relatively the same with the largest difference being 2 percent. This difference is between mix 1 and 3 on the No. 8 (2.36mm) sieve.

When designing the blends, the slag content was increased in equal amounts of 15 percent to keep changes consistent. The percent of the limestone sand not changed between the mixtures. The amount of No. 8 limestone was decreased in proportion to the change in the change in the slag content. The resulting blends were:

Mix 1: 43% L/S No. 8, 12% Slag No. 8, and 45% L/S sand

Mix 2: 28% L/S No. 8, 27% Slag No. 8, and 45% L/S sand

Mix 3: 13% L/S No. 8, 42% Slag No. 8, and 45% L/S sand

Table 7 - Combined Mixture Gradations & Properties

		Percent Passing			Control Points	
Sieve Size (US)	Sieve Size (mm)	Mix 1	Mix 2	Mix 3	Lower	Upper
1/2	12.5	100.0	100.0	100.0	100	
3/8	9.5	93.8	94.2	94.5	90	100
4	4.75	58.2	59.1	60.0	-	90
8	2.36	38.5	39.5	40.5	32	67
16	1.18	25.3	26.2	27.0	-	-
30	0.6	17.0	17.6	18.2	-	-
50	0.3	11.0	11.3	11.6	-	-
200	0.075	5.0	5.1	5.2	2	10
	G_{sb}	2.621	2.607	2.594		
	G_{sa}	2.727	2.716	2.705		

3.5 SAMPLE CREATION

Aggregate samples were weighed out according to a weigh table created for each mix. A sample of this table is show in Table 8.The aggregates were dried in the oven overnight prior to weighing to ensure there was no moisture in any of the stone. Once the sample was weighed, the trays along with a container of bag house fines, were placed in the oven the night prior to mixing and left at the mixing temperature. Also, the night before the bucket, paddle, binder, and tools were placed in a second oven with a timer to start so that everything was at the mix temperature prior to blending.

Once everything was at the correct mixing temperature, the aggregate was added to the mixing bucket. A crater was made in the aggregates for the asphalt binder. The required amount of binder was weighed into the aggregates. The sample was then mixed with a bucket mixer to ensure adequate coating of all the aggregates. After mixing, the samples were placed in the oven at compaction temperature for two hours with stirring after one hour. After conditioning, the sample was emptied from the pans onto a stainless steel table, spread out and allowed to cool. This procedure is for the basic mixtures, there were modifications to this procedure for the two conditioning scenarios in the experiment. These modifications are explained in the following sections.

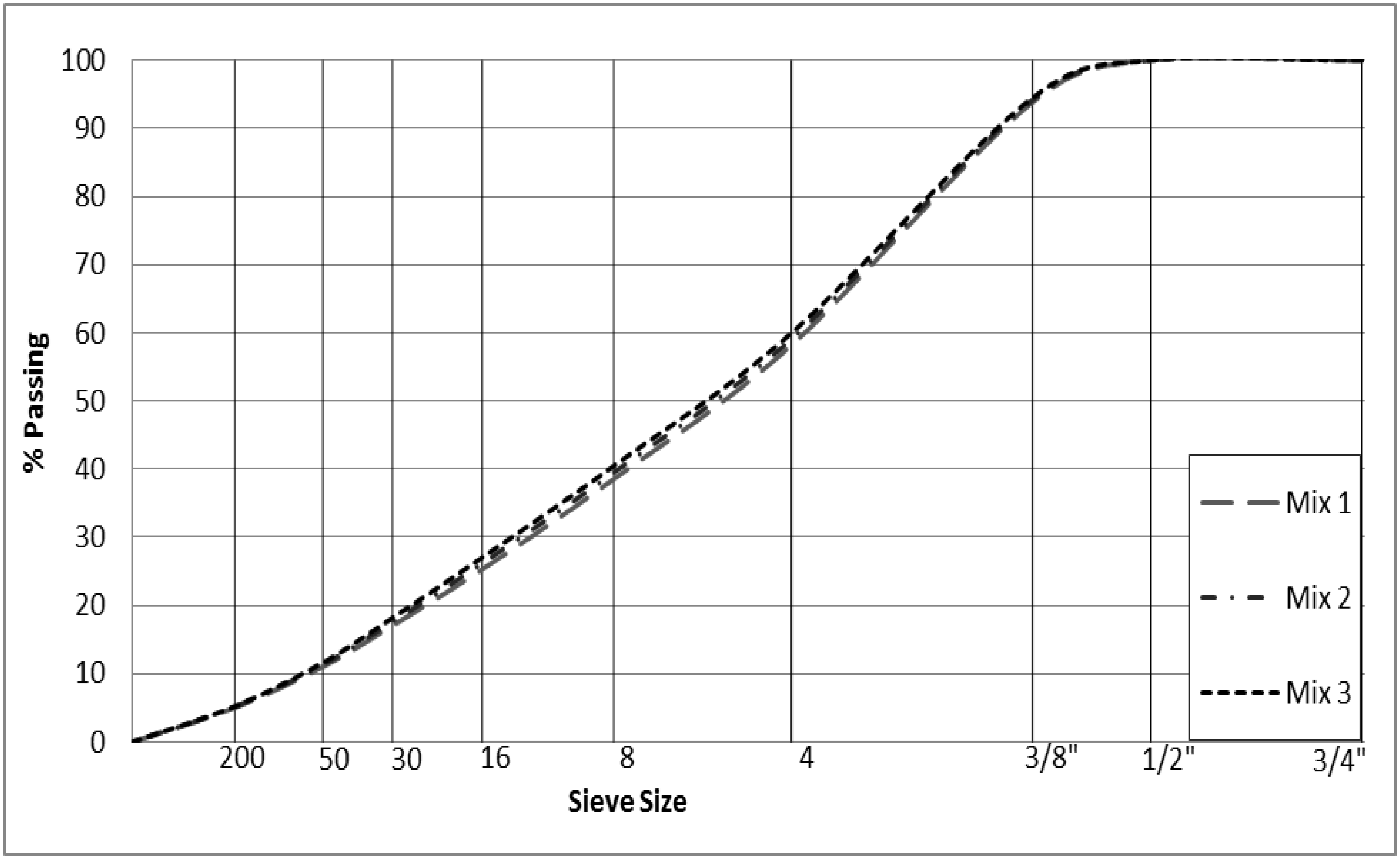

Figure 7 - Combined Mixture Gradations

Table 8–Example Aggregate Weigh-out Table

Design AC

13-42-45 +0.0% MC

	0	Gmb	2	Gmm			P_b Total	**7.00%**	
	-	g	1,515.0	g	Total Sample Weight			3,030.0	g
	Percent Stone P_s		93.0%		% Virgin Binder			7.0%	
	Weight of Stone W_s		2,817.9	g	Weight of Binder W_b			**212.1**	g
	Stockpile	L/S #8	g	Stockpile	Slag #8	g	Stockpile	L/S Man	g
	Blend	13.0%	366.3	Blend	42.0%	1183.5	Blend	45.0%	1268.1
Sieve Size	% Passing	% Retained	Weight	% Passing	% Retained	Weight	% Passing	% Retained	Weight
25	100.0	0.0	**0.0**	100.0	0.0	**0.0**	100.0	0.0	**0.0**
19	100.0	0.0	**0.0**	100.0	0.0	**0.0**	100.0	0.0	**0.0**
12.5	100.0	0.0	**0.0**	100.0	0.0	**0.0**	100.0	0.0	**0.0**
9.5	88.3	11.7	**42.9**	90.5	9.5	**112.4**	100.00	0.0	**0.0**
4.75	26.1	62.2	**227.9**	32.0	58.5	**692.3**	95.88	4.1	**52.2**
2.36	8.3	17.8	**65.2**	15	17.0	**201.2**	73.80	22.1	**280.0**
1.18	5.2	3.0	**11.2**	12	3.0	**35.5**	48.28	25.5	**323.6**
0.06	4.2	1.0	**3.8**	10.5	1.5	**17.8**	31.70	16.6	**210.3**
0.03	3.5	0.6	**2.4**	8	2.5	**29.6**	19.61	12.1	**153.2**
0.075	2.9	0.6	**2.3**	3	5.0	**59.2**	7.41	12.2	**154.8**
Pan	0.0	2.9	**10.7**	0.0	3.0	**35.5**	0.00	7.4	**93.9**
Total		100.0	**366.4**		100.0	**1183.5**		100.0	**1268.0**

3.5.1 Additional Procedures for Water Addition

The main conditioning scenario for this experiment involves the remnants of water inside the slag aggregate when it is in the mixture. After mixing, the water in the slag begins to evaporate and the water vapor may pierce the asphalt coating, which can create small voids for water to get in during the testing process. For the samples that include residual water in the aggregates the procedure was modified to include: saturation, drying, and mixing.

3.5.1.1 Saturation

During the weigh out procedure the slag was separated at the No. 8 sieve. The material that was retained above the No. 8 sieve was the only material that was saturated with water. The finer material was added to the mixture completely dry. This was done because in a blast furnace the finer material would be able to heat up faster than the larger material, therefore the moisture is most likely able to evaporate quicker. This was also done so that finer material would not be lost when excess water was emptied from the tray.

The material retained on the No. 8 sieve was saturated by placing it in a container, covering with water, and vibrating while a vacuum was applied. The vacuum was set to 55 ± 2.5 mmHg. The sample was subjected to the vacuum for 30 minutes and then submerged under water for an additional 24 ± 1 hour. The quantity of aggregate for the high, 42 percent, slag mix was too large to fit in the container, so it was split in half and each half underwent the vacuum process one after the other and then were submerged together for the 24 hour period.

3.5.1.2 Drying

The following morning the sample was drained of the excess water. This was done over a No. 200 sieve to avoid the loss of material. Afterwards the sample was placed in the oven to heat up and dry to the desired moisture content. The saturated aggregate was placed in a separate oven from the other materials and bucket. This was done to limit the heat loss of the other material from opening the oven door to many times. After the slag had been in the oven for a short time, the weight was taken to see if it had reached the weight needed for the required two percent moisture content. This two percent moisture is based on the entire weight of the slag portion of the mixture. For example if there was 1000 grams of slag in the mix, 20 grams of water was required to be retained in the material retained above the No. 8 (2.36mm) sieve. The slag was stirred multiple times during the drying process to resemble what happens to the rocks when they go through the plant dryer.

3.5.1.3 Mixing

Once the slag had reached the required 2% moisture content it was removed from the oven and placed in the bucket that was already at the correct mixing temperature. To avoid further moisture loss, the slag was always placed in the bucket first and quickly followed by the sand, dust, and limestone. After all the materials were in the bucket it was weighed and recorded. Then the sample was weighed again after mixing was completed to see how much water had evaporated during the mixing process.

3.5.1 Additional Procedures for Zero Conditioning Time

The other main conditioning scenario investigated was zero conditioning time. When a sample is taken from the plant it is immediately brought to the lab and tested. Since this occurs, a shorter conditioning time for lab created samples was examined. Zero conditioning time was chosen to show the extreme case of the lack of conditioning in plant produced samples. The only change to the procedure was that the sample was taken straight from the mixing bucket and spread out on the stainless steel table top. The samples that had an addition of water to the mix followed the same mixing procedures that were listed in the above section, but the two hour conditioning time was again eliminated.

3.6 SAMPLE TESTING

After the samples were mixed and conditioned (if required) they were spread on the table for cooling. While still lukewarm and pliable, the samples were broken apart into small pieces and stirred to make sure no large clumps formed. The sample was stirred again after a few minutes and then allowed to cool to near room temperature.

Once the sample cooled, it was gathered into a pile and split into quarters, as per the AASHTO T-268's sampling method. The entire sample consisted of two test samples. Each of these test samples were originally set to weigh 1515 grams. The required sample size for a Rice test is at least 1500 grams for a 9.5 mm mix, and the CoreLok has a maximum sample size of 2000 grams. Each sample was then tested with each test method. The data collected during the dry-back procedure was used for the conventional Rice method, simply ignoring the weight recorded after the additional dry-back.

3.6.1 Test Methods

Three test methods were used for this investigation: the conventional AASHTO T-209 Rice method, the T-209 with additional Dry-Back procedure, and the CoreLok. Each test was completed using the procedures listed in the respective manuals; are described in Chapter 2. In order to complete the two test samples for the dry-back procedure, a drying rack was fabricated that held two No. 30 sieves held at an angle for each material. A fan was then placed behind each of the sieves and blew air up through the bottom of the sieves. Figure 8 shows the drying rack.

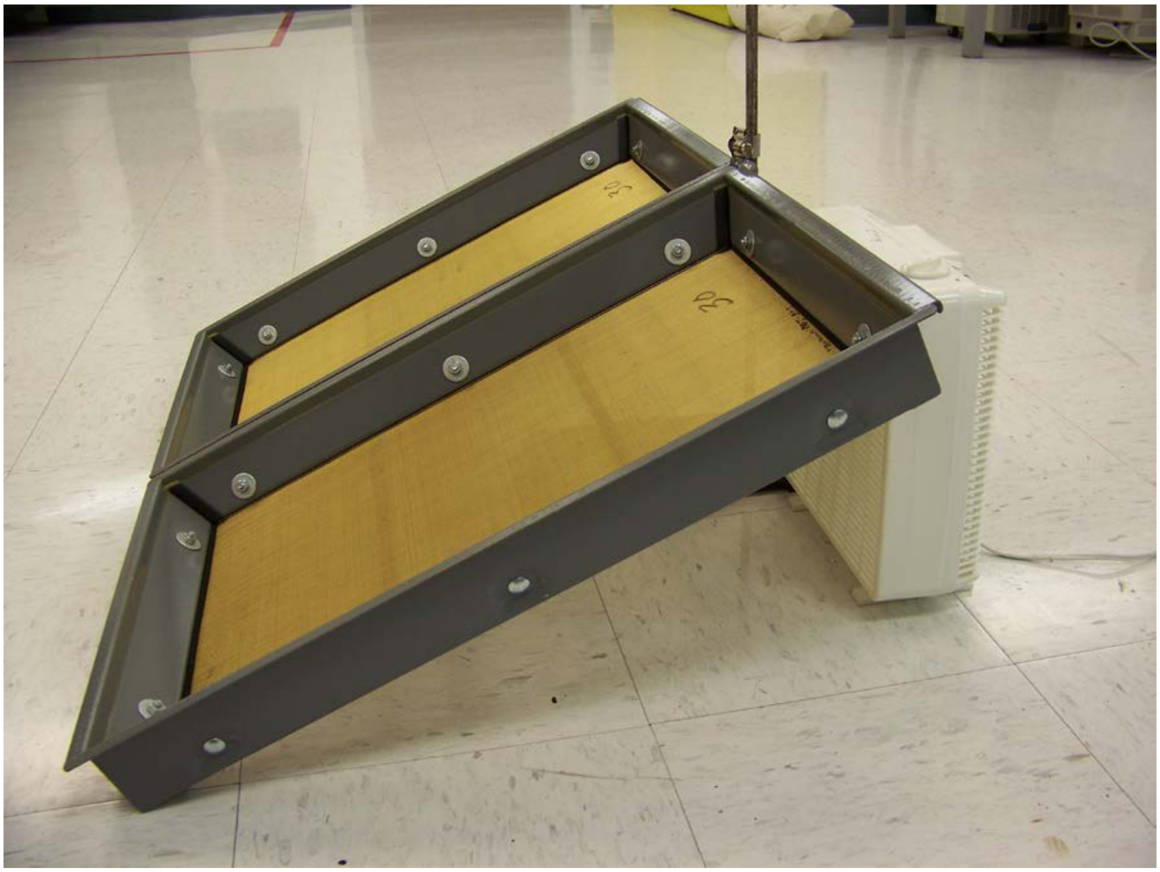

Figure 8 - Drying Rack

CHAPTER 4 RESULTS AND ANALYSIS

4.1 INTRODUCTION

A total of 18 mixes were tested for determining maximum theoretical specific gravity use CoreLok, and AASHTO's T-209 method with and without the dry-back procedures. The factors and levels of the experiment are shown in Table 9. Two samples were made and used for each testing device, totaling 36 samples and 108 tests. Each group of results was given an acronym to describe its mixture properties and test procedure, as defined in Table 10. For example LPCM means **L**ow slag content (12 percent), **P**lus an additional half percent asphalt, and **C**oreLok test method, and two percent **M**oisture.

Table 9 - Experimental Factors and Levels

		% Slag					
		12%		27%		42%	
%Asphalt Conditioning	Test Method	% Moisture					
		0	2	0	2	0	2
+0.50% 2 hr	CoreLok	LPC	LPCM	MPC	MPCM	HPC	HPCM
	RICE	LPR	LPRM	MPR	MPRM	HPR	HPRM
	Dry-Back	LPD	LPDM	MPD	MPDM	HPD	HPDM
Design 2 hr	CoreLok	LDC	LDCM	MDC	MDCM	HDC	HDCM
	RICE	LDR	LDRM	MDR	MDRM	HDR	HDRM
	Dry-Back	LDD	LDDM	MDD	MDDM	HDD	HDDM
Design 0 hr	CoreLok	LZC	LZCM	MZC	MZCM	HZC	HZCM
	RICE	LZR	LZRM	MZR	MZRM	HZR	HZRM
	Dry-Back	LZD	LZDM	MZD	MZDM	HZD	HZDM

Table 10 - Description of Acronyms

First Letter	
L	Low-12% SLAG
M	Medium-27% SLAG
H	High-42% SLAG

Third Letter	
C	CORELOK
R	RICE METHOD
D	DRYBACK

Second Letter	
P	Plus additional 0.5% asphalt
D	Design AC
Z	Zero curing time

Forth Letter	
M	Residual Moisture

4.2 RESULTS

The G_{mm} data are presented in Table 11 and Table 12 shows the means and standard deviations of the G_{mm} values. The raw data used for the following analysis is presented in the Appendix.

Table 11 - G_{mm} Test Results

%Asphalt Conditioning	Test Method	Trial	% slag: 12%, % Moisture 0	12%, 2	27%, 0	27%, 2	42%, 0	42%, 2
+0.50% 2 hr	CoreLok	1	2.435	2.426	2.419	2.426	2.398	2.408
		2	2.426	2.432	2.414	2.426	2.402	2.409
	Rice	1	2.427	2.431	2.419	2.415	2.397	2.400
		2	2.435	2.434	2.417	2.428	2.403	2.406
	Dry-Back	1	2.424	2.420	2.411	2.396	2.392	2.372
		2	2.426	2.424	2.412	2.407	2.398	2.376
Design 2 hr	CoreLok	1	2.454	2.445	2.439	2.450	2.417	2.423
		2	2.443	2.444	2.438	2.440	2.417	2.425
	Rice	1	2.447	2.450	2.439	2.439	2.417	2.427
		2	2.451	2.450	2.440	2.436	2.415	2.426
	Dry-Back	1	2.439	2.438	2.428	2.423	2.406	2.391
		2	2.443	2.437	2.425	2.422	2.406	2.395
Design 0 hr	CoreLok	1	2.430	2.445	2.423	2.432	2.407	2.429
		2	2.430	2.447	2.427	2.440	2.398	2.434
	Rice	1	2.431	2.445	2.427	2.442	2.398	2.436
		2	2.434	2.447	2.426	2.437	2.403	2.430
	Dry-Back	1	2.427	2.422	2.401	2.400	2.381	2.373
		2	2.422	2.422	2.401	2.405	2.389	2.367

Table 12 - G_{mm} Means and Standard Deviations

		Gmm											
		% slag											
		12%				27%				42%			
		% Moisture											
	Test	0		2		0		2		0		2	
% Asphalt	Method	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
0.50%	CoreLok	2.431	0.006	2.429	0.004	2.416	0.004	2.426	0.000	2.400	0.002	2.409	0.001
	Rice	2.431	0.006	2.432	0.002	2.418	0.001	2.422	0.009	2.400	0.004	2.403	0.004
	Dry-Back	2.425	0.002	2.422	0.003	2.411	0.000	2.402	0.008	2.395	0.004	2.374	0.002
Design	CoreLok	2.449	0.008	2.445	0.001	2.438	0.000	2.445	0.007	2.417	0.001	2.424	0.001
	Rice	2.449	0.003	2.450	0.000	2.439	0.001	2.438	0.002	2.416	0.001	2.427	0.001
	Dry-Back	2.441	0.003	2.438	0.001	2.427	0.003	2.423	0.000	2.406	0.000	2.393	0.003
Zero Condition Time	CoreLok	2.430	0.000	2.446	0.002	2.425	0.002	2.436	0.006	2.402	0.007	2.431	0.003
	Rice	2.432	0.002	2.446	0.001	2.426	0.001	2.439	0.003	2.401	0.003	2.433	0.004
	Dry-Back	2.424	0.004	2.422	0.000	2.401	0.000	2.402	0.003	2.385	0.005	2.370	0.004

4.2.1 G_{mm} Analysis of Test Methods

If the three test methods are equally effective at measuring G_{mm} then they should produce equal results. The t-test, used to compare means when fewer than 30 observations are available, evaluates if the null hypothesis, H_n, of equal means can be rejected for a certain confidence level. The alternative hypothesis, H_o, is for non-equal means. The decision provided by the t-test is either to reject the null hypothesis or there is insufficient evidence to reject the null hypotheses. The t-test does not determine if the null hypothesis should be accepted, but this is the implication of not rejecting the null hypothesis. A confidence level of 95% was used for the decision for all of the following statistical analysis. An inherent assumption of the t-test is the data are normally distributed. The following analysis was performed on the average of two replicate observations. In this situation the central limits theorem applies which justifies the normality assumption.

4.2.1.1 Rice versus CoreLok

Table 13 presents the results of the t-test's comparing the Rice versus CoreLok, Rice versus Dry Back and CoreLok versus Dry Back. The analysis was performed with Excel assuming equal variance of the populations. The comparison of the Rice and the CoreLok methods indicates the null hypothesis cannot be rejected with the inference that the results of the two methods are the same. The comparisons of the Rice versus Dry Back and CoreLok versus Dry back indicates the null hypothesis of equal means can be rejected with the inference that the test methods produce difference results with a confidence level of 95%.

The t-test does not provide any in site into the relationships between the data sets. To further evaluate the data a line of equality was used. When two test methods should produce the same results, a plot of the results of one method versus the other should produce a straight line with an intercept at the origin and a slope of one. A linear regression line fit to the data would have the equation:

$$Y = aX + b \pm e$$

Where a is the slope of the line and b is the intercept and e is the standard error. The coefficients can then be tested to determine if a = 1 and b = 0 for a given confidence level.

Table 13 - t-test comparisons of test methods

	Rice	CoreLok	Dry-Back	CoreLok	Dry-Back	Rice
Mean	2.428	2.428	2.409	2.428	2.409	2.428
Variance	0.000241	0.000214	0.000409	0.000214	0.000409	0.000241
Observations	36	36	36	36	36	36
Pooled Variance	0.000228		0.000312		0.000325	
Hypothesized Mean Difference	0		0		0	
df	70		70		70	
t Stat	0.044		-4.501		-4.444	
P(T<=t) one-tail	0.482		0.000		0.000	
t Critical one-tail	1.667		1.667		1.667	
P(T<=t) two-tail	0.965		0.000		0.000	
t Critical two-tail	1.994		1.994		1.994	
Decision	cannot reject Hn		reject Hn		reject Hn	

Figure 9 presents the line of equality for the Rice versus CoreLok comparison. The data appear very similar as would be expected from the results of the t-test. A trend line was fit to the data. The R^2 is 0.97, which indicates almost all of the variability in the data is explained by the regression equation. The slope of 1.05 is very close to the expected value of 1.0 and the intercept of -0.12 is close to the expected value of 0.0.

The Excel trend line analysis does not provide the statistics needed to evaluate the statistical significance of the regression coefficients. The regression feature of Excel provides these statistics. Table 14 presents the regression analysis for the Rice versus CoreLok comparison. Since the trend line equation on the graph provides the coefficients, the only information needed from the regression table is the p-values for the intercept and slope. Since the p-value of the intercept, 0.380, is greater than 0.05, the null hypothesis that the intercept is equal to 0 cannot be rejected, inferring that the computed intercept is not statistically significantly different from 0. The p-value Excel computes

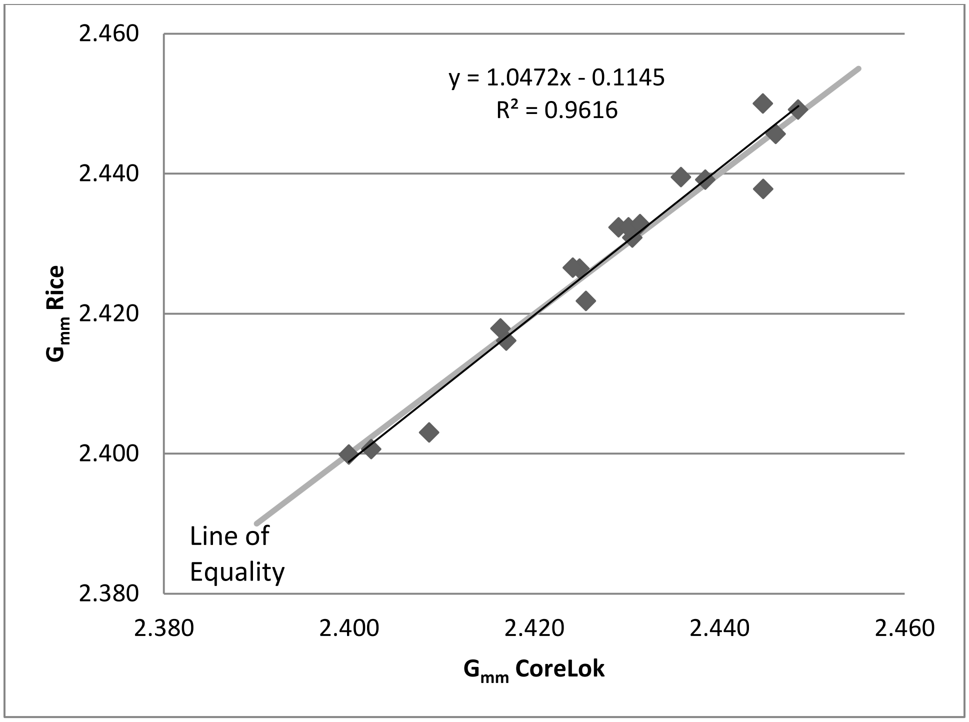

Figure 9 - Line of Equality Chart for Rice versus CoreLok G_{mm} Results.

for the intercept is for a null hypothesis of 0. A supplemental calculation is required to test for a null hypothesis of the slope equal to 1. The adjusted t-value for a slope of 1 is computed as:

t = (Slope – 1)/(Standard Error)

Then the p-value is computed using the TDIST function using the adjusted t-value, the residual degrees of freedom and the two tail assumption as the arguments for the function. In Table 14 the computed p-value is 0.380. Since this value is greater than 0.05 the null hypothesis cannot be rejected, inferring that the regression slope is not statistically different from 1.0.

The line of equality analysis results, shown in Table 14 agree with the t-value analysis in that the conclusion is the Rice and CoreLok methods produce results that are not significantly different. The advantage of the line of equality approach is that the relationship between the data is shown. In addition, the line of equality approach has the ability to determine if there is a bias between the two methods as the intercept of the regression equation.

Table 14 - Results of Regression Analysis for Rice versus CoreLok

Regression Statistics	
Multiple R	0.981
R Square	0.962
Adjusted R Square	0.959
Standard Error	0.003
Observations	18

ANOVA

	df	*SS*	*MS*	*F*
Regression	1	0.004	0.004	401.164
Residual	16	0.000	0.000	
Total	17	0.004		

	Coefficients	*Std Error*	*t Stat*	*P-value*
Intercept	-0.114	0.127	-0.902	0.380
X Variable 1	1.047	0.052	20.029	0.000
tails	2		Decision	
t for Hn = 1	0.903		Intercept	cannot reject Hn
p-value for Hn = 1	0.380		Slope	cannot reject Hn

4.2.1.2 Dry Back versus Rice

Figure 10 presents the line of equality graph for the Dry Back versus Rice test methods. The p-value for the slope and intercept, 0.887 and 0.910 respectively, indicate the null hypothesis cannot be rejected; the inference is that the slope is equal to one and the intercept is equal to zero. However, the t-test analysis that the Rice and Dry Back results are equal in Table 13 show that the null hypothesis can be rejected with the p-value equal to 0.0 which is less than the required 0.05. This rejection is apparent when examining the means values for the Rice and Dry Back samples, 2.428 and 2.409 respectively.

While the regression analysis states that the slope and intercept are not significantly different from the line of equality, Figure 10 shows a bias between the two samples. If the slope is exactly 1, then the bias between the two test methods is the intercept of the regression equation. Even though the slope of the regression between the

Rice and Dry Back methods is not statistically significantly different from 1, the intercept is not an accurate estimator of the bias. The bias is the difference in the overall means of the data of the two test methods. The means of the data sets are 2.428 and 2.409 for the Rice and Dry Back tests respectively. Subtracting the difference, 0.019, from the Rice values adjusts the results for the difference between the methods. Figure 11compares the adjusted Dry Back values to the Rice values. The adjusted Dry Back values agree well with the Rice test results.

If the results of this experiment are applicable to general testing of asphalt then the impact of the bias on volumetric analysis should be considered. If Rice G_{mm} results are used without considering the impact of absorptive aggregates then the computed voids in the mix, VTM, will be overestimated by 0.6 to 0.8 percent relative to Dry Back results. For example, if G_{mb} is 2.500 and the Rice G_{mm} is 2.650 the VTM would be 5.7 percent. However, if G_{mb} is 2.500 and the Dry Back Gmm is 2.631, the VTM would be 5.0 percent

4.2.1.3 Dry Back versus CoreLok

Figure 12 presents the line of equality graph for the Dry Back versus CoreLok test methods. The p-value for the slope and intercept indicate the null hypothesis cannot be rejected; the inference is that the slope and intercept are not significantly different from one and zero, respectively. The variability in the comparison is much greater than for the comparison between the Rice and CoreLok, due to the variability in the Dry Back results. The bias between the Dry Back and CoreLok is 0.019, indicating the Dry Back results are consistently lower than the CoreLok results.

4.2.2 Analysis of Conditioning Time

A main concern for this experiment was the lack of conditioning time of the production samples before testing. For this comparison samples at the design binder content with and without the two hour conditioning time were tested. A graphical result is illustrated in Figure 13. On Figure 13 the bars with hash marks indicate comparisons where the null hypothesis could not be rejected. In five of the nine comparisons for samples with moisture, the null hypothesis could not be rejected. For the dry samples the null hypothesis could not be rejected for two of the nine comparisons. This indicates there may be differences in the effect of conditioning depending on the moisture states of the aggregates when the HMAC was blended. A comparison of all the dry samples conditioned for two hours versus the dry samples that were not conditioned determined the null hypothesis could be rejected (p-value=0.039), inferring the conditioning time affects the G_{mm} results. A t-test comparison of all the moist samples conditioned for two hours versus the moist samples that were not conditioned determined the null hypothesis could not be rejected (p-value=0.545), inferring the conditioning time does not affect the G_{mm} results in moist samples.

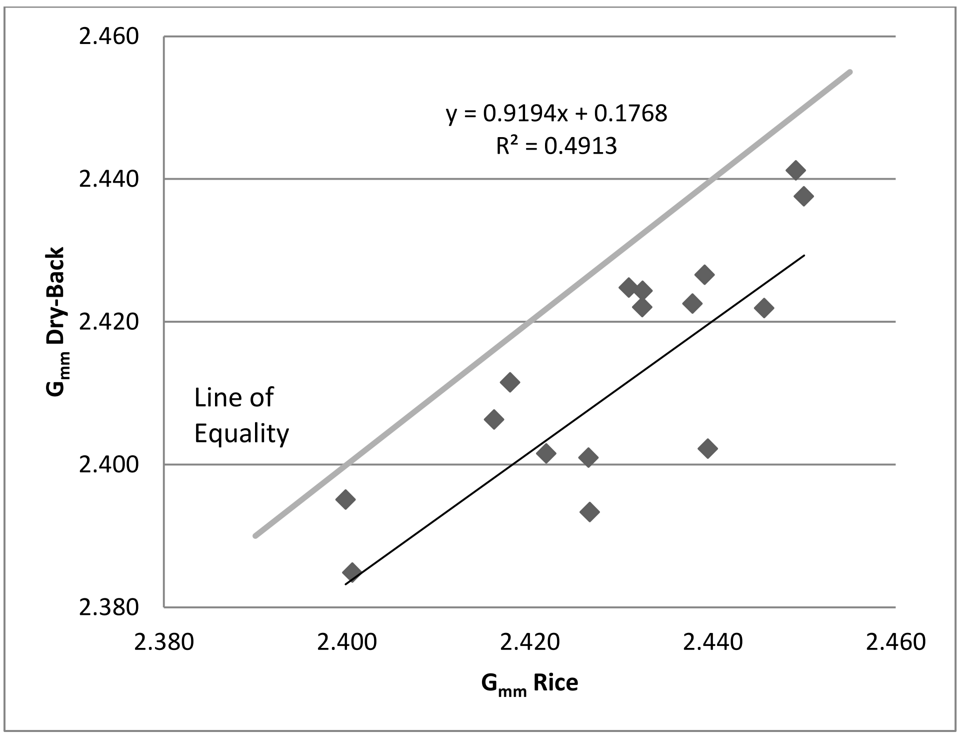

Figure 10 - Line of Equality Chart for Dry Back versus Rice G_{mm} Results.

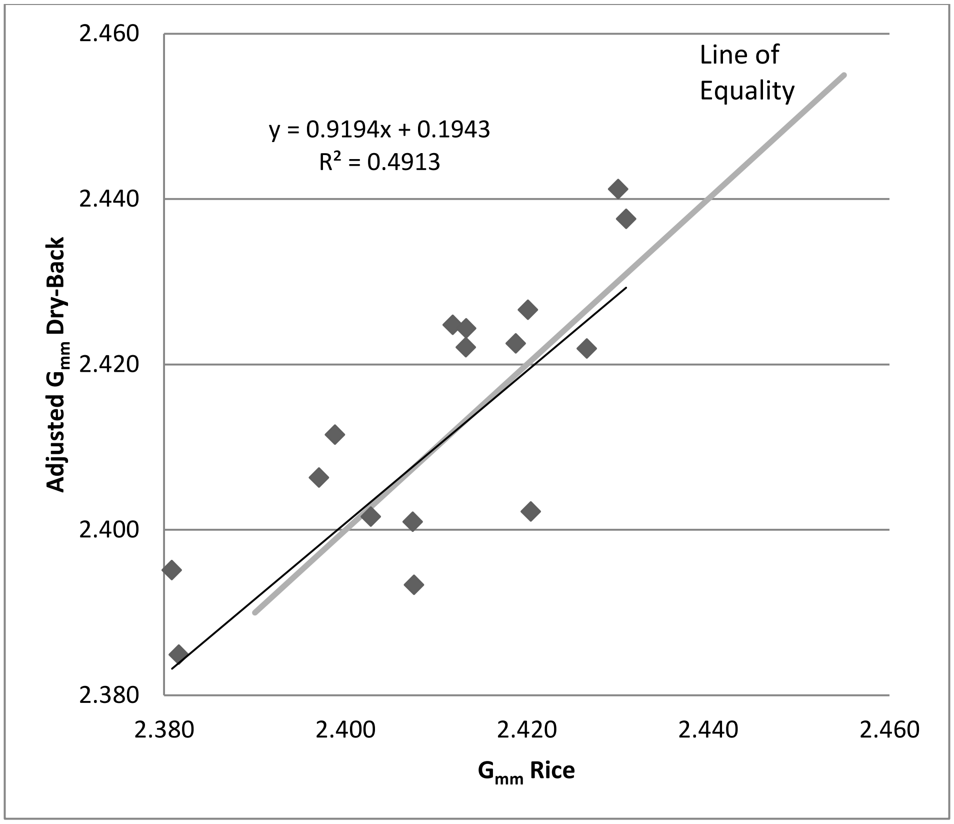

Figure 11 - Adjusted Line of Equality Chart for Dry Back versus Rice G_{mm} Results

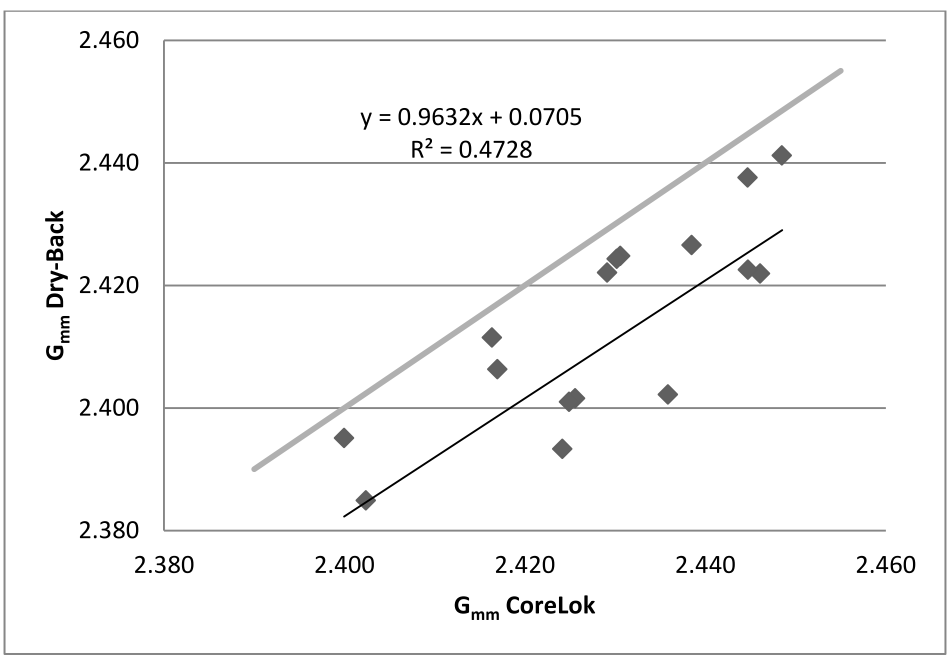

Figure 12 - Line of Equality Chart for Dry Back versus CoreLok G_{mm} Results.

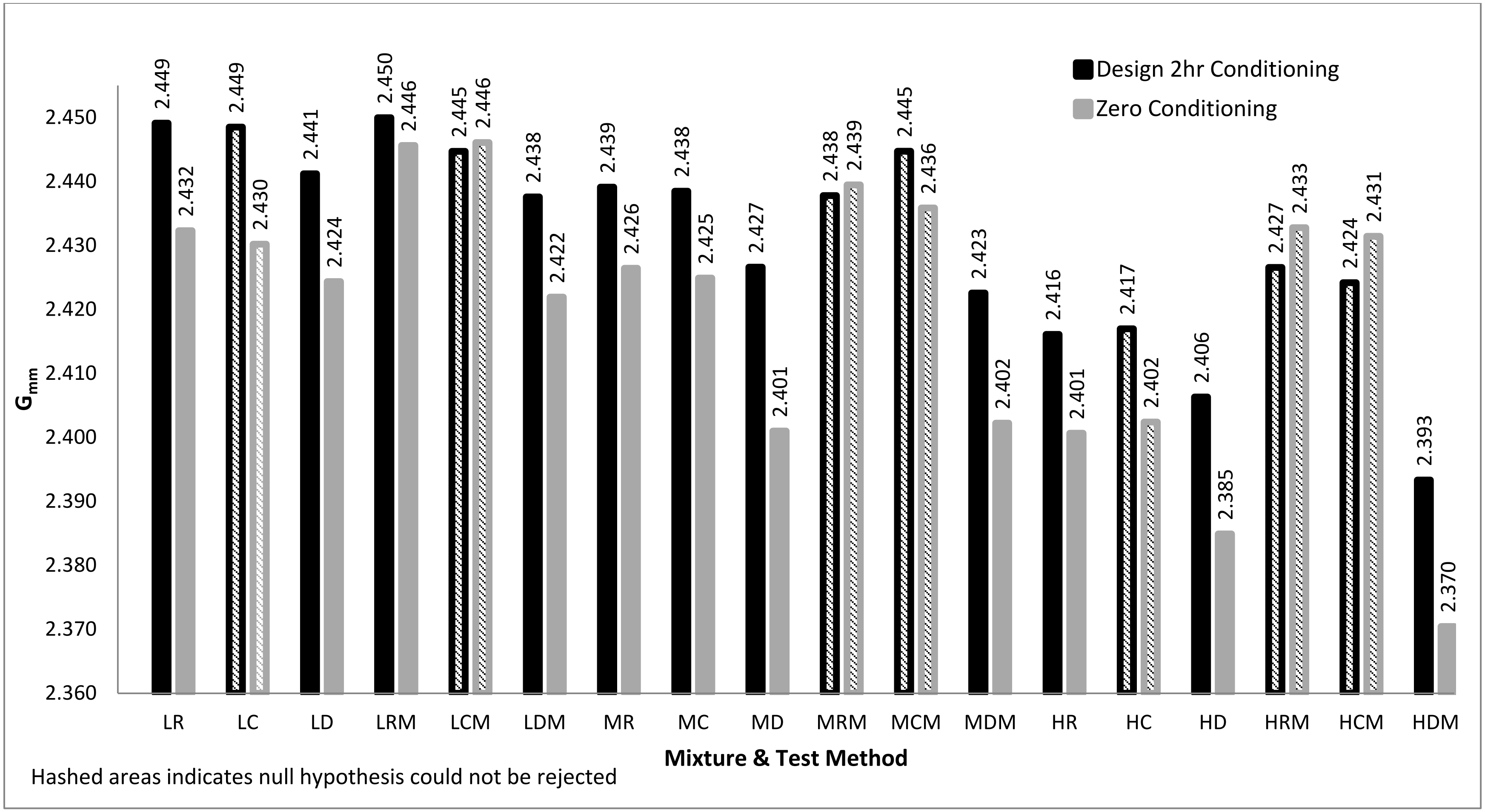

Figure 13 - Conditioning Time Means

4.2.3 G_{se} Analysis

For the following comparison, the effective specific gravity of the aggregate, G_{se}, was computed for each sample. For a given blend of aggregates G_{se} should be constant, independent of percent binder, thus G_{se} allows a direct comparison of the samples prepared at the design binder content and samples prepared at 0.5 percent above design binder content. G_{se} is computed as:

$$G_{se} = \frac{P_s}{\left(\frac{100}{G_{mm}} - \frac{P_b}{G_b}\right)}$$

Where:

P_s = percent weight of the aggregates
P_b= percent weight of the asphalt binder
G_s= specific gravity of the asphalt binder
G_{se} = effective specific gravity of aggregates coated in asphalt

4.2.3.1 Effects of Slag Content

The individual G_{se} values are presented in Table 15 while Table 16 shows the means and standard deviations of the G_{se} values. From the definition of the different types of aggregate specific gravity, $G_{sb} < G_{se} < G_{sa}$. Figure 14 shows that on average this relationship holds. However, the moisture additive samples with high slag contents results of the Rice and CoreLok test methods are suspect of error in that the samples for each method had G_{se} values equal to or larger than the G_{sa}. Samples tested with the Dry Back method did not display this problem.

Figure 14 compares the G_{se} values for the three testing methods and the three slag contents. The magnitude of the G_{se} constantly decreases going from CoreLok and Rice to the Dry Back. Table 17 is a summary of the t-tests comparing the three test methods for each slag content. At all three slag contents the Rice – CoreLok comparison could not be rejected but both the Rice – Dry Back and the Dry Back – CoreLok comparisons were rejected. This indicates that the Rice and CoreLok produce statistically similar results and the Dry Back method produces statistically different results from the Rice and CoreLok no matter the slag content.

Table 15 - G_{se} Data Sheet

			Gse					
			% slag					
			12%		27%		42%	
			% Moisture					
% Asphalt	Test Method	Trial	0	2	0	2	0	2
+0.5%	CoreLok	1	2.704	2.692	2.697	2.706	2.693	**2.706**
		2	2.692	2.700	2.690	2.706	2.697	**2.707**
	Rice	1	2.693	2.699	2.697	2.692	2.691	2.695
		2	2.704	2.702	2.694	2.710	2.699	2.703
	Dry-Back	1	2.689	2.684	2.687	2.666	2.685	2.658
		2	2.692	2.689	2.687	2.681	2.692	2.662
Design	CoreLok	1	2.705	2.694	2.699	2.714	2.694	2.703
		2	2.690	2.692	2.699	2.700	2.695	**2.705**
	Rice	1	2.696	2.700	2.699	2.700	2.694	**2.708**
		2	2.701	2.700	2.700	2.696	2.692	**2.706**
	Dry-Back	1	2.686	2.684	2.686	2.678	2.680	2.660
		2	2.691	2.683	2.681	2.678	2.680	2.665
Zero Condition Time	CoreLok	1	2.675	2.693	2.679	2.690	2.681	**2.710**
		2	2.674	2.696	2.683	2.701	2.669	**2.717**
	Rice	1	2.675	2.693	2.684	2.703	2.669	**2.720**
		2	2.679	2.695	2.683	2.698	2.676	**2.711**
	Dry-Back	1	2.670	2.663	2.650	2.648	2.647	2.636
		2	2.663	2.664	2.650	2.655	2.656	2.628

* Bold values indicate $G_{se} \geq G_{sa}$

Table 16 - G_{se} Means and Standard Deviations

		Gse											
		% slag											
		12%				27%				42%			
		% Moisture											
	Test	0		2		0		2		0		2	
% Asphalt	Method	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
0.50%	CoreLok	2.698	0.008	2.696	0.006	2.694	0.005	2.706	0.000	2.695	0.003	2.707	0.001
	Rice	2.699	0.008	2.701	0.002	2.696	0.002	2.701	0.013	2.695	0.006	2.699	0.006
	Dry-Back	2.691	0.002	2.687	0.004	2.687	0.000	2.674	0.011	2.689	0.005	2.660	0.003
Design	CoreLok	2.698	0.011	2.693	0.001	2.699	0.000	2.707	0.010	2.695	0.001	2.704	0.001
	Rice	2.699	0.004	2.700	0.000	2.700	0.001	2.698	0.003	2.693	0.001	2.707	0.001
	Dry-Back	2.689	0.004	2.684	0.001	2.684	0.004	2.678	0.000	2.680	0.000	2.663	0.004
Zero Condition Time	CoreLok	2.675	0.001	2.695	0.002	2.681	0.003	2.696	0.008	2.675	0.008	2.714	0.005
	Rice	2.677	0.003	2.694	0.001	2.684	0.001	2.701	0.004	2.673	0.005	2.716	0.006
	Dry-Back	2.667	0.005	2.664	0.001	2.650	0.000	2.652	0.005	2.652	0.006	2.632	0.006

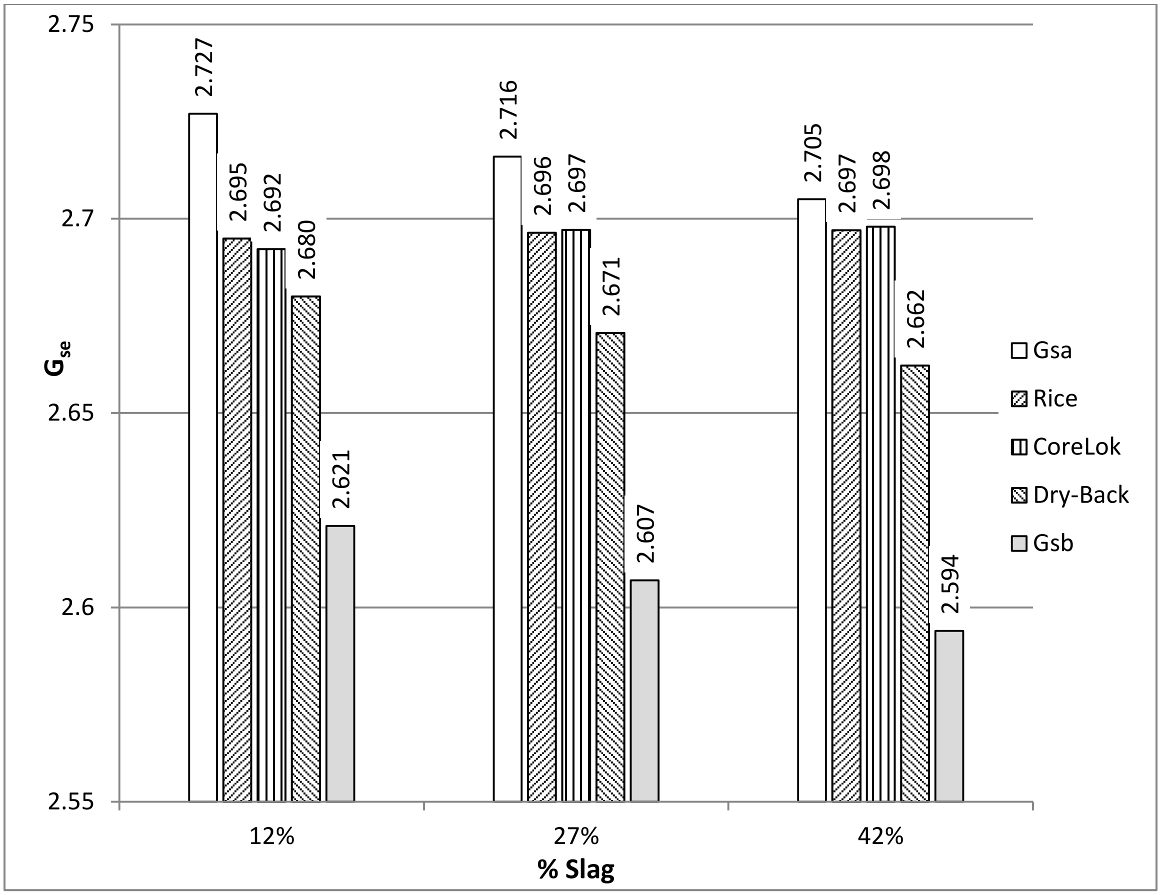

Figure 14 - G_{se} Means

Table 17 - Slag Content Analysis Using G_{se}

% Slag	Comparison	Means		Degree of Freedom	P-value	Decision
12%	Rice-CoreLok	2.695	2.692	22	0.483	cannot reject Hn
	Rice-DryBack	2.695	2.680	22	0.002	**reject Hn**
	CoreLok-DryBack	2.692	2.680	22	0.009	**reject Hn**
27%	Rice-CoreLok	2.696	2.697	22	0.837	cannot reject Hn
	Rice-DryBack	2.696	2.671	22	0.000	**reject Hn**
	CoreLok-DryBack	2.697	2.671	22	0.000	**reject Hn**
42%	Rice-CoreLok	2.697	2.698	22	0.884	cannot reject Hn
	Rice-DryBack	2.697	2.662	22	0.000	**reject Hn**
	CoreLok-DryBack	2.697	2.662	22	0.000	**reject Hn**

Figure 15 show a scatter diagram of the G_{se} values for each test method and slag content where in each case the values are similar between the CoreLok and Rice and then decrease to the Dry Back. The trend lines from Figure 15 show that the increase in slag content produces a decrease in G_{se} for the Dry Back method. This is expected due to the fact that the G_{sb} value for the slag aggregate is lower than the G_{sb} value for the limestone aggregates. Therefore the combined G_{sb} for the mix will be lowered with the increase in slag content. However, the Rice and CoreLok do not capture the same trend. These values are relatively the same no matter the slag content. This is possible due to the absorptive nature of the slag and neither test account for account for that. The R^2 values from the figure show the high variability of the G_{se} values which resulted in not being able to reject the null hypothesis of equal means. Since the variability is high there would be more overlapping of the values which causes a greater probability of equal means.

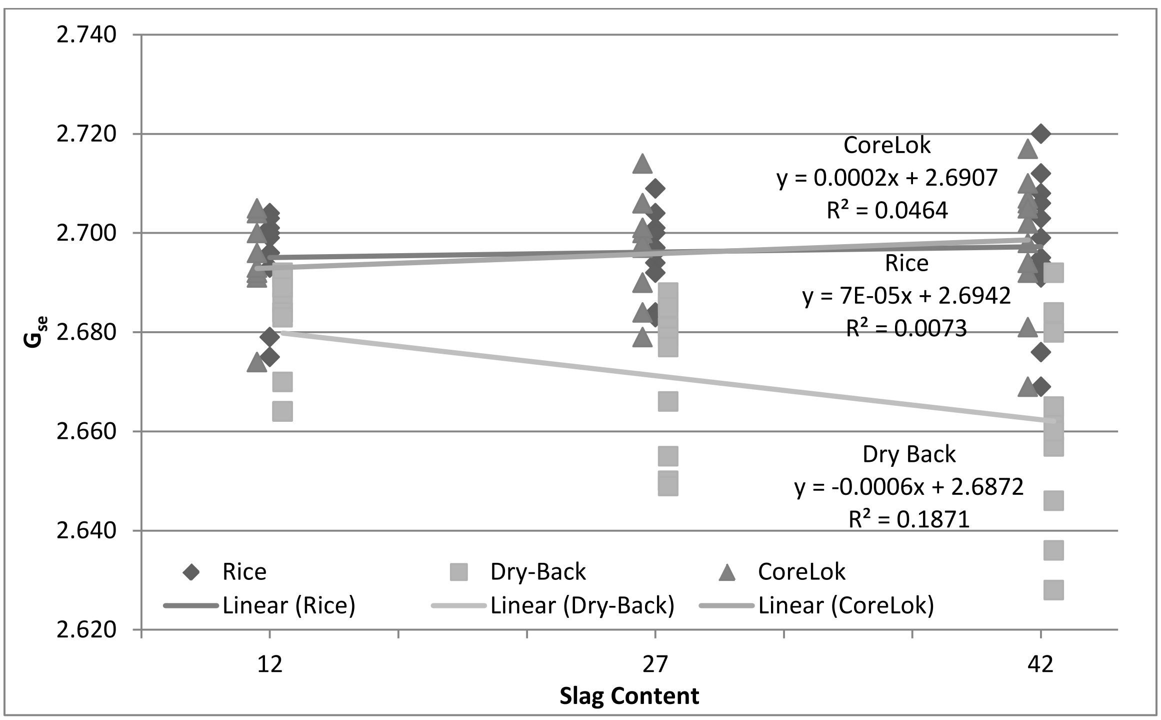

Figure 15 - G_{se} Test Data versus Slag Content

4.2.3.2 Effect of Additional Binder

When slag is used in hot mix asphalt there is a chance that since there are large amounts of voids that the aggregates do not get completely coated with asphalt. For the experiment a set of samples were prepared with an additional 0.5 percent asphalt in order to overcome this issue and insure adequate coating of the aggregates. Table 18 shows the comparisons for each test method comparing the G_{se} values at the design binder content and the G_{se} values at the design plus 0.5 percent binder content. Table 18 shows that there is little effect on the Gse between the two binder levels for each group of slag percentages. The differences between the results are even lower than the precision statement standard deviation given in AASHTO, with the exception of the two bolded numbers. A statistical analysis was performed and showed that the null hypothesis for equal means could not be rejected for any of the test methods, inferring that there is no statistical difference between the design asphalt content test results and the results from adding additional asphalt. From these comparisons it is apparent that the concept of using additional binder to adequately stabilize the G_{se} values, and therefore G_{mm} values is not effective, nor desirable.

Table 18 - G_{se} Comparison for Additional Binder

% Slag	Test Method	Moisture	Design	+0.5 %	Difference	Average
12%	CoreLok	0	2.698	2.698	-0.001	-0.0015
		2	2.693	2.696	-0.003	
	Rice	0	2.699	2.699	0.000	
		2	2.700	2.701	0.000	
	Dry-Back	0	2.689	2.691	-0.002	
		2	2.684	2.687	-0.003	
27%	CoreLok	0	2.699	2.694	0.005	0.0014
		2	2.707	2.706	0.001	
	Rice	0	2.700	2.696	0.004	
		2	2.698	2.701	-0.003	
	Dry-Back	0	2.684	2.687	-0.003	
		2	2.678	2.674	0.005	
42%	CoreLok	0	2.695	2.695	-0.001	-0.0005
		2	2.704	2.707	-0.003	
	Rice	0	2.693	2.695	-0.002	
		2	2.707	2.699	**0.008**	
	Dry-Back	0	2.680	2.689	**-0.009**	
		2	2.663	2.660	0.002	
					Average	-0.0002

4.2.3.3 Effect of the Addition of Moisture

The moisture absorption was addressed in this experiment so a t-test was conducted to see if a significant difference existed between the samples that were mixed normally and those with water induced into the slag portion of the mix.

Figure 16 shows the line of equality between all the dry samples and all the samples with residual moisture.

Figure 16 shows that most of the data are similar, and when examining the regression analysis the slope and intercept are quite close one and zero, respectively. Furthermore the p-values for the slope and intercept are 0.941 and 0.960 respectively, indicating that the null hypothesis cannot be rejected. Also, from the R^2 value is 0.65 so there is variability not explained with the regression line. When the data is compared using a t-test with a 95% confidence level, shown in Table 19, over a third, 10 out of the 27 comparisons can reject the null hypothesis of equal means. Five of the nine zero-conditioned samples can reject the null hypothesis but only five of the 18 two hour conditioned samples can reject the null hypothesis. Also, only two of the nine Dry Back samples rejected the null hypothesis when the Rice and CoreLok both rejected twice that.

Figure 17 shows the line of equality of the mean G_{se} values for the zero cured samples comparing the effects of moisture. All of the dry back samples are triangular shaped and are all located at or above the line of equality. The Rice and CoreLok samples are all located below the line of equality. There is insufficient data however to make any good observations, especially due to the high variability in the data.

4.3 COMPARISON TO PREVIOUS RESEARCH

The Rajagopal and Crago (2007) study provided results that can be directly compared to the research performed in this report. The data points from Table 2 were entered into Excel to produce a line of equality chart, Figure 18 and a regression analysis shown in Table 20. Table 2 shows the average of the two tests are equal, the analysis conducted in this research show that the tread line is not similar to the predicted intercept and slope values of zero and one respectively. According to the regression analysis the null hypothesis could be rejected for both the slope and the intercept. The R-squared value is 0.5325, which means there is a much larger variability in the results then the results collected in this study. While there is a larger variability in Rajagopal and Crago's results they are explainable due to the high number of technicians working on the same project at once, whereas this study used only one person completed the laboratory work. Ignoring the variability these two studies could have produced similar results for the comparison between the CoreLok and the Rice methods for determining G_{mm}.

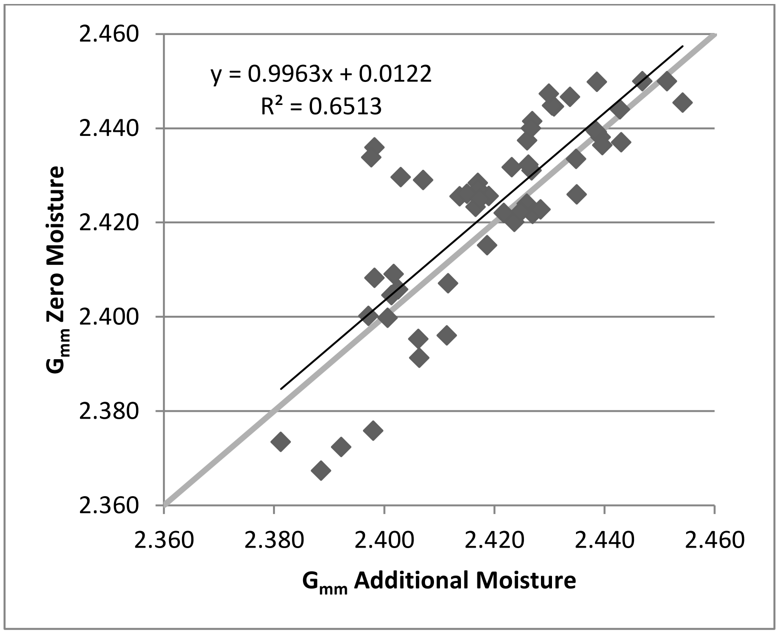

Figure 16 - Line of Equality for Dry vs. Moist sample comparison

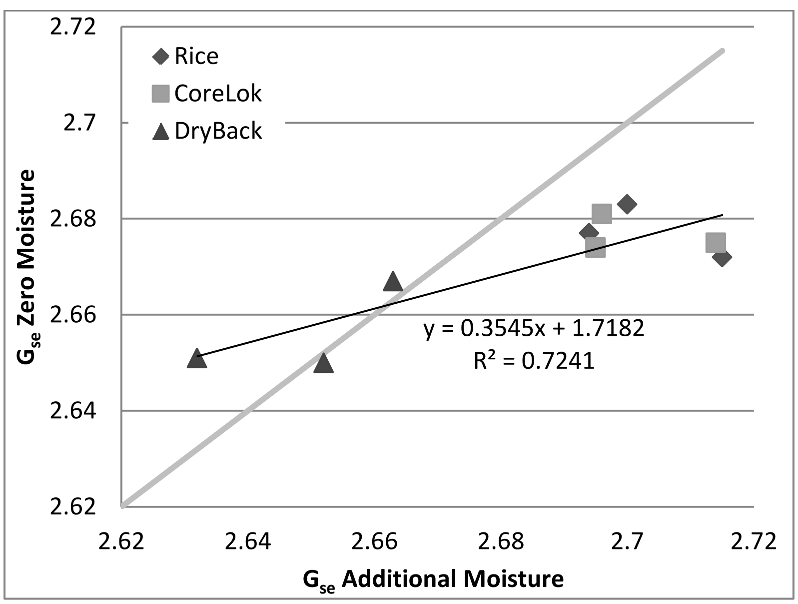

Figure 17 - Moisture Addition Line of Regression for Zero conditioned samples

Table 19 – G_{mm} Moisture Addition t-test Table

	Average	T-test (p-values)	Average	
LPC	2.431	0.76307	2.432	LPCM
LPR	2.431	0.81077	2.429	LPRM
LPD	2.425	0.34699	2.422	LPDM
LDC	2.449	0.73508	2.450	LDCM
LDR	2.449	0.57739	2.445	LDRM
LDD	2.441	0.20272	2.438	LDDM
LZC	2.432	0.01711	2.446	LZCM
LZR	2.430	0.00639	2.446	LZRM
LZD	2.424	0.45164	2.422	LZDM
MPC	2.418	0.61433	2.422	MPCM
MPR	2.416	0.07400	2.426	MPRM
MPD	2.411	0.21509	2.402	MPDM
MDC	2.439	0.46468	2.438	MDCM
MDR	2.438	0.34627	2.445	MDRM
MDD	2.427	0.15405	2.423	MDDM
MZC	2.426	0.02492	2.439	MZCM
MZR	2.425	0.13373	2.436	MZRM
MZD	2.401	0.65918	2.402	MZDM
HPC	2.400	0.50289	2.403	HPCM
HPR	2.400	0.04003	2.409	HPRM
HPD	2.395	0.02488	2.374	HPDM
HDC	2.416	0.01194	2.427	HDCM
HDR	2.417	0.01642	2.424	HDRM
HDD	2.406	0.02323	2.393	HDDM
HZC	2.401	0.01501	2.433	HZCM
HZR	2.402	0.03157	2.431	HZRM
HZD	2.385	0.09300	2.370	HZDM

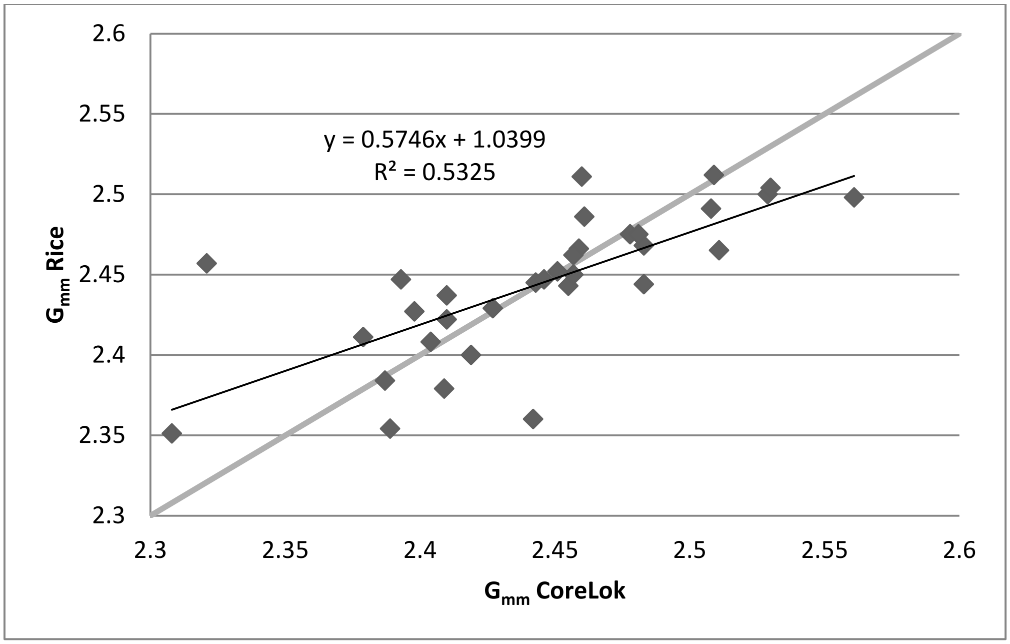

Figure 18 - Line of Equality on Rajagopal and Crago study

Table 20 - Regression analysis on Rajagopal and Crago Study

Regression Statistics	
Multiple R	0.729746
R Square	0.532529
Adjusted R Square	0.517449
Standard Error	0.031010
Observations	33

ANOVA

	df	*SS*	*MS*	*F*
Regression	1	0.033959	0.033959	35.314227
Residual	31	0.029811	0.000962	
Total	32	0.063770		

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.03988	0.23638	4.39910	0.00012
X Variable 1	0.57457	0.09669	5.94258	0.00000
tails	2		Decision	
t for Hn = 1	-4.400		Intercept	reject Hn
p-value for Hn = 1	0.000		Slope	reject Hn

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The first objective of this study was to determine a possible cause for the difference in theoretical maximum specific gravity (G_{mm}) results between a laboratory created sample and a sample pulled from the production line in the plant. Possible causes thought to affect this were the residual moisture that is held in the slag after it passes through the drying drum and the lack of any conditioning time as the samples are pulled from the plant for testing. Both of these were tested and analyzed.

The analysis compared multiple mixture designs, asphalt contents, and test methods. The addition of water prior to the mixing procedure revealed minimal influence on the end values for theoretical maximum specific gravity, only affecting one-third of the values. It is important to point out that about seventy percent of those affected were found to be in the high slag content mixture. There was also an increase with the variability of the results when moisture was induced in the samples. Even though the moisture had an effect on the test data, overall it was in the wrong direction. The moist samples had G_{mm} values were higher than those samples with dry aggregates.

The second theory involving the lack of a conditioning time for plant produced samples proved to be probable. With 75 percent of the samples showing significant differences between the standard two hours and the simulated plant produced sample with no conditioning. There were only two of nine samples without residual moisture that the null hypothesis could not be rejected, inferring that there is a significant difference between conditioning times.

The second objective was to determine if the Dry Back procedure was necessary. According to the G_{se} results the Dry Back samples were the only samples to account for the effects of the additional slag. Figure 15 showed that the Dry Back values were the only ones to decrease as the slag content increase. This indicates the standard method is not capturing the effect of absorption; hence there is no basis for discontinuing the use of the Dry Back method at this time.

The final objective was to determine if the CoreLok could replace the Rice test (AASHTO T-209). The G_{mm} analysis for the test methods revealed there was a strong correlation between all the testing methods. The CoreLok showed no statistical difference from the Rice method results. While there is a strong correlation between the Rice and CoreLok there was bias when comparing the Dry Back to the Rice and CoreLok. The CoreLok and Rice test methods always overestimate the Dry Back method results. The bias between the Rice and Dry Back and between the CoreLok and Dry Back were equal to 0.019; this is interesting because InstroTek claims that the CoreLok eliminates the need for the Dry Back procedure. Due to these and the results conducted by the University of Cincinnati, it appears that the CoreLok can be used in lieu of T-209 if there are no absorptive aggregates being used in the mix design. However, if there are absorptive aggregates then the Dry Back will need to be used to account for the absorption.

Table 21 is a list of statistical analyses used when comparing the results. Other G_{se} analysis was conducted to be able to compare results between design binder content and samples with the additional 0.5 percent binder more accurately then G_{mm} can. This is because G_{se} is not dependent on the asphalt content like G_{mm} is. These analyses revealed that adding additional binder to aid in sealing the stones better had little influence on the end results. Since G_{se} had been calculated, F, the absorption factor was calculated. F captures the difference in the amount of asphalt absorbed in the aggregate compared to the amount of water absorbed. These values while not included in this report since the analysis would show the same results the G_{se} had. However, the data did show that there was a significant difference from the AASHTO assumed value of 0.8, which may have to do with the high void content in slag aggregates.

5.2 RECOMMENDATIONS FOR FURTHER STUDY

This research was limited to following the certain test procedure associated with the three test methods used. Knowing this, further research could be conducted to analyze the potential need for a Dry Back procedure for the CoreLok vacuum sealing device. The researched mixture designs for this thesis were limited to only slag No.8, without the use of slag sands. Further investigations should be conducted to see the

Table 21 - Summary of Analytical Tests

Statistical Test	Data Tested	Results
T-test	G_{mm} data for each Test Method	Null hypothesis could not be rejected between Rice and CoreLok. Null hypothesis was rejected between Dry Back and Rice and CoreLok.
Linear Regression	G_{mm} data for each test method	Showed the Rice and CoreLok procedures produced very similar results. Showed that the Dry Back data was correlated to the Rice and CoreLok but offset by 0.019.
T-test	G_{mm} data with design binder contents	Null hypothesis could be rejected with dry samples. Null hypothesis could not be rejected with moist samples due to high variability.
T-test	G_{se} data separated by slag contents	Null hypothesis could not be rejected between Rice and CoreLok. Null hypothesis was rejected between Dry Back and Rice and CoreLok.
	G_{se} data separated by slag contents	As slag content increased G_{se} became closer to the G_{sa} upper limit especially when studying the samples with residual moisture.
Mean differences	G_{se} data between standard mix design and mix design with additional 0.5 percent binder	Reveled little difference between the samples, less variability then the precision statement in AASHTO's T209 permits, with the exception of four samples.
T-test	G_{se} data between dry and moist mixtures	The null hypothesis could be rejected in 10 of the 27 comparisons with 70 percent being high slag mixtures.
Linear Regression	G_{se} data between dry and moist mixtures	Overall the data was correlated over the line of equality but had a mediocre r-squared value due to the variability in the moist samples.

possible influence that different size aggregates have on the change in testing results. Also, the addition of slag sand instead of limestone sand could have influence in the G_{mm} results. The mixtures were also limited to a maximum of 42 percent slag to resemble a high amount of slag present in mixtures. From discussions with West Virginia Paving, the highest amount of course slag they had ever used in a mixture was 50 percent. It is possible that in extreme cases, where slag is the abundant material, the moisture addition could become even more apparent.

As conditioning time appears to be a large contributor to the change in theoretical maximum specific gravity results, further investigations should be done to see the effects at various times. The research should explore the possibility of adding additional short conditioning times (15 to 30 minutes) to plant samples to best account for the absorption of certain aggregates. Also, possible research could be conducted to analyze the absorption factor, F, for absorbent materials such as slag, that way mix designs can better resemble the material used.

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APPENDIX – DATA SHEETS

Table 22 - LD DATA

LD
43 LS - 12 Slag - 45 Sand

Rice

Dry	1508
Submerged	2146.7
Gmm	2.447

Dry	1516.4
Submerged	2152.8
Gmm	2.451

Dry Back

Dry	1508	
Submerged	2146.7	
Drying Rack	7334.6	
DB 1	8845.9	1511.3
DB 2	8845	1510.4
DB 3	8844.5	1509.9
DB 4		
DB 5		
Gmm	2.439	

Dry	1516.4	
Submerged	2152.8	
Drying Rack	6312.2	
DB 1	7835.3	1523.1
DB 2	7832.2	1520
DB 3	7831.2	1519
DB 4	7830.7	1518.5
DB 5		
Gmm	2.443	

CoreLok

Bags	75
Dry	1509.2
Sub + Bags	886.2
Gmm	2.454

Bags	74.4
Dry	1514.8
Sub + Bags	886.7
Gmm	2.443

	Rice	Dry Back	CoreLok
Averages	2.449	2.441	2.449
Stddev	0.0032	0.0026	0.0081

Table 23 - MD DATA

MD
28 LS - 27 Slag - 45 Sand

Rice

Dry	1505.6
Submerged	2143.2
Gmm	2.439

Dry	1515.5
Submerged	2149.3
Gmm	2.440

Dry Back

Dry	1505.6	
Submerged	2143.2	
Drying Rack	7334.5	
DB 1	8849.4	1514.9
DB 2	8845.6	1511.1
DB 3	8844	1509.5
DB 4	8843	1508.5
DB 5	8842.7	1508.2
Gmm	2.428	

Dry	1515.5	
Submerged	2149.3	
Drying Rack	6313	
DB 1	7842.2	1529.2
DB 2	7835.4	1522.4
DB 3	7833.8	1520.8
DB 4	7832.8	1519.8
DB 5	7832.3	1519.3
Gmm	2.425	

CoreLok

Bags	74.3
Dry	1518.1
Sub + Bags	887.6
Gmm	2.439

Bags	74.2
Dry	1497.2
Sub + Bags	875.2
Gmm	2.438

Rice		**Dry Back**		**CoreLok**	
Averages	2.439	Averages	2.427	Averages	2.438
Stddev	0.0007	Stddev	0.0025	Stddev	0.0002

Table 24 - HD DATA

HD
13 LS - 42 Slag - 45 Sand

Rice

Dry	1511.2
Submerged	2141
Gmm	2.417

Dry	1514
Submerged	2142.1
Gmm	2.415

Dry Back

Dry	1511.2	
Submerged	2141	
Drying Rack	7334.5	
DB 1	8849.5	1515
DB 2	8848.5	1514
DB 3		
DB 4		
DB 5		
Gmm	2.406	

Dry	1514	
Submerged	2142.1	
Drying Rack	6312.2	
DB 1	7832	1519.8
DB 2	7829	1516.8
DB 3	7828.5	1516.3
DB 4		-6312
DB 5		
Gmm	2.406	

CoreLok

Bags	74.6
Dry	1492.7
Sub + Bags	867
Gmm	2.417

Bags	74.2
Dry	1531.7
Sub + Bags	890.1
Gmm	2.417

	Rice		Dry Back		CoreLok
Averages	2.416	Averages	2.406	Averages	2.417
Stddev	0.0015	Stddev	0.0001	Stddev	0.0005

Table 25 - LDM DATA

LDM
43 LS - 12 Slag - 45 Sand + 2%MC

Rice

Dry	1509.2
Submerged	2148.2
Gmm	2.450

Dry	1514.8
Submerged	2151.5
Gmm	2.450

Dry Back

Dry	1509.2	
Submerged	2147.2	
Drying Rack	6312.5	
DB 1	7823.7	1511.2
DB 2	7825.6	1513.1
DB 3	7824.9	1512.4
DB 4		
DB 5		
Gmm	2.438	

Dry	1514.87	
Submerged	2151.5	
Drying Rack	7334.5	
DB 1	8860.8	1526.3
DB 2	8856.4	1521.9
DB 3	8854.1	1519.6
DB 4	8853.1	1518.6
DB 5	8852.6	1518.1
Gmm	2.437	

CoreLok

Bags	74.1
Dry	1456.6
Sub + Bags	853
Gmm	2.445

Bags	74.8
Dry	1571.4
Sub + Bags	920.4
Gmm	2.444

Rice		**Dry Back**		**CoreLok**	
Averages	2.450	Averages	2.438	Averages	2.445
Stddev	0.0000	Stddev	0.0008	Stddev	0.0010

Table 26 - MDM DATA

MDM

28 LS - 27 Slag - 45 Sand +2% MC

Rice

Dry	1510.1
Submerged	2146
Gmm	2.439

Dry	1509.6
Submerged	2145
Gmm	2.436

Dry Back

Dry	1510.1	
Submerged	2146	
Drying Rack	7334.5	
DB 1	8858.2	1523.7
DB 2	8851.7	1517.2
DB 3	8850	1515.5
DB 4	8849.2	1514.7
DB 5	8848.8	1514.3
Gmm	2.423	

Dry	1509.6	
Submerged	2145	
Drying Rack	6312.2	
DB 1	7829.5	1517.3
DB 2	7826.6	1514.4
DB 3	7825.7	1513.5
DB 4	7825.4	1513.2
DB 5		
Gmm	2.422	

CoreLok

Bags	74.5
Dry	1526
Sub + Bags	895.1
Gmm	2.450

Bags	74.8
Dry	1495.4
Sub + Bags	874.4
Gmm	2.440

	Rice	Dry Back	CoreLok
Averages	2.438	2.423	2.445
Stddev	0.0020	0.0003	0.0072

Table 27 - HDM DATA

HDM
13 LS - 42 Slag - 45 Sand +2% MC

Rice

Dry	1510.6
Submerged	2143.2
Gmm	2.427

Dry	1512.9
Submerged	2144.3
Gmm	2.426

Dry Back

Dry	1510.6	
Submerged	2143.2	
Drying Rack	6312.5	
DB 1	7837	1524.5
DB 2	7834.4	1521.9
DB 3	7833.3	1520.8
DB 4	7832.6	1520.1
DB 5	7832.4	1519.9
Gmm	2.391	

Dry	1512.9	
Submerged	2144.3	
Drying Rack	7334.5	
DB 1	8859.7	1525.2
DB 2	8857.4	1522.9
DB 3	8856.5	1522
DB 4	8855.7	1521.2
DB 5	8855.4	1520.9
Gmm	2.395	

CoreLok

Bags	74.1
Dry	1502.8
Sub + Bags	874.7
Gmm	2.423

Bags	74.3
Dry	1531.7
Sub + Bags	892.1
Gmm	2.425

Rice		**Dry Back**		**CoreLok**	
Averages	2.427	Averages	2.393	Averages	2.424
Stddev	0.0007	Stddev	0.0028	Stddev	0.0012

Table 28 - LZ DATA

LZ

43 LS - 12 Slag - 45 Sand   00 min Curing Time

Rice

Dry	1510.3
Submerged	2144
Gmm	2.431

Dry	1517.7
Submerged	2149.1
Gmm	2.434

Dry Back

Dry	1510.3	
Submerged	2144	
Drying Rack	7334.9	
DB 1	8850.3	1515.4
DB 2	8847.7	1512.8
DB 3	8846.6	1511.7
DB 4	8846.2	1511.3
DB 5		
Gmm	2.427	

Dry	1517.7	
Submerged	2149.1	
Drying Rack	6312.5	
DB 1	7835.5	1523
DB 2	7834.4	1521.9
DB 3	7833.7	1521.2
DB 4	7833.3	1520.8
DB 5		
Gmm	2.422	

CoreLok

Bags	73.8
Dry	1440
Sub + Bags	839.6
Gmm	2.430

Bags	73.6
Dry	1588.9
Sub + Bags	927.1
Gmm	2.430

Rice		**Dry Back**		**CoreLok**	
Averages	2.432	Averages	2.424	Averages	2.430
Stddev	0.0021	Stddev	0.0037	Stddev	0.0004

Table 29 - MZ DATA

MZ

28 LS - 27 Slag - 45 Sand 00 min Curing Time

Rice

Dry	1510
Submerged	2142.8
Gmm	2.427

Dry	1510.9
Submerged	2143.1
Gmm	2.426

Dry Back

Dry	1510	
Submerged	2142.8	
Drying Rack	7334.6	
DB 1	8854.5	1519.9
DB 2	8853	1518.4
DB 3	8852	1517.4
DB 4	8851.4	1516.8
DB 5		
Gmm	2.401	

Dry	1510.9	
Submerged	2143.1	
Drying Rack	6312.2	
DB 1	7831.6	1519.4
DB 2	7830.2	1518
DB 3	7829.5	1517.3
DB 4		
DB 5		
Gmm	2.401	

CoreLok

Bags	74.3
Dry	1512.1
Sub + Bags	880.1
Gmm	2.423

Bags	73.7
Dry	1512
Sub + Bags	881
Gmm	2.427

Rice		**Dry Back**		**CoreLok**	
Averages	2.426	Averages	2.401	Averages	2.425
Stddev	0.0006	Stddev	0.0005	Stddev	0.0025

Table 30 - HZ DATA

HZ

13 LS - 42 Slag - 45 Sand 00 min Curing Time

Rice

Dry	1512.8
Submerged	2137
Gmm	2.398

Dry	1505.5
Submerged	2134
Gmm	2.403

Dry Back

Dry	1512.8	
Submerged	2137	
Drying Rack	7334.4	
DB 1	8857.4	1523
DB 2	8853.2	1518.8
DB 3	8852.2	1517.8
DB 4	8851.7	1517.3
DB 5		
Gmm	2.381	

Dry	1505.5	
Submerged	2134	
Drying Rack	6312.2	
DB 1	7832.8	1520.6
DB 2	7824	1511.8
DB 3	7822.1	1509.9
DB 4	7821.5	1509.3
DB 5		
Gmm	2.389	

CoreLok

Bags	74.8
Dry	1513.5
Sub + Bags	876.7
Gmm	2.407

Bags	73.8
Dry	1508.8
Sub + Bags	871.6
Gmm	2.398

Rice		**Dry Back**		**CoreLok**	
Averages	2.401	Averages	2.385	Averages	2.402
Stddev	0.0034	Stddev	0.0052	Stddev	0.0067

Table 31 - LZM DATA

LZM

43 LS - 12 Slag - 45 Sand 00 min Curing Time + 2%MC

Rice

Dry	1505.4
Submerged	2144.6
Gmm	2.445

Dry	1517.4
Submerged	2152.2
Gmm	2.447

Dry Back

Dry	1505.4	
Submerged	2144.6	
Drying Rack	7334.4	
DB 1	8846.2	1511.8
DB 2	8845.6	1511.2
DB 3		
DB 4		
DB 5		
Gmm	2.422	

Dry	1517.4	
Submerged	2152.2	
Drying Rack	6312.2	
DB 1	7845.6	1533.4
DB 2	7838.1	1525.9
DB 3	7836.5	1524.3
DB 4	7835.9	1523.7
DB 5		
Gmm	2.422	

CoreLok

Bags	73.9
Dry	1520.6
Sub + Bags	890.7
Gmm	2.445

Bags	73.7
Dry	1505.8
Sub + Bags	882.6
Gmm	2.447

	Rice		Dry Back		CoreLok
Averages	2.446	Averages	2.422	Averages	2.446
Stddev	0.0014	Stddev	0.0002	Stddev	0.0018

Table 32 - MZM DATA

MZM
28 LS - 27 Slag - 45 Sand + 2%MC 00min curing

Rice

Dry	1503
Submerged	2142.4
Gmm	2.442

Dry	1519
Submerged	2150.8
Gmm	2.437

Dry Back

Dry	1503	
Submerged	2142.4	
Drying Rack	7334.5	
DB 1	8851.7	1517.2
DB 2	8849.4	1514.9
DB 3	8848.8	1514.3
DB 4	8848.2	1513.7
DB 5		
Gmm	2.400	

Dry	1519	
Submerged	2150.8	
Drying Rack	6313.3	
DB 1	7849.4	1536.1
DB 2	7844.5	1531.2
DB 3	7842.9	1529.6
DB 4	7841.4	1528.1
DB 5	7840.8	1527.5
Gmm	2.405	

CoreLok

Bags	74.5
Dry	1505
Sub + Bags	878.1
Gmm	2.432

Bags	74.8
Dry	1518.8
Sub + Bags	888.3
Gmm	2.440

Rice		**Dry Back**		**CoreLok**	
Averages	2.439	Averages	2.402	Averages	2.436
Stddev	0.0029	Stddev	0.0034	Stddev	0.0058

Table 33 - HZM DATA

HZM

13 LS - 42 Slag - 45 Sand + 2%MC 00min curing

Rice

Dry	1508.1
Submerged	2144
Gmm	2.436

Dry	1516.8
Submerged	2147.5
Gmm	2.430

Dry Back

Dry	1508.1	
Submerged	2144	
Drying Rack	6313.2	
DB 1	7843.8	1530.6
DB 2	7841.4	1528.2
DB 3	7840	1526.8
DB 4	7838.2	1525
DB 5	7837.6	1524.4
Gmm	2.373	

Dry	1516.8	
Submerged	2147.5	
Drying Rack	7334.6	
DB 1	8872.5	1537.9
DB 2	8870.6	1536
DB 3	8869.3	1534.7
DB 4	8868.2	1533.6
DB 5	8867.8	1533.2
Gmm	2.367	

CoreLok

Bags	74.4
Dry	1510
Sub + Bags	880.3
Gmm	2.429

Bags	74.4
Dry	1516
Sub + Bags	885.3
Gmm	2.434

Rice		**Dry Back**		**CoreLok**	
Averages	2.433	Averages	2.370	Averages	2.431
Stddev	0.0045	Stddev	0.0043	Stddev	0.0034

Table 34 - LP DATA

LP

43 LS - 12 Slag - 45 Sand +0.5% AC

Rice

Dry	1511.4
Submerged	2143.6
Gmm	2.427

Dry	1512.3
Submerged	2146.2
Gmm	2.435

Dry Back

Dry	1511.4	
Submerged	2143.6	
Drying Rack	6312.6	
DB 1	7835.8	1523.2
DB 2	7828.9	1516.3
DB 3	7826.3	1513.7
DB 4	7825.3	1512.7
DB 5	7824.8	1512.2
Gmm	2.424	

Dry	1512.3	
Submerged	2146.2	
Drying Rack	7334.6	
DB 1	8853.2	1518.6
DB 2	8851.5	1516.9
DB 3	8850.2	1515.6
DB 4	8849.5	1514.9
DB 5	8849.2	1514.6
Gmm	2.426	

CoreLok

Bags	73.8
Dry	1506.7
Sub + Bags	880
Gmm	2.435

Bags	73.7
Dry	1514.4
Sub + Bags	882.3
Gmm	2.426

	Rice	Dry Back	CoreLok
Averages	2.431	2.425	2.431
Stddev	0.0057	0.0016	0.0062

Table 35 - MP DATA

MP

9.5mm 28 LS - 27 Slag - 45 Sand +0.5% AC

Rice

Dry	1514.6
Submerged	2143.4
Gmm	2.419

Dry	1509.9
Submerged	2140.2
Gmm	2.417

Dry Back

Dry	1514.6	
Submerged	2143.4	
Drying Rack	6312.2	
DB 1	7831.1	1518.9
DB 2	7829.2	1517
DB 3	7828.7	1516.5
DB 4		
DB 5		
Gmm	2.411	

Dry	1509.9	
Submerged	2140.2	
Drying Rack	7334.5	
DB 1	8859.3	1524.8
DB 2	8850.2	1515.7
DB 3	8847.5	1513
DB 4	8846.2	1511.7
DB 5	8845.8	1511.3
Gmm	2.412	

CoreLok

Bags	74
Dry	1525.8
Sub + Bags	887.1
Gmm	2.419

Bags	74.7
Dry	1499.1
Sub + Bags	870
Gmm	2.414

Rice		**Dry Back**		**CoreLok**	
Averages	2.418	Averages	2.411	Averages	2.416
Stddev	0.0012	Stddev	0.0001	Stddev	0.0038

Table 36 - HP DATA

HP

13 LS - 42 Slag - 45 Sand +0.5% AC

Rice

Dry	1511.4
Submerged	2135.9
Gmm	2.397

Dry	1511.7
Submerged	2137.5
Gmm	2.403

Dry Back

Dry	1511.4	
Submerged	2135.9	
Drying Rack	7334.5	
DB 1	8850	1515.5
DB 2	8848.1	1513.6
DB 3	8847.5	1513
DB 4	8847.2	1512.7
DB 5		
Gmm	2.392	

Dry	1511.7	
Submerged	2137.5	
Drying Rack	6312.2	
DB 1	7827.4	1515.2
DB 2	7825.6	1513.4
DB 3	7825.1	1512.9
DB 4		
DB 5		
Gmm	2.398	

CoreLok

Bags	74.5
Dry	1510.4
Sub + Bags	872.6
Gmm	2.398

Bags	74.4
Dry	1511.9
Sub + Bags	874.4
Gmm	2.402

	Rice	Dry Back	CoreLok
Averages	2.400	2.395	2.400
Stddev	0.0038	0.0041	0.0025

Table 37 - LPM DATA

LPM

43 LS - 12 Slag - 45 Sand +0.5%AC + 2%MC

Rice

Dry	1509.2
Submerged	2143.4
Gmm	2.431

Dry	1511.7
Submerged	2145.5
Gmm	2.434

Dry Back

Dry	1509.2	
Submerged	2143.4	
Drying Rack	6312.2	
DB 1	7831.1	1518.9
DB 2	7827.7	1515.5
DB 3	7825.8	1513.6
DB 4	7824.6	1512.4
DB 5	7824.2	1512
Gmm	2.420	

Dry	1511.7	
Submerged	2145.56	
Drying Rack	7334.5	
DB 1	8852.5	1518
DB 2	8851.3	1516.8
DB 3	8850.1	1515.6
DB 4	8849.2	1514.7
DB 5	8848.7	1514.2
Gmm	2.424	

CoreLok

Bags	74.3
Dry	1510.2
Sub + Bags	879.7
Gmm	2.426

Bags	73.8
Dry	1509.9
Sub + Bags	881.2
Gmm	2.432

Rice		Dry Back		CoreLok	
Averages	2.432	Averages	2.422	Averages	2.429
Stddev	0.0017	Stddev	0.0027	Stddev	0.0045

Table 38 - MPM DATA

MPM

28 LS - 27 Slag - 45 Sand +0.5% AC +2% MC

Rice

Dry	1510.7
Submerged	2140.2
Gmm	2.415

Dry	1509.5
Submerged	2142.9
Gmm	2.428

Dry Back

Dry	1510.7	
Submerged	2140.2	
Drying Rack	7334.4	
DB 1	8855.1	1520.7
DB 2	8852.1	1517.7
DB 3	8850.6	1516.2
DB 4	8850.1	1515.7
DB 5		
Gmm	2.396	

Dry	1509.5	
Submerged	2142.9	
Drying Rack	6312.2	
DB 1	7834.5	1522.3
DB 2	7830.8	1518.6
DB 3	7828.5	1516.3
DB 4	7827.5	1515.3
DB 5	7827.2	1515
Gmm	2.407	

CoreLok

Bags	74.1
Dry	1514.4
Sub + Bags	882.1
Gmm	2.426

Bags	73.7
Dry	1511.8
Sub + Bags	880.6
Gmm	2.426

	Rice	Dry Back	CoreLok
Averages	2.422	2.402	2.426
Stddev	0.0093	0.0078	0.0000

Table 39 - HPM DATA

HPM

13 LS - 42 Slag - 45 Sand + .5%AC + 2%MC

Rice

Dry	1513.1
Submerged	2137.7
Gmm	2.400

Dry	1507
Submerged	2135.6
Gmm	2.406

Dry Back

Dry	1513.1	
Submerged	2137.7	
Drying Rack	7335.4	
DB 1	8861	1525.6
DB 2	8858	1522.6
DB 3	8857.1	1521.7
DB 4	8856.3	1520.9
DB 5	8855.9	1520.5
Gmm	2.372	

Dry	1507	
Submerged	2135.6	
Drying Rack	6312.2	
DB 1	7835.9	1523.7
DB 2	7830.7	1518.5
DB 3	7828.3	1516.1
DB 4	7827.5	1515.3
DB 5	7827.1	1514.9
Gmm	2.376	

CoreLok

Bags	74.7
Dry	1519.3
Sub + Bags	880.4
Gmm	2.408

Bags	74.8
Dry	1507.5
Sub + Bags	873.7
Gmm	2.409

Rice		Dry Back		CoreLok	
Averages	2.403	Averages	2.374	Averages	2.409
Stddev	0.0040	Stddev	0.0025	Stddev	0.0006