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Evaluation Of Conventional And Non-Conventional Asphalt Mixes

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EVALUATION OF CONVENTIONAL AND NON-CONVENTIONAL ASPHALT MIXES

by

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Bachelor of Engineering, Tribhuwan University, 2012

A Thesis

Submitted to the Graduate Faculty

of the

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for the degree of

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This thesis, submitted by Rabindra Pariyar in partial fulfillment of the requirements for the Degree of Master of Science 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.

Dr. Nabil Suleiman, Chairperson

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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Dr. Grant McGimpsey
Dean of the School of Graduate Studies

Date

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Title	Evaluation of Conventional and Non-Conventional Asphalt Mixes
Department	Civil Engineering
Degree	Master of Science

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ABSTRACT

Various types of additives have been applied in the past to Hot Mix Asphalt (HMA) to improve pavement performance. Different techniques including Warm Mix Asphalts (WMA) have helped to increase the workability and strength of pavement as well as decrease greenhouse gas emissions and production costs. Pavement construction can be a challenge in regions with short construction seasons due to various factors including cold weather. It is believed that additives can be a solution for some of those challenges due to lower rate of cooling for such mixes.

This study is carried out to evaluate two hot mix asphalts in the field. One has been modified with the Proprietary additive (creating a non-conventional mix), while the other is kept as a conventional hot mix asphalt with PG 58-28 binder. Asphalt mix field samples for the study were collected from a Cass County, North Dakota project in Summer 2015. Both the conventional and non-conventional specimens were subjected to three different types of tests: rut resistance tests, moisture sensitivity tests, and compaction aid tests.

Six specimens from each conventional and non-conventional mix categories were tested for rut resistance using the Asphalt Pavement Analyzer (APA). The results indicated that the non-conventional mix had higher rut resistance than the conventional mix. Eight specimen from each mix category were tested for moisture sensitivity using the Modified Lottman test under dry and wet conditions. The results showed that the non-conventional mix had higher strength than the conventional mix under both dry and wet conditions. Finally, three specimens from each mix category were compacted at three different temperatures.

The air voids of the mixes were compared with the corresponding compaction temperatures. The results suggested that the non-conventional mix had lower air void content, thus better compactibility was achieved than conventional mix. The overall results of the study indicate that Proprietary additive can work as a warm mix additive in North Dakota with favorable performance compared to conventional HMA mixes.

CHAPTER 1

INTRODUCTION

1.1 Introduction and Background

Over the years, engineers have tried different technologies to improve the properties of asphalt mixes. Warm mix asphalt is the technology recently developed that has been proven effective in combating various production and performance issues related to hot mix asphalt (HMA). Hot mix asphalt has been prepared traditionally at a temperature within the range of 285 °F- 320 °F. But, the use of WMA technology reduces that temperature by 68 °F (20 °C) to 104 °F (40 °C) (Rubio, et al, 2011). This lowering of the production temperature reduces the viscosity, reduces the aging of binder and increases the workability. It is also very helpful considering the short paving season in region with cold climate like North Dakota.

WMA was first introduced to decrease the emissions of greenhouse gases (Angelo, et al, 2008). But with new researches and usage, various other advantages of WMA have been discovered. Additives like Evotherm and Sasobit in WMA also improve compactibility of the mix (Hurley and Prowell, 2006). Sasobit increases the resistance to permanent deformation (Gandhi, 2008). WMA mix has better rut resistance than HMA (Zhang, 2010). Since, WMA reduces the temperature, it also decreases the aging process that can result in increased rut depth (Hurley and Prowell, 2006). Additives like Styrene Butadiene Styrene improves the moisture resistance of

HMA (Gorkerm and Sengoz, 2008). Hydrated lime also helps in reducing moisture damage (Al-Qadi, et al, 2014; Hasan, et al, 2015).

1.2 Objectives

The primary objectives of this thesis are as follows:

- To perform a literature review of previous research related to the use of additives in Hot Mix Asphalt as well as research done on warm mix asphalts.
- To analyze the effect of Proprietary additive on rut resistance of HMA mix using the APA rut resistance test and compare the results to a conventional control mix.
- To assess the effect of Proprietary additive on moisture susceptibility of HMA mix using the modified Lottman test and compare the results to a conventional control mix.
- To evaluate the compactibility of HMA mix with and without the Proprietary additive at three different temperatures and whether the Proprietary additive can be used as a compaction aid, thus act as a warm mix additive.

1.3 Motivation

Various types of additives have been used in the past to improve the property of Hot mix asphalt. Lower compaction temperature, improved durability, increased strength and reduced project cost have been some of the well-known effects of the additives like Evotherm, Sasobit, etc. Proprietary is a new type of additive used in Cass County, North Dakota project. This study is conducted to evaluate the effects on the said additive on HMA mixes in lab condition.

North Dakota experiences cold weather for almost half a year which doesn't allow for a long construction season. Therefore, the necessary pavement work needs to be done within a span of few months. Considering the situation, additives can be of great help for pavement construction in the region. The premise is that the use of warm mix asphalt with low production and placement temperature in North Dakota can be successful in cold weather paving.

This thesis is aimed at evaluating rut resistance performance, moisture susceptibility and compaction of hot mix asphalt with Proprietary additive. The traditional Hot Mix Asphalt mix is termed as conventional mix while the HMA with Proprietary additive is termed as non-conventional mix in this study. Different tests were conducted for each mix specimen to assess the properties mentioned before. A comparison was made between conventional and non-conventional mix specimens to find out if the additives had any effect on HMA and its utility in region like North Dakota. The study is also done to see if Proprietary additive can be used as Warm Mix Asphalt.

1.4 Thesis Framework

Chapter 1 presents the background and introduction about the research, additives, motivation, objectives and a framework of the thesis. Chapter 2 is comprised of literature review. Chapter 3 includes the explanation of the preparation of specimens and tests performed. Chapter 4 describes the results of the tests and the comparison of the two mix categories. Chapter 5 states the conclusions of the thesis. The flowchart in the next page displays the framework of the thesis.

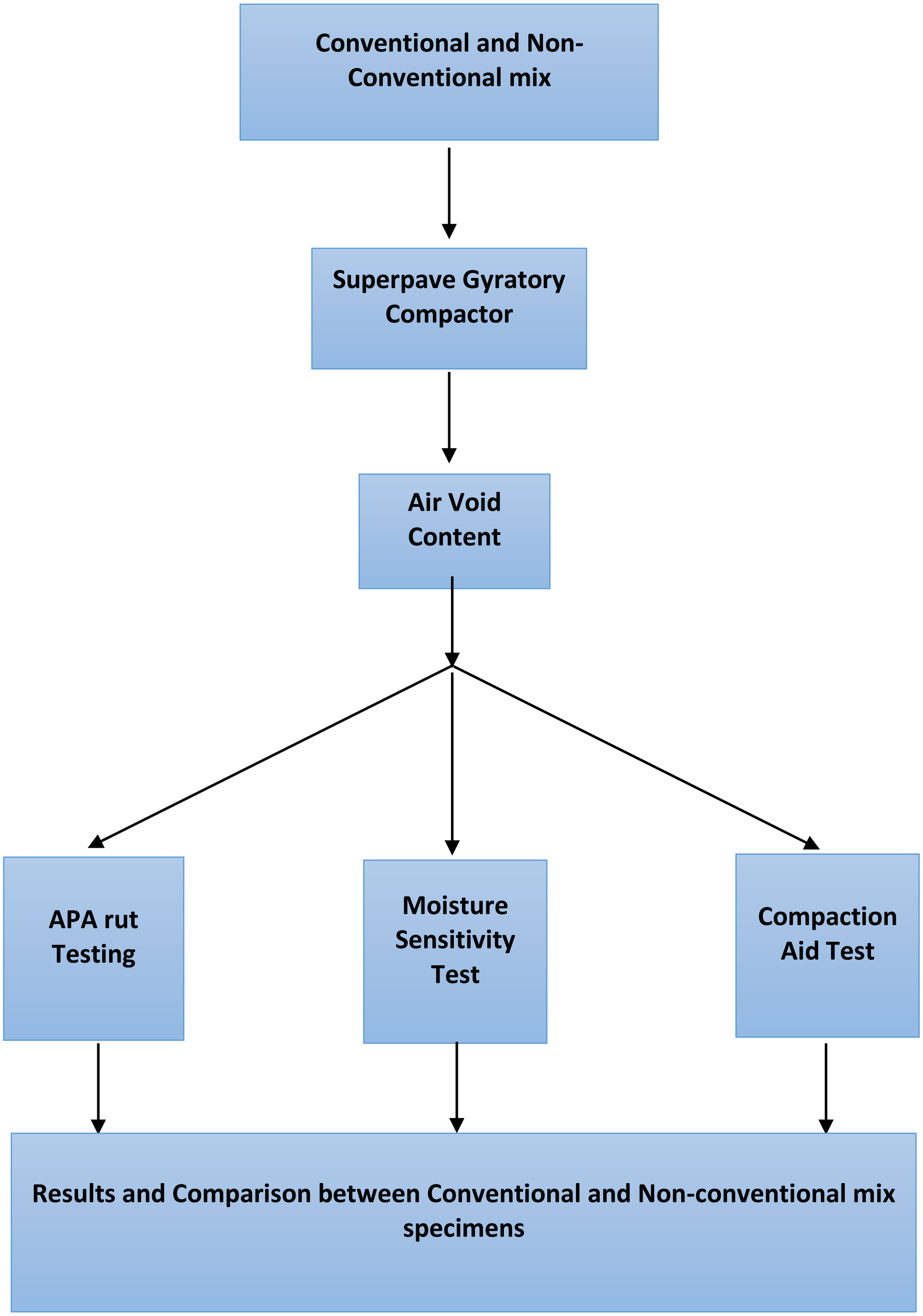


Figure 1 Flowchart of the sequence of the thesis

CHAPTER 2

LITERATURE REVIEW

2.1 Warm-mix asphalt

Warm-mix asphalt (WMA) is a group of technologies that allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to reduce the viscosity of the asphalt and provide for the complete coating of aggregates at lower temperatures (D'Angelo, et al, 2008). Warm Mix Asphalt technology is good for the environment because it produces asphalt at temperatures 20°- 40°C lower in comparison to Hot Mix Asphalt (Rubio, et al, 2011). Rubio, et al (2011) stated that the main aim of WMA technology is to reduce the viscosity of asphalt, thus improving workability, producing lower emissions and creating better working conditions. According to them, lower production temperature also reduces the aging of the bitumen during the production stage, which results in an improved thermal and fatigue cracking resistance.

Gandhi (2008) observed that the addition of Sasobit considerably reduced the viscosity of the binders at 135 °C and 120 °C, whereas, the addition of Aspha-min did not have any significant effect on the viscosity of the binders at 135 °C and 120 °C. However, the addition of warm asphalt additives increased the viscosities of the binders at 60 °C (140 °F). Akisetty, et al (2009) concluded that the viscosity properties of rubberized binders can be changed significantly through the use of warm asphalt additives. Sasobit improves the compactability of asphalt mixture and results in acceptable density at temperature of 20°C-40°C below normal compaction temperatures and improves the resistance against permanent deformation (Kanitpong, et al, 2007).

Viscosity tests conducted by Mo, et al (2012) indicated that chemical additive had a limited effect on viscosity reduction. The same study determined that the asphalt mixtures containing 2% chemical additive allowed compacting at lower temperatures and mixture compaction was less dependent on bitumen viscosity. Lee, et al (2008) stated that the addition of Sasobit decreased the viscosity at 135° C of recycled binders while adding Aspha-min increased the viscosity.

Akisetty, et al (2011) suggested that he increase in the mixing and compaction temperatures due to the addition of crumb rubber can be offset by adding the warm asphalt additives, which lowers the mixing and compaction temperatures of rubberized mixtures comparable to those of conventional HMA.

2.2 Compaction

A proper compaction of the mix is required for longevity and acceptable performance. Laboratory compaction of HMA is often designed to simulate field conditions (Peterson, et al, 2004). The SUperior PERforming Asphalt PAVEments (Superpave) gyratory compactor was developed for Superpave mix design system to better simulate the field compaction of hot-mix asphalts (Buchanan and Brown, 2001). A study by Peterson, et al, (2004) showed that the specimens produced with current gyratory protocol had significantly different mechanical properties than field conditions. But adjustments to certain parameters (specimen height, compaction pressure, temperature and angle of gyration) of the gyratory could produce specimens that better simulate the mechanical properties of pavement cores.

Tashman (2000) in his research stated that it was possible to simulate the internal structure of asphalt pavements by changing the angle of gyration and specimen height in the SGC. Also, he concluded that increasing the temperature of base plates and mold of the gyratory compactor assisted in producing random distribution of air voids within a specimen. The study by Hurley and Prowell (2006) showed the addition of Evotherm, Sasobit and Aspha-min improved the compactability of mixtures in the SGC. The same study indicated an overall reduction in air voids. Their data showed an improved compaction at temperatures as low as 190°F (88°C). Superpave gyratory compactor results indicated that all three additives may lower the optimum asphalt content (Hurley and Prowell, 2006).

2.3 Rutting

Rutting is the formation of depressions along the pavement's wheel path as a result of traffic loads (Gandhi, 2008). Asphalt pavement Analyzer (APA) has been a very popular device to evaluate the rutting potential of asphalt mixes. A research conducted by the State of Florida (1998) indicated that the APA may be an effective tool to rank asphalt mixes in terms of their respective rut performance. The Minnesota Department of Transportation (Mn/DOT) (2002) also researched the use of APA as a tool for evaluating the rutting susceptibility of Minnesota HMA and concluded that APA gave better results than other devices.

Suleiman and Mandal (2013) tested 24 core samples (12 dry and 12 wet) representing the WMA and the control HMA sections using the asphalt pavement analyzer (APA). WMA for the research contained Evotherm 3G as additive. Samples were submerged underwater for 24 hours for wet condition. The results indicated that the average rut values for WMA mixes were 13 percent and 29 percent higher than those of the HMA mixes under dry and wet conditions, respectively. Mandal (2012) also concluded that the warm mix asphalt exhibited greater rut depth values than hot mix asphalt under both dry and wet testing conditions. Mashhadi and Suleiman (2015) compared rut result of 24 aged samples with the rut result of unaged samples from the previous research by Suleiman and Mandal (2013). They concluded that aged specimens were more rut resistant than un-aged specimens for both WMA and HMA mixes under dry and wet conditions.

Gandhi (2008) observed in his study that unaged mixes with Sasobit as additives had lower rut values than other mixes by analyzing the APA rutting depths. He also studied the binder properties and concluded that the addition of Sasobit increased the resistance to permanent deformation. Study by Zhang (2010) also concluded that non-conventional asphalt mixtures presented better rut resistance than their hot mix asphalt counterparts, and use of Sasobit increased the rut resistance significantly after Asphalt Pavement Analyzer (APA) Test under Water. Akisetty (2008) evaluated the effects of Aspha-min and Sasobit on Crumb Rubber Modified (CRM) binders and indicated that the addition of warm mix additives did not have any significant effect on the rutting resistance of CRM mixes. However, the CRM mixtures required a high mixing and compaction temperatures compared to the conventional HMA. The aggregate sources were, in most cases, found to have a significant effect on the rut depth values of warm CRM mixtures.

Hurley and Prowell (2006) studied the effects of Sasobit, Aspha-min and Evotherm on mixes at different compaction temperature. They used two different aggregate type (granite and limestone). The results suggested that the Evotherm lowered the rut depths the most. Compared to the hot mix asphalt none of the additives significantly increased or decreased the rutting potential. However, the rutting potential increased with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder resulting from the lower temperatures. The mixes with Sasobit were less sensitive (in terms of rutting) to the decreased production temperature than the mixes without any additives were.

According to Sanchez-Alonso, et al (2013), reducing the manufacturing temperature caused an increase in rut depth in all asphalt mixtures manufactured, due to the increment in the percentage of air voids. Zhao, et al (2011) also agreed that lowering mixing temperature increased the rut depth due to less aging. The addition of warm wax stiffened the binder and increased the mixture rutting temperature.

2.4 Moisture Sensitivity

If the moisture contained in the aggregate does not completely evaporate during mixing due to the low mixing temperatures, water may be retained in the aggregate which could in turn lead to increased susceptibility to moisture damage (Hurley and Prowell, 2006). The aggregate source has significant effect on moisture susceptibility (Akisetty, 2008). The acid aggregate like gneiss must use some anti-stripping additive to resist water damage (Huang, et al, 2009). Hydrated lime is best known as an anti-stripping additive since 1910 (Huang, et al, 2009) Hydrated lime used with zeolite for granite aggregate and alternate Evotherm for limestone aggregate provided good results for moisture susceptibility (Hurley and Prowell, 2006).

Modified Lottman test (AASHTO T283) is recommended to determine potential moisture susceptibility of HMA mixes (Kandhal, 1994). Gorkem and Sengoz (2008) used the modified Lottman test to evaluate the moisture susceptibility of asphalt mixes containing additives. They suggested that Styrene butadiene styrene (SBS) addition showed a greater degree of improvement in moisture resistance of asphalt mixture compared to Ethylene vinyl acetate (EVA) polymer addition. The result of the study also displayed that the addition of hydrated lime reduced moisture susceptibility.

A study by Hurley and Prowell (2006) suggested that the lower mixing and compaction temperatures can result in incomplete drying of the aggregate. According to the same study, mixtures containing Sasobit and Magnabond gave good results for moisture sensitivity and rutting resistance after Hamburg wheel tests. The Tensile Strength Ratio (TSR) values for mixture containing Sasobit were acceptable only after adding AKZO Nobel Magnabond (Kling Beta 2912) after the modified Lottman test.

Evotherm and zeolite increases the potential of moisture damage (Zhang, 2010). According to him, this could be due to lower mixing and compaction temperatures. In the case of Sasobit, the TSR values for both conventional mixes and non-conventional mixes with additives were below the minimum requirement and showed no obvious difference. Gandhi (2008) in his study indicated that additives affect the TSR values of the mixtures as they age. Unaged mixes showed better moisture resistance with the use of additives than aged mixes. He also noted that aged mixes with Sasobit had lower TSR values than mixes with Aspha-min.

Effects of Wetfix I, Lilamin VP 75P, Chemcrete, and rubber on moisture sensitivity of asphalt mixes were studied by Aksoy, et al (2004). The study concluded that the moisture damage of asphalt mixes was used reduced after the use of additives. Al-Qadi, et al (2014) studied the effects of Liquid anti-strip (LAS), SBS, polyphosphoric acid (PPA), and hydrated lime on asphalt mixes. The study found that LAS and hydrated lime might reduce moisture susceptibility of asphalt mixes. The addition of lime and SBS together in hot mix asphalt exhibited improved performance of mixtures especially the resistance to moisture damage (Kok and Yilmaz, 2008).

Hasan, et al (2015), for their study, prepared WMA samples using additives Advera, Sasobit, Cecabase RT, and water as a foaming agent. They concluded that the presence of hydrated lime in the WMA resulted in the TSR values passing the minimum requirement of 0.80, thus improving the moisture susceptibility of the WMA.

CHAPTER 3

METHODOLOGY

3.1 Mix

Cass County, North Dakota provided both the conventional and non-conventional field mixes for the research. The mix information is as below:

Asphalt Cement	PG 58-28
Aggregate Blend	29 % Crushed rock
	20% Natural Fines
	31% Crushed Fines
	20% RAP
Total Asphalt Content	5.9 %
Maximum Theoretical Specific Gravity	2.419

3.2 Superpave Gyratory compactor

The Superpave Gyratory Compactor (SGC) was used for the preparation of the sample. Before the preparation of the specimens, SGC was calibrated as follows:

3.2.1 Consolidation Pressure

- Power to the SGC and the computer was turned on.
- In the software, calibrate option was chosen.
- Password was entered.
- The pressure calibration procedure was chosen.
- The load cell meter was connected to a power source and the load cell was connected to the load cell meter.
- Load cell was inserted inside the compaction chamber and centered under the ram.
- The guard door was closed.
- The three boxes on the PC display were checked as each task was completed.
- The ram extended down against the load cell.
- The consolidation pressure was adjusted to approximately 200 kPa.
- “Read” was clicked.
- The value displayed on the load cell was entered in a new window.
- The consolidation pressure was adjusted to 1000 kPa and “Read” was clicked again.
- The new value displayed on the load cell was entered once again.
- Once the ram retracted, a new window opened and “Apply” was chosen.

3.2.2 Specimen Height

- First three steps were repeated from above.
- The specimen height calibration procedure was chosen.
- A 1” ×2” ×3” gauge block was centered under the ram.
- The guard door was closed and the three boxes were checked as each task was completed.

- The PC extended the ram down onto the gauge block and the output was recorded from the specimen height transducer.
- The ram retracted and the guard door was opened.
- Two gauge blocks were stacked under the compaction ram on top of each other.
- The door was closed and two boxes were checked.
- The PC extended the ram once again onto the gauge and recorded the output from the specimen height transducer.
- Once the ram retracted, a new window opened and "Apply" was chosen.

3.2.3 Turntable RPM

The turntable was factory set at 30 rpm. It was chain driven and didn't need any adjustment.

3.2.4 Ram Travel Speed

Compaction Ram Speed was factory set to 10mm/ sec.

- First three steps were repeated from above.
- The "RAM speed" calibration procedure was chosen.
- The guard door was closed and "OK" was clicked.
- The ram extended down and the PC calculated the ram travel speed.
- After the ram retracted, the computer displayed the ram travel speed.

3.2.5 Angle of Gyration

The angle of gyration was factory set to 1.25°. The tolerance was .02°.

- First three steps were repeated from above.
- The "Angle" calibration procedure was chosen.

- The calibration pin was lowered and so was the calibration foot down to its bottom stop.
- The foot was rotated till the “zero step” was centered under the tip of the angle.
- The foot wasn’t pushed up against the bottom of the angle transducer tip. The PC lowered the ram down so that the angle transducer tip rested on the foot.
- Two 1” ×2” ×3” gauge blocks were stacked under the ram so that their combined height was 6”.
- “OK” was clicked.
- The ram extended down onto the gauge allowing the tip of the angle transducer to rest on the “zero step” of calibration foot.
- The PC recorded the output, and the ram was retracted automatically lifting the angle transducer up off the calibration foot.
- The foot was rotated so the second step was centered under the tip of the angle transducer.
- “OK” was clicked.
- The ram extended down onto the gauge blocks, allowing the tip of the angle transducer to rest on the second step of the calibration foot.
- The PC recorded the output and the ram was lifted automatically.

Figure 2 Superpave Gyratory Compactor

3.3 Specimen Preparation

The mixes were heated in the oven at 285°F for 4 hours. The 150 mm diameter mold along with mold bottom, spatula and chute were also preheated in accordance to asphalt mix specification to avoid losing the temperature. Few trial samples were prepared to determine the weight of mix needed to achieve standard 7 percent air voids after compaction

The SGC was turned on and so was the computer. The Rainhart Gyratory icon was double clicked on the desktop to begin the program. The mix was taken out of the oven and mixed together with a spatula. A 150 mm diameter paper disk was placed on the bottom of the mold before the mix was put in. The desired amount of mix was weighed and the mix was poured into the mold in a single lift. A paper disk was placed on top of the mix after that.

In the PC, new file was created. Necessary information was entered. Consolidation pressure was adjusted at 600 kPa. The charged mold was centered under the ram. It was made sure that the index mark on the mold was facing the front of the compaction chamber. Guard door was closed and “Start” was selected in the PC window. The ram extended down into the mold onto the sample. This began the gyration process. The angle of gyration was observed on the PC. When it had unsatisfactory value, angle adjustment needed to be done. The guard door was opened mid- gyration to stop the turntable. A 3/16 nut driver was used to adjust the stop screw for small decrease or increase in the angle. For larger adjustment, a tilt handle was inserted into the adjustment socket. The handle was removed and guard door was closed again to start the gyration.

After the compaction was completed, guard door was opened. The tilt handle was inserted to remove the angle. This squared the mold. Guard door was closed and “OK” was clicked to retract the ram. The mold was removed from the compaction chamber and placed over the extraction piston and back against the two side posts. The extruder switch was moved up. The sample was pushed up by the extraction piston out of the mold. The compacted sample was transferred to a table with the help of a wooden plank and the top and bottom paper disk were removed. The samples were labeled and left at room temperature for about 24 hours before testing to determine maximum specific gravity and air void ratio.

3.4 Air Void Content

At the end of 24 hours, dry weight (A) of each sample was measured. The samples were then submerged underwater for 4 minutes to measure their submerged weight (B). The samples were then towel dried and saturated surface dry weight (C) for each was determined. The bulk specific gravity (Gmb) (AASHTO T166-13) and air void content were calculated follows:

$$\mathrm{Gmb} = \frac{A}{C - B}$$

$$Air\ Voids\ (\mathrm{Va}) = \left(\frac{\mathrm{Gmm} - \mathrm{Gmb}}{\mathrm{Gmm}}\right) * 100\%$$

Where, Gmm = Maximum theoretical specific gravity

Va = Air void content

3.5 Rut Resistance Test

3.5.1 Asphalt Pavement Analyzer Calibration

The calibration of APA includes following procedures:

3.5.1.1 APA Vertical Calibration

- Power to both the APA and PC was turned on.
- “Calibrate” was clicked on the APA Control Bar and “Vertical” was clicked in the APA Load Calibration.
- The hose rack was removed from the APA.
- All the doors were closed.
- “Vertical Cal Off” (Red Button) was clicked which changed to “Vertical Cal On” (Green Button).
- The PC extended and then retracted all three wheels at the same time. The “Vertical Cal On” reverted back to “Vertical Cal Off”.

3.5.1.2 Wheel Load Calibration

The contact pressure for Rut testing is 100 psi.

- The hose rack was removed and the door was closed.
- “Calibrate” was clicked on the APA Control Bar.
- “Set Left Load” was clicked.
- Each wheel was lowered and raised 20 times by clicking “Down” and “UP”. This loosen the cylinders.
- The load cell was plugged into the receptacle on the APA front panel.
- The load cell was placed under the first wheel.
- Two empty mold turned upside down were placed under the other two wheels.
- Each wheel was lowered by clicking “Down”.
- The wheel that was being calibrated was raised if any adjustment was needed. The regulator button was moved up and down all while the other two wheels were left in the down position.
- The wheel was lowered and the meter was allowed to stabilize.
- The load cell was placed next under the second wheel and the steps were repeated and then under third wheel.
- The calibration of all the three-wheel load was within 5 lbs. of each other.

3.5.1.3 APA Hose Pressure Check

The pressure was adjusted as necessary with the hose pressure setting in the setup menu. The range 100 ± 5 psi was acceptable for the test**.**

3.5.1.4 APA Temperature Calibration

The test temperature was entered as 58° C.

3.5.1.6 Load Cell Calibration

The APA load cell is calibrated at the factory and needed no further calibration.

3.5.2 APA Rut Resistance Test

After the determination of required amount of mix needed to achieve 7 % air void, specimens of both conventional and non-conventional samples were prepared accordingly in SGC and labeled. Specimens of 75mm height were prepared for rutting resistance test. A total of 6 specimens attaining the required air void content of each mix were tested. The Asphalt Pavement Analyzer was used for the test. The APA was calibrated according to the standard. Specimen compacted with conventional mix were tested first. The test temperature was 140°F. Three molds were used each containing two specimens (150mm diameter x 75mm) each.

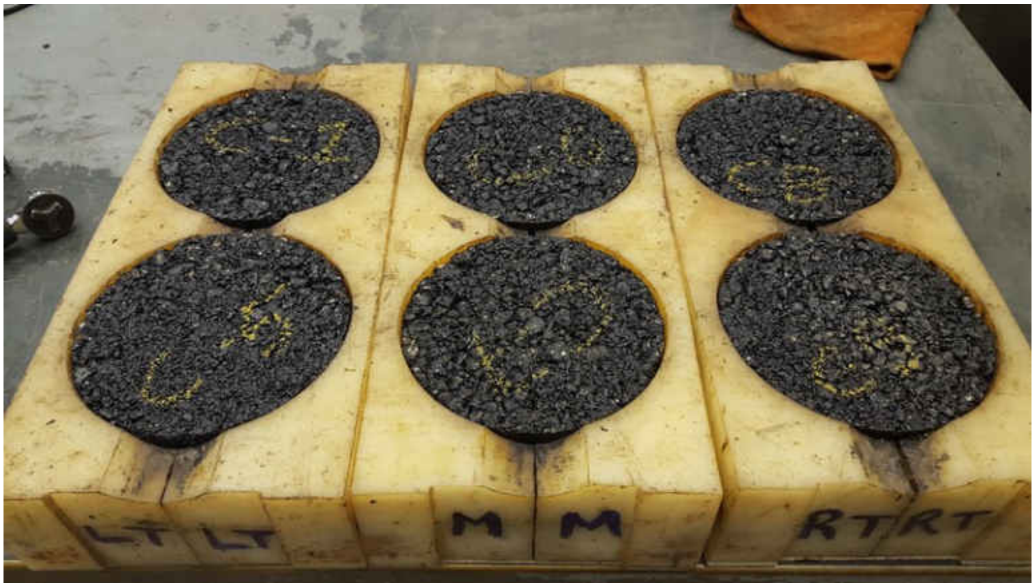


Figure 3 Specimens in mold for rut resistance test

The molds were cleaned and preheated before putting in specimens in them. Then, the molds along with the specimens were placed inside the APA for 6 hours at 140°F before the test was started. After 6 hours, specimens were subjected to 8000 load cycles using a 100 psi hose pressure that took to 2 hours to complete. At the end of the test, the results were obtained from the computer attached to the APA in graphical and numerical format. The samples were taken out of the mold. Same process was repeated for the non-conventional asphalt mix.

Figure 4 Asphalt Pavement Analyzer

3.6 Moisture Sensitivity Test

For moisture sensitivity test, specimen heights were kept constant at 95mm during preparation. Modified Lottman test (AASHTO T283-07) was conducted. Eight specimens for each mixes were compacted; 4 for the dry test and 4 for the wet test. Wet test included partially vacuum-saturated, freezing and soaking in warm water before testing. Dry test specimens were stored at room temperature for 24 hours. They were placed inside an airtight plastic bag and immersed in water bath for 2 hours at 77 ± 1°F with a minimum 25 mm of water above the surface of samples.

Figure 5 Wet test specimen subjected to vacuum saturation.

The wet test specimens were placed in the vacuum container two at a time and the container was filled with portable water so that samples have at least 25mm of water above their surface. Vacuum was then applied at 10-26 Hg mm partial pressure for 10 minutes. Vacuum was removed and specimens were left submerged in water for further 10 minutes. At the end, water was drained. The mass of saturated surface dry specimen was measured (B′). The volume of absorbed water (J′) was calculated.

$$\mathrm{J}' = \mathrm{B}' - \mathrm{A}$$

Where, A= Dry weight of the specimen

Degree of saturation (S′) was calculated next.

$$S' = \frac{100*J'}{\mathrm{Va}}$$

Where, Va = air void ratio

Specimens with degree of saturation between 70-80 percent were accepted for the test. The procedure was repeated for specimens with less than 70 percent degree of saturation while the specimens with more than 80 percent degree of saturation were discarded.

Each accepted specimen was then covered with a plastic film and wrapped in a plastic bag with 10 ml of water and sealed. The bags were kept in a freezer for 16 hours. They were then removed and immersed in a water bath for 24 hours at 140°±2°F. Plastic bags were removed along with the film as soon as specimens were placed in the water bath. The specimens were kept for 2 hours in another water bath at 77°F.

Both the dry and wet test specimens were placed in between the bearing plates one after another. Then the load was applied at a constant rate of 2 inches/minute. Maximum load was noted and loading was continued until a vertical crack appeared. The tensile strength of the specimens ($S_{t)}$ was calculated.

$$St = \frac{2000 * P}{\Pi * t * D}$$

Where:

S_t = tensile strength, kPa

P = maximum load, N

t = specimen thickness

D = specimen diameter, mm

Tensile strength ratio (TSR) was calculated as:

$$TSR = \frac{\mathrm{S2}}{\mathrm{S1}}$$

Where

S_1: average tensile strength of the dry subset, kPa

S_2: average tensile strength of the wet subset, kPa

TSR should be more than 80 percent to make sure that the potential for moisture damage is not high.

The same process was repeated for non-conventional asphalt mix and TSR of both were compared.

Figure 6 Specimen placement between bearing plates

3.7 Compaction Aid

This test was conducted to find out if additives help in producing proper compaction even in low temperature condition. For compaction aid test, specimens were subjected to full compaction at 75 gyrations at three different temperatures; 275°F, 245°F, 215°F. The weight of each sample was fixed at 4700 g. Bulk specific gravity was determined for each of them after the curing period as before. Specimens with air void percentages of 4±1 percent were accepted.

Figure 7 Using 3 thermometers to ascertain even temperature before compaction.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Trial Samples

Few trial samples were compacted to determine the required mix weight, needed to achieve 7 ± 0.5 percent air void content. After compaction, their bulk specific gravity and air void content was calculated as shown in the following table:

Table 1. Non-conventional Trial Samples

Sample ID	Mix Weight (g)	WD (g)	WSUB (g)	WSSD (g)	Gmb	Gmm	Air Voids (%)
4A	3020	3021.8	1733.4	3027.1	2.335781	2.419	3.4
4B	2980	2980.1	1697	2987.9	2.308544	2.419	4.6
4C	2940	2937.4	1660.4	2947.2	2.282717	2.419	5.6
4D	2900	2898	1635	2917.6	2.259473	2.419	6.6
4E	2880	2878.6	1608.9	2898.7	2.231819	2.419	7.7
4F	2860	2858.6	1590	2881.1	2.214081	2.419	8.5

The table shows the information about 6 trial samples. The first sample, 4A, had a weight of 3020 g which resulted in air void content of 3.4%. This was well below standard 7%. The weight was increased 20 g for each subsequent samples. Sample 4D weighed 2900 g and had air void 6.6%. Sample 4E and 4F had more weight than 4D and air void content for them were 7.7%

and 8.5% which are above the standard. Therefore, it was determined that 2890 g of mix was required to achieve the 7% air content.

4.2 Rut Resistance test

The following table shows the sample information for non-conventional mix.

Table 2. Air Void Content for Non-Conventional Mix APA

Sample ID	Mix Weight (g)	WD (g)	WSUB (g)	WSSD (g)	Gmb	Gmm	Air Voids (%)	Remark
5A-1	2890	2890.1	1616.6	2904.9	2.243344	2.419	7.3	
5A-2	2890	2881.8	1613.4	2895.7	2.247368	2.419	7.1	
5A-3	2890	2887.1	1619.2	2902.8	2.249221	2.419	7.0	
5A-4	2890	2890.3	1615	2907.3	2.236555	2.419	7.5	
6A-1	2890	2890.5	1622.1	2907.6	2.248541	2.419	7.0	
6A-2	2890	2882.7	1613.9	2901.9	2.238121	2.419	7.5	
6A-3	2890	2889.5	1622.1	2909	2.245318	2.419	7.2	
6A-4	2890	2881.7	1618.9	2905.2	2.240302	2.419	7.4	

The table shows that all the specimens were prepared with mix weight 2890 g. All of the specimens compacted had acceptable air void content.

Calculation of Air voids for 5A-1

Dry weight (A) =2890.1 g

Submerged weight (B) = 1616.6 g

Water saturated surface dry weight (C) = 2904.9 g

Gmb= 2890.1/ (2904.9-1616.6) = 2.243344

Gmm= 2.419

Air void Content (Va) = (2.419 - 2.243344) / 2.419 × 100% = 7.3%

The table 3 below shows that the specimens with weight of 2890±5 g have air void content that satisfies the standard requirement. Also sample C-5 had 7.1% air void content. Specimen C-2, C-3, C-4 and C-10 had higher than desired air void content, therefore, were discarded. The 6 specimens C-1, C-5, C-6, C-7, C-8 and C-9 were tested in the APA for rut resistance.

Table 3. Air Void Content for Conventional Mix APA

Sample ID	Mix Weight (g)	WD (g)	WSUB (g)	WSSD (g)	Gmb	Gmm	Air Voids (%)	Remark
C-1	2890	2883.5	1623	2906.7	2.246241	2.419	7.1	
C-2	2880	2873.5	1616.9	2902	2.236013	2.419	7.6	Not used
C-3	2870	2860.4	1603.2	2894.9	2.214446	2.419	8.5	Not used
C-4	2860	2853.3	1602.2	2890.6	2.214607	2.419	8.4	Not used
C-5	2900	2907.8	1639.5	2933.2	2.247662	2.419	7.1	
C-6	2895	2894.9	1623.1	2910.2	2.249165	2.419	7.0	
C-7	2895	2883.9	1618.8	2904.9	2.242361	2.419	7.3	
C-8	2890	2888.9	1622.3	2910.2	2.243109	2.419	7.3	
C-9	2890	2888.4	1620.2	2909.6	2.240112	2.419	7.4	
C-10	2895	2882.9	1623.6	2907.9	2.244725	2.419	7.2	Not used

Six specimens were tested for rut resistance test. Two specimens were placed in each of the three molds. Two readings were recorded for each specimen. The computer recorded rut depth after each cycle which meant there were 8000 recorded rut depth values for each point. For calculation, rut depth at 8000 cycle and rut depth at 25 cycle was used. The difference of the two values was determined as the final rut depth. Rut depth values for the first 25 cycles were omitted during calculation to account for proper seating.

Table 4. Rut Depth for Non-Conventional Specimens

	Non-Conventional			
Sample		Rut at 25 cycles (mm)	Rut at 8000 cycles(mm)	total rut depth (mm)
5A1	left-1	0.233631134	2.37710762	2.143476486
	left-2	0.163169861	2.410482407	2.247312546
5A2	left-4	-0.248466492	1.349870682	1.598337173
	left-5	-0.040792465	1.461122513	1.501914978
5A3	centre-1	0.186847687	1.44619751	1.259349823
	centre-2	0.044843674	0.799705505	0.754861832
6A1	centre-4	-0.848287582	1.221981049	2.070268631
	centre-5	-1.180875778	0.713756561	1.894632339
6A3	right-1	0.279378891	3.076898575	2.797519684
	right-2	0.201152802	3.080623627	2.879470825
6A4	right-4	1.087717056	3.080623627	1.99290657
	right-5	1.03556633	3.080623627	2.045057297

Table 5. Average rut depth of non-conventional specimens

Sample	5A1	5A2	5A3	6A1	6A3	6A4	Average
Average rut depth(mm)	2.195	1.550	1.007	1.982	2.838	2.018	1.932

Table 4 above shows that there were few negative values at the beginning which could be because of the uneven surface on the top of the specimen occurred during compaction or handling. The results show that the specimens in the center mold experienced lower rutting than the ones in left and right molds. The minimum rut depth was 1.007 mm for specimen 5A3 while the maximum was 2.838 for specimen 6A3. The average rut depth value for the non-conventional specimens was 1.932 mm.

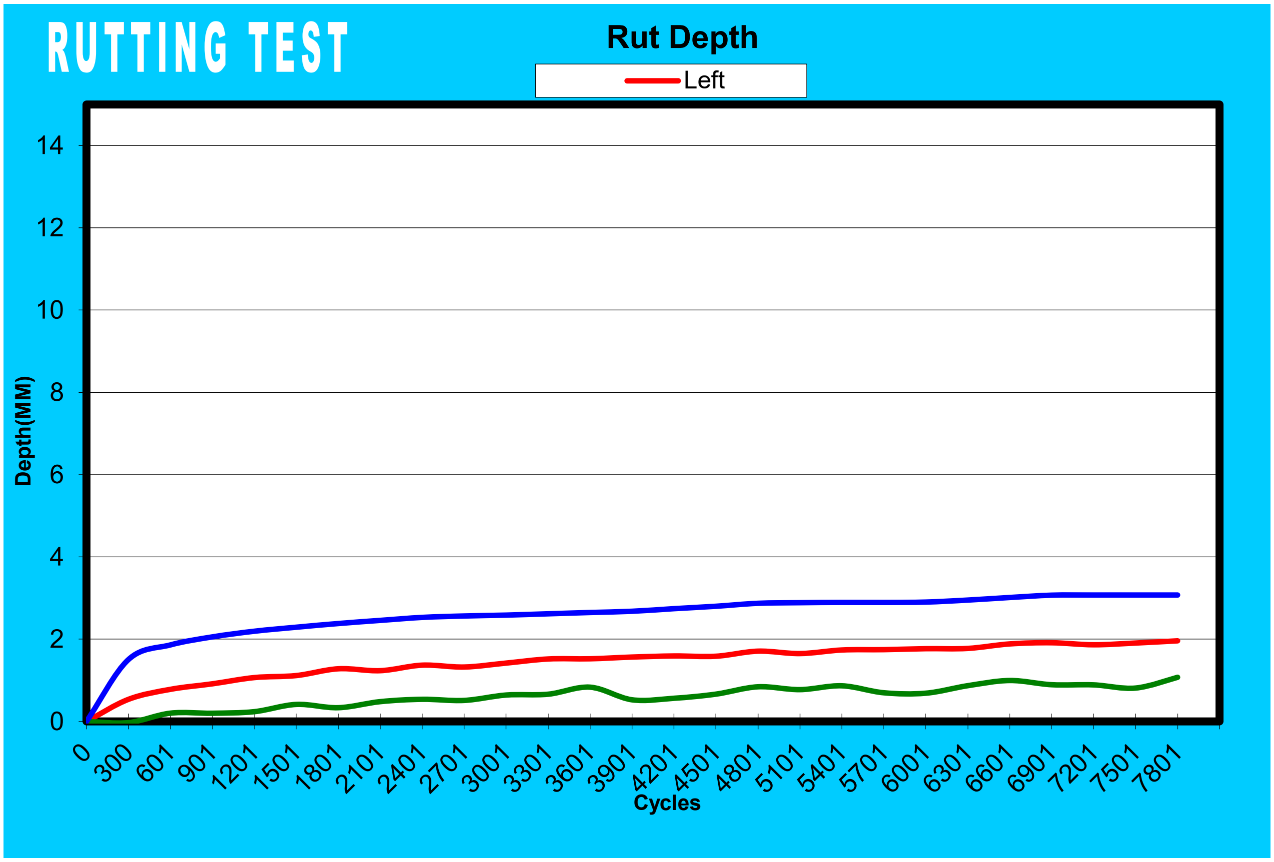
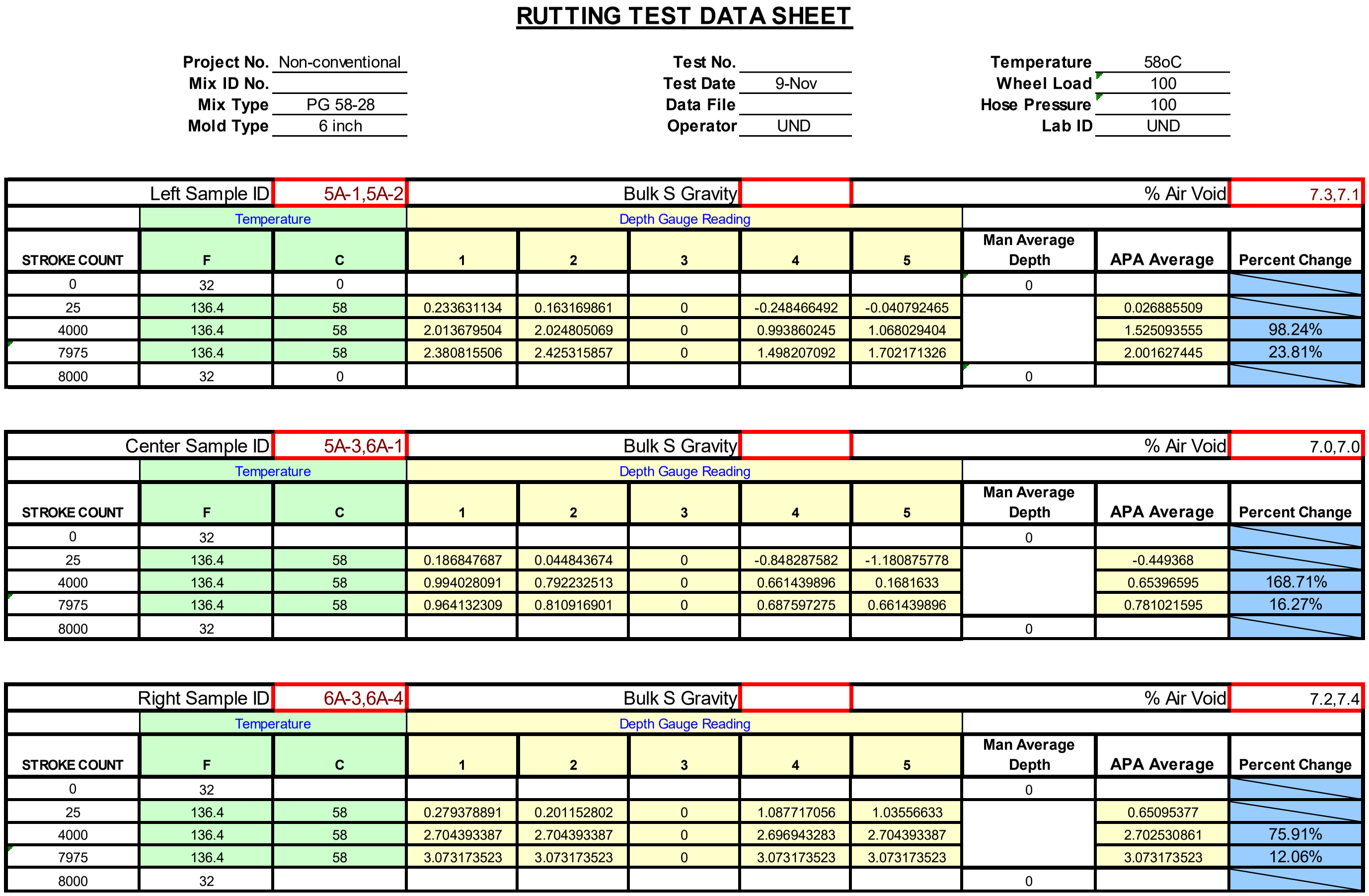


Figure 8 Rut Depth Chart from APA for non-conventional Mix



RUTTING TEST DATA SHEET

Project No. Non-conventional
Mix ID No.
Mix Type PG 58-28
Mold Type 6 inch

Test No.
Test Date 9-Nov
Data File
Operator UND

Temperature 58oC
Wheel Load 100
Hose Pressure 100
Lab ID UND

Left Sample ID	5A-1,5A-2		Bulk S Gravity				% Air Void		7.3,7.1
	Temperature		Depth Gauge Reading						
STROKE COUNT	F	C	1	2	3	4	5	Man Average Depth	APA Average	Percent Change
0	32	0						0		
25	136.4	58	0.233631134	0.163169861	0	-0.248466492	-0.040792465		0.026885509	
4000	136.4	58	2.013679504	2.024805069	0	0.993860245	1.068029404		1.525093555	98.24%
7975	136.4	58	2.380815506	2.425315857	0	1.498207092	1.702171326		2.001627445	23.81%
8000	32	0						0		

Center Sample ID	5A-3,6A-1		Bulk S Gravity				% Air Void		7.0,7.0
	Temperature		Depth Gauge Reading						
STROKE COUNT	F	C	1	2	3	4	5	Man Average Depth	APA Average	Percent Change
0	32							0		
25	136.4	58	0.186847687	0.044843674	0	-0.848287582	-1.180875778		-0.449368	
4000	136.4	58	0.994028091	0.792232513	0	0.661439896	0.1681633		0.65396595	168.71%
7975	136.4	58	0.964132309	0.810916901	0	0.687597275	0.661439896		0.781021595	16.27%
8000	32							0		

Right Sample ID	6A-3,6A-4		Bulk S Gravity				% Air Void		7.2,7.4
	Temperature		Depth Gauge Reading						
STROKE COUNT	F	C	1	2	3	4	5	Man Average Depth	APA Average	Percent Change
0	32							0		
25	136.4	58	0.279378891	0.201152802	0	1.087717056	1.03556633		0.65095377	
4000	136.4	58	2.704393387	2.704393387	0	2.696943283	2.704393387		2.702530861	75.91%
7975	136.4	58	3.073173523	3.073173523	0	3.073173523	3.073173523		3.073173523	12.06%
8000	32							0		

Figure 9 Rut Depth Values from APA for non-conventional Mix

The table 6 below shows the rut depth of each specimen.

Table 6. Rut Depth values for conventional Specimen

Sample		Conventional Mix		
		Rut at 25 cycles (mm)	Rut at 8000 cycles(mm)	total rut depth (mm)
C1	left-1	0.207672119	2.291812897	2.084140778
	left-2	0.140920639	1.854217529	1.71329689
C5	left-4	-0.189130783	1.424037933	1.613168716
	left-5	-0.118671417	1.579792023	1.69846344
C6	centre-1	0.220479965	2.432750702	2.212270737
	centre-2	0.231689453	2.294483185	2.062793732
C7	centre-4	-0.411064148	1.748889923	2.159954071
	centre-5	-0.661439896	1.756362915	2.417802811
C8	right-1	0.227230072	2.287185669	2.059955597
	right-2	0.216054916	2.294635773	2.078580856
C9	right-4	0.130378723	2.287185669	2.156806946
	right-5	0.22350502	2.287185669	2.063680649

Table 7. Average rut depth of conventional specimens

Sample	C1	C5	C6	C7	C8	C9	Average
Average rut depth(mm)	1.898	1.656	2.137	2.289	2.069	2.110	2.027

Conventional mix specimen endured more rutting than the non-conventional Mix Specimen as evidenced by the tables above. The specimens on the left experienced lower rutting than the specimens on the center and right mold. The minimum rut depth value for conventional mix was 1.656 mm for C5 while the maximum was 2.289 mm for C7. The average rut depth was 2.027 mm.

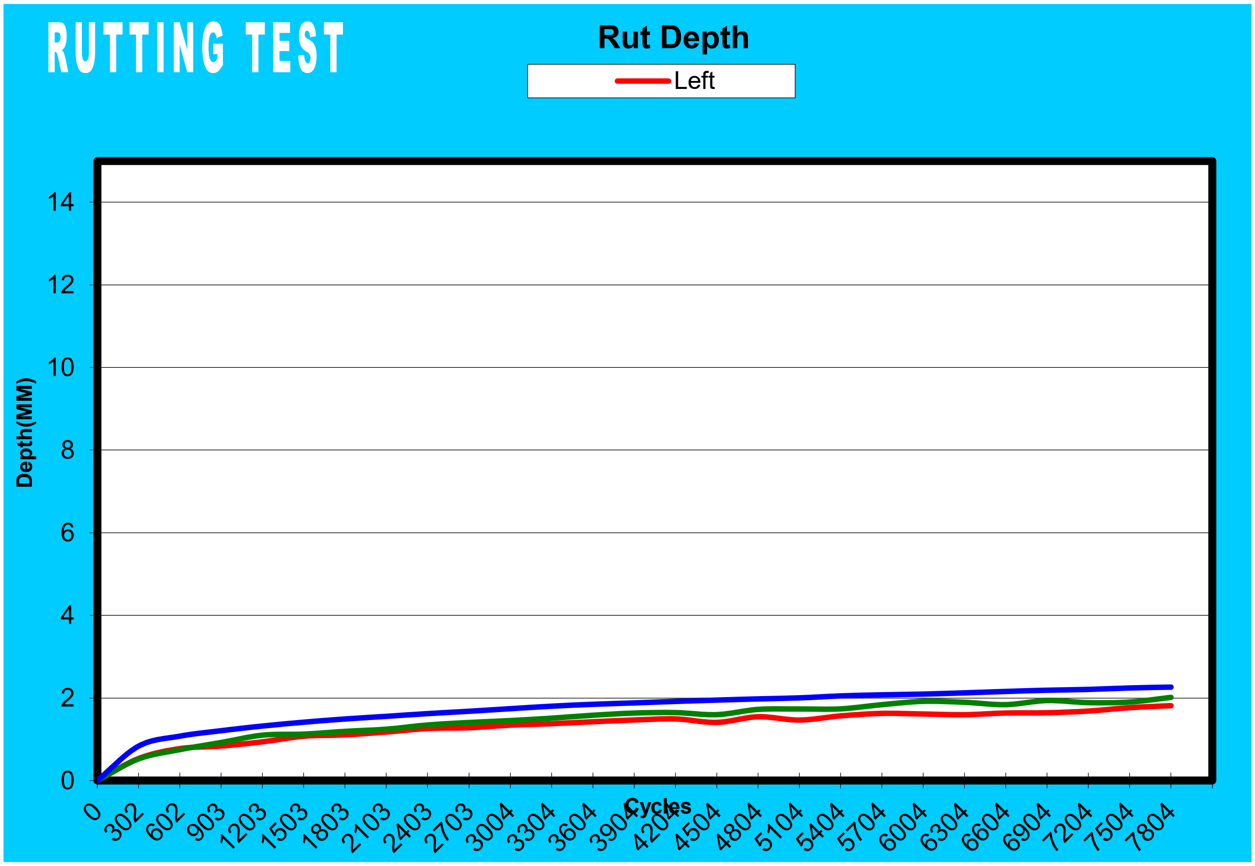
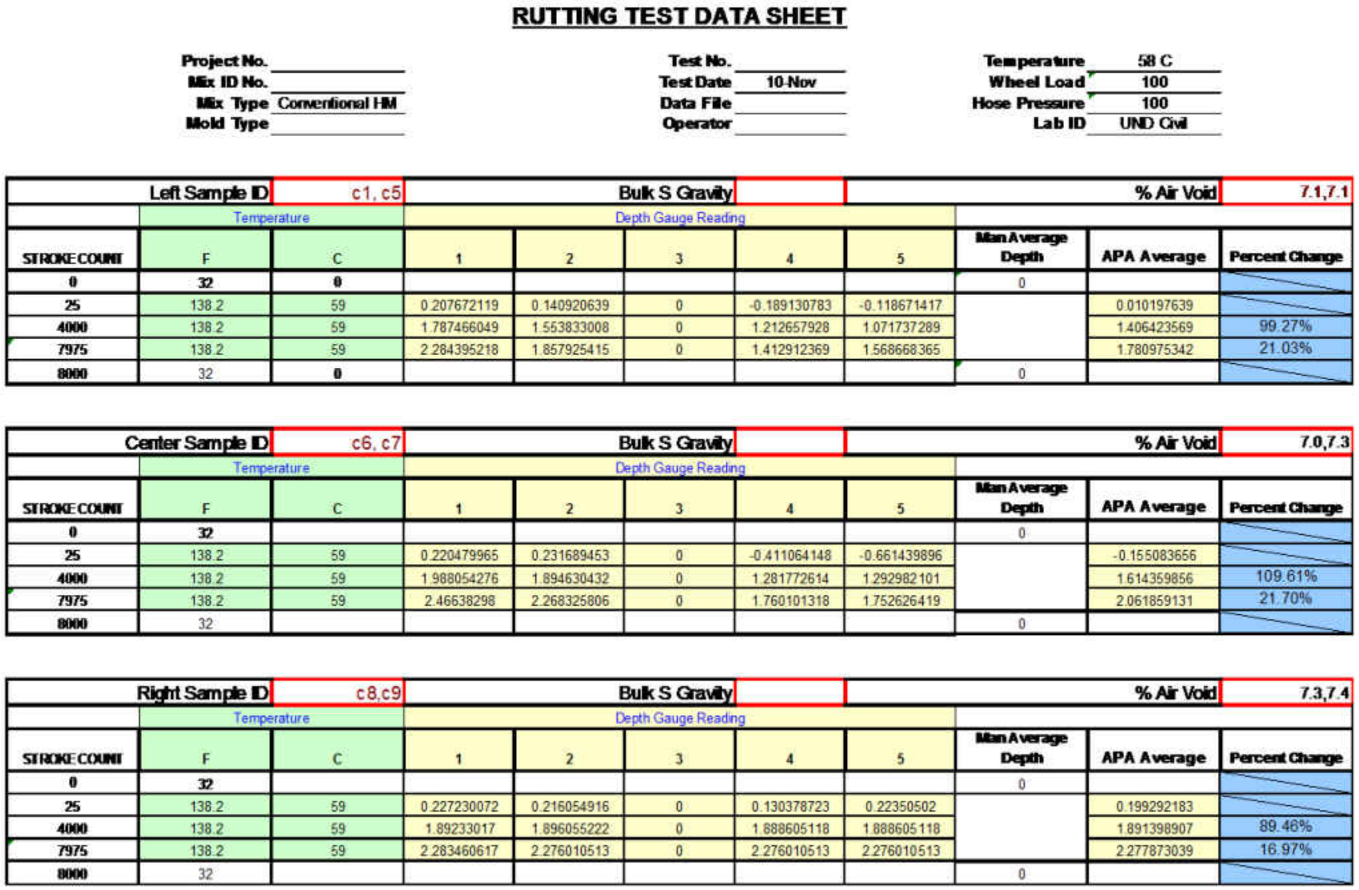


Figure 10 Rut Depth Chart from APA for Conventional Mix



RUTTING TEST DATA SHEET

Project No.
Mix ID No.
Mix Type Conventional HM
Mold Type

Test No.
Test Date 10-Nov
Data File
Operator

Temperature 58 C
Wheel Load 100
Hose Pressure 100
Lab ID UND Civil

Left Sample ID	c1, c5		Bulk S Gravity					% Air Void	7.1,7.1
	Temperature		Depth Gauge Reading						
STROKE COUNT	F	C	1	2	3	4	5	Man Average Depth	APA Average	Percent Change
0	32	0						0		
25	138.2	59	0.207672119	0.140920639	0	-0.189130783	-0.118671417		0.010197639	
4000	138.2	59	1.787466049	1.553833008	0	1.212657928	1.071737289		1.406423569	99.27%
7975	138.2	59	2.284395218	1.857925415	0	1.412912369	1.568668365		1.780975342	21.03%
8000	32	0						0		

Center Sample ID	c6, c7		Bulk S Gravity						% Air Void	7.0,7.3
	Temperature		Depth Gauge Reading							
STROKE COUNT	F	C	1	2	3	4	5	Man Average Depth	APA Average	Percent Change
0	32							0		
25	138.2	59	0.220479965	0.231689453	0	-0.411064148	-0.661439896		-0.155083656	
4000	138.2	59	1.988054276	1.894630432	0	1.281772614	1.292982101		1.614359856	109.61%
7975	138.2	59	2.46638298	2.268325806	0	1.760101318	1.752626419		2.061859131	21.70%
8000	32							0		

Right Sample ID	c8,c9		Bulk S Gravity						% Air Void	7.3,7.4
	Temperature		Depth Gauge Reading							
STROKE COUNT	F	C	1	2	3	4	5	Man Average Depth	APA Average	Percent Change
0	32							0		
25	138.2	59	0.227230072	0.216054916	0	0.130378723	0.22350502		0.199292183	
4000	138.2	59	1.89233017	1.896055222	0	1.888605118	1.888605118		1.891398907	89.46%
7975	138.2	59	2.283460617	2.276010513	0	2.276010513	2.276010513		2.277873039	16.97%
8000	32							0		

Figure 11 Rut Depth Values from APA for Conventional Mix

Figure 12 and figure 13 show the comparison between individual specimens corresponding to their seating position in APA.

Figure 12 Comparison of rut depth at different position between Non-Conventional and Conventional Mix Specimen

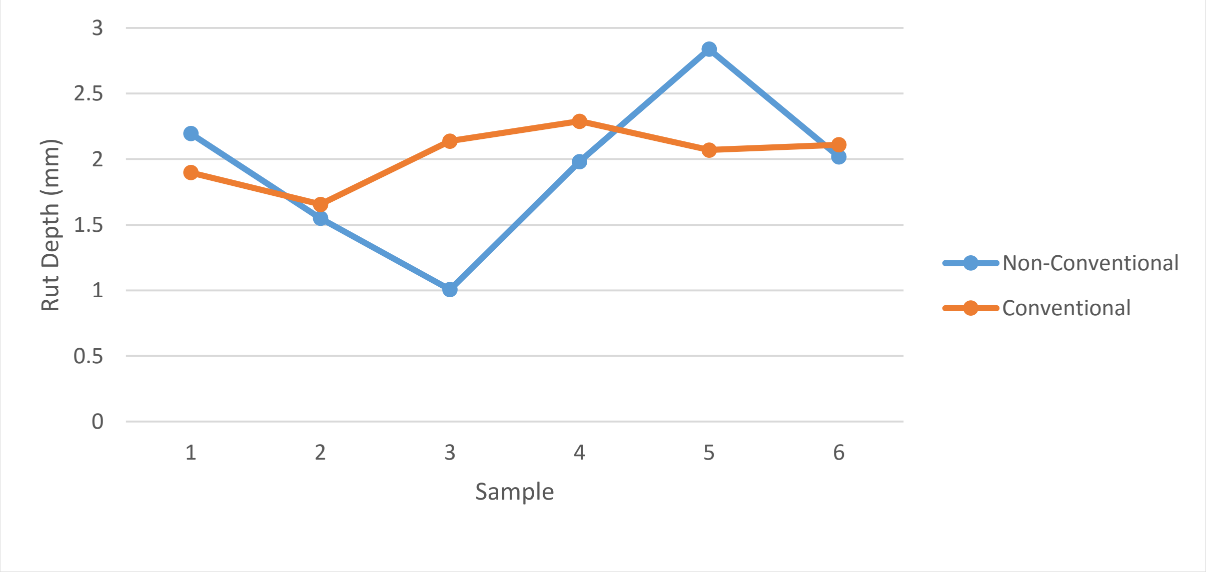


Figure 13 Comparison of average rut depth between non-conventional and conventional Mix Specimens

Figure 14 illustrates the difference between the average rut depth of non-conventional and Conventional mix specimens.

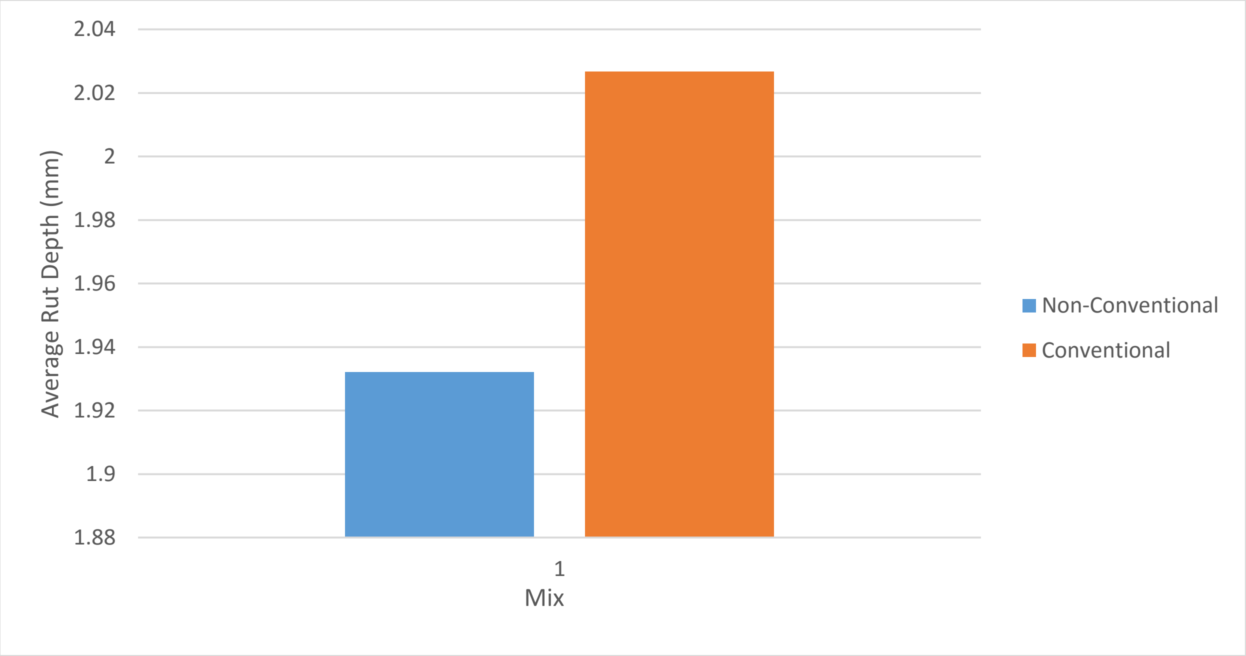


Figure 14 Comparison of average rut depth of non-conventional and conventional Mix Specimen.

. The average rut depth of non-conventional specimen was 1.932 mm while the average rut depth of conventional mix specimens was 2.027 mm. The difference between the two averages was 0.095 mm. The conventional mix specimens experienced 4.91 percent more rutting in average compared to non-conventional mix specimens. This result shows that the use of additives increases the rut resistance in hot mix asphalt.

The table 8 shows the result of the t test performed for the rut resistance test comparing non-conventional mix specimens and conventional mix specimens

Table 8. t Test for Rut Resistance test

t-Test: Two-Sample Assuming Unequal Variances		
	Non-Conventional	Conventional
Mean	1.932092349	2.026742935
Variance	0.360217468	0.055347141
Observations	12	12
Hypothesized Mean Difference	0	
df	14	
t Stat	-0.508621431	
P(T<=t) one-tail	0.309469075	
t Critical one-tail	1.761310136	
P(T<=t) two-tail	0.618938151	
t Critical two-tail	2.144786688	

Since, the test was done for two different mixes and the variance was not known, Two-sample Assuming Unequal Variances was performed in Microsoft Excel. Twelve data points were considered for each mix. The mean difference was unknown beforehand, therefore was set as 0. The alpha value was specified as 0.05.

The variance was 0.360 for non-conventional mix specimen while it was 0.055 for conventional mix. This shows that the non-conventional mix specimens experienced inconsistent rutting compared to conventional mix specimens. However, the average rut depth of the Non-Conventional mix specimen was lower than conventional mix specimen.

The degrees of freedom were 14. Here, test was done to compare the mean of the two mixes, thus, the result of two tail test was considered as the solution. The p value of the two tail test was 0.619. This was higher than the 0.05. So, the null hypothesis cannot be rejected. That means that the difference in the rut values between Non-Conventional mix specimens and Conventional mix specimens is not significant statistically. However, the numerical difference between the average rut depth value was 0.095 mm. Since the t test was done with low number of data values, the result cannot be recognized as the conclusion.

4.3 Moisture Sensitivity

Table 9 below shows the air void content for non-conventional specimens compacted for the moisture sensitivity test.

Table 9. Non-Conventional Moisture Sensitivity Samples Air Void Content.

Sample ID	Mix Weight (g)	WD (g)	WSUB (g)	WSSD (g)	Gmb	Gmm	Air Voids (%)	Remark
MH1	3700	3693	2080.2	3714.5	2.259683	2.419	6.6	
MH2	3660	3655.6	2044.2	3677.8	2.237757	2.419	7.5	
MH3	3620	3614.2	2028.9	3655.2	2.222345	2.419	8.1	
MH4	3680	3675.7	2069.2	3708.6	2.242101	2.419	7.3	
MH5	3680	3671	2060	3702.2	2.235416	2.419	7.6	
MH6	3680	3665.6	2063.8	3703.9	2.234986	2.419	7.6	
MH7	3680	3670.5	2065.2	3696.2	2.25046	2.419	7	
MH8	3680	3671.6	2064.6	3698.7	2.246864	2.419	7.1	
MH9	3680	3679.6	2072.2	3707.8	2.249694	2.419	7	

A basic unitary method was used to determine the weight of the specimen required to achieve 95 mm specimen height. As 2900 g of mix amount was used to achieve 75 mm specimen height for rut resistance test, 3690 was determined as the mix amount required to achieve 95 mm specimen height for moisture sensitivity test. Air void ratio was calculated as before and results were tabulated. The table shows that all the specimens except sample MH-3 had the optimal air void ratio and were further tested for moisture sensitivity. The average air void ratio of the specimen was 7.2 percent. Eight specimens were divided into two groups of four such that the average air void ratio of the groups were similar.

Samples were divided as above such that the average air void content of the two groups were similar. Dry test subset had the air void ratio of 7.2 percent while the wet test subset had the air void ratio of 7.225 percent. Modified Lottman test was carried out for the assorted specimens accordingly.

Table 10. Non-Conventional Specimen divided into two subset

Dry Test	Air void (%)	Wet test	Air Void (%)
MH2	7.5	MH1	6.6
MH4	7.3	MH5	7.6
MH7	7	MH6	7.6
MH9	7	MH8	7.1
Average	7.2	Average	7.225

Table 11. Moisture Sensitivity Test results for Non-Conventional Mix

		Wet				Dry			
Sample Identification		**MH1**	**MH5**	**MH6**	**MH8**	**MH2**	**MH4**	**MH7**	**MH9**
Diameter (mm)	D	149.6	149.77	149.73	149.73	149.79	149.45	149.69	149.75
Thickness (mm)	t	94.75	94.8	94.32	94.48	94.35	94.62	94.28	94.31
Dry Mass in Air (g)	A	3693	3671	3665.6	3671.6	3655.6	3675.7	3670.5	3679.6
SSD Mass (g)	B	3714.5	3702.2	3703.9	3698.7	3677.8	3708.6	3696.2	3707.8
Mass in Water (g)	C	2080.2	2060	2063.8	2064.6	2044.2	2069.2	2065.2	2072.2
Volume (B-C), cm^3	E	1634.3	1642.2	1640.1	1634.1	1633.6	1639.4	1631	1635.6
Bulk Specific Gravity (A/E)	Gmb	2.260	2.235	2.235	2.247	2.238	2.242	2.250	2.250
Maximum Specific Gravity	Gmm	2.419	2.419	2.419	2.419	2.419	2.419	2.419	2.419
% Air Voids	Pa	6.586	7.589	7.607	7.116	7.492	7.313	6.967	6.999
Volume of Air Voids	Va	107.636	124.631	124.763	116.283	122.397	119.888	113.637	114.476
Load (lb)	P					2286.5	2408.8	2585.6	
Saturated min @ mmHg		25	25	26	26				
Thickness (mm)	t'	94.75	94.8	94.32	94.48				
SSD Mass (g)	B'	3779.1	3764.6	3762.5	3761.3				
Volume of Absorbed Water (B'-A)	J'	86.1	93.6	96.9	89.7				
% Saturation	S'	79.992	75.102	77.667	77.140				
Load (lb)	P'		2229.6	2304	2516.3				
Dry Strength	S1					0.2291	0.2412	0.2594	
Wet Strength	S2		0.222335	0.23099	0.251842				
Average Strength, S (kPa)		0.235054409				0.2432			
Visual Moisture Damage	No								
Cracked/Broken Aggregate?	No								
TSR (S2/S1)		**96.64532893**							

MH1 was compacted on a different date than the rest of the specimen while the loading rate for MH9 was increased even after load failure as the failure load was not recorded. Therefore, both the specimens were discarded for the TSR calculation from their respective subset.

The table shows the results after the Modified Lottman test. A sample calculation for wet specimen is shown below for MH-5:

Volume of absorbed water = (3764.6- 3671) g = 93.6 g

Degree of saturation = 100 × 93.6 / 7.589 % = 75.102%

Since, degree of saturation was between 70% - 80 %, it was accepted.

Tensile strength was calculated for both wet and dry specimens as shown below for MH5:

Wet strength = $(2000\times 2229.6) / (\pi \times 94.8 \times 149.77) = 0.222335$ kPa

Tensile strength for all wet samples were calculated and averaged. The same was done for dry samples. Samples MH1 was compacted on a different date and MH-9 failed on higher load, therefore wasn't included in the calculation. The maximum load at which a wet sample failed was 2516.3 lbs for MH8 and the minimum was 2229.6 lbs for MH5. For the dry test, the maximum was 2585.6 lbs for MH7 and the minimum was for 2286.5 for MH2.

The average strength for both the wet and dry specimen were calculated as shown in the table 12 below.

Table 12. Non-conventional Specimen Strength

Wet Sample	Strength(kpa)		Dry Sample	Strength(kpa)
MH-5	0.222		MH-2	0.229
MH-6	0.230		MH-4	0.241
MH-8	0.251		MH-7	0.259
Average	0.235		Average	0.243
TSR		96.645		

The dry specimens have higher average strength than the wet specimens. This is due to the presence of moisture in the wet specimens that makes them weaker.

Tensile strength Ratio (TSR) was calculated as follows:

$$TSR = 0.243 / 0.235 \times 100 \% = 96.645 \%$$

The TSR value was higher than the standard 80 %. Therefore, it was concluded that the moisture resistance is good with the use of additives.

Figure 15 Visible Cracking in the dry Non-Conventional specimens after Modified Lottman Test

The table 13 below shows the air void ratio of the specimens prepared with conventional mix. All the prepared specimens had optimal air void ratio with the average of 7.0 percent. Four specimens were classified in a dry subset while the rest four were classified under wet subset as shown in table 14 such that the average air void ratio of the two groups were similar.

Table 13. Conventional Moisture Sensitivity Samples Air Void Content

Sample ID	Mix Weight (g)	WD (g)	WSUB (g)	WSSD (g)	Gmb	Gmm	Air Voids (%)	Remark
MC1	3685	3674	2067.3	3702	2.247507	2.419	7.1	
MC2	3690	3682.3	2068.6	3707.9	2.246264	2.419	7.1	
MC3	3690	3681.1	2071.3	3707.8	2.249374	2.419	7.0	
MC4	3690	3684.3	2078.7	3712.6	2.254912	2.419	6.8	
MC5	3690	3670.7	2065.7	3696.7	2.250582	2.419	7.0	
MC6	3690	3684.4	2080.6	3712.7	2.25746	2.419	6.7	
MC7	3690	3670.2	2068.2	3706	2.240933	2.419	7.4	
MC8	3690	3682.9	2074.9	3709	2.253779	2.419	6.8	

Table 14. Conventional Mix divided into two subset

Dry Test	Air void (%)	Wet test	Air Void (%)
MC3	7	MC1	7.1
MC6	6.7	MC2	7.2
MC7	7.4	MC4	6.8
MC8	6.8	MC5	7
Average	6.975	Average	7.025

Table 15 Moisture Sensitivity Test Results for Conventional Mix

		Wet				Dry			
Sample Identification		**MC1**	**MC2**	**MC4**	**MC5**	**MC3**	**MC6**	**MC7**	**MC8**
Diameter (mm)	D	149.480	149.980	149.800	149.800	149.600	149.900	149.940	150.100
Thickness (mm)	t	94.400	94.500	94.500	94.700	94.500	94.400	94.600	94.500
Dry Mass in Air (g)	A	3674.000	3682.300	3684.300	3670.700	3681.100	3684.400	3670.200	3682.900
SSD Mass (g)	B	3702.000	3707.900	3712.600	3696.700	3707.800	3712.700	3706.000	3709.000
Mass in Water (g)	C	2067.300	2068.600	2078.700	2065.700	2071.300	2080.600	2068.200	2074.900
Volume (B-C), cm^3	E	1634.700	1639.300	1633.900	1631.000	1636.500	1632.100	1637.800	1634.100
Bulk Specific Gravity (A/E)	Gmb	2.248	2.246	2.255	2.251	2.249	2.257	2.241	2.254
Maximum Specific Gravity	Gmm	2.419	2.419	2.419	2.419	2.419	2.419	2.419	2.419
% Air Voids	Pa	7.089	7.141	6.783	6.962	7.012	6.678	7.361	6.830
Volume of Air Voids, cm^3	Va	115.891	117.059	110.833	113.555	114.755	108.991	120.561	111.611
Load (lb)	P					2145.500	2545.800	2027.200	2228.100
Saturated min @ mmHg		26.000	26.000	26.000	26.000				
Thickness (mm)	t'	94.400	94.500	94.500	94.700				
SSD Mass (g)	B'	3774.800	3779.800	3777.800	3768.700				
Volume of Absorbed Water (B'-A)	J'	100.800	97.500	93.500	98.000				
% Saturation	S'	86.979	83.291	84.361	86.302				
Load (lb)	P'	1763.200	1756.100	2153.800	2012.400				
Dry Strength (kPa)	S1					0.215	0.255	0.202	0.222
Wet Strength (kPa)	S2	0.177	0.175	0.215	0.201				
Average Strength, S (kPa)	No								
Visual Moisture Damage	No								
Average Strength, S (kPa)		0.192				0.224			
Cracked/Broken Aggregate?									
TSR (S2/S1)		**85.941**							

The table 15 shows the result of the Modified Lottman Test for conventional mix. The vacuum pressure was 26 mmHg for partial vacuum saturation for wet test. Even though the air voids were acceptable, the wet test specimens had a degree of saturation more than 80 % which is higher than standard. The test was further carried out nevertheless as there was not enough mix amount for preparation of new specimen.

Table 16 shows the strength of dry and wet conventional mix samples.

Table 16. Conventional Mix Specimen Strength

Wet Sample	Strength (kpa)		Dry Sample	Strength (kpa)
MC1	0.177		MC3	0.215
MC2	0.175		MC6	0.255
MC4	0.215		MC7	0.202
MC5	0.201		MC8	0.222
average	0.192			0.2235
TSR		85.941		

The maximum load at which a wet sample failed was 2153.800 lbs for MC4 and the minimum was 1756.1 lbs for MC2. For the dry test, the maximum was 2545.800 lbs for MC6 and the minimum was for 2027.200 for MC7. The average strength for dry subset was 0.224 kPa and for wet subset was 0.192 kPa.

Tensile strength Ratio (TSR) was calculated as follows:

$$TSR = 0.223 / 0.192 \times 100 \%= 85.941 \%$$

Since, this value is higher than the recommended 80 percent, it can be said that the conventional mix also has good moisture resistance.

Figure 16 Visible Cracking in the wet Conventional specimens after Modified Lottman Test

The figure 17 and figure 18 shows the comparison of strength between conventional and non-conventional samples.

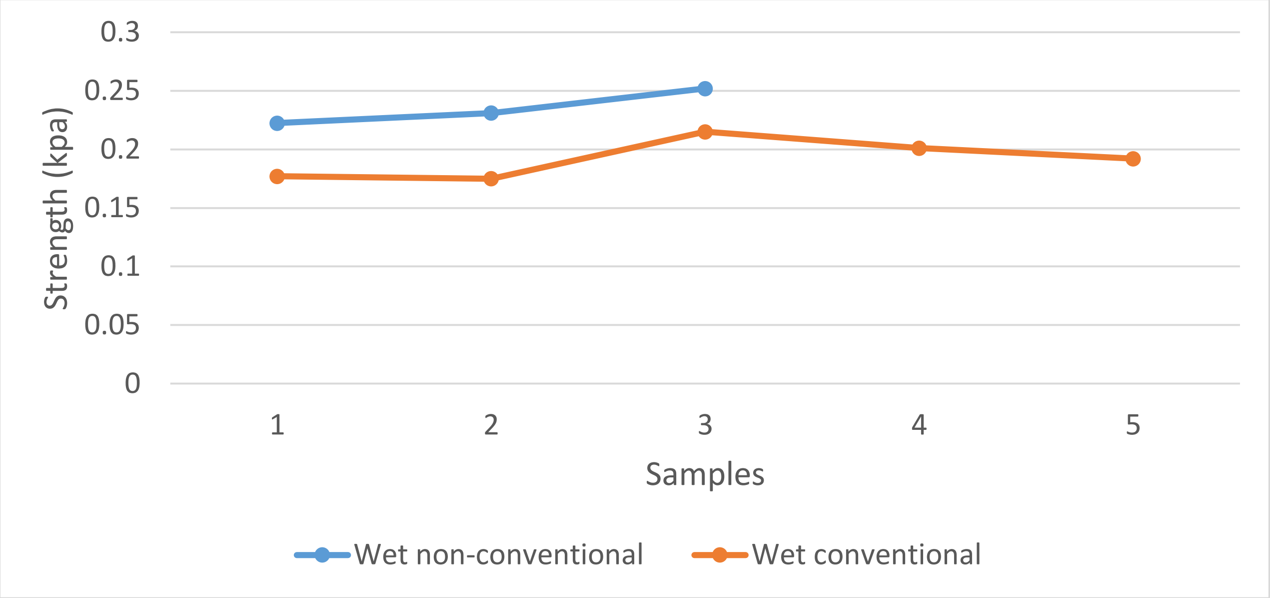


Figure 17 Wet non-conventional strength versus wet conventional strength

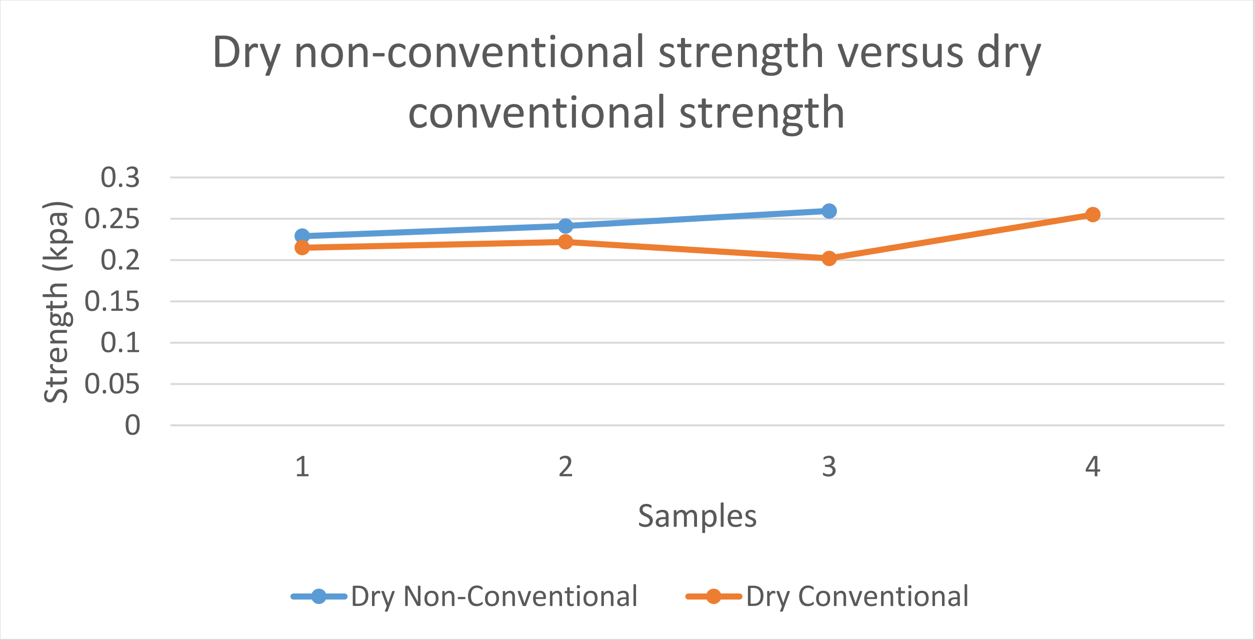


Figure 18 Dry non-conventional strength versus dry conventional strength

Both the maximum and minimum failure load for conventional mix specimens for wet and dry subset is lower than the same for non-conventional mix sample. That resulted in the conclusion that the average strength of wet non-conventional specimen is higher than the average strength of wet conventional specimen. And the average strength of dry non-conventional specimen is higher than the average strength of dry conventional specimen.

The charts above illustrate the result of the comparison between non-conventional and conventional specimens. The average wet strength of non-conventional specimen was 0.235 Kpa and the average wet strength of conventional specimen was 0.192 Kpa. The average strength of wet non-conventional specimen was 22.4 percent higher than that of wet conventional specimen. Similarly, the average strength of dry non-conventional specimen was 8.72 percent higher than that of dry conventional specimen. It shows that the use of additives increases the strength both in dry and wet conditions. Also, the addition of moisture resulted in weaker specimens in both non-conventional and conventional mixes. The results also show that the difference in average wet strength is higher than the difference in average dry strength by 13.68 percent. This is a significance amount as it suggests that use of additives is more effective when there is a presence of moisture.

The barchart below shows the Tensile Strength Ratio for both the Non-Conventional and conventional mixes which are 96.645 percent and 85.941 percent respectively

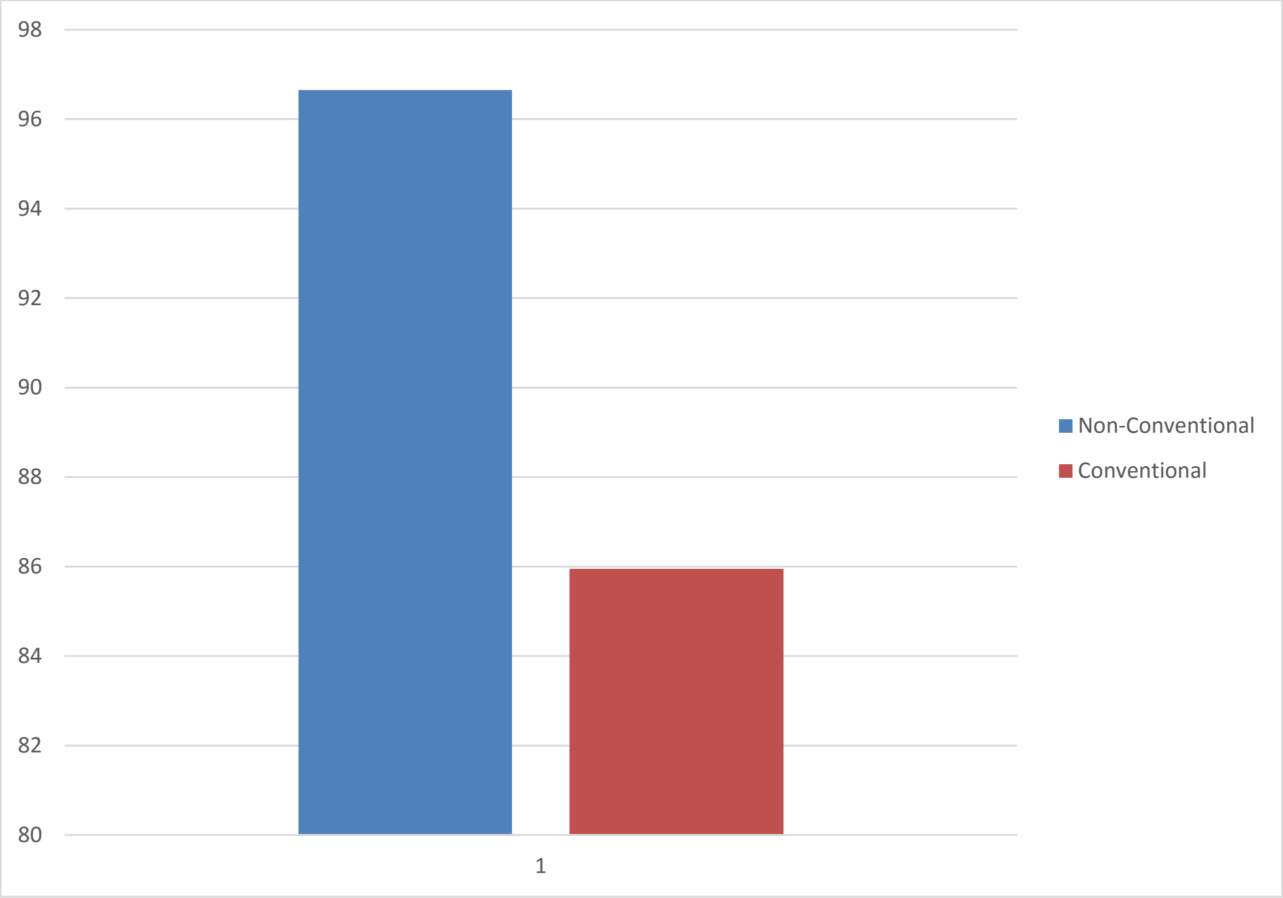


Figure 19 Non-conventional TSR v conventional TSR

The standard TSR for Modified Lottman Test is considered 80 percent. Therefore, we can conclude that both the non-conventional and conventional mixes are strong. TSR value for the Non-Conventional mix is 10.704 percent more than the TSR for conventional mix. This difference suggests that the usage of additives increases the strength significantly , no matter the weather conditions.

4.4 Compaction Aid

The table 17 below shows that 4700 g was used as the standard weight for full compaction for all the specimens.

Table 17. Compaction data for Compaction Aid of non-conventional mix specimens

ID	Weight (g)	Height (mm)	% Gmm	Comp. Temp. (oF)
CH-1	4700	117.28	94	275
CH-2	4700	119.08	92.6	245
CH-3	4700	119.03	92.6	215
CH-4	4700	117.85	93.6	275
CH-5	4700	119.13	92.6	245
CH-6	4700	120.37	91.6	215
CH-7	4700	117.03	94.2	275
CH-8	4700	117.54	93.8	245
CH-9	4700	119.13	92.3	215

Samples were prepared at three different temperatures with equal intervals; 275 °F, 245 °F and 215 °F. Three samples were prepared for each temperature. The average height of the specimens was 117. 389 mm for specimens prepared at 275 °F, 118.58 mm for 245 °F specimens and 119. 51mm for 215 °F specimens. It showed that the increase in compaction temperature led to decrease in the specimen height. The maximum height of compacted specimen was 120.37 mm at 215 °F. The average Gmm percent was 93.933 percent for samples prepared at 275 °F, 93 percent for 245 °F and 92.167 percent for 215 °F.

Table 18. Compaction data for Compaction Aid of conventional mix specimen

ID	Weight (g)	Height (mm)	% Gmm	Comp. Temp. (°F)	Remark
CC-1	4700	119.24	92.5	275	
CC-2	4700	119.03	92.6	245	*
CC-3	4700	120.21	91.7	215	**
CC-4	4700	118.36	93.2	275	
CC-5	4700	120.52	91.5	245	
CC-6	4700	122.22	90.2	215	
CC-7	4700	118.6	92.8	275	
CC-8	4700	118.26	93	245	
CC-9	4700	120.42	91.6	215	
CC-10	4700	118.98	92.7	285	

* Might have lost some material because of reheating and remixing
** Might have lost some material because of reheating and remixing

The table 18 shows the compaction data for conventional mix. Similar to the compaction of non-conventional specimens, three conventional mix specimens each were compacted at three different temperatures; 275 °F, 245 °F and 215 °F. The average height of the compacted specimen was 118.73 mm for specimen prepared at 275 °F, 119.27 mm for 245 °F and 120.95 mm at 215 °F. The maximum height of the compacted specimen was 122.22 mm at 215 °F. The average Gmm percent was 92.833 percent for samples prepared at 275 °F, 92.367 percent for samples prepared at 245 °F and 91.167 percent for samples prepared at 215 °F.

Figure 20 represents a chart that shows the average height comparison between non-conventional and conventional specimens prepared at same temperatures.

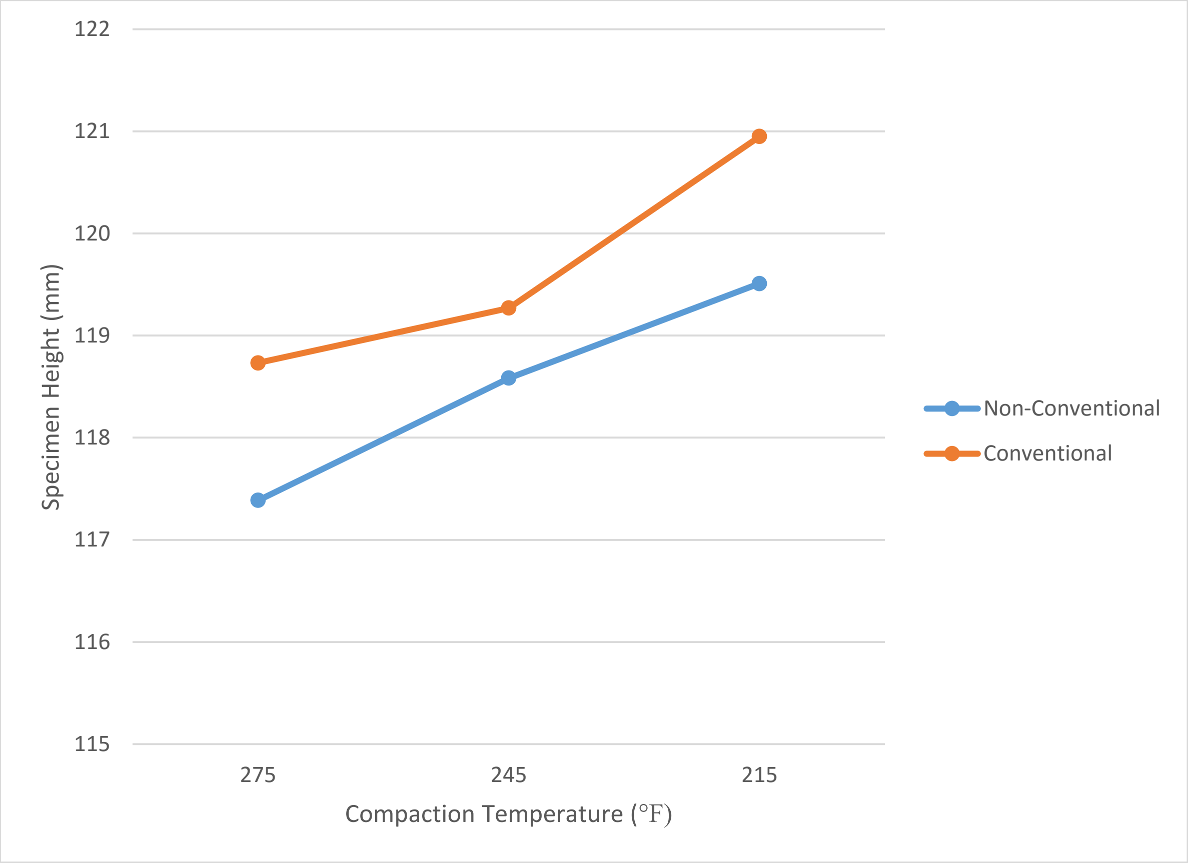


Figure 20 Comparison of Specimen Height of Non-Conventional mix and Conventional mix Specimen.

In all the temperatures, non-conventional mix specimens have lower specimen height than the conventional mix specimens. Even though both the mixes were subjected to full compaction, lower specimen height obtained in non-conventional mix specimen can be an indication as to better compaction and lower air voids.

Table 19. Non-conventional Compaction Aid Samples Air Void Contents

Sample ID	Mix Weight (g)	WD (g)	WSUB (g)	WSSD (g)	Gmb	Gmm	Air Voids (%)	Remark
CH-1	4700	4690.5	2678.5	4707.3	2.311958	2.419	4.4	275 °F
CH-2	4700	4723.3	2690.9	4751.5	2.292196	2.419	5.2	245 °F
CH-3	4700	4702.9	2677.9	4736	2.285069	2.419	5.5	215 °F
CH-4	4700	4701.1	2678	4717.5	2.305026	2.419	4.7	275 °F
CH-5	4700	4701.8	2673	4735.3	2.279882	2.419	5.8	245 °F
CH-6	4700	4698.4	2668.7	4749.7	2.257761	2.419	6.7	215 ° F
CH-7	4700	4693.8	2676.8	4711	2.307443	2.419	4.6	275 °F
CH-8	4700	4702.9	2682.1	4725.4	2.30162	2.419	4.9	245 °F
CH-9	4700	4701.2	2674	4750.5	2.264002	2.419	6.4	215 °F

The table 19 above shows the result of compaction aid test for non-conventional mix specimens. The air void ratio for each specimen was calculated according to standard procedure as before. The air void ratio of 4 ± 0.5 percent is considered as acceptable in the compaction aid test conducted in laboratory. According to the results, only CH-1 has the acceptable air void ratio. Sample CH-1 was compacted at 275° F. Other two specimens compacted at 275° F; CH-4 and CH-7 have air void ratio of 4.7 percent and 4.6 percent respectively. They are close to the required air void ratio. All the specimens compacted at 245 °F and 215 °F have higher air void ratio than allowable.

Table 20. Conventional Compaction Aid Samples Air Void Contents

Sample ID	Mix Weight (g)	WD (g)	WSUB (g)	WSSD (g)	Gmb	Gmm	Air Voids (%)	Remark
CC-1	4700	4680.2	2648.4	4705.8	2.274813	2.419	6.0	275 °F
CC-2	4700	4702.4	2665.7	4731.9	2.275869	2.419	5.9	245 °F
CC-3	4700	4707.3	2665.8	4749.4	2.259215	2.419	6.6	215 °F
CC-4	4700	4703.4	2672.2	4721.7	2.294901	2.419	5.1	275 °F
CC-5	4700	4694.1	2666.1	4748.4	2.254286	2.419	6.8	245 °F
CC-6	4700	4709.9	2672.7	4781.6	2.233344	2.419	7.7	215 °F
CC-7	4700	4697.8	2672.2	4732.6	2.280043	2.419	5.7	275 °F
CC-8	4700	4701.2	2673.7	4734.4	2.281361	2.419	5.7	245 °F
CC-9	4700	4693.7	2671.2	4760.8	2.246219	2.419	7.1	215 °F
CC-10	4700	4692	2662.3	4722.8	2.277117	2.419	5.9	285 °F

The table shows the result of compaction aid test conventional mix specimens. None of the specimens prepared had the acceptable air void ratio. Sample CC-4 had the lowest air void ratio as 5.1 percent compacted at 275 °F while sample CC-6 had the highest air void ratio as 7.7 percent compacted at 215 °F. The air void ratio decreased with the increase of compaction temperatures. However, one specimen prepared at 285 °F also did not have allowable air void ratio.

Table 21. Air void ratio at 275 °F

Non-Conventional mix (%)	Conventional mix (%)
4.4	6
4.7	5.1
4.6	5.7

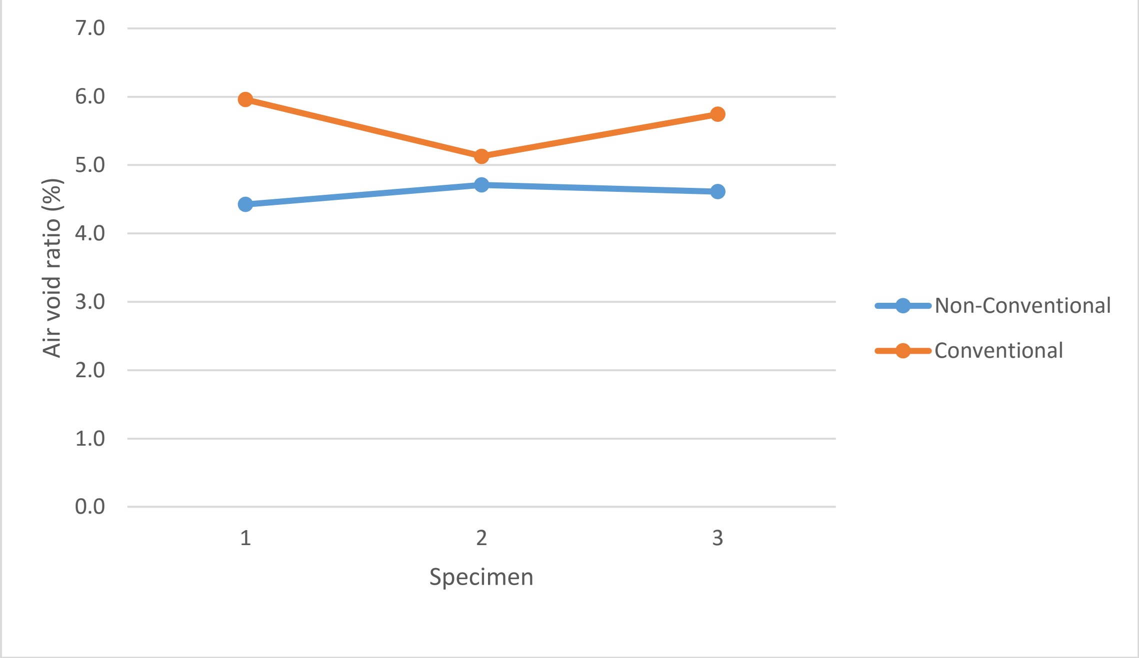


Figure 21 Comparison of air void ratio of non-conventional mix specimen and conventional mix specimen prepared at 275 °F.

The comparison of air void ratio of non-conventional specimen and conventional mix prepared at 275 °F is shown above. All the non-conventional specimens had lower air void ratio than the conventional specimens. Conventional mix produced specimens with air voids higher than 5 percent while the Non-Conventional specimen had the maximum air void of 4.7 percent.

Table 22. Air void ratio at 245 °F

Non-Conventional air void (%)	Conventional air void (%)
5.2	5.9
5.8	6.8
4.9	5.7

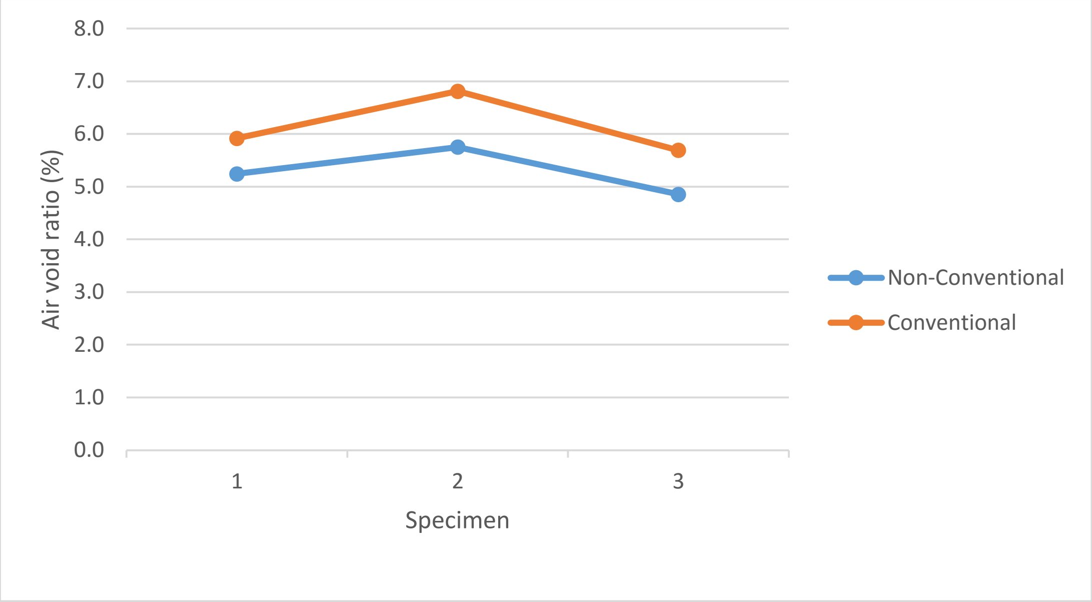


Figure 22 Comparison of air void ratio of non-conventional mix specimen and conventional mix specimen prepared at 245 °F.

The comparison of air void ratio of non-conventional specimen and conventional mix prepared at 245 °F is shown above. All the non-conventional specimens had lower air void ratio than the conventional specimens. Air void ratio for both the specimens are more than the air void ratio for specimens prepared at 275 °F.

Table 23. Air void ratio at 215 °F

Non-Conventional air void (%)	Conventional air void (%)
5.5	6.6
6.7	7.7
6.4	7.1

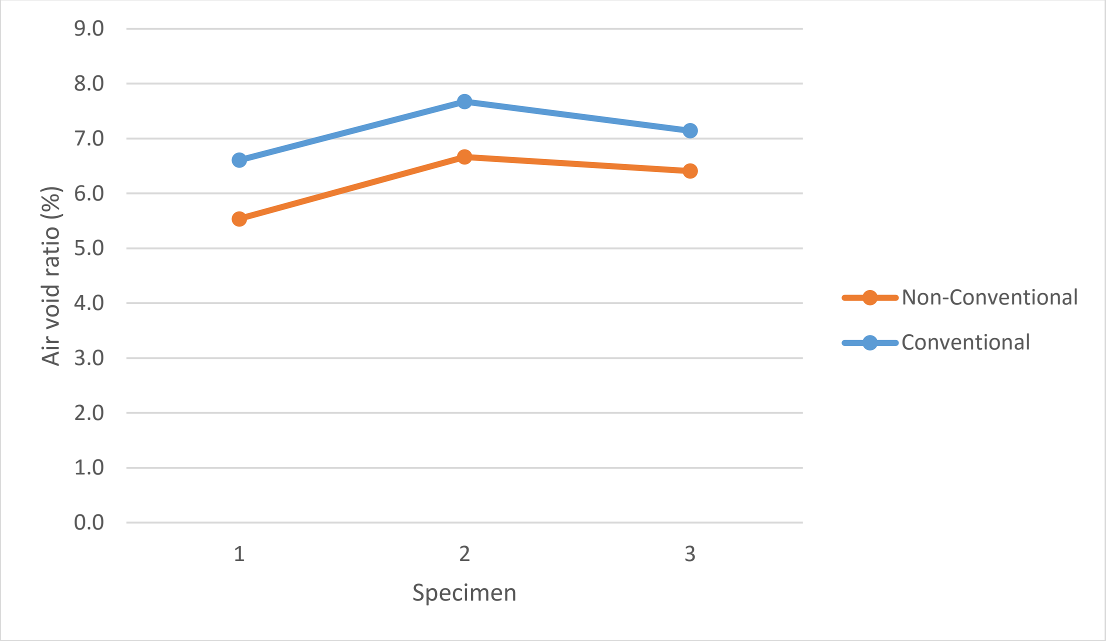


Figure 23 Comparison of air void ratio of non-conventional mix specimen and conventional mix specimen prepared at 215 °F.

The comparison of air void ratio of non-conventional specimen and conventional mix prepared at 245 °F is shown above. All the non-conventional specimens had lower air void ratio than the conventional specimens. Air void ratio for both the specimens are more than the air void ratio for specimens prepared at 275 °F and 245 °F.

Table 24. Average Air Void Ratio

	Non-Conventional air void (%)	Conventional air void (%)
275 °F	4.6	5.6
245 °F	5.3	6.1
215 °F	6.2	7.1

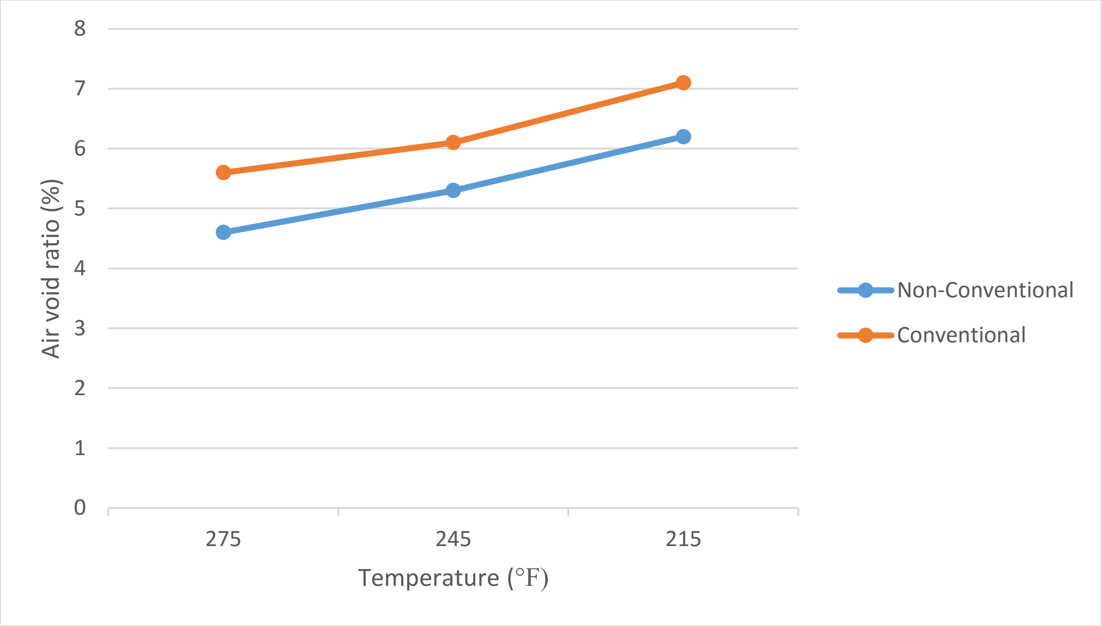


Figure 24 Comparison of average air void ratio of non-conventional and conventional mix specimen at three different temperatures.

The table 24 and the chart (figure24) above display the result of comparison of average air voids of non-conventional and conventional mix specimen compacted at three different temperatures. Non-conventional mix produced specimens with lower air voids than the ones compacted with conventional mix. At 275 °F, the difference between the average air void ratio was 1 percent; at 245 °F, the difference is 0.8 percent and at 215 °F, the difference is 0.9 percent.

The optimal air void ratio for mix designed in lab is 4 percent. Only non-conventional mix specimen managed to achieve air void ratio closer to that amount. The result of the compaction aid test clearly showed that the use of Proprietary additive resulted in lower air void ratio at all compaction temperatures. It can be thus concluded that Proprietary additive allow proper compaction at lower temperatures.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Three different tests were conducted to analyze the effects of Proprietary additive on HMA mixes and the results are summarized as follows:

- Rut resistance test was conducted using Asphalt Pavement Analyzer by comparing specimens compacted from both the non-conventional and conventional hot mix asphalt mixes. The results showed that the conventional mix specimens had 4.9 percent more rutting than non-conventional mix specimens. However, statistical analysis displayed that non-conventional mix performed similar to conventional mix.
- Moisture sensitivity test was carried out using the modified Lottman test (AASHTO T283). Specimens were compacted using both the conventional and non-conventional mixes. The Tensile Strength Ratio value of the mixes were compared and the results showed that The TSR value for non-conventional mix specimen was 10.70 percent higher than that for conventional mix specimen.
- The results also displayed that the average strength of wet non-conventional specimens was 22.4 percent higher than that of
- wet conventional specimens. Similarly, the average strength of dry non-conventional specimens was 8.72 percent higher than that of dry conventional specimens.

- Specimens using both the non-conventional and conventional mixes were compacted at three different temperatures for the compaction aid test. Compactibility of the mixes was checked by comparing the air voids of the specimens. Non-conventional mix produced specimens with lower air voids than the ones compacted with conventional mix. At 275 °F, the difference between the average air void ratio was 1 percent; at 245 °F, the difference was 0.8 percent and at 215 °F, the difference was 0.9 percent.

5.2 Conclusions

The results of this research indicate that the use of Proprietary additive affects the rut resistance, moisture sensitivity and compaction of the hot mix asphalt. The non-conventional mix produced specimen that endured lower rut depth than the conventional mix specimen. This shows that the Proprietary additive helps in improving the rut resistance of the HMA mix. Improved rut resistance of a mix can lead to construction of more stable and stronger pavement.

The results of the modified Lottman test showed that the Proprietary additive is beneficial in combating the problem of the moisture damage in HMA mixes. Non-conventional mix had higher Tensile Strength Ratio value than the conventional mix. In both the wet and dry conditions, conventional mix underperformed compared to the non-conventional mix. It is noteworthy that the non-conventional mix specimen had higher strength compared to conventional mix specimen in wet condition than in dry condition. This shows that the Proprietary additives can be recommended to use with HMA mixes in areas with constant presence of moisture.

The results of the compaction aid test showed that the non-conventional mix produced specimens with lower air voids than conventional mix at three different compaction temperatures. This means non-conventional mix produced denser specimen than conventional mix The result suggests that the use of Proprietary additive can result in better compaction at lower temperature than the normal compaction temperature. In North Dakota, where construction season is short because of cold weather for long period, this result can be considered very useful.

It can be concluded from the results of the study that Proprietary additive can act as a Warm Mix Asphalt considering its advantages.

5.3 Recommendations

In order to better understand the effects of Proprietary additive on Hot Mix Asphalt mixes, further research needs to be performed. It is recommended that tests be performed with different dosages of Proprietary additive. As only three different compaction temperatures were considered for this study, it is recommended that tests be carried out at other different temperatures. It will be advantageous to perform the compaction aid test at lower temperatures than the temperatures considered for this test. The author recommends Disk-shaped Compact Tension (DCT) test to evaluate the effect of Proprietary additive on fatigue resistance of HMA mixes in low temperatures as fatigue is one of the chief problem in North Dakota.

REFERENCES

American Association of State Highway and Transportation Officials (2013), Standard Specifications for Transportation Materials and Methods of Sampling and Testing, AASHTO.

Akisetty, Chandra K., Soon-Jae Lee, and Serji N. Amirkhanian. "High temperature properties of rubberized binders containing warm asphalt additives." Construction and Building Materials 23, no. 1 (2009): 565-573.

Akisetty, Chandra Kiran Kumar. *Evaluation of warm asphalt additives on performance properties of CRM binders and mixtures*. ProQuest, 2008.

Akisetty, Chandra, Feipeng Xiao, Tejash Gandhi, and Serji Amirkhanian. "Estimating correlations between rheological and engineering properties of rubberized asphalt concrete mixtures containing warm mix asphalt additive." Construction and Building Materials 25, no. 2 (2011): 950-956.

Aksoy, Atakan, Kurtuluş Şamlioglu, Süreyya Tayfur, and Halit Özen. "Effects of various additives on the moisture damage sensitivity of asphalt mixtures." Construction and Building Materials 19, no. 1 (2005): 11-18.

Al-Qadi, Imad L., Ibrahim M. Abauwad, Heena Dhasmana, and Aaron R. Coenen. *Effects of Various Asphalt Binder Additives/Modifiers on Moisture-Susceptible Asphaltic Mixtures*. Illinois Center for Transportation, 2014.

Buchanan, M., and E. Brown. "Effect of superpave gyratory compactor type on compacted hot-mix asphalt density." *Transportation Research Record: Journal of the Transportation Research Board* 1761 (2001): 50-60.

D'Angelo, John A., Eric E. Harm, John C. Bartoszek, Gaylon L. Baumgardner, Matthew R. Corrigan, Jack E. Cowsert, Thomas P. Harman et al. *Warm-mix asphalt: European practice*. No. FHWA-PL-08-007. 2008.

Gandhi, Tejash. "Effects of warm asphalt additives on asphalt binder and mixture properties." PhD diss., Clemson University, 2008.

Gorkem, Cagri, and Burak Sengoz. "Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime." *Construction and Building Materials* 23, no. 6 (2009): 2227-2236

Hasan, Mohd Rosli Mohd, Zhanping You, David Porter, and Shu Wei Goh. "Laboratory moisture susceptibility evaluation of WMA under possible field conditions." Construction and Building Materials 101 (2015): 57-64.

Hurley, Graham C., and Brian D. Prowell. "Evaluation of potential processes for use in warm mix asphalt." Journal of the Association of Asphalt Paving Technologists 75 (2006): 41-90.

Hurley, Graham C., and Brian D. Prowell. "Evaluation of Sasobit for use in warm mix asphalt." *NCAT report* 5, no. 06 (2005).

Kandhal, Prithvi S. "Field and laboratory investigation of stripping in asphalt pavements: State of the art report." Transportation Research Record 1454 (1994).

Kandhal, Prithvi S., and L. Allen Cooley. *Accelerated laboratory rutting tests: Evaluation of the asphalt pavement analyzer*. No. 508. Transportation Research Board, 2003.

Kanitpong, Kunnawee, Samak Sonthong, Kitae Nam, Wilfung Martono, and H. Bahia. "Laboratory study on warm mix asphalt additives." In *86th Annual Meeting of the Transportation Research Board, Washington, DC*. 2007.

Kim, Sungho, Gregory Sholar, Thomas Byron, and Jaeseung Kim. "Performance of polymer-modified asphalt mixture with reclaimed asphalt pavement." *Transportation Research Record: Journal of the Transportation Research Board* 2126 (2009): 109-114.

Kok, Baha Vural, and Mehmet Yilmaz. "The effects of using lime and styrene–butadiene–styrene on moisture sensitivity resistance of hot mix asphalt." *Construction and building materials* 23, no. 5 (2009): 1999-2006.

Lee, Soon-Jae, Serji N. Amirkhanian, Nam-Won Park, and Kwang W. Kim. "Characterization of warm mix asphalt binders containing artificially long-term aged binders." Construction and Building Materials 23, no. 6 (2009): 2371-2379.

Mandal, Subhash. "Assessing the rut resistance performance of warm mix asphalts in North Dakota." (2012).

Mashhadi, Mohammad Mahdi Rezapour and Nabil Suleiman "Rut Performance of in-situ warm mix asphalt overlays in North Dakota."(2015).

Mo, Liantong, Xun Li, Xing Fang, M. Huurman, and Shaopeng Wu. "Laboratory investigation of compaction characteristics and performance of warm mix asphalt containing chemical additives." Construction and Building Materials 37 (2012): 239-247.

Rubio, M. Carmen, Germán Martínez, Luis Baena, and Fernando Moreno. "Warm mix asphalt: an overview." Journal of Cleaner Production 24 (2012): 76-84.

Sanchez-Alonso, Elsa, Angel Vega-Zamanillo, Miguel Angel Calzada-Perez, and Daniel Castro-Fresno. "Effect of warm additives on rutting and fatigue behaviour of asphalt mixtures." Construction and Building Materials 47 (2013): 240-244.

Skok, Eugene L., Eddie N. Johnson, and Amir Turk. "Asphalt pavement analyzer (APA) evaluation." (2002).

Suleiman, Nabil, and Subhash Mandal. "Evaluating the Rut Resistance Performance of Warm Mix Asphalts in North Dakota." In *Transportation Research Board 92nd Annual Meeting*, no. 13-4855. 2013.

Tashman, Laith Suleiman, Eyad Masad, Bob Peterson, and Habeeb Saleh. "Internal structure analysis of asphalt mixes to improve the simulation of superpave gyratory compaction to field conditions." Master's thesis, Washington State University, 2000.

Zhang, Jun. "Effects of warm-mix asphalt additives on asphalt mixture characteristics and pavement performance."(2010).

Zhao, Wenbin, Feipeng Xiao, Serji N. Amirkhanian, and Bradley J. Putman. "Characterization of rutting performance of warm additive modified asphalt mixtures." *Construction and Building Materials* 31 (2012): 265-272.