Understanding the Effects of Moisture on Hot Mix Asphalt (HMA)

A Major Qualifying Project

Submitted to the Faculty of

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in partial fulfillment of the requirements for the

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in

Civil Engineering

By

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Approved:

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Abstract

Moisture has major effects on Hot Mix Asphalt (HMA) over time. Moisture damage in asphalt can lead to deterioration of asphalt pavements in the form of cracking, potholes, and rutting that effect the ease and safety of travel along roads paved with HMA. One objective of the study was to evaluate the change in functional groups, specifically carbonyl and sulfoxide, of asphalt binder as a result of moisture damage. Changes in functional groups after moisture damage were found, but no direct correlation between asphalt performance and change in functional groups could be identified. The other objective was to design a fiber reinforced mix with enhanced resistance against moisture damage. An ideal fiber content of 0.25% fiber by total mass was found and was proven to increase the tensile strength of asphalt by more than 20%, both before and after being exposed to moisture damage.

Acknowledgements

I would like to thank my advisor, Professor Rajib Mallick for all of his guidance and assistance. I would also like to extend a special thanks to Ram Veeraragavan and Russell Lang for all of their help in the laboratory. I would also like to thank Professor Nima Rahbar for his help providing background and guidance in regard to fiber usage.

Capstone Design Statement

To meet the requirement of design, experiments were designed to evaluate functional groups in asphalt binder using the Fourier-Transform Infrared Spectroscopy (FTIR) and to develop a moisture-resistant mix with plastic fibers. Experiments were also designed to evaluate the effects of polypropylene fibers on asphalt tensile strength. The design and testing took into account both the restrictions and limitations that inherently exist within the experiments.

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1.0 Introduction

Asphalt pavements make up more than 90% of roadways in the US and a similarly high percentage of roadways all over the world. One of the current problems of roadway infrastructure is the short life span of certain asphalt roadways caused by moisture damage, particularly roads in high rainfall areas. This causes frequent and costly roadway maintenance in order to keep roadways functioning. Asphalt pavements with longer lifespans will need to be resistant to high moisture content. This report discusses two different ways to help improve asphalt performance when subjected to moisture.

Asphalt binder (bitumen) is one of the main components of asphalt, including Hot Mix Asphalt (HMA). Binder is a byproduct of the petroleum distillation process. The chemical composition of asphalt binder plays a large role in the cohesion of asphalt. It is suspected that when exposed to high moisture content, the chemical composition of asphalt binder changes slightly, affecting its cohesion. This report discusses the effects of moisture damage on the chemical composition of asphalt binder, specifically the sulfoxide and carbonyl groups.

Another major task was to design a moisture resistant mix with polypropylene fibers. Tests were conducted to optimize the fiber content in the mixes, as well as subject fiber mixes to Moisture Induced Stress Testing (MIST) and its impact measured by Indirect Tensile Testing (ITS) before and after moisture conditioning with the MIST.

2.0 Background

This section covers backgrounds regarding to asphalt composition as well as the use of fibers in asphalt.

2.1 Asphalt Chemical Composition

The chemical composition of asphalt binder has been researched in the past (Simpson et al, 1961; Lau et al, 1992; Peterson et al, 1993; Oyenkunle, 2006, 2007; Firozifaar et al, 2011; Wei et al, 2014; Weigal and Stephen, 2017). In order to evaluate the effect of moisture damage on asphalt binder chemical composition, Fourier-Transform Infrared Spectroscopy (FTIR) is often used. In order to simulate moisture damage in asphalt, MIST conditioning is often used. FTIR, MIST conditioning, and penetration testing were the three main methods used in this section.

2.1.1 FTIR, ICO and ISO

Fourier-Transform Infrared Spectroscopy (FTIR) has frequently been used to gain an infrared spectra of substances. From the Infrared spectra, the chemical composition of the substance can be interpreted, which can be helpful when trying to find changes in asphalt chemical composition.

There are different types of FTIR. This report uses an Attenuated Total Reflectance (ATR) technology. A FTIR ATR works by sending infrared radiation of various wavelengths through the ATR crystal to the sample. Certain wavelengths are absorbed by the sample, only allowing some of the wavelengths to be returned back to the detector (Figure 1). This results in an absorption spectrum which depicts the wavenumber (cm-1) on the x-axis, and their absorbance on the y-axis. A typical spectrum can be seen in Figure 2.

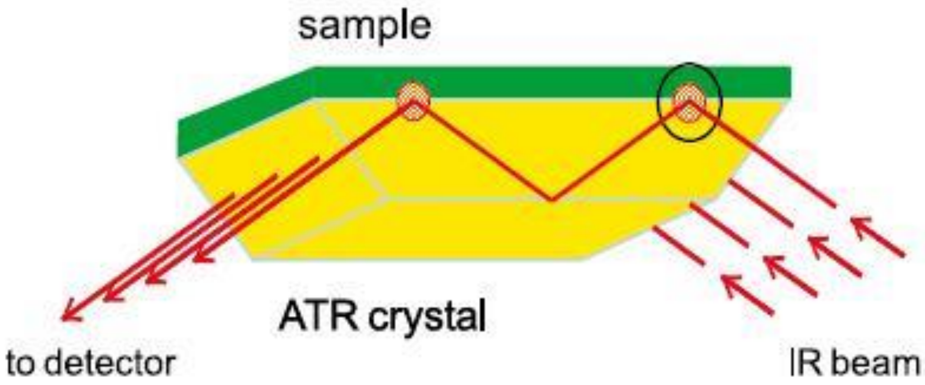


Figure 1: How FT-IR ATR Works

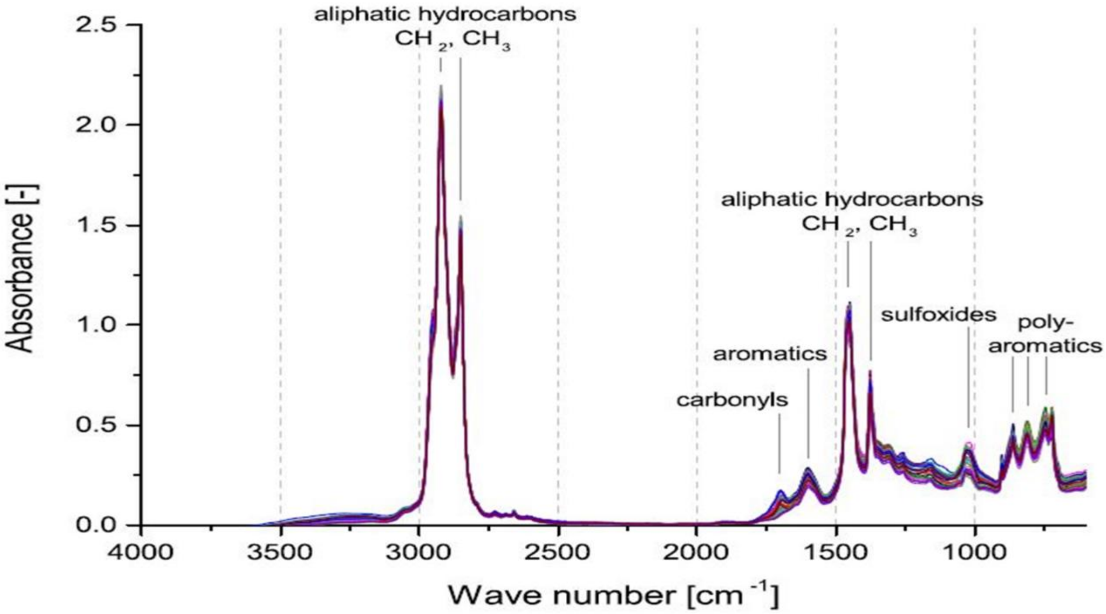


Figure 2: Typical FT-IR Spectra, courtesy of Weigel, S., & Stephan, D. (2017).

FTIR spectroscopy is a well-researched method of discovering chemical groups in substances. There has been past research correlating chemical properties of asphalt binder to mechanical properties using FTIR technology (Simpson et al, 1961; Lau et al, 1992; Peterson et al, 1993; Oyenkunle, 2006, 2007; Firozifaar et al, 2011; Wei et al, 2014; Weigal and Stephen, 2017). Bagmabadee & Karlsson, 2004 developed and used a FTIR ATR technique to study the movement of water into binder/sub-straight interfaces. In regard to binder aging, Dony et. al, 2016, helped further prove the previous work of Marsac et. al 2014, and Petersen 1993, confirming the viable use of FTIR spectroscopy for quantifying bitumen ageing. They also developed a standard methodology that could be used to detect aging in asphalt by identifying the presence of certain functional groups (Dony et. al., 2016; Marsac et. al, 2014; and Petersen, 2009).

Of the various functional groups present in asphalt binder, carbonyls/ketones as well as sulfoxides have been used to explain asphalt binder properties (Weigal and Stephen, 2017; Peterson and Glaser, 2011). This study focuses on the carbonyl and sulfoxide groups due to their ability to detect aging in asphalt, as proven by Dony et al., 2016. Chemical aging occurs due to irreversible oxidation, caused by oxygen in air. Over time, carbonyl (C=O) and sulfoxide (S=O) groups form as asphalt is exposed to oxygen. The change in chemical composition of the binder increases molecule size and polarity, which in turn makes the asphalt more brittle and prone to damage. Therefore, increased presence of both carbonyl (referred to as ICO in this paper) and sulfoxide (referred to as ISO) groups have proven to correlate with mechanical properties of older asphalts (Marsac et. al, 2014; Petersen, 2009). Sulfoxides can be present in asphalt before aging, depending on the origins of crude oil used in the binder (Marsac et. al, 2014). In regard to the FTIR spectrum, carbonyls are found at 1700cm^{-1} on the spectrum, and sulfoxides at 1030cm^{-1} (Dony et. at., 2016). These groups, along with other commonly found groups, can be seen above in Figure 2.

Moisture damage, similarly to air exposure, may also be the cause of increased oxidation in asphalt. Moisture damage can cause stripping, which is characterized by the displacement of binder from aggregate (Nguyen et. al., 2005; Bagampaddee et. al., 2004; Bagampaddee et. al., 2005). This in turn can increase exposed surface area, helping to increase ICO and ISO values. There has not been much research on the effects of moisture damage in asphalt with their direct correlation to ICO and ISO values. This report discusses the ICO and ISO values present both before and after exposure to moisture damage.

2.1.2 MIST Conditioning

In order to simulate moisture damage in asphalt, a Moisture Induced Stress Tester (MIST) can be used. MIST conditioning is a procedure that is used to more accurately replicate moisture damage to asphalt in a laboratory environment. The testing is done using a pressurized chamber that pushes and pulls water through a compacted asphalt sample cyclically, inducing pore pressure. The MIST is designed to simulate existing field conditions such as temperature, traffic, and moisture. MIST conditioning has been used extensively in asphalt research to simulate stripping, and has proven to be quite effective (Mallick & Pelland, 2005; Chen, 2008; Chen & Huang, 2007; Shu et. al., 2012).

This report further discusses the use of MIST conditioning and FTIR ATR analysis to detect the effects of moisture damage on asphalt ICO and ISO values. MIST Testing was also utilized in the second section of this report on asphalt samples containing fibers.

2.2 Use of Fibers

The second aspect of this report evaluates the possibility of utilizing fibers in asphalt mixes in order to help resist moisture damage.

2.2.1 Previous Fiber Use in Concrete

Fibers are frequently used in concrete in order to increase tensile strength. A variety of fibers have been researched, including nylon, polypropylene, metal, and self-healing fibers. To varying degrees, fibers have helped improve the strength of concrete (Shah, Batson, 1987; Beaudoin, 1990; Hannant,1978). Other than increasing the initial tensile strength, if the concrete gets cracked, the fibers can help bridge the crack. The fiber bridging prevents the concrete from completely crumbling (Li, V. C. *et al*., 1993). An example of fiber bridging in concrete can be seen in Figure 3. Despite the use of these fibers in concrete, the use of them in asphalt has not been extensively tested. This report evaluates the use of polypropylene fibers in asphalt.

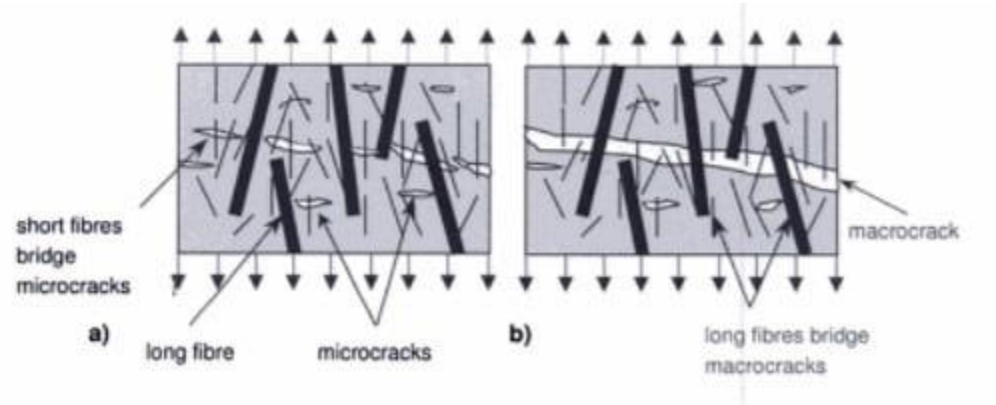


Figure 3: Fiber Bridging in Concrete

2.2.2 High Tenacity Polypropylene Fibers

The fibers that were chosen for this study were High Tenacity Polypropylene Fibers (PPHT). Polypropylene fibers are used frequently in concrete mixes and are generally cheap and readily available (Kalbskopf *et al*., 2003). PPHT fibers were also chosen because they have shown to increase tensile strength in concrete. Although other fibers, such as Nylon, do also increase the tensile strength, PPHT fibers have a higher melting point, between 160°C and 170°C (Qin, Y. *et al.*, 2019), which is necessary for asphalt mixing. They also have a lower specific gravity, so you can gain more material for the same weight (Exelto Product Data Sheet, see Appendix A). A table of PPHT fiber properties can be seen in Table 1 (Exelto Product Data Sheet, see Appendix A). A typical polypropylene molecule can be seen in Figure 4, which shows why polypropylene fibers are strong when in a chain. The specific fibers used in this study were purchased from Staint Gobain Brazil and are 10mm (0.39 in) in diameter and 12 µm (4.7 x 10^{-4} in) in length.

Table 1: Physical Properties PPHT Fiber

Titer	2,8 to 6 dtex
Cut-length	40-120 mm
Tenacity	3,8-5,4 cN/dtex
Elongation	>40% - >80%
Specific Weight	0.91 g/cm^3
Melting Point	163°C
Color	White

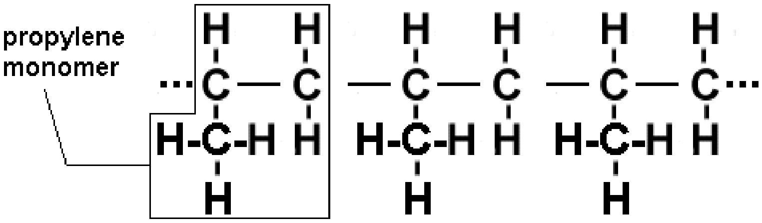


Figure 4: Typical Polypropylene Molecule

3.0 Methodology

This section outlines both methodologies for the chemical research, as well as for the fiber research completed in this study.

3.1 Chemical Properties Experiment

3.1.1 Sample Acquisition

Samples for this study were supplied by Maine Department of Transportation (MDOT) from various paving projects throughout the state. Loose mixes were taken off the truck while paving. There were a variety of mixes, including some containing anti-strip and hydrated lime a list of mixes, their binder types, and their additives can be seen in Table 2. The loose mixes were compacted into samples in the lab after being heated to a temperature of 150°C (302°F). Six separate asphalt samples 15.24 cm (6 in) in diameter and 5.08cm (2 in) high were made.

Table 2: List of Asphalt Mixes

Mix	Binder Grade	Binder Additives
AW	PG6428	
FF	PG6428	
SM	PG6428	
SN	PG6428	
CF	PG6428	Hydrated lime (1%)
LW	PG6428	
AT	PG6428	
MR	PG6428	Hydrated lime (1%)
BB	PG6428	
VTG	PG7028	
VTP2	PG5828	
MEG	PG6428	
MEP2	PG6428	Anti-stip (NovaGrip 1212-0.5%)
MEM	PG6428	
NHG	PG6428	
MB	PG6428	
FB	PG6428	
VTP1	PG5828	Anti-strip (Rediset -0.5%)

MDOT workers also classified each mix as either a “poor” performance mix or a “good” performance mix, based on their performance in the field.

3.1.2 3.1.2. MIST Conditioning

MIST conditioning was done in a InstroTek, Inc. MIST., according to the ASTM D7870/D7870M−13 standard, *Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure*. Out of the 6 total samples for each asphalt mix, 3 samples were subjected to MIST conditioning. MIST conditioning was performed at 276 kPa (40 psi), 60°C, and for 3500 cycles. After conditioning, water was drained from the chamber and the sample was allowed to cool. Samples were then placed in a water container at 25°C for 2 to 3 hours.

3.1.3 Binder Extraction

After MIST conditioning, all asphalt samples were subjected to various mechanical tests for a different study. After mechanical testing, binder was extracted from the asphalt samples using the centrifuge extraction method.

3.1.3.1 Centrifuge

Extraction of binder from asphalt samples was done following ASTM D2172/D2172M-11, *Standard Test Methods for Quantitative Extraction of Bitumen for Bituminous Paving Mixtures*. The sample was first broken into smaller pieces before being put in a centrifuge. 500g of the sample was then placed in the basin of the centrifuge below the top rim. Filter paper was placed on top of the rim, followed by the centrifuge basin cover. Toluene (450mL) was then added through the basin cover and allowed to sit for 20 minutes. After 20 minutes, the centrifuge containing the sample and toluene was then spun. The rotation per minute (RPMs) were increased by steps of two until significant amounts of liquid began to run out of the centrifuge. Once significant flow was reached, the centrifuge was kept at that RPM until flow had decreased. These steps were continued until 20 RPM's and no flow was achieved. The centrifuge was then stopped, and 450mL more of toluene was added to the centrifuge and was allowed to sit for 20 minutes. The centrifuge was then spun a second time as described above.

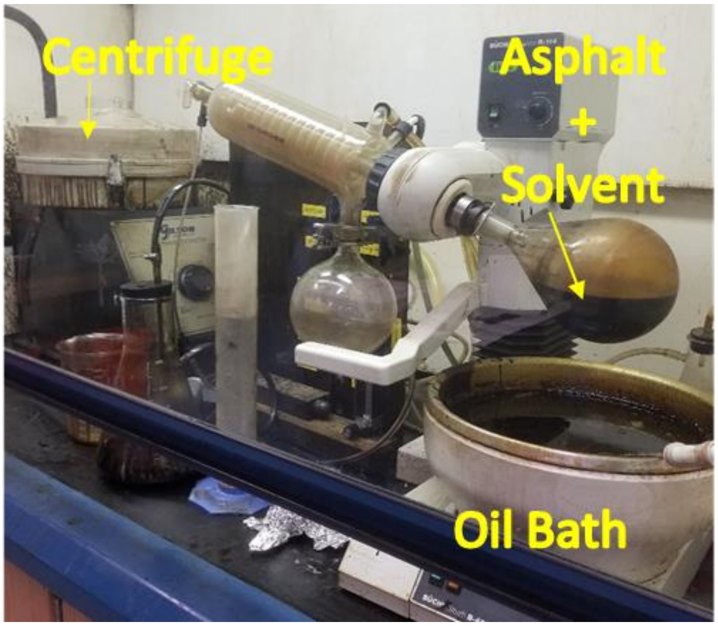


Figure 5: Binder Extraction Set-Up

3.1.3.2 Rotary Evaporator

Recovery of Asphalt binder from the centrifuge solution was done following ASTM D5404/D5404M, *Standard Practice for Recovery of Asphalt from Solution using the Rotary Evaporator*. Asphalt binder was extracted from the toluene using a Rotary Evaporator (Figure 5). The mixture was drawn into the flask using a vacuum and nitrogen combination created in the laboratory. While being drawn into the flask, the mixture passed through a 20 micron filter to remove larger particles that passed through the centrifuge stage. Running water was then turned on in the condensing chamber of the roto-evaporator to a constant level so that no air bubbles were visible. Nitrogen was supplied to the roto-evaporator, while a vacuum was also applied. The nitrogen was maintained at 500 while the vacuum was maintained at 2.66 kPa (20 mmHg). The flask containing the mixture was put on a constant rotation, then lowered into an oil bath that was maintained at a temperature between 120-140°C (248-284°F). The roto-evaporator was allowed to run until all toluene was evaporated out of the sample. The roto-evaporator in use can be seen in Figure 6.

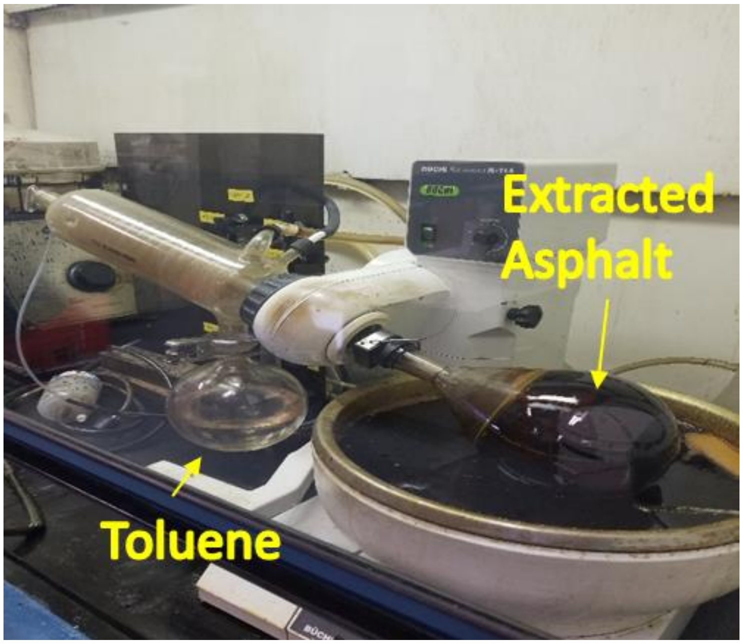


Figure 6: Rotary Evaporator in Use

3.1.3.3 Cooling and Sample Prep

After the binder was extracted from the toluene, the flask filled with asphalt binder was then placed in an oven at 150°C (302°F) over a sample can to collect the extracted binder. The flask was left in the oven for approximately half an hour, or until no significant flow was coming from the flask. The extracted binder in the can was then weighed directly after being taken out of the oven. Once the weight was recorded, the sample sat at room temperature for approximately 24 hours before further testing occurred. The sample container can be seen in Figures 7 and 8. Testing was not performed unless at least 100g of asphalt binder was present.

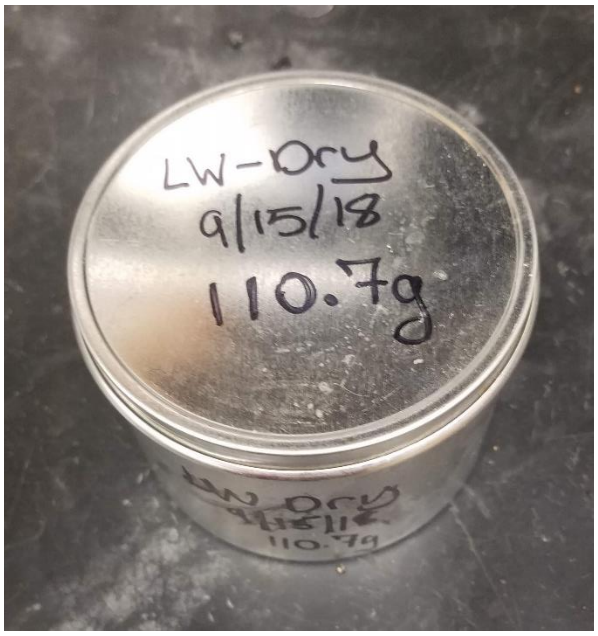


Figure 7: Labeled Binder Collection Can

Figure 8: Extracted Binder

3.1.4 Penetration Testing

Penetration Testing was completed following ASTM D5-06, *Standard Test Method for Penetration of Bituminous Materials*. The sample was placed in a water bath at 25°C (77°F) for one hour prior to testing. After one hour, the sample was taken out of the water bath and centered under the needle on the apparatus (see Figure 9), and the needle was lowered as close to the surface of the bitumen as possible without penetrating. The needle was then dropped for 5 seconds. The reading was taken, needle removed from the sample, and cleaned with toluene. The needle was then placed one centimeter from the first penetration, and not within one centimeter from the side of the container. Three penetration readings were taken, and then averaged.

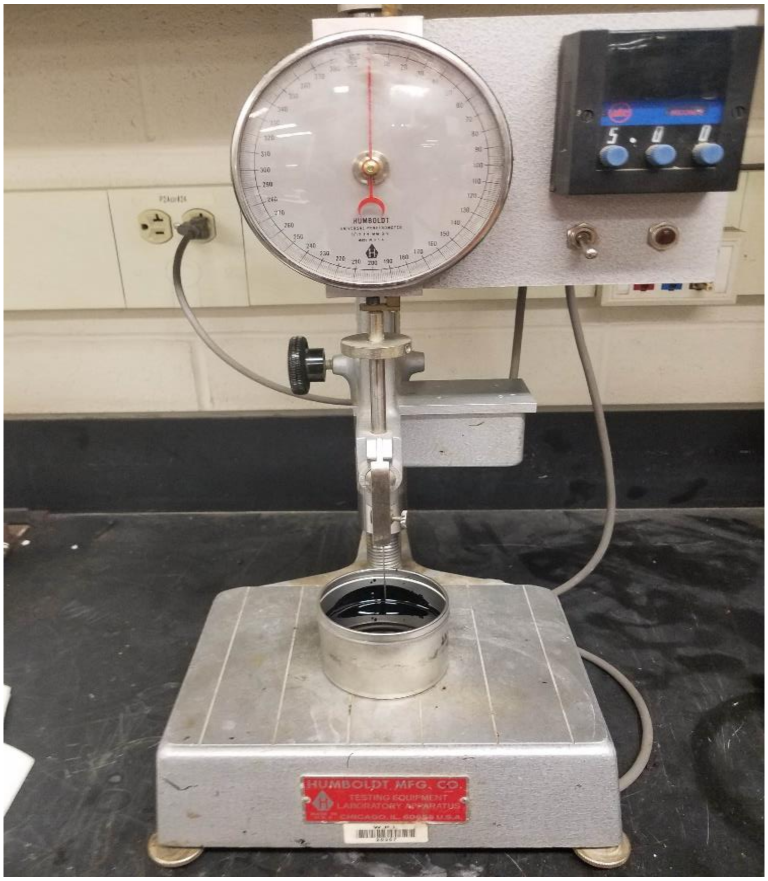


Figure 9: Sample Prepared for Penetration Testing

3.1.5 FTIR ATR

3.1.5.1 FTIR Testing

FTIR testing was conducted on a PerkinElmer Spectrum Two with a universal ATR sampling accessory, as seen in Figure 10 and 11. Before testing began, a background scan was completed with no sample on the crystal. No more than 0.1g of extracted asphalt binder was rolled into a ball and placed on the FTIR crystal (Figure 12). The ATR attachment was then lowered (Figure 13). The scan was then run and the absorption spectrum was acquired. The crystal was cleaned with acetone to remove binder residue. This process was repeated three times with three different samples per asphalt binder. All collected FTIR spectra can be seen in Appendix B.

Figure 10: FTIR ATR

Figure 11: FTIR Before Scanning

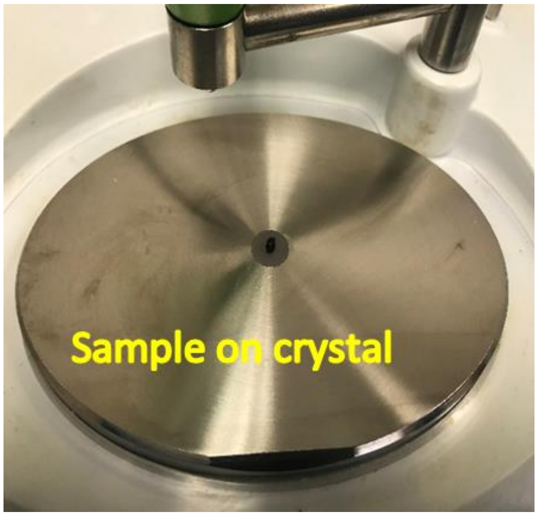


Figure 12: Sample on FTIR Crystal

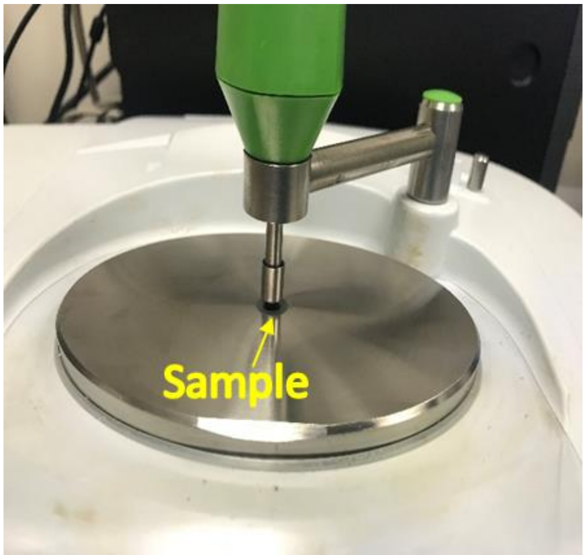


Figure 13: Sample Ready to be Scanned by FTIR

3.1.5.2FTIR Analysis Using Origin

Changes in carbonyl (ICO) and sulfoxide (ISO) groups were chosen to be evaluated due to their proven correlation with aging in asphalt (Weigal and Stephen, 2017; Peterson and Glaser, 2011; Dony et. al. 2016). ICO and ISO values were calculated by finding the area under each respective peak in the spectroscopy using Orgin software to calculate the integrals, which can be seen in Figure 12. First, a baseline of the spectrum was taken. An example of a spectrum before and after the baseline was taken can be seen in Figure 15. The areas under the designated peaks were determined by manually dragging integral areas to the outer bounds of the peaks, as seen in Figure 16. The ICO and ISO values were recorded for all mixes both Pre and Post MIST conditioning.

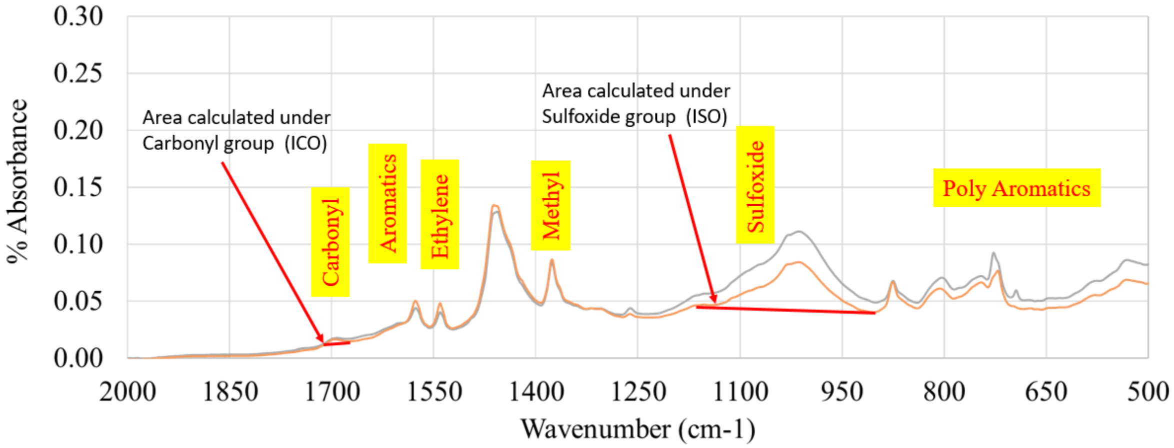
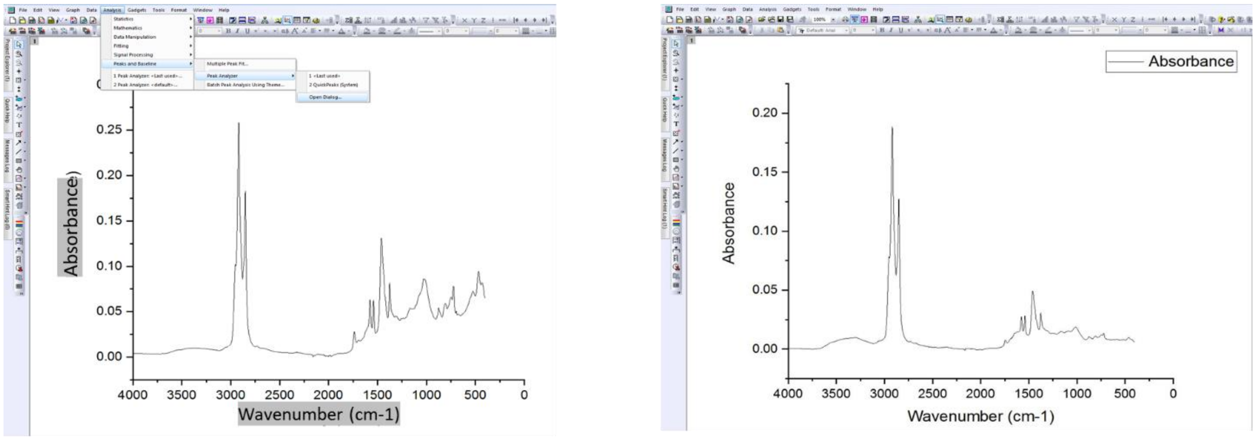


Figure 14: Areas Calculated on FT-IR Spectrum



a) Before Baseline Correction

b) After Baseline Correction

Figure 15: Baseline Correction in Orgin

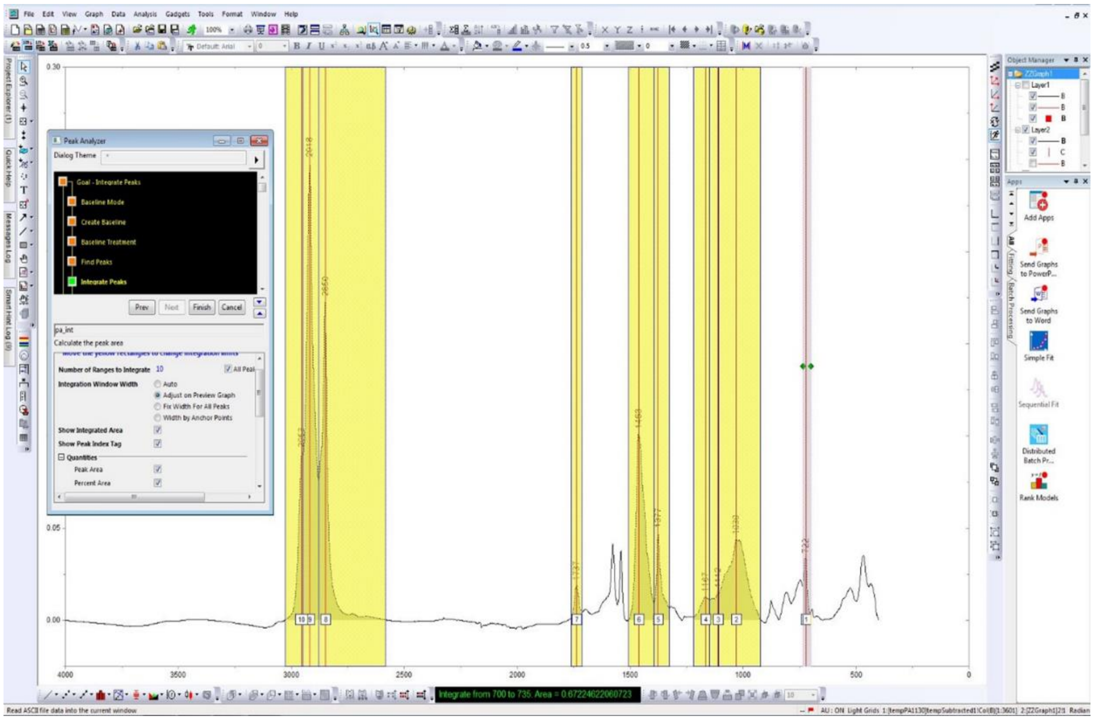


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Figure 16: Area Calculations Using Orgin

3.1.6 ANOVA Analysis

ICO and ISO values were statistically analyzed using ANOVA. Each mix had three Pre MIST ICO readings and three post MIST ICO readings. Using the ANOVA: Single Variable function in Microsoft Excel, ANOVA was conducted for each set of 3 readings. An asphalt mix was considered statistically different if their F value was greater than their $F_{critical}$. ANOVA values for ICO and ISO values can be seen in Appendices C and D respectively.

3.2 Fiber Mix Methodology

3.2.1 Fiber Sample Creation

A loose asphalt mix, MEM, was chosen for fiber aspect of this study. MEM was obtained from MDOT off a truck on a real project and was classified as a poor mix by MDOT. Properties of MEM can be seen in Table 3. First, the mix was heated in an oven at 150°C for 2 hours. For the MEM mix, in order to make a cylindrical sample 6in in diameter and 2in high, 2037g of loose asphalt mix was needed (determined by the supplier). Roughly 2050g (to help account for some loss of material during transferring) of asphalt was measured out into a pan, and then covered in aluminum foil and placed back into the 150°C oven for a half an hour. PPHT fibers, 5.1g for 0.25% fiber samples, were then measured out in a separate container (Figure 17). The mass of fibers placed in the sample was based on the total mass, i.e. for a 0.25% fiber content sample, 0.0025*2037=5.1g of fiber added. A table showing all fiber contents created can be seen in Table 4.

Table 3: MEM Mix Properties

Mix name	Win/Town	ID	Performance	Binder grade
LAN-HE15-50B-12R-V1-64	Hermon	MEM	Moderate-Poor	PG6428

Figure 17: PPHT Fibers for 0.25% Sample Before Mixing

Table 4: Fiber Content for Each Sample

% Fiber Content	Mix	Mix Mass (g)	Fiber Mass (g)
.25%	MEM	2037	5.1g
0.5%	MEM	2037	10.2g
1.0%	MEM	2037	20.37

The hot mix was placed in a mechanical mixer along with the fiber. The asphalt mix and fiber were mixed together for one minute, and then they were placed back in the pan and put back in the oven for a half hour. After a half hour, the asphalt and fiber mix were taken out of the oven and mixed in a mechanical mixer again for 1 minute (see Figure 18). Exactly 2037g was then measured out and placed into a compaction core. Compaction of samples was done in a Pine Gyratory Compactor (see Figure 19) and were compacted to a 2.54 cm (2 in) height using 150 gyrations. Once compacted samples were cooled to 70°C (158°F), they were taken out of the compactor and allowed to cool overnight. Typical compacted asphalt samples can be seen in Figure 20. Once the samples had cooled, they were labeled with marker. A list of all compacted samples can be seen in Table 5.

Table 5: List of Created Samples

Mix	MIST Conditioning	% PPHT Fiber	Sample Number
MEM	PRE	1.00%	1
MEM	PRE	1.00%	2
MEM	PRE	1.00%	3
MEM	PRE	0.50%	1
MEM	PRE	0.50%	2
MEM	PRE	0.50%	3
MEM	PRE	0.25%	1
MEM	PRE	0.25%	2
MEM	PRE	0.25%	3
MEM	POST	0.25%	4
MEM	POST	0.25%	5
MEM	POST	0.25%	6

Figure 18: Asphalt-Fiber Mixture After Mixing

GYRATIONS: 150
HEIGHT: 50.0 mm
MOLD DIAM.: 150 mm
COMPACT: Height

Figure 19: Gyratory Compactor

Figure 20: 0.25% PPHT Fiber Asphalt Samples After Compaction

3.2.2 Air Void Calculations

Once samples were at 25°C (77°F), their air voids were calculated. The mass of the sample as well as the mass of the vacuum bag were taken. The asphalt sample was then placed in the vacuum bag, and placed in a CORELOCK machine, where the bag was sealed, and all air removed (see Figure 21). The mass of the sample in the sealed vacuum bag suspended in water was then taken (Figure 22). The percentage of air voids in the sample was then calculated using an Excel Spreadsheet supplied by the CORELOCK. The bag was then cut open and the sample removed.

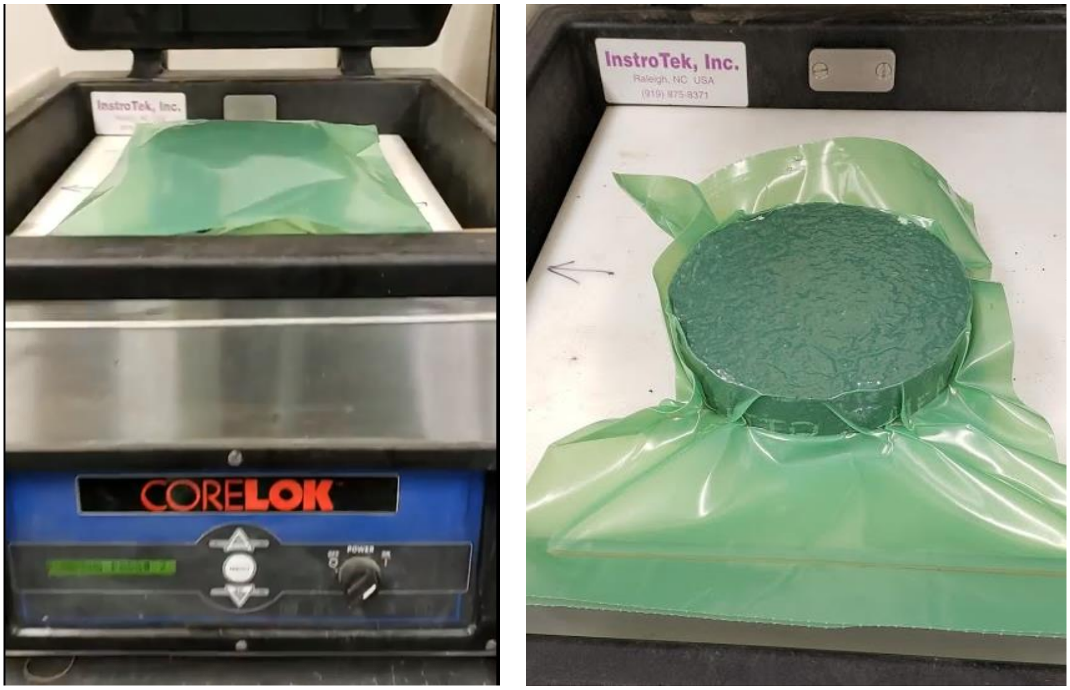


Figure 21: Sample Before and After Vacuum Sealing for Air Void Testing

Figure 22: Sample Suspended in Water

3.2.3 Moisture Induced Stress Testing (MIST)

Of the six 0.25% fiber content samples, 3 were subjected to MIST conditioning. MIST (Moisture Induced Stress Tester) testing was done according to ASTM Standard

D7870/D7870M−13, *Standard Practice for Moisture Conditioning Compacted Asphalt Mixture, Specimens by Using Hydrostatic Pore Pressure*, the same procedure that was utilized in the chemical experiment in this report. Conditioning was completed by InstoTek MIST and can be seen in Figure 23. Maximum pressure was set to 276 kPa (40 psi), temperature to 60°C (140°F), time to 20 hours, and the number of cycles to 3500. The chamber was filled with water and then sealed (Figure 24). Once the conditioning was complete, the chamber was drained and sample removed.

Figure 23: MIST Conditioner

Figure 24: Sample in MIST Chamber Filled with Water

3.2.4 ITS Testing

ITS testing was done according to ASTM Standard D6931-17, *Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures*. Samples subjected to ITS testing can be seen in Table 6. Before ITS Testing, the sample was conditioned at 25°C for 2 hours. The sample was then loaded into the machine, as can be seen in Figure 25. The loading was applied at 5.08 cm (2 in) per minute and was run until 90% failure was reached. The resulted data was then saved.

Table 6: Samples Subjected to ITS Testing

PRE 0.25% MEM 1
PRE 0.25% MEM 2
PRE 0.25% MEM 3
POST 0.25% MEM 4
POST 0.25% MEM 5
POST 0.25% MEM 6
PRE 0.5% MEM 1
PRE 0.5% MEM2
PRE 0.5% MEM3

Figure 25: Sample Loaded for ITS Testing

4.0 Results and Discussion

The following results will be discussed in this section:

- Chemical Analysis
    - Pre MIST Penetration versus Post MIST Penetration
    - ICO (post-pre) versus asphalt performance, and ISO (post-pre) vs. asphalt performance
    - ICO (post-pre) versus Pre MIST penetration and ISO (post-pre) vs. Pre MIST penetration
- Fiber Analysis
    - Air Voids versus Fiber Concentration
    - Fiber Bridging
    - ITS Averages for Different Fiber Concentrations
    - ITS Averages for Pre and Post MIST Conditioning
    - Economic Analysis of Fiber Usage

4.2 Chemical Analysis

4.2.1 MIST Penetration vs. Post MIST Penetration

Penetration results are shown in Figure 26. Penetration values did change between Pre and Post MIST conditions, but to varying degrees. A higher penetration means a more fluid asphalt, and a lower penetration means a stiffer asphalt (as would be expected in an oxidized or aged asphalt). Asphalt that shows a lower penetration means it has been oxidized, and if it shows a higher penetration then it means that the relative proportion of low molecular weight components (such as maltenes) to high molecular weight components (such as asphaltenes) has increased as a result of moisture conditioning. This can be attributed to the varying types of asphalt binder, as well as different additives (i.e. lime, anti-strip) that were present.

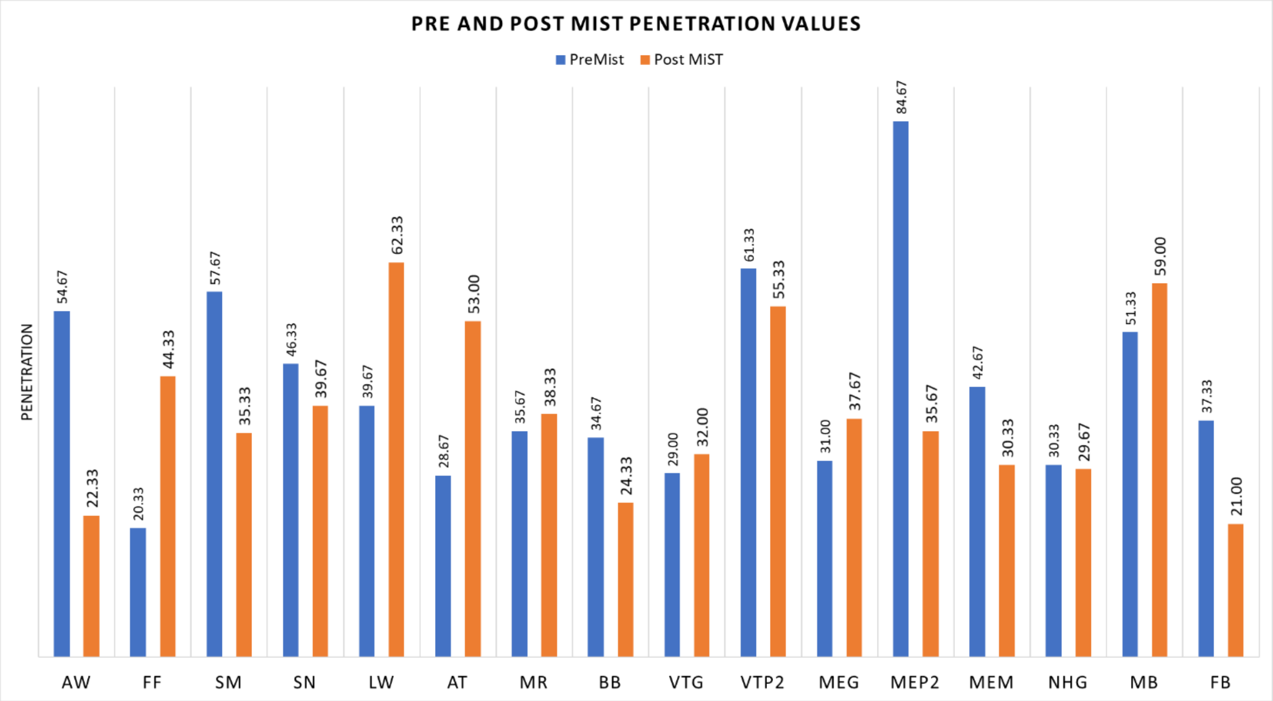


Figure 26: Penetration Values, Pre and Post MIST Conditioning

It was found that asphalt binders with initially high penetration values tend to show a higher degree of change in penetration (Figure 27). This can be attributed to asphalts with higher penetration values are more fluid and have not been oxidized. Once MIST conditioning occurs, the asphalt starts to oxidize due to moisture under high pressure and temperature.

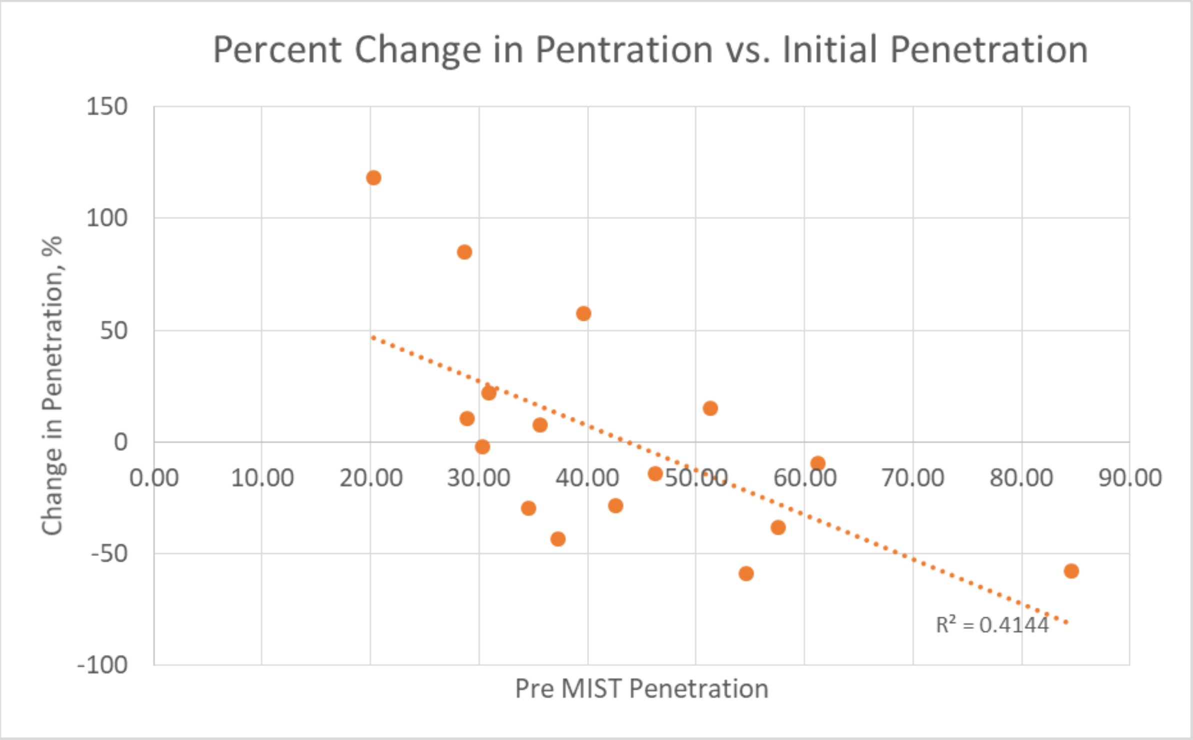


Figure 27: Initial Penetration vs Change in Penetration

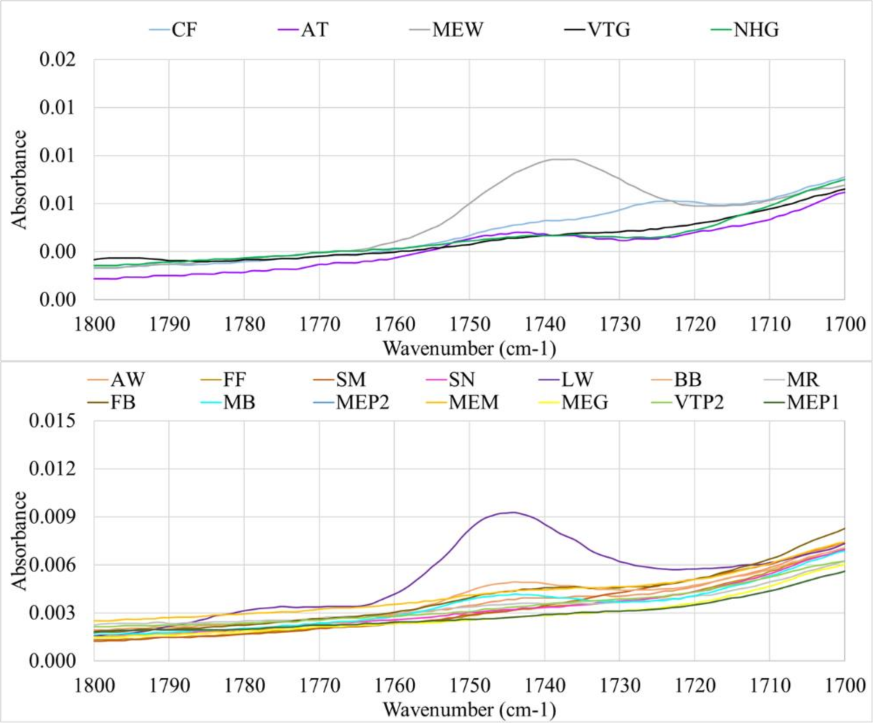
4.2.2 ICO and ISO Values vs. Performance

Areas under both the carbonyl (ICO) and sulfoxide (ISO) groups of the spectroscopy were calculated and can be seen in Table 7. The carbonyl section of the spectroscopy for all mixes can be seen in Figure 28 and are broken down between good performing mixes and poor performing mixes, as classified by MaineDOT. The sulfoxide section of the spectroscopy for all mixes can be seen in Figure 29 and are broken down between good performing mixes and poor performing mixes as well.

Table 7: ICO and ISO Calculated Areas

	ICO Areas			ISO Areas		
Mix	**Pre Ico**	**Post Ico**	**Post-Pre**	**Pre Iso**	**Post Iso**	**Post-Pre**
AW	0.063101	0.048651	-0.01445	0.238396	0.127892	-0.1105
FF	0.055006	0.047384	-0.00762	0.154367	0.111641	-0.04273
SM	0.08946	0.046339	-0.04312	0.101221	0.120595	0.019374
SN	0.068901	0.082016	0.013115	0.280576	0.268922	-0.01165
CF	0.05075	0.066665	0.015915	0.078776	0.158695	0.07992
LW	0.073419	0.046807	-0.02661	0.103501	0.144269	0.040768
AT	0.066336	0.108943	0.042607	0.20794	0.263366	0.055426
MR	0.055131	0.043394	-0.01174	0.204636	0.122939	-0.0817
BB	0.072031	0.08296	0.010929	0.334501	0.378591	0.044091
VTG	0.03726	0.039217	0.001957	0.091013	0.080842	-0.01017
VTP2	0.038254	0.036938	-0.00132	0.195947	0.171878	-0.02407
MEG	0.061686	0.081051	0.019365	0.183071	0.23913	0.056059
MEP2	0.070039	0.042922	-0.02712	0.164012	0.143186	-0.02083
MEM	0.059264	0.091501	0.032238	0.23721	0.249139	0.011928
NHG	0.076278	0.079985	0.003706	0.252266	0.257766	0.0055
MB	0.097563	0.091044	-0.00652	0.27861	0.280117	0.001507
FB	0.062648	0.032316	-0.03033	0.166956	0.139764	-0.02719
VTP1	0.070477	0.040049	-0.03043	0.160475	0.148657	-0.01182

CARBONYL



Good mixes

Poor mixes

283

Figure 28: FT-IR Spectroscopy, Carbonyl Group

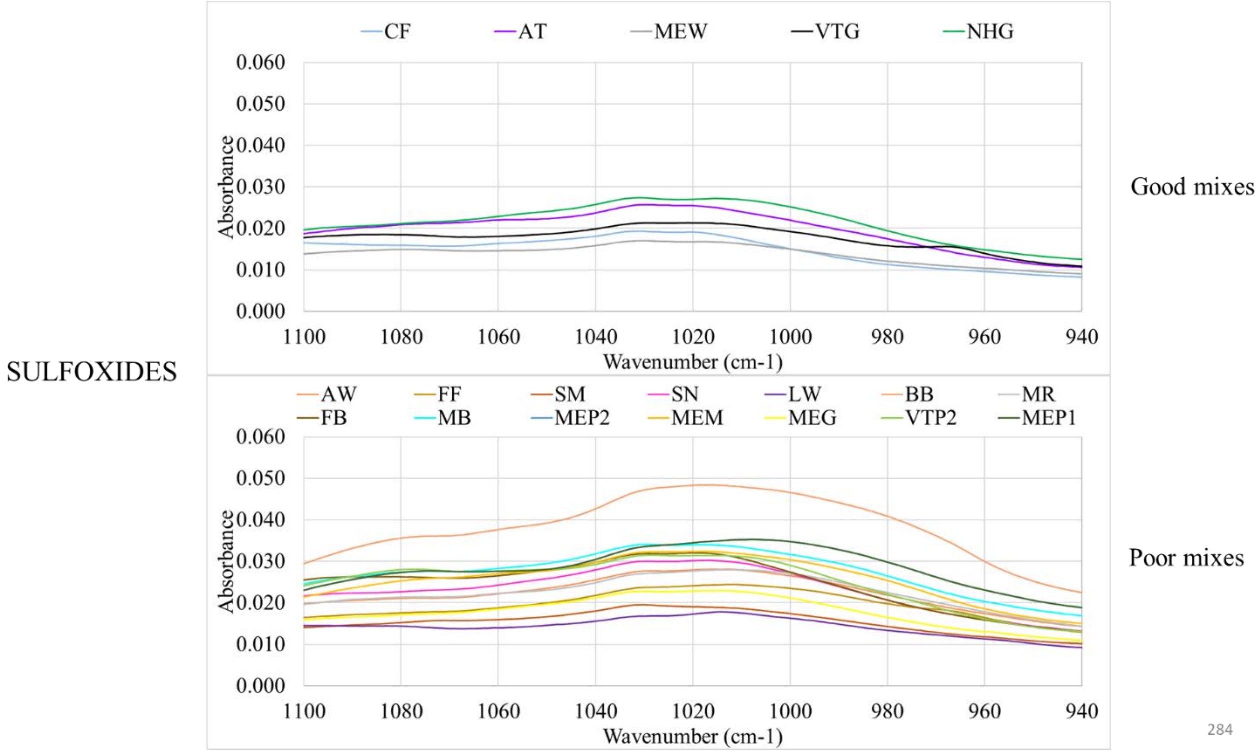


Figure 29: FT-IR Spectroscopy, Sulfoxides

ANOVA was used to calculate the significant difference between Pre and Post MIST ICO and ISO values, and the results can be seen in Tables 8 and 9 respectively. It was found that 38.89% of mixes had a significant difference between Pre and Post MIST ICO values, and 27.78% of mixes had a significant difference between Pre and Post MIST ISO values. These values were lower than expected. The difference also varied between increasing and decreasing values, so there was no direct correlation that could be found. This could be attributed to the difference additives as well as the binder origin.

Of those found to be significantly different, their field performance did not correlate to a significant change in ICO or ISO values. This meant that poor performing mixes did not necessarily have a significant change in ICO or ISO values. This could be due to other functional groups affecting the performance of the asphalt, MIST conditioning was not accurately depicting real field conditions, or that their field performance classification was not accurate (which is most likely).

Table 8: Significantly Different ICO Mixes

Mix	Performance	Significant
AW	POOR	NO
FF	POOR	NO
SM	POOR	NO
SN	POOR	NO
CF	GOOD	NO
LW	POOR	YES
AT	GOOD	YES
MR	POOR	YES
BB	POOR	NO
VTG	GOOD	NO
VTP2	POOR	NO
MEG	POOR	YES
MEP2	POOR	YES
MEM	POOR	NO
NHG	GOOD	NO
MB	POOR	NO
FB	POOR	YES
VTP1	POOR	YES

Table 9: Significantly Different ISO Mixes

Mix	Performance	Significant
AW	POOR	NO
FF	POOR	NO
SM	POOR	NO
SN	POOR	NO
CF	GOOD	YES
LW	POOR	NO
AT	GOOD	YES
MR	POOR	YES
BB	POOR	NO
VTG	GOOD	NO
VTP2	POOR	YES
MEG	POOR	YES
MEP2	POOR	NO
MEM	POOR	NO
NHG	GOOD	NO
MB	POOR	NO
FB	POOR	NO
VTP1	POOR	NO

4.2.3 Significantly Different ICO and ISO Values vs. Penetration

When comparing ICO values with penetration values, it was found that asphalts with Pre MIST penetration values above 30 tend to be losing carbonyls after MIST conditioning, while those with Pre MIST penetration values below 30 show increase in carbonyls (Figure 30). This can be attributed to the higher viscosity that is associated with a larger presence of carbonyls.

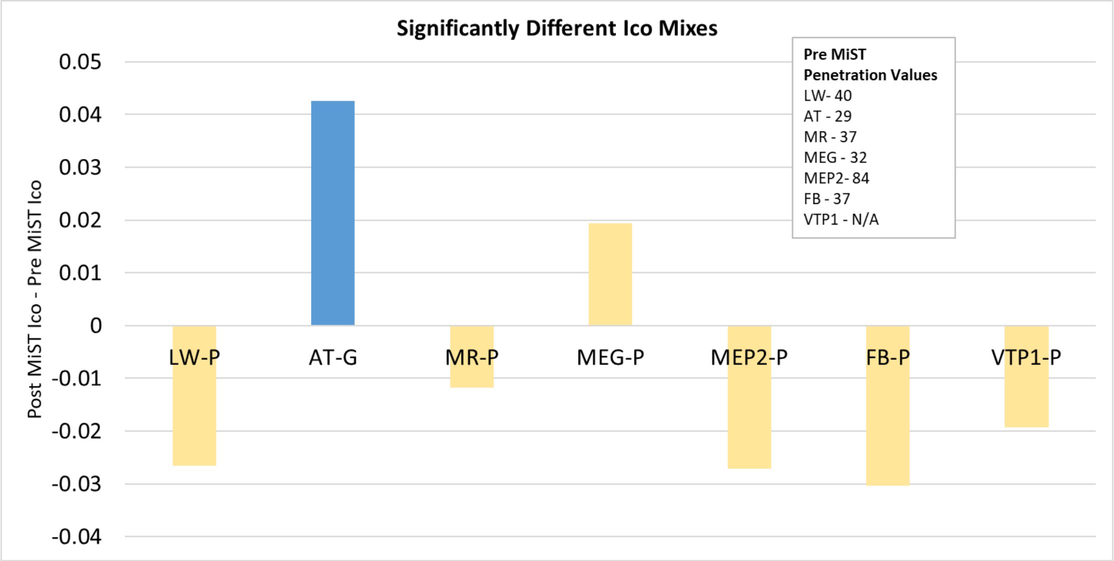


Figure 30: Significantly Different ICO Mixes

When comparing ISO values with penetration values, it was found that asphalts with Pre MIST penetration values above 30 are losing sulfoxides after MIST conditioning, while those with Pre MIST penetration values below 30 exhibit increase in sulfoxides (Figure 31), which is similar to carbonyls. This can be attributed to the higher viscosity that is associated with a larger presence of sulfoxides.

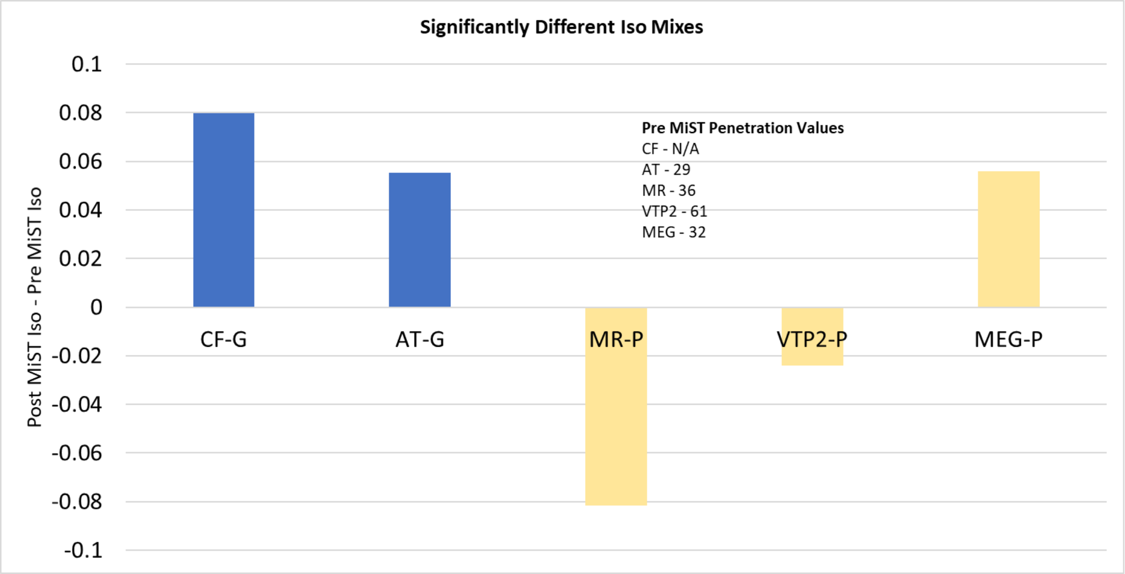


Figure 31: Significantly Different ISO Mixes

4.3 Fiber Analysis

4.3.1 Air Voids vs. Fiber Concentration

While making the samples, it was found that samples containing 0.5% and 1% fiber by mass were not able to be compacted to the correct height, 5.08cm (2in.), and had too high of an air void content (above 7%). A graph showing the fiber content compared to the percent air voids can be seen in Figure 32. It was found that 0.25% fiber content by mass was able to be compacted to the correct height and air void content.

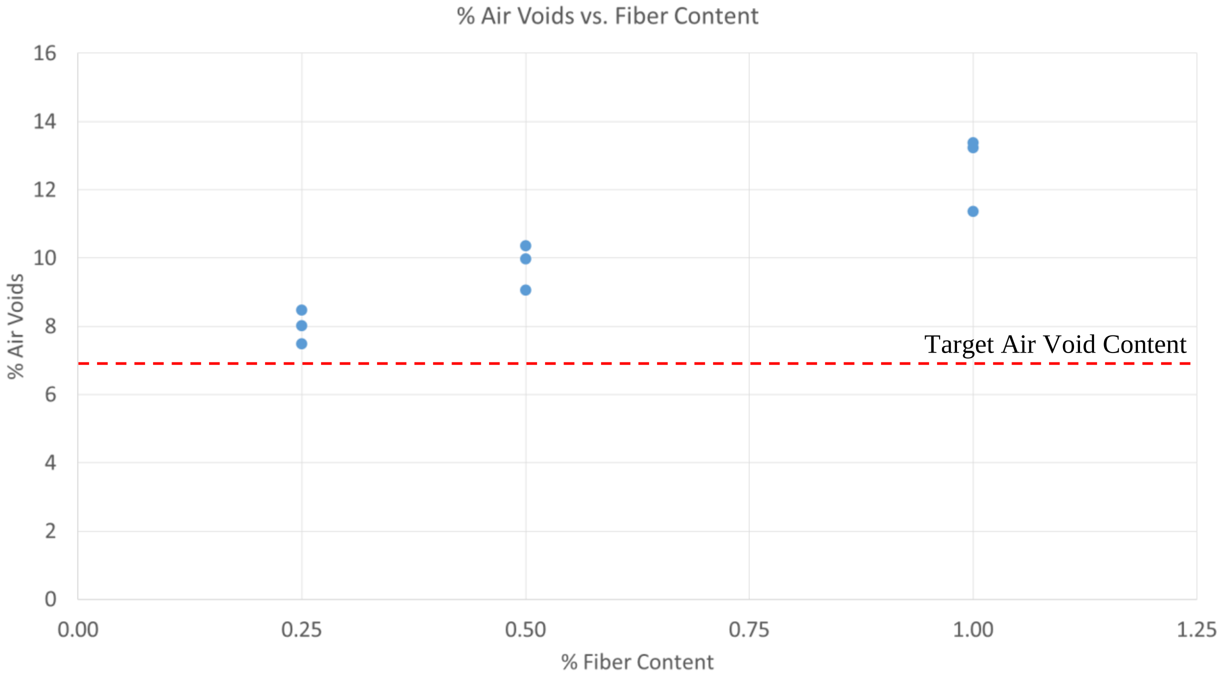


Figure 32: Percent Air Voids vs. Fiber Content

4.3.2 Fiber Bridging

After ITS testing, it was clear there was a significant amount of fiber bridging in the cracking asphalt and can be seen in Figure 33. This visual helps show that the fibers were evenly dispersed throughout the mix from the mechanical mixing methodology. Once testing was complete, the samples were broken apart by hand. Half of a sample is shown in Figures 34 and 35, where is can be seen clearly the dispersion of fibers throughout the sample

Figure 33: Fiber Bridging in Asphalt Sample

Figure 34: Fiber Sample in Half with Fibers Exposed

Figure 35: Close-up of Fiber Sample in Half

4.3.3 ITS Averages for Different Fiber Concentrations

The ITS strength of samples without fiber (created in a previous study) were compare to the strength of samples with both 0.25% fiber content and 0.5% fiber content. It was found that under dry (without moisture conditioning) conditions samples with 0.25% fiber content have on an average approximately 21 % higher ITS strength compared to those without fibers. For samples containing 0.5% fiber, it was found that under dry (without moisture conditioning) conditions samples have on an average approximately 12.6 % higher ITS strength compared to those without fibers. These results can be seen in Figure 36. The 0.5% samples were found to have a large variability in both the air void content and ITS strength, so it was determined that 0.25% fiber content was the most suitable fiber content of the samples tested.

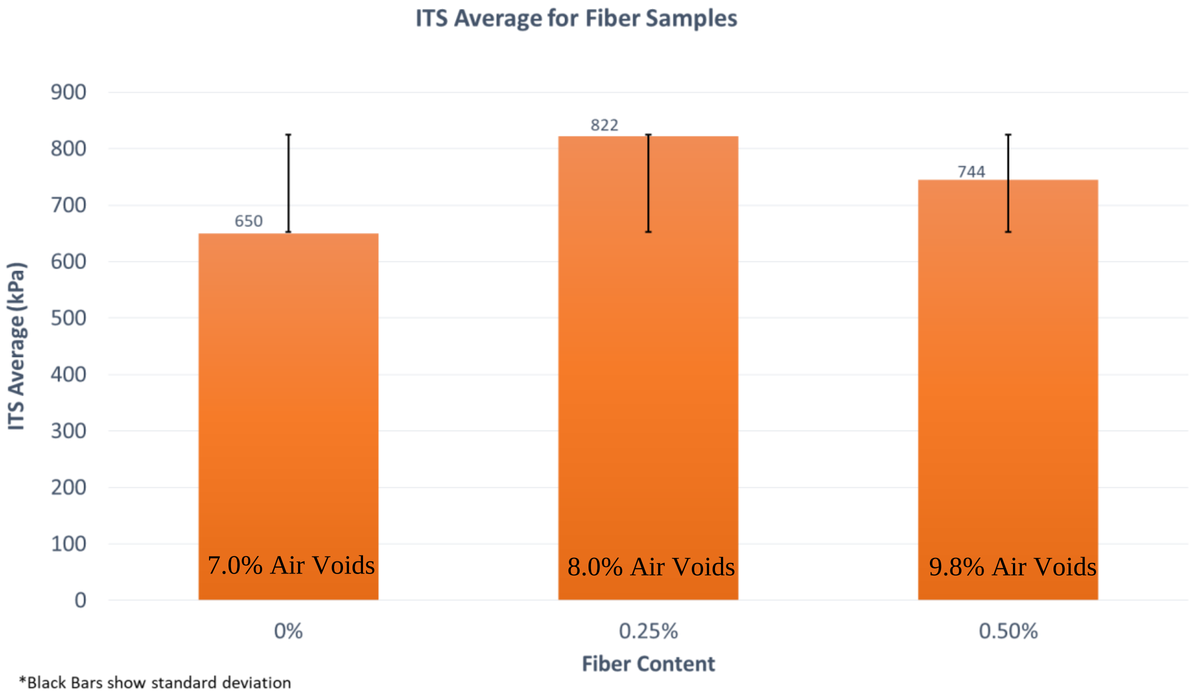


Figure 36: ITS Average for Fiber Samples

4.3.4 ITS Averages for Pre and Post MIST Conditioning

Once 0.25% fiber content was decided to be the most successful, three more samples were created and subject to MIST conditioning in order to compare ITS strength both before and after conditioning. The results can be seen in Figure 37. The percent retained strength Post MIST conditioning for the 0.25% fiber sample was 79.6%, which is roughly what is desired for asphalts in the field. The samples with no fiber only had 67.9% retained strength, which is lower than desired. The Post MIST 0.25% samples increased the ITS strength by 22.78% compared to the Post MIST samples without fiber. This proves that asphalt with 0.25% PPHT fiber by weight greatly improve both the initial strength as well as its strength over time.

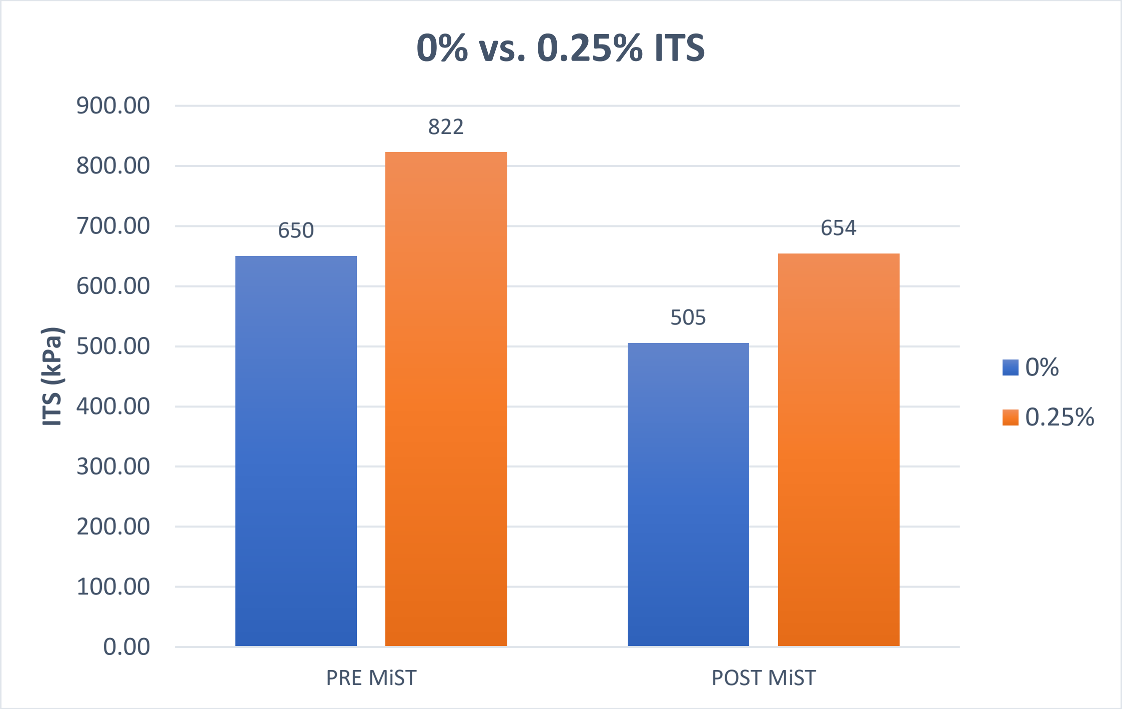


Figure 37: ITS vs. Pre and Post MIST

4.3.5 Economics of Including Fibers in HMA

One aspect of using fibers in HMA asphalt is the additional cost of fibers. For 1 ton of HMA, 2,500g of fibers are required for a mix with 0.25% fiber content. The average cost of HMA is $150 per metric ton (Mallick, 2005). The average cost of polypropylene fibers is roughly $1,500 per metric ton (Alibaba, n.d.). For one ton of HMA, $3.75 would be the addition cost of polypropylene fibers (not including labor, the one-time fixed cost of plant modification needed for adding the fibers). Therefore, adding polypropylene fibers to HMA would result in 2.5% additional cost. This small cost increase initially would help reduce the amount of repair and replacement necessary in the future, which would be much more costly than the initial 2.5%. This is because if the mix is more resistant to moisture damage (as evident from higher retained tensile strength after moisture conditioning), then it is more likely to survive the impacts of moisture and hence last longer than a moisture susceptible mix. Paying a little more in the beginning could potentially save hundreds of thousands of dollars in maintenance in the future. As an extension of this study, a complete life cycle cost analysis could be conducted, with a consideration of increase in pavement life due to the inclusion of fibers. Also, note that further experiments might help us to reduce the amount of fiber to a lower amount (and hence lower the cost) and still achieve significant resistance against moisture damage.

5.0 Conclusions and Future Work

This study looked at the effects of moisture damage on the chemical composition of asphalt binder for asphalt mixes with known field performance. Both good and poor performing asphalt was acquired from MDOT for the study. Asphalt binder was extracted, and penetration testing was performed on the binder. FT-IR ATR testing was also performed to obtain ICO and ISO values. It was found that MIST conditions did effect penetration values, but in varying degrees. When comparing ICO, ISO, and penetration values, it was found that Pre MIST penetration values below 30 typically resulted in an increase in both ICO and ISO values. This can be attributed to the higher viscosity of the binder caused by an increased presence of carbonyls and sulfoxides, further validating previous research. ICO and ISO values were calculated from the FTIR spectra, and it was found that no direct increase or decrease in ICO and/or ISO values correlated to asphalt performance in the field, although this could partially be attributed to poor classification of performance in the field.

Further work regarding asphalt performance in relation to chemical composition of binder should be conducted. Future work should develop a more standardized method of categorizing good vs. poor performance mixes in the field in order to more accurately correlate mix performance to chemical composition. Larger sample sizes should also be taken. Further research in this area can help with correlating particular asphalt binders to poor performing asphalt mixes in high moisture conditions.

This paper also looked at the effects of polypropylene fibers on asphalt tensile strength, both dry and wet conditions. It was found that 0.25% PPHT fiber by weight is the maximum fiber content that can be used in asphalt without increasing air voids while still increasing ITS strength. It was also found that the use of 0.25% fiber in asphalt samples increased the ITS by 20% or more compared to the same asphalt mix without fibers. The samples with 0.25% fiber content also had 80% retained strength after MIST conditioning, which is encouraging. This means that moisture resistance of asphalt mixes can be enhanced with the use of 0.25% fiber. Further research should be done to see if an even lower fiber content (< 0.25% by weight) could still yield similar results while reducing the cost of the asphalt. A feasibility study should also be conducted to see if mass production of HMA with fibers is practically achievable with limited investment, such as that required for plant modification (for example, a chute for adding fibers to the mixing drum).

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7.0 Appendices

Appendix A – Exelto Fiber Product Data Sheet

Product Data Sheet

exelto FIBERS

PP HIGH TENACITY FIBERS
FOR GEO- AND AGRO-TEXTILES

EXELTO® Polypropylene fibers for Geotextiles are 100% virgin polypropylene fibers, specially developed and designed for the demanding tasks in Nonwoven geotextiles applications.

Main characteristics

EXELTO® offers a.o. the following:

- Fine or course denier: From very fine filtration nets to thick protective screens
- Treated UV : Sunlight resistant
- Anti oxidant treatment : Reduces degradability
- Hydrophilic and hydrophobic treatment
- Low static : special chemical treatment in spin finish
- Anti bacteriological / anti - fungi: stain and soil resistant
- Very lightweight (PP and PE fibers have the lowest specific gravity of all fibers)
- Halogen free FR additive: free of heavy metal substances

Application fields

Agrotech
- erosion control
- subsurface drains
- crop protection
- supportive underlying ground structure

Buildtech
- railways, roads : separation subsoil and layer of the road
- tunnel rehabilitation
- industrial building: protective layers
- ground improvement: reinforcement, stabilisation, filtration

Geotech
- waterproofing of dams, canals
- coastal protection, erosion control
- hydraulic engineering: water resources management, filtration
- landfill engineering: liners and covers

www.exelto.com

Product Data Sheet

Technical benefits Polypropylene fiber vs Polyester fiber in geotextile nonwoven

- \+ Lightweight: Lower specific weight (more material for same weight)
- \+ Excellent resistance towards acids, alkalis (caustic solutions) and other chemicals
- \+ Better abrasion results in nonwoven geotextiles.

Technical data

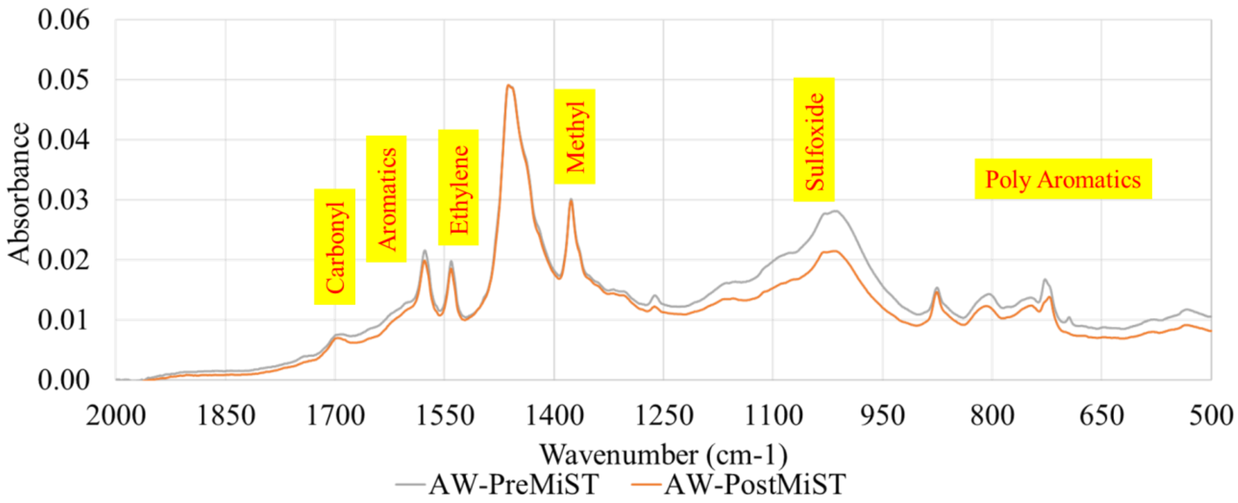
Titer	2,8 to 6 dtex
Cutlength	40 – 120 mm
Tenacity	3,8 – 5,4 cN/dtex
Elongation	> 40% - > 80%
Crimps	2 - 6 per cm
Specific weigth	0.91 g/cm3
Melting point	163 °C
Color	Ecru or any color

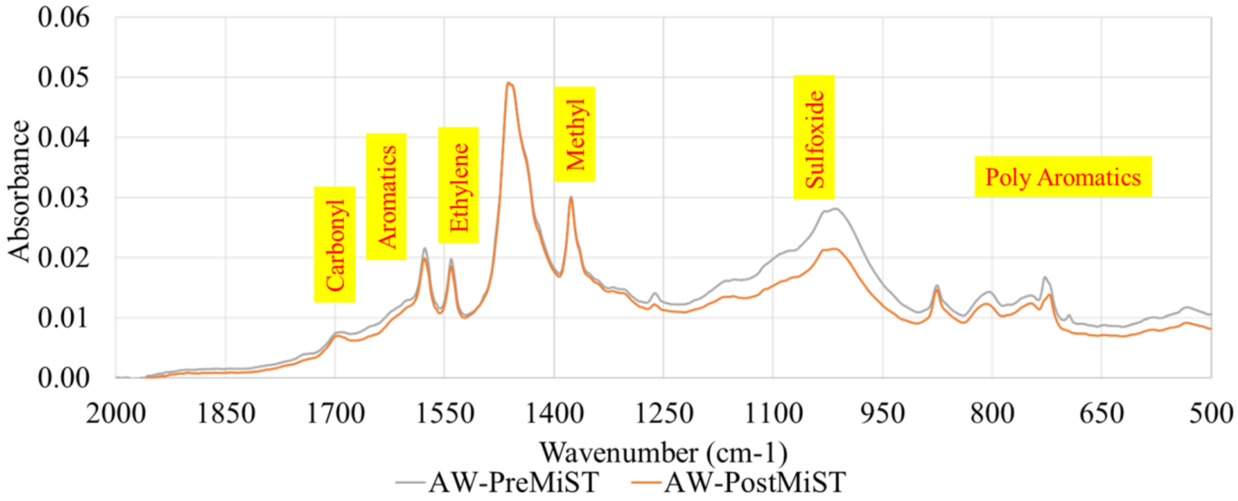
Packaging

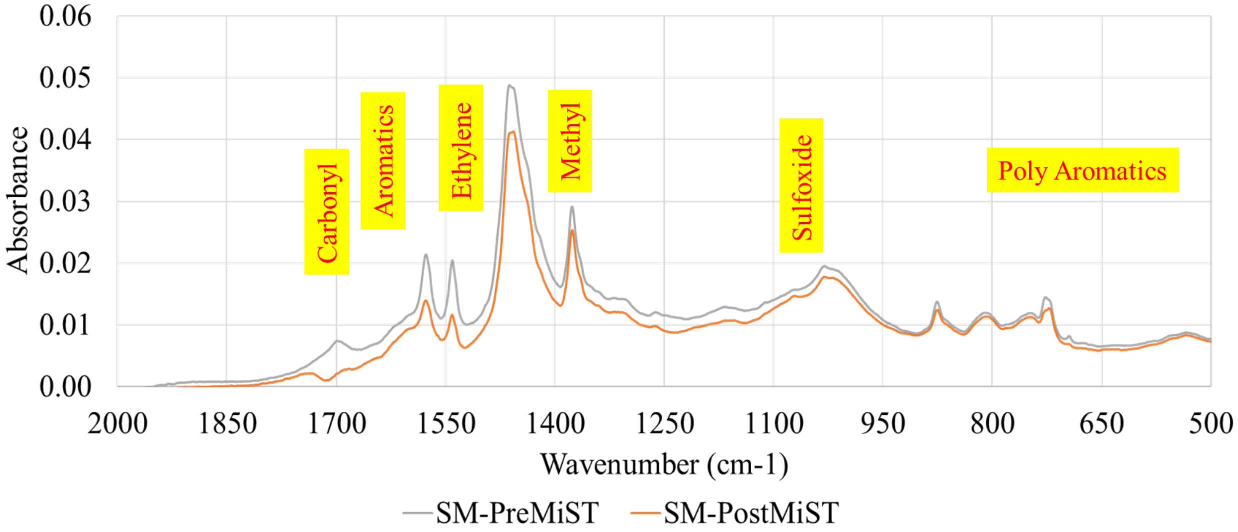
Bales:
net weight 170 – 240 kg
Dimensions 115 x 110 x 60 cm
PP or PE wrapping with PES Plastic binders (straps)

Loading daily, for worldwide delivery,
in full trucks (approx. 96 bales = 20-22 Tons)
20 ft containers (approx. 40 bales = 8-9 Tons)
40 ft containers HC (approx. 86 bales = 17-19 Tons)

Appendix B – FTIR Spectra for Each Mix



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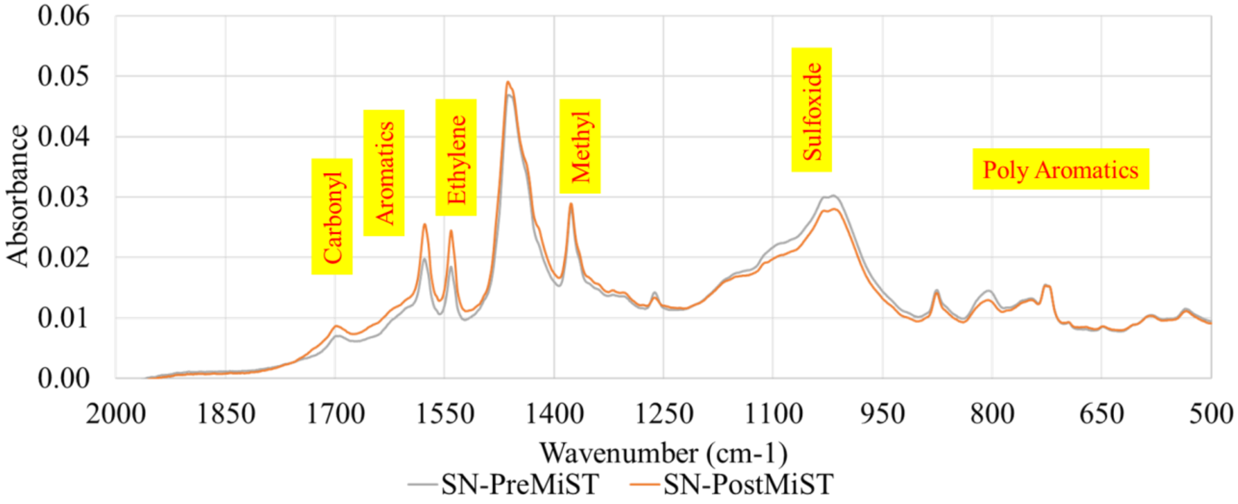
SM-PostMiST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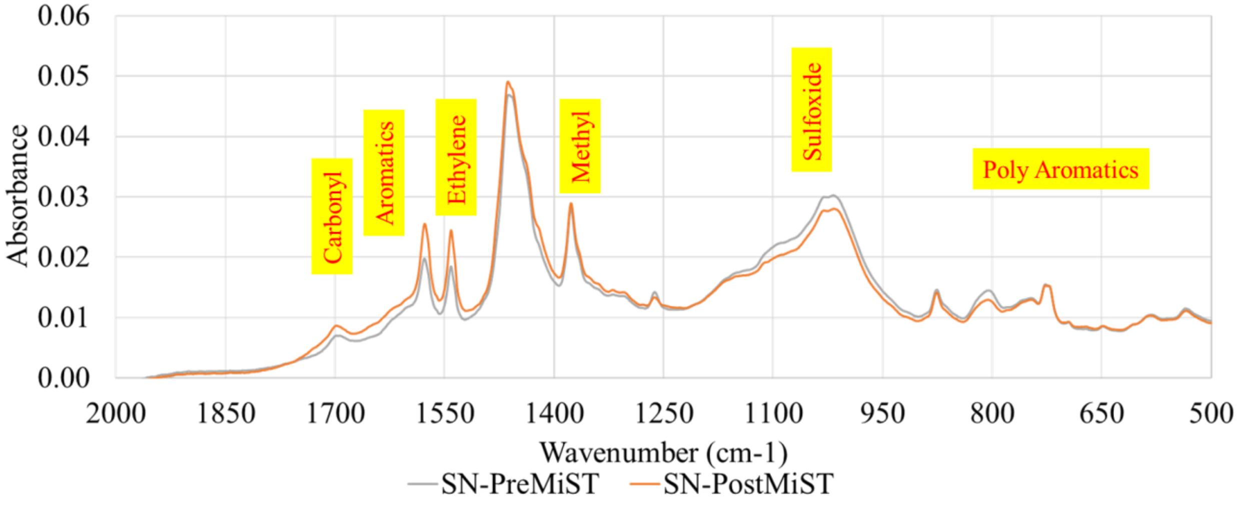
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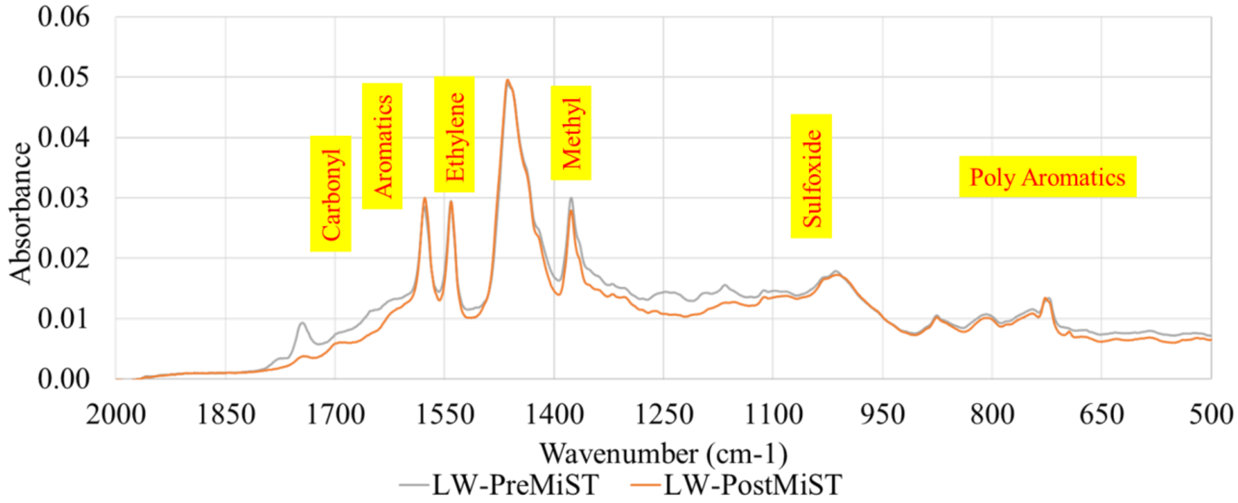
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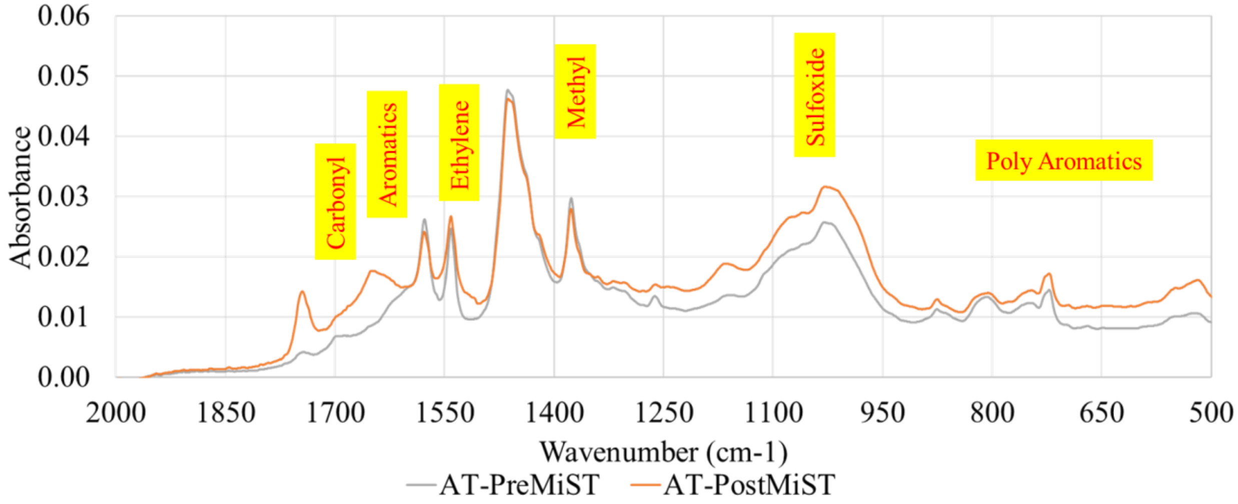
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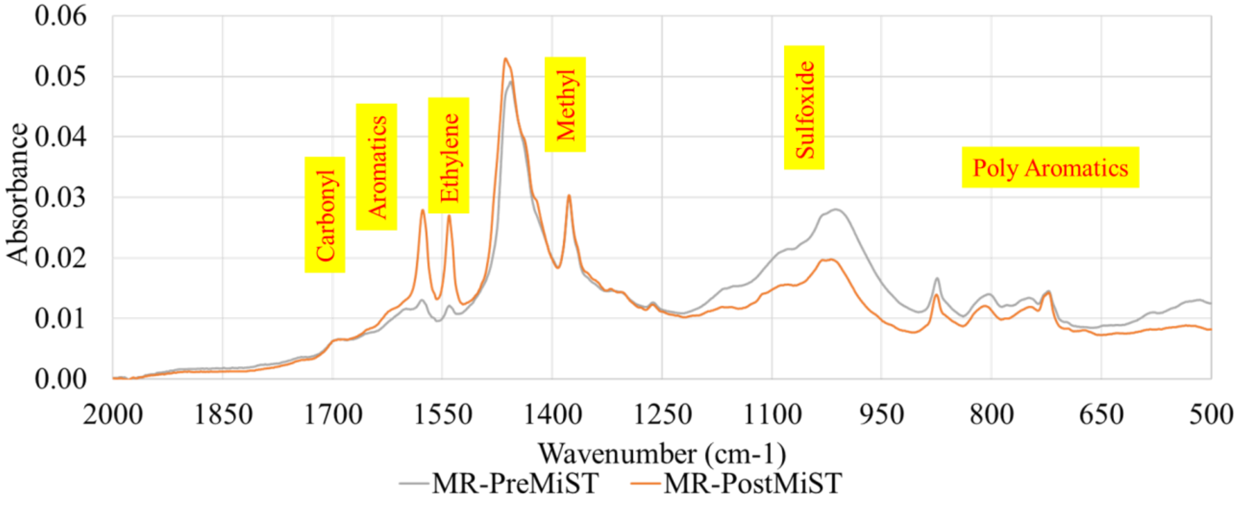
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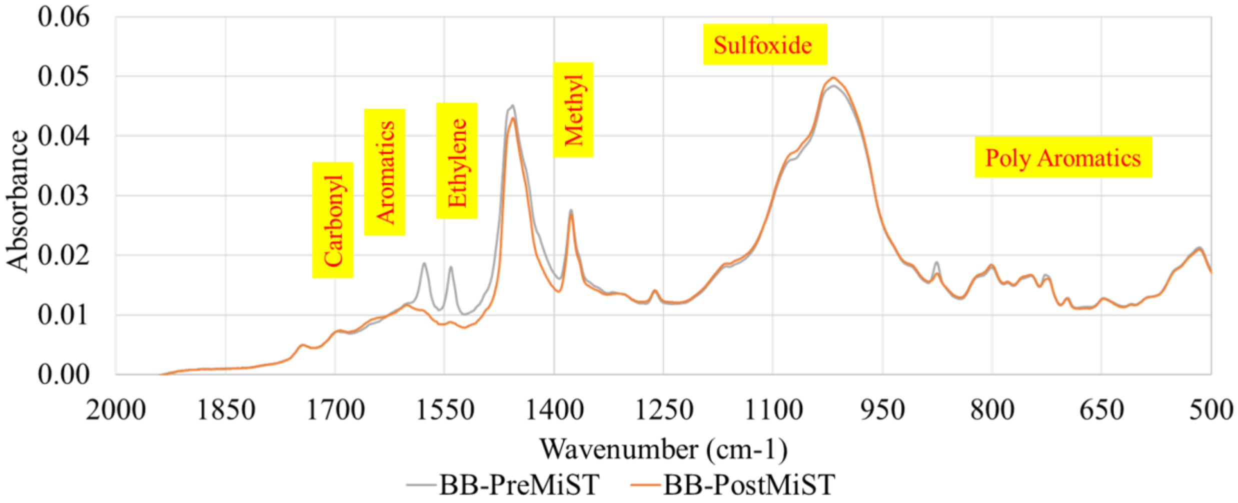
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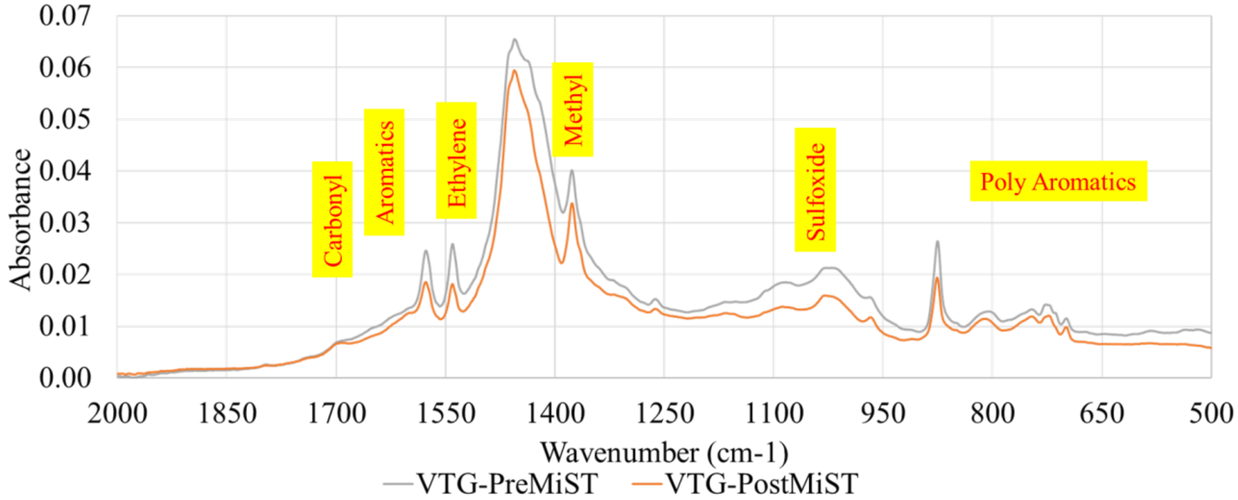
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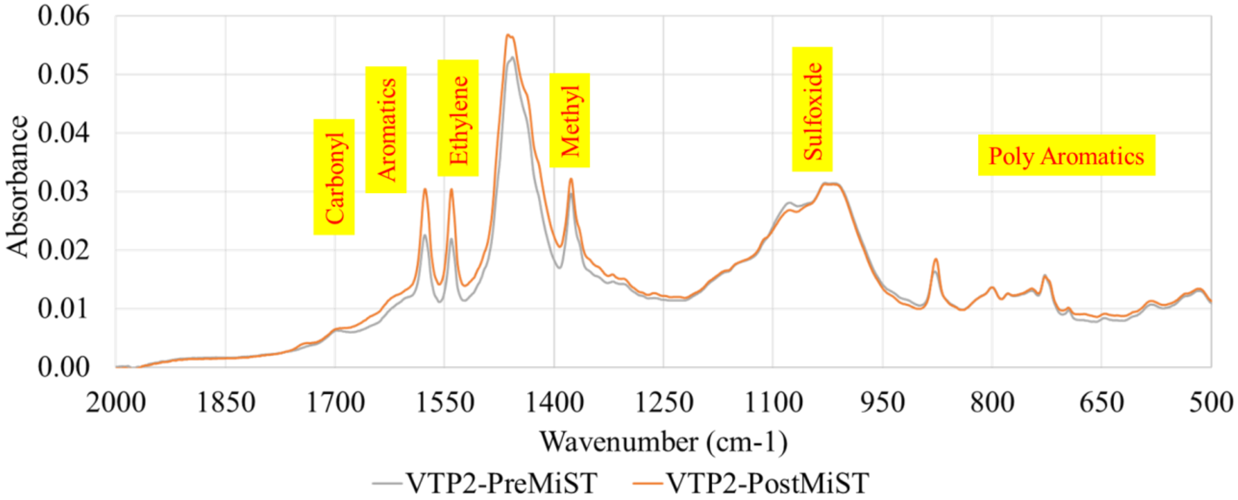
VTG-PreMiST
VTG-PostMiST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Absorbance
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Aromatics
Ethylene
Methyl
Sulfoxide
Poly Aromatics
2000
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1400
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1100
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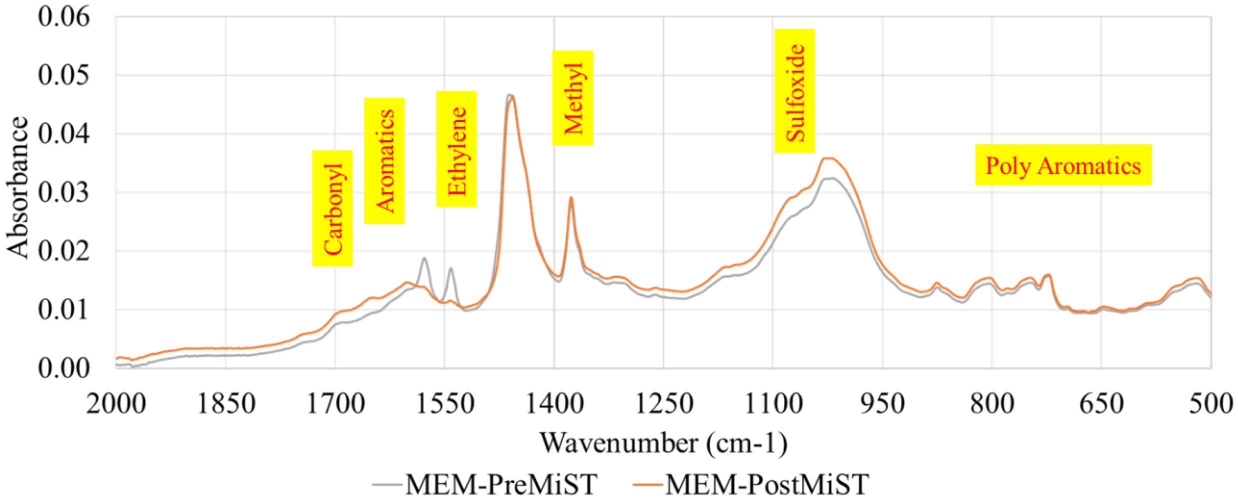
Wavenumber (cm-1)
VTP2-PreMiST
VTP2-PostMiST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Sulfoxide
Poly Aromatics
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1250
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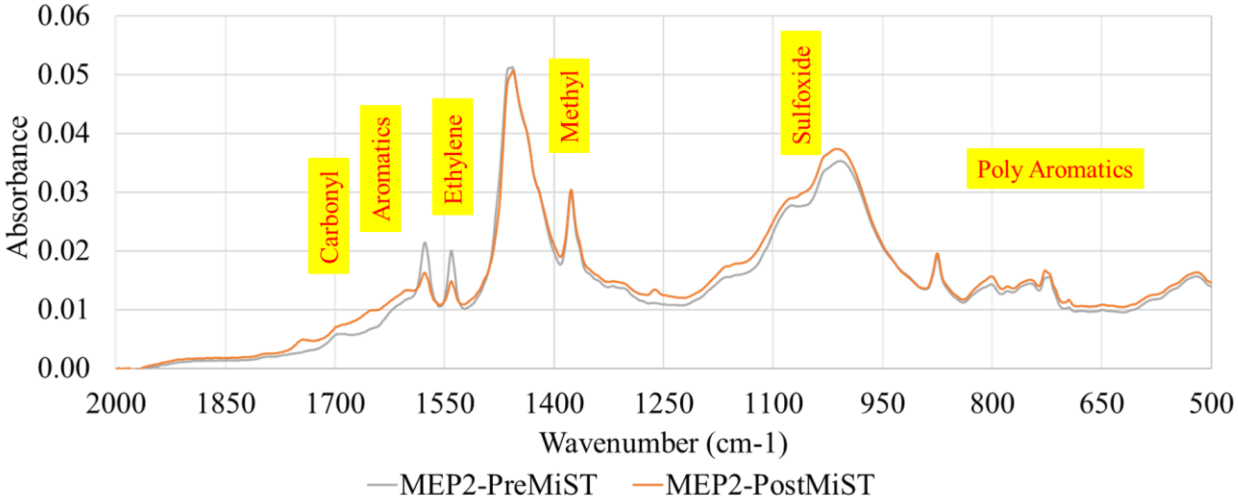
Wavenumber (cm-1)
MEM-PreMiST
MEM-PostMiST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Absorbance
Carbonyl
Aromatics
Ethylene
Methyl
Sulfoxide
Poly Aromatics
2000
1850
1700
1550
1400
1250
1100
950
800
650
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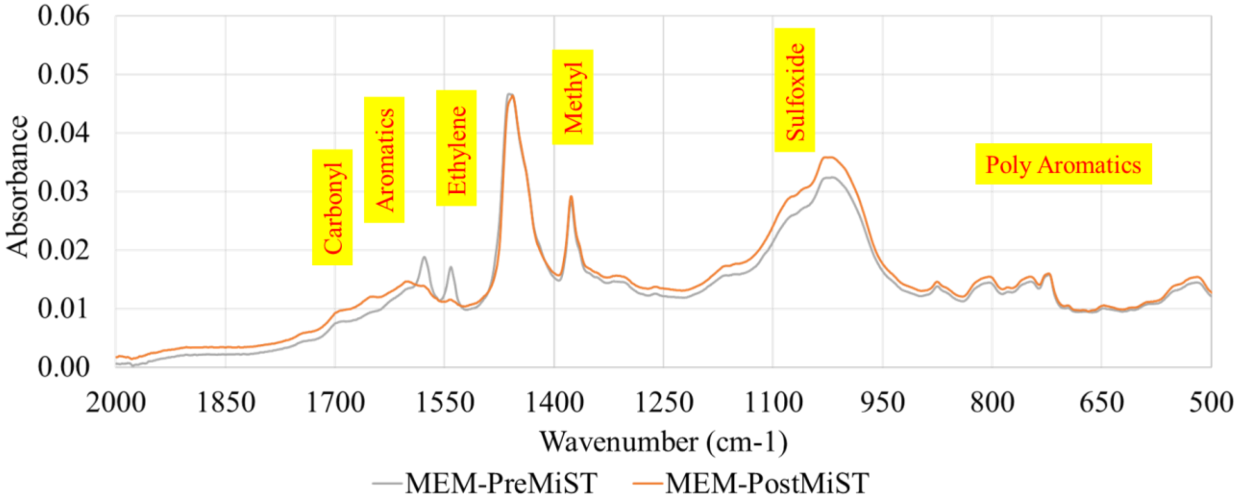
Wavenumber (cm-1)
MEP2-PreMiST
MEP2-PostMiST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Poly Aromatics
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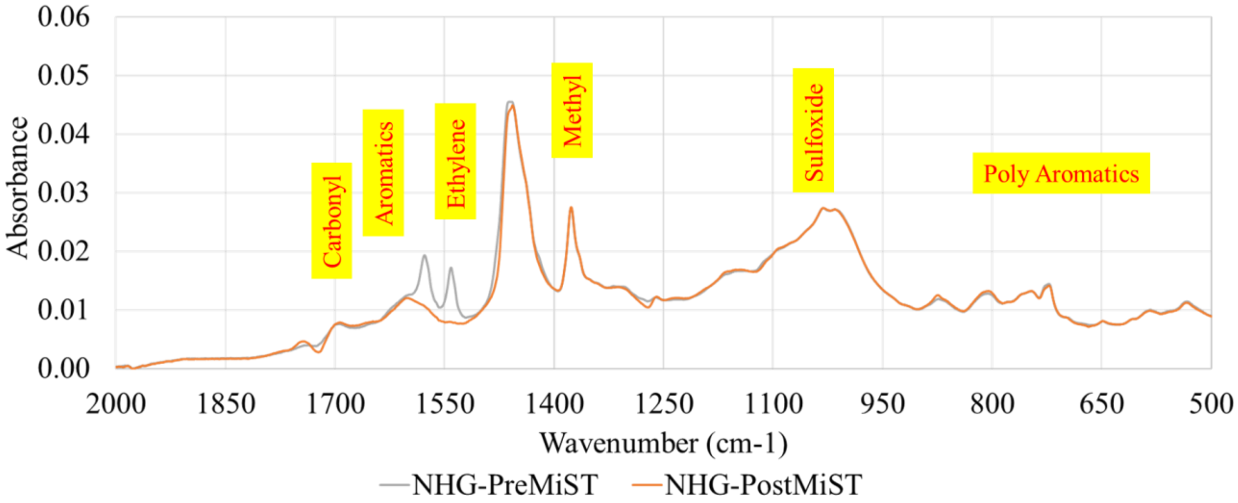
Wavenumber (cm-1)
MEM-PreMiST
MEM-PostMiST



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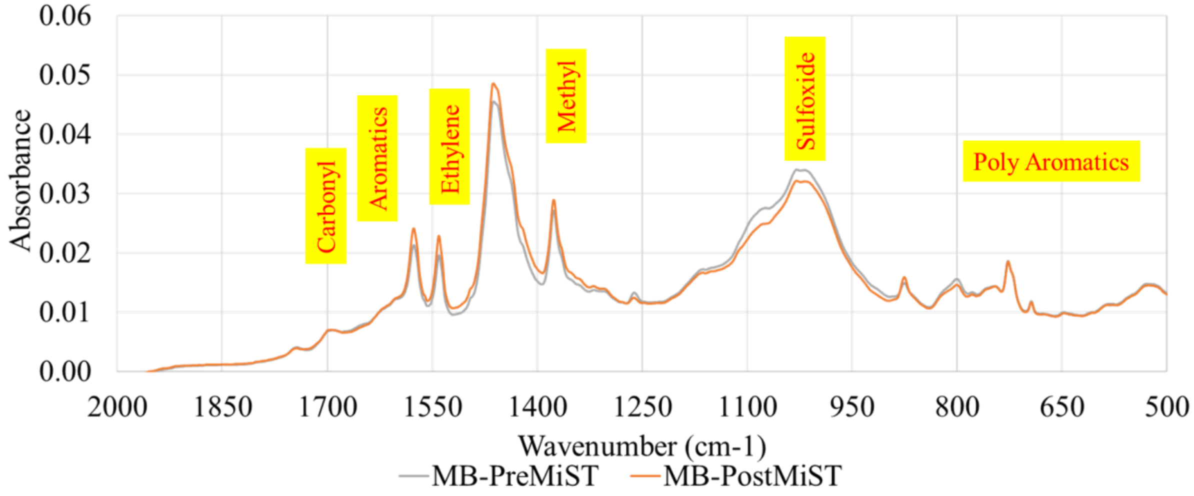
Wavenumber (cm-1)
NHG-PreMiST
NHG-PostMiST



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Sulfoxide
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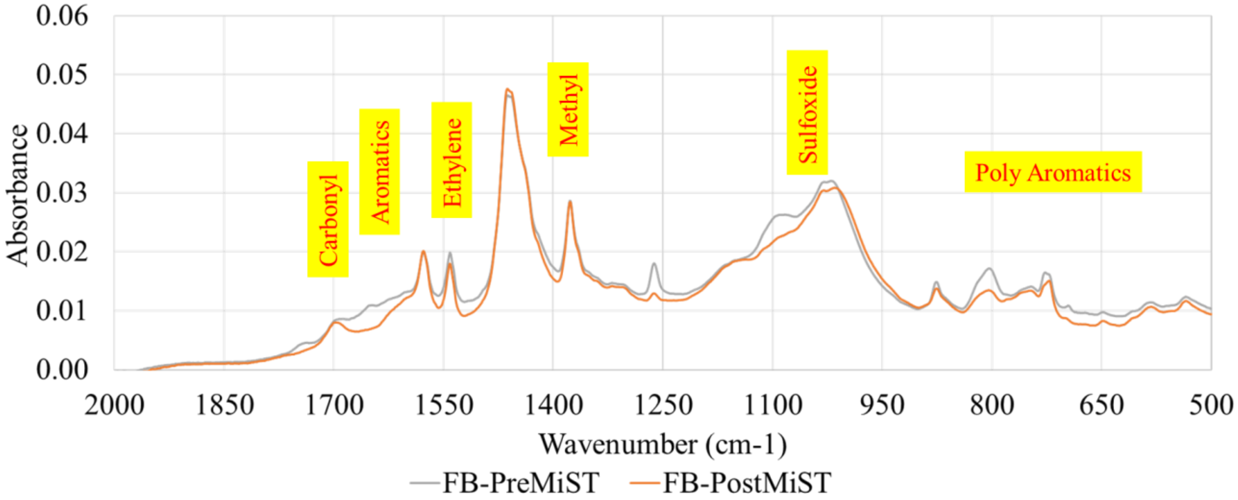
Wavenumber (cm-1)
MB-PreMiST
MB-PostMiST



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Absorbance
Carbonyl
Aromatics
Ethylene
Methyl
Sulfoxide
Poly Aromatics
2000
1850
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1400
1250
1100
950
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500
Wavenumber (cm-1)
FB-PreMiST
FB-PostMiST

Appendix C – ANNOVA Calculations for ICO Values

Anova: Single Factor	**AW ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Ico Pre	3	0.189304	0.063101	3.32E-05		
Ico Post	3	0.145954	0.048651	0.000303		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0003132	1	0.000313	1.863704	0.243938	7.708647
Within Groups	0.00067221	4	0.000168			
Total	0.00098541	5				

Anova: Single Factor	**FF ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.165017	0.055006	3.54E-05		
Column 2	3	0.142153	0.047384	5.09E-05		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.713E-05	1	8.71E-05	2.019551	0.228331	7.708647
Within Groups	0.0001726	4	4.31E-05			
Total	0.0002597	5				

Anova: Single Factor **SM ICO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.268381	0.08946	0.000993
Column 2	3	0.139017	0.046339	0.001785

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002789	1	0.002789	2.007998	0.229432	7.708647
Within Groups	0.005556	4	0.001389			
Total	0.008345	5				

Anova: Single Factor **SN ICO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.206704	0.068901	0.000187
Column 2	3	0.246048	0.082016	0.000311

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000258	1	0.000258	1.035677	0.366377	7.708647
Within Groups	0.000996	4	0.000249			
Total	0.001254	5				

Anova: Single Factor **CF ICO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.152251	0.05075	0.000301
Column 2	3	0.199995	0.066665	5.11E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00038	1	0.00038	2.156987	0.215846	7.708647
Within Groups	0.000705	4	0.000176			
Total	0.001084	5				

Anova: Single Factor **LW ICO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.220257	0.073419	7.87E-05
Column 2	3	0.140422	0.046807	3.2E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001062	1	0.001062	19.18327	0.011876	7.708647
Within Groups	0.000221	4	5.54E-05			
Total	0.001284	5				

Anova: Single Factor	**AT ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.199007	0.066336	7.72E-06		
Column 2	3	0.326829	0.108943	1.15E-05		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002723	1	0.002723	283.272	7.3E-05	7.708647
Within Groups	3.85E-05	4	9.61E-06			
Total	0.002762	5				

Anova: Single Factor	**MR ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.165392	0.055131	2.85E-07		
Column 2	3	0.130183	0.043394	1.86E-05		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000207	1	0.000207	21.85263	0.009485	7.708647
Within Groups	3.78E-05	4	9.45E-06			
Total	0.000244	5				

Anova: Single Factor **BB ICO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.216094	0.072031	3.16E-05
Column 2	3	0.248881	0.08296	5.28E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000179	1	0.000179	4.247586	0.108334	7.708647
Within Groups	0.000169	4	4.22E-05			
Total	0.000348	5				

Anova: Single Factor **VTG ICO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.11178	0.03726	5.61E-05
Column 2	3	0.11765	0.039217	1.42E-06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.74E-06	1	5.74E-06	0.199677	0.678108	7.708647
Within Groups	0.000115	4	2.88E-05			
Total	0.000121	5				

Anova: Single Factor	**MEG ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.185057	0.061686	2.17E-05		
Column 2	3	0.243152	0.081051	3.77E-05		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000563	1	0.000563	18.93413	0.012144	7.708647
Within Groups	0.000119	4	2.97E-05			
Total	0.000681	5				

Anova: Single Factor	**VTP2 ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.114762	0.038254	3.09E-06		
Column 2	3	0.110813	0.036938	3.6E-06		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.6E-06	1	2.6E-06	0.777058	0.427827	7.708647
Within Groups	1.34E-05	4	3.34E-06			
Total	1.6E-05	5				

Anova: Single Factor	**MEP2 ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.210117	0.070039	4.98E-05		
Column 2	3	0.128766	0.042922	1.68E-05		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001103	1	0.001103	33.11595	0.004522	7.708647
Within Groups	0.000133	4	3.33E-05			
Total	0.001236	5				

Anova: Single Factor	MEM ICO					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.1777909	0.059264	0.000644		
Column 2	3	0.2745042	0.091501	5.62E-06		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001559	1	0.001559	4.801627	0.09356	7.708647
Within Groups	0.001299	4	0.000325			
Total	0.002858	5				

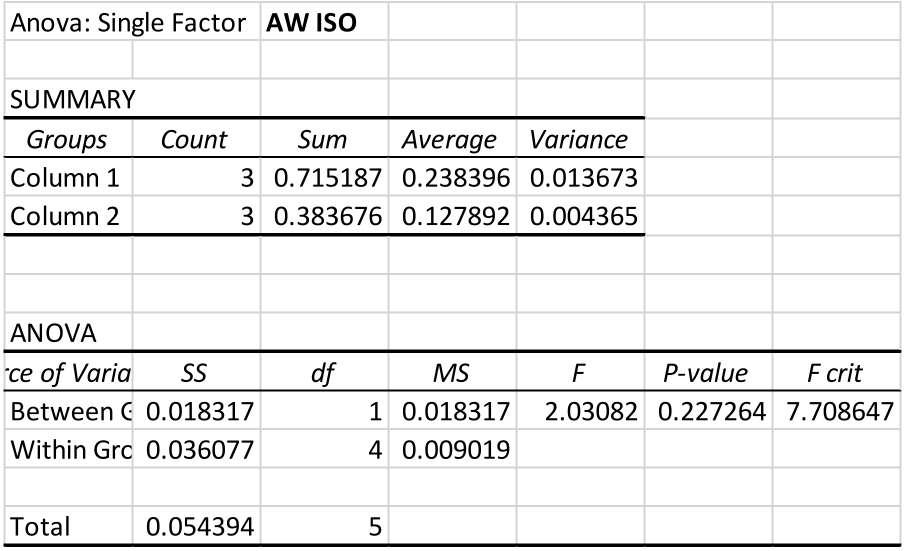
Anova: Single Factor	**NHG ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.228835	0.076278	7.37E-06		
Column 2	3	0.239955	0.079985	8.51E-05		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.06E-05	1	2.06E-05	0.445456	0.541033	7.708647
Within Groups	0.000185	4	4.63E-05			
Total	0.000206	5				

Anova: Single Factor	**MB ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.292689	0.097563	9.64E-05		
Column 2	3	0.273133	0.091044	0.000677		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.37E-05	1	6.37E-05	0.164801	0.705552	7.708647
Within Groups	0.001547	4	0.000387			
Total	0.001611	5				

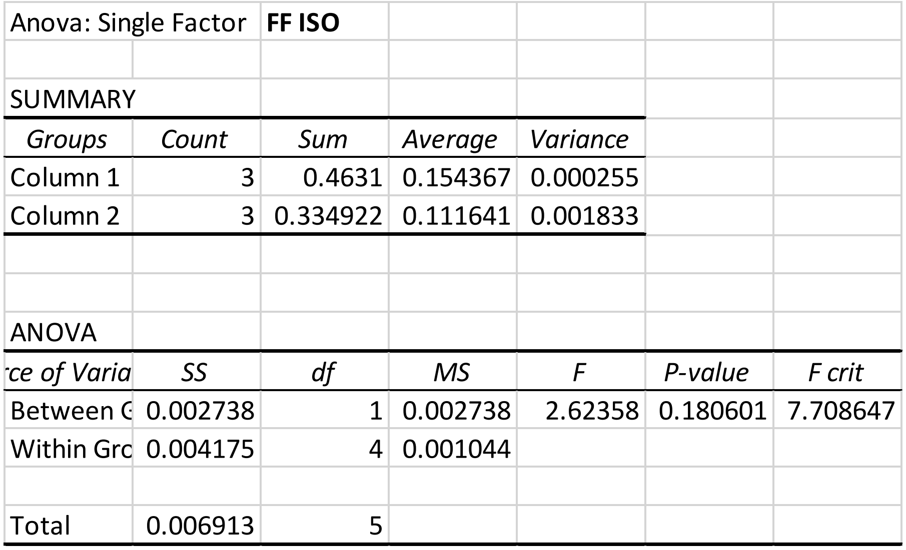
Anova: Single Factor	**FB ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.187945	0.062648	1.11E-05		
Column 2	3	0.096947	0.032316	1.93E-05		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00138	1	0.00138	90.98189	0.000675	7.708647
Within Groups	6.07E-05	4	1.52E-05			
Total	0.001441	5				

Anova: Single Factor	**VTP1 ICO**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.21143	0.070477	2.85E-06		
Column 2	3	0.120146	0.040049	5.19E-06		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001389	1	0.001389	345.4885	4.93E-05	7.708647
Within Groups	1.61E-05	4	4.02E-06			
Total	0.001405	5				

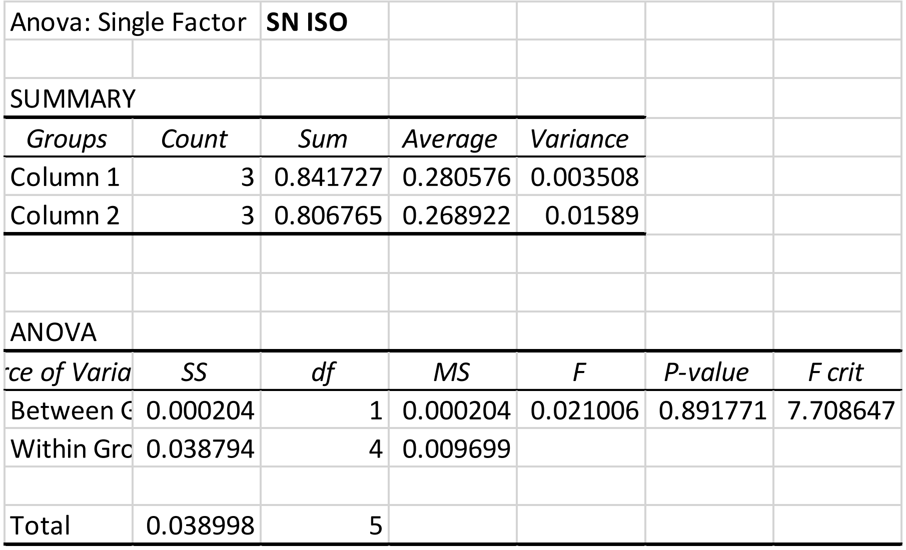
Appendix D – ANNOVA Calculations for ISO Values



Anova: Single Factor		**AW ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.715187	0.238396	0.013673		
Column 2	3	0.383676	0.127892	0.004365		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.018317	1	0.018317	2.03082	0.227264	7.708647
Within Grc	0.036077	4	0.009019			
Total	0.054394	5				



Anova: Single Factor		**FF ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.4631	0.154367	0.000255		
Column 2	3	0.334922	0.111641	0.001833		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.002738	1	0.002738	2.62358	0.180601	7.708647
Within Grc	0.004175	4	0.001044			
Total	0.006913	5				



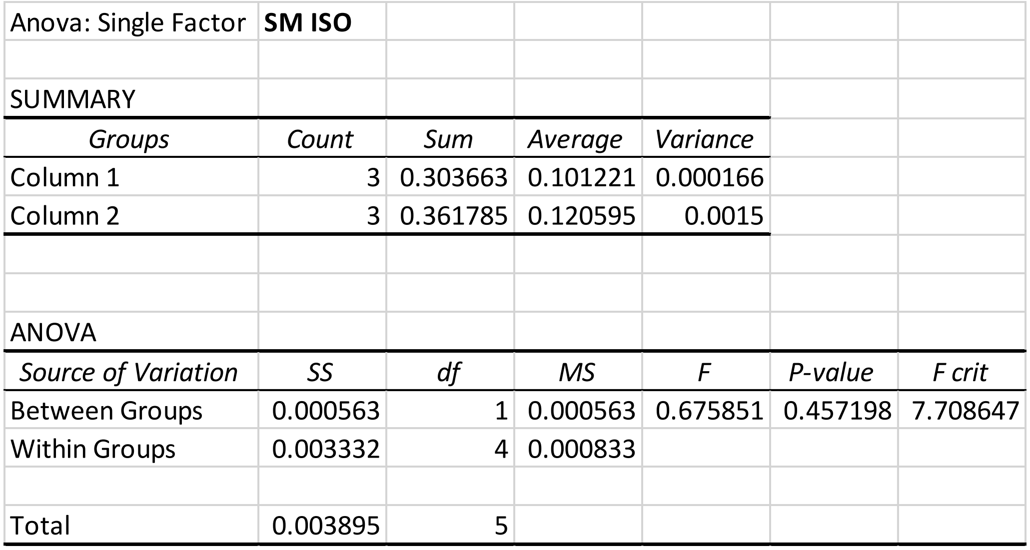
Anova: Single Factor **SN ISO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.841727	0.280576	0.003508
Column 2	3	0.806765	0.268922	0.01589

ANOVA

ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.000204	1	0.000204	0.021006	0.891771	7.708647
Within Gr	0.038794	4	0.009699			
Total	0.038998	5				



Anova: Single Factor **SM ISO**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	0.303663	0.101221	0.000166
Column 2	3	0.361785	0.120595	0.0015

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000563	1	0.000563	0.675851	0.457198	7.708647
Within Groups	0.003332	4	0.000833			
Total	0.003895	5				

Anova: Single Factor		**CF ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.236327	0.078776	1.33E-05		
Column 2	3	0.476086	0.158695	0.000198		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.009581	1	0.009581	90.78973	0.000677	7.708647
Within Grc	0.000422	4	0.000106			
Total	0.010003	5				

Anova: Single Factor		**LW ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.310503	0.103501	0.001886		
Column 2	3	0.432806	0.144269	8.02E-06		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.002493	1	0.002493	2.632156	0.180039	7.708647
Within Grc	0.003789	4	0.000947			
Total	0.006282	5				

Anova: Single Factor		**AT ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.623819	0.20794	1.93E-05		
Column 2	3	0.790098	0.263366	6.73E-06		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.004608	1	0.004608	354.2413	4.69E-05	7.708647
Within Grc	5.2E-05	4	1.3E-05			
Total	0.00466	5				

Anova: Single Factor		**MR ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.613908	0.204636	0.000151		
Column 2	3	0.368817	0.122939	0.000172		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.010012	1	0.010012	61.90636	0.00141	7.708647
Within Grc	0.000647	4	0.000162			
Total	0.010659	5				

Anova: Single Factor		**BB ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	1.003502	0.334501	0.000824		
Column 2	3	1.135774	0.378591	0.001291		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.002916	1	0.002916	2.75869	0.172064	7.708647
Within Grc	0.004228	4	0.001057			
Total	0.007144	5				

Anova: Single Factor		**VTG ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.273038	0.091013	9.65E-05		
Column 2	3	0.242527	0.080842	1.59E-06		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.000155	1	0.000155	3.164542	0.149874	7.708647
Within Grc	0.000196	4	4.9E-05			
Total	0.000351	5				

Anova: Single Factor		**VTP2 ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.587841	0.195947	2.13E-06		
Column 2	3	0.515633	0.171878	3.88E-06		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.000869	1	0.000869	289.2546	7.01E-05	7.708647
Within Grc	1.2E-05	4	3E-06			
Total	0.000881	5				

Anova: Single Factor		**MEP 2 ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.492036	0.164012	0.000113		
Column 2	3	0.429558	0.143186	0.000518		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.000651	1	0.000651	2.062637	0.224296	7.708647
Within Grc	0.001262	4	0.000315			
Total	0.001912	5				

Anova: Single Factor		**MEG ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.549214	0.183071	8.14E-06		
Column 2	3	0.71739	0.23913	9.66E-05		
ANOVA						
rce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.004714	1	0.004714	89.99835	0.000689	7.708647
Within Grc	0.00021	4	5.24E-05			
Total	0.004923	5				

Anova: Single Factor		**MEM ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.711631	0.23721	0.000744		
Column 2	3	0.747416	0.249139	4.76E-05		
ANOVA						
rce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.000213	1	0.000213	0.53915	0.503506	7.708647
Within Grc	0.001583	4	0.000396			
Total	0.001797	5				

Anova: Single Factor		MB ISO				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.835831	0.27861	3.14E-06		
Column 2	3	0.840351	0.280117	4.03E-05		
ANOVA						
rce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	3.41E-06	1	3.41E-06	0.156955	0.7122	7.708647
Within Grc	8.68E-05	4	2.17E-05			
Total	9.02E-05	5				

Anova: Single Factor		**NHG ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.756798	0.252266	0.000631		
Column 2	3	0.773299	0.257766	0.001723		
ANOVA						
rce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	4.54E-05	1	4.54E-05	0.038553	0.85391	7.708647
Within Grc	0.004708	4	0.001177			
Total	0.004754	5				

Anova: Single Factor		**FB ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.500868	0.166956	0.000213		
Column 2	3	0.419293	0.139764	0.000706		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.001109	1	0.001109	2.413208	0.195278	7.708647
Within Grc	0.001838	4	0.00046			
Total	0.002947	5				

Anova: Single Factor		**VTP1 ISO**				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	3	0.481426	0.160475	7.2E-06		
Column 2	3	0.445972	0.148657	6.45E-05		
ANOVA						
ce of Varia	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between G	0.000209	1	0.000209	5.845299	0.072944	7.708647
Within Grc	0.000143	4	3.58E-05			
Total	0.000353	5				