Evaluating The Effect of Warm Mix Additive Dosage Rate on Workability of Asphalt

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Abstract

Asphalt concrete construction using hot mix asphalt causes enormous greenhouse gases emissions. Warm mix additives help decrease the production temperatures of asphalt concrete, thus reducing emissions and improving workability at lower temperatures. Generally, the manufacturer recommends the additive dosage rate. This project aimed to study the effect of dosage rate on the viscosity and workability of asphalt. Two asphalt binders, PG 58S-28 and PG 58H-28, with two warm mix additives, Zycotherm and Evotherm, with different dosage rates, were selected. The results of asphalt binder tests showed no significant difference in penetration grade, softening point and rotational viscosity of binder after the incorporation of additives. However, the steady shear flow test did show some reduction in mixing and compaction temperatures in the case of Evotherm. Moreover, densification curves showed additives worked better at an optimum dosage of 0.07% for Zycotherm and 0.4% for Evotherm, achieving a 10°C reduction in compaction temperatures.

Dedication

To my Parents, Teachers and Friends for their longing support and love.

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List of Symbols, Nomenclature, or Abbreviations

AASHTO – American Association of State Highway and Transportation Officials

ASTM – American Society for Testing Materials

ESALs – Equivalent Standard Axle Loads

HMA – Hot Mix Asphalt

WMA – Warm Mix Asphalt

PG – Performance Grade

BRD – Bulk Relative Density

MRD – Maximum Relative Density

SSF – Steady Shear Flow

Chapter 1: Introduction

According to the book *Hot Mix Asphalt* by Carter *et al*. (2018), Canada has over 1,000,000 km of roads, out of which 40 % are paved. Flexible pavements comprise about 95 % of the paved roads. Generally, flexible pavements are made using hot mix asphalt. Hot mix asphalt is a mixture of asphalt binder and aggregates. As the term hot indicates, the binder and the aggregates are heated to high temperatures for mixing and then compacted at high temperatures to achieve the required density. The compaction is proportional to the temperature of the mix. Achieving the required density, usually 6-8 % air voids content in the field, is crucial for adequate performance of pavement during its expected service life. Incorrect asphalt concrete density can lead to early deterioration of pavement. Undercompaction can make the pavement more susceptible to moisture infiltration, moisture damage, rutting and cracking. On the other hand, overcompaction can also cause cracking and bleeding of asphalt binder (Zaltuom, 2018).

The transportation sector is the single largest contributor to greenhouse gas emissions in the United States (Kay, *et al*., 2014). The high mixing and compaction temperature during the production of asphalt mixture is the main source of greenhouse gas emissions in pavement construction. Aggregate heating accounts for 67%, asphalt heating 14% and asphalt concrete mixing 11% of the total CO_2 emissions in the road construction process (Peng, *et al*., 2015). Since the major research focus in the 21st century has been on sustainability, researchers have tried to find different technologies for the production of asphalt concrete. One of the alternatives is warm mix asphalt.

Warm mix asphalt makes use of warm mix additives to reduce binder viscosity and improve workability at lower temperatures than hot mix asphalt with no compromise on

the performance of pavements. In 2010, Kandhal reported that a 30% reduction in fuel consumption could be achieved by using warm mix additives. Warm mix technology can be achieved by using the foaming process, organic additives or chemical additives. The chemical and organic additives are added to the asphalt binder by weight. Based on temperature reduction, asphalt can be classified into warm mix, half-warm mix asphalt, and cold mix asphalt (D'Angelo, *et al*., 2008). The production temperatures for warm mix asphalt are in the range of 110-145°C, for half warm mix below 100°C and for cold mix asphalt below 60°C. By comparison, production temperatures for hot mix asphalt are in the range of 145°C to 175°C. Although cold mix asphalt has the most environmentally friendly temperatures, the performance of pavement is not satisfactory when compared to hot mix asphalt. The mixing and compaction temperatures for warm mix asphalt and dosage rate are usually recommended by the manufacturer of the warm mix additives based on aggregate characteristics and reclaimed asphalt content.

Since the manufacturer makes a recommendation on dosage rate as a range, this project aimed to study the effect of changing the dosage rate within that recommended range on the viscosity and workability of asphalt concrete by keeping other variables constant.

1.1 Problem Statement

Warm mix additive dosages are being selected by the New Brunswick paving industry without knowledge of the effect of dosage rate on the viscosity and workability of asphalt concrete. The Department of Transportation has perceived impacts on the compaction of mixes with different additives or dosage rates.

Since the New Brunswick Department of Transportation has fully adopted the use of warm mix asphalt, there was a research gap in the effect of the dosage rate of warm mix asphalt. Hence, this study aimed to cover this research gap.

1.2 Research Question and Hypothesis

1.2.1 Research Question

What is the effect of dosage rate on the viscosity and workability of asphalt concrete?

1.2.2 Research Hypothesis

It was hypothesised that increasing the amount of additive in the binder would decrease the viscosity of the asphalt binder and improve workability. The mixing and compaction temperatures would decrease by increasing the additive percentage.

1.3 Research Goals and Objectives

1.3.1 Research Goals

The goal of this project was to quantify the effect of the dosage rate of warm mix additives.

1.3.2 Research Objectives

The research goal was accomplished by completing the following objectives:

1. Select the binder grade and warm mix additives commonly used by the New Brunswick Department of Transportation (NBDTI).
2. Select an asphalt mix design approved by NBDTI.
3. Develop a testing plan with different dosage rates of warm mix additives and control binders.

4. Evaluate the mixing and compaction temperatures of control binders and binders modified with warm mix additives.
5. Evaluate the compaction effort of control and warm mix asphalt concrete.

1.4 Scope and Limitations

1.4.1 Scope

The scope of this project was limited to studying the consistency of asphalt binder after the addition of warm mix additives by standard binder testing, including penetration, softening point and viscosity at high and intermediate temperatures. The asphalt concrete compaction effort was also studied.

1.4.2 Limitations

One of the major limitations was the time required to conduct this study, and as such, a single experiment was performed for each test. It is important to clarify that for some standards, a single experiment includes two or three readings on the same sample, but others only deliver one result per specimen, and due to time and materials constraints, multiple specimens could not be prepared to obtain the average and standard deviation. The sources and supply of warm mix additives were also reduced. The amount of aggregates for the study of densification curves was also constrained.

1.5 Assumptions

The following assumptions were made during the study:

- The tests selected could detect differences caused by the additive dosage.

- The equipment used is consistently accurate and will not produce any discrepancies in the results.

1.6 Report Layout

This report is subdivided into the following sections:

- Chapter 2 familiarizes the reader with background information on flexible pavements, hot mix asphalt, warm mix asphalt, types of warm mix technologies, and advantages of warm mix asphalt.
- Chapter 3 covers a literature review on warm mix additives dosage rate and different mixing and compaction temperatures determination tests and techniques.
- Chapter 4 covers materials, methodology, sample preparation, tests standards and tests description.
- Chapter 5 covers the results and analysis of the tests conducted.
- Chapter 6 provides conclusions and recommendations for further studies.

Chapter 2: Background

2.1 Pavement Engineering

Pavement engineering is the branch of transportation engineering that specializes in the design of pavement cross sections, maintenance, and rehabilitation of the pavements, depending on environmental and load stresses (Michigan State University, 2021). There are three broad categories of pavements:

- Rigid pavements, which consist of portland cement concrete slabs resting directly on either coarse aggregate base or compacted soil foundation.
- Flexible pavements, which consist of hot mix asphalt concrete laid on layers of coarse and fine aggregates.
- Composite pavements, in which asphalt concrete is laid on rigid pavement to support traffic.

2.2 Flexible Pavement Structure

Flexible pavements are generally comprised of several layers performing different functions in order to support the traffic flow. The layers can be divided into surface layers, granular layers and subgrade. The subgrade is the underneath foundation and consists of natural soil. It is compacted, graded, and stabilized before other layers are laid upon it. It can be any soil type with known characteristics in order to design other layers precisely. Granular layers are usually divided into two: the granular subbase and the granular base. The granular subbase consists of crushed stone aggregates laid, stabilized and compacted on top of the subgrade. The granular base course also consists of crushed stone aggregates

but of higher quality because this layer is directly underneath the asphalt layer and has to resist higher stresses than the subbase. Surface layers are also typically divided into two: base course and surface or wearing course. The base course is the main asphalt layer, which is composed of hot mix asphalt and has to resist and distribute stresses and strains to the underneath foundation. It also provides fatigue cracking resistance. The surface course or wearing course is the layer of hot mix asphalt that comes directly in contact with traffic and environmental disturbances. It has to provide smooth and comfortable ride quality while withstanding external disturbances (Carter, *et al.*, 2018).

2.2 Hot Mix Asphalt

Hot Mix Asphalt (HMA) is the mixture of asphalt binder and aggregates heated and mixed at very high temperatures, typically in the range of 145-175 °C. This mixture is then laid on a granular base course and compacted in the range of 110-135 °C. The quantity of asphalt binder and gradation of aggregates is typically determined following a volumetric design approach. The asphalt concrete produced should have the following properties (Carter, *et al.*, 2018):

- Compactability and workability
- Permanent deformation resistance
- Fatigue cracking resistance
- Thermal cracking resistance
- Durability and moisture resistance
- Skid resistance

2.3 Warm Mix Asphalt

Warm mix asphalt, as the name indicates, is prepared at lower temperatures than hot mix asphalt but has similar mechanical properties in the field. This reduction in temperature is

usually in the range of 20-30°C and is achieved by the addition of warm mix additives (Rubio, *et al*., 2012). These warm mix additives can be broadly classified, based on the technology used, into chemical additives, organic additives and water-based or containing foaming processes. The manufacturing and technological processes of these additives could be different, but they all work by reducing the viscosity of asphalt binder and improving the workability of asphalt mix at lower temperatures than hot mix asphalt (Rubio, *et al*., 2012).

2.3.1 Foaming Process

The foaming process works by injecting a small amount of cold water into the hot asphalt binder or mixing chamber. When water comes in contact with the hot binder, it evaporates into steam. The steam gets trapped and creates a large amount of foam in the asphalt binder. This temporarily increases the volume of the asphalt binder and reduces the viscosity of the asphalt mix. This process enhances the coating and workability of the mix but for a limited amount of time (Kheradmand, *et al*., 2014). However, the amount of water added must be small in order to prevent stripping. Anti-stripping additives are also recommended for preventing loss of adhesion (Kheradmand, *et al*., 2014) (Rubio, *et al*., 2012).

The foaming process can be divided into two categories based on the way water is added. If water is added directly, it is called the water-based foaming process, and if water is added indirectly, it is called the water-containing foaming process.

Water-based technologies make use of special nozzles to inject cold water to produce foaming and increase the volume of the binder, which slowly collapses. It is a more direct way of adding water.

Water-containing technologies make use of synthetic zeolite for foaming creation. Synthetic zeolite is hydro-thermally crystallized and is composed of aluminosilicates of alkali metals. About 20% of water is contained in crystallization, which is released when the temperature rises and produces foaming in the binder, which lasts about 6-7 hours (Rubio, *et al*., 2012).

2.3.2 Organic Additives

Organic or wax additives work by decreasing the viscosity of asphalt binders above their melting points. These waxes are usually added at a rate of 2-4% by weight of binder. These additives also improve the deformation resistance of asphalt concrete when crystallization occurs (Shang, et al., 2011). However, care is taken to choose the wax whose melting point is greater than pavement service temperatures. The right wax is solid at service temperatures and also minimizes the embrittlement of asphalt at low temperatures (Shang, *et al*., 2011) (Rubio, *et al*., 2012).

2.3.3 Chemical Additives

Chemical additives do not work by reducing the viscosity of binder to lower mixing and compaction temperatures; instead, they make use of polymers, surfactants and adhesion promoters to achieve workability at lower temperatures (Rubio, *et al*., 2012). They are mixed with asphalt binder before they are batched for the asphalt concrete mixing process, and the quantity of the additive depends on the manufacturer, usually based on aggregate quality and the amount of reclaimed asphalt material.

2.3.4 Advantages of Warm Mix Asphalt

Based on research, there are several advantages of using warm mix asphalt. The first and foremost advantage is that they behave similarly mechanically in the field, like hot mix asphalt at lower production temperatures. The use of lower production temperatures reduces fuel consumption. According to Kandhal (2010), a 30 percent reduction in fuel consumption is achieved on average by the inclusion of warm mix technologies. This reduction in fuel also has financial savings. The lower production temperatures also reduce greenhouse gas emissions. Kheradmand *et al*. (2014) constructed a table summarising the reduced greenhouse emissions present in the literature. The amounts of greenhouse gas reduction are reproduced here in Table 1.

Table 1: Percentage reduction in gas emissions, from (Kheradmand, *et al*., 2014)

Gas (%)	Vaitkus[a]	Bueche[b]	Larsen[c]	D'Angelo[d]	Evotherm
CO_2	30-40	30-40	31	15-40	46
SO_2	35	-	-	20-35	81
VOC	50	50	-	>50	30
CO	10-30	-	29	10-30	63
NO_x	60-70	-	62	60-70	58
Dust	20-25	-	-	25-55	-

[a]Vaitkus ***et al***., (2009)
[b]Bueche ***et al***., (2009)
[c]Larsen ***et al***., (2004)
[d]D'Angelo ***et al***., (2008)

Another advantage of using Warm Mix Asphalt (WMA) is that the difference between production temperature and ambient temperature is less than in hot mix asphalt. This enables greater hauling distances and time for compaction. The use of warm mix additives also reduces the viscosity of the binder. Some binders are modified with polymers to

enhance the performance of the mix in the field. These polymers can make the binder stiffer and require greater mixing and compaction temperatures. The addition of warm mix additives in these binders makes them workable at lower temperatures. Warm mix asphalt also helps prevent ageing of the binder. Long exposures to high temperatures cause loss of volatile oils in the binder. This loss can cause short-term ageing, making binder stiffer when asphalt is produced, thus reducing pavement durability. The use of warm mix additives lowers the exposure to high temperatures, thus resulting in lower loss of these oils and improving the performance of asphalt pavement (Gandhi, *et al*., 2009). Warm mix additives also enable the use of reclaimed asphalt pavement in greater quantities, thus making asphalt pavements more sustainable.

Chapter 3: Literature Review

3.1 Effect of Evotherm 3G on viscosity and performance of asphalt

Zawawi *et al*. (2023) studied the effect of Evotherm 3G on the viscosity and performance of asphalt mixture by performing penetration grade test, softening point test, rotational viscosity test and Marshall stability and flow test. Three dosage rates of Evotherm 3G, 0.4%, 0.45% and 0.5%, were used for the Marshall stability and flow test, while one dosage rate, 0.4%, was used for all other tests. A control sample was also tested to compare the results. It was found that there was no significant difference in penetration grade and softening point and viscosity by the addition of 0.4% Evotherm 3G when compared to virgin binder; however, at lower temperatures, the viscosity of binder increased by the addition of Evotherm 3G. The results of Marshall stability and flow indicated that a 0.4% dosage rate yields the best stability. The 0.4% Evotherm sample was also compared to the control HMA sample, and it was found that the Evotherm sample performed better than the HMA sample in the Marshall stability and flow test. It was concluded that 0.4% was the optimum dosage for Evotherm 3G for 60/70 grade bitumen (Zawawi, *et al*., 2023).

3.2 Effect of Zycotherm on viscosity and performance of asphalt

The effect of Zycotherm on the viscosity and performance of asphalt mixture was studied by Hasan *et al*. (2017) using 0.1% Zycotherm by weight in two binders, 60/70 and 80/100. Penetration test, softening point test and rotational viscosity test were performed on control and Zycotherm samples. Complex shear modulus (G*) and phase angle were also determined by the use of a dynamic shear rheometer to study the viscous and elastic properties of the binder. A modified Lottman test, Hamburg wheel tracking test, and dynamic creep test were also performed to characterize the performance of the mixtures. It

was found that the addition of Zycotherm did not alter the penetration grade of the binder but lowered the softening point when compared to virgin binder. The rotational viscosity test could not differentiate between modified and virgin binders. The dynamic shear rheometer showed that both binders performed comparably in rutting, and the addition of Zycotherm did not adversely affect resistance to permanent deformation of the binders. The workability and compactability indexes showed that the Zycotherm-modified sample required less compaction energy than the HMA sample. Comparable results were found for the moisture susceptibility and dynamic creep tests; however, the Hamburg wheel tracking test showed lower resistance to rutting for the modified binder sample when compared to the HMA sample. It was attributed to less ageing of the binder due to lower exposure to high temperatures (Hasan, *et al*., 2017).

3.3 Assessment of workability and compactability of warm mix asphalt mixtures

In 2010, Bennert *et al*. conducted a detailed study to assess the workability and compactability of warm mix asphalt concrete. A control sample was compared with different dosages of Rediset, Sasobit and Evotherm warm mix additives by using the rotational viscometer test, lubricity test, asphalt workability device test, Marshall compactor and gyratory compactor. The results concluded that the rotational viscosity test resulted in unrealistically high mixing and compaction temperatures because chemical additives do not change the viscosity of the binder. The lubricity test was able to rank the samples according to rational thinking that increasing the dosage rate of warm mix additive would increase the workability of the asphalt mixture. The gyratory compactor appeared to be insensitive to dosage rate and compaction temperatures. The Marshall compactor and

asphalt workability device were also able to rank the samples rationally (Bennert, *et al*., 2010).

3.4 Effect of warm mix additives on high-viscosity asphalt

Liang *et al*. (2022) studied the effect of warm mix additives on high-viscosity asphalt binder, which is used for porous pavements. Control binders with four different warm mix additives, Sasobit, EC120, Evotherm and foam with varying dosage rates, were studied using penetration test, softening point test, rotational viscosity test, ductility test, absolute viscosity test, bending beam rheometer creep stiffness and creep rate test and rutting factor and zero shear viscosity test using dynamic shear rheometer. The rotational viscosity results at 135°C showed that adding any warm mix additive decreased the viscosity of asphalt binder with increasing dosages. Organic wax additives increased absolute viscosity at 60°C with increasing dosages, and the foaming process did not significantly affect the absolute viscosity. However, the addition of Evotherm initially increased the absolute viscosity and then a decreasing trend was observed with increasing dosages. The toughness and tenacity values decreased with the inclusion of organic and chemical warm mix additives by increasing the dosage, but the foaming technique resulted in an insignificant difference. The penetration values were significantly reduced by the inclusion of organic additives, while chemical additives and the foaming technique had no significant effect. Similarly, the softening point of the binder increased significantly with increasing dosage of organic additives, while chemical additives did not result in a significant increase in softening point, and the foaming technique resulted in a random trend. Ductility results showed a decreasing trend with the inclusion of organic wax additives and a random trend with chemical additives and the foaming technique. Other tests concluded that organic wax

additives and chemical additives improve high-temperature performance while the foaming technique of warm mix asphalt has adverse effects. The organic wax additives and foaming technique also reduce the intermediate cracking resistance of high-viscosity asphalt, while chemical additives improve it. Similar results were obtained for low-temperature cracking resistance. Based on the results, it was determined that the chemical additive Evotherm with a dosage rate of 1% is most suitable for high-viscosity porous asphalt (Liang, *et al*., 2022).

3.5 Mixing and compaction temperature techniques

There are many methods to determine the mixing and compaction temperature of asphalt binders. Some of them are the conventional rotational viscosity method, also known as the equiviscous method, zero shear viscosity method, high shear rate method, high shear rate evolution approach, flow behaviour method, and steady shear flow method. Sukhija *et al*. (2021) reviewed all these methods in their study and found that since chemical additives do not influence binder viscosity, these methods are not sufficient to determine the mixing and compaction temperature of warm mix modified asphalt. The study did not include steady shear flow method evaluation because it was conducted at intermediate temperatures. However, some researchers found the steady shear flow method to be suitable for the determination of mixing and compaction temperatures of modified asphalt binders. The study also proposed the workability approach prototype and found consistent and rational results (Sukhija, *et al*., 2021).

The literature about viscosity and workability of warm mix asphalt has contradicting results, with some researchers accurately predicting mixing and compaction temperatures with either rotational viscometer or steady shear flow test while others developing and

proposing new methodologies because none of the methods could determine mixing and compaction temperatures of the modified binder.

Chapter 4: Materials and Methodology

This chapter presents details of the materials used in this study with their corresponding properties and describes the methodology of each of the tests conducted.

4.1 Materials

4.1.2 Asphalt Binder

Two asphalt binders, PG 58S-28 and PG 58H-28, were used in the testing because these were mainly used in road construction in New Brunswick at the time of testing. The 'S' stands for Standard Traffic and is used if traffic is less than 3 million ESALs while 'H' stands for High Traffic and is used if traffic is between 3 and 10 million ESALs during the service life of asphalt pavement. This type of grading is done using Multi-Stress Creep Asphalt Binder (MSCR) Specification by performing MSCR test. From the asphalt mix design used, the optimum asphalt content was determined to be 5.9%.

4.1.3 Warm Mix Additives

Two warm mix additives, Evotherm and Zycotherm, were selected for testing based on current use by agencies in New Brunswick. The dosage rate was selected based on the minimum, maximum, and average recommendations of the manufacturer. Evotherm M1, formerly known as Evotherm 3G, is a fatty amine derivative chemical anti-stripping and warm additive manufactured by Ingevity Corporation. The recommended dosage rate of Evotherm M1 is 0.25-0.5%, depending on the quantity of recycled asphalt content. Zycotherm is an organosilane-based liquid anti-stripping additive by Zydex, which has the additional benefit of acting as a warm mix additive. It works on very low dosage rates when compared to other warm mix additives. The dosage rate recommended by Zydex is 0.03-0.1% by weight of binder for non-modified asphalt binders and 0.07-0.125% for polymer

modified and RAP mixes by weight of total binder. The shelf life claimed by the manufacturer is up to 48 months.

4.1.4 Aggregates

The aggregates were provided by the New Brunswick Department of Transportation and Infrastructure, which sourced them from a quarry in Bathurst, New Brunswick. The properties of these aggregates, as provided by NBDTI, are reproduced in Table 2. The gradation used for the densification curve test is given in Table 3 and represented by the fuller curve and NBDTI limits in Figure 1.

Table 2: Aggregates Properties, by NBDTI

Fine Aggregates	**Bulk Specific Gravity**	**2.834**
	Absorption (%)	1.2
	Micro Deval loss (%)	13.4
	Uncompacted Void Content (%)	49.6
Coarse Aggregates	Bulk Specific Gravity	2.865
	Absorption (%)	0.44
	Micro Deval Loss (%)	6.6
	Freeze-Thaw Loss (%)	1.4
	Flat and Elongated 4:1 (%)	9

Table 3: Aggregates Gradation

Sieve Size	% Passing
12.5	100
9.5	91.2
6.3	71.2
4.75	58.6
2.36	37.3
1.18	25.2
0.6	18.1
0.3	12.8
0.15	8.57
0.075	5.87

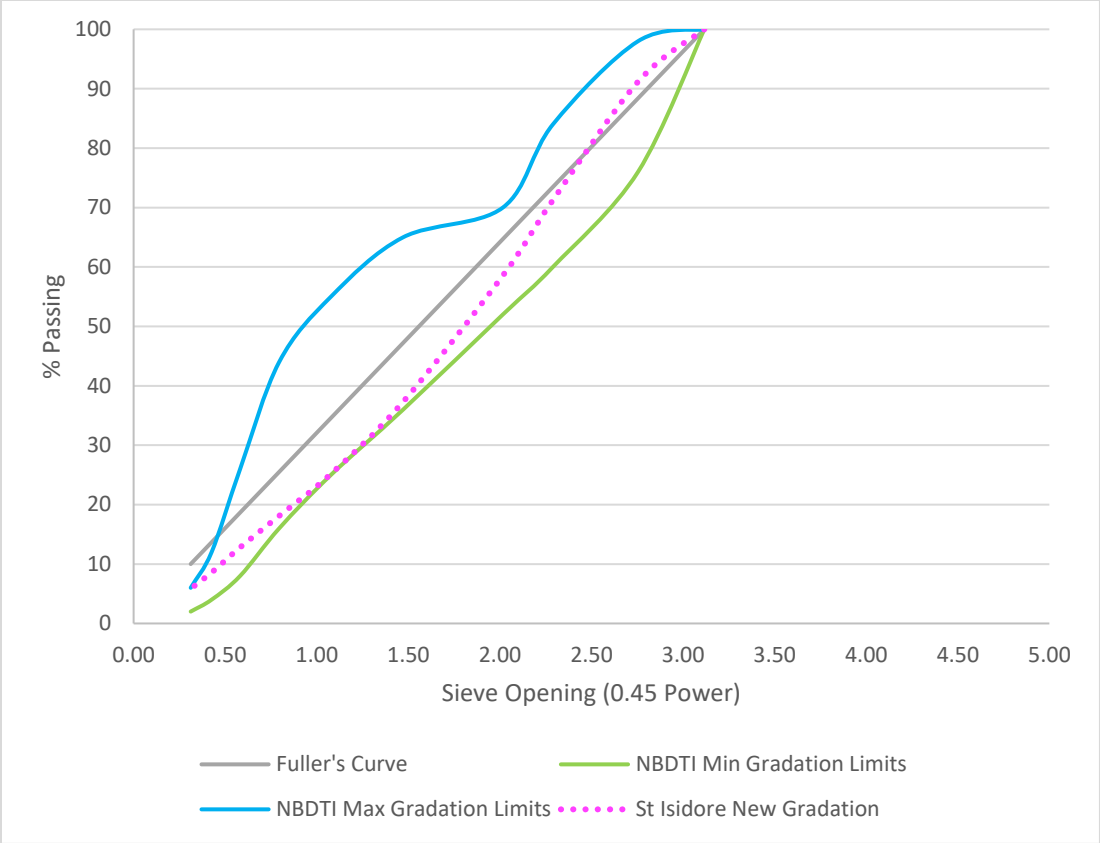

Figure 1: Aggregates Gradation with NBDTI Limits, from (Ruiz Salom, 2023)

4.2 Methodology

4.2.1 Testing Plan

Three dosage rates for both Evotherm M1 and Zycoherm were selected for testing. Tests were performed for six warm mix modified binders and one control binder. All tests were performed for PG 58S-28 binder, but steady shear flow and densification curve tests were not performed for PG 58H-28. The testing plan is shown in Figure 2, and the tests conducted are summarized in Table 4.

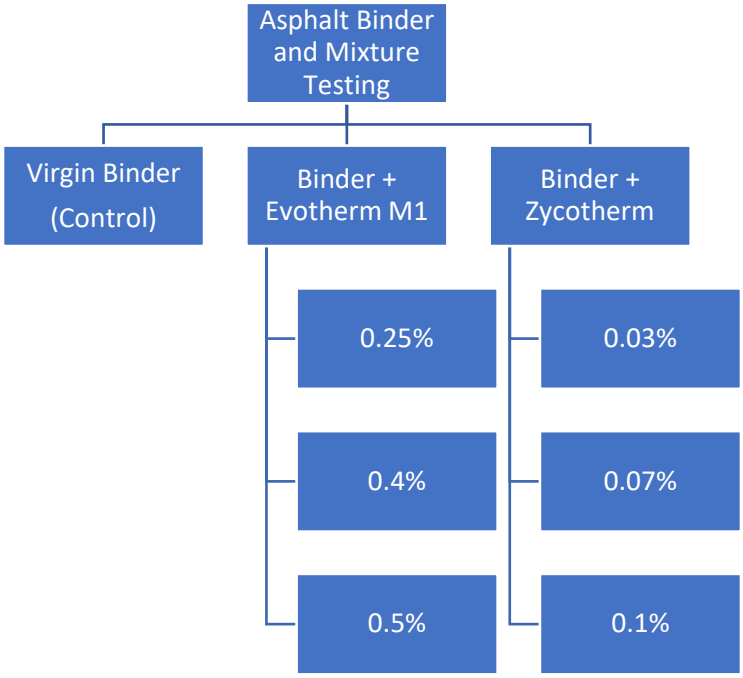

Figure 2: Testing Plan

Table 4: Tests Conducted

Test	Standard	PG 58S-28	PG 58H-28
Penetration Grade Test	ASTM D5/D5M	✓	✓
Softening Point Test	ASTM D36/D36M	✓	✓
Rotational Viscosity Test	ASTM D4402/D4402M	✓	✓
Steady Shear Flow Test		✓	×
Densification Curves		✓	×

Warm Mix Asphalt Binder Preparation:

Warm mix asphalt binders were prepared by heating virgin asphalt binders of approximately 275g in different cans to 130°C in an oven and then adding warm mix additives in different dosages by weight of the binder. The binder was then placed on a hot

plate to keep the temperature in the 130-135°C range when the mechanical agitator mixed the additive and binder for homogenous mixing. The speed of the agitator was set to 250 rpm, and a 15-minute timer was used for each mixing.

4.2.2 Penetration Grade Test

Penetration grading is the old grading system which was used before the Superpave grading system or performance graded system for characterization of asphalt binders. The penetration grade test was performed to characterize binders. The ASTM Standard D5/D5M (ASTM, 2020) regulates the penetration grade test. This test measures the consistency or hardness of asphalt binders in 10^{th} of millimetres when a standard needle and spindle of 50g weight with an additional 50g weight penetrates asphalt binder at a standard temperature of 25°C for 5 seconds.

Testing Procedure :

Control and warm mix asphalt binders were heated to 130°C in the oven and then transferred to small containers, conforming to the volumetric requirements of the ASTM D5/D5M standard. The binders were allowed to cool down for 60 minutes and then transferred to a water bath at 25°C and temperature was maintained for 90 minutes. The binders were then tested using a digital penetrometer, as shown in Figure 3.

Figure 3: Digital Penetrometer

Three penetration readings were collected, making sure that they were at least 10 mm apart from each other and the sides of the container. The needle was also cleaned between consecutive tests. It was made sure that the difference between the highest and lowest reading is less than 4 (0.01 mm) as recommended by the standard, and readings not confining to these requirements were neglected.

4.2.3 Softening Point Test

The softening point test is used to determine the softening point of asphalt binders. The softening point is the temperature at which asphalt binder becomes soft enough it cannot support the weight of a 3.5g steel ball. ASTM standard D36/D36M (ASTM, 2020) standardizes the procedure for softening point tests of bitumen. Two horizontal asphalt binder discs supporting steel balls are heated at a controlled rate, and the softening point is determined as the average of two temperatures when steel balls fall to a distance of 25mm. The test apparatus is shown in Figure 4.

Figure 4: Ring and Ball Apparatus

Testing Procedure :

The binder and brass rings were heated to 120°C in the oven, and then the binder was poured into the brass rings and allowed to cool down. The top surface was made flat using a hot spatula. The ring holder with brass rings and steel balls was placed inside the beaker containing water at 5°C in the fridge for 15 minutes. After 15 minutes, the steel balls were placed on the discs with ball centering guides. The beaker with the thermometer was then placed on the hot plate at 400°C, and an 8°F/min rate of heating was maintained throughout the duration of the test. The temperatures at which the balls touched the bottom plate 25mm apart were noted and averaged to determine the softening point. If the difference between two temperatures exceeded 1°C, the test was repeated.

4.2.4 Rotational Viscosity Test

The rotational viscosity test determines the dynamic viscosity of asphalt binder by measuring the torque required to rotate a cylindrical spindle in a binder at a constant speed

of 20 RPM. The test is standardized in ASTM D4402/D4402M standard (ASTM, 2022) and is also called equiviscous method. The standard requires maintaining a resisting torque of 10% to 98% of the instrument capacity. The speed can be changed if the binder behaves like a Newtonian fluid. A Newtonian fluid is a fluid whose viscosity does not depend on the shear rate; it remains constant irrespective of the change in shear rate. Lamy Rheology's RT-1 Plus rotational viscometer with spindle mk sv 21 was used for testing, as shown in Figure 5.

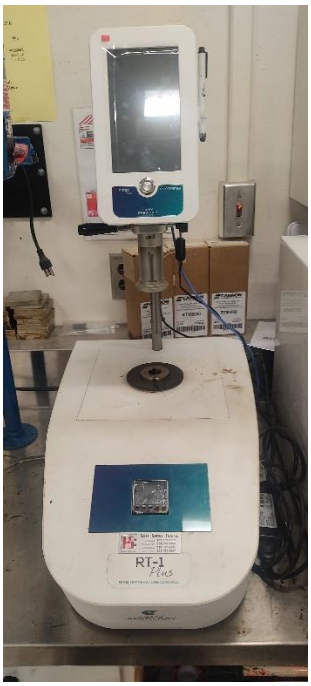

Figure 5: Rotational Viscometer

Testing Procedure:

Binders, disposable cups, and spindle were heated in an oven at 120°C, and then 7.5 grams of binder was poured into disposable cups. The disposable cup was then inserted into the heating chamber of the viscometer at 125°C temperature. The spindle was then attached to the viscometer after zeroing the torque head. After the testing temperature was reached, the

spindle was lowered into the binder, and 15 minutes time was allowed for temperature equilibrium without the spindle rotating and 5 minutes with the spindle rotating. After the thermal equilibrium was reached, the viscosity recorded by the machine was noted for 3 minutes at each 1-minute interval. These readings were then averaged to get the viscosity of asphalt binder at the respective temperatures. The test was performed for 3 temperatures: 125°C, 135°C and 145°C for all binders. The viscosity of the binders against these temperatures was then plotted on a log viscosity-temperature scale and extrapolated. The laboratory mixing and compaction temperatures were determined when the viscosity of the binder reached 0.17 Pa.s and 0.28 Pa.s as recommended by the Asphalt Institute (Asphalt Institute, 2016).

4.2.5 Steady Shear Flow Test:

The equiviscous method using a rotational viscometer determines very high mixing and compaction temperatures for modified asphalt binders, so Reinke proposed a new method for calculating the viscosity of binders with a dynamic shear rheometer. This method uses a 25mm parallel plate geometry with a 500-micron gap and determines viscosity at a target shear stress of 500 Pa. A range of shear stress from 0 to 500 Pa is applied at 76, 82 and 88°C temperatures, and a viscosity value at 500 Pa is chosen because, at this temperature, binders appear to be stabilized and in a steady state. The mixing and compaction temperatures are determined by plotting log viscosity and temperature graphs and determining temperatures at which the binder reaches a viscosity of 0.17 Pa.s and 0.35 Pa.s, respectively (Reinke, 2003).

Testing Procedure :

Binders were heated to 120°C in the oven and then poured approximately 0.7 grams in circular disc form on paraffin paper and allowed to cool down. Dynamic shear rheometer and heating system were turned on. 20 mm parallel plate geometry was used because of the availability at the time of testing. The rheometer was zeroed before placing the sample on the plate. Once the sample reached the testing temperature, a 500-micron gap was achieved with a software command. The sample was then trimmed from the sides of the plate, and temperature was maintained for 10 minutes for thermal equilibrium. After thermal equilibrium was achieved, the test was started by applying shear stress from 0 to 500 Pa in logarithmic mode with at least 5 shear stresses per decade with a tolerance of 2%. The viscosity value at 500 Pa shear stress at temperatures 76, 82 and 88°C was plotted in log viscosity versus temperature scale and extrapolated to determine mixing and compaction temperatures.

4.2.6 Densification Curves

Densification curves show the level of compaction with the number of gyrations, which can be used as an indicator of the compaction effort required to densify the sample. This curve is plotted as the percentage of theoretical maximum relative density achieved versus the number of gyrations. Superpave gyratory compactors have the ability to measure height with the number of gyrations, which enables the determination of the density of the mix at specific gyration. The more the relative density is achieved with the number of gyrations with other variables constant, the better the workability of the mix is. The procedure is described in the following sections:

Mixing and Compaction Procedure :

Approximately 4500g of aggregates and binder were heated to a temperature of 130°C, and mixed using a mechanical mixer shown in Figure 6 and divided into two pans. 1550g was used to determine the theoretical maximum relative density and 1500g was used for compaction. For compaction, the asphalt mix was heated to 130°C for hot mix asphalt control sample 1 and 120°C for hot mix asphalt control sample 2 and warm mix asphalt samples. During this time, the mix was also conditioned for four hours at 116°C with stirring at each hour interval following AASHTO R30 (AASHTO, 2022) short-term conditioning guidelines. After conditioning, the mixes were heated until they reached compaction temperatures, and then a Gyrocomp gyratory compactor was used for compacting the mixes with a 100mm diameter setting following AASHTO T 312 (AASHTO, 2019). The number of gyrations was set to 120 and used as the only limiting parameter to stop the test. This number of gyrations was chosen to achieve more than 92% of maximum relative density.

Figure 6: Asphalt Concrete Mixer

Maximum Theoretical Relative Density :

Maximum theoretical relative density was determined following ASTM D2041 (ASTM, 2019) using the Rice test apparatus, as shown in Figure 7.

Figure 7: Asphalt Rice Test Apparatus

The asphalt mix was heated to 110°C and then spread on cardboard so that the mix did not form lumps. When the mix reached room temperature, it was rolled between hands to make sure aggregates were separate. The mix was then put in a flask of known mass, and the dry weight was determined. After that, water was slowly added to the flask so that no air was trapped, and all the mix was submerged. The flask was then placed on the shaker, and a vacuum of 27.5 ± 2.5 mm of Hg pressure was achieved and maintained for 15 minutes. During this time, the bowl was also shaken to make sure air bubbles were popped. After 15 minutes, vacuum pressure was gradually released, and the mix was weighed under water with the flask after leaving it for 10 minutes. The flask without mix was also weighed under

water, leaving it for 5 minutes. Maximum theoretical relative density was determined by using equation (1)

$$G_{mm} = \frac{A}{A-(C-B)} \quad (1)$$

Where:

A = Mass of dry sample in air (g)

B = Mass of flask under water (g)

C = Mass of flask and sample under water (g)

Gmm = Maximum Theoretical Relative Density

Bulk Specific Relative Density :

After the sample was compacted, it was cooled down to room temperature and the bulk relative density was determined following ASTM D2726/D2726M (ASTM, 2011). The dry weight of the sample was measured, and then its submerged weight was determined in water at 25°C after waiting for 5 minutes. The saturated surface dry weight was also determined after removing the sample from the water and drying its surface. The bulk relative density was determined using the equation (2).

$$G_{mb} = \frac{A}{B-C} \quad (2)$$

Where:

A = Dry mass of the sample (g)

B = Mass of saturated surface dry sample

C = Mass of the sample under water

Calculating Percentage Gmm at Gyrations :

After calculating the bulk and maximum relative density of the samples, the densification curve was plotted by calculating the estimated bulk relative density of the sample with each gyration. This relative density was estimated by first calculating height factor 'C' by using equation (3). The estimated relative density at a number of gyrations was calculated by using equation (4), and the percentage maximum relative density achieved was calculated using equation (5). This % Gmm was then plotted against the number of gyrations to form a densification curve.

$$C_n = \frac{hieght\ at\ 120th\ gyration}{height\ at\ nth\ gyration} \quad (3)$$

$$Gmb\ est = C_n * Gmb \quad (4)$$

$$\%\ Gmm = \frac{Gmb\ est}{Gmm} * 100 \quad (5)$$

Chapter 5: Results and Analysis

5.1 Penetration Grade Test

The results of the penetration grade test for PG 58H-28 and PG 58S-28 with standard deviation between three readings as error bars are presented in Figure 8 and Figure 9, respectively. The detailed results can be found in Appendix A. The inclusion of Zycotherm made the binder softer, as seen by results at 0.03% and 0.07% in PG 58H-28 and at all dosages in PG 58S-28. There was an exception to that only in the case of Zycotherm 0.1% dosage in PG 58H-28 binder. The addition of Evotherm at all dosages in both binders made the binder harder; however, no specific trend was observed.

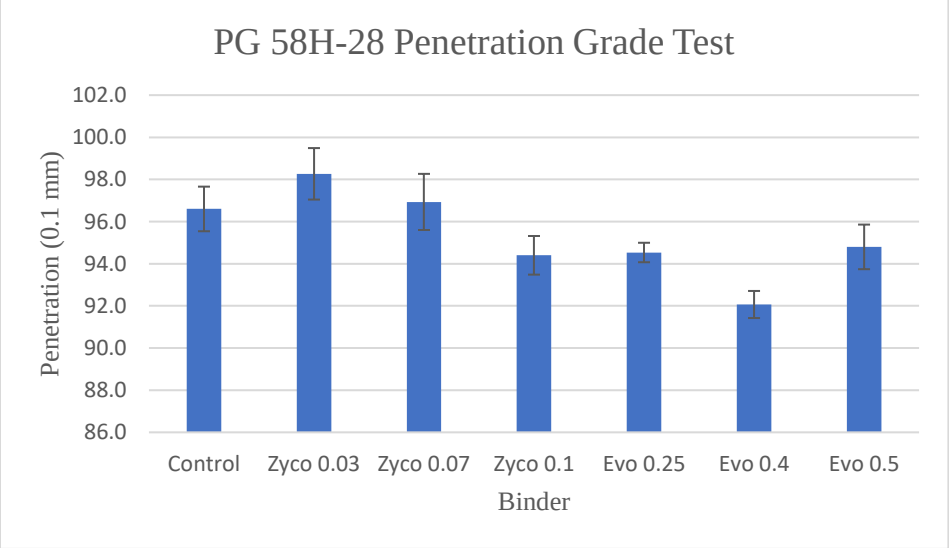

Figure 8: PG 58H-28 Penetration Grade Results

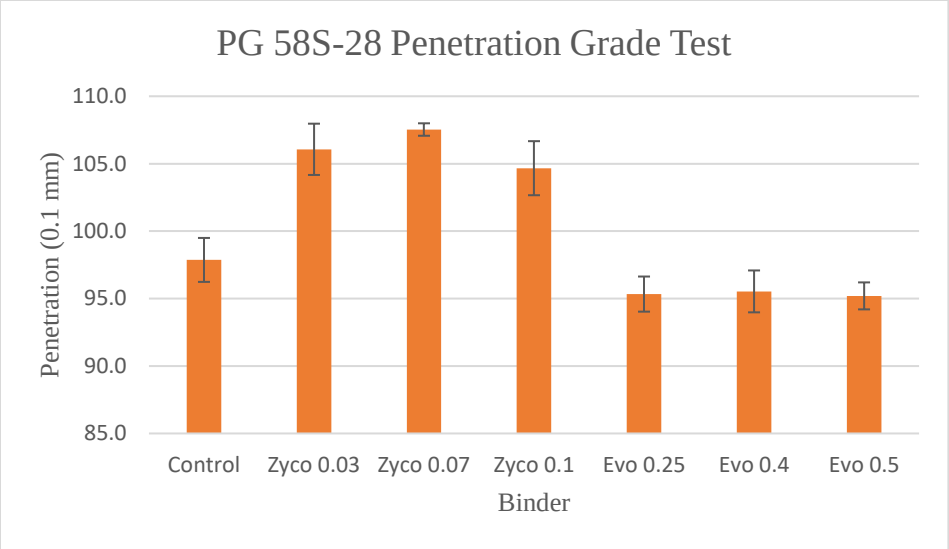

Figure 9: PG 58S-28 Penetration Grade Results

Although the sample size was very small (three readings per specimen), a two-tailed t-test was performed with a significance level of 0.05 to test if the differences with the control were statistically significant or not. The p values of the t-test are presented in Table 5. Although, in some cases, the difference is statistically significant, it is not big enough to cause any change in penetration grading. This means that the properties of the binder would not change significantly with the incorporation of these additives.

Table 5: T-Test Probability Value for Penetration Grade Results

P-Value (α = 0.05)				
Binder	**PG 58H-28**	**Significant**	**PG 58S-28**	**Significant**
Zyco 0.03	0.042	Yes	0.025	Yes
Zyco 0.07	0.71	No	0.013	Yes
Zyco 0.1	0.019	Yes	0.075	No
Evo 0.25	0.071	No	0.019	Yes
Evo 0.4	0.035	Yes	0.311	No
Evo 0.5	0.012	No	0.206	No

5.2 Softening Point Test Results

Figure 10 and Figure 11 show softening points of control and warm mix binders for PG 58H-28 and PG 58S-28, respectively. The detailed results are attached in Appendix B. The Addition of Zycotherm in PG 58H-28 resulted in a decrease in the softening point of the binder with an increase in dosage, and although the addition of Evotherm also decreased the softening point, no trend was observed with increasing dosage rate.

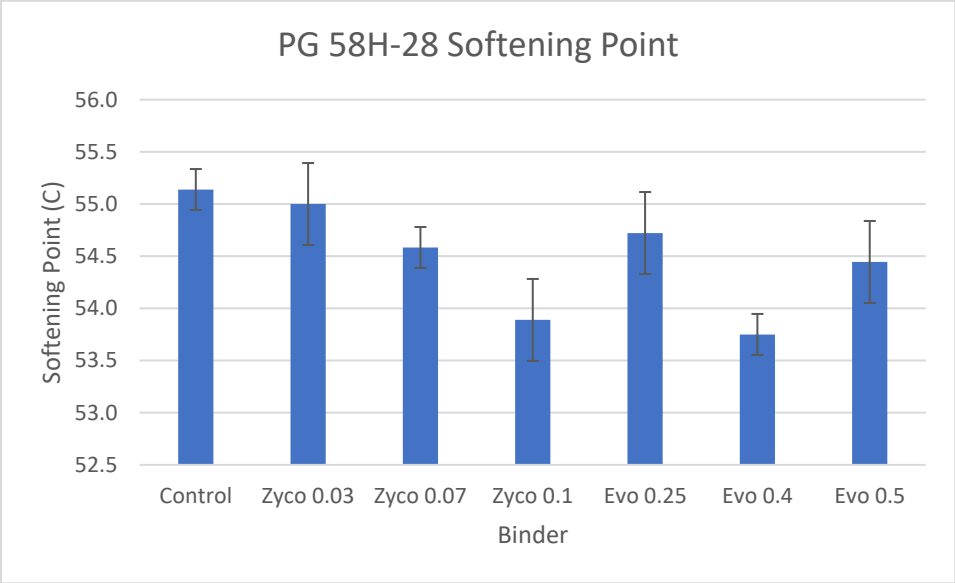

Figure 10: PG 58H-28 Softening Point Results

In the case of the PG 58S-28 binder, the addition of Zycotherm at 0.03% and 0.1% dosage rates decreased the softening point when compared to the virgin binder but increased it at 0.07% dosage rate with no trend. The addition of Evotherm at a 0.25% dosage rate had no effect on the softening point, but by increasing the dosage rate to 0.4%, the softening point decreased. However, further increasing the dosage rate resulted in an increasing softening point.

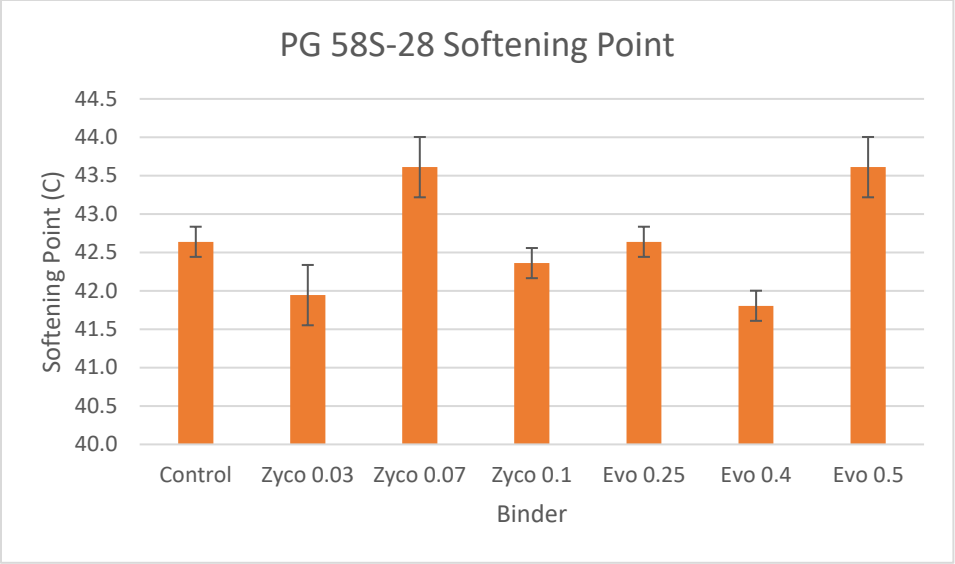

Figure 11: PG 58S-28 Softening Point Results

5.3 Rotational Viscosity Results

The rotational viscosity as measured by rotational viscometer at 125°C, 135°C and 145°C for PG 58H-28 and PG 58S-28 is presented in Figure 12 and Figure 13, respectively. The detailed results are attached in Appendix C.

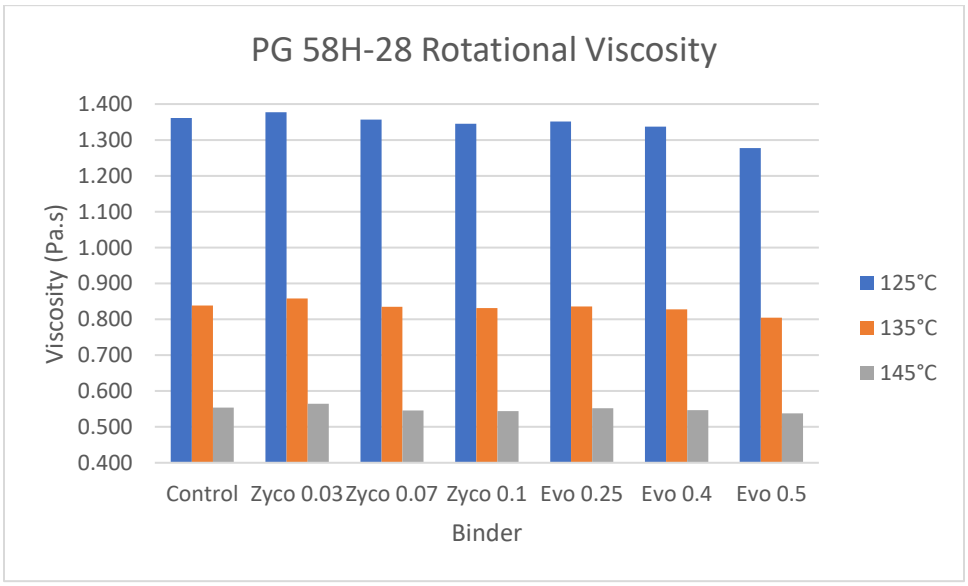

Figure 12: PG 58H-28 Rotational Viscosity

For PG 58H-28, the addition of Zycotherm at a 0.03% dosage rate slightly increased the viscosity of the binder, while at 0.07% and 0.1%, the viscosity of the binder decreased slightly. The addition of Evotherm in the binder showed slightly decreasing viscosity with increasing dosages. However, the change in viscosity was so minimal that it did not translate into a reduction in mixing and compaction temperatures as calculated by log viscosity and temperature chart on 0.17 Pa.s and 0.28 Pa.s viscosities. The mixing and compaction temperatures are shown in Table 6.

Table 6: PG 58H-28 Mixing and Compaction Temperatures by Rotational Viscosity

	PG 58H-28	
Sample	**Mixing Temp (°C)**	**Compaction Temp (°C)**
Control	171	160
Zyco 0.03	172	161
Zyco 0.07	170	160
Zyco 0.1	170	159
Evo 0.25	171	160
Evo 0.4	171	160
Evo 0.5	171	160

In the case of PG 58S-28 binder, the addition of Zycotherm at all dosage rates and Evotherm at 0.25% slightly increased the viscosity of the binder. However, the addition of Evotherm at higher dosage rates showed a slight decrease in the viscosity of the binder at all temperatures. Similarly, in this case, the slight change in viscosity did not translate into a reduction in mixing and compaction temperatures, as shown in Table 7.

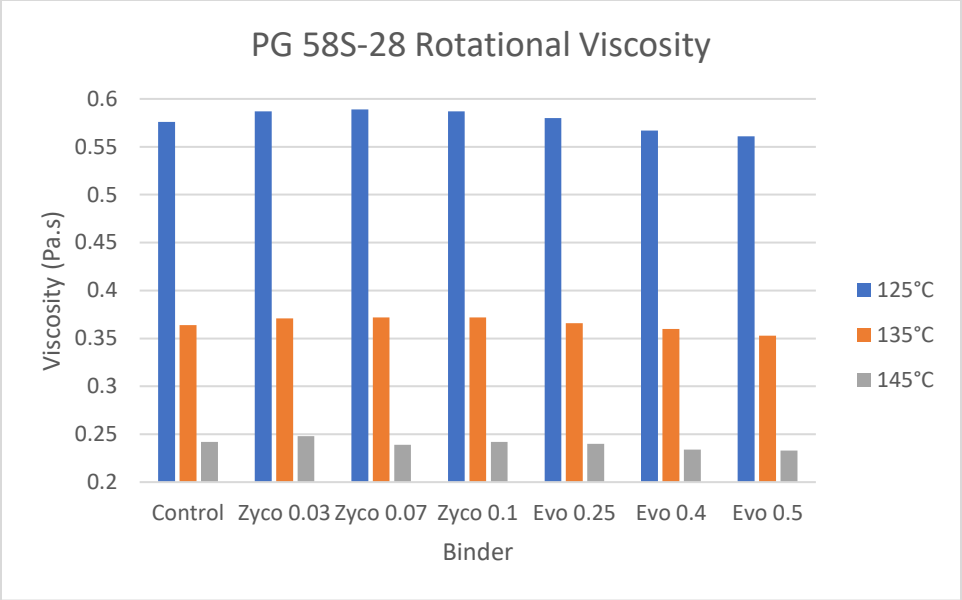

Figure 13: PG 58S-28 Rotational Viscosity

Table 7: PG 58S-28 Mixing and Compaction Temperature by Rotational Viscosity

	PG 58S-28	
Sample	**Mixing Temp (°C)**	**Compaction Temp (°C)**
Control	153	141
Zyco 0.03	154	142
Zyco 0.07	153	141
Zyco 0.1	153	142
Evo 0.25	153	142
Evo 0.4	152	141
Evo 0.5	152	141

5.4 Steady Shear Flow Test Results

Figure 14 presents the viscosities of control and warm mix binders at 76°C, 82°C, and 88°C temperatures when tested by a steady shear flow test using a dynamic shear rheometer. The warm mix binder with Zycotherm at 0.3% showed a reduction in viscosity when compared to the control binder at all temperatures. This reduction started to decrease when the dosage

rate was increased to 0.07% and 0.1%, with 0.1% showing the least reduction. In the case of Evotherm, at a 0.25% rate, no significant change in viscosity was observed at all temperatures when compared to the control binder. However, at 0.4%, the viscosity of binder at all temperatures decreased significantly, but when dosage was increased to 0.5%, the viscosity was observed to increase slightly.

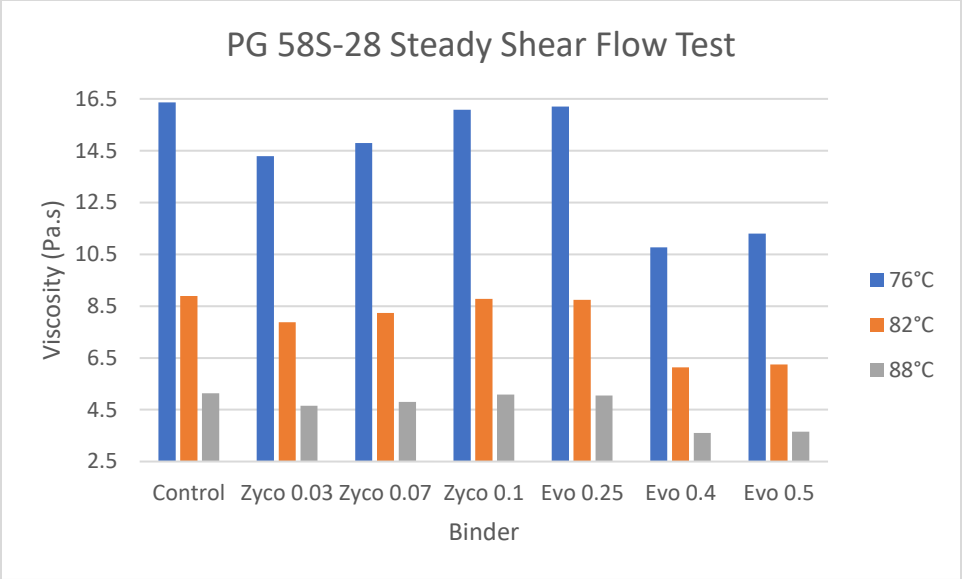

Figure 14: PG 58S-28 Steady Shear Flow Test Viscosities

Table 8: PG 58S-28 Mixing and Compaction Temperature by SSF Test

	PG 58S-28	
Sample	**Mixing Temp (°C)**	**Compaction Temp (°C)**
Control	124	116
Zyco 0.03	123	116
Zyco 0.07	124	116
Zyco 0.1	124	116
Evo 0.25	124	116
Evo 0.4	121	114
Evo 0.5	121	114

The mixing and compaction temperatures of control and warm mix binders at 0.17 Pa.s and 0.35 Pa.s, as recommended by Reinke, are presented in Table 7. Zycotherm at all dosages and Evotherm at 0.25% showed similar mixing and compaction temperatures as the control binder, while Evotherm at 0.4% and 0.5% showed a reduction of 3°C in mixing temperature and a reduction of 2°C in compaction temperatures. As the control binder is considered to be a Newtonian fluid, the viscosities determined by the rotational viscosity test and steady shear flow test should have been similar. However, in this study, they were observed to be different. This could be attributed to the use of 20mm plate geometry in DSR instead of 25mm plate geometry. The heating assembly used in DSR was a Peltier plate instead of a water bath, which could also have influenced the results.

5.5 Densification Curves

The densification curves for the control binder mix with compaction temperatures of 130°C and 120°C and warm mix binder mix at 120°C are presented in Figure 15. Warm mix asphalt with Zycotherm at 0.03% and 0.1% dosage rate did not improve the workability of asphalt mix and reached a similar air voids content at 120 gyrations as the control mix at 120°C. This shows that these dosage rates did not decrease compaction effort. Similarly, for the Evotherm modified mix, 0.25% and 0.5% did not decrease compaction effort when compared to the control mix and reached a similar air voids content at 120 gyrations as the control mix at 120°C. However, warm mix with Zycotherm 0.07% and Evotherm 0.4% showed comparable workability at 120°C compaction temperature to hot mix asphalt compacted at 130°C temperature. This shows that Zycotherm and Evotherm at 0.07% and 0.4% dosage rates, respectively, were able to achieve a 10°C reduction in compaction temperatures.

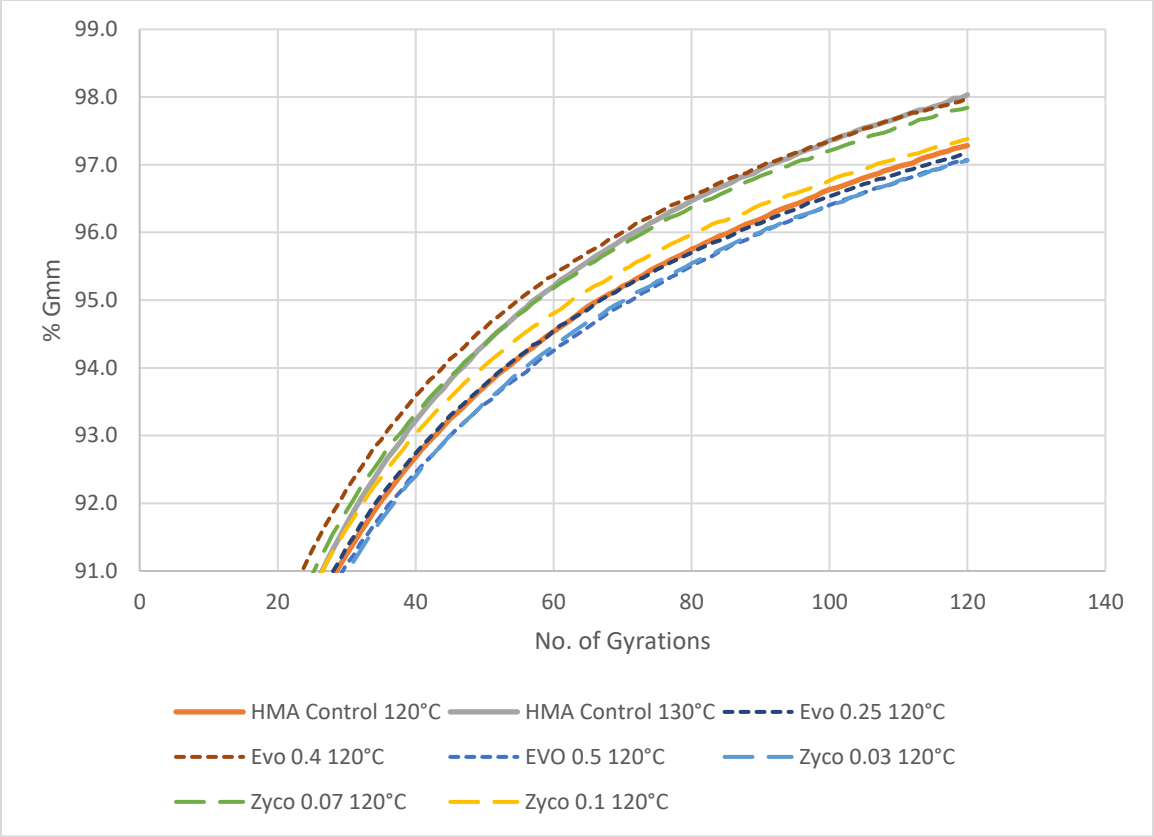

Figure 15: PG 58S-28 with WMA Additives Densification Curves

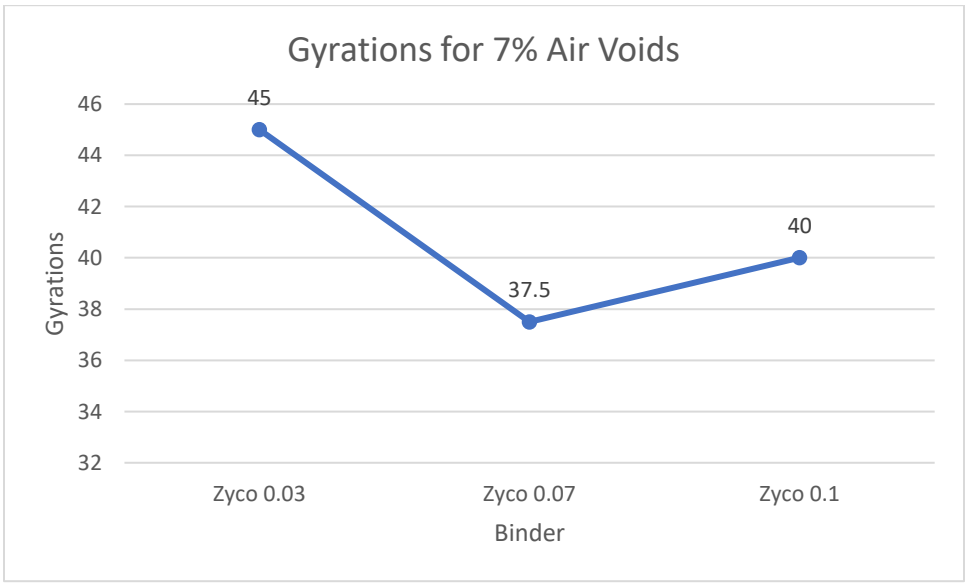

Figure 16: Gyrations for 7% Air Voids with Zycotherm

Figure 16 and Figure 17 show the number of gyrations required to reach 93% Gmm or 7% air void content for the Zycotherm and Evotherm mixes, respectively. An air void content of 7% was chosen for this interpretation because this is the target air voids when asphalt concrete is compacted in the field. Warm mix asphalt with Zycotherm at 0.03% dosage rate required 45 gyrations, at 0.07% required 37.5% and at 0.1% required 40 gyrations to achieve 7% air void content. Similarly, warm mix asphalt with Evotherm at 0.25% dosage rate required 42 gyrations, at 0.4% required 35.5 gyrations and at 0.5% required 45 gyrations to reach 7% air void content. In both of these cases, it was found that reduction in compaction effort is achieved only at optimum dosage, which was 0.07% for Zycotherm and 0.4% for Evotherm.

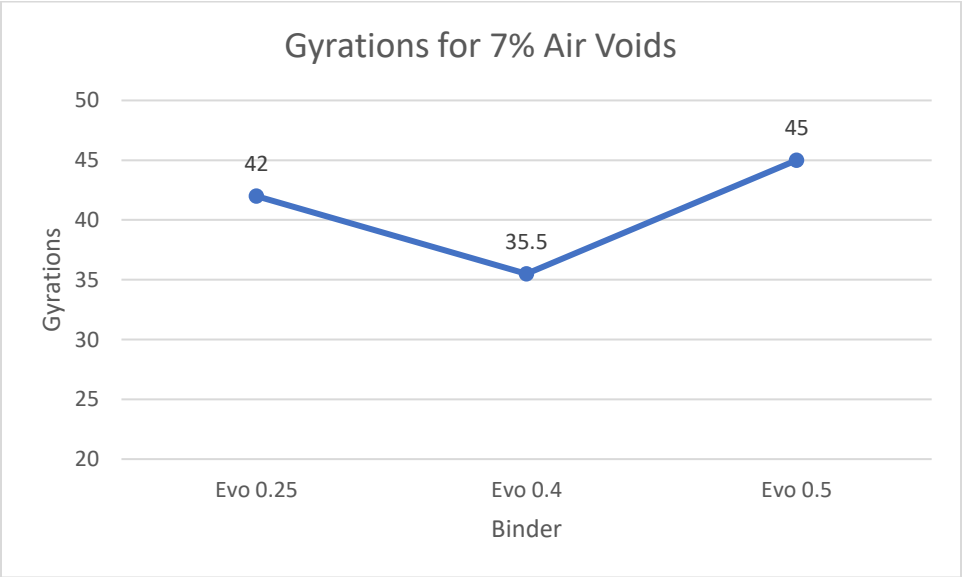

Figure 17: Gyrations for 7% Air Voids with Evotherm

Chapter 6: Conclusions and Recommendations

PG 58S-28 and PG 58H-28 asphalt binder were tested with Evotherm and Zycotherm warm mix additives in various dosages to determine the effect of dosage rate on the workability of asphalt concrete. The binder testing included penetration grade test, softening point test, rotational viscosity test and steady shear flow test. Compaction effort was also analyzed by plotting densification curves and determining the number of gyrations required to achieve 7% air void content. The findings of this study are summarized below.

6.1 Conclusions

From the tests performed to analyze the effect of dosage rate on the viscosity and workability of asphalt, the following conclusions were drawn:

- The addition of Zycotherm additive generally made the asphalt binder softer, while the addition of Evotherm generally made it harder, as determined by penetration grade. Although, in some cases, the difference between penetration units was significant, the change was not large enough to affect the grading of asphalt binder. Similar results were found by Zawawi *et al*., and Hasan *et al*., in their studies. There was no clear relationship between penetration and additive dosage rate.
- The inclusion of Zycotherm and Evotherm in the PG 58H-28 binder decreased its softening point. In the case of PG 58S-28, the effect on the softening point depended on the additive and the dosage rate. There was not a clear relationship between softening point and additive dosage rate, except for the combination PG 58H-28 Zycotherm, which showed decreasing softening points with increasing the amount of additive.

- The rotational viscosity test showed minimal viscosity changes with the addition of warm mix additives. The mixing and compaction temperatures determined by this test were also ±1 °C to that of the control binder. The rotational viscosity test could not differentiate effectively between the control binder and warm mix binders. Similar results were found by Hasan *et al*., Zawawi *et al*., and Bennert *et al*.

- The steady shear flow test performed for PG 58S-28 showed an apparent increase in the viscosity with an increase in Zycotherm dosage. However, the viscosities were lower when compared to the control binder. The inclusion of Evotherm decreased the viscosity of the binder, but no clear relationship was identified with the additive dosage. The mixing and compaction temperature determined by this method did not show any reduction with Zycotherm. However, a reduction in mixing and compaction temperatures was observed for higher dosages of Evotherm.

- The densification curves data showed that the workability of PG 58S-28 binder improved with Zycotherm at 0.07% and Evotherm at 0.4%, achieving similar density with a similar number of gyrations to that of hot mix asphalt. A decrease of 10 °C in compaction temperature was observed. However, with other dosages, the mix could not achieve the density of the hot mix asphalt.

6.2 Recommendations

Based on findings from this study, the following recommendations were made for future testing:

- The homogenizer used for mixing warm mix additives with the binder in this study was only able to reach the speed of 250 rpm instead of the recommended speed of 500 rpm. A high-shear mixer could mix the materials more homogeneously.
- The heating plate used for the softening point test could only achieve an 8° F/min change in temperature instead of 9° F/min as recommended in ASTM standards. This could also have affected the results of this study; hence, the heating rate of 9° F/min is recommended for future testing.
- The rotational viscometer could only test at temperatures up to 145°C because of the instrument's limitations. However, viscosity testing is generally done up to 165°C in literature. This could also have affected the mixing and compaction temperatures determined in this study. Hence, two temperatures, 135°C and 165°C, are recommended for determining viscosities using a rotational viscometer.
- The use of a 25 mm plate in DSR instead of 20 mm, as suggested by the standard, is recommended for comparison of the results.
- Out of all testing performed in this study, densification curves showed the most potential in determining the reduction in compaction temperature with dosage rates. Hence, this test is recommended for determining the optimum dosage rate for warm mix additives.
- The warm mix dosage rate determined should also be confirmed with performance testing of asphalt concrete to ensure both reduction in production temperature and quality of asphalt concrete.

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Appendix A

Table A1: PG 58H-28 Penetration Grade Results

	PG 58H-28			
Sample	**1st Reading**	**2nd Reading**	**3rd Reading**	**Average**
Control	97.8	95.8	96.2	96.6
Zyco 0.03	99.6	98	97.2	98.3
Zyco 0.07	97.8	97.6	95.4	96.9
Zyco 0.1	95.4	94.2	93.6	94.4
Evo 0.25	94.8	94.8	94	94.5
Evo 0.4	91.8	92.8	91.6	92.1
Evo 0.5	96	94.4	94	94.8

Table A2: PG 58S-28 Penetration Grade Results

	PG 58S-28			
Sample	**1st Reading**	**2nd Reading**	**3rd Reading**	**Average**
Control	96	99	98.6	97.9
Zyco 0.03	106	108	104.2	106.1
Zyco 0.07	107.8	107	107.8	107.5
Zyco 0.1	106.6	104.8	102.6	104.7
Evo 0.25	94	96.6	95.4	95.3
Evo 0.4	96.8	93.8	96	95.5
Evo 0.5	96.2	95.2	94.2	95.2

Appendix B

Table B1: PG 58H-28 Softening Point Results

	PG 58H-28			
Sample	**1st Reading**	**2nd Reading**	**Average (F)**	**Celsius**
Control	131	131.5	131.25	55.1
Zyco 0.03	130.5	131.5	131	55.0
Zyco 0.07	130	130.5	130.25	54.6
Zyco 0.1	128.5	129.5	129	53.9
Evo 0.25	130	131	130.5	54.7
Evo 0.4	128.5	129	128.75	53.8
Evo 0.5	129.5	130.5	130	54.4

Table B2: PG 58S-28 Softening Point Results

	PG 58S-28			
Sample	**1st Reading**	**2nd Reading**	**Average (F)**	**Celsius**
Control	108.5	109	108.75	42.6
Zyco 0.03	107	108	107.5	41.9
Zyco 0.07	110	111	110.5	43.6
Zyco 0.1	108	108.5	108.25	42.4
Evo 0.25	108.5	109	108.75	42.6
Evo 0.4	107	107.5	107.25	41.8
Evo 0.5	110	111	110.5	43.6

Appendix C

Table C1: PG 58H-28 Rotational Viscosity Results

	PG 58H-28											
Sample	**125**			**Average**	**135**			**Average**	**145**			**Average**
Control	1.362	1.361	1.36	1.361	0.835	0.84	0.841	0.839	0.553	0.554	0.554	0.554
Zyco 0.03	1.38	1.376	1.376	1.377	0.858	0.859	0.856	0.858	0.564	0.565	0.565	0.565
Zyco 0.07	1.357	1.357	1.355	1.356	0.835	0.835	0.835	0.835	0.547	0.547	0.544	0.546
Zyco 0.1	1.354	1.344	1.337	1.345	0.831	0.832	0.832	0.832	0.544	0.544	0.544	0.544
Evo 0.25	1.354	1.352	1.347	1.351	0.836	0.833	0.838	0.836	0.551	0.552	0.552	0.552
Evo 0.4	1.336	1.336	1.338	1.337	0.826	0.827	0.829	0.827	0.545	0.547	0.547	0.546
Evo 0.5	1.28	1.277	1.275	1.277	0.806	0.804	0.804	0.805	0.538	0.538	0.536	0.537

Table C2: PG 58S-28 Rotational Viscosity Results

	PG 58S-28											
Sample	**125**			**Average**	**135**			**Average**	**145**			**Average**
Control	0.575	0.577	0.577	0.576	0.364	0.364	0.364	0.364	0.241	0.242	0.242	0.242
Zyco 0.03	0.588	0.586	0.586	0.587	0.371	0.371	0.371	0.371	0.248	0.248	0.247	0.248
Zyco 0.07	0.59	0.589	0.588	0.589	0.372	0.372	0.371	0.372	0.239	0.239	0.239	0.239
Zyco 0.1	0.588	0.586	0.586	0.587	0.373	0.372	0.372	0.372	0.242	0.242	0.242	0.242
Evo 0.25	0.582	0.58	0.578	0.580	0.366	0.366	0.365	0.366	0.241	0.24	0.24	0.240
Evo 0.4	0.567	0.567	0.567	0.567	0.36	0.36	0.359	0.360	0.235	0.234	0.234	0.234
Evo 0.5	0.562	0.562	0.56	0.561	0.353	0.354	0.353	0.353	0.232	0.233	0.233	0.233

Appendix D

Table D1: PG 58S-28 SSF Test at 76°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
3.058	50	16.35	1.004	76	5.017	0.086	5.017
3.495	57.25	16.38	1	76	10.07	-0.111	10.07
3.999	65.56	16.39	1	76	15.12	-0.22	15.12
4.577	75.07	16.4	1.001	76	20.18	-0.228	20.18
5.238	85.95	16.41	1	76	25.28	-0.079	25.28
5.996	98.42	16.41	1.001	76	30.38	-0.001	30.38
6.839	112.7	16.48	0.9993	76	35.47	0.141	35.47
7.855	129	16.43	1.001	76	40.53	0.133	40.53
8.995	147.8	16.43	1.001	76	45.58	0.048	45.58
10.29	169.2	16.44	1.001	76	50.63	-0.003	50.63
11.8	193.7	16.42	1.001	76	55.68	0.01	55.68
13.47	221.8	16.46	0.9985	76	60.74	0.154	60.74
15.44	254	16.45	1.001	76	65.79	0.322	65.79
17.73	290.9	16.4	1.003	76	70.88	0.16	70.88
20.32	333	16.39	1.001	76	75.98	0.088	75.98
23.2	381.3	16.43	0.9982	76	81.08	0.341	81.08
26.61	436.7	16.41	1.001	76	86.18	0.452	86.18
30.56	500	16.36	1.001	76	91.28	0.214	91.28

Table D2: PG 58S-28 SSF Test at 82°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
5.641	50	8.863	1.009	82	5.05	-0.026	5.05
6.444	57.25	8.884	1.001	82	10.15	-0.268	10.15
7.391	65.56	8.87	1.002	82	15.25	-0.125	15.25
8.421	75.07	8.914	1.001	82	20.34	-0.094	20.34
9.667	85.95	8.891	1.002	82	25.39	-0.077	25.39
11.06	98.42	8.895	1.001	82	30.45	-0.12	30.45
12.67	112.7	8.895	1.002	82	35.5	-0.032	35.5
14.48	129	8.915	1.001	82	40.56	-0.009	40.56
16.58	147.8	8.912	1.002	82	45.61	0.028	45.61
18.97	169.2	8.92	1.001	82	50.65	-0.049	50.65
21.7	193.7	8.927	1.001	82	55.75	-0.032	55.75
24.85	221.8	8.926	1.001	82	60.84	-0.058	60.84
28.44	254	8.93	1.001	82	65.94	0.053	65.94
32.58	290.9	8.927	1.001	82	70.99	0.222	70.99
37.23	333	8.945	1	82	76.04	0.347	76.04
42.83	381.3	8.904	1.001	82	81.1	0.218	81.1
48.9	436.7	8.929	1.001	82	86.15	0.126	86.15
56.23	500	8.891	1.002	82	91.2	0.074	91.2

Table D3: PG 58S-28 SSF Test at 88°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
9.737	50	5.135	1.014	88	6.653	-0.394	6.653
11.16	57.25	5.129	1.001	88	11.71	-0.26	11.71
12.77	65.56	5.132	1.003	88	16.76	-0.154	16.76
14.63	75.07	5.132	1.002	88	21.81	-0.086	21.81
16.68	85.95	5.152	1.002	88	26.86	-0.059	26.86
19.14	98.42	5.142	1.005	88	31.91	-0.13	31.91
21.9	112.7	5.146	1.002	88	36.97	0.023	36.97
25.06	129	5.15	1.002	88	42.07	-0.021	42.07
28.53	147.8	5.18	1	88	47.16	-0.278	47.16
32.69	169.2	5.176	1.001	88	52.21	-0.53	52.21
37.48	193.7	5.169	1.002	88	57.26	-0.73	57.26
43	221.8	5.159	1.003	88	62.32	-0.405	62.32
49.23	254	5.16	1.003	88	67.37	-0.246	67.37
56.41	290.9	5.156	1.003	88	72.42	-0.209	72.42
64.62	333	5.154	1.003	88	77.47	-0.203	77.47
74.07	381.3	5.149	1.002	88	82.57	-0.227	82.57
84.88	436.7	5.144	1.003	88	87.66	-0.361	87.66
97.3	500	5.138	1.003	88	92.76	-0.409	92.76

Table D4: PG 58S-28 with Evo 0.25% SSF Test at 76°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
3.094	50	16.16	1.004	76	5.018	0.29	5.018
3.544	57.25	16.16	1.001	76	10.07	0.005	10.07
4.049	65.56	16.19	1.001	76	15.12	-0.197	15.12
4.636	75.07	16.19	1.001	76	20.17	-0.336	20.17
5.311	85.95	16.18	1.001	76	25.23	-0.563	25.23
6.061	98.42	16.24	0.9995	76	30.31	-0.283	30.31
6.956	112.7	16.2	1.001	76	35.41	-0.003	35.41
7.943	129	16.25	0.9991	76	40.51	0.317	40.51
9.092	147.8	16.25	1	76	45.61	-0.012	45.61
10.42	169.2	16.24	1.001	76	50.7	-0.264	50.7
11.92	193.7	16.25	1.004	76	55.75	-0.134	55.75
13.69	221.8	16.21	1.002	76	60.8	-0.164	60.8
15.69	254	16.18	1.001	76	65.85	0.143	65.85
17.89	290.9	16.26	0.9982	76	70.9	0.279	70.9
20.53	333	16.23	1.001	76	75.96	0.161	75.96
23.55	381.3	16.19	1.001	76	81.01	-0.081	81.01
26.99	436.7	16.18	1.001	76	86.1	-0.122	86.1
30.87	500	16.2	1.001	76	91.2	-0.133	91.2

Table D5: PG 58S-28 with Evo 0.25% SSF Test at 82°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
5.727	50	8.731	1.01	82	5.017	-0.118	5.017
6.539	57.25	8.755	1.001	82	10.09	-0.063	10.09
7.498	65.56	8.744	1.002	82	15.19	-0.294	15.19
8.61	75.07	8.718	1.003	82	20.28	-0.207	20.28
9.854	85.95	8.723	1.001	82	25.38	-0.241	25.38
11.25	98.42	8.747	1.002	82	30.47	-0.568	30.47
12.89	112.7	8.743	1.002	82	35.53	-0.576	35.53
14.76	129	8.741	1.002	82	40.58	-0.705	40.58
16.9	147.8	8.741	1.002	82	45.64	-0.802	45.64
19.34	169.2	8.748	1.001	82	50.69	-0.899	50.69
22.14	193.7	8.752	1.003	82	55.74	-0.947	55.74
25.37	221.8	8.744	1.001	82	60.79	-0.855	60.79
28.91	254	8.786	0.9987	82	65.88	-0.615	65.88
33.13	290.9	8.78	1.002	82	70.98	-0.742	70.98
38	333	8.764	1.003	82	76.07	-0.558	76.07
43.48	381.3	8.771	1.001	82	81.12	-0.442	81.12
49.83	436.7	8.763	1.003	82	86.17	-0.365	86.17
57.18	500	8.744	1.003	82	91.23	-0.174	91.23

Table D6: PG 58S-28 with Evo 0.25% SSF Test at 88°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
9.953	50	5.024	1.014	88	6.974	0.164	6.974
11.39	57.25	5.026	1.002	88	12.03	0.169	12.03
13.04	65.56	5.027	1.003	88	17.08	0.12	17.08
14.93	75.07	5.029	1.003	88	22.13	0.13	22.13
17.09	85.95	5.03	1.003	88	27.18	0.296	27.18
19.56	98.42	5.032	1.003	88	32.24	0.374	32.24
22.26	112.7	5.063	1	88	37.29	-0.01	37.29
25.57	129	5.047	1.004	88	42.39	0.184	42.39
29.25	147.8	5.051	1.002	88	47.48	0.033	47.48
33.51	169.2	5.049	1.005	88	52.58	0.26	52.58
38.25	193.7	5.065	1.001	88	57.63	0.217	57.63
44.01	221.8	5.04	1.005	88	62.68	-0.02	62.68
50.14	254	5.067	1	88	67.74	-0.245	67.74
57.57	290.9	5.052	1.003	88	72.79	-0.351	72.79
65.92	333	5.053	1.003	88	77.84	-0.225	77.84
75.36	381.3	5.061	1.003	88	82.89	0.024	82.89
86.53	436.7	5.046	1.004	88	87.98	0.058	87.98
99.03	500	5.049	1.003	88	93.08	0.228	93.08

Table D7: PG 58S-28 with Evo 0.4% SSF Test at 76°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
0.000283	50	1.77E+05	0.00051	76	10.02	-0.041	10.02
0.01959	57.25	2923	1.343	76	20.08	-0.218	20.08
0.04596	65.56	1427	1.284	76	30.17	-0.027	30.17
0.01167	75.07	6432	0.6298	76	40.22	0.075	40.22
0.03046	85.95	2822	0.8982	76	50.28	-0.208	50.28
0.008135	98.42	1.21E+04	0.2968	76	60.37	-0.144	60.37
0.01086	112.7	1.04E+04	0.9451	76	70.43	-0.056	70.43
0.03701	129	3486	1.452	76	80.49	-0.18	80.49
10.61	147.8	13.92	1.713	76	90.54	-0.031	90.54
13.63	169.2	12.41	1.177	76	100.6	-0.194	100.6
16.68	193.7	11.62	1.13	76	110.7	0.032	110.7
19.84	221.8	11.18	1.038	76	120.7	-0.054	120.7
23.12	254	10.99	1.024	76	130.8	0.043	130.8
26.45	290.9	11	1.004	76	136.7	0.2	136.7
30.29	333	11	0.9983	76	141.7	0.283	141.7
35.4	381.3	10.77	1.009	76	146.8	0.273	146.8
40.45	436.7	10.8	1.002	76	151.8	0.339	151.8
46.43	500	10.77	0.9988	76	156.9	0.201	156.9

Table D8: PG 58S-28 with Evo 0.4% SSF Test at 82°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
8.103	50	6.17	1.27	82	10.05	0.342	10.05
8.779	57.25	6.521	1.124	82	20.11	0.228	20.11
10.04	65.56	6.529	1.053	82	30.17	0.165	30.17
12.27	75.07	6.117	1.079	82	40.22	0.324	40.22
13.47	85.95	6.381	1.031	82	50.28	0.139	50.28
15.88	98.42	6.2	1.043	82	60.33	0.107	60.33
17.86	112.7	6.311	1.02	82	70.39	0.173	70.39
20.78	129	6.21	1.022	82	80.44	0.233	80.44
22.76	147.8	6.493	0.9781	82	90.54	0.193	90.54
27.1	169.2	6.243	1.006	81.9	97.13	0.321	97.13
31.28	193.7	6.194	1.008	82	102.2	0.244	102.2
35.49	221.8	6.251	0.9997	82	107.2	0.451	107.2
41.07	254	6.184	1.007	82	112.3	0.713	112.3
46.95	290.9	6.195	1.003	82	117.3	0.491	117.3
54.01	333	6.166	1.003	82	122.4	0.361	122.4
61.78	381.3	6.173	1	82	127.4	0.197	127.4
70.85	436.7	6.163	1.005	82	132.5	0.173	132.5
81.48	500	6.136	1.002	82	137.6	0.041	137.6

Table D9: PG 58S-28 with Evo 0.4% SSF Test at 88°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
9.409	50	5.314	0.8151	88	10.02	-0.033	10.02
15.7	57.25	3.646	1.06	88	20.08	0.354	20.08
17.76	65.56	3.691	1.064	88	30.17	0.339	30.17
20.43	75.07	3.675	1.051	88	40.23	0.042	40.23
22.65	85.95	3.795	1.014	88	50.28	-0.153	50.28
26.79	98.42	3.673	1.032	88	60.38	0.315	60.38
30.56	112.7	3.688	1.025	88	70.44	0.398	70.44
34.68	129	3.721	1.006	88	80.49	0.282	80.49
40.37	147.8	3.66	1.019	88	88.36	0.047	88.36
45.45	169.2	3.723	0.9983	88	93.41	-0.153	93.41
52.77	193.7	3.672	1.007	88	98.46	-0.153	98.46
60.43	221.8	3.671	1.002	88	103.5	0.05	103.5
69.53	254	3.653	1.004	88	108.6	0.426	108.6
79.91	290.9	3.64	1.002	88	113.6	0.689	113.6
91.94	333	3.622	1.003	88	118.7	0.79	118.7
105.6	381.3	3.612	1.004	88	123.8	1.013	123.8
121.2	436.7	3.604	1.003	88	128.9	0.924	128.9
138.7	500	3.605	1.003	88	133.9	0.824	133.9

Table D10: PG 58S-28 with Evo 0.5% SSF Test at 72°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
4.408	50	11.34	1.008	76	5.028	0.001	5.028
5.052	57.25	11.33	1.001	76	10.13	-0.047	10.13
5.8	65.56	11.3	1.002	76	15.22	-0.039	15.22
6.639	75.07	11.31	1.001	76	20.33	-0.028	20.33
7.606	85.95	11.3	1.001	76	25.42	-0.224	25.42
8.694	98.42	11.32	1.001	76	30.53	-0.311	30.53
9.949	112.7	11.33	1.002	76	35.63	-0.161	35.63
11.4	129	11.32	1.001	76	40.72	-0.268	40.72
13	147.8	11.37	0.9994	76	45.82	-0.069	45.82
14.93	169.2	11.33	1.001	76	50.92	0.04	50.92
17.06	193.7	11.35	1	76	56.02	-0.151	56.02
19.55	221.8	11.35	1.001	76	61.12	-0.177	61.12
22.39	254	11.34	1.001	76	66.22	-0.374	66.22
25.62	290.9	11.35	1	76	71.32	-0.114	71.32
29.36	333	11.34	1.002	76	76.42	-0.059	76.42
33.67	381.3	11.33	1.002	76	81.51	-0.106	81.51
38.61	436.7	11.31	1.001	76	86.57	-0.074	86.57
44.26	500	11.3	1.001	76	91.62	-0.225	91.62

Table D11: PG 58S-28 with Evo 0.5% SSF Test at 82°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
7.979	50	6.266	1.012	82	6.094	-0.246	6.094
9.07	57.25	6.312	0.9993	82	11.15	-0.264	11.15
10.44	65.56	6.277	1.003	82	16.2	-0.223	16.2
11.94	75.07	6.288	1.003	82	21.25	-0.292	21.25
13.72	85.95	6.264	1.004	82	26.3	-0.346	26.3
15.7	98.42	6.269	1.002	82	31.36	-0.189	31.36
17.91	112.7	6.293	1.001	82	36.41	-0.123	36.41
20.56	129	6.278	1.003	82	41.51	-0.248	41.51
23.55	147.8	6.275	1.002	82	46.6	-0.252	46.6
26.96	169.2	6.275	1.002	82	51.65	-0.305	51.65
30.89	193.7	6.271	1.002	82	56.7	-0.174	56.7
35.4	221.8	6.267	1.002	82	61.75	-0.21	61.75
40.53	254	6.267	1.002	82	66.8	-0.203	66.8
46.47	290.9	6.259	1.002	82	71.86	-0.167	71.86
53.22	333	6.258	1.002	82	76.91	-0.134	76.91
60.97	381.3	6.254	1.002	82	82.01	-0.149	82.01
69.9	436.7	6.247	1.002	82	87.1	0.177	87.1
80.03	500	6.247	1.002	82	92.2	0.355	92.2

Table D12: PG 58S-28 with Evo 0.5% SSF Test at 88°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
13.81	50	3.619	1.013	88	9.302	-0.145	9.302
15.8	57.25	3.624	1.001	88	14.35	0.045	14.35
18.05	65.56	3.631	1.003	88	19.4	-0.043	19.4
20.76	75.07	3.617	1.005	88	24.45	0.388	24.45
23.72	85.95	3.624	1.004	88	29.51	0.3	29.51
27.1	98.42	3.632	1.004	88	34.56	0.456	34.56
30.98	112.7	3.638	1.003	88	39.62	0.321	39.62
35.51	129	3.634	1.004	88	44.71	0.161	44.71
40.64	147.8	3.636	1.003	88	49.81	0.092	49.81
46.37	169.2	3.649	1.003	88	54.91	0.237	54.91
53.16	193.7	3.644	1.005	88	60.01	0.6	60.01
60.98	221.8	3.638	1.004	88	65.1	0.644	65.1
69.51	254	3.654	1.003	88	70.15	0.776	70.15
79.67	290.9	3.651	1.003	88	75.21	0.781	75.21
91.2	333	3.652	1.004	88	80.26	0.601	80.26
104.5	381.3	3.65	1.003	88	85.31	0.61	85.31
119.7	436.7	3.648	1.004	88	90.36	0.736	90.36
137	500	3.649	1.006	88	95.41	0.672	95.41

Table D13: PG 58S-28 with Zyco 0.03% SSF Test at 76°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
3.482	50	14.36	1.004	76	5.021	0	5.021
3.998	57.25	14.32	1.001	76	10.07	0	10.07
4.573	65.56	14.34	1.001	76	15.16	0	15.16
5.231	75.07	14.35	1	76	20.26	0.174	20.26
5.998	85.95	14.33	1	76	25.36	0.197	25.36
6.876	98.42	14.31	1.002	76	30.46	0.304	30.46
7.857	112.7	14.34	1	76	35.56	0.457	35.56
8.991	129	14.35	1.003	76	40.66	0.535	40.66
10.3	147.8	14.34	1.001	76	45.76	0.405	45.76
11.77	169.2	14.38	0.9997	76	50.85	0.318	50.85
13.47	193.7	14.38	1	76	55.9	0.54	55.9
15.45	221.8	14.36	1.001	76	60.96	0.714	60.96
17.67	254	14.38	1	76	66.01	0.604	66.01
20.19	290.9	14.41	1.002	76	71.07	0.702	71.07
23.17	333	14.37	1	76	76.12	0.778	76.12
26.59	381.3	14.34	1.001	76	81.17	0.772	81.17
30.49	436.7	14.32	1.001	76	86.26	0.776	86.26
34.99	500	14.29	1.001	76	91.35	0.916	91.35

Table D14: PG 58S-28 with Zyco 0.03% SSF Test at 82°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
6.332	50	7.896	1.01	82	5.333	0.012	5.333
7.254	57.25	7.892	1.002	82	10.39	-0.111	10.39
8.285	65.56	7.913	1.001	82	15.44	-0.133	15.44
9.481	75.07	7.917	1.001	82	20.49	-0.227	20.49
10.85	85.95	7.921	1.003	82	25.54	-0.227	25.54
12.41	98.42	7.931	1.001	82	30.6	-0.262	30.6
14.19	112.7	7.945	1.001	82	35.65	-0.132	35.65
16.3	129	7.917	1.002	82	40.75	-0.365	40.75
18.65	147.8	7.924	1.002	82	45.84	-0.365	45.84
21.32	169.2	7.934	1.001	82	50.94	-0.031	50.94
24.44	193.7	7.928	1.001	82	56.04	-0.002	56.04
27.9	221.8	7.95	1	82	61.14	0.119	61.14
31.94	254	7.953	1.001	82	66.19	0.141	66.19
36.67	290.9	7.933	1.002	82	71.24	0.281	71.24
41.99	333	7.932	1.001	82	76.3	0.304	76.3
48.35	381.3	7.887	1.002	82	81.35	0.362	81.35
55.32	436.7	7.894	1.002	82	86.4	0.363	86.4
63.43	500	7.882	1.002	82	91.45	0.049	91.45

Table D15: PG 58S-28 with Zyco 0.03% SSF Test at 88°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
10.82	50	4.619	1.013	88	7.666	0	7.666
12.4	57.25	4.616	1.003	88	12.72	0	12.72
14.15	65.56	4.633	1.001	88	17.77	0	17.77
16.18	75.07	4.64	1.003	88	22.82	0	22.82
18.54	85.95	4.636	1.003	88	27.88	0.329	27.88
21.2	98.42	4.641	1.002	88	32.93	0.45	32.93
24.25	112.7	4.647	1.003	88	37.99	0.337	37.99
27.83	129	4.637	1.003	88	43.08	0.511	43.08
31.84	147.8	4.641	1.003	88	48.18	0.212	48.18
36.48	169.2	4.638	1.003	88	53.28	0.381	53.28
41.75	193.7	4.64	1.003	88	58.37	0.371	58.37
47.68	221.8	4.652	1.001	88	63.42	0.495	63.42
54.57	254	4.655	1.002	88	68.48	0.615	68.48
62.5	290.9	4.653	1.001	88	73.53	0.616	73.53
71.72	333	4.644	1.003	88	78.58	0.56	78.58
82.14	381.3	4.643	1.002	88	83.63	0.756	83.63
94.15	436.7	4.638	1.003	88	88.69	0.823	88.69
107.6	500	4.649	1.004	88	93.78	0.913	93.78

Table D16: PG 58S-28 with Zyco 0.07% SSF Test at 76°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
-3.42E-05	50	1.46E+06	-0.1281	76	10.06	0.057	10.06
-5.61E-05	57.25	1.02E+06	-0.9957	76	20.12	0.449	20.12
4.474	65.56	14.65	1.099	76	30.17	0.505	30.17
5.135	75.07	14.62	1.002	76	35.22	0.302	35.22
5.866	85.95	14.65	0.9993	76	40.27	0.333	40.27
6.704	98.42	14.68	0.9993	76.1	45.33	0.227	45.33
7.648	112.7	14.74	1.001	76	50.38	0.292	50.38
8.746	129	14.75	0.9998	76	55.46	0.495	55.46
10.04	147.8	14.71	1	76	60.56	0.522	60.56
11.51	169.2	14.7	1.001	76	65.65	0.513	65.65
13.14	193.7	14.74	0.9997	76	70.7	0.712	70.7
15.02	221.8	14.77	1.001	76	75.75	0.403	75.75
17.19	254	14.78	1.001	76	80.81	0.496	80.81
19.7	290.9	14.76	1.001	76	85.86	0.634	85.86
22.48	333	14.81	0.9994	76	90.92	0.734	90.92
25.79	381.3	14.79	0.9997	76	95.97	0.554	95.97
29.46	436.7	14.82	0.9999	76	101.1	0.75	101.1
33.8	500	14.79	1.001	76	106.2	0.978	106.2

Table D17: PG 58S-28 with Zyco 0.07% SSF Test at 82°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
6.08	50	8.224	1.011	82	5.018	-0.16	5.018
6.992	57.25	8.189	1.002	82	10.07	-0.168	10.07
7.994	65.56	8.201	1.003	82	15.12	0.042	15.12
9.153	75.07	8.201	1.002	82	20.22	-0.247	20.22
10.47	85.95	8.207	1.002	82	25.32	-0.21	25.32
11.94	98.42	8.245	0.9996	82	30.41	-0.199	30.41
13.56	112.7	8.308	1.002	82	35.46	-0.144	35.46
15.52	129	8.315	1.003	82	40.51	0.241	40.51
17.84	147.8	8.285	1.003	82	45.57	0.116	45.57
20.41	169.2	8.289	1.001	82	50.62	0.107	50.62
23.28	193.7	8.322	1	82	55.67	0.097	55.67
26.82	221.8	8.273	1.003	82	60.72	0.085	60.72
30.71	254	8.272	1.001	82	65.82	0.103	65.82
35.24	290.9	8.254	1.005	82	70.91	0.175	70.91
40.37	333	8.25	1.001	82	76.02	0.173	76.02
46.26	381.3	8.243	1.001	82	81.12	0.366	81.12
53.03	436.7	8.234	1.002	82	86.22	0.267	86.22
60.75	500	8.23	1.001	82	91.31	0.224	91.31

Table D18: PG 58S-28 with Zyco 0.07% SSF Test at 88°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
10.36	50	4.828	1.014	88	7.057	-0.151	7.057
11.88	57.25	4.818	1.002	88	12.11	-0.086	12.11
13.6	65.56	4.819	1.002	88	17.16	-0.245	17.16
15.52	75.07	4.836	1.001	88	22.21	-0.358	22.21
17.71	85.95	4.853	1.002	88	27.26	-0.13	27.26
20.23	98.42	4.866	1.004	88	32.32	-0.292	32.32
23.14	112.7	4.869	1.002	88	37.38	-0.097	37.38
26.6	129	4.85	1.004	88	42.47	-0.074	42.47
30.53	147.8	4.839	1.003	88	47.56	0.128	47.56
35.06	169.2	4.826	1.003	88	52.61	0.234	52.61
40.27	193.7	4.811	1.004	88	57.66	0.258	57.66
46.19	221.8	4.802	1.003	88	62.72	0.249	62.72
52.65	254	4.824	1.001	88	67.77	0.147	67.77
60.24	290.9	4.828	1.002	88	72.82	0.197	72.82
69.21	333	4.812	1.004	88	77.87	0.221	77.87
79.07	381.3	4.823	1.003	88	82.97	0.182	82.97
90.8	436.7	4.809	1.003	88	88.06	0.376	88.06
104.2	500	4.8	1.003	88	93.16	0.391	93.16

Table D19: PG 58S-28 with Zyco 0.1% SSF Test at 76°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
3.095	50	16.16	1.004	76	5.019	0.006	5.019
3.546	57.25	16.15	1.001	76	10.11	-0.187	10.11
4.061	65.56	16.14	1.002	76	15.2	-0.199	15.2
4.639	75.07	16.18	0.9988	76	20.29	-0.341	20.29
5.308	85.95	16.19	1.001	76	25.35	-0.165	25.35
6.08	98.42	16.19	1.002	76	30.4	-0.019	30.4
6.952	112.7	16.21	1	76	35.45	-0.079	35.45
7.956	129	16.22	0.9999	76	40.5	-0.122	40.5
9.127	147.8	16.19	1.001	76	45.55	-0.086	45.55
10.42	169.2	16.24	0.9998	76	50.61	-0.052	50.61
11.97	193.7	16.18	1	76	55.71	-0.166	55.71
13.75	221.8	16.13	1	76	60.81	0.026	60.81
15.74	254	16.14	1	76	65.9	-0.033	65.9
18.05	290.9	16.11	1.002	76	71	-0.002	71
20.68	333	16.1	1	76	76.05	0.012	76.05
23.72	381.3	16.08	1.002	76	81.1	0.189	81.1
27.14	436.7	16.09	1	76	86.16	0.173	86.16
31.1	500	16.08	1	76	91.21	0.186	91.21

Table D20: PG 58S-28 with Zyco 0.1% SSF Test at 82°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
5.709	50	8.758	1.011	82	5.017	-0.068	5.017
6.517	57.25	8.785	0.9998	82	10.07	-0.231	10.07
7.473	65.56	8.772	1.002	82	15.12	0.039	15.12
8.525	75.07	8.806	1	82	20.17	0.173	20.17
9.798	85.95	8.772	1.002	82	25.23	0.182	25.23
11.21	98.42	8.779	1.001	82	30.31	0.232	30.31
12.81	112.7	8.798	1.001	82	35.41	0.161	35.41
14.61	129	8.835	0.9999	82	40.51	0.116	40.51
16.8	147.8	8.797	1.002	82	45.61	0.095	45.61
19.21	169.2	8.806	1.001	82	50.71	0.014	50.71
21.97	193.7	8.817	1.001	82	55.81	0.102	55.81
25.21	221.8	8.799	1.001	82	60.91	0.284	60.91
28.79	254	8.824	1.001	82	66.01	0.191	66.01
33.03	290.9	8.806	1.002	82	71.11	0.234	71.11
37.84	333	8.801	1.001	82	76.21	0.188	76.21
43.37	381.3	8.792	1.001	82	81.3	0.142	81.3
49.69	436.7	8.787	1.001	82	86.4	0.251	86.4
56.94	500	8.781	1.001	82	91.45	0.265	91.45

Table D21: PG 58S-28 with Zyco 0.1% SSF Test at 88°C

Shear Rate 1/s	Shear Stress Pa	Viscosity Pas	Steady State	Temperature °C	Time s	Thrust g	Accumulated Time s
9.939	50	5.031	1.015	88	7.455	0.2	7.455
11.35	57.25	5.045	1.001	88	12.51	0.25	12.51
12.97	65.56	5.056	1.003	88	17.56	0.141	17.56
14.81	75.07	5.069	1.001	88	22.61	0.068	22.61
17.03	85.95	5.047	1.003	88	27.67	-0.108	27.67
19.48	98.42	5.052	1.002	88	32.72	-0.083	32.72
22.29	112.7	5.056	1.002	88	37.77	0.149	37.77
25.49	129	5.063	1.002	88	42.87	0.167	42.87
29.2	147.8	5.06	1.005	88	47.97	0.304	47.97
33.37	169.2	5.07	1.002	88	53.06	-0.009	53.06
38.2	193.7	5.072	1.003	88	58.11	0.148	58.11
43.75	221.8	5.07	1.002	88	63.16	0.236	63.16
49.95	254	5.085	1.003	88	68.22	0.283	68.22
57.32	290.9	5.075	1.004	88	73.27	0.432	73.27
65.73	333	5.067	1.004	88	78.32	0.267	78.32
75.26	381.3	5.067	1.002	88	83.37	0.19	83.37
85.91	436.7	5.083	1.001	88	88.47	0.139	88.47
98.41	500	5.081	1.003	88	93.56	0.335	93.56

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