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Cracking And Rutting Performance Of Field And Laboratory Hma Mix Designs

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CRACKING AND RUTTING PERFORMANCE OF FIELD AND LABORATORY HMA MIX DESIGNS

by

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This thesis, submitted by Anthony Berg in partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Anthony Berg
Date 12/13/2016

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ABSTRACT

The ability to create a hot-mix asphalt (HMA) design in a laboratory setting that matches the HMA mix that was done in a field setting is important to ensure proper mixing techniques are being done in both situations. A laboratory setting is a more controlled environment compared to the field where the environment can be more complicated with heat and weather control. Doing performance measures such as rutting and cracking resistance are viable tests to see the effect of lab versus field mix. The research was done to compare laboratory and field mix when it came to rutting resistance and cracking performance of HMA mixes. Performance grade (PG) 58-28 and PG64-28 were considered for testing. Both performance grades were taken from highways in North Dakota with separate mix designs. The nominal maximum aggregate side (NMAS) for all mixes was 12.5mm. Ten specimens for both lab and field (mixes 150 mm diameter and 75 mm high) were compacted to a target of 7% air voids using a gyratory compactor. Six were used for the Asphalt Pavement Analyzer (APA), which measured rutting resistance of the specimens. The remaining four were used to find cracking resistance using the Disk-Shaped Compact Tension (DCT) test. The DCT was performed at 10^{o}C above the PG lower limit of the asphalt binders in the mixes. Cracking resistance was measured in terms of fracture energy. The results showed that for PG58-28 the lab mix rutted less than field mix whereas PG64-28 showed field mix rutting less than lab mix. The lab mix performed better than field mix in cracking resistance for both performance grades.

CHAPTER I

INTRODUCTION

Hot Mix Asphalt Pavement

Hot mix asphalt (HMA) pavement is one of the more widely used road pavement designs. There is also cold mix asphalt pavement and concrete pavement. HMA pavement is formed by mixing hot aggregate material with hot asphalt binder to create a solid but flexible layer of what is called asphalt pavement. It requires machines or storage containers that can achieve high temperatures to heat the ingredients before mixing can occur. This research paper focuses on the comparison of laboratory and field HMA mixes.

Asphalt Pavement Failures

There are numerous ways that asphalt pavement can fail and it is necessary to understand how the components of a HMA design work. A full asphalt pavement design consists of three layers which include the asphalt pavement, sub-base aggregate layer, and a sub-grade. Any of these three layers can fail, which could lead to one or more of the subsequent layers failing.

Fatigue cracking, low temperature cracking, and rutting are the three major and most common asphalt pavement failure modes. Low temperature cracking is more prominent in the northern states and occurs when the pavement freezes and the pavement becomes stiff. Fatigue cracking occurs because of repetitive traffic loading on a pavement at a wide range of temperatures. Rutting is caused by poor compaction of any of the three layers causing the pavement layer to deform. Another way rutting can happen is by high pavement temperatures that occur during the summer months. Rutting is unique to asphalt and will not happen in concrete. In this research paper the previous three failure types are compared for laboratory and field mix designs.

Problem Statement

Ensuring that a field mix can be reproduced in the laboratory is essential. Having the ability to compare the two can show whether or not mixing done in the field, which can be more difficult to control, can be replicated and the same properties can be achieved in a more controlled environment of a laboratory setting. Doing various performance tests on prepared asphalt pavement samples created from both the field and lab mixes can provide evidence to show if the two produce similar results. The secondary problem statement was to investigate the effect of reclaimed asphalt pavement (RAP) on the performance of asphalt pavement with lab and field mixes.

Objectives of Study

Objectives of this research are to:

1. Compare field and laboratory HMA mix cracking properties.
2. Compare field and laboratory HMA mix rutting resistance.
3. Investigate the effect of RAP on performance properties for field and laboratory mixes.

Organization of Thesis

Chapter I gives slight background on HMA mix and what types of asphalt pavement failure can occur. Chapter II expands on Chapter I and gives more detail on how HMA mixes are designed. It also goes into further detail on each asphalt pavement failure. Chapter III deals with methodology which includes material selection, mix designs, mixing and compaction procedures, performance testing procedures, and data analysis. Chapter IV is the actual results collected and analyzed from the research. Chapters V includes the conclusions, limitations and future work.

Chapter II

LITERATURE REVIEW

Superpave Mix Design

While hot mix asphalt (HMA) pavement is one type of pavement design, there are several other such as virgin mix, recycled asphalt mix, or dense-graded mix design. A Superior Performing Asphalt Pavement (Superpave) mix design is a comprehensive design method that incorporates all of design types to create a mix in which certain performance requirements are met. Creating an economical blend of asphalt binder and aggregate is the main objective of Superpave mix design where the mix has sufficient asphalt binder, voids in the mineral aggregate (VMA), air voids, workability and satisfactory performance over the pavement's service life (Cominsky et al 1994).

When it comes to the Superpave mix design there are several distinctive features of the method. Performance based and related properties are used in the selection of the mix design. Performance based properties are useful in predicting how a pavement will respond to a given load such as traffic or environmental loading. From the predicted performance of the pavement the asphalt and aggregate mixture is selected. This asphalt-aggregate mixture can be adjusted accordingly to comply with specifications such as rut depth, area of fatigue cracking, and spacing of low-temperature cracking to be expected over the design life. Superpave mix can integrate mix design and structural design into one system. By integrating the two, Superpave can provide an objective measure of the pros and cons of using different materials with varying levels of quality (Cominsky et al 1994).

Creating a Superpave mix design has numerous steps including: aggregate selection, asphalt binder selection, density and voids calculations, and optimum binder content selection (Winkle 2014). Aggregates in a mix design is the largest component compared to asphalt binder and air voids. They are selected based on consensus properties, source properties, availability, and economics. Consensus properties are coarse aggregate angularity, fine aggregate angularity, flat and elongated particles, and clay content. Source properties are toughness, soundness, and deleterious material (Teng 2001). After aggregates are selected, the asphalt binder grade needs to be selected and this is done by predicting the maximum and minimum pavement temperatures for the design area. Having selected the aggregate and binder types, samples can be made at varying binder contents to find volumetric properties. Using these samples, graphs can be made to find the optimum binder content based on air voids of 4% (Winkle 2014).

Superpave Binder Performance Grading

Superpave binder has its own grading system with a maximum and minimum performance temperature of the binder. For example, PG64-28, this means the maximum temperature of the binder is 64 degrees Celsius and the minimum temperature is negative 28 Celsius. The two temperatures mean that within the maximum and minimum range the asphalt binder will perform as expected. If the temperature goes beyond the range, then the binder could fail and have significantly reduced performance. In order to test the binder strength, a dynamic shear rheometer is used for both the high and low temperature ratings. These ratings are based on the asphalt binders resistance to rutting, fatigue cracking, and low-temperature cracking. Being based on these criteria is unique to the Superpave classification (Teng 2001).

Asphalt Pavement Rutting

The Federal Highway Administration defines rutting as a longitudinal surface depression in the wheel path. It may have associated transverse displacement (Miller and Bellinger 2014). Rutting is one of three major asphalt pavement distresses measured. It is unique to asphalt because it is a flexible pavement compared to concrete which is rigid. Permanent deformation of the HMA layer is another way to state rutting. Rutting can occur because of issue with the HMA layer, base or sub-grade. Repetitive loading of the asphalt is what causes ruts to form because with each load a small amount of unrecoverable strain accumulates. This value may be extremely small but with enough loads over a period of time the rut depth can be significant (Brown et al 2001). To minimize rutting of a pavement, stress analysis is done so the strength of the layers can be found under varying loads. Structural designs, mix designs, and construction are all performed with the goal of minimizing rutting (White et al 2002).

Mix design properties can have an impact on rutting performance. The performance grade of the binder used has a positive or negative effect on rut depth. If a higher PG is used the rut depth tends to decrease because the higher PG's are a stiffer binder. Conversely, if you have a higher binder content the rut depth will increase since the mix will be more flexible. Nominal Maximum Aggregate Size (NMAS) will affect rutting as well. The higher the NMAS, rut depth decreases. It was found to not be a strong relationship but there could be justification in that larger aggregates are stronger and resist deformation easier (Williams 2002). Having a higher number of small aggregates could reduce rutting as well because they are more tightly packed and will resist rutting due to the already high level of compaction. Reclaimed Asphalt Pavement (RAP) included in a mix design contributes to the reduction in permanent deformation. RAP is a stiff material from being in service. When a mix has a larger percentage of RAP the rut depth tends to decrease at the same number of simulated traffic passes (Winkle 2014). In another study, done by Xiao et al 2005, similar results to Winkle were found. They used RAP along with rubber mesh to improve performance properties. Two different aggregate sources were tested as well. As expected, when RAP was increased the rut depth generally decreased. It should be noted that the two aggregate sources had significant differences in rut depth along with the RAP (Xiao et al 2005).

Asphalt Pavement Fatigue Cracking

Fatigue cracking occurs in areas where there are repeated traffic loadings. The cracks may be smaller individual cracks or a series of interconnected cracks. In its severe stages, fatigue cracking is often referred to as alligator cracking (Miller and Bellinger 2014). This type of failure is considered more of a structural failure than a material failure. The big structural issue that happens is inadequate drainage of one or more layers. Poor drainage leads to the softening of a particular layer and make the structure weak and prone to higher deflections when loaded. From this repetitious loading resulting in high strains a crack is able to form either from the top or bottom of the HMA layer. It is thought that a fatigue crack will start at the bottom for thin HMA layers and at the top for thicker layers (Brown et al 2001).

Testing of the mix design fatigue cracking performance is done by the Semi-Circular Bending (SCB) Fracture Test. Through these tests it was shown that varying temperature has a significant effect on fracture energy, which is the measurement of crack formation. Fatigue cracking simulations can be done at a wide range of temperatures but intermediate temperatures are the generally accepted testing area. This range is 20 to 25 degrees Celsius. A test was done at three different temperatures: 15, 21, and 40 degrees Celsius to see how fatigue cracking changed with a range of temperatures. From this experiment, it was determined that 21 degrees

Celsius was the best choice because it had the least amount of testing repeatability. The lowest testing temperature gave the highest peak load whereas the higher testing temperature gave the lowest peak load. This is expected because of asphalt binder's viscoelastic properties. Also from a practical standpoint, testing near room temperature made the most sense since any sophisticated conditioning chamber to test at larger temperature ranges is not needed (Nsengiyumva 2015). Reclaimed asphalt pavement (RAP) mixes are also tested for fatigue cracking. With the introduction of RAP into the mix design, it was shown that generally as the amount of RAP increased, the fracture energy was lower in most cases. This experiment depended on temperature as well. When the temperature was decreased the fracture energy decreased as well (Tang 2014). Both of the results in relation to RAP are expected since RAP makes a mix stiffer. How much stiffer, depends on the amount of RAP introduced in the mix.

Asphalt Pavement Low-Temperature Cracking

Low temperature cracking is common to the northern United States and Canada due to the lower temperatures during the winter months. This distress is caused by the shrinking of asphalt pavement in cold weather. From that, it is known that low temperature cracking is an environmental issue compared to a traffic loading issue like fatigue cracking. However, low temperature cracking can happen from fatigue due to freezing and unfreezing cycles. Most cracks of this nature are from a single low temperature event. When the pavement shrinks, a tensile stress is formed and the cracking starts when the stress exceeds the tensile strength of the pavement. Tension is also created because when asphalt gets cold, it stiffens and acts more like concrete. Cracks start at the top of the HMA layer and propagate downwards (Brown et al 2001).

Like with fatigue cracking, there is a certain test to help analyze this issue in the lab. The SCB can be used but the more common way is the DCT. Samples are cooled down to a desired testing temperature and subjected to a tension stress like how it would happen in a real world scenario. From a pooled study done by the University of Minnesota it was shown that the fracture energy varied with the roads tested at low temperature. The fracture energy did trend downward as the road importance decreased from interstates to US highways. The SCB tests were done at low temperatures and the same trends continued as with the DCT results related to fracture energies of different roads. (Marasteanu et al 2007). Again with low temperature testing, RAP has been added to designs. When RAP was added and tested with the DCT, the results implied that as RAP percentage increases the fracture energy decreased with PG58-28. In the same study, PG64-22 had a more significant variation. It increased to a peak at 30% RAP and then fracture energy decreased as RAP increased (Behnia et al 2011). There are certain observations that could be made from Behina's results.The PG58-28 results are to be expected because as more RAP is added, it makes the already stiff mix at low temperature that even stiffer and would result in a brittle material susceptible to lower fracture enegies. The PG64-22 case is curious since those are not the expected results. One would expect a trend downwards from the beginning and further testing probably needs to be done to explain why there is a rise and then fall.

Laboratory vs. Field Mix Performance

The purpose of comparing laboratory and field mix is to ensure that there is a correlation between the two. Having a strong correlation between the mixes indicates that procedures of mixing done in the field are similar to those done in the laboratory. Doing tests on lab and field mixes are a way of doing Quality Assurance and Quality Control (QA/QC). Field tests are done by the contractor while lab tests are usually done by the agency. When comparing lab and field mix, both are analyzed by the agency. Common tests preformed are volumetric tests such as specific gravities and voids mixed with asphalt. Paired t-tests are analyzed between the lab and field mixes. It was found that certain aspects of the volumetric properties correlate. When a property does not correlate it means that the differences are likely to occur from chance (MDOT, 2014).

Another set of test preformed are performance tests. These include rutting and cracking resistance. Rutting resistance is analyzed using the Asphalt Pavement Analyzer (APA). The APA results can be compared to field rutting data. Also, the APA results can be correlated to the air voids of the specimens. When specimens have higher air voids, it is expected that rut depths are higher because there is extra space for compression under wheel loads. Doing a comparison between lab and field mixes of the APA is another QA/QC technique. It was shown that there was little to no correlation between the rut depths and air voids. R-squared values, which is the correlation value, were 0.11 and 0.12 in a few different experiments (Brown and Cross, 1991).

CHAPTER III

RESEARCH METHODOLOGY

Material Selection

The aggregate and binder materials used for this research were pre-selected by Knife River Materials and Danny Schmidt. The aggregates were donated by each of the pits for the individual mix designs. Fordville was responsible for the PG58-28 aggregates and Deerwood township along with Kittson Co MN donated aggregates for PG64-28. In the northern states, it is common to use PG58-28 and PG64-28 asphalt binders. These two binder grades were selected because of the extreme temperature ranges that can occur within North Dakota. Asphalt binder was donated by Flint Hills Resources and Husky Energy. The RAP was donated from the removal of the old asphalt pavement being replaced on the respective roadways being studied. Both roads being analyzed are in North Dakota. The PG58-28 mix design was done on North Dakota State Highway 32 while the PG64-28 mix design was done on Interstate 29.

HMA Mix Design

Two different mix designs were used, one for the PG58-28 and the other for PG64-28. This was done because two individual field mix designs were analyzed in this research. Both mix designs were provided by the mix design technician, Danny Schmidt. This HMA mix design was based off the AASHTO MP2 specification for Superpave volumetric mix design. Tables 1 and 2 show the mix gradations of the individual aggregates and blend gradation of PG58-28 and PG64-28, respectively. Figures 1 and 2 are sample showings of the aggregates used in the mix designs.

Table 1. PG58-28 Aggregate Gradation

	N Fines	Rock	Washed Dust	Dirty Dust	RAP Recycled Pavement	Blend Gradation	Lower Control Pt	Upper Control Pt
Sieve Size	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing
5/8" (16mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2" (12.5mm)	100.0	92.0	100.0	100.0	94.0	96.6	90.0	100.0
3/8" (9.5mm)	99.0	62.0	100.0	100.0	80.0	85.5		
#4 (4.75mm)	83.0	3.0	86.0	93.0	62.0	59.0		
#8 (2.36mm)	65.0	1.0	45.0	68.0	44.0	40.7	28.0	58.0
#16 (1.18mm)	45.0	1.0	26.0	47.0	31.0	27.5		
#30 (0.6mm)	23.0	1.0	14.0	33.0	20.0	16.3		
#50 (0.3mm)	8.0	1.0	7.0	23.0	12.0	8.7		
#100 (0.15mm)	6.0	1.0	4.0	16.0	8.0	6.0		
#200 (0.075mm)	4.5	1.0	2.1	12.7	6.8	4.7	2.0	7.0
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2. PG64-28 Aggregate Gradation

	N Fines	Rock	Washed Dust	Dirty Dust	RAP Recycled Pavement	Blend Gradation	Lower Control Pt	Upper Control Pt
Sieve Size	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing
5/8" (16mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2" (12.5mm)	100.0	100.0	100.0	100.0	98.0	99.6	90.0	100.0
3/8" (9.5mm)	100.0	63.0	100.0	100.0	91.0	91.5		
#4 (4.75mm)	90.0	2.0	81.0	81.0	74.0	66.2		
#8 (2.36mm)	76.0	1.0	42.0	53.0	55.0	41.3	28.0	58.0
#16 (1.18mm)	62.0	1.0	25.0	37.0	40.0	28.1		
#30 (0.6mm)	47.0	1.0	13.0	28.0	29.0	18.5		
#50 (0.3mm)	26.0	1.0	9.0	21.0	18.0	12.0		
#100 (0.15mm)	5.0	1.0	4.0	13.0	12.0	6.0		
#200 (0.075mm)	2.9	1.0	2.2	10.8	8.6	4.1	2.8	7.0
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

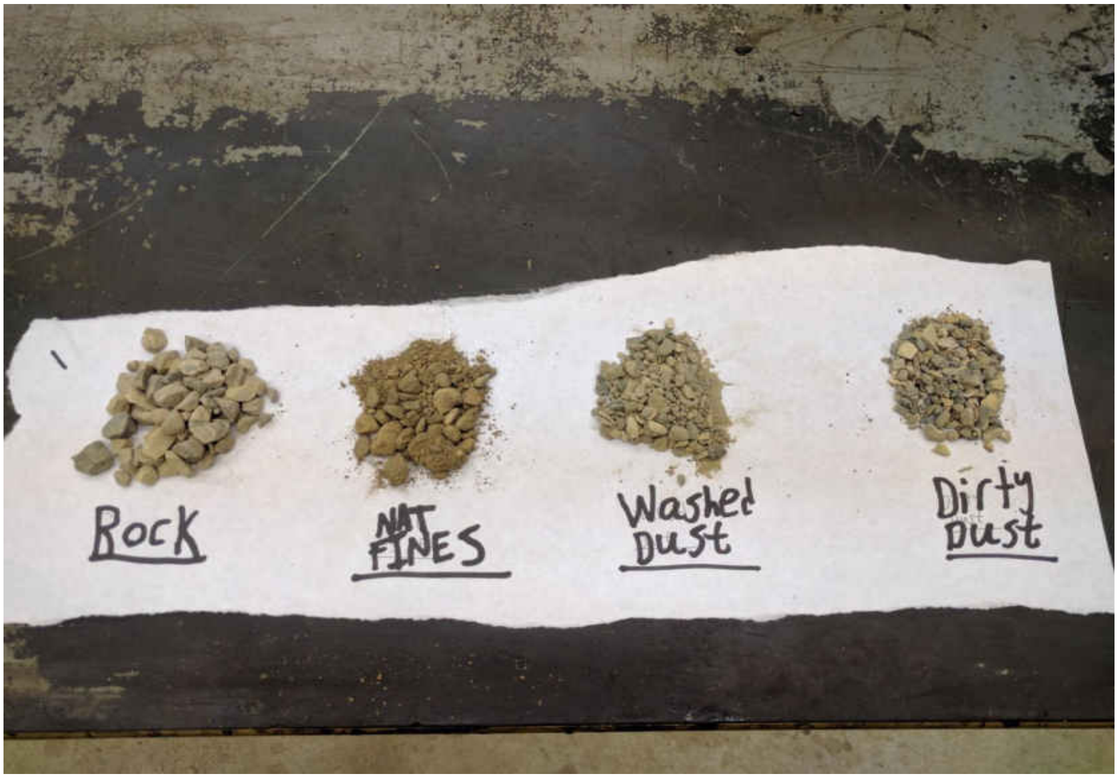

Figure 1. PG58-28 Mix Aggregates

Figure 2. PG64-28 Mix Aggregates

The 0.45 power charts of the sieve analysis are shown in Figures 3 and 4. They show the gradation and density of the aggregate blends. Along with these aggregate blends, asphalt binder needs to be added. For PG58-28, a total binder content of 6.1% needed to be obtained. This value includes the binder from the RAP so 4.4% virgin binder was added to the total aggregate and RAP mix weight. As for PG64-28, a binder content of 5.4% is the target which leads to 4.1% additional virgin binder added to the total aggregate and RAP weight.

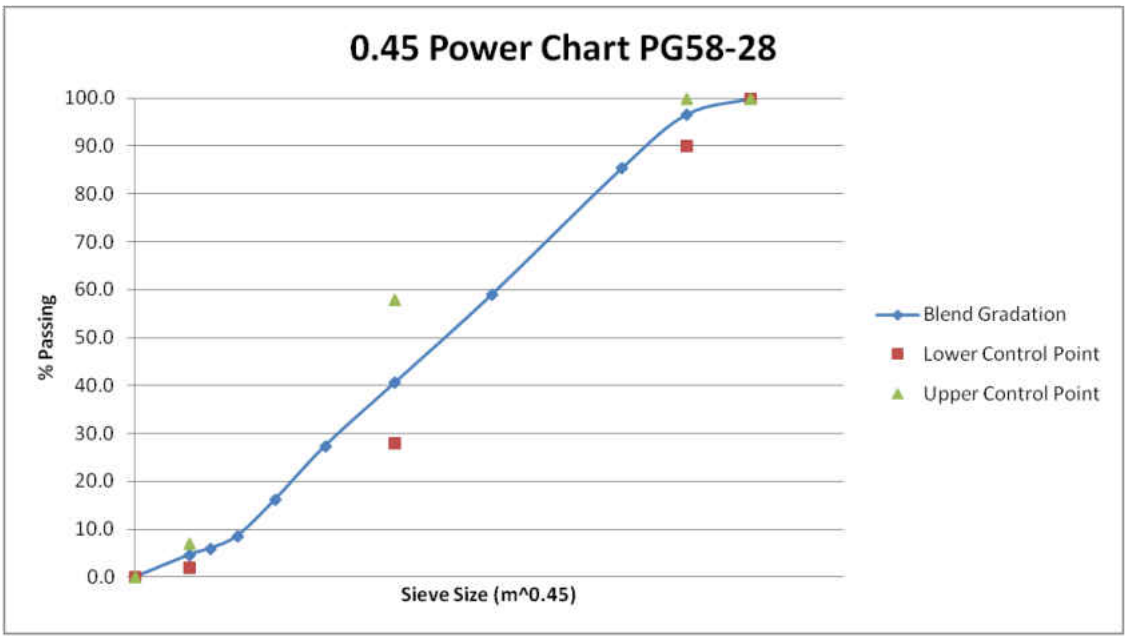

Figure 3. PG58-28 0.45 Power Chart

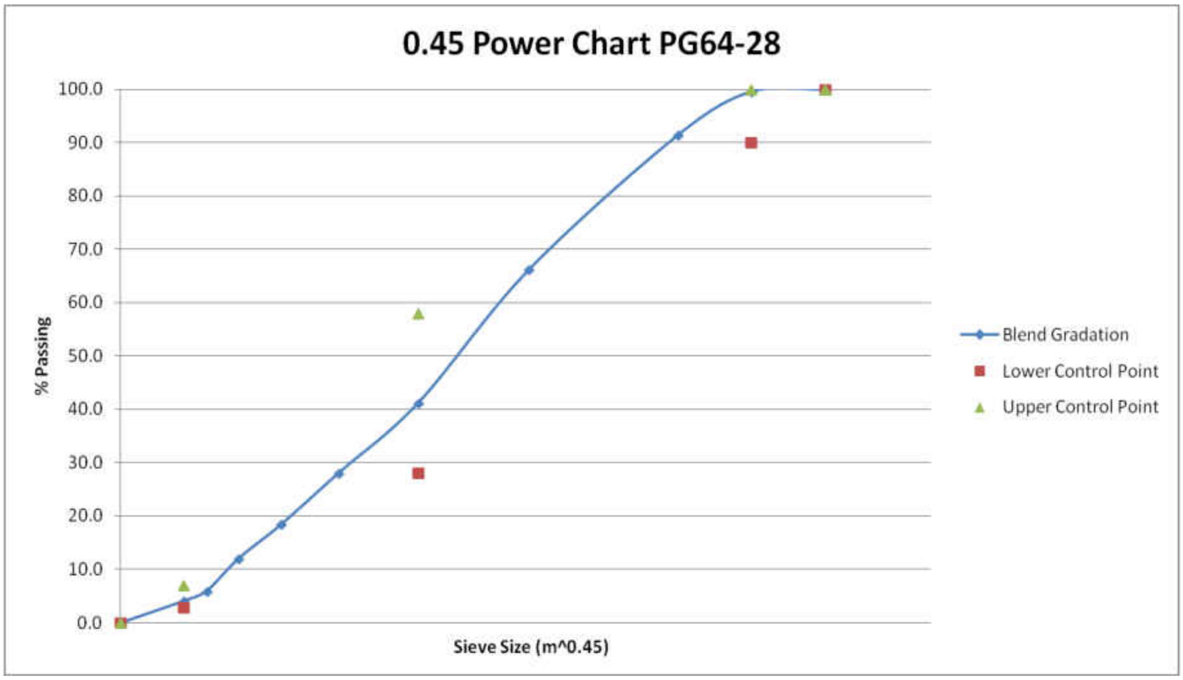

Figure 4. PG64-28 0.45 Power Chart

HMA Compaction

The compaction of the HMA samples were done using the SuperPave Gyratory Compactor (SGC) by following ASTM D6925-15. Field mixture was provided in specified containers and just needed to be reheated to compaction temperature. No additional steps were done to compact the field mix. Laboratory mixtures were required to be mixed using the lab equipment available. This was done by taking the measured proportions of aggregate, RAP, and virgin binder provided in Tables 3 and 4. Since the mix designs that were provided included RAP, a virgin mix had to be created. Additional proportions of aggregate were added to a virgin mixes by analyzing the gradation of the RAP in each performance grade. For each laboratory virgin sample created, a batch mix of 3100 grams was prepared. The mix designs are shown in Tables 3 and 4 as well. HMA requires that all of the components be at a certain temperature before mixing. The aggregates were heated to 325^{o}F, asphalt binder was heated to 290^{o}F, and RAP was heated to mixing temperature. The mixing temperature used was 280^{o}F.

Table 3. PG58-28 Mix Designs

PG 58-28	Virgin Mix		Mix with RAP	
Material	Percent	Mass (g)	Percent	Mass (g)
Natural Fines	25	727.7	19	566.3
Rock	38	1106.1	28	834.6
Dirty Dust	18	524.0	16	476.9
Washed Dust	19	553.1	13	387.5
RAP	0	0.0	24	698.7
Binder	6.1	189.1	4.4	136.0

Table 4. PG64-28 Mix Designs

PG64-28	Virgin Mix		Mix with RAP	
Material	Percent	Mass (g)	Percent	Mass (g)
Natural Fines	12	351.9	5	149.2
Rock	24	703.8	18	537.2
Dirty Dust	23	674.5	20	596.9
Washed Dust	41	1202.4	35	1044.6
RAP	0	0.0	22	645.2
Binder	5.4	167.4	4.1	126.8

Once the mix was completed, each batch mix was put into the oven for 2 hours to simulate a short term aging process. At the end of the aging period, samples were compacted using SuperPave Gyratory Compactor (SGC). As with mixing, all components of the compaction needed to be at a certain temperature. Compaction molds were placed in an oven heated to a compaction temperature, which was 275°F for this research. When the mold and mix are at the desired temperature, the mold is removed from the oven and a paper disk is placed inside the mold to prevent any mix from sticking to the bottom. A pre-weighted amount of asphalt mixture is placed in the mold and another disk is placed on the top. Then the mold is loaded into the SGC and compaction can begin. A ram is lowered by the machine to a pressure of 600 kPa and an angle of $1.25^{\circ} \pm 0.02^{\circ}$ to try and simulate a vehicle-tire interaction in the field. Compaction continues until the desired properties are reached and the ram retracts. Recorded values are the specimen height, %Gmm, and number of gyrations. Finally, extrude the specimen and remove the paper disks promptly.

In this research, the SGC was set to stop at a specimen height of 75 mm and air void percentage of 7 ± 1% was targeted. A trial and error process was done to find the appropriate mixture weight to be compacted to achieve the air void requirement. It was found through this and previous experiments done in the lab that the desired amount of mix was around 2900 grams. There were a total of four different mix designs used in this research. PG58-28 had two designs, one for the field and lab mix and one for the virgin mix. The same goes for the PG64-28 mix designs. Knowing that the two performance grade mix designs were not the same, the comparisons cannot be made between the two binder grades. To determine the air voids of the compacted samples, the dry weight, saturated surface dry (SSD) weight, water submerged weight, and maximum specific gravity (Gmm) of the mix were needed. The Gmm of the mixes were assumed to be the same as the field mix properties provided. By using the three different weights, the bulk specific gravity (Gmb) of the mix could be determined. The air voids were found by using the Gmm and Gmb. Tables 5 and 6 are sample summary tables of the specimens. They show the three different weights and calculated Gmb and subsequent air void content. Figures 25 and 26 in the Appendix show the summary of the mix properties and volumetrics of the field mix provided for the research.

Table 5. PG58-28 Sample Properties

Field Specimens									
Specimen	Mass (g)	Height (mm)	Rev	Gmm (%)	Dry (g)	Wet (g)	SSD (g)	Gmb	Air Voids (%)
1	2900	74.91	29	91.6	2848.4	1575.4	2865.4	2.208	7.96
2	2885	74.91	42	91.5	2883.7	1611.8	2903.3	2.233	6.93
3	2885	74.91	41	91.1	2887	1615.7	2904.5	2.240	6.62
4	2885	74.97	48	91	2887.7	1614.1	2904.7	2.237	6.73
5	2885	74.91	74	91.1	2887.3	1601.3	2899.4	2.224	7.28
6	2885	74.97	72	91	2886.7	1601.7	2900	2.223	7.32
7	2885	74.97	71	91	2879.7	1601.8	2896.9	2.224	7.31
8	2885	74.91	78	91	2883	1608.1	2896.8	2.237	6.75
9	2885	74.97	88	91	2877.3	1600	2891.9	2.227	7.16
Laboratory Specimens									
Specimen	Mass (g)	Height (mm)	Rev	Gmm (%)	Dry (g)	Wet (g)	SSD (g)	Gmb	Air Voids (%)
1	2885	74.97	65	91	2879.9	1602.5	2894.1	2.230	7.06
2	2885	74.97	56	91	2886.8	1599.6	2896.2	2.226	7.19
3	2885	74.97	58	91	2889.5	1606.9	2903.7	2.228	7.12
4	2885	74.97	50	91	2884.9	1598.2	2896.5	2.222	7.38
5	2885	74.97	49	91	2884.7	1604.7	2899.1	2.229	7.10
6	2885	74.91	57	91.1	2885.5	1601.4	2898.8	2.224	7.29
7	2885	74.97	58	91	2877.7	1594.9	2892.7	2.217	7.57
8	2885	74.97	83	91	2886.4	1602.9	2901.7	2.222	7.36
9	2885	74.91	75	91.1	2883.7	1594.6	2895.4	2.217	7.59
10	2885	74.97	60	91	2878.4	1592.4	2894.6	2.210	7.86
Virgin Specimens									
Specimen	Mass (g)	Height (mm)	Rev	Gmm (%)	Dry (g)	Wet (g)	SSD (g)	Gmb	Air Voids (%)
1	2910	74.97	114	93.1	2899.5	1612.4	2907.4	2.239	6.67
2	2895	74.97	72	91.4	2904.3	1620.5	2910.9	2.251	6.18
3	2895	74.97	61	91.4	2900.9	1614.5	2910.2	2.239	6.67
4	2895	74.97	53	91.4	2897.2	1616.8	2904.8	2.249	6.24
5	2895	74.91	53	91.4	2893.6	1607.4	2902.9	2.234	6.90
6	2895	74.97	62	91.4	2893.2	1606.9	2902.3	2.233	6.90
7	2895	74.97	86	91.4	2898.2	1610.7	2905.8	2.238	6.72
8	2895	74.97	58	91.4	2898.6	1612.6	2905.3	2.242	6.53
9	2890	74.91	63	91.3	2883.4	1593.5	2888.8	2.226	7.21
10	2890	74.91	90	91.2	2890.5	1606.7	2899.9	2.235	6.83

Table 6. PG64-28 Sample Properties

Field Samples									
Specimen	Mass (g)	Height (mm)	Rev	Gmm (%)	Dry (g)	Wet (g)	SSD (g)	Gmb	Air Voids (%)
1	2975	74.91	26	90.6	2983.2	1701.1	2998	2.300	7.58
2	2990	74.97	33	90.9	2999.7	1720.1	3017.8	2.312	7.13
3	2990	74.97	39	90.9	2993.6	1722.2	3013.3	2.319	6.84
4	2990	74.97	28	91	2993.9	1716.1	3011.8	2.311	7.17
5	2990	74.91	25	91	2989.6	1717	3008.3	2.315	6.98
6	2990	74.86	26	91.1	2991.5	1720.1	3014.6	2.311	7.15
7	2990	74.86	30	91.1	2987.2	1711.1	3007.7	2.304	7.44
8	2990	74.91	31	91	2991.2	1718.8	3007.3	2.321	6.73
9	2990	74.97	30	90.9	2987.3	1714.8	3004.3	2.317	6.93
10	2990	74.86	34	91.1	2990.8	1717.6	3007.3	2.319	6.83
Laboratory Samples									
Specimen	Mass (g)	Height (mm)	Rev	Gmm (%)	Dry (g)	Wet (g)	SSD (g)	Gmb	Air Voids (%)
1	2990	74.97	31	90.9	2988.8	1713.8	2999.7	2.324	6.62
2	2990	74.81	17	91.1	2985.8	1703.3	2995	2.312	7.13
3	2990	74.86	19	91.1	2989.3	1701.7	2997.2	2.307	7.29
4	2990	74.91	22	91	2990.8	1711.8	3001.2	2.320	6.81
5	2990	74.97	24	90.9	2990.7	1710.1	3004	2.311	7.14
6	2990	74.91	28	91	2986.7	1706.1	2997.1	2.313	7.05
7	2990	74.81	34	91.1	2988.6	1711.8	3000.5	2.319	6.83
8	2990	74.97	33	90.9	2985.7	1706.1	2998.4	2.310	7.18
9	2990	74.97	39	90.9	2989.8	1708.7	3002.5	2.311	7.16
10	2991	74.97	27	90.9	2982.6	1701.6	2998.4	2.300	7.59
Virgin Samples									
Specimen	Mass (g)	Height (mm)	Rev	Gmm (%)	Dry (g)	Wet (g)	SSD (g)	Gmb	Air Voids (%)
1	2990	74.81	29	91.1	2982.2	1701.2	2990.8	2.313	7.09
2	2990	74.86	19	91.1	2988.1	1703.7	2998.8	2.307	7.30
3	2990	74.97	31	90.9	2985.3	1703.3	2993	2.315	7.00
4	2990	74.86	18	91.1	2982.1	1704.4	2990.6	2.319	6.85
5	2990	74.97	39	90.9	2977.4	1700.3	2989.7	2.309	7.23
6	2990	74.86	11	91.1	2986.2	1697.4	2993.9	2.303	7.46
7	2990	74.91	31	91	2982.9	1701	2993.5	2.308	7.28
8	2990	74.86	30	91.1	2991.2	1705.3	3003.4	2.304	7.42
9	2990	74.97	18	90.9	2977.6	1697.4	2988.2	2.307	7.32
10	2990	74.76	21	91.2	2998.2	1715.2	3004.8	2.325	6.59

Data Collection

Two different testing machines were used to compare the mix designs. The Asphalt Pavement Analyzer (APA) was used to understand the rutting behavior of the asphalt at the upper limit of the performance grade. To determine cracking properties, the Direct Compact Tension Test (DCT) and Semi-Circular Bending (SCB) Test were done. The DCT was used for low temperate cracking and the SCB was done for fatigue cracking.

Asphalt Pavement Analyzer (APA)

The purpose of the APA machine is to analyze the rutting resistance of HMA mixes. AASHTO TP 63-03: "Standard Method of Test for Determining Rutting Susceptibility of Asphalt Paving Mixtures" was the standard used to do the APA testing. The molds of the APA in the lab are circular and the specimens created by the SGC were made to fit the molds at 150mm in diameter and 75 mm in thickness. Samples are tested at their upper PG temperature limits because asphalt is susceptible to rutting at higher temperatures. Doing a test at the upper limit creates an extreme scenario and shows one of the worst case rutting occurrences. The molds are loaded into the machine under a pressurized hose with a wheel load applied to the hose. Before the test begins, the specimens are conditioned at the testing temperature for 5 to 6 hours to make sure they are at a unified temperature. When the test begins, the wheel load is applied to the hose mechanism on a track moving back and forth over the molds. Hose pressure and wheel load are 690 kPa and 445 N (100 psi and 100 lb), respectively. The APA test is set to carry out 8,000 cycles and takes about 2 hours to complete. For each cycle, completed the APA records the average rut depth in millimeters and creates a rut depth vs. cycle graph. Any rut created in the APA should not exceed 12.5 mm because that is the failure rut depth.

Disk-Shaped Compact Tension Test (DCT)

Low temperature cracking is an important property to analyze when dealing with asphalt mix designs in the northern states. The DCT test is a common way to simulate a low temperature cracking scenario. This test was done following ASTM D7313-13. Sample preparation is a little more in-depth with the DCT. From the 75 mm thick specimens made, a circular saw cut was used to reduce the required thickness of 50 ± 5 mm. A flat face of 50 mm wide is cut along any part of the sample parallel to the thickness. Then a starter notch of 35 ± 2.5 mm is made at the center of the flat face. Two loading holes on either side of the prefabricated notch are made at 25 mm diameters with the center of the hole at 25 mm from the notch. Figure 5 shows the exact layout of these dimensions. Once the specimen is created, the DCT testing machine is used to run the test. If testing low temperature cracking, the sample is loaded into the machine at the test temperature to condition. The test temperature is specified at 10 degrees above the lower PG limit. For example, PG58-28 would be tested at -18^{o}C. Conditioning of the specimens should take 8 to 16 hours. When conditioning is completed, the test can proceed. The sample is loaded into the apparatus in the DCT machine. How the sample is setup for testing can be seen in Figure 6. The DCT equipment comes with a program showing how to run the machine. The sample is preloaded to 0.1 kN and then the test begins. It reaches a peak load and then descends back to the preloaded force to end the test. A graph of constant crack mouth opening (CMOD) versus peak load is graphed. Fracture energy is the main value that is one of the more generally accepted result numbers from the test. It is found by taking the area under the CMOD vs. peak load graph and dividing it by the specimen thickness times the initial ligament length. The given program does the calculation and the output is fracture energy given in J/m^2.

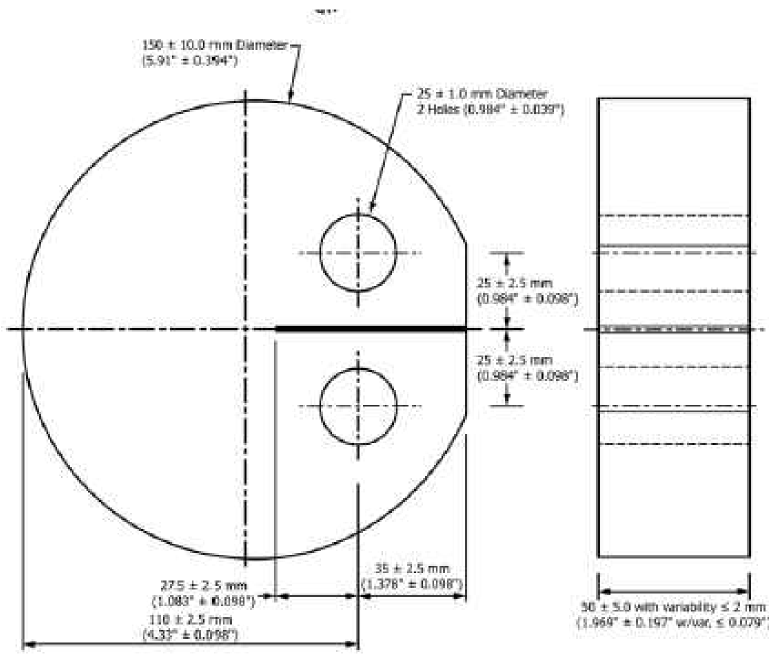

Figure 5. DCT Sample Dimensions (from ASTM D7313-13)

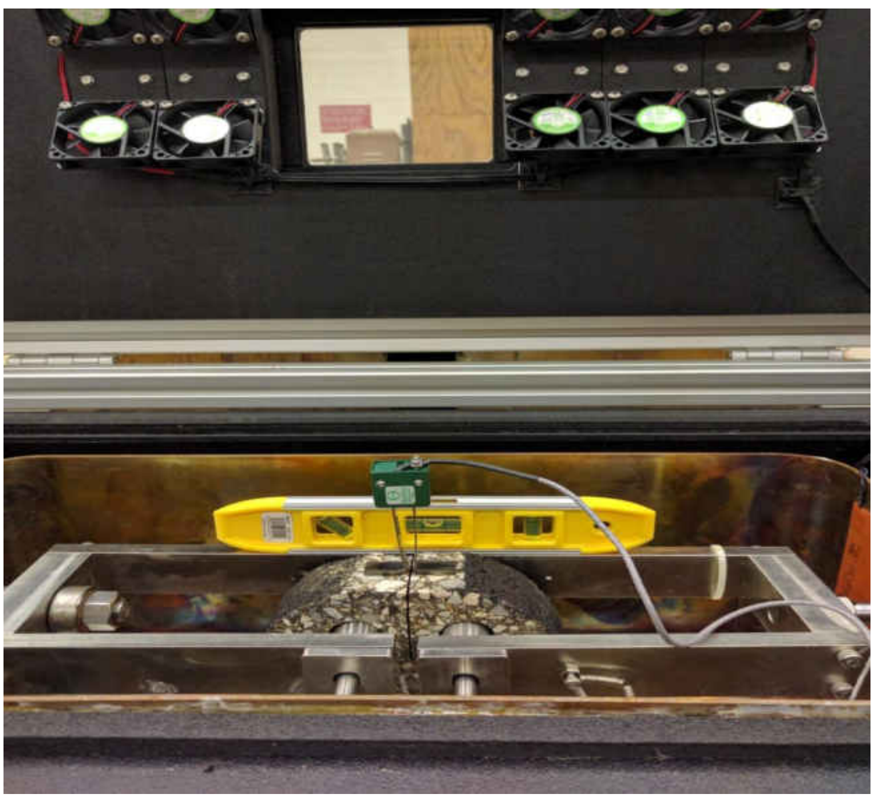

Figure 6. Setup of DCT Specimen

Semi-Circular Bending Test (SCB)

Unlike the other tests performed, the SCB does not have a standard test designated for it. Many states have varying ideas on how to perform the test based on sample thickness, notch length, and testing temperature. For this research, the Illinois - Flexibility Index Tester (I-FIT) was done because it is the most fine-tuned test that could accurately represent North Dakota's situations. Fatigue cracking is the property being analyzed with this test. Typically, a sample is tested at a thickness of 50 mm like the DCT but with the limited materials available, the samples tested were at 25 ± 2 mm. Like the name suggests the specimen is a semi-circle and a notch length of 15 mm is cut into the flat end of the semi-circle. The manufacturer made this machine to mainly test the DCT however, it was retrofitted it to accommodate the SCB test. Figure 7 gives an idea of how the SCB test is set up. Testing temperature is set at 25^{o}C or room temperature. Again, the manufacturer has software to run the I-FIT test. A preloaded force of 0.1 kN is applied and then the test runs. In this case nothing is graphed or the fracture energy is not given. With I-FIT they require the user to use their post processing software to get the fracture energy.

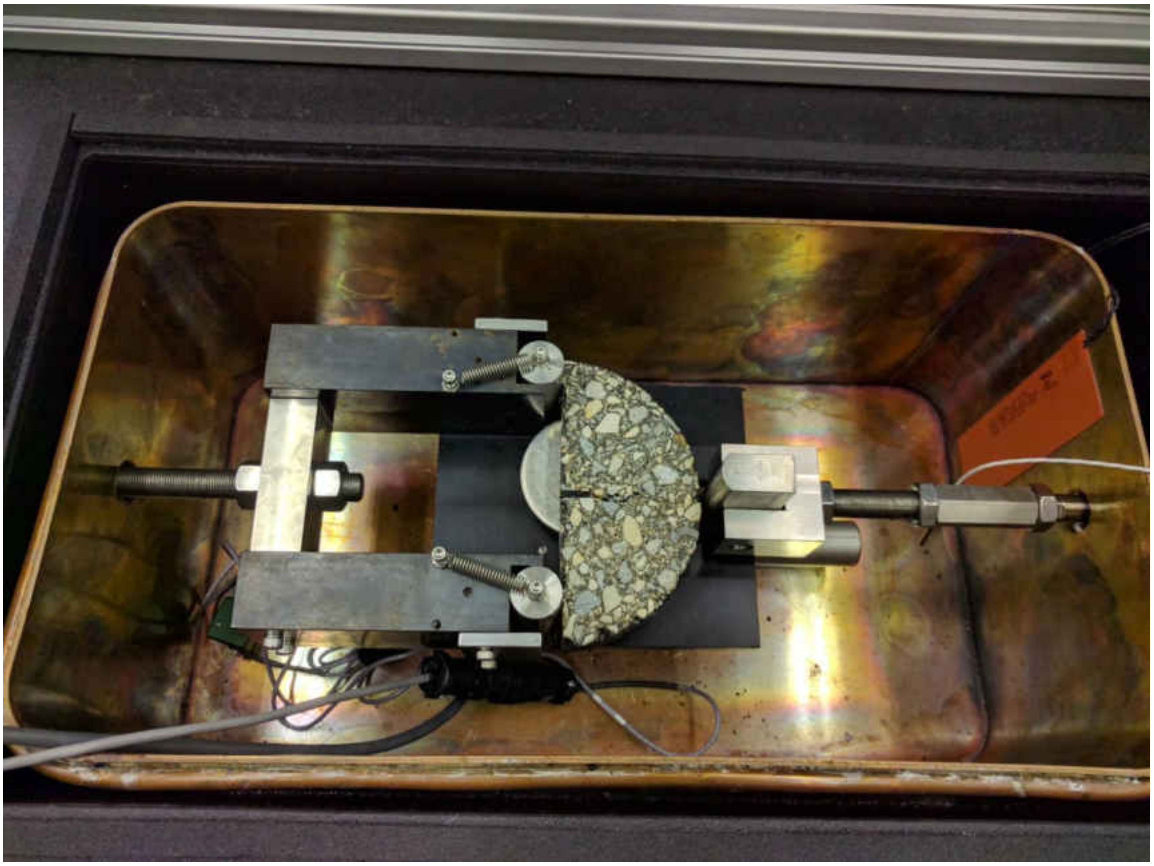

Figure 7. Setup of SCB Test

Data Analysis

Analysis of the data was the key to this research to understand performance properties of laboratory and field mixes. The results of the APA were analyzed by comparing rut depths at 2000, 4000, 6000, and 8000 passes. Values of the left, middle, and right molds were averaged, and the standard deviation and coefficient of variation were found. Also the progression of rut depth was calculated to see how much the rut depth slowed between pass checkpoints. Graphical images of the average rutting at designated passes of the virgin, lab and field mixes were created. Finally, independent t-tests were done to find out about statistical significance between mix designs at a 0.05 significance level. This means if the p-value was higher than 0.05 there is no statistical significant difference and there is a significant difference if the p-value is lower than 0.05.

As for the DCT and SCB, the analysis of the two were almost identical. The only difference is that for the SCB an extra step had to be taken to analyze the data given by the testing machine. To obtain fracture energy of fatigue cracking, the use of I-FIT's post processing software needed to be used. The data was in a text file and had to be uploaded to the software and then the fracture energy was calculated. When that was completed a full data analysis could take place. For both the DCT and SCB the average, standard deviation, and coefficient of variation of the fracture energies were calculated. Graphs of the average fracture energies made it easy to visually compare the three mix designs for both tests. Just like the APA, independent t-tests were done for statistical significance at the 0.05 significance level. All the results of the APA, DCT, and SCB are found in the next chapter.

CHAPTER IV

RESULTS AND DISCUSSION

Rutting Resistance

The use of the APA helped find the rutting resistance comparison of laboratory and field mixtures. Lab and field mixes are expected to have similar properties to ensure repeatability between the two mixing locations. Along with comparing lab and field mixes, a virgin mix design was tested that had no RAP in order to see how reclaimed asphalt affected rutting properties. Table 7 is a summary table of the average rut depths, standard deviations, and coefficients of variations for both PG grades tested. Each different mix had six specimens tested in the APA and then all the rutting values were averaged.

Table 7. APA Summary Results

Binder Grade	Mix	2000			4000			6000			8000		
		Avg (mm)	Std Dev (mm)	COV (%)	Avg (mm)	Std Dev (mm)	COV (%)	Avg (mm)	Std Dev (mm)	COV (%)	Avg (mm)	Std Dev (mm)	COV (%)
PG58-28	Virgin	1.33	0.13	9.72	1.61	0.22	13.81	1.78	0.22	12.12	1.88	0.29	15.23
	Lab	1.46	0.35	23.96	1.68	0.36	21.51	1.88	0.46	24.59	2.03	0.49	23.95
	Field	1.82	0.22	12.00	2.18	0.22	10.06	2.35	0.22	9.55	2.48	0.22	8.96
PG64-28	Virgin	3.52	0.99	28.26	4.56	1.32	28.83	5.15	1.41	27.33	5.60	1.38	24.73
	Lab	2.52	0.24	9.48	3.23	0.32	10.02	3.73	0.35	9.35	4.12	0.42	10.11
	Field	2.02	0.26	12.75	2.54	0.34	13.41	2.88	0.39	13.59	3.15	0.46	14.67

From Table 7, as expected from both binder grades when the number of passes increases to the maximum of 8,000 the rut depth of the specimens increases. At 2,000 passes PG58-28 showed interesting results where the virgin mix had the lowest averages while the field mix had the highest average rut depths. This trend continued as the passes increased. Having the virgin mix be the lowest value is not what is expected because it has no RAP in the mix design so it is expected that it would have the highest rut values. Comparing the lab and field results, throughout the test the field mix averaged a rut depth of 0.4 mm higher than the lab mix. PG 64-28 showed results more consistent with what would be expected from the APA with the mixtures in question. The field mix had the least amount of rutting, followed by the lab mix, and the largest depths were achieved by the virgin mix. Like with the PG58-28, the PG64-28 virgin design had zero percent RAP which should lead to lower rutting resistance and this was the case with PG64-28. By 8000 passes, the field mix had an average rut depth of 1 mm less than the laboratory mix. This could be contributed to the fact that the field mix had more aging time before testing which made the mix stiffer. Figures 8 and 9 give a visual representation of the average rutting resistance for each performance grade. Once the APA test was complete, Figures 10 and 11 are images of the final rut depth of the specimens after 8000 passes.

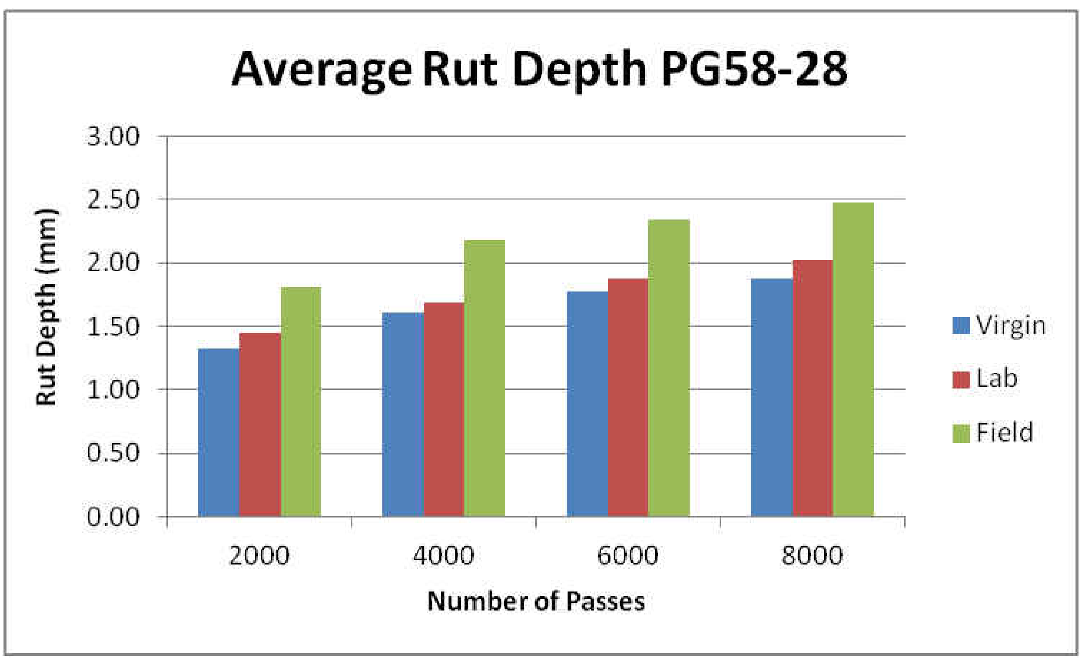

Figure 8. PG58-28 Average Rut Depth

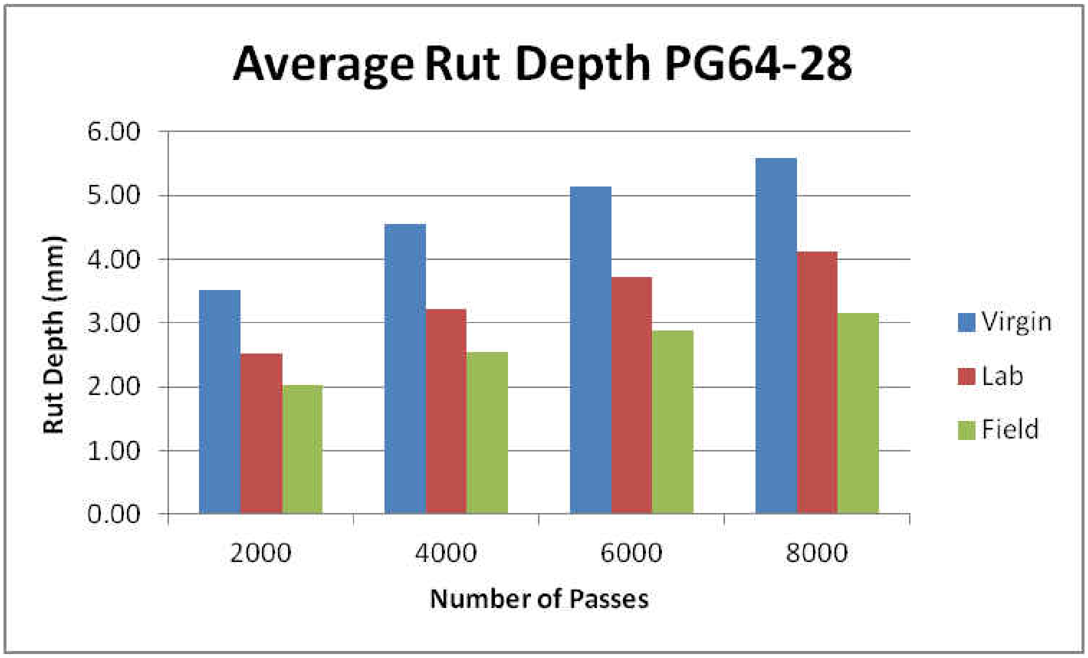

Figure 9. PG64-28 Average Rut Depth

Figure 10. PG58-28 Sample Rutting Specimens

Figure 11. PG64-28 Sample Rutting Specimens

While looking at average rut depth is useful, knowing what the progression of the rut depth shows how the rut progression slows down at specified passes. Seen in Table 8 are these advancements in depth from 2000 to 4000, 4000 to 6000, and 6000 to 8000 passes in the APA. There is a trend of the increase in rut depth decreasing at each specified interval. This is to be expected. Again the field mix was a surprise and had the highest percent increase and then turned to be on the lower end of percent rut depth increase at the end of the trial. PG 64-28 showed a more typical result where the lab and field mix had the least amounts of rut increase in millimeters compared to the virgin mix.

Table 8. Progression of Rut Depth

Binder Grade	Mix	Increase in Rut Depth (mm)			% Increase in Rut Depth		
		2k to 4k	4k to 6k	6k to 8k	2k to 4k	4k to 6k	6k to 8k
PG58-28	Virgin	0.28	0.17	0.10	20.94	10.84	5.35
	Lab	0.23	0.20	0.15	15.58	11.76	7.79
	Field	0.36	0.16	0.14	20.07	7.49	5.78
PG64-28	Virgin	1.05	0.58	0.45	29.81	12.78	8.74
	Lab	0.71	0.50	0.40	28.35	15.45	10.61
	Field	0.52	0.34	0.27	25.84	13.45	9.44

Along with the average rut depth and progression of rutting, independent t-test were done to test for any significant difference between the mixtures. Table 9 has the results of these test. All of the t-test were done at a 0.05 significance level. A cell with an 'N' indicates no significant difference whereas a cell with a 'Y' means there is a significant difference between the mix performance. Both PG58-28 and PG64-28 showed there is no significant difference between the laboratory and field mixes when it comes to rutting. That result is what is expected. However, the same test said that there is no significant difference between lab and virgin mix but there is a difference between field and virgin mix. What should happen is that both lab and field should be different than virgin because of the absence of RAP.

Table 9. APA Independent T-Tests

Binder Grade	Mix	APA		
		Virgin	Lab	Field
PG58-28	Virgin	x	N	Y
	Lab	x	x	N
	Field	x	x	x
PG64-28	Virgin	x	N	Y
	Lab	x	x	N
	Field	x	x	x

Air void content of the specimens test could be correlated to the rut depths. Figures 12 and 13 show the PG58-28 rut depth vs. air voids. The correlations are given by the R^2 values. Virgin samples have a good correlation between rutting and air voids. As rut depth increases so do the air voids. However, the samples with RAP in them have no correlation between the rut depth and air voids. Figures 14 and 15 are the PG64-28 rutting samples correlated with air voids. There is a weak correlation between rut depth and air voids in virgin samples but no correlation for RAP samples.

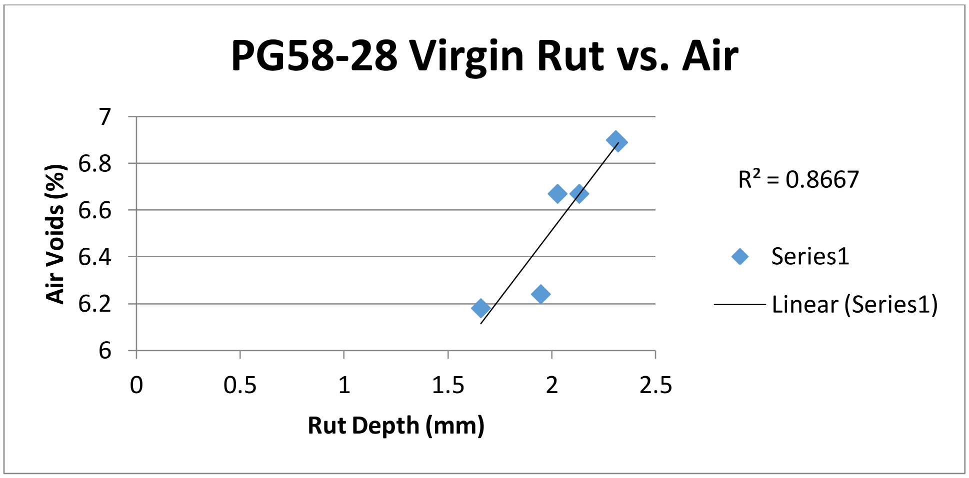

Figure 12. PG58-28 Virgin Rut Depth vs. Air Voids

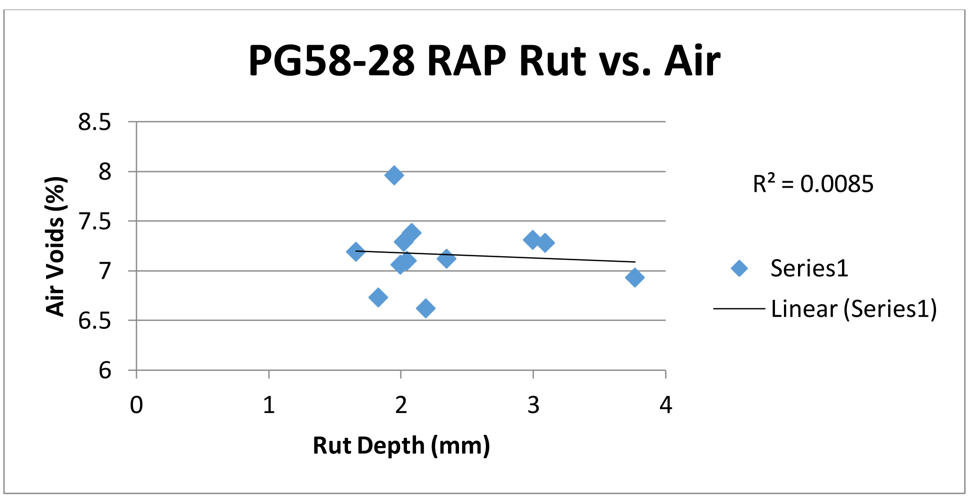

Figure 13. PG58-28 RAP Rut Depth vs. Air Voids

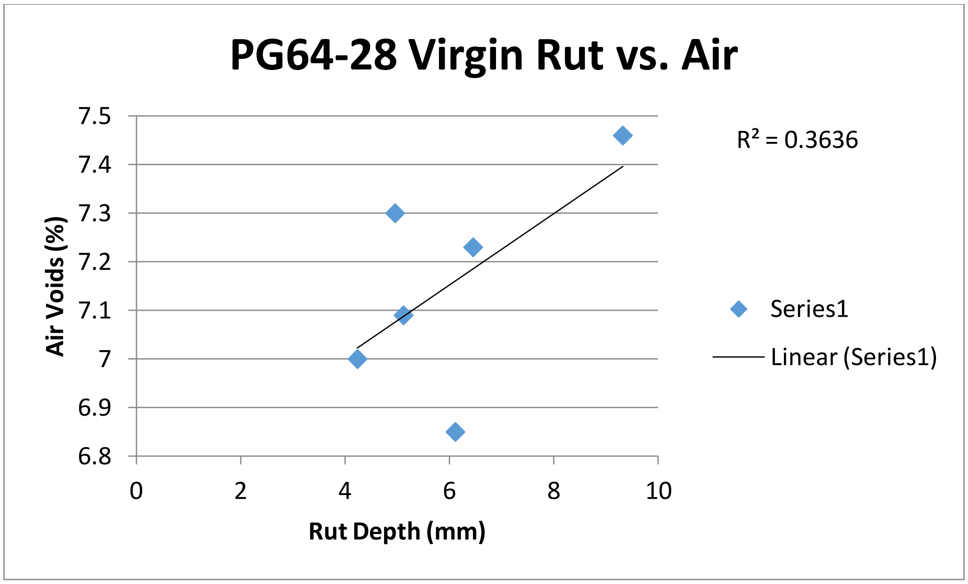

Figure 14. PG64-28 Virgin Rut Depth vs. Air Voids

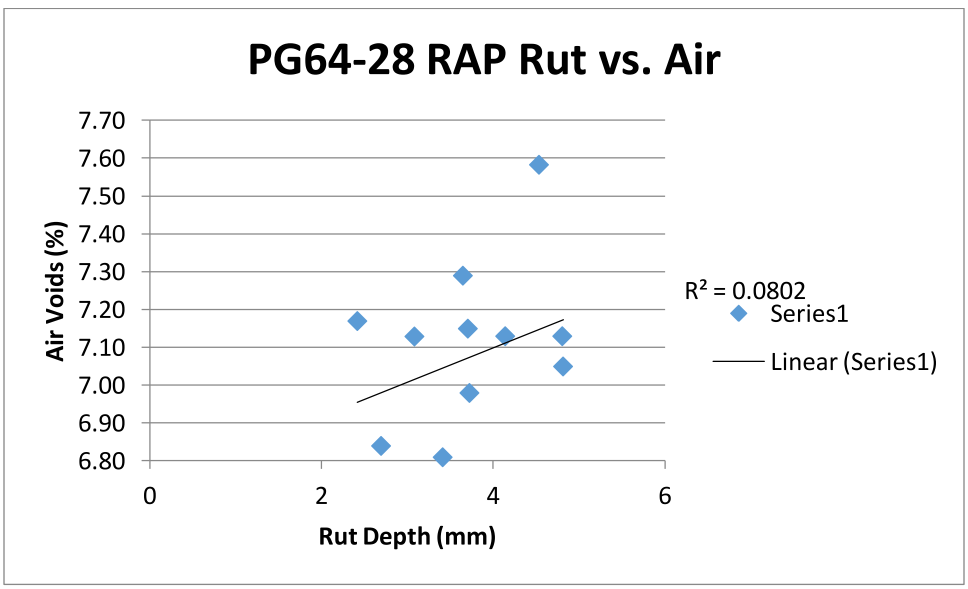

Figure 15. PG64-28 RAP Rut Depth vs. Air Voids

Low Temperature Cracking Performance

The testing of low temperature cracking of the mix designs in question was accomplished by using the DCT. As with the APA, it is expected that the lab and field mixes have similar cracking properties but both should be different than the virgin mix design. Fracture energy is the key value that describes cracking in asphalt pavement tests. Tables 10 and 11 have the individual results for each test along with the air void content of each sample. The summary statistics for low temperature cracking can be found in Table 12. To accompany Table 12, Figures 16 and 17 are graphs of the average fracture energies of the mixes for both performance grades. In this test, four DCT specimens were created for each mix for both performance grades. The PG58-28 averages indicate that the virgin mix has the best resistance to cracking while the lab and field mixes have lower resistance. Seeing that the virgin design had no RAP and RAP makes a design more brittle, these results are justified. Looking at the lab and field cracking averages, the lab mix had a higher fracture energy than the field. This could be contributed to the field mix being slightly more stiff than the lab. What seems more likely is that the mix design was not good for cracking to begin with because during testing some samples prematurely failed and had extremely low fracture energies. This implies that the mix is brittle at low temperatures and are unstable. PG64-28 mixes implied that the lab and field mixes were similar because the average energies were close to one another. They varied by only 50 J/m^2 compared to the virgin mix being about 170 J/m^2 higher than the lab mix. These variations in energy cannot be correlated to air void content in the samples because there is no evidence showing whether higher energy is from higher air voids. Also if a sample has lower air voids the energy should be less since the specimen would be more brittle but that is not always the case. Figures 18 and 19 are example graphs where the energy is calculated. The energy is calculated by the area under the curve of the peak load vs. CMOD. In both performance grades, the virgin was the highest followed by laboratory and then field mix in order of fracture energies. Figure 20 illustrates how the DCT test crack was formed.

Table 10. PG58-28 DCT Specimen Results

PG58-28 DCT Samples				Air Voids		
	Virgin	**Lab**	**Field**	**Virgin**	**Lab**	**Field**
Sample	Energy (J/m^2)	Energy (J/m^2)	Energy (J/m^2)			
1	392	256	210	6.72	7.57	7.31
2	220	240	238	6.53	7.63	7.16
3	305	285		7.21	7.59	

Table 11. PG64-28 DCT Specimen Results

PG64-28 DCT Samples				Air Voids		
	Virgin	**Lab**	**Field**	**Virgin**	**Lab**	**Field**
Sample	Energy (J/m^2)	Energy (J/m^2)	Energy (J/m^2)			
1	519	405	322	7.28	6.83	7.44
2	530	312	271	7.42	7.18	6.73
3	525	376	306	7.32	7.16	6.93
4	512	328	318	6.59	7.59	6.83

Table 12. DCT Summary Results

Binder Grade	Mix	DCT		
		Average Energy (J/m^2)	**Std Dev (J/m^2)**	**COV (%)**
PG58-28	Virgin	305.67	86.00	28.14
	Lab	260.33	22.81	8.76
	Field	224.00	19.80	8.84
PG64-28	Virgin	521.50	7.77	1.49
	Lab	355.25	42.89	12.07
	Field	304.25	23.19	7.62

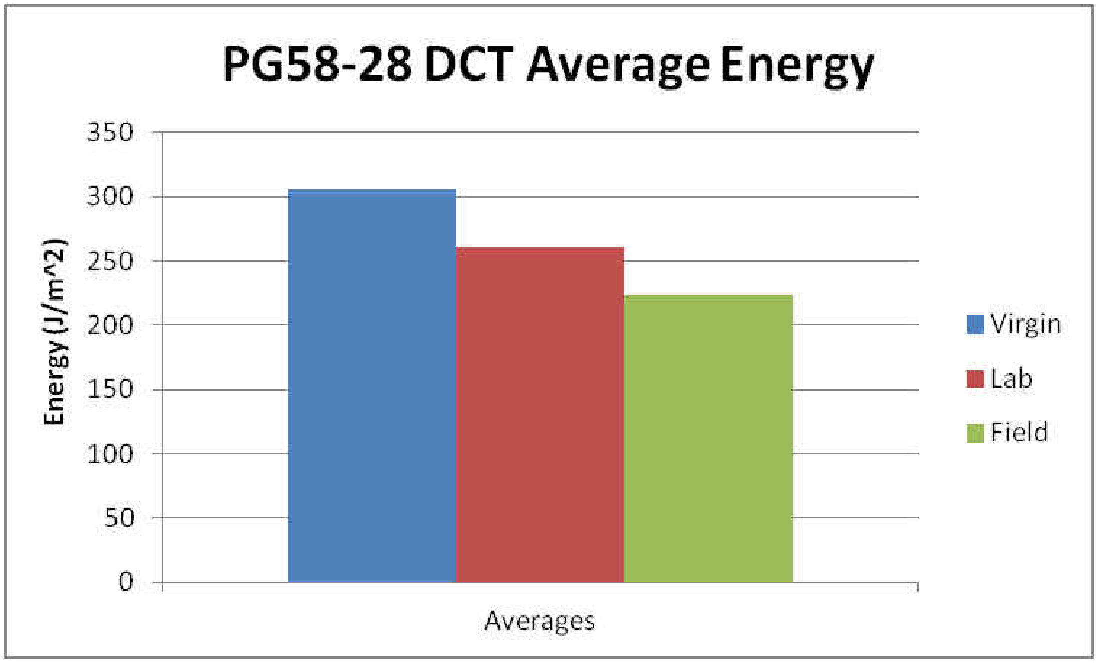

Figure 16. PG58-28 DCT Average Fracture Energies

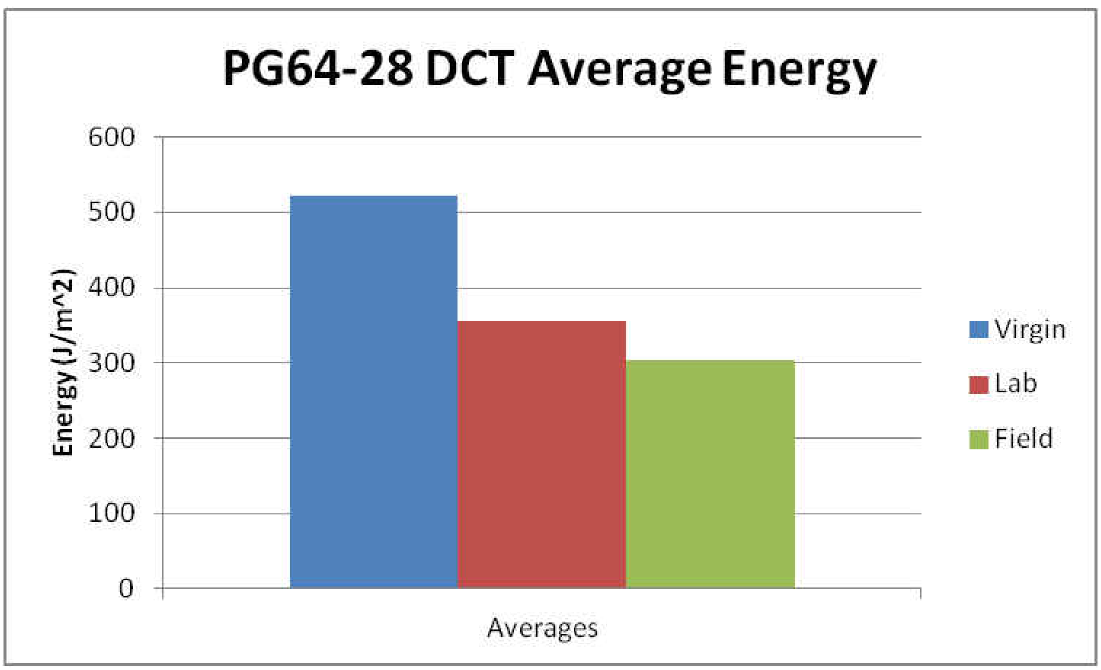

Figure 17. PG64-28 DCT Average Fracture Energies

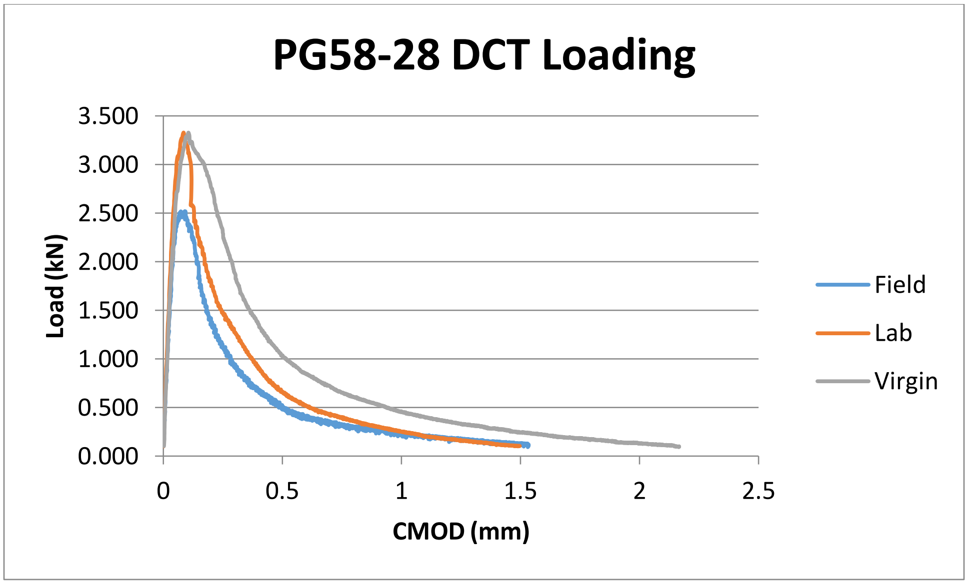

Figure 18. PG58-28 Example DCT Energy Graph

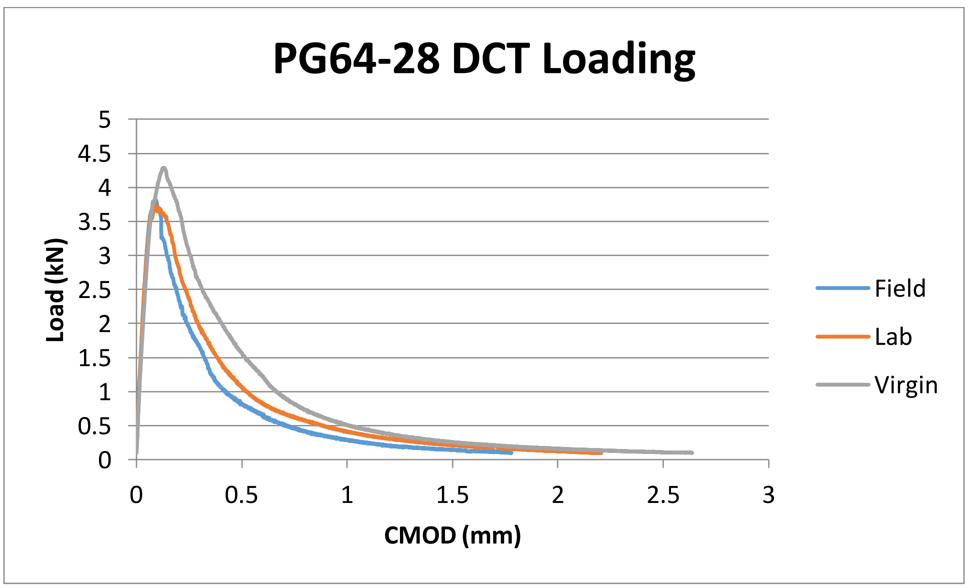

Figure 19. PG64-28 Example DCT Energy Graph

Figure 20. Sample DCT Test Specimen

Independent t-tests were performed on the DCT results for significant difference. Table 13 has the summary of these tests. From analyzing the PG58-28 DCT results, it was found to be inconclusive whether there was any significant difference between the lab and field mixes. The issue was for a t-test, at least three data points were needed to perform the test and there were only 2 field samples for the DCT because there was a failed sample in each of the three mixes. It could only be shown that there is no statistical significance between virgin and lab mixes. Again, this may be because of the limited number of tests performed. PG64-28 gave more concrete results. All of the t-test comparisons had results that were expected. The lab and field mixes had no significant difference and the virgin versus lab and field showed that there was a significant difference. This difference is again because of the RAP, which makes the mix more brittle and susceptible to cracking. The PG64-28 results were similar as with Winkle and Xiao et al. where the inclusion of RAP reduced the rutting in the samples. However the rutting in PG58-28 was opposite of the Winkle and Xiao et al. where RAP increased the rut depth. This has to be attributed to some material issue in the mix design. Behnia et al found that as RAP percentage in a mix increased the low temperature cracking energy decrease. The results of this study show that this is a valid result. For both performance grades, RAP reduced average fracture energy. Also, the fracture energies of PG58-28 were lower than PG64-28 which was expected. PG58-28 was from what would be considered a less important highway compared to the PG64-28 asphalt. These were consistent with the results found by Marasteanu et al.

Table 13. DCT Independent T-Tests

Binder Grade	**Mix**	**DCT**		
		Virgin	**Lab**	**Field**
PG58-28	**Virgin**	x	N	x
	Lab	x	x	x
	Field	x	x	x
PG64-28	**Virgin**	x	Y	Y
	Lab	x	x	N
	Field	x	x	x

Fatigue Cracking Performance

For this analysis the SCB test was used in determining fatigue cracking performance of the mix designs at an intermediate temperature. Like with the DCT test, fracture energy is the important variable calculated to compare the mixes. Eight samples were created for each mix design and performance grade. As mentioned previously, the sample were about half the thickness of what is usually tested because of limited resources. The smaller samples could affect the results since they are probably easier to fracture than larger specimens. Tables 14 and 15 are individual results of the SCB test for each performance grades. These tables include the air voids of the specimens in order to indicate if there is any correlation to fatigue cracking and air void content. Table 16 shows the summary results from the SCB tests. Starting with PG58-28, the lab and field results fracture energies were lower than the virgin. The lab energy was higher with a lower COV than the field. Having the higher COV means that the field samples had more variation in the fracture energies than the lab samples. Virgin samples having the highest fracture energy is no surprise because that is expected with the lack of stiff RAP material. Fatigue cracking results from PG64-28 were more consistent just like the low temperature results. The expected larger fracture energy of the virgin mix occurred again. Between the lab and field mixtures, the field had lower average energy and a higher COV. Laboratory samples had an exceptionally low COV compared to the field samples. Like with the DCT samples, there is no direct correlation between SCB fracture energy and air voids. For specimens with the same air void content, the fracture energies can be both on the higher and lower ends of the overall results. Figures 21 and 22 depict the average fracture energies between the mixes and performance grades. The SCB also calculates the fracture energy by the area under the curve of peak load vs. displacement and Figure 23 is an example graph of this curve. How the crack formed during the SCB test is shown in Figure 24.

Table 14. PG58-28 Individual SCB Results

PG58-28 SCB Specimens				Air Voids		
	Virgin	Lab	Field	Virgin	Lab	Field
Sample	Energy Avg (J/m^2)	Energy Avg (J/m^2)	Energy Avg (J/m^2)			
1	937.77	730.68	916.425	6.72	7.57	7.31
2	1216.285	913.35	430.45	6.72	7.57	7.31
3	1212.905	581.91	599.165	6.53	7.36	7.16
4	926.09	815.555	615.745	6.53	7.36	7.16
5	635.14	832.28		7.21	7.59	
6	781.305	623.09		7.21	7.59	
7	773.99	872.705		6.83	7.86	
8	1159.035	951.8		6.83	7.86	

Table 15. PG64-28 Individual SCB Results

PG64-28 SCB Samples				Air Voids		
	Virgin	Lab	Field	Virgin	Lab	Field
Sample	Energy Avg (J/m^2)	Energy Avg (J/m^2)	Energy Avg (J/m^2)			
1	1219.595	1340.985	985.88	7.28	6.83	7.44
2	1305.77	1319.205	1194.58	7.28	6.83	7.44
3	1454.15	1433.365	715.87	7.42	7.18	6.73
4	1861.155	1165.42	1009.295	7.42	7.18	6.73
5	1892.945	1114.75	1158.69	7.32	7.16	6.93
6	1565.415	1388.705	1212.97	7.32	7.16	6.93
7	1418.815	1268.78	1309.14	6.59	7.59	6.83
8	1606.615		841.395	6.59		6.83

Table 16. SCB Summary Results

Binder Grade	Mix	SCB		
		Average Energy (J/m^2)	**Std Dev (J/m^2)**	**COV (%)**
PG58-28	Virgin	955.32	221.29	23.16
	Lab	790.17	133.82	16.94
	Field	640.45	202.14	31.56
PG64-28	Virgin	1540.56	242.71	15.75
	Lab	1290.17	115.78	8.97
	Field	1053.48	202.58	19.23

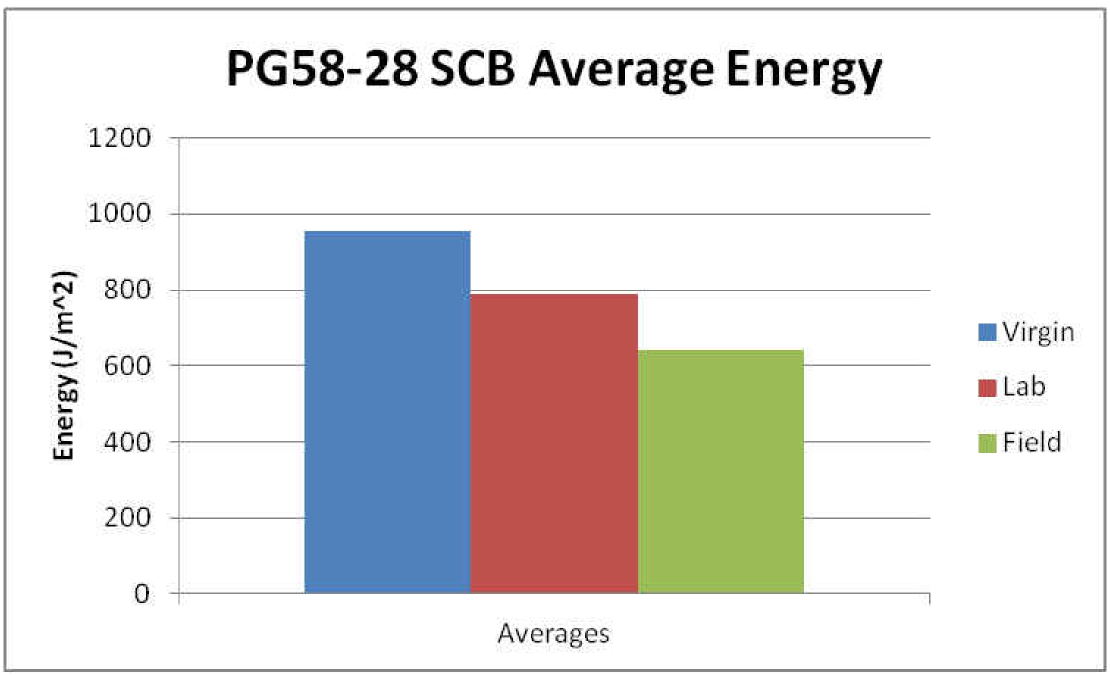

Figure 21. PG58-28 SCB Average Fracture Energies

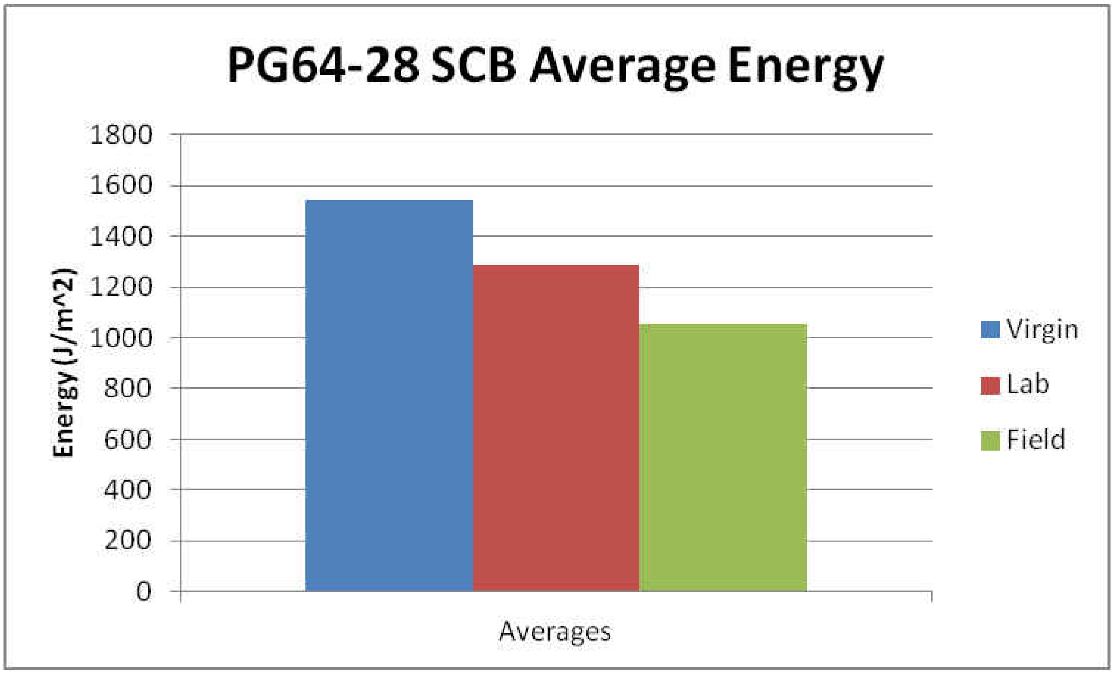

Figure 22. PG64-28 SCB Average Fracture Energies

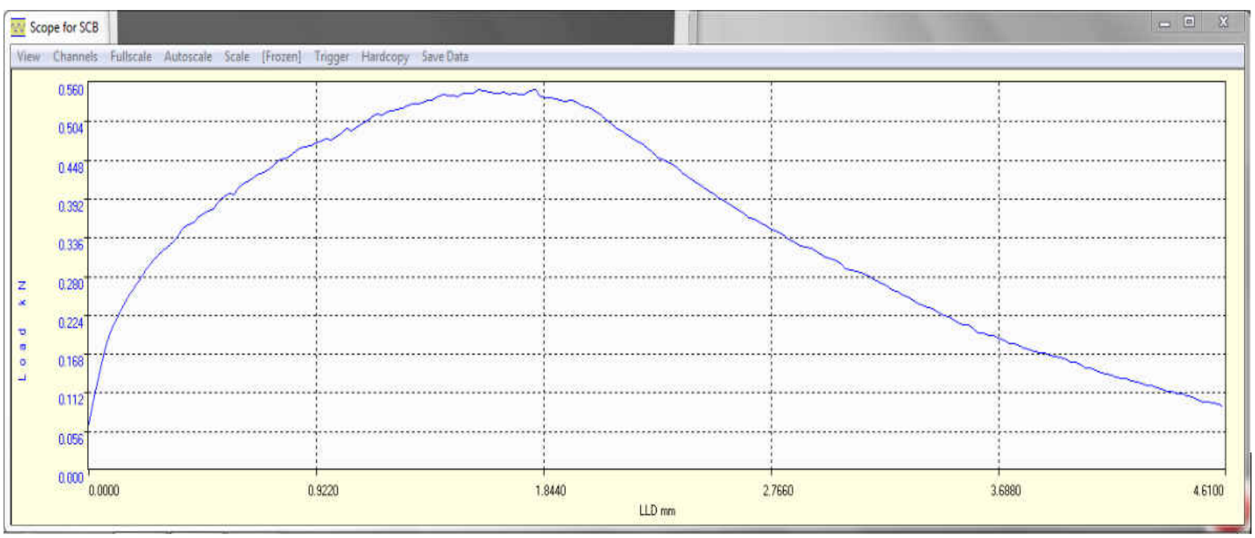

Figure 23. Example SCB Energy Graph

Figure 24. Sample SCB Test Specimen

As with the previous two performance properties, independent t-tests were performed on the SCB results and can be seen in Table 17. What is expected to happen is that there should be a significant difference between virgin mix and the lab and field mix. PG58-28 tests had there being no significant difference between virgin and lab but a significant difference in virgin and field mix. For this performance grade, the lab and field mix had no significant difference, which is the expected result. PG64-28 t-test concluded that all three comparisons were significantly different. Virgin versus lab and field mixes give the anticipated results because any time there is a virgin mix without RAP, it should be statistically different than those mix designs including RAP. Lab versus field being significantly different is not what is supposed to happen. This could be attributed to a number of variables, such as not enough samples tested, specimen height or the type of SCB test performed. As with Tang's results, the introduction of RAP reduced the fracture energy of the fatigue cracking. The results did vary significantly but the overall trend was downward with RAP in the mix design.

Table 17. SCB Independent T-Tests

Binder Grade	**Mix**	**SCB**		
		Virgin	**Lab**	**Field**
PG58-28	**Virgin**	x	N	Y
	Lab	x	x	N
	Field	x	x	x
PG64-28	**Virgin**	x	Y	Y
	Lab	x	x	Y
	Field	x	x	x

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Rutting of Laboratory and Field Specimens is Similar

By analyzing the data from the APA, it was determined that there is no significant difference between the rutting resistance of laboratory and field mixes for both performance grades. The average rut depth of all the samples may be different between the two mixtures but that does not mean they are statistically different. It was also found that the addition of RAP both helps and hinders the rutting of asphalt pavement specimens. Even though it is anticipated that RAP improves this property, from this research it is inconclusive.

Low Temperature Cracking Performance of Lab and Field Mix is Inconclusive

When looking just at the raw numbers of the DCT tests, it could be assumed that lab and field samples are comparable. In the case of PG64-28, a full statistical analysis was able to be completed and showed that the lab and field specimens are not significantly different. Conversely, PG58-28 could not have a full statistical analysis done because of the limited number of samples collected. Knowing that the lab and field samples contained RAP, it was also difficult to make a conclusion on the effect of RAP. With cracking, it is assumed RAP makes a mix design stiffer and essentially more brittle. A more brittle mix can result in significantly more cracks forming. PG64-28 showed a significant difference between mix with RAP and those without, so the assumption holds. Again, with PG58-28 there were not enough samples to have conclusive evidence on the effect of RAP use.

Fatigue Cracking Performance of Lab and Field Mix is Inconclusive

Just like with either rutting or low temperature cracking, it is expected that laboratory and field mixtures should have similar fatigue cracking performance. A t-test result showed there is no statistically significant difference between lab and field mix for PG58-28. However, PG64-28 results showed the opposite. Looking at the averages of the tests, one might assume that lab and field mixes are comparable but that cannot be assumed without a more in-depth statistical analysis. There were not a lack of useable samples for the experiment but having a smaller specimen size then recommended could be an issue. In general, RAP introduction into the mix designs gave the expected result. The addition of RAP decreased fracture energy in fatigue cracking samples.

LIMITATIONS

Over the course of the research there were limitations that may have influenced the results. Having to use smaller SCB sample sizes then recommended by I-FIT had to be done because of the limited number of specimens. Limited samples were made because only a certain amount of field mix was provided for the research. Having a certain amount of mix influenced the amount of DCT and SCB specimens made. Since Gmm of the laboratory and virgin mixes were assumed, this may have skewed the results. Gmm directly affects the calculation of air voids in a sample and the value was assumed to be the same as the field mix due to time and material limitations.

FUTURE WORK

Further investigation into the comparison of laboratory and field mixes should be done to confirm the validity of the data collected in this research study. Additional tests should be run on the un-compacted mixes to do a complete comparison analysis between the mixes designs before and after compaction. Making sure that both the lab and field mixes have aged the same amount of time before compaction may help the consistency among the two.

Once proper tests and compaction have been done, additional APA, DCT and SCB samples should be created if the materials are available. Having more specimens to test will increase the accuracy of the results from each of the tests. As for the SCB samples, creating proper 50 mm thickness samples could prove beneficial because that is what the test recommends as the test size.

APPENDIX

HOT MIX DESIGN DATA - SUPERPAVE

Department of Transportation, Materials and Research (Rev. 3-16) 6/1/16

Mix Design Company: Knife River Materials

Lab. No.	
Location	Adams to Edinberg
Project	H-6-032(057)191 PCN-21538 SS-6-017(042)096 PCN-21276
District	Grand Forks
County	Walsh
Date	6/1/16
Pit Owner(s)	KRM Gabriel Const
Pit #1 Location	Pioneer (Fordville)
Pit #2 Location	Gabriel
Pit #3 Location	

Project Specification	Section 430
Type of AC (top lift)	58-28
Type of AC (bot lift)	58-28
Letting Date	5/13/16
Plus #4 (%)	41.0
Minus #4 (%)	59.0

Gyratory Compactive Effort

Ninitial	7
Ndesign	75
Nmaximum	115

Mix Properties at Recommended Asphalt Content

	Mix Design	Specification
Optimum AC (%)	6.1	
Density (pcf)	143.7	
Air Voids (%)	4.0	2.0-6.0
VMA (%)	14.2	14.0 min
VFA (%)	71.6	65-78
%Gmm @ Ninitial	87.4	89%max
%Gmm @ Nmaximum	96.9	98%max
AC Film Thickness (m)	10.0	7.5-13.0
Dust/Effective AC Ratio	1.0	.6-1.3
Fine Agg Angularity (%)	43.8	43min
Sand Equivalent (%)	49.5	40min
Coarse Agg Angularity (%)	87.0	75min
Flat/Elongated Pieces (%)	0.0	10max
Maximum SpG @ Ndes	2.399	

Summary of Aggregate Characteristics from Mix Design

Gradation (% passing)	Blend	Virgin
5/8"	100.0	100.0
1/2"	96.6	97.3
3/8"	85.5	86.9
#4	59.0	58.2
#8	40.7	39.9
#16	27.5	26.7
#30	16.3	15.4
#50	8.7	7.9
#100	6.0	5.5
#200	4.7	4.2

Virgin Add AC (%)	4.6 4.4
Virgin Agg. FAA (%)	43.5
Asphalt Absorption (%)	1.64
Water Absorption (%)	2.06
Light Wt Particles (%)	4.8
Toughness (% Loss)	NA

Final Aggregate Blend (%)

24	N Fines	Fordville
27	rock	Ford/Gab
13	D Dust	Ford/Gab
16	Washed dust	Ford/Gab
20	RAP	

Specific Gravity Information

Combined Bulk (Gsb).	2.520
-No. 4 Combined Bulk (Gsb)	2.470
-No. 4 Virgin Bulk (Gsb)	2.431
Apparent (Gsa)	2.720
Effective (Gme)	2.625

Remarks:

Mix Design Technician & ID: Danny Schmidt 1366

Distribution:
Materials and Research
Grand Forks

Figure 25. PG58-28 Summary Volumetrics

HOT MIX DESIGN DATA - SUPERPAVE

Department of Transportation, Materials and Research (Rev. 3-16) 6/8/16

Mix Design Company:	Knife River Materials
Lab. No.	
Location	I-29 near St Thomas, Bowesmont
Project	SIM-6-029(128)183 PCN-20796
	NH-6-081(069)204 PCN-21130
District	Grand Forks
County	Pembina, Walsh
Date	6/8/16
Pit Owner(s)	Thygeson
Pit #1 Location	Deerwood township, Kittson co MN
Pit #2 Location	
Pit #3 Location	

Project Specification	Section 430
Type of AC (top lift)	64-28
Type of AC (bot lift)	58-28
Letting Date	12/16/15
Plus #4 (%)	33.8
Minus #4 (%)	66.2

Gyratory Compactive Effort

Ninitial	7
Ndesign	75
Nmaximum	115

Mix Properties at Recommended Asphalt Content

	Mix Design	Specification
Optimum AC (%)	5.4	
Density (pcf)	149.1	
Air Voids (%)	4.0	2.0-6.0
VMA (%)	14.1	14.0 min
VFA (%)	71.7	65-75
%Gmm @ Ninitial	87.0	89%max
%Gmm @ Nmaximum	97.5	98%max
AC Film Thickness (m)	9.5	7.5-13.0
Dust/Effective AC Ratio	0.9	.6-1.3
Fine Agg Angularity (%)	45.5	45min
Sand Equivalent (%)	71.3	40min
Coarse Agg Angularity (%)	88.0	85min
Flat/Elongated Pieces (%)	0.0	10max
Maximum SpG @ Ndes	2.489	

Summary of Aggregate Characteristics from Mix Design

Gradation (% passing)	Blend	Virgin
5/8"	100.0	100.0
1/2"	99.6	100.0
3/8"	91.5	91.7
#4	66.2	64.2
#8	41.3	37.8
#16	28.1	25.1
#30	18.5	15.8
#50	12.0	10.5
#100	6.0	4.5
#200	4.1	2.9

Virgin Add AC (%)	4.1
Virgin Agg. FAA (%)	45.1
Asphalt Absorption (%)	1.02
Water Absorption (%)	1.08
Light Wt Particles (%)	0.0
Toughness (% Loss)	NA

Final Aggregate Blend (%)

9	N Fines	Deerwood
18	rock	Deerwood
44	washed dust	Deerwood
9	dust	Deerwood
20	RAP	

Specific Gravity Information

Combined Bulk (Gsb)	2.633
-No. 4 Combined Bulk (Gsb)	2.625
-No. 4 Virgin Bulk (Gsb)	2.618
Apparent (Gsa)	2.705
Effective (Gme)	2.703

Remarks:
Also project SIM-6-029(110)183 PCN-18961

Mix Design Technician & ID: Danny Schmidt 1366

Distribution:
Materials and Research
Grand Forks

Figure 26. PG64-28 Summary Volumetrics

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