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# Performance Characteristics of Polyethylene Terephthalate (PET) Modified Asphalt

Matthew D. Earnest

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# PERFORMANCE CHARACTERISTICS OF POLYETHYLENE TEREPHTHALATE (PET) MODIFIED ASPHALT

by

MATTHEW EARNEST

(Under the Direction of Junan Shen)

## ABSTRACT

Polyethylene terephthalate (PET) plastic is utilized primarily in food and beverage packaging. Although a portion of waste PET is recycled, the majority of the waste is buried in landfills. Therefore, the use of ground PET particles in asphalt may provide an environmentally friendly solution for the disposal of large quantities of PET waste. This study evaluated the performance of PET as an asphalt modifier with both asphalt binder and asphalt mixture testing. The binder testing was conducted on wet process blends produced with a high shear mixer at PET contents of 5, 10, and 15 percent by weight of the binder. Dynamic Shear Rheometer (DSR) and Rotational Viscosity (RV) tests were performed on the unaged and Rolling Thin Film Oven (RTFO) aged mixtures. The mixture tests were conducted on the PET modified mixtures in both wet and dry process, and an unmodified control mixture. The wet and dry process mixtures contained 10% PET by weight of the binder. The mixture performance tests included Asphalt Pavement Analyzer (APA) rutting test, retrofitted APA Hamburg test, Indirect Tensile Strength (ITS), and Asphalt mixture Performance Tester (AMPT) dynamic modulus. The results showed: 1) the addition of PET increased the high temperature performance resulting in a bump in PG grade. Additionally, the viscosity and resulting workability of the modified binders were not adversely affected. 2) PET modified mixtures have higher maximum specific gravity and lower bulk specific gravity than the control mixture. 3) The wet process mixture exhibited better rutting resistance and a higher TSR than the control in ITS testing. 4) The dry process mixture exhibited better resistance to permanent moisture damage in APA Hamburg testing and also exhibited a higher TSR than the control in ITS testing. 5) The modified mixtures exhibited lower  $E^*$  and higher phase angles than the control in AMPT modulus testing.

INDEX WORDS: PET, Recycled, Modified asphalt, APA rut test, APA Hamburg test, AMPT modulus, ITS, PG grade, High shear mixing

**PERFORMANCE CHARACTERISTICS OF POLYETHYLENE TEREPHTHALATE  
(PET) MODIFIED ASPHALT**

by

**MATTHEW EARNEST**

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A Thesis Submitted to the Graduate Faculty of Georgia Southern University in Partial  
Fulfillment of the Requirements for the Degree

**MASTER OF SCIENCE in APPLIED ENGINEERING**

**STATESBORO, GEORGIA**

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## CHAPTER 1: INTRODUCTION

### 1.1 Background

Traditional asphalt mixtures contain liquid asphalt binder, or bitumen, and aggregate as the two principal constituents. Although the mechanical and chemical properties of the aggregates can vary significantly depending on source, the overall durability and other performance characteristics of asphalt mixtures are generally limited by the performance of the asphalt binder. Failure of asphalt pavement due to the asphalt binder can be attributed to three primary sources. These include rutting that occurs at high temperatures as asphalt softens and the elasticity of the binder decreases, fatigue cracks from repeated loading and aging of the pavement, and low temperature cracking as the asphalt becomes brittle (Somayaji 2001). Failure of asphalt binders is obviously undesirable, and attempts have been made to maximize the effectiveness of asphalt binders selected for construction projects. As a result, the selection of a suitable asphalt binder for each paving project is based on a standard asphalt binder classification system.

In 1987, as part of the Superior Performing Asphalt Pavements Program (Superpave), an asphalt binder classification system that evaluated the performance properties of asphalt and classifies binders based on specified maximum and minimum service temperatures was developed. This performance grading, or PG grading, system entails two values assigned to each asphalt grade. A high temperature grade ranging from 46°C to 82°C (in increments of six degrees) and a low temperature grade ranging from -10°C to -46°C (also in increments of six degrees) are assigned to commercially available asphalts (Somayaji 2001). For example, PG 67-22 asphalt would have a

maximum failure temperature of 67°C and a minimum failure temperature of -22°C.

Engineers select the appropriate asphalt binder for the project based on environmental and climactic conditions for the region in which the project will be located.

Although the PG grading system provides satisfactory results in determining the appropriate asphalt binder for a construction project, it leaves room for improvements that address inherent problems with asphalt binders. Studies of raw asphalt have shown that the asphalt binders can contain approximately ten percent wax, depending on the source of the binder. This wax softens at high temperatures leading to reduced cohesion, strength, and stability of asphalt mixtures (Al-Hadidy and Tan 2011). Softening of asphalt poses a problem in that it decreases the durability and service life of the pavement against failures such as rutting. This and other inherent problems with asphalt binders can be addressed by using modifiers that are added to the asphalt in small percentages to enhance rutting and fatigue cracking resistance as well as to increase the PG grade of the asphalt binder (Somayaji 2001). Polymer modifiers are a popular means to increase the field performance and longevity of asphalt mixtures. However, the costly nature of polymer modifiers has stimulated research into cheaper, more cost-effective modifiers produced from recycled materials (Ahmadinia et al. 2012)

The polymer modifier of interest to this study is waste PET, or polyethylene terephthalate, plastic. Studies of other waste plastic products incorporated in asphalt mixtures have shown promising results in improving durability of asphalt mixtures, and it can be concluded that PET may perform similarly. Some studies have been conducted utilizing PET as a modifier in the dry process and as aggregate replacement. However,

only one current study has evaluated PET as a modifier in the wet process, and no studies have evaluated PET as a modifier in the wet process with high shear mixing.

The idea of using PET plastic as an asphalt additive is fairly new to the asphalt industry. Therefore studies regarding the durability of PET modified mixtures, specifically those produced in the wet process, are limited. The goal of this study was to expand the knowledge of the engineering properties of PET modified asphalt mixtures and to ultimately prove that waste PET plastic has a viable use as an asphalt modifier.

## **1.2 Objectives**

The overall objective of the study was to evaluate the possibility of using PET particles as an asphalt modifier by investigating the properties of both modified asphalt binders and modified mixtures with the PET particles. Additionally, the study investigated the effects of the mixing process (i.e. wet or dry process) on the properties of PET modified mixtures as compared with controls (mixtures using unmodified asphalt).

The research scope included one Superpave 12.5mm aggregate gradation, one unmodified base PG67-22 asphalt binder, and one PET source. The modified binders were produced at three PET percentages. Modified asphalt binders with PET particles were produced using a high shear mixer. Tests for modified binders included DSR, RTFO, and RV. Tests for modified mixtures included maximum specific gravity, bulk specific gravity, APA rutting, APA Hamburg, AMPT modulus, and indirect tensile strength (ITS).

## CHAPTER 2: LITERATURE REVIEW

### 2.1 Context

PET is a plastic product commonly used in the production of beverage and food containers. In 2010, about 2,675 thousand tons of PET waste was generated in the United States alone. Only 29.1 percent, or 778.5 thousand tons, of this PET waste was recycled, meaning that the remaining 1,896.5 thousand tons was discarded (Container Recycling Institute 2015). Figure 2.1 shows the sales and waste of PET plastics from 1991 to 2010. This discarded plastic is ultimately buried in landfills or incinerated, both of which are not environmentally friendly options. As a global movement towards more sustainable practices is taking place, governments and industries are searching for more environmentally friendly options for the repurposing of waste plastics.

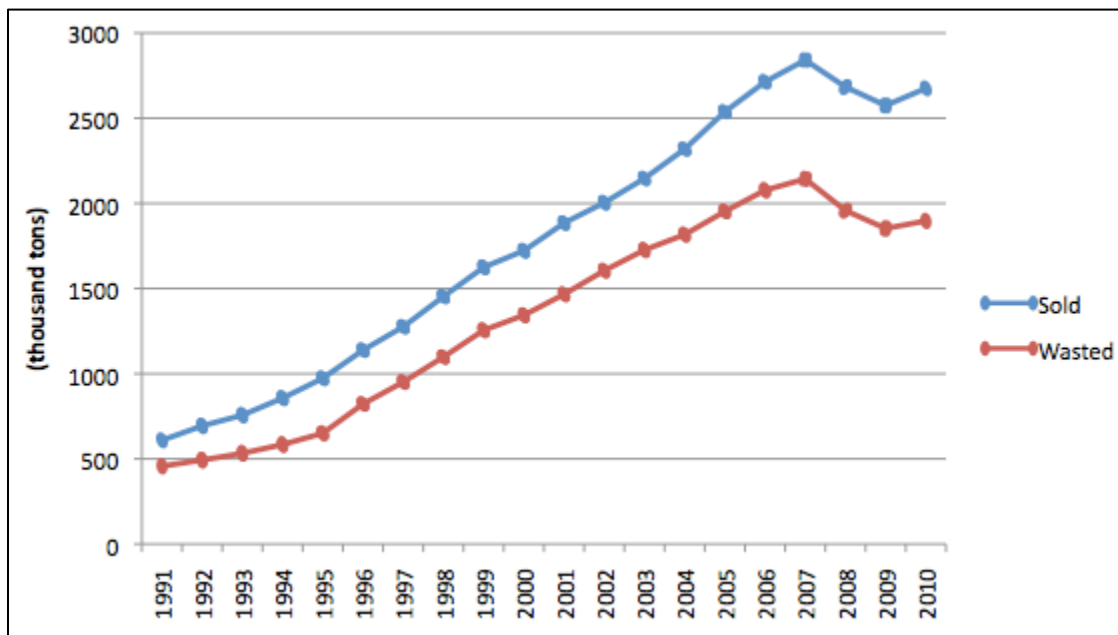


Figure 2.1. PET plastic sales and waste from 1991 to 2010 (Container Recycling Institute 2015)



One viable solution for preventing vast quantities of PET from being buried in landfills or incinerated is increased recycling efforts. PET can be recycled by chemical or physical means. Chemical recycling is costly because it is conducted at elevated temperatures and pressures as well as in the presence of different chemical catalysts. Physical recycling (grinding or chipping) is cheaper, but it produces an inferior grade product because of the presence of outside contaminants (Moghaddam, Soltani, and Karim 2014). The cost of the recycling method and quality of the recycled product seem to be the limiting factors in the overall percentage of PET plastic recycled since many post-recycling applications require a high quality, pure product. However, PET plastic does not need to be extensively purified for use in asphalt applications (Hassani, Ganjidoust, and Maghanaki 2005). Therefore, cheaper recycling methods can be used to produce a PET product for use in asphalt pavements with less emphasis on the purity and quality of the recycled product.

The United States has about 2.2 million miles of paved roads, 93 percent of which are paved with asphalt (Asphalt Pavement Alliance 2015). The US Department of Transportation uses a network of 4000 continuous traffic counting stations nationwide to estimate the percent changes in traffic volumes from month to month and year to year. In 1993, the traffic counting stations reported approximately 2.297 million vehicle miles of travel. In 2013, the stations reported approximately 2.967 million vehicle miles of travel (USDOT 2015). As nationwide traffic volumes increase, existing roads are experiencing increased rates of deterioration and need to be resurfaced. Additionally, new highway projects are being constructed to keep pace with traffic demands. Therefore, the asphalt industry could potentially provide a viable market for the large-

scale use of PET waste if a reliable process is developed for the incorporation of PET plastic into asphalt pavement.

The use of recycled materials in asphalt pavements is not a new concept. Crumb rubber manufactured from scrap tires has been successfully utilized in asphalt pavements for decades. A 1964 project by Charles McDonald employed crumb rubber as a modifier for asphalt binder utilized in crack sealing of airport runways in Phoenix, Arizona. This is widely regarded as the first successful application of crumb rubber modified asphalt (Plemons 2013). Since then, crumb rubber has seen more widespread use by state departments of transportation in asphalt paving projects because of its wide variety of performance benefits. In 1997, the United States government recognized this and issued a mandate requiring states to use crumb rubber modified asphalt in at least 20 percent of their annual asphalt tonnage (MacLeod, et al. 2007). The successful history of crumb rubber as a recycled asphalt additive indicates that traction can successfully be generated in industry and government for the utilization of recycled products in asphalt pavement.

## **2.2 Asphalt Modification Methods**

Three primary methods exist for the incorporation of waste plastics into asphalt pavements. These methods include the wet process, the dry process, and aggregate replacement. In the wet process, the PET is thoroughly mixed with the liquid asphalt binder to form a homogeneous mixture before it is added to the aggregate in the mixing process. In mixture calculations, the PET is substituted for a portion of the bitumen. The interaction between the binder and PET results the production of a modified binder. Casey et al. conducted a study in which the researchers attempted to use PET as a

binder modifier in the wet process. The study concluded that PET was not a suitable modifier in the wet process because a homogeneous mixture could not be produced due to the high melting point of the PET (Casey et al. 2008).

In the dry process, the aggregate and bitumen are thoroughly mixed in the mixing apparatus. Once the aggregate has been coated with bitumen, the PET is then introduced, and the mixing process continues until the PET is thoroughly incorporated into the asphalt mixture. In the dry process, the PET is still substituted as a portion of the bitumen, similar to the wet process. However the binder and PET are not allowed to interact to the same degree as the wet process due to the brief mixing window, so the asphalt binder in the dry process is not truly a modified binder. The majority of current studies on PET modified asphalt mixtures use the dry process (Modarres and Hamed 2014; Moghaddam, Karim, and Syammaun 2012; Moghaddam, Soltani, and Karim 2014; Ahmadinia et al. 2012).

PET plastic is also incorporated into asphalt mixtures as aggregate replacement. In the aggregate replacement process, a portion of the coarse or fine aggregate is replaced with PET particles of similar size, resulting in a plasti-asphalt mixture. Hassani, Ganjidoust, and Maghanaki conducted a study in which up to 60 percent by volume of the coarse aggregate with a size of 2.36mm to 4.75mm was replaced with 3mm PET plastic particles (Hassani, Ganjidoust, and Maghanaki 2005). Rahman and Wahab conducted a study in which up to 25 percent by volume of the fine aggregate with sieve size from 1.18 mm to 2.36 mm was replaced with PET particles of the same size (Rahman and Wahab 2013).

### 2.3 Performance PET Modified Asphalt

Fatigue cracking in asphalt occurs when vertical compressive loads create horizontal compressive stresses on the top half of asphalt layers and horizontal tensile stresses on the lower half of the asphalt layers. Cracks form in the lower layers and propagate to the surface after increasing numbers of loading cycles. Fatigue cracking most often occurs at low or moderate temperatures because the stiffness of asphalt increases as temperature decreases (Modarres and Hamedi 2014). Fatigue life can be increased by adding different types of fibers to the mixture. However, the use of virgin materials significantly increases construction costs (Moghaddam, Karim, and Syammaun 2012). Therefore, it is desirable to use recycled products like PET as additives to decrease the overall construction costs.

Modarres and Hamedi evaluated the fatigue life of asphalt mixtures modified with PET plastic in the dry process. The study found that the substitution of PET for two to ten percent of the weight of the bitumen improved fatigue properties of mixtures at 5°C and 20°C (Modarres and Hamedi 2014). Moghaddam, Karim, and Syammaun also performed a study evaluating the fatigue properties of asphalt mixtures containing PET plastic added in the dry process. In the study, PET was added at zero to one percent of the weight of the aggregate in increments of 0.2 percent. The researchers observed that the high melting point of PET (in excess of 250°C) prevented the plastic from melting during the mixing process. Therefore, the PET assumed crystal properties and strengthened the mixtures. The study found that increasing levels of PET increased the fatigue life of the mixtures, and higher levels of PET improved the elastic properties of

the mixtures. Also, the cracking of PET mixtures was more likely to be plastic in nature, while unmodified mixtures experienced brittle fractures (Moghaddam, Karim, and Syammaun 2012).

Rutting in asphalt mixtures is defined as the sum of the small permanent deformations that occur in asphalt after repeated loading. It is undesirable mainly because it decreases the service life of the pavement and may adversely affect driving conditions and safety. Moghaddam, Soltani, and Karim conducted a study to evaluate rutting properties of asphalt mixtures modified in the dry process with PET particles passing a 2.36mm sieve. The PET was added from zero to one percent of the aggregate weight in increments of 0.1 percent. The study evaluated rutting performance under both static and dynamic loads. The researchers found that increasing amounts of PET decreased the mixture stiffness. Under static loading conditions, mixtures with higher PET content showed higher permanent deformation than the control. However, under dynamic loading conditions, mixtures with higher PET content showed lower permanent deformation than the control. This indicated that, although the modified mixtures did not perform as well under static applied loads, dynamic loads allowed a recovery window for the mixtures to return to the original conditions (Moghaddam, Soltani, and Karim 2014).

In a related study, Moghaddam, Karim, and Soltani found that the addition of PET up to 0.6 percent increased Marshall Stability values. Increasing amounts of PET also increased Marshall Flow values. The study also found that PET decreased the optimum asphalt content (OAC) of all mixtures. Low amounts of PET increased the stiffness of the mixture initially. However, at PET contents of greater than 0.2 percent,

the stiffness of the mixtures decreased. Fatigue life of all modified mixtures was much greater than the unmodified mixture (Moghaddam, Karim, and Soltani 2013).

Ahmadinia et al. performed a study to evaluate the performance of PET modified asphalt mixtures containing between zero and ten percent PET (in two percent increments) by weight of the bitumen added in the dry process. The researchers found that adding PET to the mixtures increased the resilient modulus, resulting in a stiffer mixture. The modified mixtures also experienced less permanent deformation (rutting) than unmodified mixtures. As PET percentages in the mixtures increased, the tensile strength of the mixtures decreased, indicating that PET did not improve the moisture susceptibility of the asphalt mixtures. However, all modified PET mixtures still met the minimum requirements for the test (Ahmadinia et al. 2012). In a related study, Ahmadinia et al. found that the addition of PET up to six percent increased the Marshall Stability and decreased the Marshall Flow values of the asphalt mixtures, resulting in a stiffer mixture. However, the study also found that increasing PET percentages corresponded to increasing air voids (Ahmadinia et al. 2011).

Rahman and Wahab evaluated the stiffness and rutting performance of asphalt with PET added via aggregate replacement for zero to 25 percent by volume of the fine aggregate. The study found that the replacement of fine aggregate with PET resulted in a decreasing resilient modulus, meaning that the PET did not enhance the stiffness of the mixture. However the modified mixtures, specifically at 20 percent PET content, exhibited better rutting resistance and recovery than the unmodified control mixture. The researchers concluded that PET could successfully be used to improve the rutting resistance of asphalt mixtures (Rahman and Wahab 2013).

Hassani, Ganjidoust, and Maghanaki evaluated properties of asphalt with PET added via aggregate replacement for zero to 60 percent of the coarse aggregate by volume. The study found that the addition of PET decreased the Marshall Stability values and increased the Marshall Flow values. However, the mixture with 20 percent PET exhibited a higher Marshall Quotient than the unmodified mixture. Additionally, the substitution of PET for coarse aggregate significantly decreased the density of the mixtures. Therefore, the researchers concluded that the 20 percent PET mixture would be effective for field applications because it would save a significant amount of virgin materials (aggregate) without adversely affecting performance. The researchers also concluded that low density of the mixture would make it suitable for bridge overlay applications (Hassani, Ganjidoust, and Maghanaki 2005).

## CHAPTER 3: METHOD

### 3.1 Materials

#### 3.1.1 Asphalt Binder

The bitumen utilized in the study was an unmodified PG 67-22 binder obtained from Axion (Savannah, GA) with a specific gravity of 1.0425. Table 3.1 shows Georgia's PG specifications for unmodified PG 67-22 binders.

**Table 3.1. Specifications for PG 67-22 asphalt binders (Asphalt Institute 2014, 2)**

Property		Test Method (AASHTO)	Requirements for PG 67-22
<b>Original</b>			
Flash Point (°C)		T48	230 min
Rotational Viscosity, Pa*s	135°C	T316	3.0 max
Dynamic Shear, kPa ( $G^*/\sin\delta$ , 10rad/sec)	At grade temperature	T315	1.0 min
<b>RTFO Residue</b>			
Mass Change, %		T240	0.5 max
Dynamic Shear, kPa ( $G^*/\sin\delta$ , 10rad/sec)	At grade temperature	T315	2.20 min

#### 3.1.2 PET

Recycled PET plastic in a chipped form with a specific gravity of 1.380 was obtained from AYU Global and was utilized in both the binder and mixture tests. The gradation of the PET is presented in Table 3.2. The PET particles used in the study are also shown in Figure 3.1.



**Table 3.2. Gradation of PET particles**

Sieve	10	30	40	50
Percentage Passing	91.9	17.1	7.2	3.1

**Figure 3.1. PET plastic particles**

### *3.1.3 Aggregate*

Crushed granite aggregate was used for all asphalt mixtures prepared in the study. The aggregate was obtained in coarse, middle, and fine sizes from a local Reeves asphalt plant. It was then blended to obtain a 12.5mm Superpave mixture with a gradation that was within the limits set by the Georgia DOT. The bulk specific gravity of the aggregate when mixed within the gradation limits was 2.633. Lime was added as

one percent of the total aggregate in all mixtures for anti-stripping purposes. Figure 3.2 shows the gradation of the aggregate.



**Figure 3.2. Superpave 12.5mm aggregate gradation**

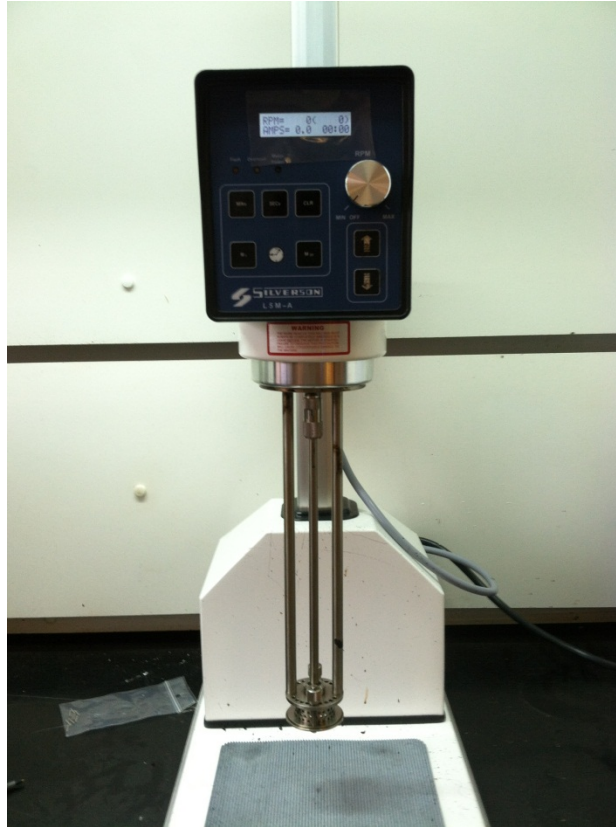
### 3.2 Procedure

The procedure followed in the study was comprised of two distinct units. The first section included binder tests conducted on bitumen samples without aggregate. The second section included mixture tests conducted on asphalt mixtures containing bitumen, recycled PET plastic, and aggregate.

#### 3.2.1 Binder Preparation and Testing Sequence

Binder tests were conducted on each of 12 different modified binder blends mixed in the wet process. An unmodified PG 67-22 binder was utilized for all mixtures. PET plastic was added at 5, 10, and 15 percent of the total weight of the binder. Mixtures were produced with each PET percentage at mixing speeds of 3000 and 5000 rpm using a Silverson high shear mixer and high shear mixing screen shown below in

Figure 3.3. The modified binders were mixed for one and two hours at each mixing speed, resulting in 12 total blends. Table 3.3 summarizes the modified binder blends produced.



**Figure 3.3. Silverson L5M-A high shear mixer**

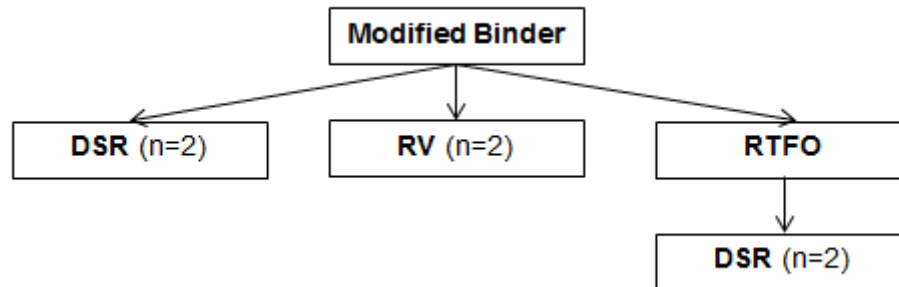
**Table 3.3. Modified binder blends**

	<b>% Plastic</b>	<b>Mixing Speed (RPM)</b>	<b>Mixing Time (h)</b>
<b>PG 67-22 Binder</b>	5	3000	1
			2
		5000	1
			2
	10	3000	1
			2
		5000	1
			2
	15	3000	1
			2
		5000	1
			2

The mixing procedure for all modified binder blends produced in the binder testing phase is as follows. First, the PG 67-22 binder was heated in an oven to  $150\pm 5^{\circ}\text{C}$ . Approximately 400 grams were poured into an empty can, and the PET plastic was stirred in by hand. The can was then placed under the mixing head, and the mixing head was lowered to approximately two thirds of the total depth of the asphalt in the can. No outside heat sources were applied during mixing. The friction produced by the high shear mixing head was sufficient to maintain a mixing temperature between  $175^{\circ}\text{C}$  and  $225^{\circ}\text{C}$ , depending on the mixing speed and plastic percentage.

The binder testing procedure consisted of two tests that produced quantifiable data and an aging process. The two binder tests utilized were the Rotational Viscometer (RV) and the Dynamic Shear Rheometer (DSR). The aging process utilized in the study was the Rolling Thin Film Oven (RTFO). For each modified binder, two samples were prepared for initial DSR testing, and two samples were prepared for RV testing. The

remaining binder was then aged in the RTFO, and two additional DSR samples were prepared. Figure 3.4 summarizes the binder testing sequence utilized in the study.



**Figure 3.4. Binder testing sequence**

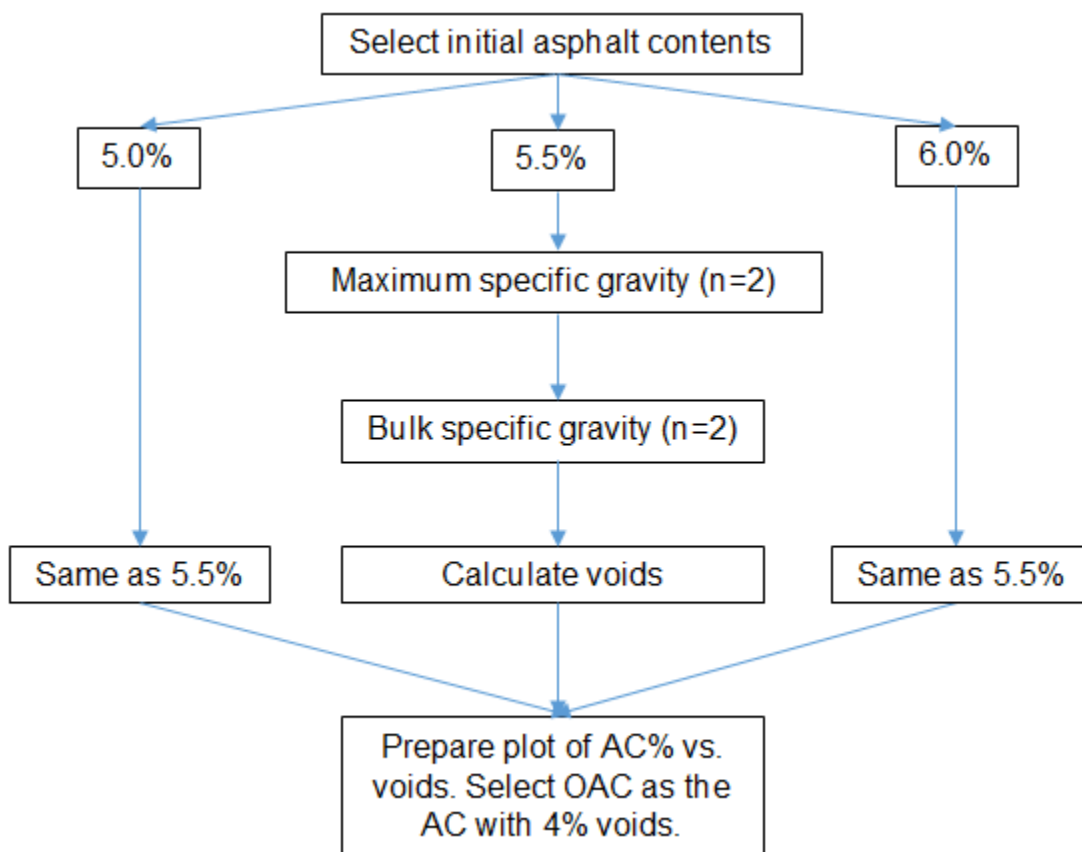
### 3.2.2 Mixture Design and Testing Sequence

The same mixture design procedure was followed for the unmodified control mixture as well as the wet and dry process mixtures. The goal of the mixture design process was to determine the optimum asphalt content (OAC) for each mixture (unmodified, wet, and dry). Three different asphalt contents at 0.5 percent intervals were initially selected for testing (ex. 5.0%, 5.5%, 6.0%). Two maximum specific gravity samples were prepared at each of the asphalt contents, and the maximum specific gravity was measured following AASHTO T 209. The reported maximum specific gravity values for each of the asphalt contents were the average of the two measurements.

After the maximum specific gravity at each of the asphalt contents was determined, two samples were prepared at each of the initially selected asphalt contents for bulk specific gravity testing following the procedure for AASHTO T 166. Bulk specific gravity samples were compacted in the SGC at 65 gyrations and a height

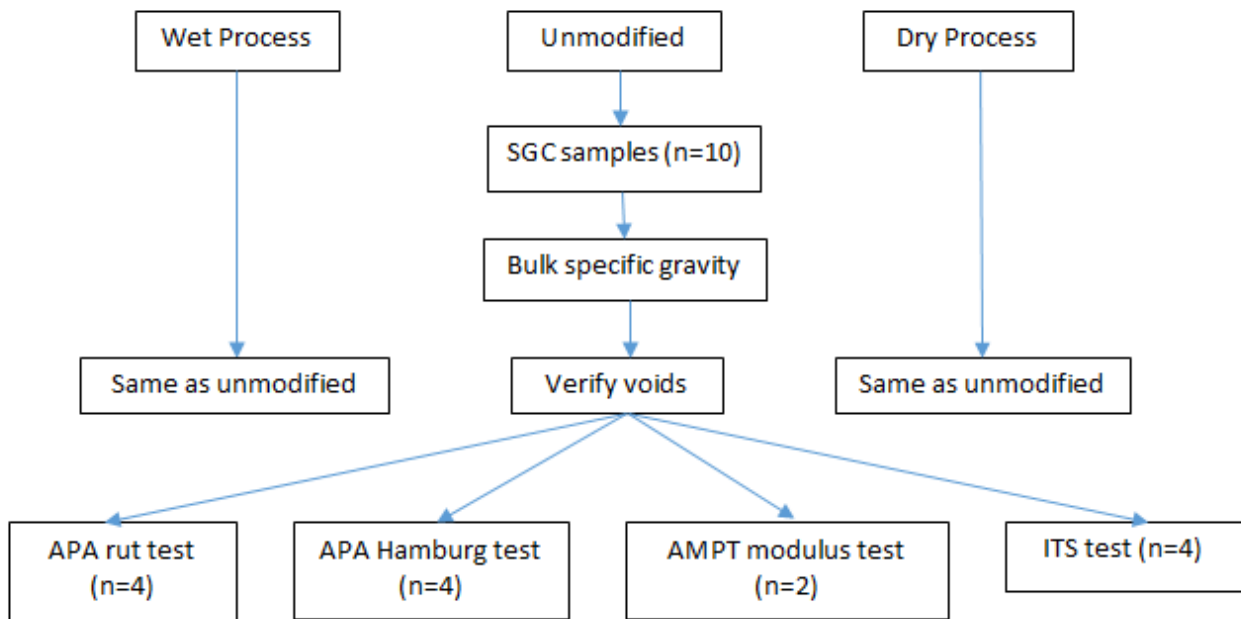
of 100mm. The reported bulk specific gravity value for each of the asphalt contents was the average of the two values.

Once the maximum specific gravity and bulk specific gravity for each of the asphalt contents were obtained, the air voids in each mixture were calculated. A plot of asphalt content versus air voids with a linear regression line was generated for the unmodified, wet, and dry process mixtures. OAC was determined as the asphalt content at which four percent voids were obtained. Figure 3.5 shows a sample mixture design procedure.



**Figure 3.5. Sample mixture design procedure**

After the OAC for the unmodified, wet, and dry process mixtures was determined, a series of SGC samples were prepared at the OAC for the asphalt mixture tests. For each binder type, ten SGC samples were compacted at 65 gyrations. The bulk specific gravity of each sample was measured so that the air voids could be calculated and verified. Two samples were utilized for APA rut testing, two samples were utilized for APA Hamburg testing, cores were obtained from two samples for AMPT modulus testing, and four samples were used for ITS testing. The samples used for APA rut testing and APA Hamburg testing were cut in half to yield a total of four samples for each test. Figure 3.6 shows the asphalt mixture testing procedure.



**Figure 3.6. Mixture testing procedure**

### 3.2.3 Mixture Preparation

Preparation of all asphalt mixtures began with measuring the aggregate needed for each sample. Coarse, middle, and fine aggregate were each weighed and combined

at the appropriate ratios. Water was added at five percent of the total aggregate weight, and the mixture was stirred until the aggregate was evenly coated in water. The addition of water to the mix activated the lime and ensured that it was able to adhere to and evenly coat the aggregate. Lime was then added, and the mixture was stirred until the aggregate was evenly coated in lime. The samples were placed in an oven overnight at 95°C to allow the water to evaporate.

Three different asphalt mixtures were utilized in the study. A mixture using only unmodified PG 67-22 binder was designated as a control for baseline measurements. Another mixture was prepared using the dry process, in which the aggregate and unmodified PG 67-22 binder were combined prior to the addition of the PET plastic in the mixing process. In the dry process, the PET plastic was substituted for ten percent of the total binder weight calculated for the mixture. The final mixture was prepared using the wet process. In the wet process, the PET plastic was first combined with the bitumen and then added to the aggregate during the mixing process.

Preparation of the binder for the wet process mixtures followed the same procedure outlined for the modified binder mixtures in section 3.2.1. First, approximately 700 to 800 grams of PG 67-22 asphalt were heated to 150±5°C. PET plastic was then added at ten percent of the weight of the binder and was stirred into the asphalt by hand. The can was then placed under the mixing head, and the mixing head was lowered to approximately two thirds of the total depth of the asphalt in the can. No outside heat sources were applied during mixing. The friction produced by the high shear mixing head was sufficient to maintain a mixing temperature between 180°C and 200°C.



Before mixing the aggregate and bitumen, both constituents were heated for at least two hours to the appropriate temperatures. The aggregate and mixing bucket were heated to the selected mixing temperature of 160°C. The binder and compaction mold were heated to the selected compaction temperature of 145°C. After the mixture components reached the appropriate temperatures, the aggregate was poured into the mixing bucket, and the designated amount of bitumen was added. The aggregate and bitumen were then mixed for approximately five minutes, until the aggregate was thoroughly coated in bitumen. For dry process mixtures, the PET plastic was added after the aggregate and bitumen had been mixing for approximately two minutes. The asphalt samples were transferred to a pan and spread to a thickness of one to two inches. The mixtures were placed in an oven set at the compaction temperature (145°C) and aged for two hours. After the first hour, mixtures were stirred to maintain uniform aging. At the end of the second hour, mixtures were poured into the compaction mold and placed in the Superpave Gyrotory Compactor (SGC). The SGC was set at the appropriate height and gyrations, and the samples were compacted. The compacted samples were allowed to cool and were then extracted from the mold.

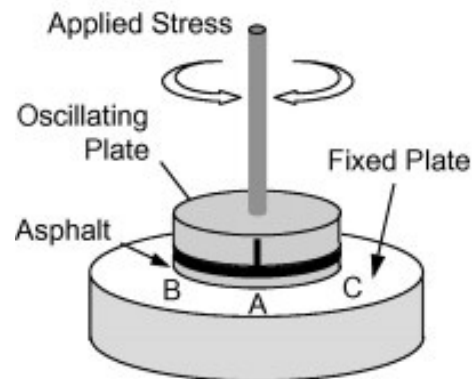
### **3.3 Test Methods**

The test methods utilized in the study consisted of two distinct portions. The first portion included binder tests conducted on bitumen samples without aggregate. The second portion included mixture tests conducted on asphalt mixtures containing bitumen, recycled PET plastic, and aggregate.

#### *3.3.1 Binder Test Methods*

##### *DSR Testing*

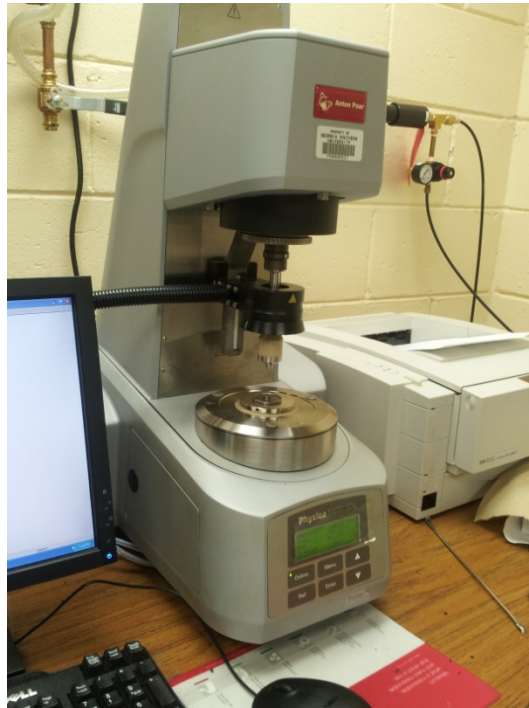
Since asphalt is neither perfectly viscous nor perfectly elastic, the DSR is utilized to determine the viscous and elastic behavior of asphalt binders. It consists of an oscillating spindle and fixed plate with a gap between the two of one millimeter. The spindle and plate sandwich a round asphalt sample between them. A sample of 25mm in diameter was utilized in this study. As the spindle rotates, shear stress is applied to the asphalt by the spindle. The responsive shear strain of the asphalt is then measured by the DSR software (USDOT 2000). Figure 3.7 shows a schematic of the spindle and plate.



**Figure 3.7. Schematic of DSR spindle and plate (USDOT 2000)**

AASHTO T 315 was followed for all DSR testing in this study. DSR testing began at 67°C for PG 67-22 asphalt. The DSR then determined the  $G^*/\sin\delta$  value of the asphalt sample at that temperature. The minimum acceptable value for unaged binders according to AASHTO M 320 is 1.000 kPa, and the minimum value for RTFO aged binders is 2.200 kPa. If the  $G^*/\sin\delta$  value for the asphalt sample at the specified temperature was greater than the minimum acceptable value, the DSR increased the test temperature by one PG grade (6°C) and repeated the test loop. After successive loops, the  $G^*/\sin\delta$  reached a value below the minimum acceptable value. The DSR

software then interpolated the failure temperature at which the  $G^*/\sin\delta$  was equal to the minimum acceptable value. This failure temperature can then be used to determine a new PG grade (Putman, Thompson, and Amirkhanian 2005). Figure 3.8 shows the Anton Paar Physica MCR 301 DSR employed in the study.



**Figure 3.8. Anton Paar Physica MCR 301 DSR**

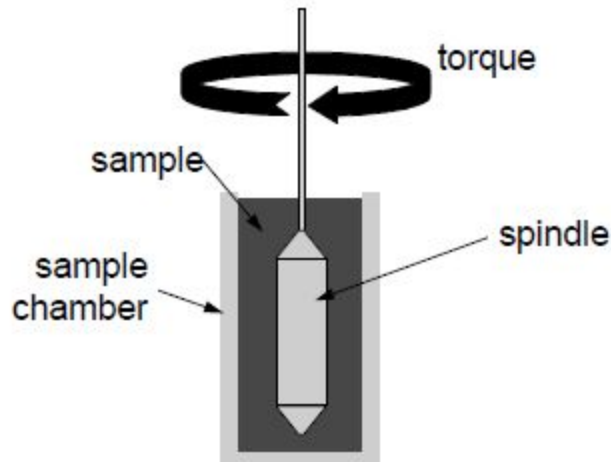
### *RV Testing*

The RV is used to measure the rotational viscosity of asphalt samples at high temperatures. The rotational viscosity of asphalt can provide an indication of the high temperature workability of the asphalt. The rotational viscosity of liquid asphalt is determined by measuring the torque required to maintain a constant rotation speed of a spindle that is submerged in the liquid asphalt sample at constant temperature (USDOT 2000). Figure 3.9 shows the Brookfield rotational viscometer utilized in the study.



**Figure 3.9. Brookfield rotational viscometer**

The procedure for RV testing in this study followed AASHTO T 316. To prepare a sample for RV testing, 30 grams of asphalt were heated to no more than 150°C. The asphalt was then poured into a test tube and allowed to cool to room temperature. After cooling, the tube was placed in a heating chamber set to 135°C and allowed to reach the testing temperature. The rotational viscometer spindle was then attached to the motor and submerged in the sample. The spindle rotated at a speed of 50rpm. After approximately 15 minutes, the viscosity reading on the display of the viscometer stabilized. At this point, three viscosity readings were recorded at one minute intervals (USDOT 2000). The final viscosity reported was an average of these three values. Figure 3.10 shows the schematic of the RV spindle submerged in a sample.



**Figure 3.10. Schematic of RV spindle and sample (USDOT 2000, 6)**

#### *RTFO Aging*

The RTFO aging process simulates the aging of asphalt that occurs during production and construction. RTFO testing in this study followed AASHTO T 240. The apparatus consists of a convection oven with a vertical carriage that accommodates eight glass bottles. The oven was preheated to a temperature of  $163 \pm 0.5^\circ\text{C}$ . Each bottle was then filled with  $35 \pm 0.5\text{g}$  of liquid asphalt binder and loaded into the carriage. The carriage was engaged and rotated allowing pressurized air to be blown into each bottle. Samples remained in the RTFO for 85 minutes and were then unloaded. The residue was poured into a common can and mixed for homogeneity. The bottles were weighed before and after aging in the RTFO in order to determine mass loss as a percentage. High mass loss (or percent loss) indicates the presence of excessive volatile components in the asphalt binder that are vaporized while the sample is inside the RTFO. These components may cause the asphalt binder to age excessively and prematurely and are therefore undesirable (USDOT 2000). Percent loss was calculated

using Equation 3.1. Figure 3.11 shows the RTFO and one of the bottles utilized in the study.

$$\text{Percent loss} = \frac{(A-B)-(C-B)}{(A-C)} * 100 \quad 3.1$$

where:

A = weight of bottle and asphalt before aging

B = weight of empty bottle

C = weight of bottle and asphalt after aging



**Figure 3.11. RTFO and bottle**

### 3.3.2 Mixture Test Methods

#### *Maximum Specific Gravity*

Maximum specific gravity of an asphalt mixture is defined as the specific gravity of loose asphalt samples with no air voids. It is essential for volumetric calculations and the calculation of air voids in compacted samples. The procedure for obtaining

maximum specific gravity outlined in AASHTO T 209 was followed in this study. The test apparatus consists of a vacuum pump, a vacuum bowl, and an orbital shaker. The asphalt sample is weighed and placed in the vacuum bowl, and enough water is added to cover the sample to a depth of one to two inches. The vacuum bowl is placed on the shaker, covered, and connected to the vacuum pump. The pump is turned on and set at a residual pressure of  $27.5 \pm 2.5$  mm Hg. The orbital shaker is then engaged and allowed to run for 15 minutes. After 7.5 minutes, the direction of the shaker is reversed. After 15 minutes, a bleeder valve allows the pressure in the vacuum bowl to be released. The bowl is then completely filled with water, a lid is placed on top to remove all remaining air, and the bowl containing the asphalt and water is weighed. Figure 3.12 shows the Humboldt H-1782 Orbital Shaker and Fischer LAV-3 High Vacuum Pump utilized in the study.



**Figure 3.12. Humboldt H-1782 orbital shaker and Fischer LAV-3 high vacuum pump**

In this study, a 4000 gram maximum specific gravity sample was prepared at each of the initially selected asphalt contents, following the procedure outlined in section 3.2.3. The 4000 gram sample was spread on a table and allowed to cool to room temperature. All particles were separated by hand until the fine aggregate portion contained no particles larger than 0.25 inch. The 4000 gram sample was then divided into two samples of approximately 2000 grams each for maximum specific gravity testing. Maximum specific gravity of the samples was calculated using Equation 3.2.



$$G_{mm} = \frac{A}{A+D-E} \quad 3.2$$

where:

A = mass of dry sample in air (g)

D = mass of vacuum bowl filled with water (g)

E = mass of vacuum bowl, sample, and water (g)

### *Bulk Specific Gravity*

Bulk specific gravity of an asphalt sample is defined as the specific gravity of compacted asphalt samples containing air voids. Bulk specific gravity of all SGC samples in this study was calculated so that the air voids of the samples could be determined. The procedure for bulk specific gravity testing outlined in AASHTO T 166 was followed in this study. First the dry samples were weighed to obtain an initial weight. They were then submerged in water on a basket suspended from an electronic balance. After four minutes, the submerged weight was recorded. The sample was then removed from the water, and the surface was dried with a towel. The final saturated surface dry (SSD) weight was recorded. Bulk specific gravity was calculated using Equation 3.3. Additionally, the percentage of water absorbed by volume was calculated. If this exceeds two percent, it indicates the voids in the mixture are too high for AASHTO T 166, and an alternative method must be used to determine bulk specific gravity. Water absorption was calculated using Equation 3.4.

$$G_{mm} = \frac{W_D}{W_{SSD} - W_{SUB}} \quad 3.3$$

$$Absorption (\%) = \frac{(W_{SSD} - W_D)}{(W_{SSD} - W_{SUB})} * 100 \quad 3.4$$

where:

$W_D$  = mass of dry sample (g)

$W_{SSD}$  = mass of sample in SSD condition (g)

$W_{SUB}$  = mass of sample submerged in water (g)

### *APA Rutting*

The Asphalt Pavement Analyzer (APA) rutting test is used to predict field rutting performance in asphalt mixes. The apparatus consists of two sets of pneumatic wheels mounted on a carriage that moves forward and backward inside a temperature-controlled chamber. The wheels apply constant downward pressure and track over two pressurized rubber hoses that rest on asphalt samples mounted securely in a plastic mold. Computer software records the rut depths at four positions on both sets of samples, and an average rut depth for each set of samples is recorded in real time on a plot in Microsoft Excel. At the end of testing, an average rut depth for each set of samples is reported in the software.

GDT 115 was followed for APA rut testing. Four samples were compacted to a void content of  $5.0 \pm 1.0\%$ . The 150mm diameter samples were cut to a height of  $75 \pm 1$ mm and placed in the plastic molds. The samples were allowed to condition at the testing temperature inside the chamber for six hours before the test began. The test temperature for all samples was  $64^\circ\text{C}$ , and the duration of the test was 8000 cycles. The wheels applied a downward pressure of 100lbf and moved over the samples at a speed of 60Hz. The hoses were pressurized to 100psi. Figure 3.13 shows the APA with

samples loaded for rut testing. Table 3.4 provides a summary of APA rut tests conducted and testing conditions.

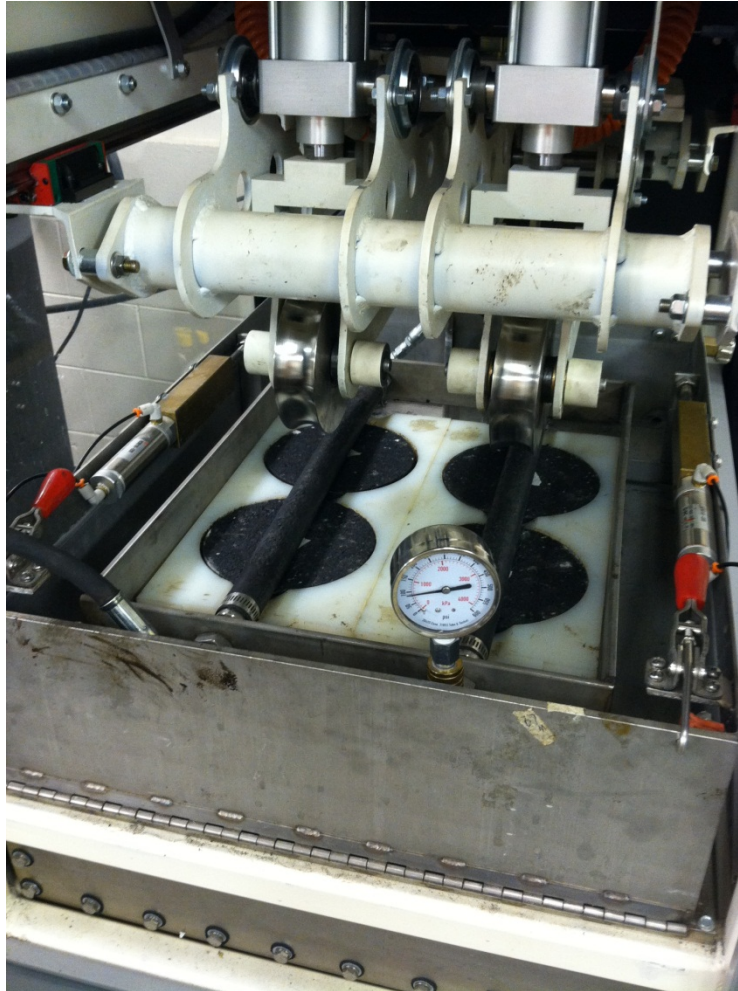


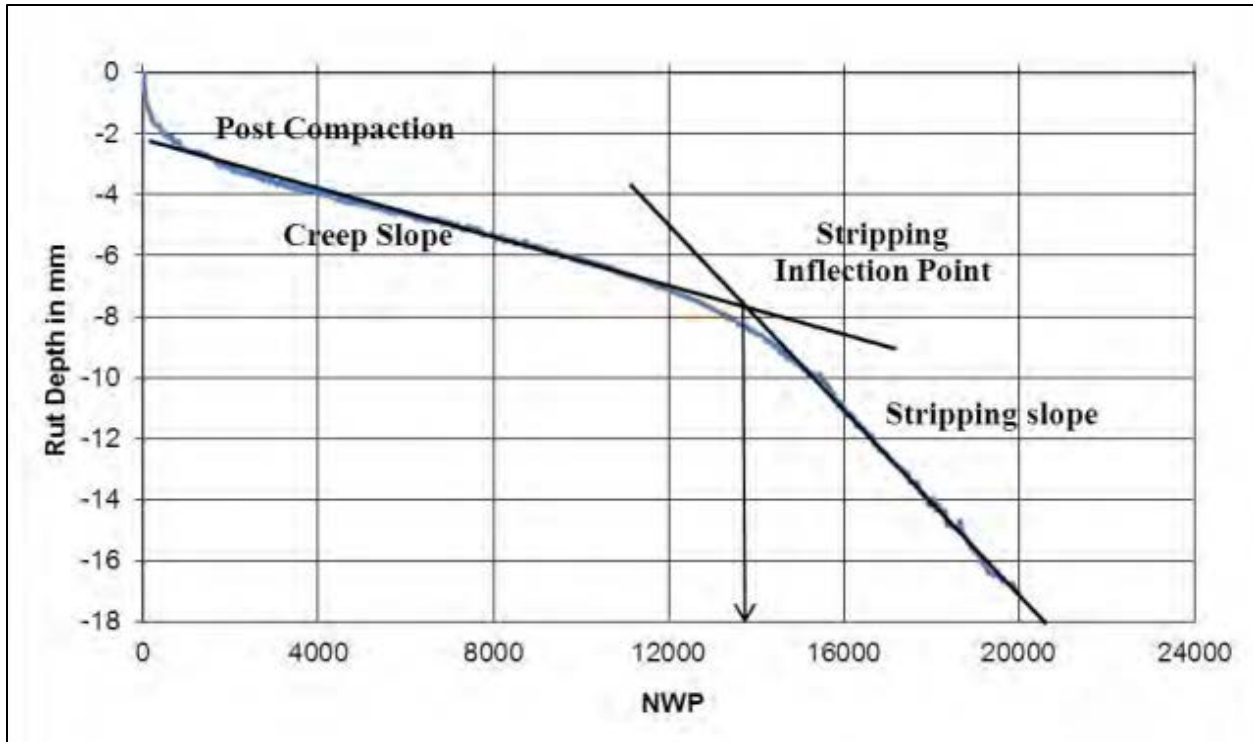
Figure 3.13. APA with samples for rut testing

Table 3.4. APA rut testing summary

Mixture	Samples	Temperature (°C)	Speed (Hz)	Duration (cycles)	Wheel Load (lbf)	Hose Pressure (psi)
Unmodified	4	64	60	8000	100	100
Wet Process	4					
Dry Process	4					

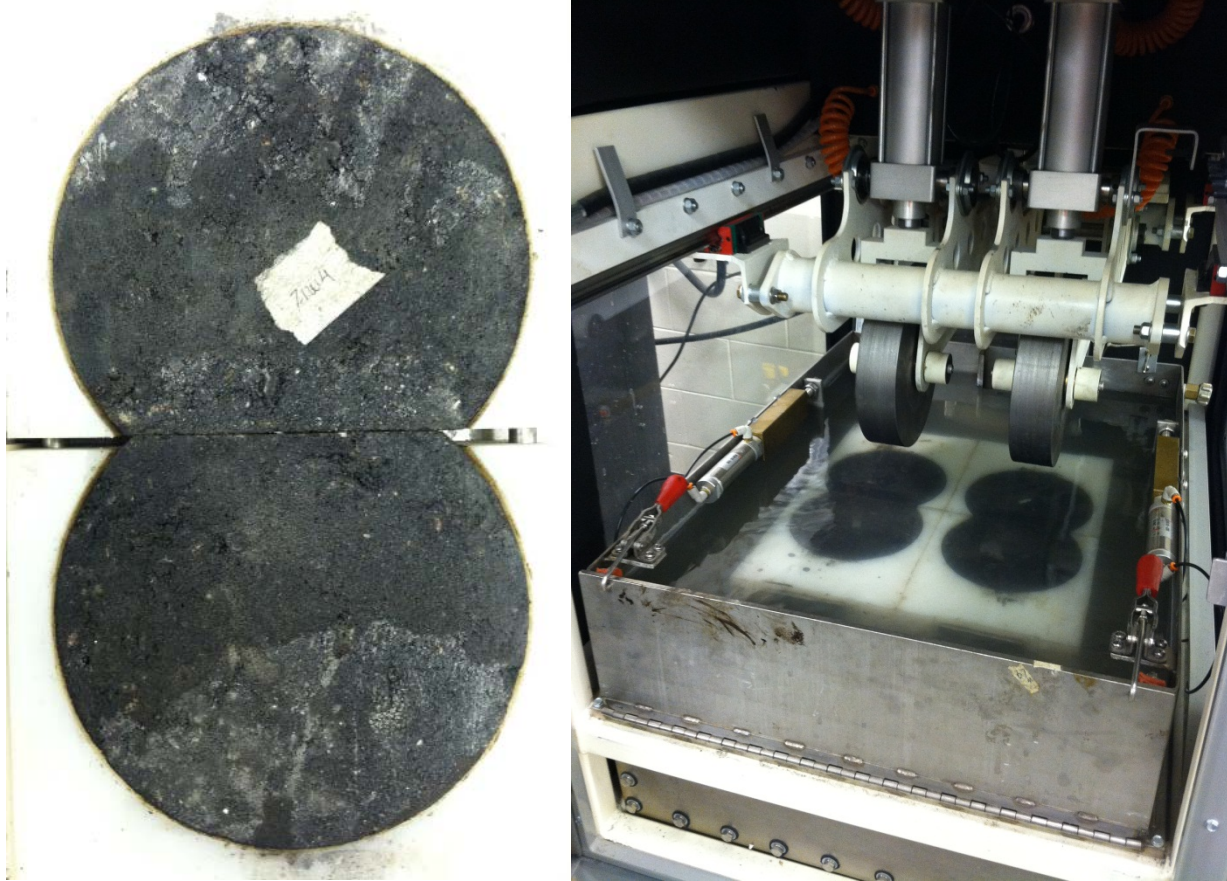
### *APA Hamburg*

The APA Hamburg test is used to evaluate both rutting and moisture damage characteristics of asphalt mixtures. It utilizes the same test apparatus as the APA rutting test with a few modifications. The wheels utilized for the APA Hamburg test are larger than the wheels utilized for the APA rutting test at 8 inches in diameter and 0.90 inches in width. Additionally, the wheels rest directly on the asphalt samples that are cut to fit together into one continuous piece and secured in plastic molds. Since the test evaluates moisture damage, it is conducted with the samples submerged in water. During the test, computer software records the rut depth at the center point of the two samples, and it is plotted in Microsoft Excel. The plots can be analyzed to find the post compaction consolidation, creep slope, stripping inflection point, and stripping slope. The post compaction consolidation occurs during the first 1000 cycles of the test. It occurs rapidly as the test wheel makes the sample denser due to the applied load. The creep slope is an indicator of rutting susceptibility and occurs during the linear portion of the plot prior to stripping. The stripping slope is an indicator of permanent deformation of the asphalt mixture due to moisture damage and occurs during the linear portion of the plot after stripping begins. The stripping inflection point is the number of cycles at which the stripping slope and creep slope intersect (Yildirim et al 2007). These parameters are illustrated below in Figure 3.14.



**Figure 3.14. Hamburg plot and parameters (Rahman and Mustaque 2014)**

In this study, four cylindrical samples were compacted to a void content of  $5.0 \pm 1.0\%$ . The samples were 150mm in diameter were cut to a height of  $60 \pm 1$ mm. The samples were then trimmed to fit together inside the mold with a gap of approximately 7.5mm between the two halves of the mold. All samples were submerged in water at  $50^{\circ}\text{C}$  for thirty minutes before the test began, and the duration of the test was 20,000 cycles or until the samples reached a maximum rut depth of 12.5mm. The wheels applied a downward pressure of 158lbf and moved at a speed of 25Hz. Figure 3.15 shows Hamburg samples in a mold and the APA with samples loaded for Hamburg testing. Table 3.5 provides a summary of APA Hamburg tests conducted and testing conditions.



**Figure 3.15. Hamburg samples in mold and APA with Hamburg samples**

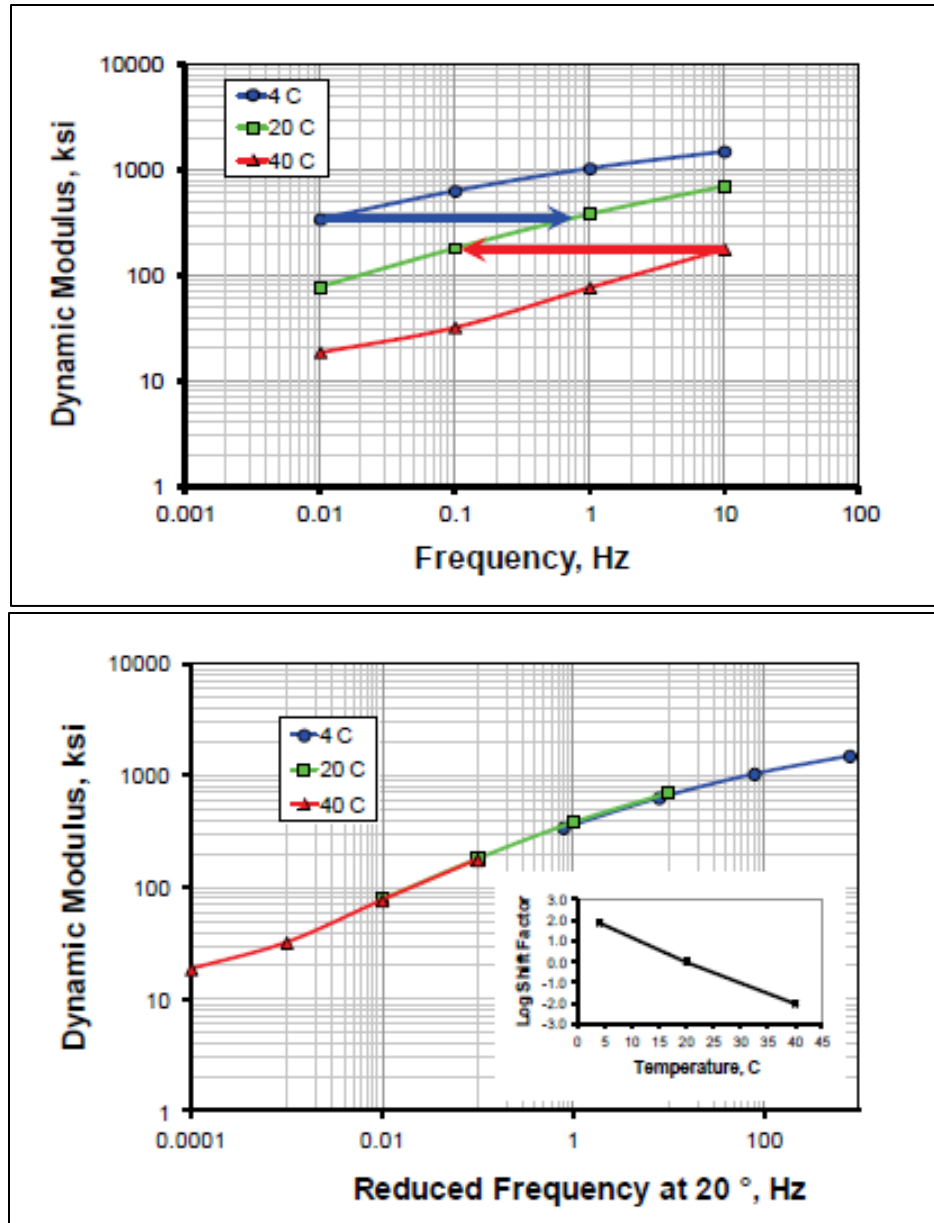
**Table 3.5. APA Hamburg testing summary**

Mixture	Samples	Temperature (°C)	Speed (Hz)	Duration (cycles)	Wheel Load (lbf)
Unmodified	4	50	25	20000	158
Wet Process	4				
Dry Process	4				

#### *AMPT Dynamic Modulus*

The Asphalt Mixture Performance Tester (AMPT) is utilized to find the dynamic modulus ( $E^*$ ) of asphalt mixtures. The dynamic modulus of asphalt is an important indicator of mixture stiffness at a variety of temperatures and loading frequencies. The

testing apparatus consists of a temperature-controlled chamber with a hydraulic piston that is regulated by computer software. An asphalt sample is loaded onto the piston inside the chamber, and three LVDT sensors are attached to pairs of glue-on measuring points positioned at 120 degrees around the sample. When the test begins, the computer software prompts the piston to apply a sinusoidal, stress-controlled load to the asphalt sample. The applied stress and resulting strain are recorded in the software, and the  $E^*$  at a specified temperature and loading frequency is calculated by dividing the peak stress by the peak strain. The software simultaneously obtains the corresponding phase angle at each  $E^*$  value. The phase angle is the time lag between the applied stress and the resulting strain. A smaller phase angle indicates a more elastic mixture (Shen, Xie, and Li 2015). After  $E^*$  values are obtained at a variety of test temperatures and loading frequencies, they can be input into computer software that uses time-temperature superposition to shift the data until they align into a smooth master curve. The high frequencies on the right side of the master curve represent cold temperatures and fast traffic speeds. The low frequencies on the left side of the master curve represent high temperatures and slow traffic speeds (USDOT 2013). Figure 3.16 shows a typical dynamic modulus master curve before and after time-temperature superposition has taken place.



**Figure 3.16. Construction of  $E^*$  master curve with reduced frequency (USDOT 2013)**

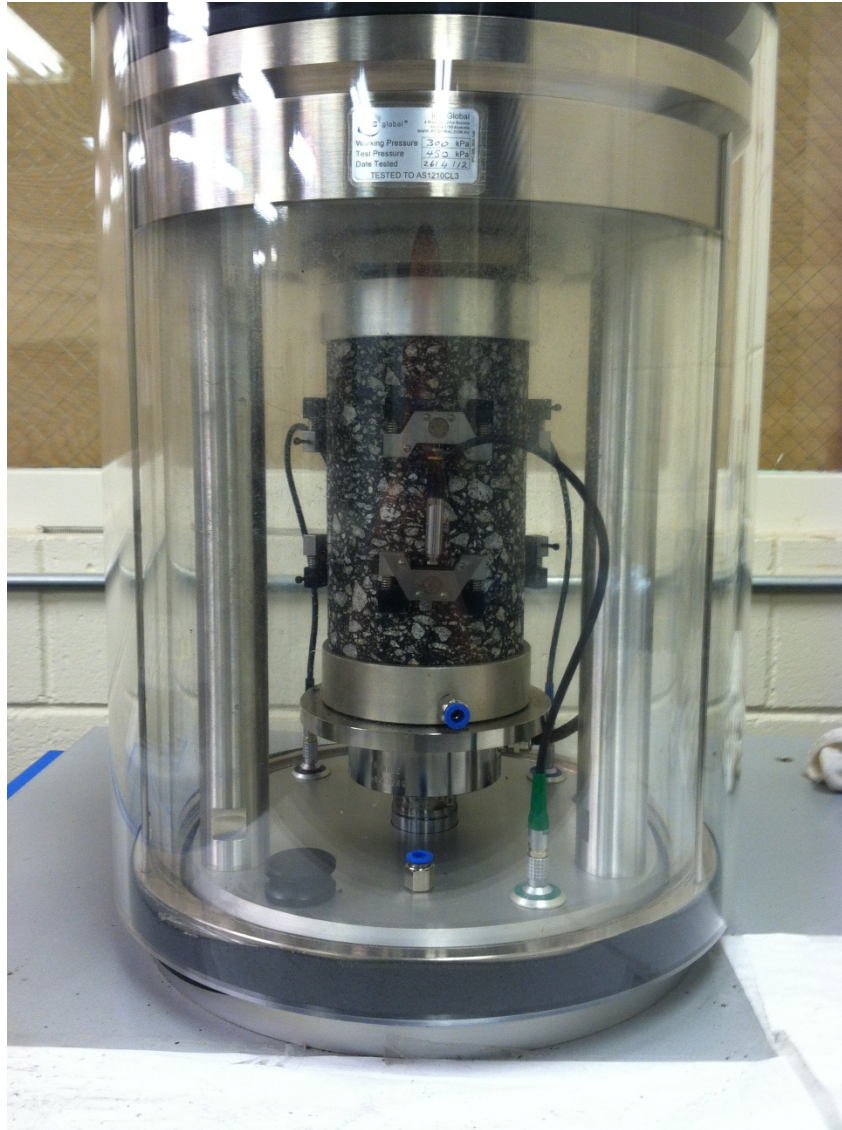
In this study, two duplicate samples for each mixture (wet, dry, and unmodified) were prepared. The samples were compacted to a void content of  $5.0 \pm 1.0\%$ , cut with a coring bit to a diameter of 100mm, and trimmed with a masonry saw to a height of  $150 \pm 2$ mm. Testing took place at 4°C, 20°C, and 40°C for the unmodified mixture. Testing



took place at 4°C, 20°C, and 45°C for the modified mixtures. At 4°C and 20°C, the loading frequencies were 0.1Hz, 1.0Hz, and 10Hz. At 40°C and 45°C, the loading frequencies were 0.01Hz, 0.1Hz, 1.0Hz, and 10Hz. Samples were conditioned at 4°C for at least 18 hours prior to testing, 20°C for at least 3 hours prior to testing, and 40/45°C for no more than an hour prior to testing. Table 3.6 summarizes the dynamic modulus testing conditions. Figure 3.17 shows the AMPT with a sample in the chamber.

**Table 3.6. Summary of E\* testing conditions**

<b>Sample</b>	<b>Testing Temperature (°C)</b>	<b>Loading Frequency (Hz)</b>
<b>Unmodified (n=2)</b>	4, 20	0.1, 1, 10
	40	0.01, 0.1, 1, 10
<b>Wet Process (n=2)</b>	4, 20	0.1, 1, 10
	45	0.01, 0.1, 1, 10
<b>Dry Process (n=2)</b>	4, 20	0.1, 1, 10
	45	0.01, 0.1, 1, 10



**Figure 3.17. AMPT with core sample**

### *Indirect Tensile Strength*

The ITS test is utilized to evaluate the stripping resistance and moisture sensitivity of asphalt mixtures. The test apparatus consists of a modified Lottman breaking head mounted on a Marshall loading apparatus that applies an increasing load at a rate of 50mm per minute. Figure 3.18 shows the test apparatus. This compressive load is applied along the vertical diametric plane of a cylindrical sample. This results in a

tensile stress that acts in a direction perpendicular to the applied load. The load is applied until failure of the sample, which usually occurs along the plane of the applied load (Ebrahim and Behiry 2013). The test consists of two sets of samples, tested with and without water conditioning. The ITS values of the two sets of samples are compared using the tensile strength ratio (TSR) to evaluate the moisture susceptibility of the asphalt mixture.



**Figure 3.18. Geotest compression machine and modified Lottman breaking head**

ITS testing in this study followed the procedure outlined in ALDOT 361. First, four SGC samples were prepared for each mixture to a height of 100mm and an air void content of  $6.0 \pm 1.0$  percent. The bulk specific gravity of each sample was measured so that the air voids of the sample could be calculated. Samples for each mixture were

divided into two groups with similar average air void contents. One half of the samples was tested dry, meaning that the samples were held at room temperature prior to testing and submerged in a water bath at 25°C for one hour prior to testing. The other half of the samples were tested wet. Each wet sample was submerged in water and subjected to a partial vacuum of 300mmHg for two minutes. The vacuum was then removed, and the sample remained under water for five more minutes. After removing the sample from the vacuum container, the SSD weight was obtained for saturation calculations. Equation 3.5 was used to calculate saturation of the samples. Saturation values of 55 to 80 percent were desired, meaning that 55 to 80 percent of the air voids in the sample were filled with water. If the calculated value was below 55 percent, the vacuum process was repeated until the saturation was within the desired range. If the calculated value was above 80 percent, the sample was regarded as damaged and discarded. After the desired level of saturation was obtained, the samples were placed in a water bath at 60°C for 24 hours and then transferred to a 25°C water bath for one hour prior to testing. Both subsets of samples were subjected to an increasing load applied at a rate of 50mm per minute until failure. The maximum load applied was recorded and used to calculate the ITS (Equation 3.6). ITS values of the wet and dry samples were compared using the TSR (Equation 3.7)

$$\text{Saturation (\%)} = \left[ \frac{W_{ssd2} - W_D}{W_{ssd2} - W_{sub}} * 100 \right] * 100 \quad 3.5$$

where:

$W_{ssd2}$  = SSD weight after applied vacuum

$W_D$  = air dry weight

$W_{sub}$  = weight of sample submerged in water

Voids = air voids of sample

$$ITS = \frac{2 * P}{\pi * h * d} \quad 3.6$$

where:

ITS = indirect tensile strength (kPa)

P = maximum load (kN)

h = height of sample (m)

d = diameter of sample (m)

$$TSR = \frac{S_2}{S_1} \quad 3.7$$

where:

$S_1$  = average ITS of dry (unconditioned) samples

$S_2$  = average ITS of wet (conditioned) samples

## CHAPTER 4: PROPERTIES OF MODIFIED BINDERS WITH PET

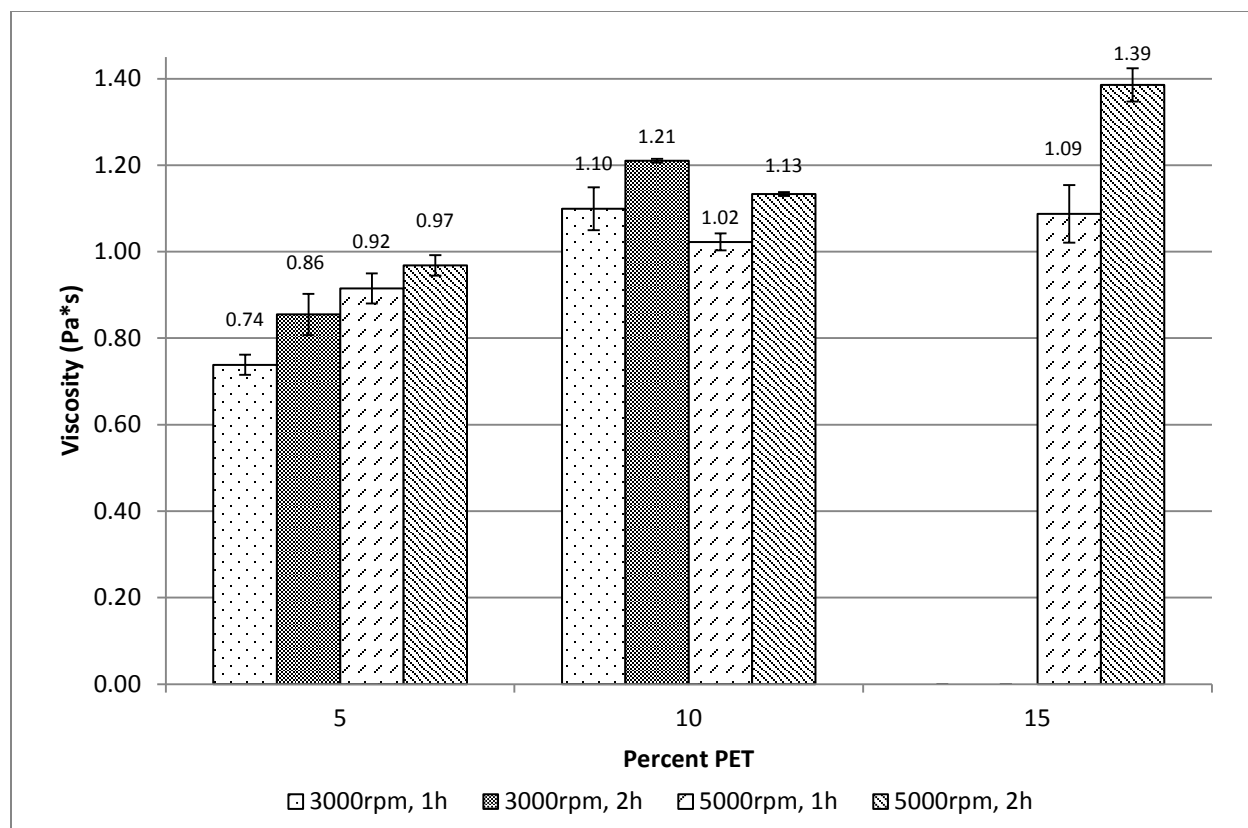
### 4.1 Viscosity

RV testing was conducted on all unaged binder blends containing 5, 10, and 15 percent PET. Two samples were measured for each set of mixing conditions. Viscosity readings were recorded at 0, 1, and 2 minutes and averaged for a final reported value. The results are presented in Table 4.1.

**Table 4.1. Viscosity data**

%Plastic	RPM	Mixing Time	Sample	Viscosity Measurements (Pa*s)			AVG (Pa*s)
				0:00	1:00	2:00	
5	3000	1h	1	0.800	0.795	0.790	0.74
			2	0.690	0.680	0.675	
		2h	1	0.745	0.740	0.730	0.86
			2	0.980	0.970	0.965	
	5000	1h	1	0.840	0.830	0.820	0.92
			2	1.010	1.000	0.990	
		2h	1	0.920	0.910	0.900	0.97
			2	1.035	1.025	1.020	
10	3000	1h	1	0.980	0.980	0.975	1.10
			2	1.220	1.215	1.225	
		2h	1	1.190	1.215	1.225	1.21
			2	1.210	1.205	1.215	
	5000	1h	1	1.080	1.070	1.060	1.02
			2	0.980	0.975	0.970	
		2h	1	1.155	1.140	1.130	1.13
			2	1.130	1.125	1.120	
15	3000	1h	1	0.000	0.000	0.000	0.00
			2	0.000	0.000	0.000	
		2h	1	0.000	0.000	0.000	0.00
			2	0.000	0.000	0.000	
	5000	1h	1	0.925	0.925	0.925	1.09
			2	1.260	1.250	1.240	
		2h	1	1.490	1.480	1.470	1.39
			2	1.295	1.290	1.290	

The effects of PET percentage, mixing time, and mixing speed on viscosity can be observed in Figure 4.1. A statistical T-test of variance at the 5% significance level was conducted to evaluate the effects of the percentage of PET, mixing speed, and mixing time on viscosity readings. These results are presented in Appendix A. The 15 percent PET blend mixed at 3000rpm for one and two hours contained excessive amounts of PET particles that made the RV readings unstable. Therefore, measurements were not recorded for these two blends. For all blends, the viscosity increased as mixing time increased from 1 to 2 hours. Most of these increases were statistically significant. Increasing the PET percentage also produced statistically significant increases in the viscosity of all mixtures. For the 5 percent PET content, viscosity also increased as the mixing speed increased from 3000rpm to 5000rpm. For the 10 percent PET content, however, the viscosity decreased slightly as the mixing speed increased from 3000rpm to 5000rpm. The highest viscosity obtained was 1.39Pa\*s for 15 percent PET mixed at 5000rpm for 2 hours. However, this value is still well below the accepted maximum value of 3Pa\*s.



**Figure 4.1. Unaged PET modified binder RV results**

## 4.2 Rheological Properties

DSR tests were conducted on unaged binders containing 5, 10, and 15 percent PET by weight of the binder. The DSR software used in testing yielded the maximum temperature at which the binders met the  $G^*/\sin\delta$  values specified in AASHTO M 320. This temperature is referred to as the pass/fail temperature of the binder. These results are shown in Table 4.2.

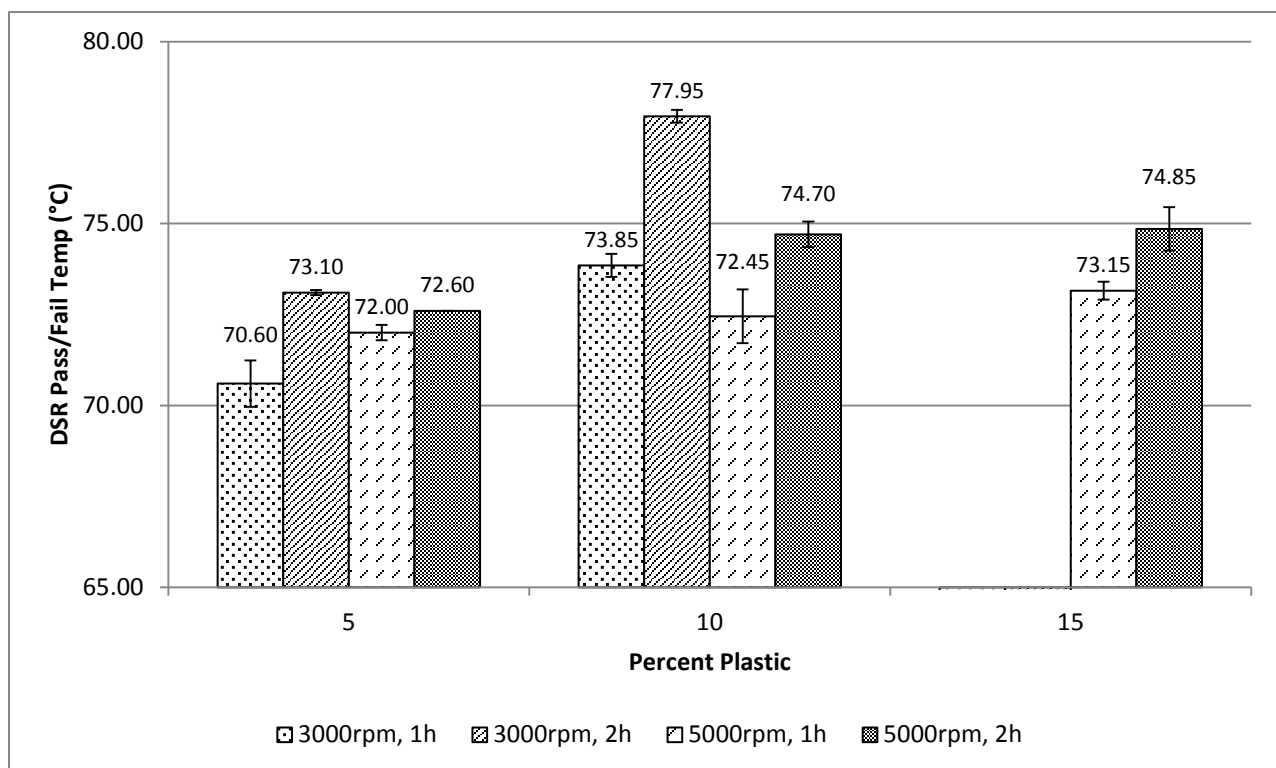


**Table 4.2. Unaged DSR pass/fail temperatures**

<b>% Plastic</b>	<b>RPM</b>	<b>Mixing time</b>	<b>Pass/fail (°C)</b>	<b>Avg Pass/Fail (°C)</b>
<b>5</b>	3000	1h	71.5	70.60
			69.7	
		2h	73.2	73.10
			73	
	5000	1h	71.7	72.00
			72.3	
2h		72.6	72.60	
		72.6		
<b>10</b>	3000	1h	73.4	73.85
			74.3	
		2h	78.2	77.95
			77.7	
	5000	1h	71.4	72.45
			73.5	
		2h	74.2	74.70
			75.2	
<b>15</b>	3000	1h	n/a	0.00
			n/a	
		2h	n/a	0.00
			n/a	
	5000	1h	72.8	73.15
			73.5	
		2h	74	74.85
			75.7	

Figure 4.2 shows the average pass/fail temperatures for all unaged binder blends. A statistical T-test of variance at the 5% significance level was conducted to compare the effects of the percentage of PET, mixing speed, and mixing time on pass/fail temperatures of the modified blends. These results are presented in Appendix B. The PG67-22 base binder could be expected to have a pass/fail temperature of 67°C based on the PG grading system. Therefore, all PET blends increased the high temperature performance of the binder to some degree. Six of the 12 blends increased the PG grade of the binder by at least one grade (6°C). Increasing percentages of PET generally led to an increase in the average pass/fail temperature across all blends.

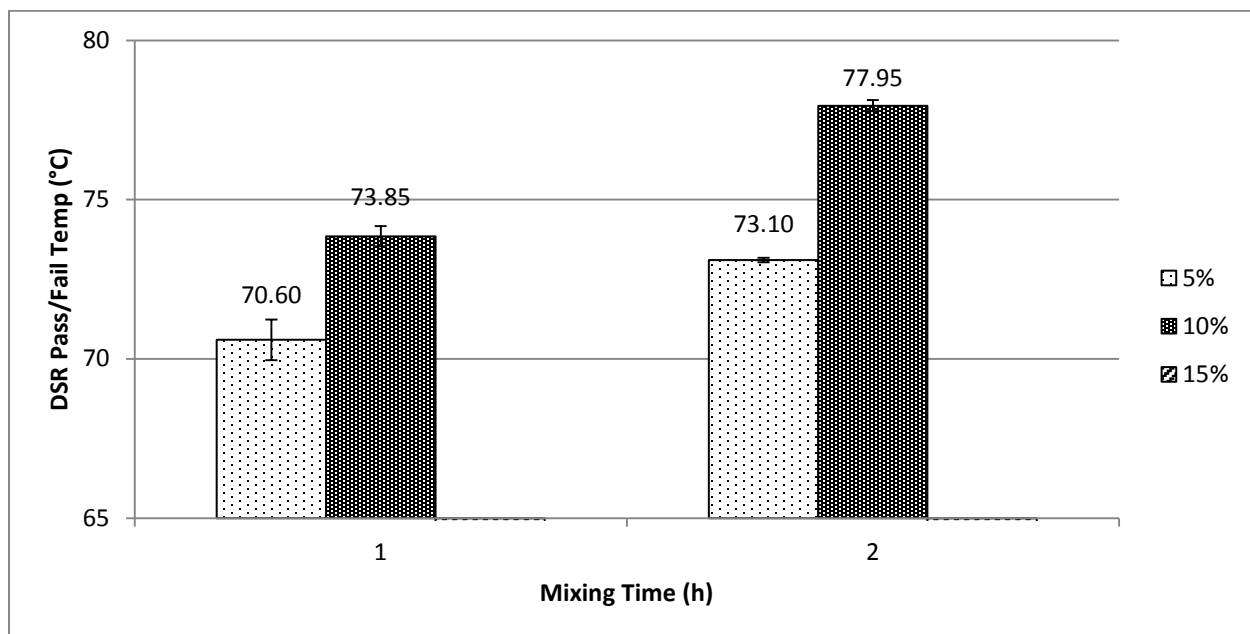
Additionally, the 3000rpm mixing speed produced higher pass/fail temperatures than the 5000rpm mixing speed in most cases. However, most of these increases were not statistically significant. Therefore, the effect of mixing speed on pass/fail temperature is unclear. The 10 percent PET blend mixed at 3000rpm for 2 hours yielded the greatest increase in average pass fail temperature, at 77.95°C and exhibited statistically significant increases in pass/fail temperature over all other blends. Values for 15 percent PET at the 3000rpm mixing speed were not obtained because excessive amounts of relatively large PET particles prevented the DSR from reaching the 1mm test gap.



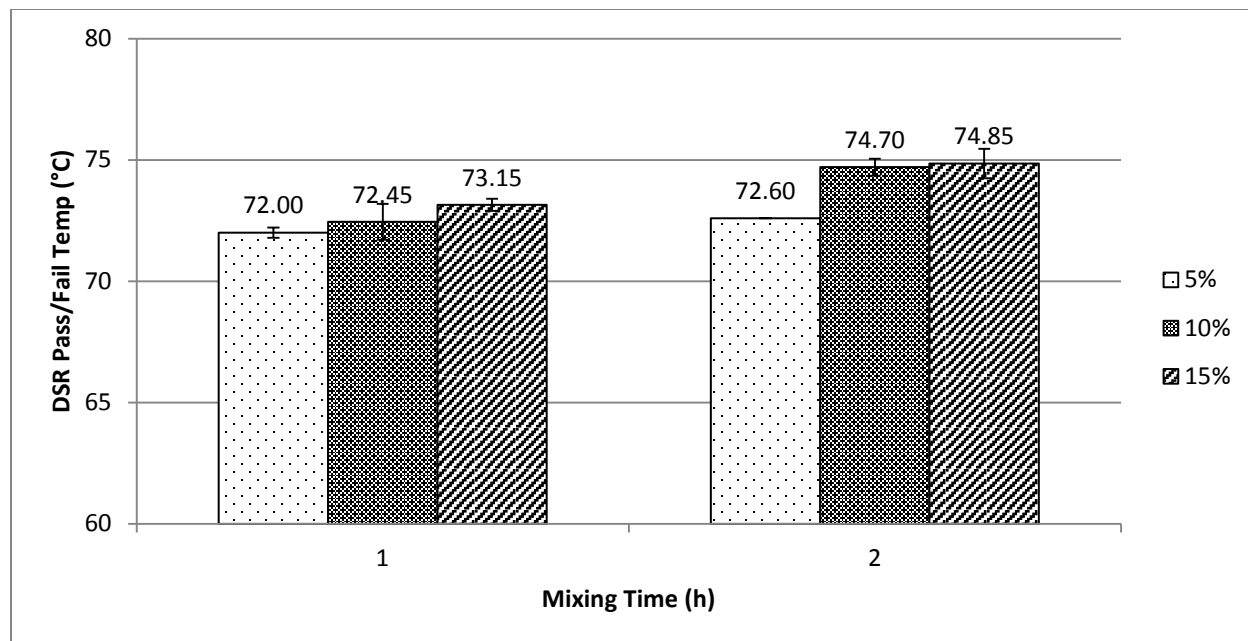
**Figure 4.2. Average pass/fail temperatures for all modified binders**

Additional insight into the effects of the mixing time on the high temperature performance of the PET modified asphalt binders can be gained from Figures 4.3 and

4.4. As the figures show, the average pass/fail temperature of modified blends at both mixing speeds and all PET percentages increased with mixing time. In most cases, except for the 10 percent blend mixed at 3000rpm for 1 and 2 hours, these increases were not statistically significant. However, the small increases in pass/fail temperature due to mixing time could be attributed to two factors. First, the mixing temperatures produced during the high shear mixing process were between 175°C and 225°C, depending on the PET content of the mixtures. These temperatures are higher than the 163°C temperature used in RTFO aging. Therefore, the elevated mixing temperatures could have contributed to premature aging of the binder, making it stiffer and resulting in a higher pass/fail temperature the longer the binder was exposed to the elevated temperatures. Second, the two hour mixing time could have simply resulted in better distribution of the PET throughout the binder and a more homogeneous mixture.



**Figure 4.3. Average pass/fail temperatures at 3000rpm mixing speed**



**Figure 4.4. Average pass/fail temperature at 5000rpm mixing speed**

Since RV and DSR data could not be obtained for two of the four unaged 15 percent PET blends, all 15 percent PET blends were discarded after the initial RV and DSR testing phase. RTFO aging and subsequent DSR testing on the aged blends was only conducted on the 5 and 10 percent PET blends. The results are presented in Table 4.3.

**Table 4.3. RTFO aged DSR pass/fail temperatures**

<b>% Plastic</b>	<b>RPM</b>	<b>Mixing time</b>	<b>Pass/fail (°C)</b>	<b>Avg Pass/Fail (°C)</b>
<b>5</b>	<b>3000</b>	<b>1h</b>	72.7	<b>72.3</b>
			71.9	
		<b>2h</b>	73.7	<b>73.4</b>
			73.0	
	<b>5000</b>	<b>1h</b>	73.1	<b>73.7</b>
			74.3	
		<b>2h</b>	73.1	<b>73.3</b>
			73.5	
<b>10</b>	<b>3000</b>	<b>1h</b>	77.0	<b>78.9</b>
			80.7	
		<b>2h</b>	78.0	<b>77.6</b>
			77.1	
	<b>5000</b>	<b>1h</b>	73.1	<b>73.9</b>
			74.6	
		<b>2h</b>	75.8	<b>75.8</b>
			75.8	

Figures 4.5 and 4.6 show the unaged versus RTFO aged pass/fail temperatures of these blends. A statistical T-test of variance at the 5% significance level was conducted to evaluate the effects of RTFO aging on the modified blends. These results are presented in Appendix C. RTFO aging generally results in a stiffer binder and a higher pass/fail temperature. Although the figures show that the pass/fail temperature increased with RTFO aging for both PET percentages across all mixing times and speeds, these increases were statistically insignificant. Therefore, this indicates that the elevated mixing temperatures due to high shear mixing may have aged the binders in a manner similar to the RTFO aging process.

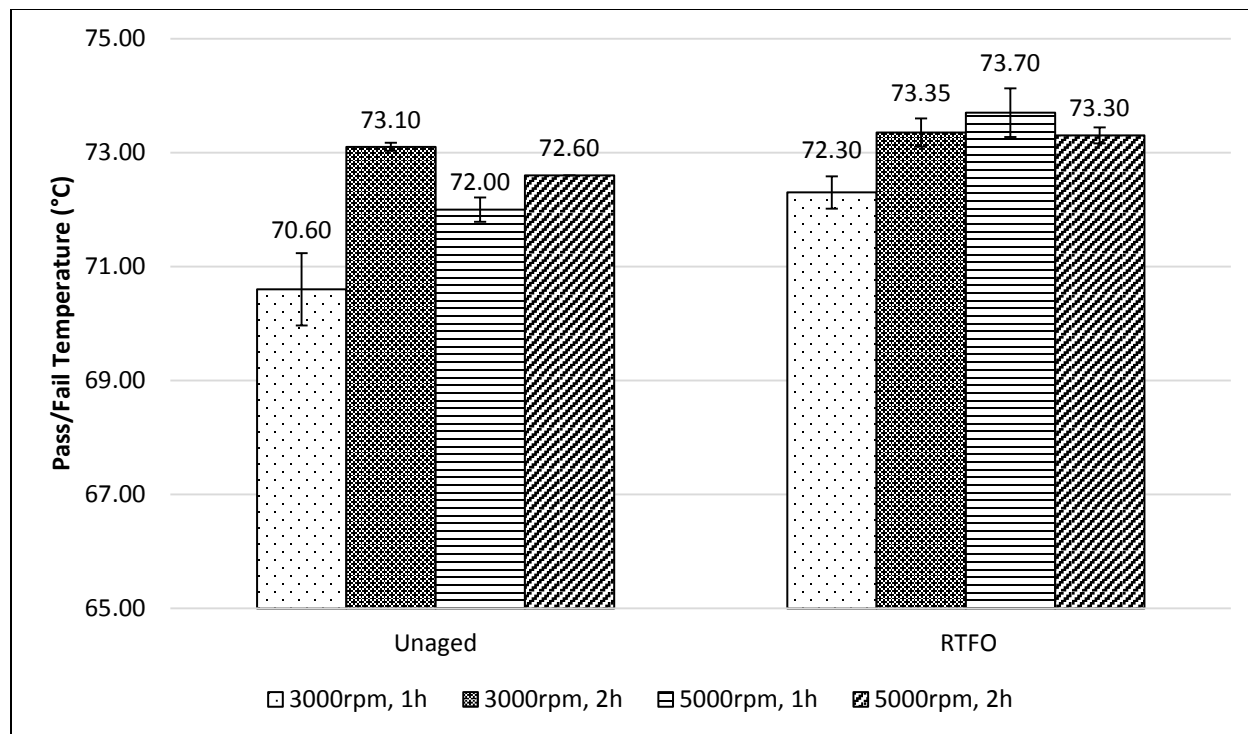


Figure 4.5. Average pass/fail temperatures of 5% PET blends, unaged vs. RTFO

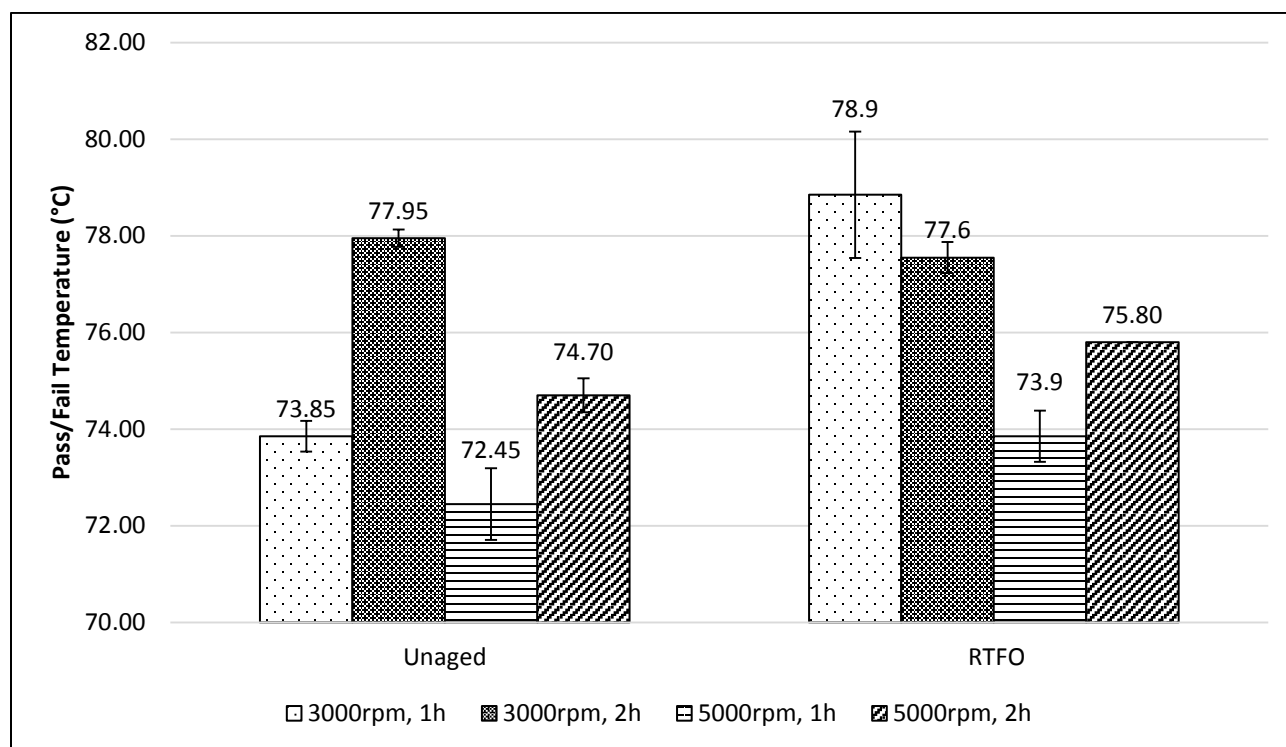


Figure 4.6. Average pass/fail temperatures of 10% PET blends, unaged vs. RTFO

The RTFO samples were also measured for percent loss during aging that indicates the presence of excessive volatiles in the mixture. Table 4.4 shows the average percent loss values for all RTFO tests. All percent loss values were well below the accepted maximum value of one percent. Therefore, it can be concluded that the PET did not contribute any excessive volatiles to the blends.

**Table 4.4. Average percent loss values for RTFO tests**

<b>%Plastic</b>	<b>Mixing Speed (rpm)</b>	<b>Mixing Time (h)</b>	<b>Avg Percent Loss</b>
<b>5</b>	3000	1	0.47
		2	0.46
	5000	1	0.43
		2	0.41
<b>10</b>	3000	1	0.33
		2	0.47
	5000	1	0.37
		2	0.29

The performance of all blends in unaged and RTFO aged DSR testing, RTFO percent loss calculations, and unaged RV testing was considered before choosing a blend to use in the asphalt mixture design phase. Based on the performance characteristics exhibited, specifically the increase in PG grade indicated by unaged DSR testing, the 10 percent PET blend mixed at 3000rpm for 2 hours was selected as the wet process binder for asphalt mixture design.

## CHAPTER 5: PROPERTIES OF MODIFIED MIXTURES WITH PET

### 5.1 Mixture Design

The mixture design process ultimately produced the AC versus air void content plots that were utilized to select the OAC for the unmodified, wet process, and dry process mixtures. These plots are shown in Figures 5.1, 5.2, and 5.3. The final OAC values selected were 6.30 percent for the unmodified mixture, 6.45 percent for the wet process mixture, and 6.66 percent for the dry process mixture. The OAC values for the wet and dry process were adjusted to find the true amount of asphalt binder in the mixture by taking into account the percentage of PET that was substituted for binder. The wet process mixture contained 0.65 percent PET, and the dry process mixture contained 0.74 percent PET.

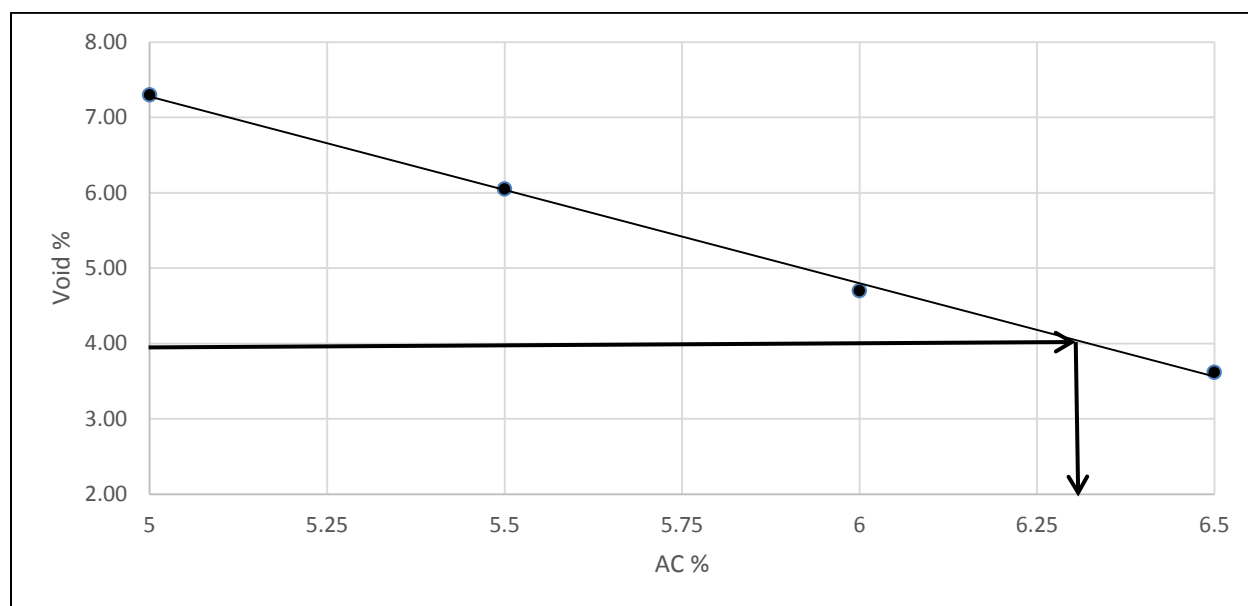
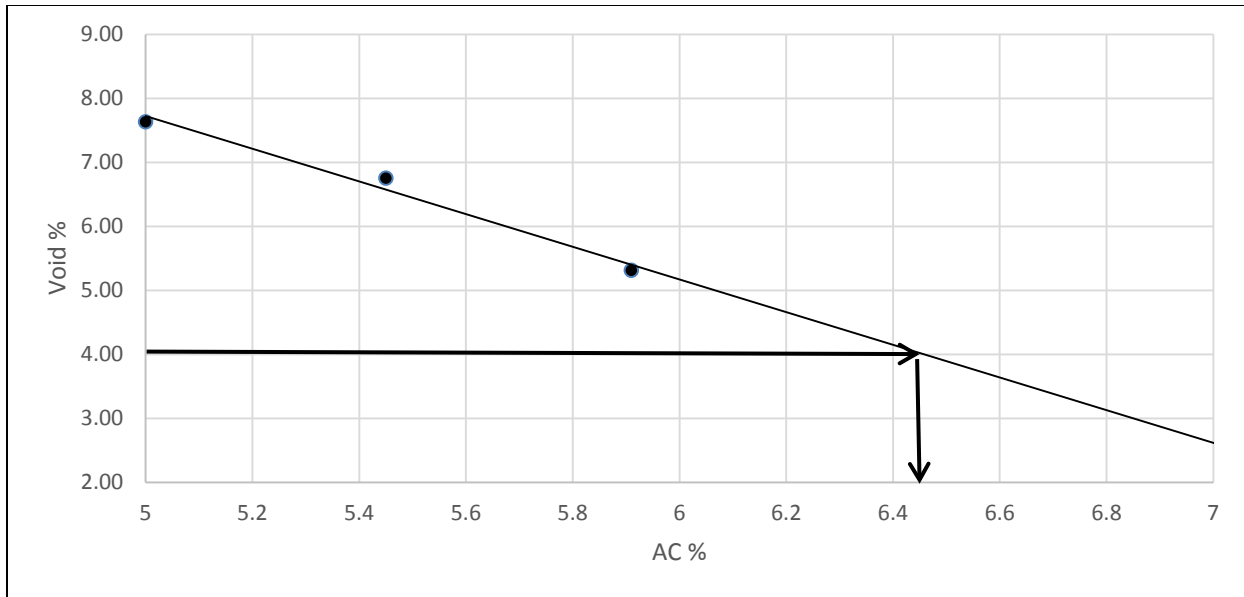
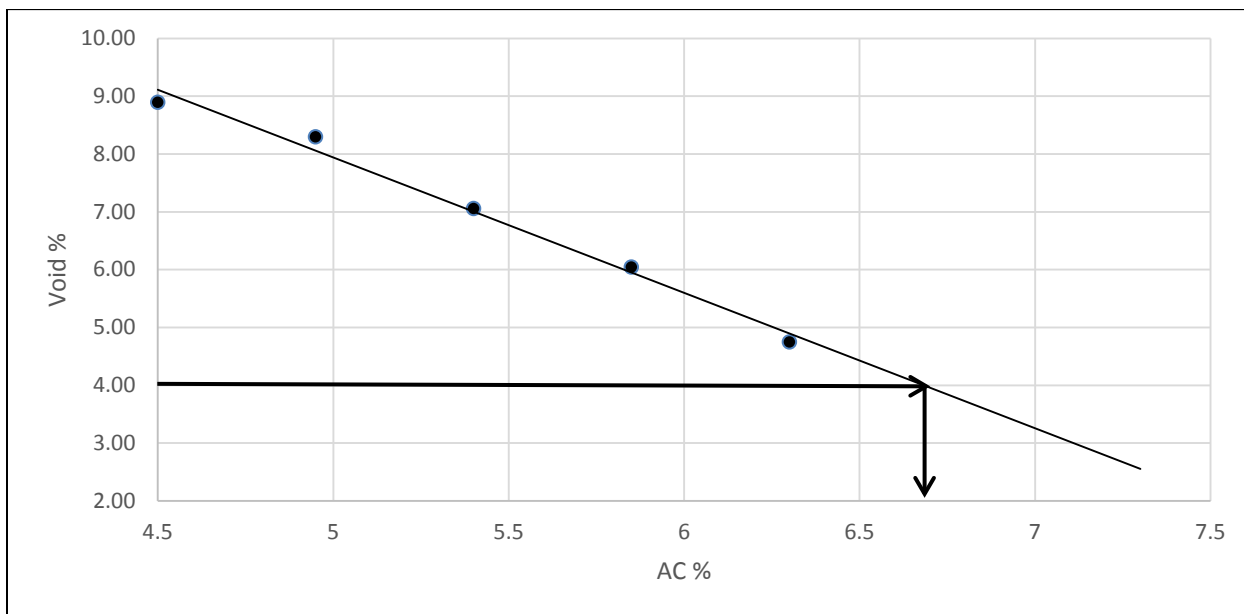


Figure 5.1. Unmodified OAC plot





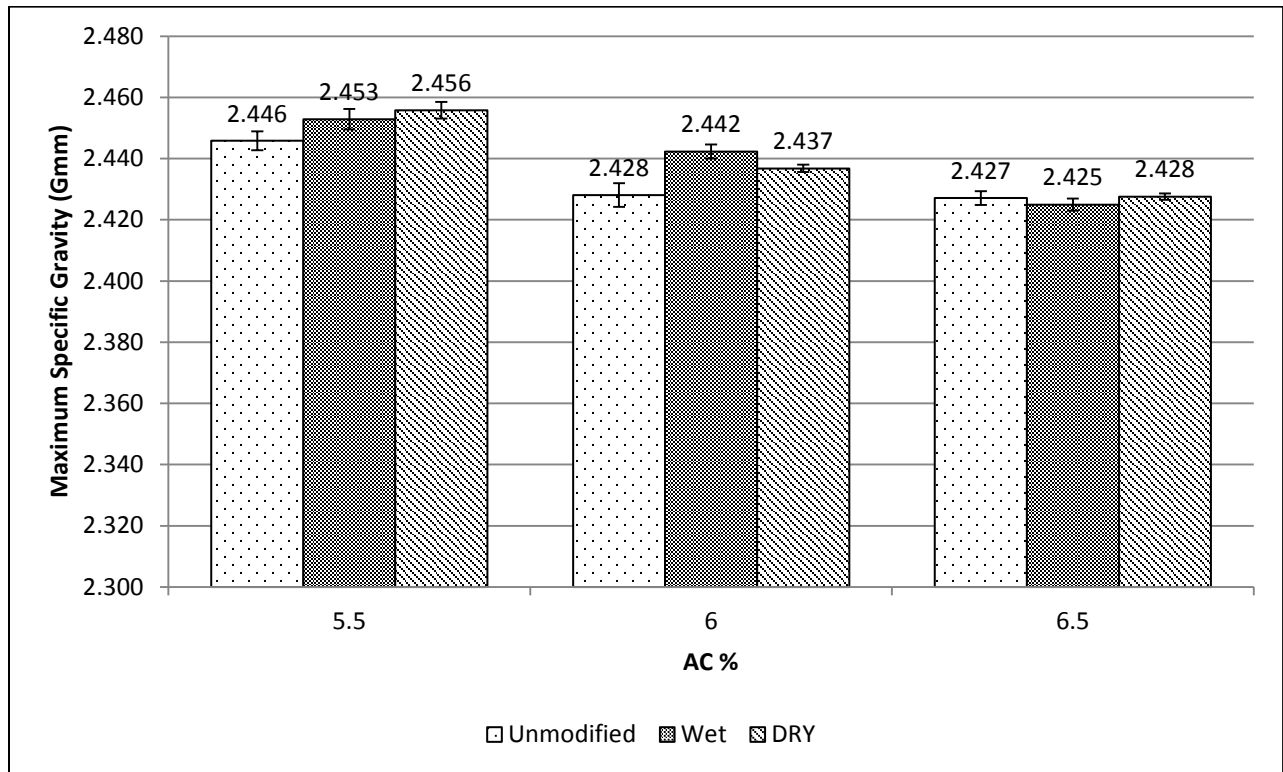
**Figure 5.2. Wet process OAC plot**



**Figure 5.3. Dry process OAC plot**

An interesting trend was also observed in maximum specific gravity values and bulk specific gravity values during the mixture design process. Figure 5.4 shows the maximum specific gravity values of all mixtures at the common AC values used for each mixture during the mixture design process. The maximum specific gravity values for

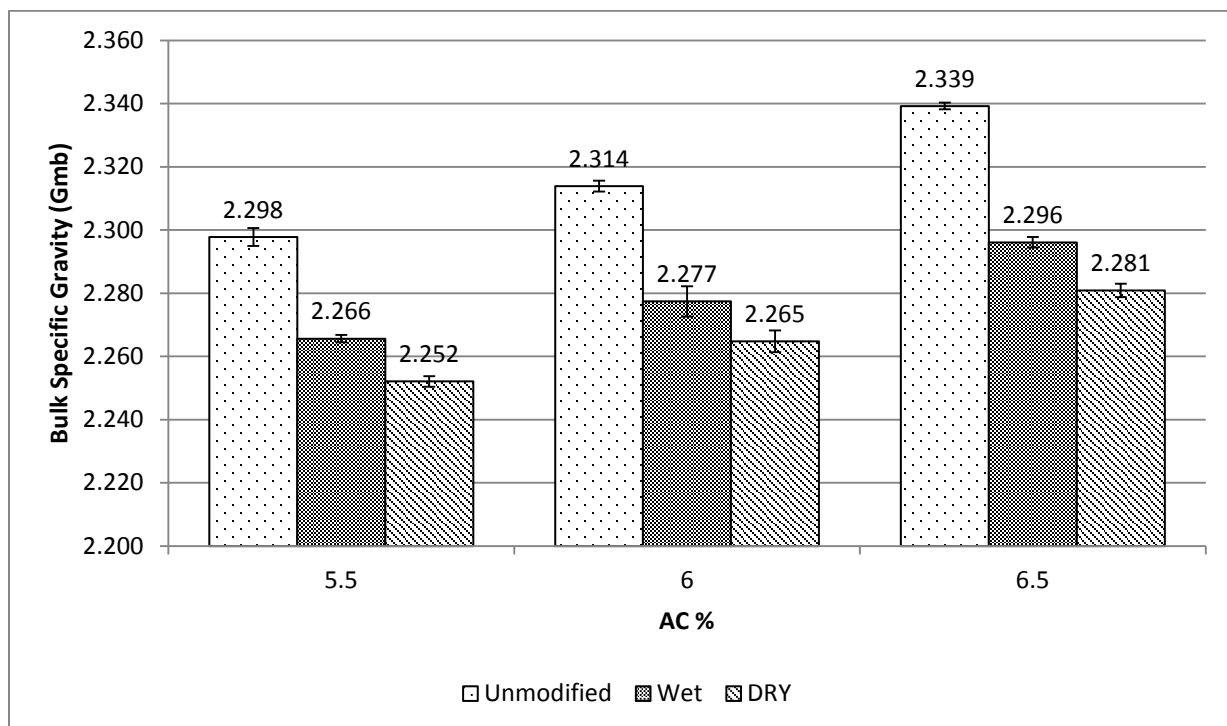
both the wet and dry process tended to be greater than the unmodified mixture. This is probably the result of the substitution of the PET for a portion of the asphalt binder. PET has a density of  $1.380\text{g/cm}^3$  while PG67-22 asphalt has a density of  $1.0425\text{g/cm}^3$ . Therefore, when the denser PET was substituted for part of the binder, the maximum specific gravity of the mixture increased.



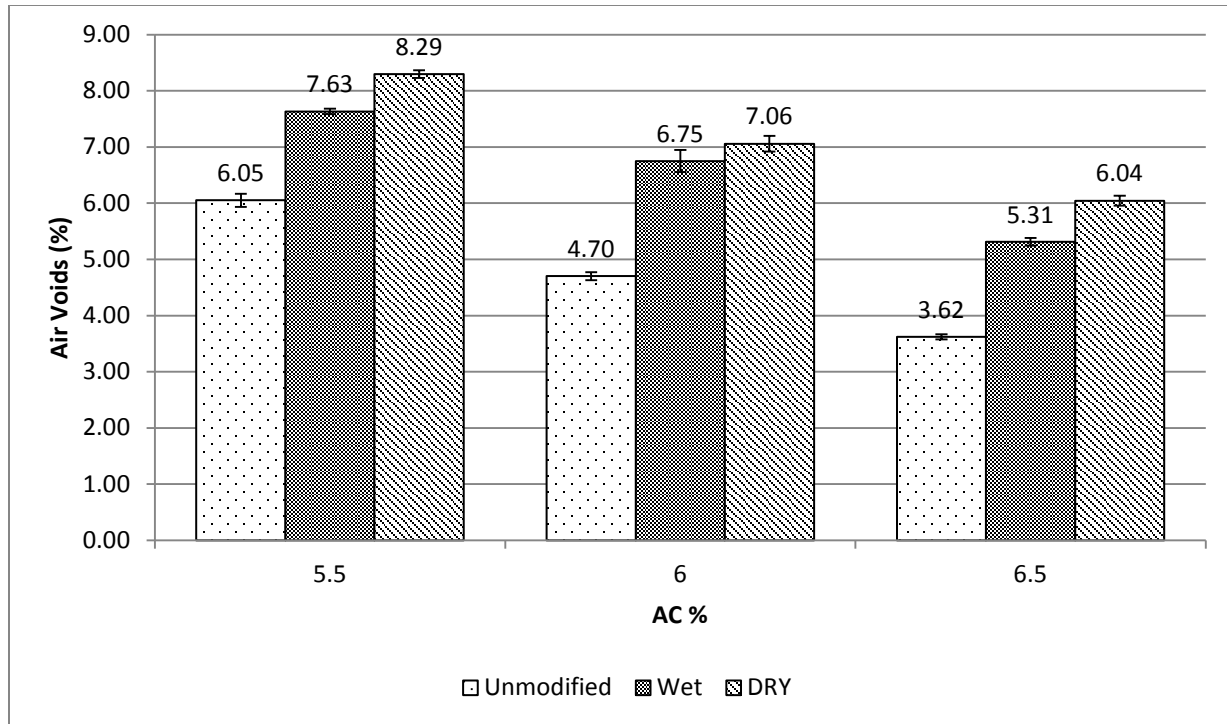
**Figure 5.4. Maximum specific gravity values of all mixtures at common AC**

Figure 5.5 shows the bulk specific gravity values of all mixtures at the common AC values. Unlike the maximum specific gravity values, the bulk specific gravity values of the wet and dry process were consistently lower than the unmodified mixtures. This phenomenon can be explained using observations by Moghaddam, Soltani, and Karim. In their study, the researchers observed that PET content up to 0.4 percent resulted in higher bulk specific gravity values, as the PET particles filled the air voids within the

samples. However, when PET values exceeded 0.4 percent, the researchers theorized that the rigid PET particles began to orient between the aggregate particles. This prevented sufficient compaction and resulted in higher air voids in the specimens that contributed to lower bulk specific gravity values (Moghaddam, Soltani, and Karim 2014). Since the PET percentages in the study were greater than the 0.4 percent threshold observed by Moghaddam, Soltani, and Karim, their observations can be considered in this situation. The orientation of PET particles between the aggregate in the wet and dry process mixtures could have prevented sufficient compaction that led to the low bulk specific gravity values. Therefore the wet and dry process mixtures required a higher AC than the unmodified mixture to reach the same void content. This is shown in Figure 5.6. Ultimately, the behavior of the PET particles necessitated a higher OAC for the wet and dry process mixtures.



**Figure 5.5. Bulk specific gravity values of all mixtures at common AC**



**Figure 5.6. Air voids of all mixtures at common AC**

## 5.2 Performance Tests

### 5.2.1 APA Rutting

The first test conducted on asphalt mixtures was the APA rutting test. The average rut depths for each mixture are shown in Figure 5.7. The wet process mixture exhibited the best performance with a final rut depth of 3.754mm. The unmodified mixture had a final rut depth of 3.907mm, and the dry process mixture had a final rut depth of 4.492mm. All rut depths were less than the GDOT specified maximum of 5mm. Visual inspection of the samples after APA rut testing revealed similar visual performance among all samples with no distinguishable differences. The post-testing samples are shown in Figure 5.8.

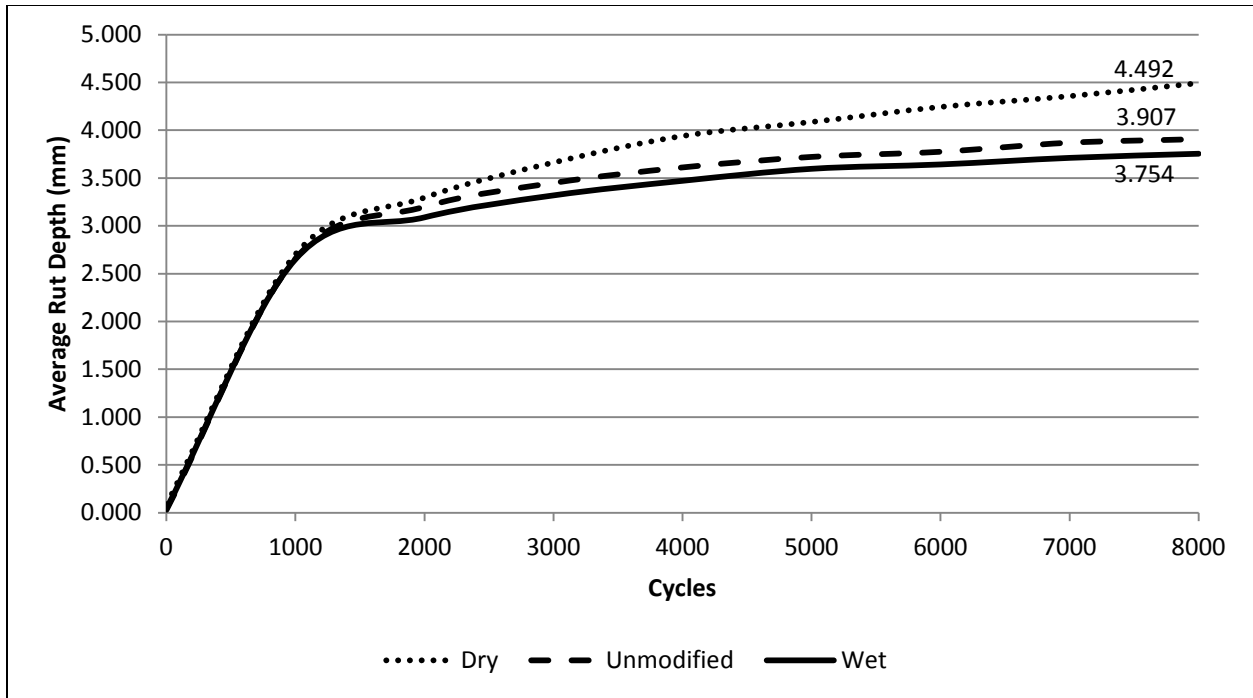


Figure 5.7 Average APA rut depths

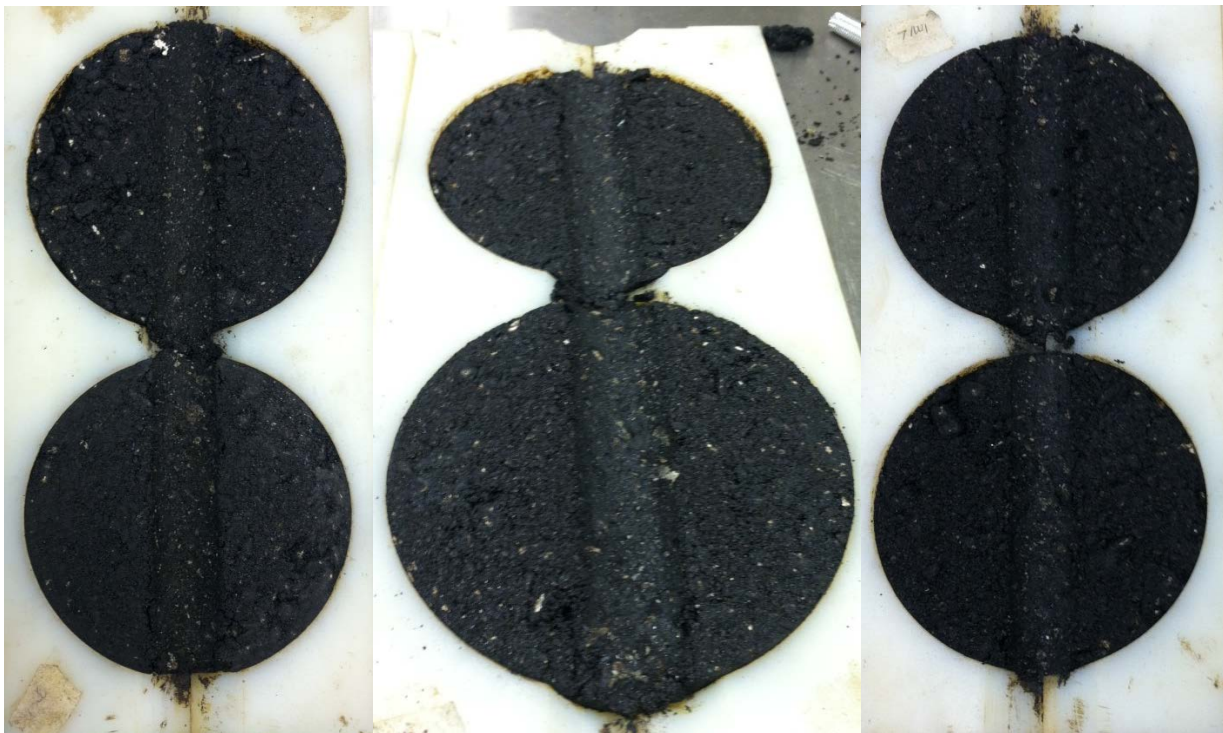
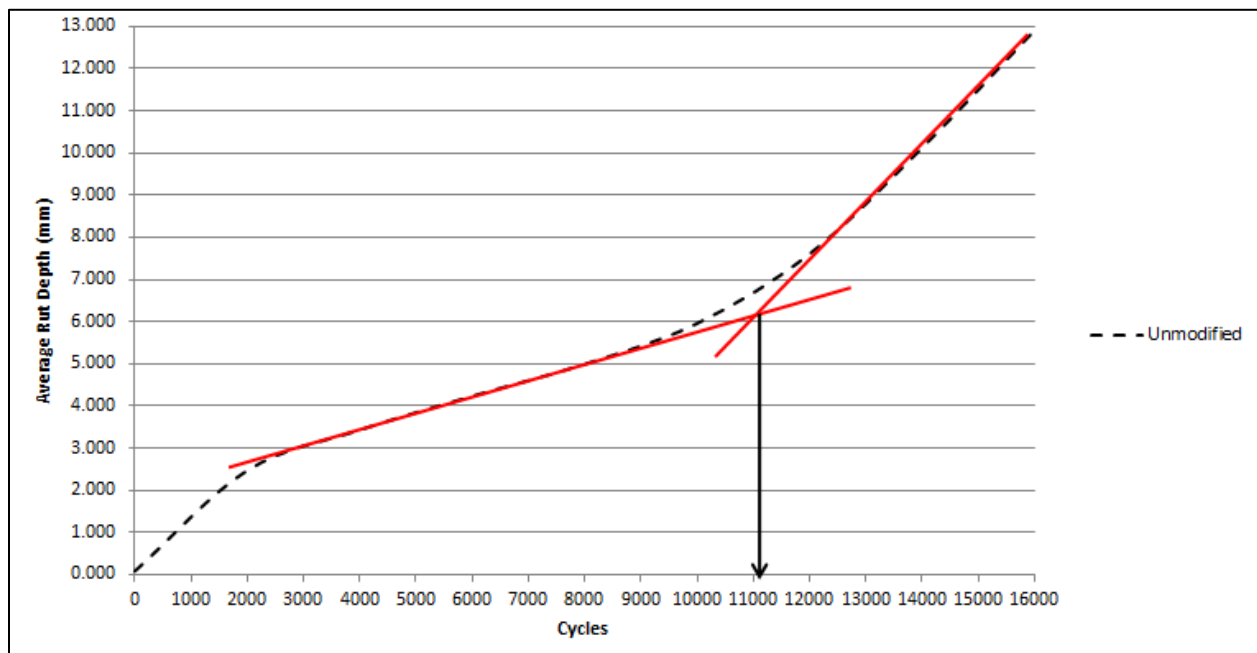


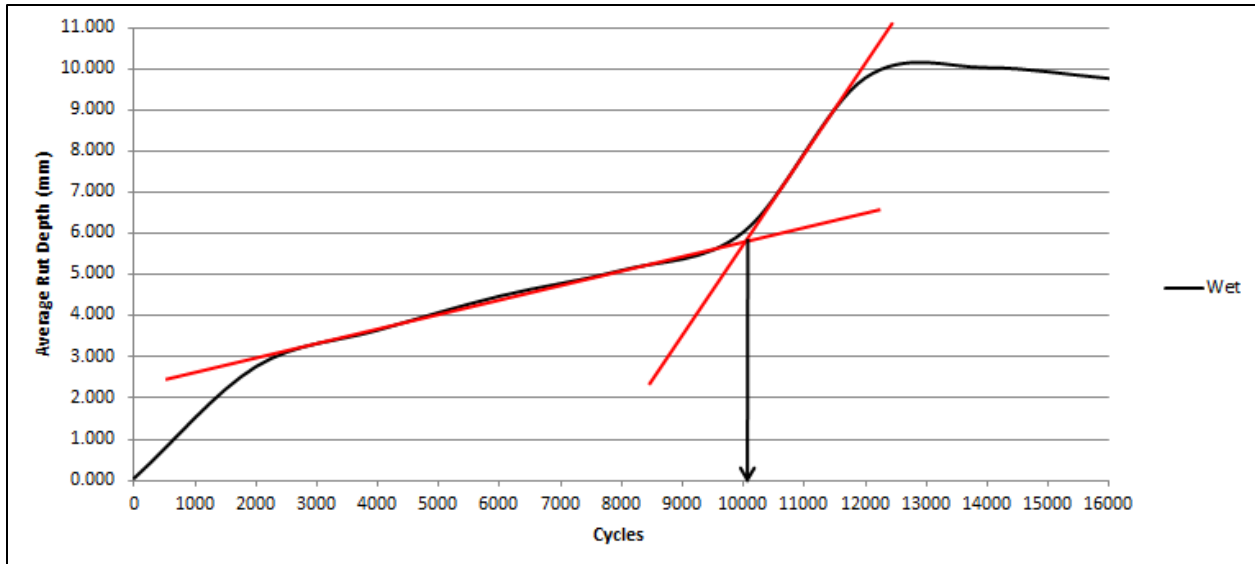
Figure 5.8 APA rutting samples (unmodified, dry, wet)

### 5.2.2 APA Hamburg

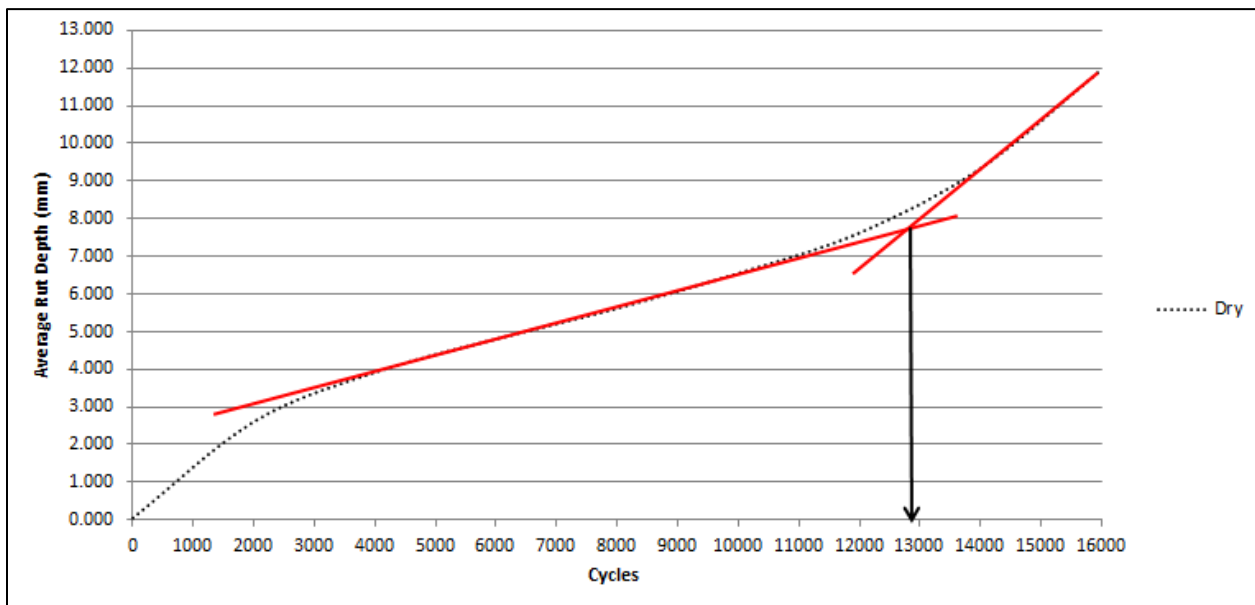
Results from the APA Hamburg test provided slightly more insight into the performance of the modified asphalt blends. Two sets of samples were tested for each blend, and the rut depths from both sets were averaged and plotted to obtain a smooth curve. The Hamburg test results for the unmodified, wet, and dry process are shown in Figures 5.9, 5.10, and 5.11, respectively. Notice that all plots only extend to 16,000 cycles. The only samples that completed the full 20,000 cycles without reaching the maximum rut depth (12.5mm) were the wet samples. As Figure 4.16 shows, the rut depth of the wet samples peaked at 10mm around 13,000 cycles and fluctuated within 1mm for the duration of the test. The unmodified mixture reached the 12.5mm rut depth shortly before 16,000 cycles, and the dry mixture reached the 12.5mm rut depth shortly after 16,000 cycles.



**Figure 5.9. Unmodified APA Hamburg results**



**Figure 5.10. Wet process APA Hamburg results**



**Figure 5.11. Dry process APA Hamburg results**

After the plots were generated, they were analyzed to obtain four properties that could be utilized to better describe and compare the performance of the modified asphalt blends. These properties are post compaction consolidation, creep slope, stripping slope, and stripping inflection point (shown in Figure 3.13). Post compaction consolidation occurred during the first 1000 cycles. Straight lines of best fit were

superimposed over the plots to obtain creep slope and stripping slope. The intersection of these lines was designated as the stripping inflection point. The four properties are summarized in Table 5.1. The unmodified mixture had the lowest post compaction value at 1.619mm, while the wet process mixture had the highest post compaction value at 2.012mm. The wet process mixture exhibited the lowest creep slope, while the dry process mixture exhibited the highest creep slope. The creep slope is an indicator of rutting resistance, and these values match the results from the APA rutting test that showed the wet process mixture to have the greatest rutting resistance. The stripping slope is an indicator of resistance to moisture induced damage. When comparing stripping slopes, a steeper stripping slope indicates more damage is done with each wheel pass. Additionally the lower the stripping inflection point, the sooner moisture damage is induced (Solaimanian et al. 2003). The wet process mixture showed the highest stripping slope and lowest stripping inflection point, indicating that it had the least resistance to permanent moisture damage. The dry process mixture showed the lowest stripping slope and highest stripping inflection point, indicating that it was most resistant to permanent moisture damage.

**Table 5.1. Summary of APA Hamburg test data**

<b>Blend</b>	<b>Post Compaction (mm)</b>	<b>Creep Slope</b>	<b>Stripping Slope</b>	<b>Stripping Inflection Point (cycles)</b>
<b>Wet</b>	2.012	0.33	2.00	10050
<b>Unmodified</b>	1.619	0.40	1.38	11150
<b>Dry</b>	1.812	0.43	1.13	12850



### 5.2.3 AMPT Modulus

The results of the AMPT modulus test can be presented in several different manners to show the effect of temperature and loading frequency on  $E^*$  and phase angle.

#### *Effect of temperature on $E^*$*

Figures 5.12, 5.13, and 5.14 show the effect of temperature on  $E^*$  at loading frequencies of 10Hz, 1Hz, and 0.1Hz. The  $E^*$  values of all mixtures at all loading frequencies reduced drastically as temperature increased, indicating that the  $E^*$  is highly dependent on test temperature. The slopes of the  $E^*$ -temperature curves of the unmodified mixture at all loading frequencies were slightly steeper than the modified mixtures. This indicated that the  $E^*$  of the unmodified mixture was slightly more temperature-sensitive than the modified mixtures. The slopes of the wet and dry process  $E^*$ -temperature curves at all loading frequencies were essentially the same, indicating that the  $E^*$  temperature sensitivity of both mixtures was similar. The unmodified mixture yielded higher  $E^*$  values at all test temperatures and loading frequencies, indicating that it was a stiffer mixture. The wet and dry process mixtures exhibited similar  $E^*$  values at all test temperatures and loading frequencies, with the  $E^*$  values of the wet process being slightly higher than the dry process in most cases.

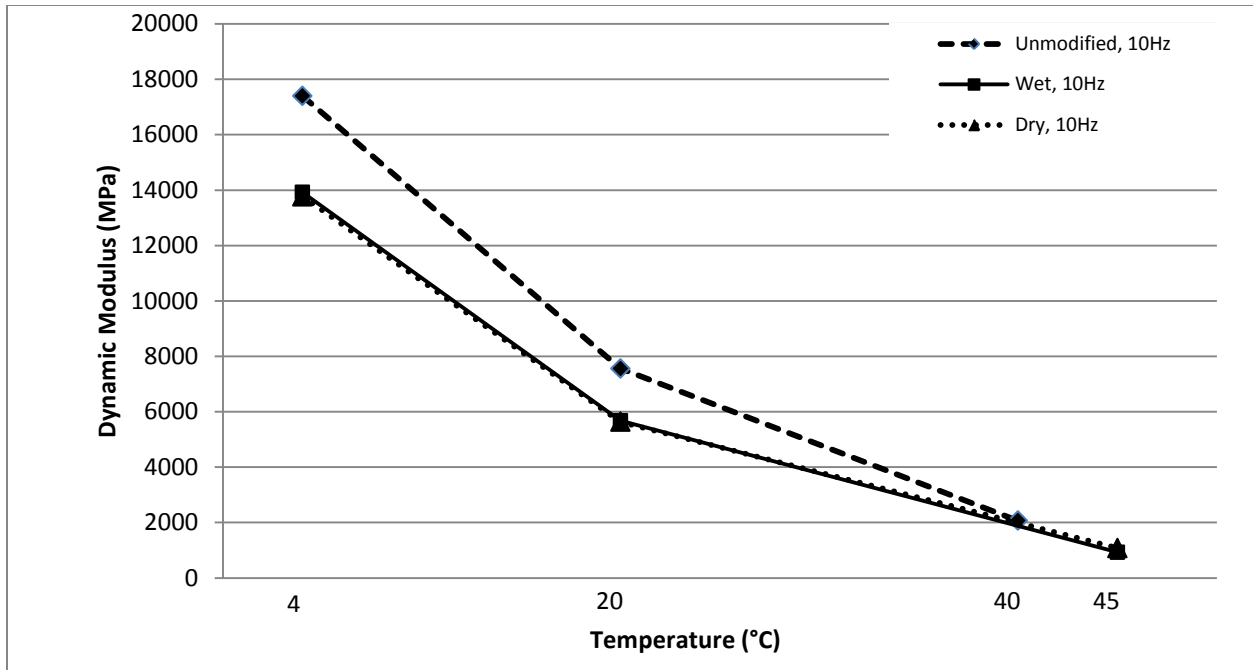


Figure 5.12.  $E^*$  vs. temperature at 10Hz

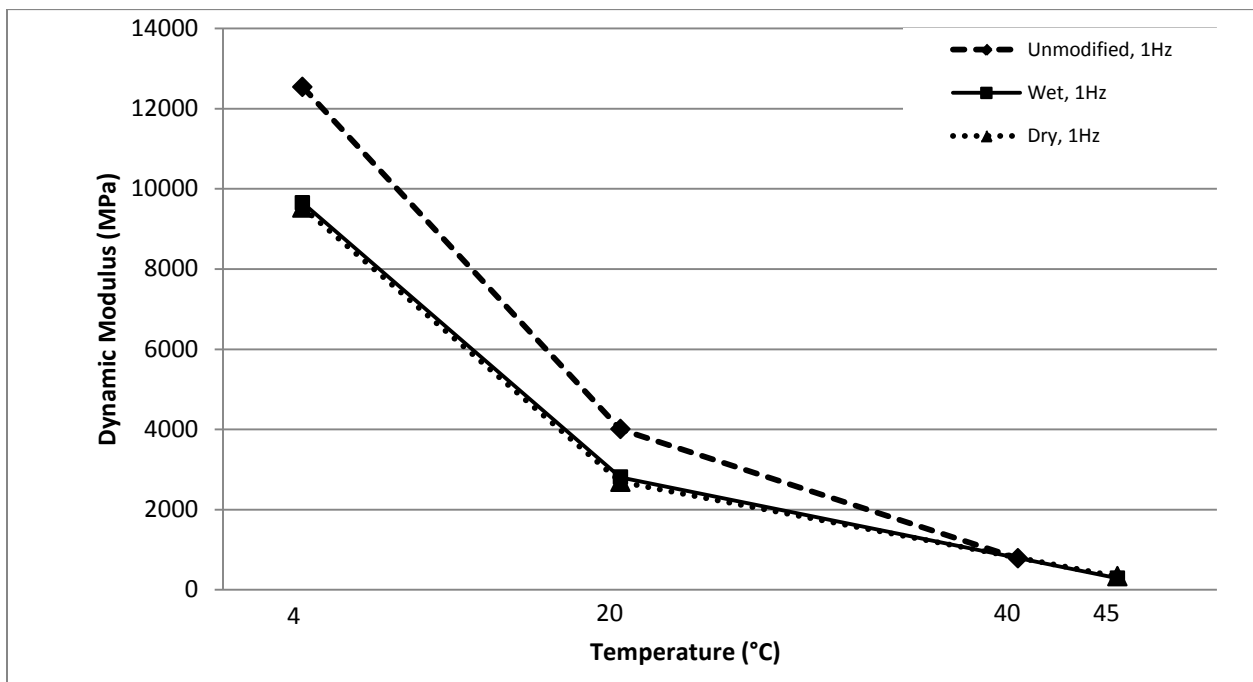
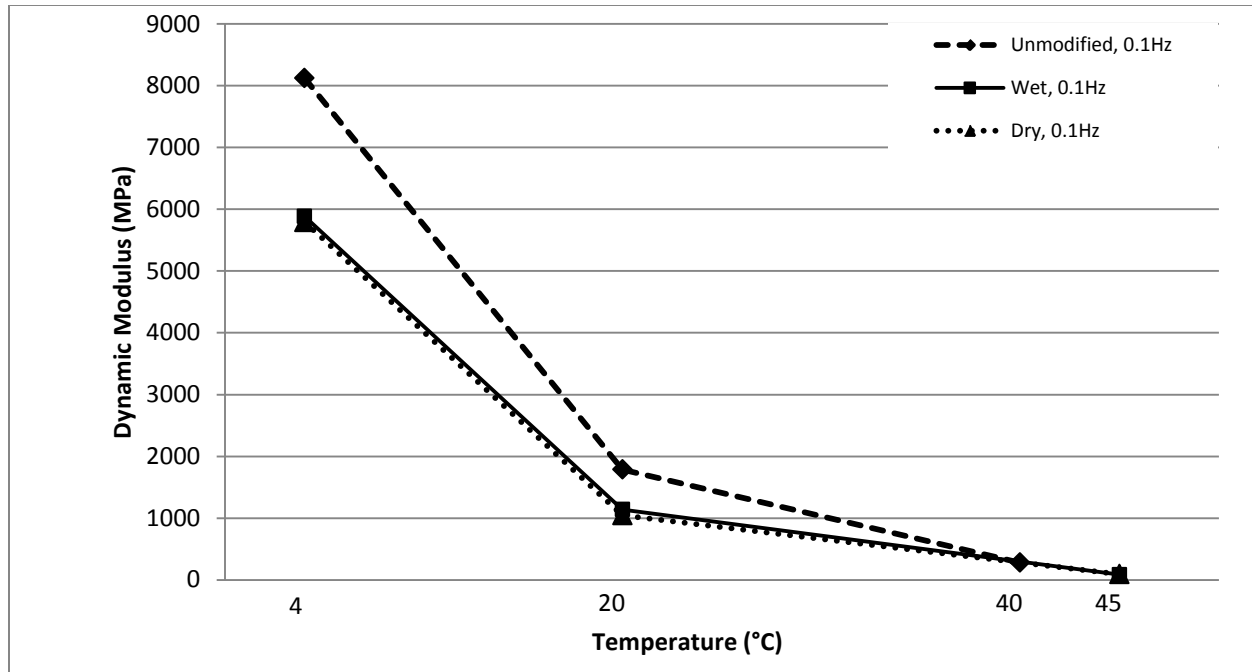


Figure 5.13.  $E^*$  vs. temperature at 1Hz



**Figure 5.14. E\* vs. temperature at 0.1Hz**

*Effect of loading frequency on E\**

Figures 5.15, 5.16, and 5.17 show the effect of loading frequency on E\* at 40/45°C, 20°C, and 4°C. When the test temperature remained constant, the E\* values of all mixtures increased as the loading frequencies increased. The slope of the E\*-loading frequency curve for the unmodified mixture was steeper than the slopes of the modified mixtures at 40°C, indicating that the E\* of the unmodified mixture was more sensitive to loading frequency at high test temperatures. As the test temperature decreased, the slopes of all E\* curves became more similar, indicating similar E\* sensitivity to loading frequency at 20°C and 4°C. The unmodified mixture exhibited higher E\* values than the modified mixtures at all test temperatures and loading frequencies. The wet and dry process mixtures showed similar E\* values at all test temperatures and loading frequencies, with the wet process E\* values being slightly higher than the dry process at

20°C and 4°C. The dry process mixture exhibited slightly higher  $E^*$  values than the wet process mixture at 45°C. The difference in the  $E^*$  values increased as loading frequency increased at this temperature.

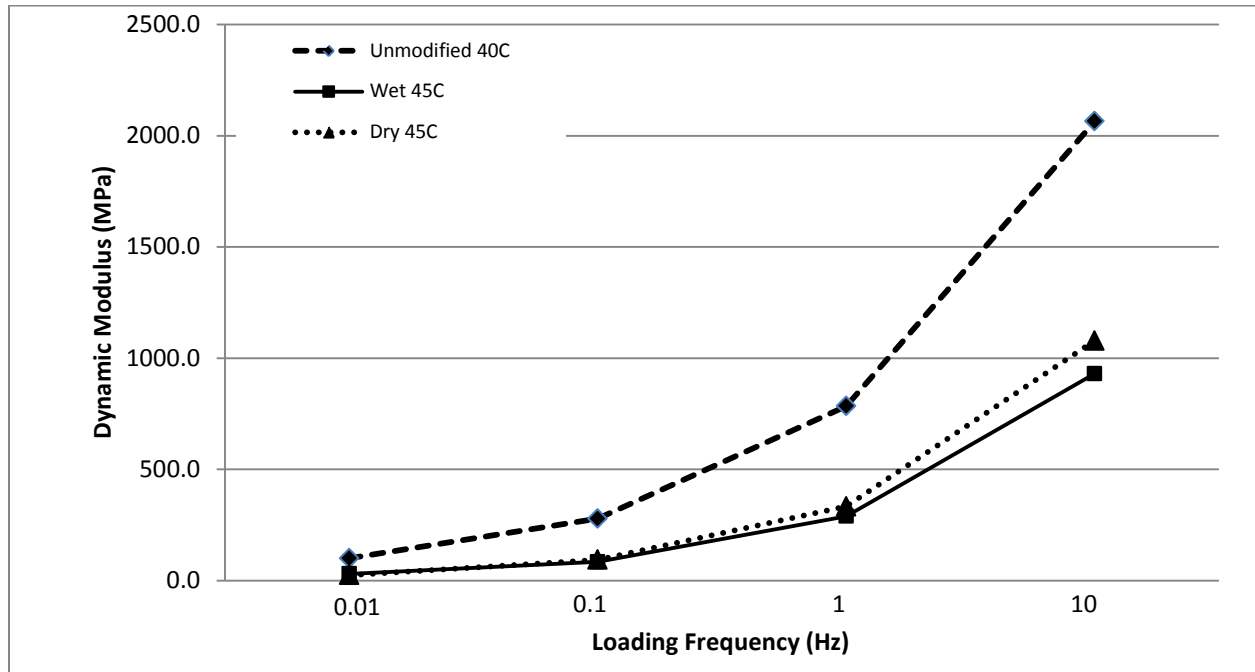


Figure 5.15.  $E^*$  vs. loading frequency at 40/45°C

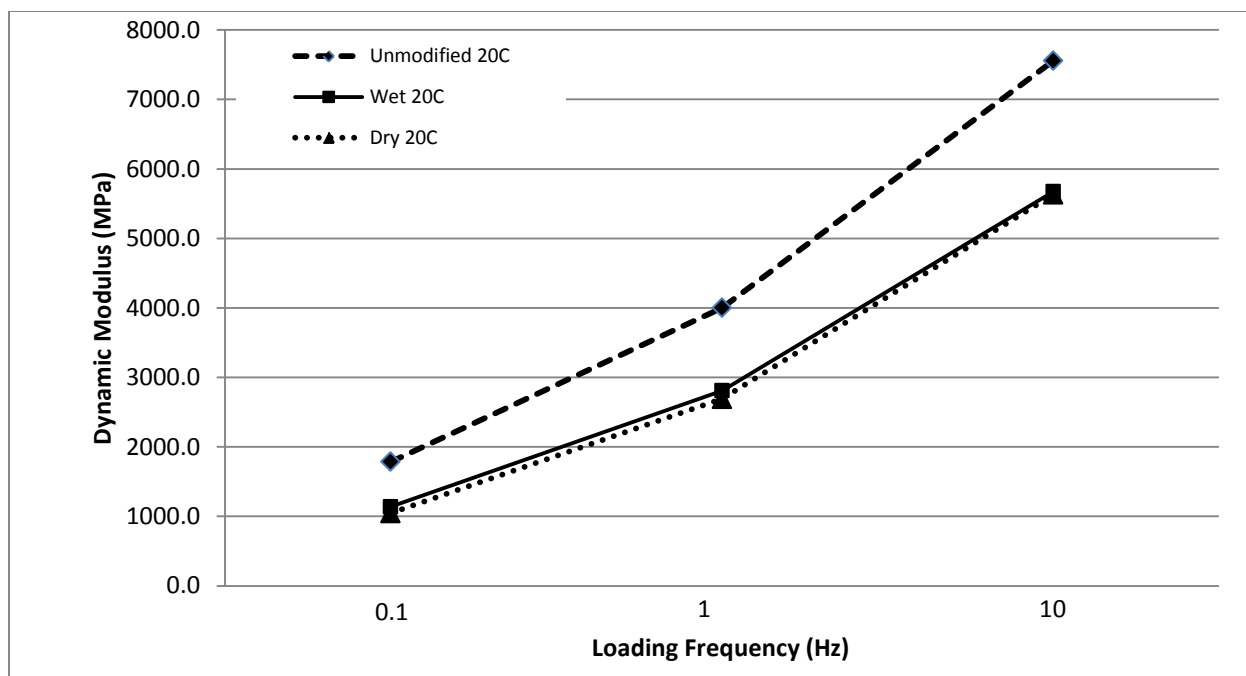


Figure 5.16.  $E^*$  vs. loading frequency at 20°C

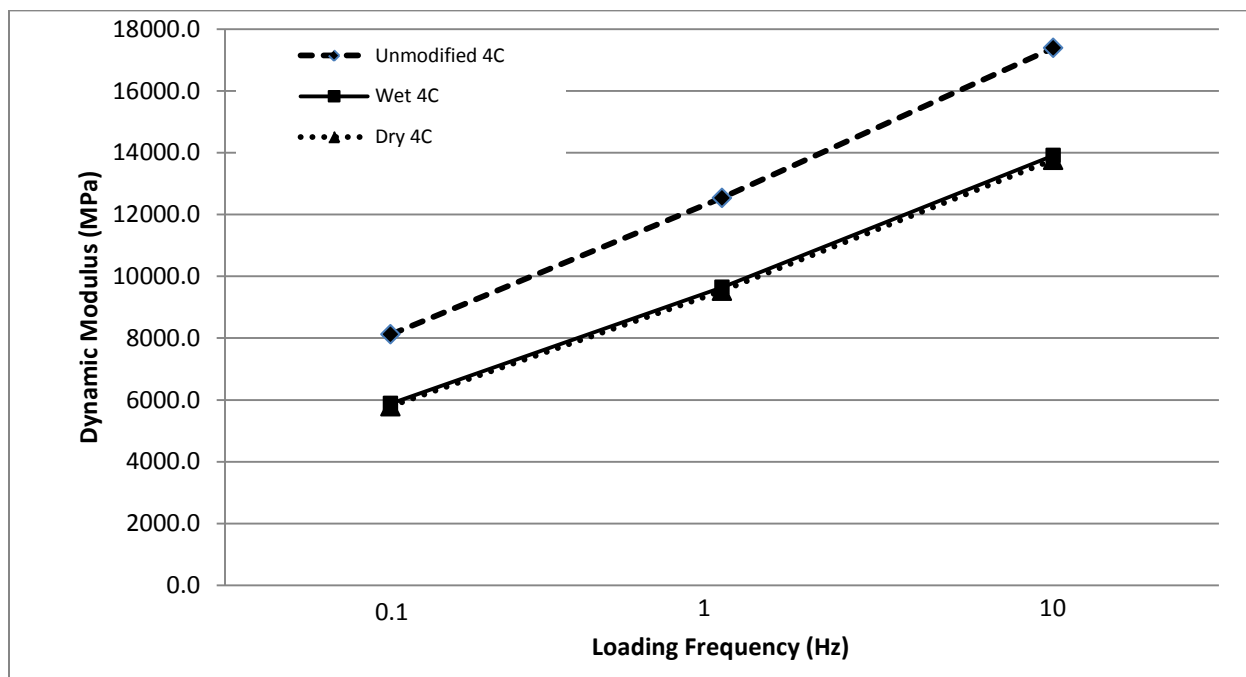


Figure 5.17.  $E^*$  vs. loading frequency at 4°C

### *Effect of temperature on phase angle*

Figures 5.18, 5.19, and 5.20 show the effect of temperature on phase angle at loading frequencies of 10Hz, 1Hz, and 0.1Hz. All mixtures showed an increase in phase angle at all loading frequencies as the test temperature increased. This indicates that the elevated temperatures made the mixtures more viscous and less elastic, increasing deformation. Generally, this increase in phase angle was sharper at higher loading frequencies. For the 0.1Hz loading frequency, the phase angle for all mixtures nearly remained the same from 20°C to 45°C. The phase angle for the unmodified mixture decreased slightly under these conditions. The unmodified mixture exhibited lower phase angles than the modified mixtures at all loading frequencies and test temperatures. The wet and dry process mixtures exhibited similar phase angles, with the wet process producing slightly lower phase angles at all loading frequencies and test temperatures, except at 45°C. This indicated that the wet process mixture was slightly more elastic than the dry process mixture at lower test temperatures.

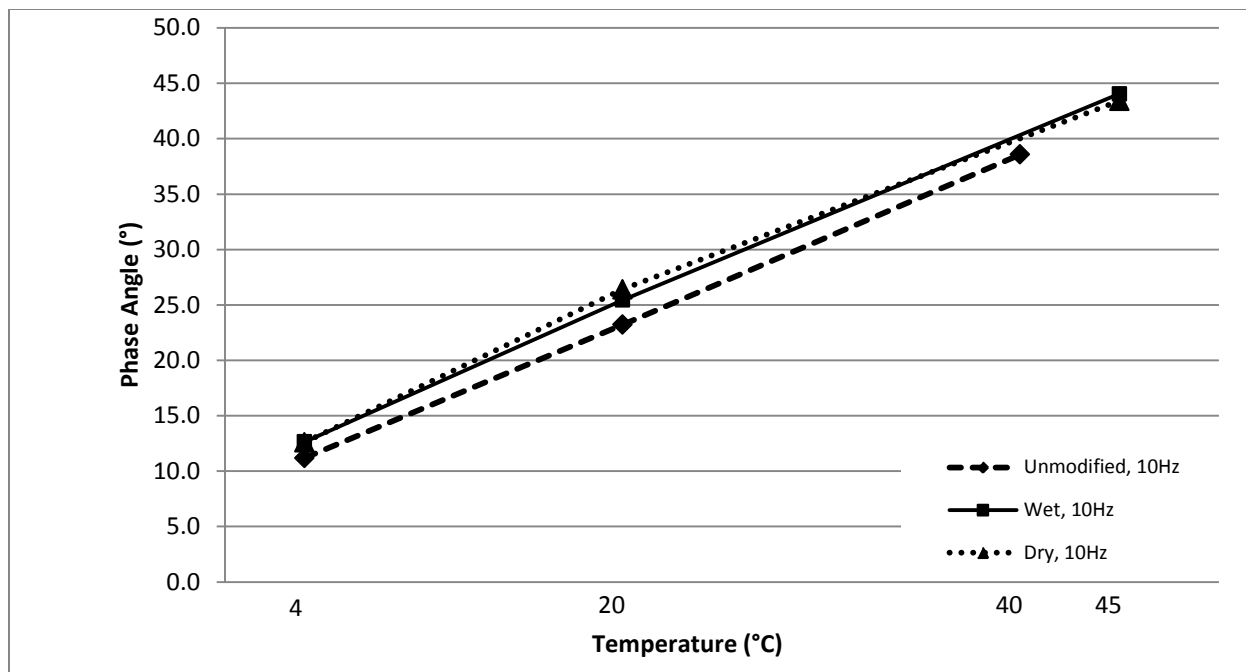


Figure 5.18. Phase angle vs. temperature at 10Hz

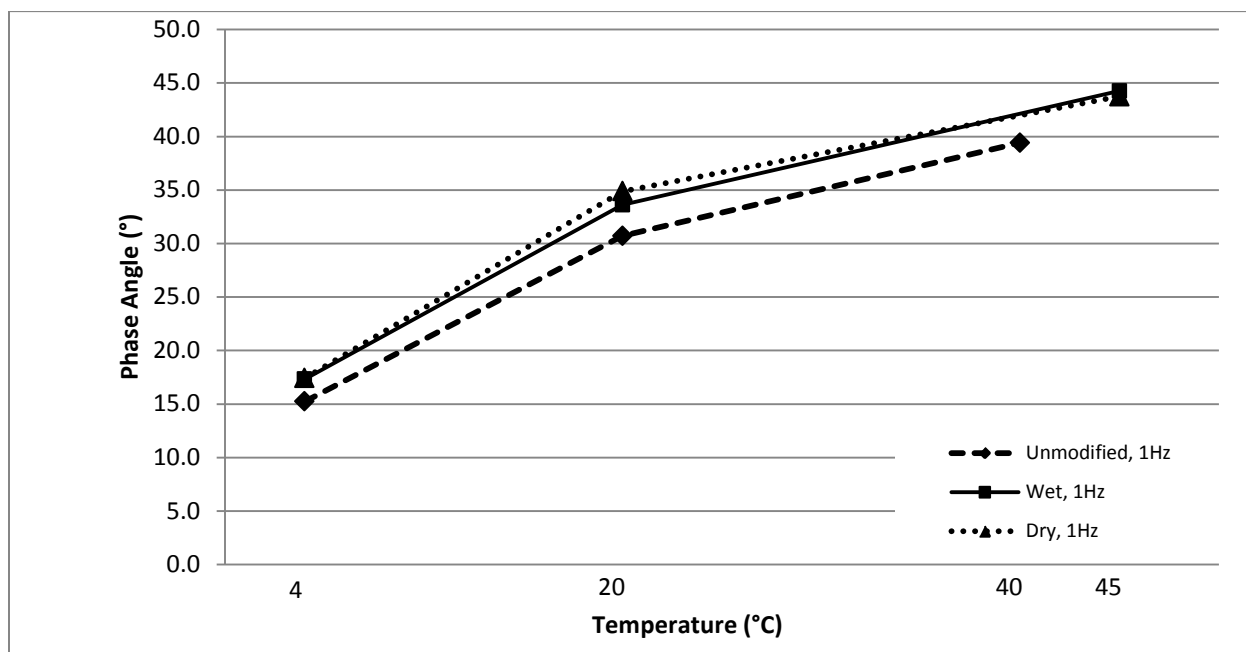
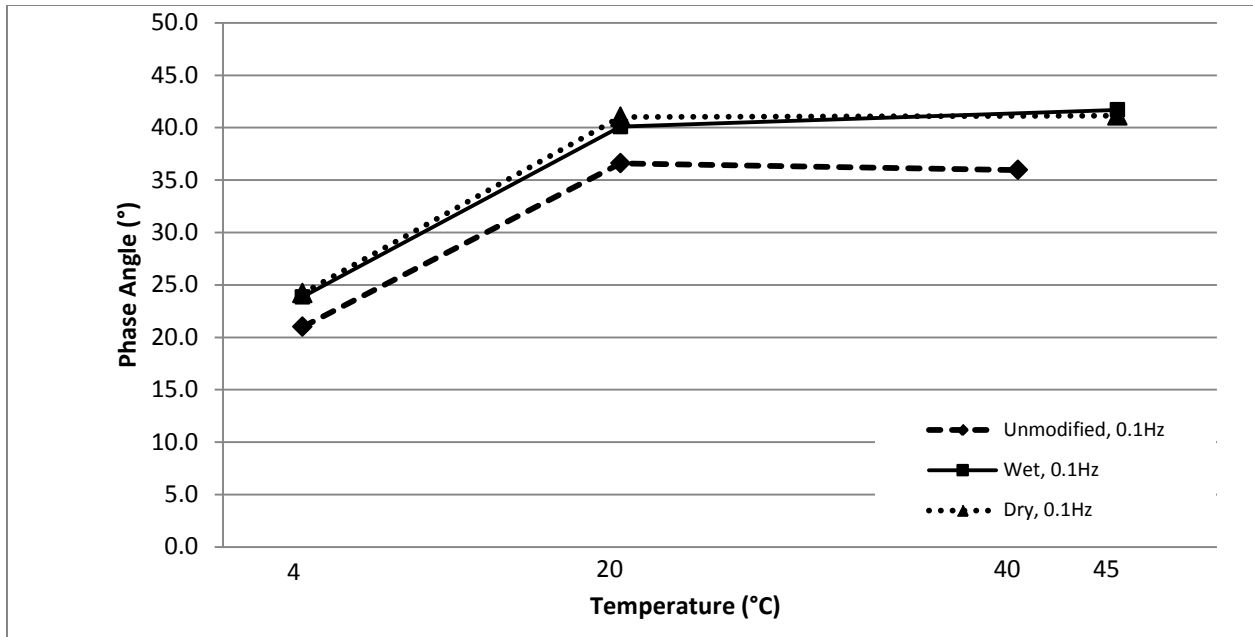


Figure 5.19. Phase angle vs. temperature at 1Hz



**Figure 5.20. Phase angle vs. temperature at 0.1Hz**

*Effect of loading frequency on phase angle*

Figures 5.21, 5.22, and 5.23 show the effect of loading frequency on phase angle at 40/45°C, 20°C, and 4°C. At 4 °C and 20 °C, the phase angles of all samples decreased as loading frequency increased. At 40/45°C, the phase angles increased as the loading frequency increased from 0.01Hz to 1Hz and decreased slightly as the loading frequency increased from 1 Hz to 10Hz. For all test temperatures and loading frequencies, the unmodified mixture exhibited lower phase angles than the modified mixtures. The wet process and dry process mixtures showed similar phase angles at all loading frequencies and test temperatures, with the wet process mixture yielding slightly lower phase angles than the dry process mixture at 20°C and 4°C. The slopes of all loading frequency-phase angle curves were similar, indicating similar phase angle sensitivity to loading frequency across all mixtures.



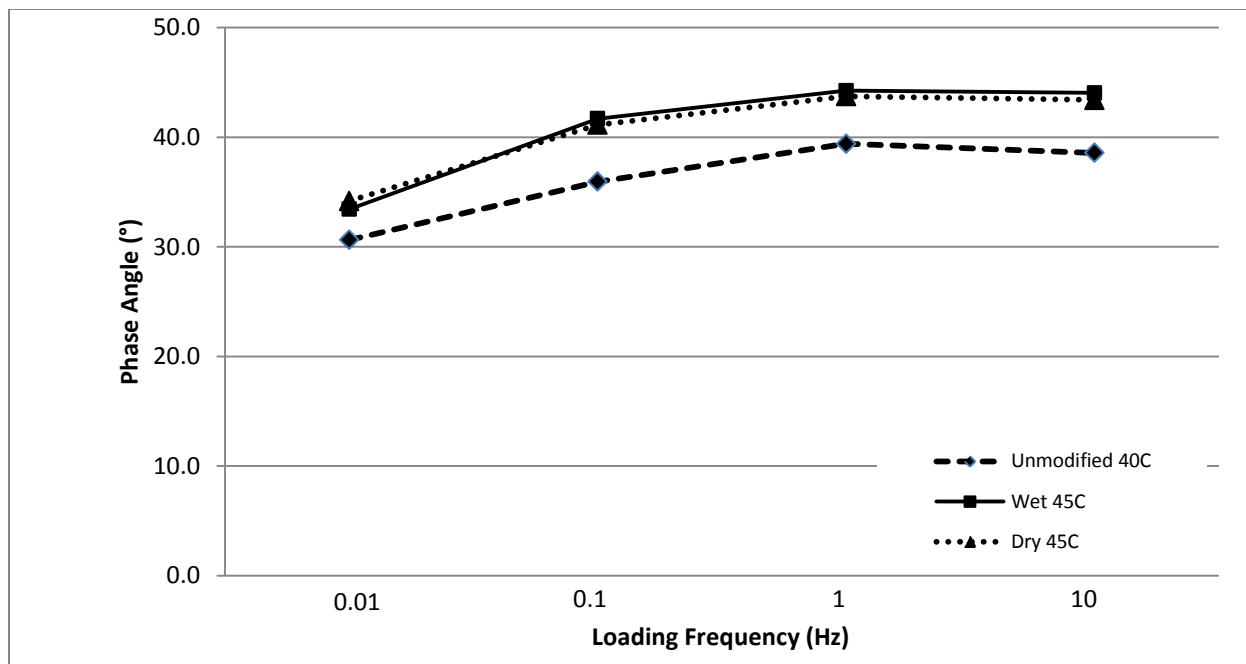


Figure 5.21. Phase angle vs. loading frequency at 40/45°C

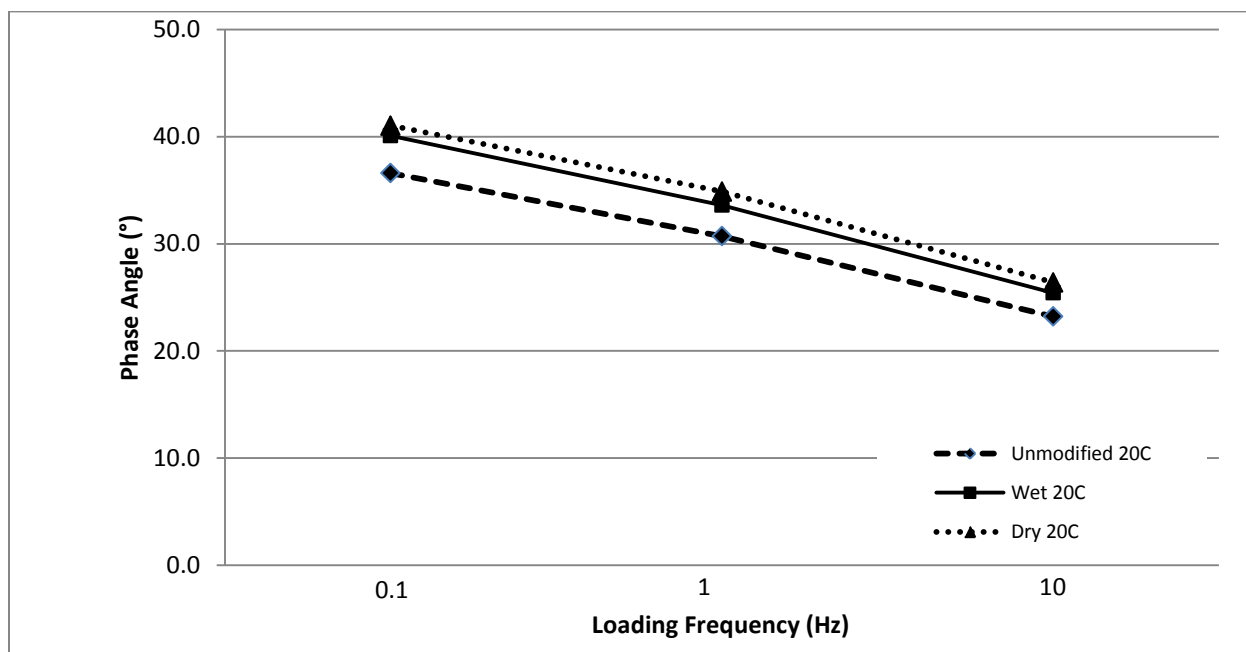
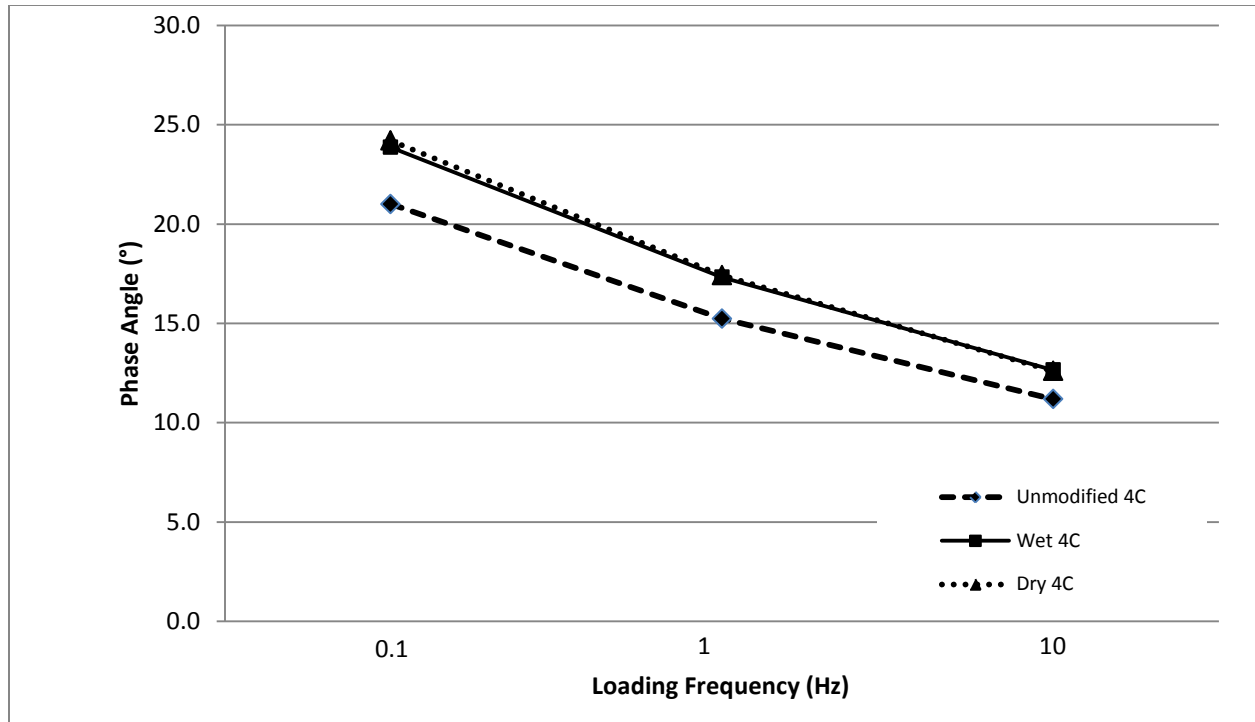


Figure 5.22. Phase angle vs. loading frequency at 20°C



**Figure 5.23. Phase angle vs. loading frequency at 4°C**

#### *Master curves of $E^*$ and phase angle*

A master curve of all  $E^*$  values at 4°C, 20°C, and 40/45°C test temperatures and 0.01Hz, 0.1Hz, 1Hz, and 10Hz loading frequencies for each mixture was obtained using an available optimization program in Microsoft Excel. The data were shifted horizontally relative to a selected reference temperature (20°C) until a smooth curve was generated. The program used a sigmoidal model (Equation 5.1) to describe the master curve and generated the required parameters for the curve based on the raw data (Shen, Xie, and Li 2015).

$$\log(|E^*|) = \log(max) + \frac{\{\log(max) - \log(min)\}}{1 + e^{[\beta + \gamma(\log f_r)]}} \quad 5.1$$

where:

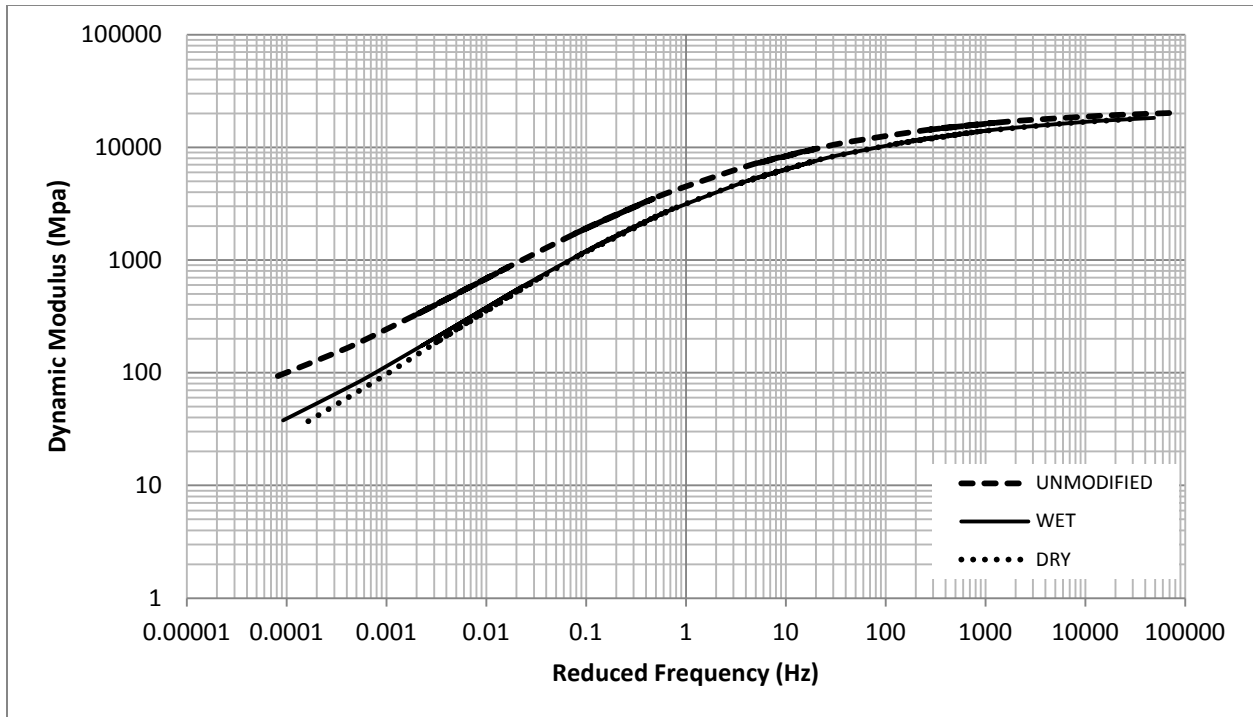
$f_r$  = reduced loading frequency (at reference temperature)

max = limiting maximum value of dynamic modulus

min = limiting minimum value of dynamic modulus

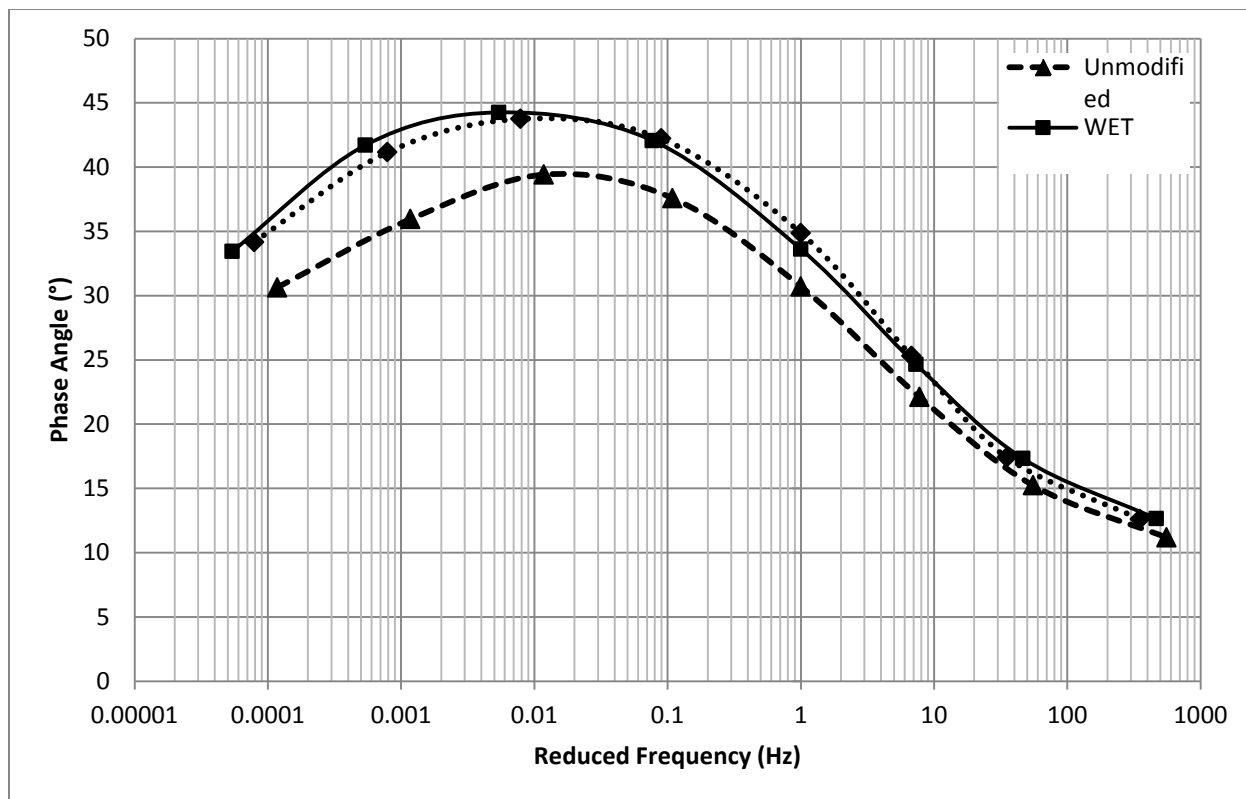
$\beta, \gamma$  = fitting parameters describing the shape of the sigmoidal function

The  $E^*$  master curves for all mixtures are shown in Figure 5.24. The master curve shows that the unmodified mixture performed significantly better than the modified mixtures at lower reduced frequencies, corresponding to high temperatures and low traffic speeds. However, at higher reduced frequencies corresponding to low temperatures and high traffic speeds, the performance of all mixtures was similar. Overall, the unmodified mixture exhibited higher  $E^*$  values at all reduced frequencies. The wet and dry process mixtures exhibited similar  $E^*$  values at all reduced frequencies, with the wet process mixture performing slightly better than the dry process mixture at low reduced frequencies.



**Figure 5.24. E\* master curves**

Figure 5.25 shows the phase angle master curves for all mixtures. The phase angles of all mixtures decreased when the reduced frequency was higher than 0.1Hz. The phase angles of the mixtures exhibited the opposite trend when the reduced frequency was lower than 0.1Hz. The unmodified mixture showed lower phase angles than the modified mixtures across all reduced frequencies. At lower reduced frequencies, equivalent to high test temperatures, the dry process mixture exhibited lower phase angles than the wet process mixture. This indicates that the dry process mixture may be more elastic and less viscous than the wet process mixture at high temperatures.



**Figure 5.25. Phase angle master curves**

#### 5.2.4 ITS Testing

The results of the ITS testing are shown in Table 5.2 and Figure 5.26. The unconditioned samples for the unmodified mixture had a slightly higher ITS value than the unconditioned samples for the modified mixtures. Both modified mixtures had similar ITS values for unconditioned samples. However, the wet process had a significantly higher ITS value for the conditioned samples than the unmodified and dry process mixtures. The wet process mixture had the highest TSR, at 0.902. The unmodified mixture had the lowest TSR, at 0.600. The ITS value for the conditioned wet process samples and the higher TSR value for the wet process indicate that this mixture was least susceptible to stripping. All samples failed in a similar manner by cracking down the vertical diametric plane. This typical failure is shown in Figure 5.27.

Table 5.2. ITS test data

Sample		Avg ITS (kPa)	TSR
Unmodified	Conditioned	665.591	0.600
	Unconditioned	1109.256	
Dry	Conditioned	687.643	0.652
	Unconditioned	1055.097	
Wet	Conditioned	951.239	0.902
	Unconditioned	1054.737	

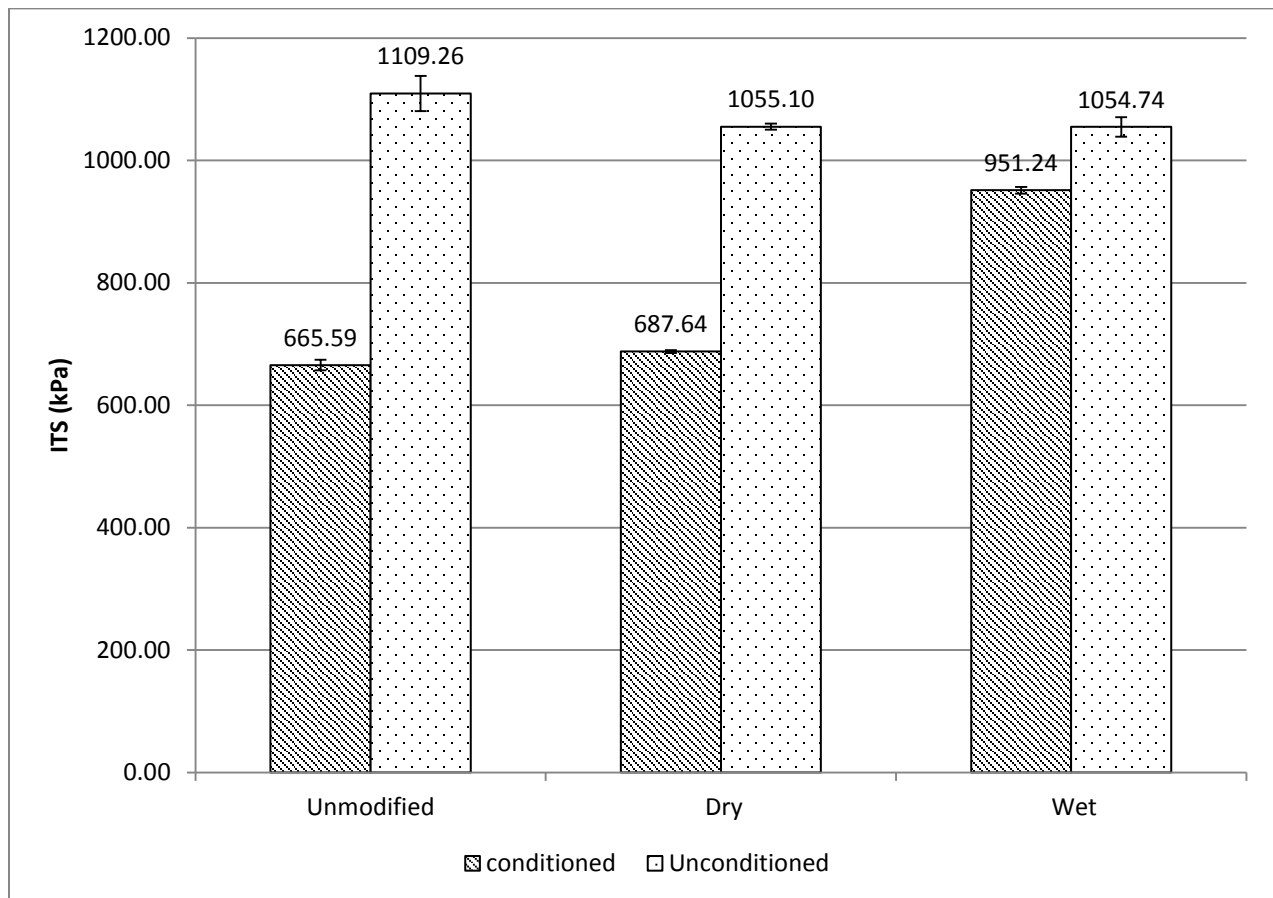


Figure 5.26. Average ITS values



**Figure 5.27. Typical failure of ITS samples**

## CHAPTER 6: CONCLUSIONS

Modified asphalt binders with PET were produced using 5, 10, and 15 percent PET mixed at 3000 and 5000 rpm for one and two hours. Properties of these binders were evaluated using the DSR and RV before aging and using the DSR after RTFO aging. The following conclusions can be drawn about the performance of modified binders:

1. Viscosity of modified binders increased with both increasing mixing time and increasing PET percentages. At 5% PET, the viscosity increased as mixing speed increased from 3000 to 5000 rpm. At 10% PET, the viscosity decreased slightly as the mixing speed increased. All viscosities were well below the standard maximum value of  $3\text{Pa}\cdot\text{s}$ , indicating that the PET did not adversely affect high temperature workability of the binder.
2. The addition of PET increased the pass/fail temperatures of all blends and resulted in a bump in PG grade, exceeding one grade ( $6^\circ\text{C}$ ) in half of the modified blends. This indicated that the PET improved the high temperature performance of all binders.
3. The pass/fail temperatures of unaged binders increased with the addition of PET, up to 10 percent. The 3000 rpm mixing speed produced higher pass/fail temperatures than the 5000 rpm mixing speed. The two hour mixing time produced higher pass/fail temperatures, possibly indicating that a more homogeneous blend was produced.
4. No statistical differences were observed in unaged and RTFO aged blends, indicating that the elevated mixing temperatures due to the high shear mixing



may have prematurely aged the binders. Percent loss in RTFO testing was well below the maximum value of one percent for all blends, indicating that the PET did not contribute excessive volatiles to the mixture.

5. Based on the DSR and RV results, the 10 percent PET blend mixed at 3000 rpm for two hours was selected for further testing in the mixture testing phase. The 15 percent PET blends were discarded because the excess PET particles in the blends made it difficult to obtain consistent DSR and RV results.

The mixture testing phase began with the mixture design process to determine the OAC of an unmodified mixture (control), a wet process mixture, and a dry process mixture. The wet process and dry process mixtures contained 0.65 and 0.74 percent PET by weight of the mixture, respectively. After the OAC of each mixture was determined, SGC samples were fabricated and their performance was evaluated using the APA rutting test, APA Hamburg test, AMPT modulus test, and ITS test. The following conclusions can be drawn about the performance of the modified mixtures:

1. The final OAC values selected were 6.30 percent for the unmodified mixture, 6.45 percent for the wet process mixture, and 6.66 percent for the dry process mixture. The addition of PET led to an increased AC content for all mixtures.
2. Maximum specific gravities for the modified mixtures were greater than the unmodified mixture due to the substitution of the denser PET for a portion of the bitumen. However, bulk specific gravities for the modified mixtures were lower than the unmodified mixture possibly due to the location of PET particles between the aggregate in the mixture, resulting in higher air voids. Therefore,

higher AC was needed in the modified mixtures to reach the same void contents as the unmodified mixture.

3. The wet process mixture exhibited the lowest APA rut depth (3.754mm) after 8000 cycles, indicating that the PET added in the wet process contributed to increased stiffness and recovery of the mixture.
4. The wet process mixture exhibited the lowest creep slope in the APA Hamburg test, indicating that it performed best in the rutting portion of the test. However, it also exhibited the lowest SIP and highest stripping slope, indicating that it was more susceptible to moisture damage than the other two mixtures. The dry process mixture exhibited the highest SIP and lowest stripping slope, indicating that it was least susceptible to moisture damage.
5. In AMPT testing, the unmodified mixture exhibited higher  $E^*$  values and lower phase angles across all test temperatures and loading frequencies indicating that it was stiffer than the modified mixtures, contrary to the APA rutting results. The wet and dry process mixtures exhibited similar  $E^*$  and phase angles across all test temperatures and loading frequencies.
6. The modified mixtures exhibited higher ITS values than the unmodified mixture for the conditioned samples in ITS testing. Additionally, both modified mixtures exhibited higher TSR values. This indicated that the PET improved stripping resistance.

Based on the performance of the modified mixtures in the binder and mixture testing, it can be concluded asphalt mixtures modified with PET may provide performance benefits over unmodified asphalt mixtures. However, the limited sample

size of the study may prevent more concrete conclusions. The results of the study show that PET added in the wet process may improve rutting and stripping resistance asphalt mixtures. The results also indicate the PET added in the dry process may improve resistance to permanent moisture damage. However, the behavior of the PET particles within the mixtures results in higher void contents and necessitates a higher AC than unmodified mixtures. Therefore, the benefits may be outweighed by the increased construction costs attributed to the excess bitumen. Although Casey et al. indicated that the wet process was not a viable method for the incorporation of PET into asphalt mixtures, the results of this study show that the wet process using high shear mixing may provide better performance results than the dry process.

Additional studies of modified binders produced with high shear mixing and PET contents of 0.1 to 0.5 percent (similar to previous studies on the dry process) may yield better results without the need for excess bitumen. Since the PET particles seem to contribute to high void and AC contents in dense mixtures due to their location between the aggregate particles, the incorporation of PET into less dense mixtures may be advantageous. Future studies could evaluate the use of PET in mixtures with higher void contents like OGFC or PEM.

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**APPENDIX B: STATISTICAL ANALYSIS OF UNAGED DSR PASS/FAIL TEMPERATURES**

	5% 3000 1h	5% 3000 2h	5% 5000 1h	5% 5000 2h	10% 3000 1h	10% 3000 2h	10% 5000 1h	10% 5000 2h	15% 5000 1h
5% 3000 2h	N	-	-	-	-	-	-	-	-
5% 5000 1h	N	Y	-	-	-	-	-	-	-
5% 5000 2h	N	Y	N	-	-	-	-	-	-
10% 3000 1h	Y	N	Y	N	-	-	-	-	-
10% 3000 2h	Y	Y	Y	Y	Y	-	-	-	-
10% 5000 1h	N	N	N	N	N	Y	-	-	-
10% 5000 2h	Y	Y	Y	Y	N	Y	N	-	-
15% 5000 1h	N	N	N	N	N	Y	N	N	-
15% 5000 2h	Y	N	Y	N	N	Y	N	N	N

**APPENDIX C: STATISTICAL ANALYSIS OF UNAGED VS. RTFO AGED DSR PASS/FAIL TEMPERATURES**

<b>% Plastic</b>	<b>RPM</b>	<b>Mixing time</b>	<b>RTFO vs. Unaged</b>
<b>5</b>	<b>3000</b>	<b>1h</b>	<b>N</b>
		<b>2h</b>	<b>N</b>
	<b>5000</b>	<b>1h</b>	<b>N</b>
		<b>2h</b>	<b>Y</b>
<b>10</b>	<b>3000</b>	<b>1h</b>	<b>N</b>
		<b>2h</b>	<b>N</b>
	<b>5000</b>	<b>1h</b>	<b>N</b>
		<b>2h</b>	<b>N</b>