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Investigation of Warm Mix Asphalt Additives Using the Science of Tribology to Explain Improvements in Mixture Compaction

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“Lubricant is a substance capable of altering the nature of surface interactions
between two contacting solids”

-Ernest Rabinowicz

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Executive Summary

Part of asphalt pavement production is the compaction process of loose mix. The quality of compaction process has a profound impact on the quality of the final product. With the advent of Warm Mix Asphalt (WMA) additive use, the compaction process became more efficient. In 2010 estimated 4 million tons of WMA asphalt were produced using the WMA additive technology (Hansen and Newcomb 2011). The additives allowed for improved compaction (requiring less compactive effort) and compaction at lower-than-typical temperatures. This thesis is focused on quantifying the improved mixture compaction through novel binder testing. The science of tribology has been used to understand and quantify the way certain WMA additives improve compaction process. It has been found that chemical WMA additives are capable of creating boundary lubrication films protecting aggregate particles from direct solid-solid contact, hence reducing friction between the particles. The new Asphalt Boundary Lubrication test was developed to quantify the boundary lubrication of binders in terms of boundary coefficient of friction. The test quantified the influence of aggregate mineralogy on the lubricating properties of certain WMA additives. It was also discovered that WMA modified binders improve boundary lubrication as compared with control binders. The binder asphalt boundary lubrication test results and mixture volumetric density data show good ranking. Additionally, at high testing temperature (145°C), boundary coefficient of friction provided explanation for changes in mastic viscosity, which can be well correlated with mixture volumetric data.

Chapter 1: Introduction

1.1 Problem Statement

Asphalt mixture compaction is an extremely complex process. Many research studies have been conducted on evaluation of laboratory and field compacted mixtures. Researchers agree that asphalt compaction is, for the most part, governed by material, field, and boundary condition properties. It is also well recognized that due to economic and mix design reasons, many of the properties, such as aggregate gradation, cannot be changed. Therefore, to control the process of compaction, engineers typically adjust the temperature at which they compact (effectively adjusting binder viscosity), and adjust the compactive effort. Pavement density is typically correlated with pavement performance. Therefore, engineers control the compaction process in order to obtain pavement of desired density (as measured by % air voids).

With the advent of asphalt polymer modification and Warm Mix Asphalt additive technologies, the process of compaction has become much more complex. Researchers noticed that

viscosity of binder was not a good estimator of compaction temperature anymore: Mixtures of same gradation and binder viscosity yielded different densities, given the same compactive effort. This problem was attempted to be solved through application of different concepts, with the most recent being the binder lubricity concept and mixture mastic viscosity concept (Hanz, 2012) (Roohi et al., 2013). This thesis will further evaluate the concepts presented by Hanz and Roohi and offer further insight into the topic of binder lubricity and mastic viscosity in order to better understand how they affect the process of asphalt mixture compaction.

1.2 Hypothesis

The hypothesis of this thesis regards asphalt mixture compaction process of WMA modified mixtures. The hypothesis is composed of two parts:

- Certain types of Warm Mix Asphalt additives are capable of aiding compaction process through lubrication of the aggregate surface.
- Mineralogy of aggregate influences the effectiveness of lubrication provided by WMA additives.

1.3 Objectives

The main objectives of this study are:

- Characterize the effects that Warm Mix Asphalt chemical additives possess on improving asphalt mixture compactability.
- Capture the effect of Warm Mix Asphalt additives on boundary lubricating properties of asphalt binders.
- Evaluate the effect of aggregate mineralogy on boundary lubricating properties of WMA modified binders.
- Evaluate the link between asphalt binder boundary lubricating properties and mastic viscosity.
- Define the limitations of using boundary lubricating properties of asphalt binders in application to asphalt mixture compaction.

1.4 Thesis Outline

This thesis is composed of the following chapters:

Chapter 1: Introduction

The problem statement of this work is presented, introducing the reader to the issues addressed by the thesis. This chapter also provides the hypothesis of the thesis along with the main objectives of the study.

Chapter 2: Literature Review

This chapter features a comprehensive literature review on topics of asphalt mixture compaction. The literature review traces how past research and practice shaped today's approach to asphalt mixture compaction and what some of the deficiencies are. Additionally, extensive literature review related to warm mix asphalt technology is included with an emphasis on chemical additives.

Chapter 3: Tribology

Basic principles of tribology are introduced in their relationship to asphalt mix compaction process. The Stribeck curve along with different lubrication regimes and their relationship to lubricant film thickness is presented. Emphasis of the chapter lies on boundary lubricants as they serve special purpose in asphalt mixtures.

Chapter 4: Materials and Methods

The chapter describes materials and existing test procedures used to evaluate lubricational properties of asphalt binders. Specific WMA additives, their concentration in binder, and asphalt mixture gradation are listed.

Chapter 5: Preliminary Results Using Existing Methods

This section provides results of the existing lubrication tests performed on the binders used in this study. The section also explains the shortcomings of those tests, justifying the need for development of a new test capable of detecting the influence of aggregate mineralogy on binder lubricating properties.

Chapter 6: Development and Application of the Asphalt Boundary Lubrication Test

Development and test results of the Asphalt Boundary Lubrication test are contained in this chapter. Statistical analysis can be found for the presented results. The test results are also contrasted with the mixture volumetric results as well as the concept of low shear mastic viscosity.

Chapter 7: Conclusions and Recommendations

The conclusions of the study are presented along with recommendations for follow-up studies.

Chapter 8: References

The chapter contains a list of all works cited across the document.

Chapter 9: Appendix

Appendix contains additional graphical representation of the results of Asphalt Boundary Lubrication Test. Technical drawings of the Asphalt Boundary Lubrication cell can be found in the appendix.

Chapter 2: Literature Review

2.1 Hot Mix Asphalt Mixture Design

Since its early use in civil engineering, asphalt binder has been mixed with rocks to form pavement. Some of the early use of flexible pavement in the United States can be traced back to Washington D.C. in the 1860s when tar was mixed with aggregates to build roads (Crawford 1989). Since then, asphalt technology has undergone a continuous process of improvement. According to a comprehensive book regarding asphalt mixtures, “Hot Mix Asphalt Materials, Mixture Design and Construction” by Roberts et al. (1996), during the decades of the 1940s and the 1950s the Hveem and Marshall methods of mix design were introduced. According to the authors, these methods were sufficient for the traffic conditions present at the time the methods were developed. However, as the traffic loads and volumes began to dramatically increase, the Hveem and Marshall design methods have been shown to provide pavement mixes of insufficient performance characteristics. Because of a growing concern about the quality of asphalt pavements produced in North America, the federal government of the United States of America initiated the Strategic Highway Research Program (SHRP) in 1988. The conceived program had a primary goal of developing an improved mix design procedure adequate to the present times (Roberts, et al. 1996). The adequacy meant extending the life or reducing the life-cycle cost of asphalt pavements, reducing maintenance cost, and minimizing premature failures (Mamlouk 2011). Completed in 1993 and referred to as Superior Performing

Asphalt Pavement System (Superpave), the new design method encompassed a novel performance grading system for binders (PG), consensus aggregate properties, a new mix design and analysis procedure (Roberts, et al. 1996). Since its completion, the Superpave mix design method has been accepted by majority of US DOTs.

2.2 Asphalt Mixture Compaction

2.2.1 Asphalt Mixture Compaction - Overview

Asphalt mixture compaction has been a topic of discussion and research for many decades (Roberts, et al. 1996). A number of scholarly works emphasizes the importance of proper compaction. Kennedy et. al. (1984) showed that tensile strength, stability, resilient and static moduli are reduced at high air voids (Kennedy, Roberts and McGennis 1984). It was found that raveling is a serious problem above 8% air voids, and becomes a severe problem above 15% air voids (Kandhal and Koehler 1984). McLeod concluded that providing sufficient density, “(...) retards the rate of hardening of the asphalt binder, and results in longer pavement life, lower pavement maintenance, and better all-around pavement performance” (McLeod 1967). Insufficient asphalt pavement density is also related to rutting (Scherocman 1984). However, it must be mentioned that current Superpave mixture design limits minimum air voids in the mix to 2% because it is believed that rutting may result in mixtures compacted to higher densities (Roberts, et al. 1996). A number of works linked increased air voids with the reduced fatigue life (Pell and Taylor 1962), (Epps, et al. 1969), (Linden, Mahoney and Jackson 1989), (Scherocman 1984). Finally, high air voids lead to increased likelihood of moisture damage due to a higher number of interconnected voids in the mix (Kandhal and Koehler 1984).

Some of the most recent work on the topic suggests that there are three major classifications of factors affecting compaction (Wang, Zhang, et al. 2007):

- properties of the materials,
- environmental variables,
- boundary conditions.

Table 1 lists the variables affecting compaction by their corresponding classification.

Table 1. *Factors affecting compaction according to (Wang, Zhang, et al. 2007)*

Properties of the materials	Environmental Variables	Boundary Conditions
Aggregate: <ul style="list-style-type: none"> • Gradation • Shape • Angularity • Texture 	<ul style="list-style-type: none"> • Air temperature • Humidity • Sunshine • Cloudiness • Wind velocity 	<ul style="list-style-type: none"> • Layer thickness • Stiffness of underlying layer • Mix laydown temperature • Base temperature
Binder: <ul style="list-style-type: none"> • PG grade • Amount of binder • Temperature sensitivity of binder 		

Since many of the factors listed in the Table 1 are predetermined during pavement and mixture designs, and some, such as environmental variables, cannot be controlled, the compaction process is typically controlled by adjusting the compactive effort (e.g. increasing number of passes or changing compactor type) and binder viscosity (e.g. delaying or rushing compaction) (Delgadillo and Bahia 2008) (De Sombre, et al. 1998). Some of the construction factors related to compaction were listed by Lenz and include the following (Lenz 2011):

Rollers:

- Type
- Number
- Sequence
- Pattern used
- Speed and timing
- Number of Passes

Others:

- Haul distance
- Haul time

After its production in asphalt plant, the loose mix is transported to the construction site. At the site, asphalt compaction is typically subjected to the following compaction train (Lenz 2011):

1. Screed
2. Breakdown Roller
3. Intermediate Roller
4. Finish Roller
5. Traffic

After asphalt mix is transported to the construction site, it is placed in and laid down by a machine typically referred to as a screed. The name *screed* comes from the part used to give a correct height to initial lift of an asphalt layer. Figure 1 illustrates a specific screed capable of laying down two asphalt lifts simultaneously (Richter 2003).

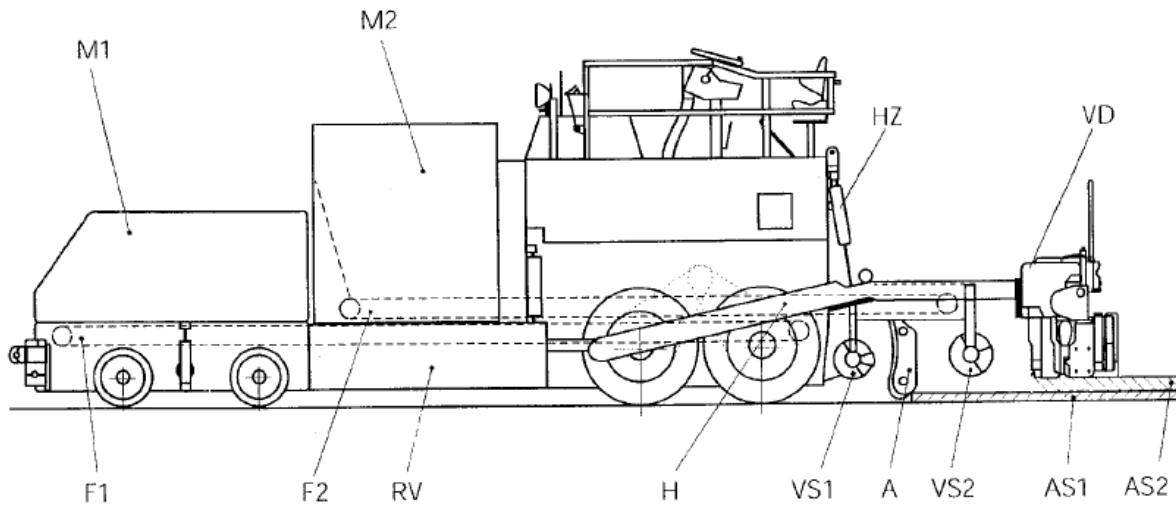


Figure 1 Cross-section of a finisher for the simultaneous installation of two asphalt layers with different composition over the entire installation width. M1, M2 – two mixture buckets, F1 - lower layer conveyor belt, F2 - upper layer conveyor belt, RV - frame extension, VS1, VS2 – two material spreader screws, A – screed plate for correct for correct thickness of the first asphalt course (AS1), AS2 – second asphalt course, VD – tamping beam for pre-compaction of two asphalt layers, HZ – hydraulic pulling system for changing the weight of the strut H. (Richter 2003)

Besides laying down loose mix, the screed provides pre-compaction and shapes the pavement profile to facilitate drainage. The machine illustrated in Figure 1 features a tamping beam which may operate in vibratory mode, providing additional pre-compaction. According to Lenz, “(...) approximately 75-85% of the theoretical maximum density of the HMA will be obtained when the mix passes out from under the screed” (Lenz 2011). This statement highlights the importance and necessity of using the screed.

Immediately after the screed lies down and pre-compacts loose mix, a breakdown roller follows. There are two basic types of rollers: the steel wheeled roller and the pneumatic tire roller (Lenz 2011). Figure 2 and Figure 3 illustrate cross-sections of steel drum roller and pneumatic tires used in pneumatic tire roller.

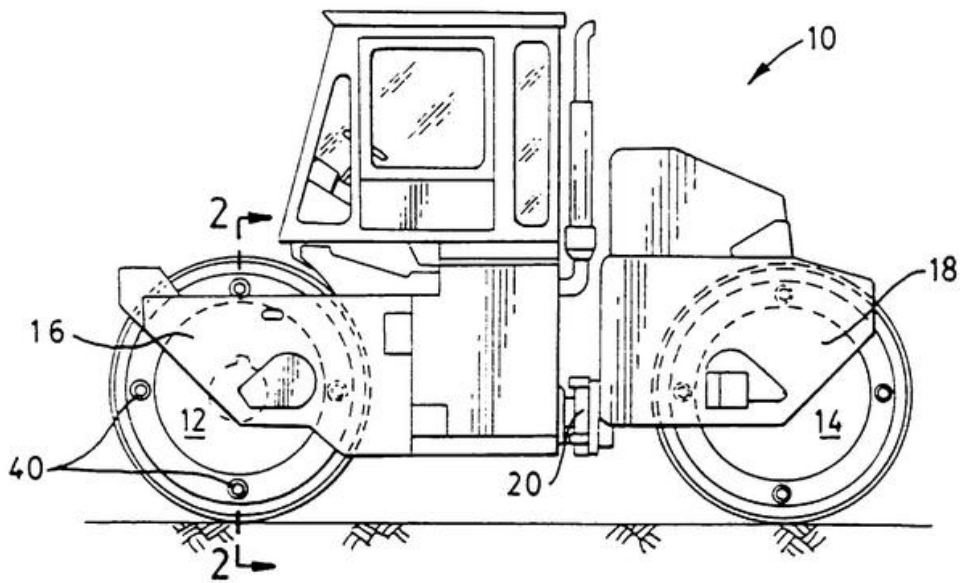


Figure 2 Cross-section of a steel-drum vibratory compactor. (Ludovic 1999)

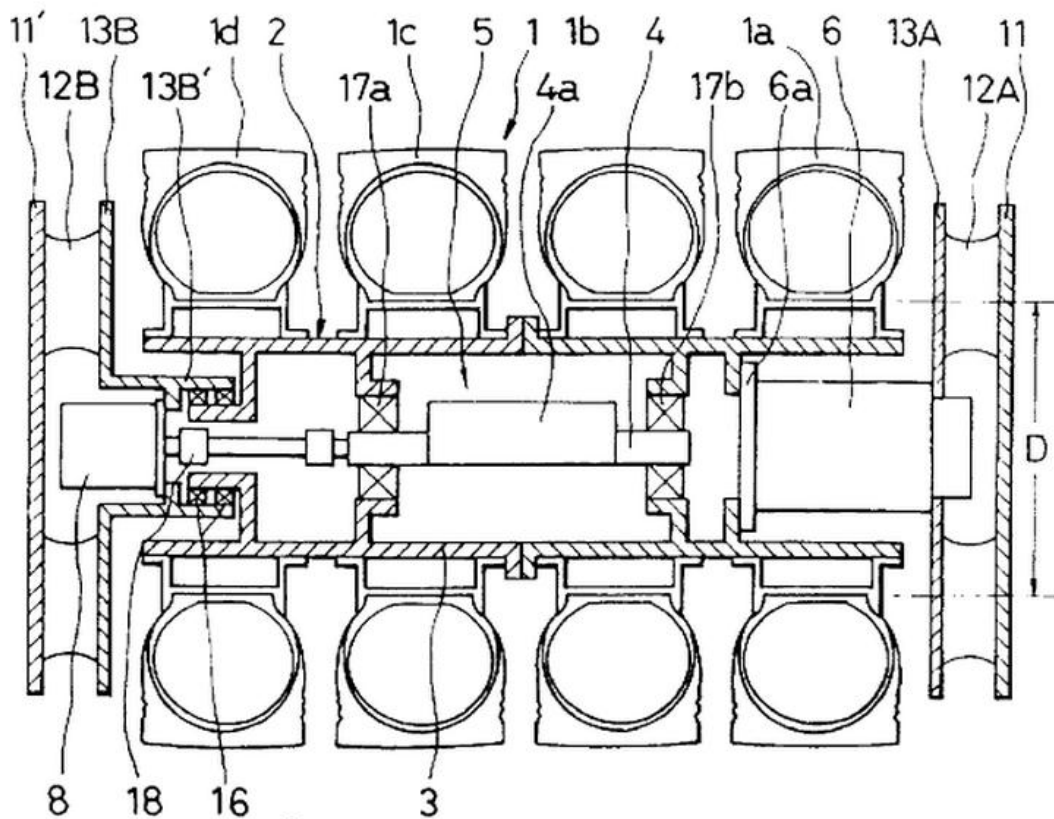


Figure 3 Cross-section of pneumatic tires used in vibratory pneumatic tire roller. Visible in the illustration are compartments used to adjust tire pressure as well as vibratory mechanism used to create vibrating action on the pavement. (Mitsui and Guard 1998)

The rollers compact asphalt mat, “(...) by creating a shear stress between the compressed material underneath the ground contact area and the adjacent uncompressed material” (Lenz 2011). The steel rollers can be equipped in a vibration module allowing for vibratory action which, if properly used, increases the compactive effort and creates a smoother mat (Lenz 2011). Pneumatic rollers have an advantage of developing, “(...) kneading action between the tires that tends to realign aggregate within the HMA” (Lenz 2011). They also provide more uniform and denser HMA layer (Lenz 2011).

After the majority of the required mat density is achieved, finish rollers are used to create a smooth surface. Figure 4 illustrates a sample graph of Density and Measured Mat Temperature vs. Time. It can be observed from the figure that the largest gains in density are obtained at the beginning of compaction when the mix is still fairly loose and the temperature is relatively high.

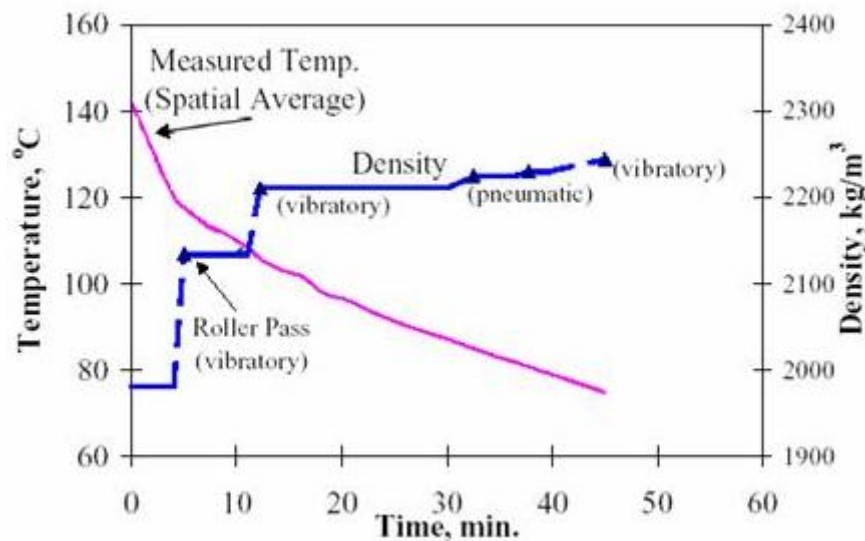


Figure 4 Density and Measured Mat Temperature vs. Time (Chadbourn, et al. 1998)

2.2.2 Asphalt Mixture Compaction – Modeling

Some parallels regarding asphalt mix compaction can be drawn from geotechnical engineering. According to Sowers, soil or particle densification is achieved through the following (Sowers 1970):

1. Reorientation of particles,
2. Fracture of grains or bonds between particles,
3. Bending and distortion of particles and their adsorbed layers.

Further, it is argued that cohesion-less materials (such as crushed rocks) are mainly densified through reorientation of particles and particle fracture (Sowers 1970). Therefore, having more angular

aggregate shape leads to increased difficulty of compaction through increased internal friction between the particles (Chadbourn, et al. 1998).

2.2.2.1 Asphalt Mixture Compaction – Modeling - Continuum Mechanics Approach

In 1967, Kari described the asphalt mixture during compaction as “loose, plastic, non-cohesive” at initial stages of compaction and “a coherent mass possessing a high degree of tensile strength” at final stages of compaction (Kari 1967). According to Chadbourn et al., “(...) The compaction of an asphalt mixture can be considered to behave somewhere between cohesive and non-cohesive soil” (Chadbourn, et al. 1998). Therefore, the cohesion of the mix decreases as the binder viscosity decreases making the mixture easier to compact (Chadbourn, et al. 1998). The non-cohesive behavior is attributed to resistance to reorientation of particles by friction between aggregates (Chadbourn, et al. 1998). Chadbourn used the Coulomb’s equation to illustrate the cohesion and friction within the mix and indicate the amount of shear strength in asphalt mixture (Chadbourn, et al. 1998):

Equation 1 *Coulomb’s equation.*

$$\tau = c + \sigma * \tan(\Phi)$$

Where:

τ = shear stress

σ = normal stress (confining pressure)

c = cohesion factor

Φ = internal friction angle

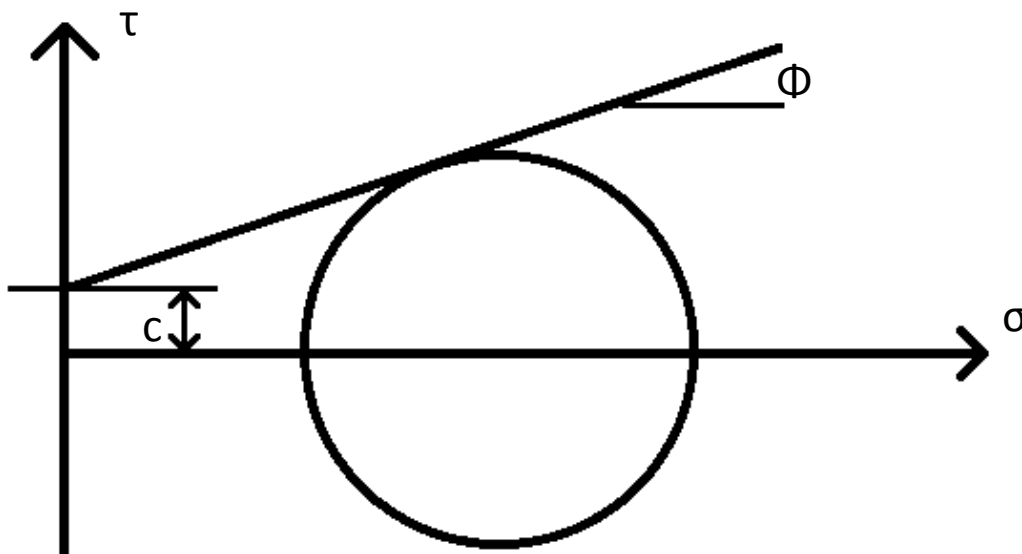


Figure 5 *Mohr-Coulomb Relationship.*

The lower the shear strength in asphalt concrete the more readily the mix can be compacted (less effort is needed by a compactor to cause compaction). Schmidt et al. suggested that the cohesion of asphalt mix is then influenced by the amount of binder and filler used, the temperature of the mix, and the nature of the asphalt, whereas the internal friction angle is mostly affected by aggregate properties and by the temperature and asphalt content of mixture (Schmidt, et al. 1959).

The Mohr-Coulomb approach was used in 1948 by Nijboer to derive an empirical relationship between the asphalt concrete triaxial tests and the mixture compactability (Nijboer 1948). Similar approach was taken by Vizi and Buttner in 1981.

Despite its early popularity, the approach to asphalt compaction in terms of Mohr- Coulomb relationship presented above is very simplistic due to continuum mechanics assumption. As it was stated by Sowers, one of the major ways particle densification occurs is through the particle reorientation. However, particle reorientation is not well-accounted for in Mohr- Coulomb relationship.

2.2.2.2 Asphalt Mixture Compaction – Modeling - Empirical Methods Using Soil Consolidation Analogy

Realizing that continuum mechanics approach assumed in Mohr- Coulomb relationship is not appropriate for asphalt mix compaction, research effort was directed towards empirical methods using soil consolidation analogy (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011). If one considers compaction as reduction in air voids of mixture the following consolidation relationship for laboratory compaction using Superpave gyratory compactor can be used (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011):

Equation 2 *Consolidation relationship for laboratory compaction using Superpave gyratory compactor.* (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011)

$$A_v = A_{v0} - K^l \times \text{Log}(N)$$

Where:

A_v = air-void content after the Nth gyration;

A_{v0} = air-void content after the first gyration;

K^l = air-void content after the first gyration;

N = gyration number

Later, the given relationship was transferred to the dissipated strain energy - effective consolidation stress space by Wang and Frost (Wang and J 2004). The assumption of accumulative volumetric strain and accumulative vertical strain, combined with constant pressure throughout compaction and non-recoverability of compaction process allows for representation of accumulated dissipated work in terms of:

Equation 3 *Representation of accumulated dissipated work.* (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011)

$$E_d = \sum_{N_0}^N P \Delta A_v$$

where:

E_d = Accumulated dissipated work;

$P \Delta A_v$ = Unit volume of sample.

Integrating the above formula yields the following form (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011):

Equation 4 *Integrated form of Equation 3* (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011).

$$E_d = PK^l \text{Log}\left(\frac{N}{N_0}\right)$$

As it was pointed out by Wang, K^l is a measurement of the dissipated strain energy rate required to consolidate asphalt concrete, and can be decomposed into three different components that are mixture specific (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011):

Equation 5 *Decomposition of K^l into mixture specific components* (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011).

$$K^l = K_g \times K_m \times K_b$$

where:

K_g = gradation contribution;

K_m = aggregate morphological contribution;

K_b = binder rheology contribution.

Determining the particular K^l values can be realized through analyzing experimental data, micromechanics models and computational simulation (L. Wang, Modeling of Asphalt Microstructure

and Micromechanics 2011). This method serves a better approximation of mixture compactability, as it is based on more realistic assumptions than the Coulomb-Mohr relationship. Additionally, the K^1 parameter can be correlated with shear modulus of mixture, instead of air-voids, as the shear modulus is a function of mixture air content (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011).

Similar empirical relationships in terms of accumulated dissipated work (E_d) can be derived for field compaction (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011). Given that field compaction is subject to more variables than the laboratory compaction, the K^1 parameter must be expanded to account for them. The following K^f factor was given by Wang and features additional field compaction related factors:

Equation 6 *K^f factor featuring additional field compaction related factors.* (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011)

$$K^f = K_g \times K_m \times K_b \times K_h \times K_l \times K_s$$

where:

K_h = layer thickness factor

K_l = load magnitude factor related to compaction procedure;

K_s = soil support factor.

Similar to previous K values, different analysis tools including micromechanics models, computational simulation and experimental data can be used to obtain K_h , K_l , K_s . Such extended models for asphalt mix compaction can be very useful for industrial use, especially so for the intelligent compaction techniques used today. It is very important, however, to be able to use accurate K values. Many asphalt researchers have realized recently that analytical micromechanics simulations are limited to certain bounds and are of a static nature. Also, Finite Element methods are limited due to lack of ability to account for large displacements. Promising alternative to the listed methods is use of Discrete Element Modeling (DEM) method which is a computer modeling tool capable of handling large deformations in the modeled materials; DEM can model aggregate shapes and particle kinematics during compaction. (L. Wang, Modeling of Asphalt Microstructure and Micromechanics 2011)

2.2.3 Asphalt Mixture Compaction – Binder Properties

Asphalt mixture compaction modeling is a complex process; it is very useful in prediction of desired compaction temperature for a given mix or compactive effort required. Modeling can also

approximate the differences in compaction due to different gradations. Nonetheless, compaction modeling, regardless of underlying principles, is an experimental method of estimating actual mixture compaction. Additionally, modeling requires detailed information input regarding all material properties. Such information input is very hard to assemble. Also, aggregate sources vary significantly from project to project and are hard to translate into a meaningful input into a model without previous empirical data regarding them.

Therefore, out of practicality, asphalt researchers and specialists in the field historically directed their effort towards optimization of compaction process by using asphalt binder viscosity. This direction is in agreement with all compaction models which are very much affected by binder viscosity. The following sub-sections discuss the developments in regard to understanding how binder viscosity affects the compaction process.

2.2.3.1 Binder Properties – Kinematic Viscosity

In 1967 McLeod published an article describing the influence of the viscosity-temperature characteristics of asphalt binders on the compaction process of dense graded asphalt concrete mixtures (McLeod 1967). The paper suggested that using low, rather than high viscosity binder led to lower compactive effort necessary to achieve desired stability and density of pavement (McLeod 1967). The author also suggested that the compaction temperature should be selected for a kinematic viscosity of approximately 0.17 Pascal Seconds (McLeod 1967). Further along, during the development of the Superpave mixture design it was decided to shift the limit of the asphalt binder kinematic viscosity to 0.28 ± 0.03 Pascal Seconds (Mamlouk 2011). As Khatri et al. pointed out, the kinematic viscosity limit was, “(...) carried over from guidelines established by the Asphalt Institute long before the Superpave Gyratory Compactor (SGC) was introduced” (Khatri, Bahia and Hanson 2001). However, the Superpave mix design method also established checkpoints for mixture density by implementing N initial, N design, and N maximum, “(...) to ensure that the mix is neither too soft nor too stiff for the service conditions of the pavement” (De Sombre, et al. 1998). It is important to note that the Superpave Gyratory Compactor was initially developed to simulate the tire pressure of the trucks during the service life of the pavement (Blankenship, Mahboub and Huber 1995).

Nonetheless, shortly after implementation of viscosity-based compaction temperature guidelines contained within Superpave procedure, it has been shown that there may be a different way to characterize asphalt pavement compaction. De Sombre et al. have shown in their study performed in 1998 that there is an optimum temperature range for asphalt compaction (De Sombre, et al. 1998). The study encompassed field and laboratory mixes of two different gradations and several different binder sources (De Sombre, et al. 1998). Asphalt compaction was characterized in terms of shear stress within the mixture during compaction (De Sombre, et al. 1998). The study has shown that for

both laboratory and field mixtures there is an optimum compaction temperature characterized by low shear stress within the mixture, leading to lower mat density (De Sombre, et al. 1998). Typical range has a parabolic shape, with high shear stresses at low mat temperatures, as well as high temperatures (De Sombre, et al. 1998). Also, the range typically occurred below the temperature dictated by Superpave binder viscosity requirement:

“(…) if the optimum compaction temperature range is considered to be 15°C (27°F) above and below the temperature where the minimum shear stress occurs, the compaction temperature specified by viscosity temperature is generally well above this range.” (De Sombre, et al. 1998)

It is important to note that the factor having the largest impact on the behavior of mixture compaction was determined to be the aggregate gradation (De Sombre, et al. 1998). However, determining the optimum compaction temperature range for the same gradation may be very useful, especially when polymer modified binder is present (De Sombre, et al. 1998). On this topic De Sombre et al. noted:

“Even if the same grade of binder is used in a mix, the compaction shear stress may be drastically different depending upon the type of polymer modifier used. This may be due to the way in which the polymer interacts with the asphalt binder.” (De Sombre, et al. 1998)

2.2.3.2 Binder Properties – Polymer Modification, Zero Shear Viscosity

With increased use of polymer modified binders, and given the issues described in the previous sections regarding the equiviscous procedure, alternative means to determine the proper compaction temperature for asphalt were required. This problem was noticed and studied by Khatri, Bahia and Hanson in their work from 2001 titled, “Mixing and Compaction Temperatures for Modified Binders Using the Superpave Gyrotory Compactor”. They expressed a particular concern about the excessive heat being used to meet the viscosity requirements prescribed in the Superpave:

“There is a serious concern that asphalt technologists in the laboratory and in the field are heating asphalt binders to excessive levels to meet these requirements that might not be necessary. Excessive heating can cause damage to asphalt binders, particularly those containing additives.” (Khatri, Bahia and Hanson 2001)

The study agreed with previous findings by De Sombre et al. about the compaction process being possible at much lower temperatures:

“(…) compaction in the SGC, and mixing using conventional laboratory mixers, can be accomplished effectively at much higher viscosity values without significantly changing asphalt content or affecting mixture volumetrics.” (Khatri, Bahia and Hanson 2001)

However, modified binders exhibit, “(…) significant shear dependency, which plays a major role in compaction” (Khatri, Bahia and Hanson 2001). They have shown that, “(…) as the modification level increases, the shear rate dependency becomes more complex and more sensitive to temperatures” (Khatri, Bahia and Hanson 2001). They claimed that, “(…) the relationship between percent air voids and viscosity is dependent on the shear rate and that the relationship is best explained by using viscosity at low shear rates” (Khatri, Bahia and Hanson 2001). In their study Khatri et al. investigated compaction using seven different modifiers, including SBS linear, SBR and crumb rubber (Khatri, Bahia and Hanson 2001).

Khatri et al. discovered that most of the modified binders they tested were shear thinning (Khatri, Bahia and Hanson 2001). Hence, they hypothesized that the compaction was more affected by low rather than high shear rate viscosity (Khatri, Bahia and Hanson 2001). Based on the understanding of compaction in the Superpave Gyrotory Compactor, they assumed that, “(…) the most critical part of densification occurs at stages when the binder-deformation rate is very low because of the high resistance to compaction” (Khatri, Bahia and Hanson 2001). They also determined that for most of the compaction time (54% of gyrations) the strain rate was less than 0.01 1/s which they called the “zero-shear-rate limit” (Khatri, Bahia and Hanson 2001).

At a typical Superpave viscosity testing shear rate (6.8 1/s and #27 spindle) the discrepancy in the relationship between viscosity and air voids at N design was high, reaching as much as 2%, and was confirmed for different aggregate types and compaction temperatures (Khatri, Bahia and Hanson 2001). As an alternative Khatri et al. chose 6.0 Pascal Seconds as the zero shear rate viscosity for which compaction could be achieved at temperatures less than 160°C (Khatri, Bahia and Hanson 2001). For the 39 binders used in the study, the estimated compaction temperatures fell below 160°C for 37 and resulted in estimated reduction of mixing and compaction temperatures of 40°C (Khatri, Bahia and Hanson 2001). Later, Khatri et al. validated the estimated temperatures for five binders and determined that at N design the corresponding compacted densities of mixes were within 1% from the target of 4% (Khatri, Bahia and Hanson 2001).

Cho, Bahia and Kamel further evaluated the use of the Zero Shear Viscosity concept in conjunction with varying Superpave Gyrotory Compactor stress applied during laboratory compaction in order to evaluate the Superpave volumetric mixture design for modified binders (Cho, Bahia and Kamel 2005). Meanwhile, the proposed 6.0 Pascal Second Zero Shear viscosity for compaction,

suggested by Khatri et al. in 2001, was lowered to 3.0 Pascal Seconds (Binder Selection Guideline Project. 2004). The study by Cho et al. further confirmed the use of Zero Shear Viscosity concept (at 3.0 Pascal Seconds) for compaction temperature and claimed that there was no reason to use the compaction temperature targeting the kinematic viscosity of 0.28 Pascal Seconds as used in the current Superpave method (Cho, Bahia and Kamel 2005).

Additionally, it was found that the compaction pressure had the most impact on the sample density (Cho, Bahia and Kamel 2005). The study has shown that in the Superpave Gyratory Compactor, a decrease in pressure from the typical 600 kPa to 300 kPa resulted in increase in air voids at N design of 3% to 4% (Cho, Bahia and Kamel 2005). The authors, therefore, hypothesized that, “(...) the size and weight of the compaction roller is one of the most important factors” (Cho, Bahia and Kamel 2005).

Since the study from 2001 by Khatri et al. it has been progressively shown in laboratory setting, that asphalt mixtures can be successfully compacted to desired 4% air voids at N design using binder viscosity much lower than the one prescribed in the Superpave mix design (Khatri, Bahia and Hanson 2001), (Binder Selection Guideline Project. 2004), (Cho, Bahia and Kamel 2005). Additionally, it has been determined that not the binder viscosity, but the compaction pressure applied by the Superpave Gyratory Compactor is critical in obtaining proper density (Cho, Bahia and Kamel 2005). Nevertheless, the data generated in the studies had yet to be supported by field measurements.

2.2.3.4 Binder Properties – Zero Shear Viscosity, Field Validation

In 2008 Delgadillo and Bahia attempted to evaluate the previously studied effects of temperature and pressure on HMA compaction by comparing field to laboratory data (Delgadillo and Bahia 2008). The goal of the study was to develop low shear viscosity limits, “(...) that will be suitable for laboratory and field compaction” (Delgadillo and Bahia 2008)”. Delgadillo and Bahia reported the following:

“The temperature for the first breakdown roller pass was between 115 and 125°C for all projects, an exception being Project 7200-05-70, where it was close to 100°C. In summary, densification was achieved in the projects until a limiting temperature was reached and/or acceptable density was achieved. Below this critical temperature, more roller passes did not result in more density. The limiting temperature appears to be between 70 and 80°C for the sampled projects.” (Delgadillo and Bahia 2008)

The data from the field was then compared with binders' zero shear viscosity values using a limit of 3.0 Pascal Seconds in order to see whether the field values would correlate. As it turned out, all zero shear values grossly overestimated the compaction temperature used in the field projects (Delgadillo and Bahia 2008). Also, the data obtained in Superpave Gyrotory Compactor suggested that changing stress level of compaction from 300 kPa to 600 kPa had, "(...) a much greater effect on densification than changing the temperature from 120 to 90°C" (Delgadillo and Bahia 2008). Nonetheless, given the limiting temperature, a proper limit for viscosity had to be established. Given the relationship between binder viscosity and field compaction data, the authors estimated that a 50 Pascal Second low shear viscosity was the most appropriate limiting value (Delgadillo and Bahia 2008). The viscosity was suggested to be obtained from a DSR creep test at a shear rate of 0.5 1/s (Delgadillo and Bahia 2008). The authors speculated that achieving desired mat density at such low temperatures may be due to in-mat stresses, "(...) high enough to cause shear thinning in the binders and generate densification nonetheless" (Delgadillo and Bahia 2008).

2.2.4 Asphalt Mixture Compaction – Aggregate Structure

In 2012 Roohi et al. published an article showing that mixtures compacted to the same density may perform differently given the same service loading (Roohi, Tashman and Bahia 2012). This observation resulted in investigation of the influence of aggregate interlock on asphalt concrete performance. The analysis of aggregate interlock is a sophisticated topic requiring appropriate technology. Yue et al. pioneered the application of digital image analysis to study asphalt concrete internal structure (Yue, Bekking and Morin 1995). In 2011 Roohi captured the effect of compaction conditions on internal aggregate structure of asphalt mixes through use of upgraded iPas software (Roohi Sefidmazgi 2011). iPas, originally introduced by Coenen et al. was developed for image analysis of 2-D representation of aggregates and asphalt in a mixture. (Coenen, Kutay and Bahia 2011). As Roohi pointed out, "(...) this software, although significantly useful was limited in the internal structure analysis capabilities" (Roohi Sefidmazgi 2011). In his assumption that the internal structure indices are better discriminatory parameters than volumetric properties, Roohi proposed three structural indices: number of contact zones, contact length per area, and contact orientation (Roohi Sefidmazgi 2011). Asphalt mixture can better distribute applied loads if the connectivity of internal structure is improved (Roohi Sefidmazgi 2011). This means increasing the number of contact zones. Additionally if the contact length per area of the aggregates is increased, there is more friction and interlocking (Roohi Sefidmazgi 2011). Finally, if the contact orientation coincides with the loading direction, "(...) the more effective the mixture is in resisting deformation under loading" (Roohi Sefidmazgi 2011). Figure 6 represents two different approaches to quantification of asphalt concrete compaction.

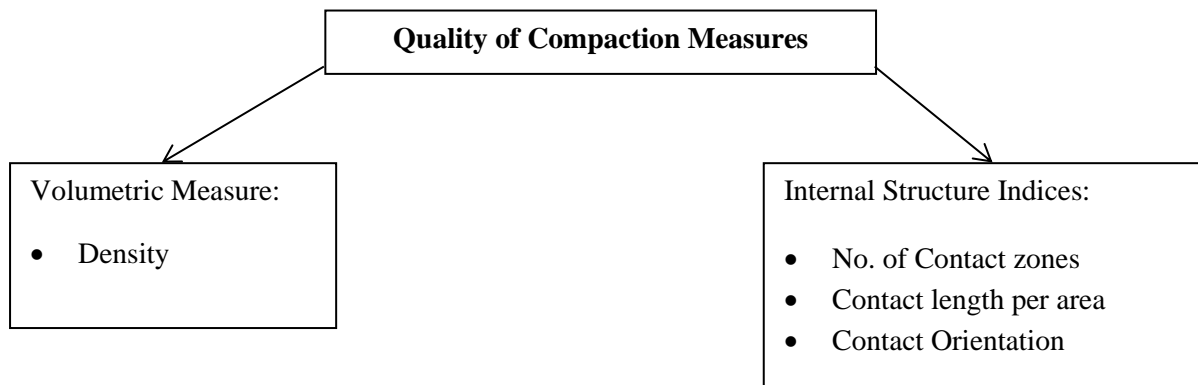


Figure 6 *Additional Compaction Indicators.*

Roohi performed image analysis on polymer modified mixes of the same design mix design and gradation (Roohi Sefidmazgi 2011). The resulting inherent internal structures of the mixes were significantly different (Roohi Sefidmazgi 2011). The difference led to a conclusion that polymer modification led to change in internal structure of mixes during compaction (Roohi Sefidmazgi 2011). The internal indices were then correlated with binder viscosity measurements (at 0.28 Pascal Seconds). The correlation resulted in a scattered distribution leading to conclusion that binder viscosity criterion specified in Superpave mixture design procedure was not a reliable compaction predictor (Roohi Sefidmazgi 2011).

2.2.5 Asphalt Mixture Compaction – Aggregate Structure Formation, Mastic Significance

More recently, Roohi et al. evaluated the effect of mastic viscosity on asphalt mixture compaction. Asphalt mastic viscosity was correlated with contact length per area for four different polymer modified binders plus a control binder at various compaction temperatures. At high compaction temperature (145°C) Roohi et al. showed that low shear rate mastic viscosity is a good indicator of contact length per area index for compacted mixes (2013). Asphalt mixtures with higher contact per area length index allowed for more particle reorientation during compaction. Roohi et al. hypothesized that the reason for higher particle reorientation ability within mixes was higher mastic viscosity; Aggregates coated with mastic of higher viscosity would be able to reorient more freely as *thicker* mastic would prohibit direct aggregate-to-aggregate contact (Roohi, Teymourpour and Bahia, Effect of Particle Mobility on Aggregate Structure Formation in Asphalt Mixtures 2013).

2.3 Warm Mix Asphalt Compaction

2.3.1 Warm Mix Asphalt Compaction – Concept of Warm Mix Asphalt

The early history of Warm Mix Asphalt traces back to Europe:

“The development of WMA was initiated in Europe in the late 1990s primarily in response to the need for greenhouse gas reduction under the Kyoto Protocol. WMA technologies such as, Aspha-min, WAM Foam, and Sasobit were developed during that time. The US National Asphalt Pavement Association (NAPA) organized a European Scan tour in 2002 to examine these three technologies. (P. S. Kandhal 2010)

The following are some of the definitions available in scholarly literature defining the Warm Mix Asphalt (WMA) technologies:

According to the most recent NCHRP Report 691 titled “Mix Design Practices for Warm Mix Asphalt”, the term Warm Mix Asphalt (WMA), “(...) refers to asphalt concrete mixtures that are produced at lower temperatures than the temperatures typically used in the production of hot mix asphalt (HMA) (50°F [28°C] lower or more)” (Bonaquist 2011).

Yet another definition is offered by Kandhal, “WMA technology allows the mixing, lay down, and compaction of asphalt mixes at significantly lower temperatures compared to Hot Mix Asphalt (HMA)” (P. S. Kandhal 2010).

A significant report sponsored by the United States Federal Highway Administration, in which the objective was to survey and evaluate Warm Mix Asphalt practices across a number of European countries provided the following WMA definition:

“Warm-mix asphalt (WMA) is a group of technologies that allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to reduce the viscosity of the asphalt and provide for the complete coating of aggregates at lower temperatures. WMA is produced at temperatures 20 to 55°C (35 to 100°F) lower than typical hot-mix asphalt (HMA).” (D’Angelo, et al. 2008)

According to Kristjánsdótti et al. “‘Warm-mix asphalt’ (WMA) is the broad term typically referring to technologies that seek to lower emissions and reduce energy consumption by lowering the temperature at which asphalt mixtures are produced and placed” (Kristjánsdótti, et al. 2007).

As it can be seen there is no single, uniform definition of Warm Mix Asphalt rather than a set of overlapping statements regarding the conditions under which the asphalt mixes are produced and/or placed. Regardless of the lack of uniformity, all above definitions agree upon lower production temperatures, which indirectly implies lower compaction temperatures.

2.3.2 Warm Mix Asphalt Compaction – Available Technologies

To achieve the objective of lowering the production temperatures, the producers of WMA employed a number of different technologies. Table 2 is derived from NCHRP Report 691 and presents the most recent list of the WMA technologies available on the market (Bonaquist 2011).

Table 2 Summary of WMA processes identified during NCHRP Project 9-43 (Bonaquist 2011).

Name	Process/Additive	Company	Website
Accu-Shear Dual Warm Mix Additive System	Foaming system	Stansteel	http://www.stansteel.com/sip.html
Adesco/Madsen Static Inline Vortex Mixer	Foaming system	Adesco/Madsen	http://www.asphalteequipment.com/documents/Static%20Inline%20Vortex%20Mixer%20Brochure.pdf
Advera	Zeolite	PQ Corporation	http://www.pqcorp.com/products/AdveraWMA.asp
AQUABLACK	Foaming system	Maxam Equipment Company, Inc.	http://maxamequipment.com/AQUABlackWMA.htm
AquaFoam	Foaming system	Reliable Asphalt Products	http://www.reliableasphalt.com/Default.asp
Asphaltan –B	Montan wax	Romonta	http://www.romonta.de/ie4/english/romonta/i_wachse.htm
Aspha-min	Zeolite	Eurovia	http://www.eurovia.fr/en/produit/135.aspx?print=y
Cecabase RT	Unspecified additive	Ceca	http://www.cecachemicals.com/sites/ceca/en/business/bitumen_additives/warm_coated_material/warm_coated_material.page
Double Barrel Green	Foaming system	Astec, Inc.	http://www.astecinc.com/index.php?option=com_content&view=article&id=117&Itemid=188
Evotherm ET	Emulsion with unspecified additives	MeadWestvaco	http://www.meadwestvaco.com/Products/MWV002106
Evotherm DAT	Unspecified additive		
Evotherm 3G	Unspecified additive		
Licomont BS-100	Fatty acid derivative	Clariant	http://clariant.com/C12576850036A6E9/A0F44E23B922E21CC12576BF00484894/\$FILE/20100203_Clariant_LowEmissionModifierBoosts.pdf
Low Emission Asphalt	Sequential coating using wet fine aggregate and unspecified additive	McConaughay Technologies	http://www.mcconnaughay.com/lowemissionasphalt_intro.php
Meeker Warm Mix Asphalt System	Foaming system	Meeker Equipment	http://www.meekerequipment.com/new_warmmixad1.html
Rediset WMX	Unspecified additive	Akzo Nobel	http://www.surfactants.akzonobel.com/asphalt/pdf/Rediset%20Brochure_0907.PDF
Sasobit	Fischer Tropsch wax	Sasobit	http://www.sasolwax.us.com/sasobit.html
Terex Warm Mix Asphalt	Foaming system	Terex Roadbuilding	http://www.terexrb.com/default.aspx?pgID=308
Thipoave	Sulfur plus compaction aid	Shell	http://www.shell.com/home/content/sulphur/your_needs/products/in_roads/
TLA-X	Trinidad Lake Asphalt plus modifiers	Lake Asphalt of Trinidad and Tobago	http://www.trinidadlakeasphalt.com/home/products/ta-x-warm-mix-technology.html
Ultrafoam GX	Foaming system	Gencor Industries, Inc.	http://gencorgreenmachine.com
WAM Foam	Soft binder followed by hard foamed binder	Kolo Veidekke, Shell Bitumen	http://www.shell.com/home/content/bitumen/bitumen/products/shell_wam_foam/

2.3.3 Warm Mix Asphalt Compaction – Accounting for WMA in Superpave guidelines

Due to the continuously increasing use of Warm Mix Asphalt technology, it became necessary to provide user guidelines. In 2011 NCHRP Report 691 titled “Mix Design Practices for Warm Mix Asphalt” was released. The objective of the study contained in the report was to, “(...) develop a mix design method for WMA in the form of a draft AASHTO recommended practice for use by engineers and technicians in the public and private sectors” (Bonaquist 2011). It was recognized by the author that WMA encompasses a number of processes. Therefore, viscosity-based mixing and compaction temperatures could not be used to control coating, workability, and compactability (Bonaquist 2011). Instead, the study resulted in the Draft Appendix to AASHTO R 35 including, “(...) evaluating the compactability of WMA mixtures by determining the number of

gyrations to 92-percent relative density at the planned field compaction temperature and 54F (30C) below the planned field compaction temperature” (Bonaquist 2011).

2.3.4 Warm Mix Asphalt Compaction – Technology Categories

According to Hanz, most of the technologies listed in Table 2 can be classified into one of three categories that are, “(...) believed to allow for reduced production temperatures: foaming, viscosity reduction, and use of chemical additives to change the surface tension or internal friction properties of the binder” (Hanz 2012).

Foaming

Foaming is achieved either by water injection, or use of water-bearing mineral additives (Hanz 2012). Foam is produced in the binder due to water evaporation. The produced foam causes reduction in asphalt binder viscosity and, hence, improved compaction (Hanz 2012). The process is controlled by the volume expansion of binder due to evaporated water, as well as the time for which the system remains foamed (half-life) (Hanz 2012). According to Hanz, a foamed asphalt, in order to be suitable for mixing at reduced temperatures, “(...) must have an expansion ratio sufficiently high to reduce asphalt binder viscosity and must be adequately stable to allow time for mixing with aggregates” (Hanz 2012). As stated previously, foaming can be achieved by introduction of zeolites, or water-bearing mineral additives. The advantage of zeolites over the mechanical water injection is that they allow, “(...) for gradual continuous release of water vapor that creates a temporary foaming effect which allows for improved mixture workability at lower temperatures” (Hanz 2012). Another possible advantage over the mechanical water injection technology is that zeolites are added to the mixing drum and do not require a specialized water injection unit. On the contrary, foaming requires a one-time investment, while zeolites need to be purchased per ton of mixture produced.

Viscosity Reduction

Another way to obtain asphalt production at lower temperatures is to reduce binder viscosity by adding a paraffinic wax additive (Hanz 2012). An example of such paraffinic wax is Sasobit, described by Damm et al. as, “asphalt flow improver” due to its ability to lower the viscosity of asphalt binder (Damm, et al. 2002). Damm et al. described it as, “(...) a fine crystalline, long chain aliphatic polymethylene hydrocarbon produced from coal gasification using the Fisher-Tropsch (FT) process” (Damm, et al. 2002). According to Hurley and Prowell, such decrease in viscosity allows, “(...) working temperatures to be decreased by 32-97°F (18-54°C) (Hurley and Prowell, Evaluation of Sasobit For Use in Warm Mix Asphalt 2005).

Chemical Additives

The last group consisting of chemical additives cannot be clearly defined in terms of governing mechanism allowing for reduced compaction temperatures. This group encompasses a large number of chemical additives. Rediset WMX, Evotherm and Cecabase RT are some of the constituents of this group. There has been a substantial research effort put into describing mechanism by which lower compaction temperatures are achieved. As the focus of this thesis is to attempt to explain the mechanism according to which such additives aid compaction, a separate section is devoted to description of the three additives and the literature review of possible mechanisms governing the effect they have on asphalt mix compaction.

According to National Asphalt Pavement Association:

“In 2009 the total tonnage of WMA is estimated at 19.2 million tons. This grew to 47.6 million tons in 2010, for a 148 percent increase. Plant foaming is used most often in producing WMA. Additives accounted for about 17 and 8 percent of the total WMA production in 2009 and 2010, respectively.” (Hansen and Newcomb 2011)

In addition to the three main types of Warm Mix Asphalt technology (foaming, viscosity reduction, chemical additives), there are several other processes/additives. However, their popularity is significantly lower as compared with the three major types of WMA technology. Therefore, such processes/additives will not be described in this section.

2.4 Chemical Additives in WMA Compaction

2.4.1 Chemical Additives in WMA Compaction - Products Overview

Recognizing that certain Warm Mix Asphalt processes may be costly to implement due to necessary changes in production facilities, several different chemical additives have been developed. Such additives can typically be added directly to the binder or the mixing drum. The following sections highlight some of the literature explaining the chemical nature of the additives.

2.4.1.1 Products Overview – Rediset WMX

In 2007 AkzoNobel introduced a Warm Mix Asphalt chemical additive called Rediset WMX (Logaraj and Almeida 2010). The chemical has a form of solid, dry pastilles added to binder before or during mixing process at 1-2% concentration by weight of binder (Logaraj and Almeida 2010). The most important aspect is the amine technology contained in the product. According to Logaraj and

Almeida, the amine technology provides the ability to displace water from the surface of damp aggregate (adhesion-promotion) as well as anti-oxidant effect. However, from the perspective of compaction, Logaraj and Almeida speculate that the improved compactability comes from, “(...) the surface activity of the amine surfactant, either from lubrication effect on the aggregate surface or a dispersant effect on the asphalt mastic” (Logaraj and Almeida 2010).

2.4.1.2 Products Overview – Evotherm

According to a study done by Hurley and Prowell Evotherm, “(...) is a chemistry package that includes materials to improve workability, adhesion promoters and emulsification agents” (Hurley and Prowell 2006). Evotherm features surface active agents (surfactants), that similar to Rediset WMX, help with coating and compaction (MWV Evotherm 2011). The technology comes in three forms: Evotherm ET (Emulsion technology), Evotherm DAT (Dispersant technology) and Evotherm 3G (Meadwestvaco n.d.).

2.4.1.3 Products Overview – Cecabase RT

Cecabase RT is a chemical additive produced by Arkema Group. It allows for asphalt production at lower temperatures by adding to bitumen at concentrations from 0.2 to 0.5% by weight of bitumen (Gonzalez Leon, Grampre and Barreto 2009). According to Gonzalez et al., “(...) observations suggest that the Cecabase RT additives act at the mineral aggregate/bitumen interphase, in an analogous way to a surfactant that, as shown in this work, do not change significantly the bitumen rheological properties (viscosity or $G^*/\sin(\delta)$)” (Gonzalez Leon, Grampre and Barreto 2009). Hence, the warm mix asphalt effect comes from the surfactant contained in the chemical formula of the additive.

2.4.1.4 Products Overview – Functionalized Polyolefin Polymers

Recently, the asphalt paving industry was introduced to another type of additive - functionalized polyolefin polymers. Functionalized polyolefin polymers are marketed as both a warm mix additive and asphalt binder modifier (Hanz 2012). They may act as plastomers (by increasing stiffness at high temperatures) or elastomers (by enhancing the elastic response after loading) (Hanz 2012). It has been shown that, “(...) properly functionalized polyolefins were identified as a viable asphalt modifier as they had potential to improve the wetting, adhesion, and strength characteristics of asphalt binders allowing for both improved workability and performance” (Hanz 2012). Hanz attributes the warm mix effect to the, “(...) the oxidized polyethylene is dissolved in the asphalt, thus acting as an internal lubricant, facilitating movement between the asphalt particles” (Hanz 2012).

2.4.2 Chemical Additives in WMA Compaction - Case Studies

There have been a number of studies performed on laboratory and field mixes using chemical warm mix asphalt additives. Generally, the use of such additives leads to better workability and compactability of the mixtures.

Rediset WMX was shown to effectively improve compactability of mixes in laboratory, as well as field setting. According to Logaraj and Almeida:

“Compaction tests performed by NCAT laboratory using a vibratory plate compactor show higher densities are obtained compared to untreated asphalts. Similar compactability data were obtained using Gyratory compaction on a dense graded binder course in Ireland. In that case the Rediset treated mixture gave slightly easier compaction (as measured by the gyrations required) than untreated mix, although the compaction temperature was 40°C lower” (Logaraj and Almeida 2010).

The same study reports that:

“The laboratory results have been confirmed in the field. In the field trial in Chico California, compacted densities of warm mixes prepared using Rediset WMX were higher than hot mix prepared and paved at some 30°C higher temperature. (...) Moreover, the number of passes needed to achieve the density were reduced, without the tender zone seen with the unmodified hot mix” (Logaraj and Almeida 2010).

Another study evaluating the effect of Warm Mix Asphalt additives on workability, moisture sensitivity and dynamic properties of compacted mixtures concluded that Rediset WMX as well as Evotherm J1 significantly improved compactability of mixtures in terms of air voids of Superpave gyratory samples compacted to 86 gyrations as compared to control binder (Sampath 2010). The mixtures were compacted at temperatures between 117°C and 121°C (Sampath 2010).

Literature review also suggests that Evotherm is an effective warm mix additive in terms of improving compactability of mixes. In a study performed by National Center for Asphalt Technology it has been shown that, “the addition of Evotherm improves compaction over the control mixture for all binder, aggregate and temperature combinations” (Hurley and Prowell, Evaluation of Evotherm For use in Warm Mix Asphalt 2006).

2.3.4 Chemical Additives in WMA Compaction - Concepts of Lubrication

Since the late 1960s it was believed that the influence of asphalt binder on compaction can be quantified by viscosity measurements (McLeod 1967). There has been a substantial effort within the asphalt research community to quantify the influence of viscosity on compaction. It has been recognized that in fact there are limiting values of viscosity below which compaction is extremely hard to achieve (Delgadillo and Bahia 2008). The introduction of polymer modified asphalts raised discussion about the practicality of using kinematic viscosity. To address the presence of polymers in binder, the zero shear viscosity (ZSV) concept was introduced (Khatri, Bahia and Hanson 2001). However, later it was shown to overestimate compaction temperatures (Delgadillo and Bahia 2008). Introduction and popularization of WMA additives in the United States spurred a new interest within the asphalt community to explain the observed improvements in compactability of WMA modified mixes.

In 2010 Hanz et al. suggested that improvements seen in WMA mixes in terms of workability and compactability may be explained by the concept of lubricity. Hanz et al. reported that:

“This study was initiated to investigate measurement of lubricity as a function of temperature and its relationship with mixture behavior. After an extensive literature review, a new test methodology for estimating asphalt binder workability by measuring its internal friction coefficient using specially developed fixture in the DSR was introduced”. (Hanz, Faheem, et al. 2010)

The lubricity test presented in the study was a modified version of four-ball lubricity test commonly used in the lubricant industry to measure wear and coefficient of friction of lubricating oils (ASTM_D6425-05 2005). The study evaluated foamed and Revix (surfactant type additive) modified WMA binders. Mixtures were compacted at 90, 110 and 135°C and compared to coefficient of friction as measured by the Asphalt Lubricity Test in terms of number of gyrations required to obtain 8% air voids. The resulting correlation supported the concept that increasing coefficient of friction leads to decreased mixture workability (Hanz, Faheem, et al. 2010).

In another study Hanz, et al. evaluated three WMA additives: Rediset WMX, Evotherm 3G and VR-1 which was a developmental chemical-based viscosity reducer. The modified binders were tested in the Asphalt Lubricity Test and viscometer. They were also used to compact mixtures. Superpave gyratory compactor was then utilized to monitor Construction Force Index for the compacted mixes. In terms of coefficient of friction at low temperatures, the WMA modified binders resulted in significantly lower values. Hanz et al. reported that, “(...) at lower temperatures the coefficient of friction significantly contributed to the predictive model for Construction Force Index”.

However, as the high compaction temperatures the influence of coefficient of friction diminished and the binder viscosity became more important. (Hanz, Mahmoud and Bahia 2011)

The concept of using lubricity to quantify the improvement in workability due to WMA additives was revisited by Bennert et al. in 2010 (Bennert, et al. 2010). The study presented a new lubricity test based on thin-thin film rheology (Bennert, et al. 2010). The test utilizes a parallel plate setup in a dynamic shear rheometer. The test is capable of measuring viscosity normal force and torque at very low gaps (as low as 25 microns) (Bennert, et al. 2010). According to the authors measuring rheological properties at such low gaps better represents the actual binder conditions in the mix (Bennert, et al. 2010). Bennert et al. claimed that:

“If it is possible with a given warm-mix additive to achieve a higher shear rate before the torque drag on DSR plates increases and peaks, more readily the warm-mix additive will achieve the internal friction reduction in the mixing and compacting process”. (Bennert, et al. 2010)

The study evaluated Rediset WMX, Evotherm 3G and Sasobit warm mix additives in terms of peak torque at 50 micron gap at 105°C. All WMA modified binders, with exception of 0.5% Sasobit led to better workability than control binder in terms of sustained shear rate (Bennert, et al. 2010). The results were in agreement with mixture workability results as measured by the Asphalt Workability Device and the Marshall Compactor mixtures (Bennert, et al. 2010).

2.4 Summary of Literature Review

Currently asphalt mixtures are designed based on volumetric principles; lower pavement air voids correspond to better compaction. Asphalt mixture compaction is controlled by numerous factors, including aggregate gradation, underlying layer stiffness, compactive effort applied, and asphalt binder properties. Significant research has been conducted to model compaction. However, during compaction in field only binder viscosity (through mix temperature) and compactive effort can be controlled. This fact directed a significant amount of research into binder viscosity. However, it has been shown that viscosity was not adequate in explaining how readily mixtures are compacted in the field; correlation was weak.

The advent of polymer modification further complicated the issue of viscosity in binders and their effect on compaction. Additionally, aggregate structure was observed not to correlate directly with mixture density. Introduction of WMA additives added even more confusion to the topic of compaction. This caused researchers to seek binder properties alternative to viscosity, which would help describe improved compaction. Most recently the concept of lubrication was introduced allowing

for more comprehensive evaluation of binder's role in compaction. Two lubricity tests were established (Hanz et al., Bennert et al.). Proper understanding of the two newly introduced lubricity tests requires basic understanding of the science of tribology. Tribology is primarily used in mechanical engineering applications. The following section is devoted to explaining some of the basic principles governing tribology; it also serves as an introduction to the topic of this thesis.

Chapter 3: Tribology

3.1 Tribology – Introduction

Friction has been recognized and utilized by people for thousands of years and dates back to prehistory when it was used to create fire as a result of frictional heat (Rabinowicz 1995). More recent proof of understanding frictional phenomena dates back to more than 3000 years ago when people started using sleds, rollers and wheels to transport heavy objects (Rabinowicz 1995). Scientific approach to the phenomena of friction is a product of the seventeenth and subsequent centuries (Rabinowicz 1995). Progress of science and increasing use of machinery during the second half of the twentieth century caused some concerns among scientists. In 1966, Jost released “A report on the Present Position and Industry's Needs” in which he claimed that an estimated 515 million pounds of sterling were lost per year due to ignorance of mechanical surface interaction phenomena (Jost 1966). As Rabinowicz claimed later, the amount was underestimated due to little attention paid to mechanical wear (Rabinowicz 1995).

In the report from 1966, Jost coined the term tribology. The word tribology was derived from the Greek word *tribo* meaning rubbing (Bhushan 2002). The main concern of the science of tribology is to understand the nature of interactions between two materials rubbing or sliding past each other and to understand the interfacial phenomena (Bhushan 2002). According to Rabinowicz, the interactions between such materials can be addressed by the following three interaction phenomena (1995):

- **Friction** – “The friction effects are those that arise from the tangential forces transmitted across the interface of contact when solid surfaces are pressed together by a normal force” (Rabinowicz 1995).
- **Wear** – “The wear phenomena consist of the removal of material from the surfaces of one of the contacting bodies, as a result of interaction with the other contacting body” (Rabinowicz 1995).
- **Adhesion** – “(...) the ability of contacting bodies to withstand tensile forces after being pressed together (...) It seldom occurs to any marked extent and has been much less investigated than the others” (Rabinowicz 1995).

Tribology finds many applications in the field of mechanical engineering. Its widespread use in that field is related to the kinematic nature of machines. One of the best examples of applied tribology is in automobile combustion engines. The surface interactions between pistons and cylinders are very apparent when engine does not have adequate oil supply. There is a significant engine deterioration observed due to friction and wear of the internal parts. For that reason the science of tribology also includes the use of lubricants. According to Rabinowicz, “Lubricant is a substance capable of altering the nature of surface interactions between contacting solids” (Rabinowicz 1995). Proper use of a lubricant may significantly reduce the friction and wear between two contacting surfaces.

3.2 Tribology - Relevance to Asphalt Mixes

Many parallels can be drawn from tribology to asphalt mixture compaction process. As it was mentioned earlier, asphalt is compacted through particle reorientation. Typically asphalt mixtures consist of a range of different particle sizes determined by the mix gradation. Regardless, whether compaction is quantified through density measurements or internal structural indices, sufficient compactive effort must be provided to obtain desirable asphalt concrete consistency. Compactive effort is partially used to overcome the friction between aggregate particles. Also, heavy loads are applied to aggregates, especially at terminal stages of compaction. This may lead to significant wear on aggregate particles and hence dissipation of some of the compactive effort applied.

Asphalt binder, therefore, acts as a lubricant facilitating the process of compaction by reducing friction between aggregate particles and providing wear protection. The better asphalt binder acts as a lubricant, the less compactive effort should be then required in order to sufficiently compact a mixture. The next section provides some of the roles through which binder can act as a lubricant.

3.3 Tribology - Fluid film lubrication

Asphalt binder behavior during the compaction process can be characterized using principles of fluid film lubrication. It is recognized that sliding two aggregate particles against each other is characterized by relatively high friction accompanied by severe wear to such particles. Introduction of a layer of binder film in between the two surfaces results in lower friction and significantly reduced wear as observed during mixture compaction. In order to properly describe different regimes governing friction between two solids separated by a self-acting lubricating film layer, one can use the Stribeck curve (Stribeck 1902). The following Figure 7 features an example of such curve.

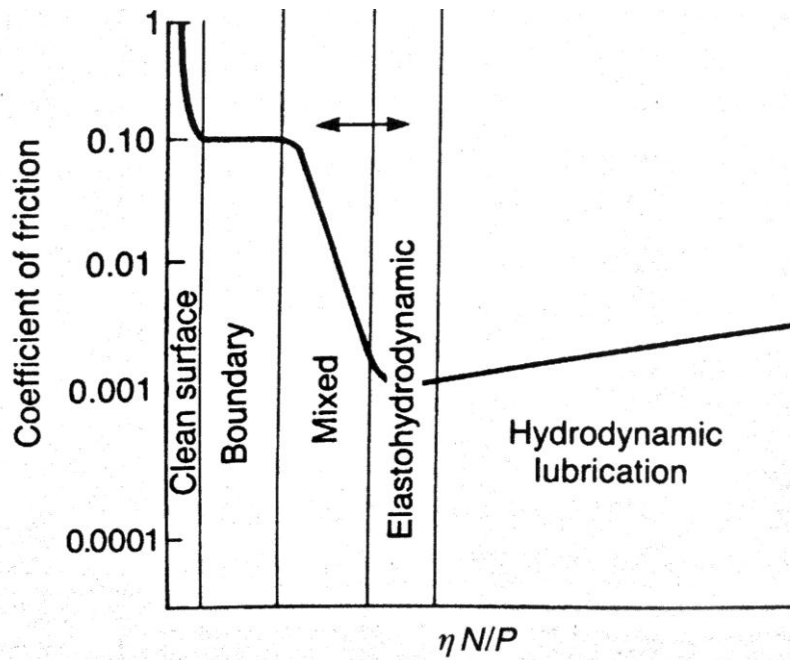


Figure 7 Example of Stribeck Curve (Bhushan 2002).

Figure 7 shows coefficient of friction, or measure of friction (vertical axis) between two solids undergoing change due to changing properties of liquid film lubricant. The horizontal axis features a function of three variables, referred to as Sommerfeld number (SN) (Rabinowicz 1995):

Equation 7 Sommerfeld Number (Rabinowicz 1995).

$$SN = \frac{\eta \times N}{P}$$

Where:

η = absolute viscosity of lubricating fluid,

N = Relative speed between two solid bodies

P = load per unit area

Changing any of the variables contained in the Sommerfeld number changes the coefficient of friction and may also cause change in fluid film lubricating regime. There are four distinct lubricating regimes governed by different principles: Boundary, Mixed, Elastohydrodynamic and Hydrodynamic. The following are descriptions of each of the regimes:

Hydrodynamic Regime:

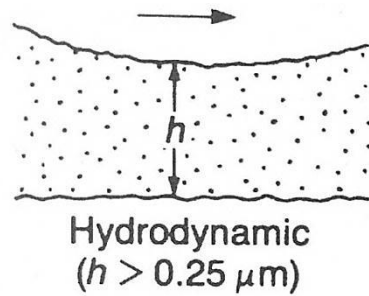


Figure 8 Schematic showing two solids lubricated through hydrodynamic regime. (Bhushan 2002)

The hydrodynamic regime results from the viscous nature of lubricating fluid. When two solids move past each other the viscous fluid that is in between requires a certain finite amount of time to be removed, or squeezed out. Therefore, there is a certain viscous drag within the fluid that creates the load carrying phenomenon. Such drag is a function of sliding speed (N), viscosity of fluid (η) and pressure (P). Therefore, from the perspective of lubricant, the frictional characteristics are governed by bulk properties of fluid (fluid viscosity). Hydrodynamic lubrication regime is desired because there is no solid-solid contact as all the load is carried by the lubricating film. This leads to a very low coefficient of friction combined with no wear on the solids (Bhushan 2002). Such a regime, however, requires a relatively high Sommerfeld Number so that the two solids do not collapse onto each other due to insufficient load carrying film capabilities.

Elastohydrodynamic Regime:

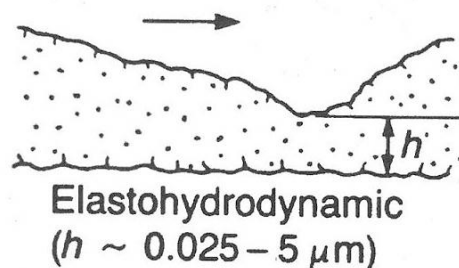


Figure 9 Schematic showing two solids lubricated through elastohydrodynamic regime. (Bhushan 2002)

As loads on the contact area increase, or sliding speed and viscosity decrease, the load bearing capacity of the lubricating layer may decrease leading to occasional contact of solids. In the case of asperity contact, boundary lubricants, providing boundary lubricating films, can be used to protect the solids from direct contact. Also, high contact pressures may lead to changes in viscosity of lubricant

and elastic deformation of contacting bodies. Nevertheless, the majority of load is still carried through the hydrodynamic layer, leading to relatively low coefficient of friction. Optimal lubrication of two solids is achieved when the fluid film is thick enough to prevent any asperity contact, but optimally low to minimize the viscous drag. (Bhushan 2002)

Mixed Regime:

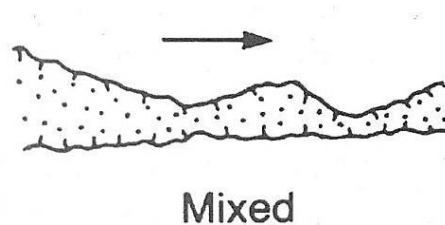


Figure 10 Schematic showing two solids lubricated through mixed regime. (Bhushan 2002)

A combination of decreasing sliding speed and viscosity combined with increasing load leads to further decrease in film thickness. The mixed regime is, therefore, a combination of hydrodynamic, elastohydrodynamic and boundary lubrication regimes. Some of the support still comes from the hydrodynamic film. However, there is an increasing amount of asperity contacts. In order to minimize such contacts, a layer of physi- or chemisorbed or chemically reacted boundary lubricant layers are used. They prevent direct solid-solid contact by protecting asperities and providing lubrication. (Bhushan 2002)

Boundary Regime:

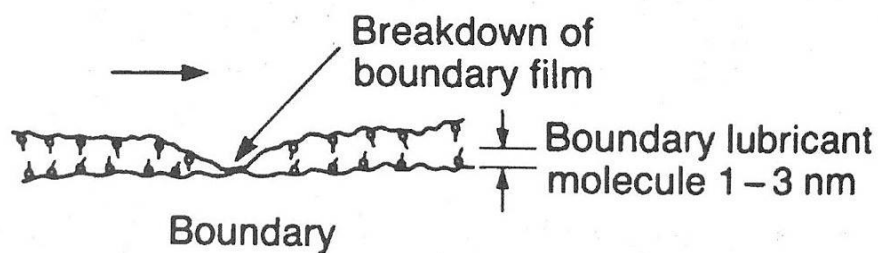


Figure 11 Schematic showing two solids lubricated through boundary regime. (Bhushan 2002)

With a further decrease in liquid viscosity and sliding speed or an increase in contact loading the hydrodynamic lubricating layer may completely cease to exist. In such case, friction is determined by mono- and multimolecular films of lubricants and solid asperity interactions. Because none of the load is carried by hydrodynamic film, the coefficient of friction is significantly higher than the ones typical of the previously described regimes. Physical properties of boundary lubricating film such as

the melting point, shear strength and hardness become important. The bulk properties of lubricating fluid, such as viscosity, become much less important.

Figure 12 is an illustration of the change in lubricant film parameter (h/σ or mean film thickness/composite standard deviation of surface heights of the two surfaces) with respect to the lubricating regime (Bhushan 2002). One can observe that as the Sommerfeld number decreases, the lubricating film thickness also decreases with the lowest values in boundary regime.

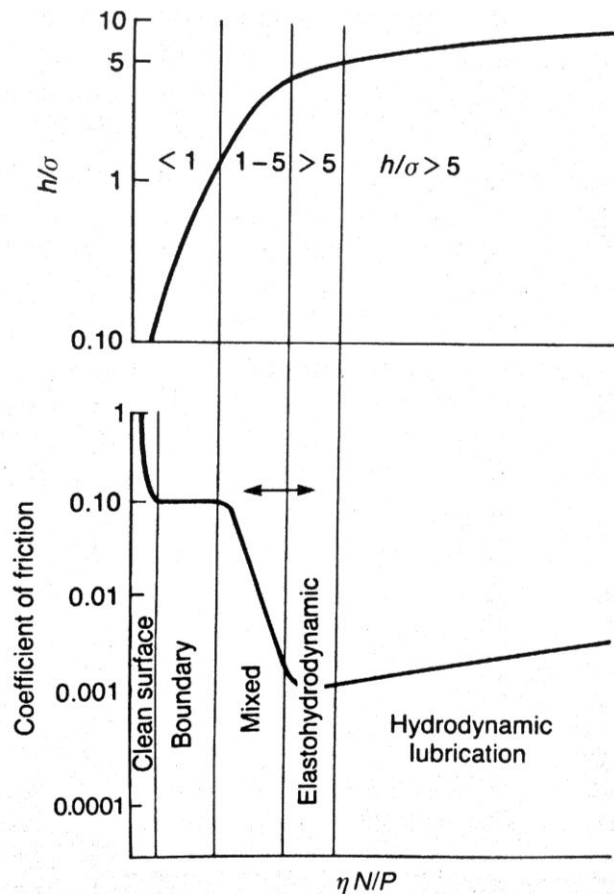


Figure 12 Lubricant Film Parameter in relationship with different lubrication regimes. (Bhushan 2002)

3.7 Tribology - Boundary Lubrication and Lubricants

The hypothesis of this thesis implies that certain Warm Mix Asphalt additives have the capacity of aiding compaction through interaction with aggregate surfaces. This, in turn, implies that such additives act in the boundary regime where lubrication is provided by mono- and multimolecular films that are either physi- or chemisorbed to the surface.

The literature review concerning Warm Mix Asphalt chemical additives mentioned that some of the additives consist of surfactants, or polar molecules (Rediset WMX, Evotherm, Cecabase RT).

The use of surfactants in boundary lubrication is quite common and this section will describe the mechanism based on which surfactants aid boundary lubrication.

3.7.1 Tribology – Boundary Lubrication and Lubricants – Surfactants

A surfactant is an organic molecule composed of two groups. The first group, being a hydrocarbon chain, is soluble only in nonpolar solvents. The second group, referred to as the head, is composed of polar constituents and therefore is soluble only in polar solvents (Biresaw 2009).

Asphalt mixtures encompass both polar and non-polar constituents. Asphalt binders are nonpolar while aggregates are polar (Moraes 2011). Asphalt binder, therefore, acts as lipophilic solvent (Biresaw 2009). Surfactants can exist in solvents in various concentrations. At low concentrations surfactants adsorb to the surface of the solvent (Biresaw 2009). In case of surfactants in asphalt binder, the nonpolar tail is dissolved in binder, while the polar head migrates to the binder's surface. However, as the concentration of surfactant increase, it will eventually reach critical micelle concentration (CMC) where micelles or surfactant structures spontaneously start forming (see Figure 13). Such micelles are formations of polar heads mutually attracting each other.

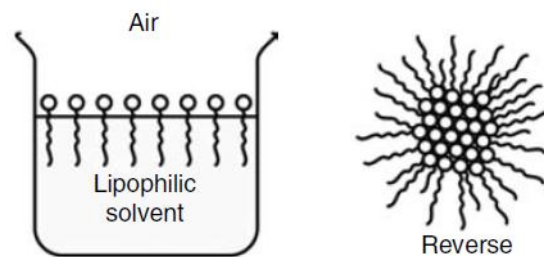


Figure 13 *Illustration of surfactants in lipophilic solvent and forming micelles. (Biresaw 2009)*

Therefore, in asphalt mixtures, the nonpolar head will quickly dissolve in the binder which acts as solvent. However, the polar heads will become attracted to the aggregates, which are polar in nature. Such attraction will cause migration of surfactant molecules to the aggregate surface, creating dense mat layer of physisorbed surfactants (Figure 14).



Figure 14 *Illustration of surfactants forming physisorbed layer around a particle (Biresaw 2009).*

Surfactants are often used as boundary lubricating agents, preventing direct surface contact of two sliding surfaces by forming previously mentioned physisorbed layers around the surfaces (Biresaw 2009). According to Mortier and Orszulik, “(...) such a layer of molecules is hard to compress but very easy to shear, thus it is easy to appreciate the slippery nature” (Mortier and Orszulik 1992). Therefore, the reduction in friction typically observed for boundary lubrication using surfactants comes from the physisorbed molecular mat low shear strength and high resistance to compression. According to Biresaw, “(...) the effectiveness of surfactants at reducing friction and wear under boundary conditions is highly dependent on the chemistries of their polar and nonpolar segments, concentrations, properties of the friction surfaces, and process conditions (e.g., temperature)” (2009). Therefore, the effectiveness of a particular surfactant additive in improving boundary lubrication in asphalt mixes may depend on the polarity of particular aggregate type used.

3.7.2 Tribology - Boundary Lubrication and Lubricants –Extreme Pressure (EP) additives and Friction Modifiers (FM)

Boundary lubrication can be aided through a series of substances other than surfactants. Their function, however, is essentially the same: the direct solid-to-solid contact is minimized through appropriate coating of asperities. Such substances are generally separated into two categories:

- Friction modifiers,
- Extreme pressure additives.

According to Kenbeck and Bunemann the extreme pressure additives create films that, “(...) are semiplastic deposits that are difficult to shear off”. Films built up by such extreme pressure additives, under shearing conditions, create high coefficient of friction. However, such coefficient of friction is low relative to coefficient of friction that would be obtained if asperities were not protected from direct solid-to-solid contact. (Kenbeck and Bunemann 2009)

On the contrary, friction modifiers build up films of, “(...) orderly and closely packed arrays of multimolecular layers”. Such layers are easily sheared off, providing low coefficient of friction. There are different types of friction modifiers differing in mode of action:

- Formation of reacted layers,
- Formation of adsorbed layers,
- Formation of polymers,
- Mechanical types.

Surfactants mentioned in previous sections are a specific example of friction modifiers. (Kenbeck and Bunemann 2009) However, certain polymers such as FPE may also be classified as extreme pressure additives or friction modifiers.

Chapter 4: Materials and Methods

4.1 Materials and Methods - Materials

One of the foci of this thesis is the investigation of binder properties and their comparison with asphalt mixture data. The mixture data used in this thesis is a courtesy of Pouya Teymourpour and Nima Roohi Sefidmazgi. The Asphalt Lubricity Test data using TA apparatus is a courtesy of Dr. Andrew Hanz. All other data was generated specifically for this thesis.

4.1.1 Materials and Methods – Materials - Binder

The binders used in the study include PG 64-22 NuStar and PG 64-22 Flint Hills. The two asphalt binders were modified by percentage of total weight according to the following:

- NuStar PG64-22 - 1%, 2% and 3% Rediset WMX (SW)
- NuStar PG64-22 - 3.5% Functionalized Polyolefin Polymer (FPE)
- NuStar PG64-22 - 0.7% Cecabase RT (CRT)
- Flint Hills PG64-22 - 1% and 2% Rediset WMX (SW)
- Flint Hills PG64-22 - 4% Functionalized Polyolefin Polymer (FPE)
- Flint Hills PG64-22 - 4% Functionalized Polyolefin Polymer (FPE) + 3.5% SBS polymer
- Flint Hills PG64-22 - 3.5% SBS polymer

Note that the modifications may cause change in binder PG grade. WMA additives were evaluated only for their effect on lubricational properties: They were not tested for changes in PG grade.

4.1.2 Materials and Methods – Materials - Mixture

All asphalt mixtures were designed using the same gradation at either 5% or 5.5% asphalt content depending on the binder type (Figure 15). All mixtures were compacted to 100 gyrations at 600kPa stress level in the Superpave Gyrotory Compactor per Wisconsin E-10 required level of gyrations of N design. The aggregate used was granite. Figure 15 shows the gradation used in this study.

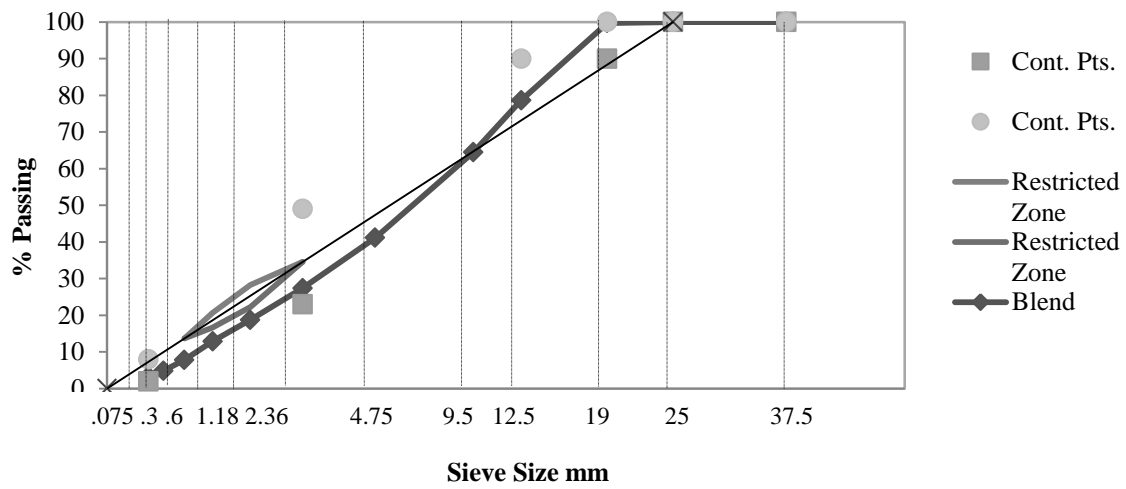


Figure 15 Gradation Chart for all mixes used in this thesis.

Table 3 documents the resulting mixture % air voids at N design, along with the mixing and compaction temperature for the selected binder used in this thesis.

Table 3. Mixture compaction data for mixes used in the study.

Base Binder	Additive	Mix Temperature (°C)	Compaction Temperature (°C)	AC Content	Air Voids at N-design
NuStar PG64-22	Control	155	145	5.0%	4.43%
		155	115		5.11%
		125	115		4.11%
		125	85		5.78%
	3.5% FPE	155	145	5.0%	4.04%
		155	115		4.52%
		125	115		3.24%
		125	85		4.33%
	1% SW	155	145	5.0%	3.50%
		155	115		3.86%
		125	115		3.10%
		125	85		4.18%
	2% SW	155	145	5.0%	2.32%
		155	115		2.64%
		125	115		2.28%
		125	85		3.44%
Flint Hills PG64-22	Control	155	145	5.5%	4.54%
		125	115		2.80%
		75	65		5.44%
	3.5% SBS	155	145	5.5%	4.05%
		125	115		3.63%
		75	65		4.75%
	4% FPE	155	145	5.5%	3.46%
		125	115		2.81%
		75	65		4.97%
	3.5% SBS + 4% FPE	155	145	5.5%	3.09%
		125	115		3.28%
		75	65		6.83%

The preliminary tests include the mixture and binder data for NuStar PG64-22 base binder only. The Asphalt Boundary Lubrication Test, which is the main part of this thesis, includes all the binders listed in this section.

4.2 Materials and Methods – Methods

The test methodology of this thesis consists of progressive steps evaluating binder lubricating properties through use of various binder tests and contrasting the results with % air voids at N design

of mixtures compacted using corresponding binders. By the binder lubricating property the author means the coefficient of friction.

The coefficient of friction (μ) was mentioned earlier in this document when the Stribeck curve was discussed. Friction is defined as “(...) the resistance a body meets with in moving over another body in respect of transmitting motion” (Mortier and Orszulik 1992). It is a ratio of tangential force (P) required to overcome the frictional force acting between two bodies to normal load (N).

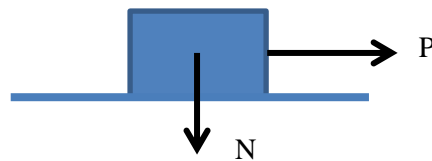


Figure 16 Schematic view of tangential force and normal load used to measure coefficient of friction between two bodies.

Equation 8 Coefficient of friction as a function of normal and tangential forces.

$$\mu = \frac{P}{N}$$

The coefficient of friction can be either static or dynamic. The static coefficient of friction is a ratio of force required to initiate sliding of two bodies to the normal load applied (Rabinowicz 1995). For the kinetic coefficient of friction, or coefficient of friction between bodies in motion, friction force is typically recorded as one body slides under constant load against a fixed body (Rabinowicz 1995).

Coefficient of friction is a *system property*, which means that it depends on the material of bodies rubbing against each other. However, the coefficient of friction, or ratio of frictional to normal force, is constant for two given materials. This means that the frictional force required to move one body past another is proportional to the normal force between two bodies (Rabinowicz 1995). This happens because as normal force increases the real contact area between two bodies also increases making the normal and tangential forces proportional. The role of an effective lubricant is to reduce the coefficient of friction. The ways of reducing the coefficient of friction were discussed in Chapter 3.

The following binder tests were used to evaluate the lubricating property through coefficient of friction measurements:

- Asphalt Lubricity Test
- Stribeck Curve Test (Anton Paar Germany GmbH)
- Asphalt Lubricity Test using Anton Paar Tribology Cell
- Asphalt Boundary Lubrication Test

All of the above test measure kinetic coefficient of friction at test- specific sliding speeds. The kinetic coefficient of friction was chosen because it can be measured more consistently through rotational tests.

It is also important to mention that since the following tests use different solids to measure the coefficient of friction (the surfaces rubbing against each other are made of different materials), the resulting coefficients of frictions from different machines cannot be directly compared for a given binder (coefficient of friction is a system property). However, the relative differences among lubricating properties of various binders can be compared acknowledging the differences in solid substrates.

3.2.1 Materials and Methods – Methods - Asphalt Lubricity Test

The Asphalt Lubricity Test was originally developed by Hanz, Faheem, Mohmoud and Bahia to measure lubricating properties of asphalt binders. The test was developed based on the Four Ball Wear Test machine commonly used in lubricant industry to measure coefficient of friction and wear. The Asphalt Lubricity Test uses apparatus, similar to the Four Ball Wear Test, but reduced in size to fit the TA AR-2000 Dynamic Shear Rheometer (Figure 17). (Hanz, Faheem, et al. 2010) (Hanz 2012)

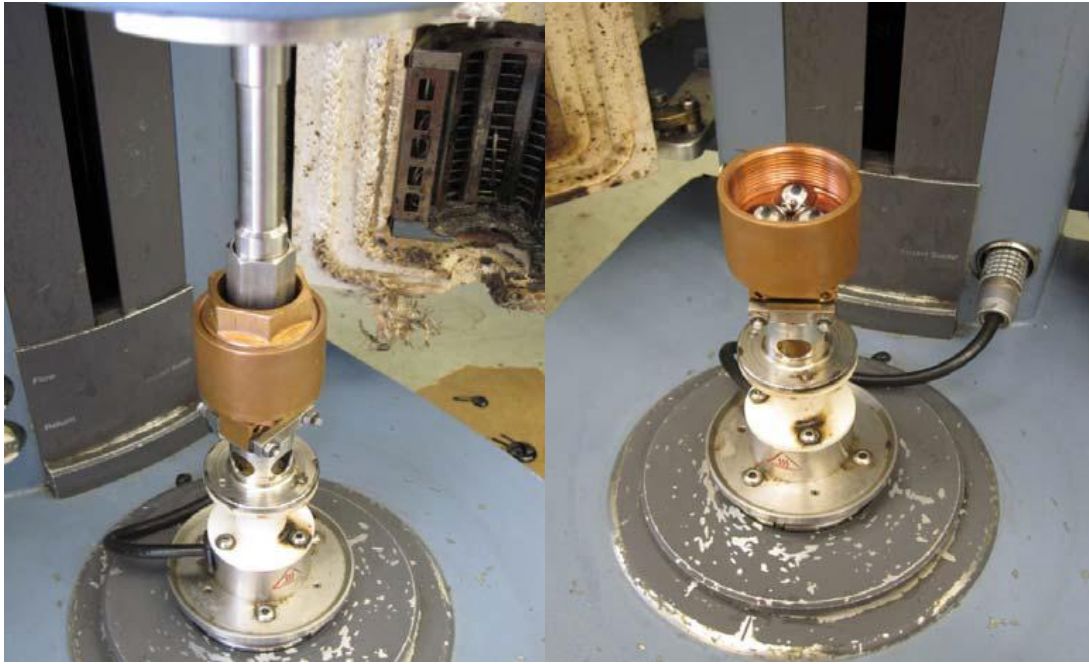


Figure 17 *Asphalt Lubricity Test Apparatus.* (Hanz, Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance 2012)

The apparatus consists of three chromed steel balls of 12.5mm diameter fixed to the bottom portion and the top chromed steel ball. The top ball is attached to the spindle portion of DSR, allowing the machine to apply normal load on the bottom three balls as well as rotation to the system.

The test begins by adding asphalt binder to the bottom cup containing the three fixed balls. Then the top spindle is lowered to apply a specified load on the bottom three balls. The load is transferred through the three contact points from top ball to the bottom three balls. After reaching the specified test temperature, the machine applies constant rotational speed and measures torque generated due to the friction at the three contact points. The coefficient of friction is then calculated using the following equation:

Equation 9 *Equation for calculation of coefficient of friction using Asphalt Lubricity Test* (Hanz, Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance 2012).

$$\mu = C \times \frac{T}{P \times d}$$

Where:

μ = Coefficient of Friction,

C = geometry constant,

T = Torque (N.m),

P = Normal Force (N),

d = ball diameter (m).

The results presented in this study come from tests run at 50 RPM at three temperatures (85, 115, 145°C) at 10N normal force. The data is a courtesy of Dr. Andrew Hanz.

The drawback of this test is limitation to single rotational speed. Restricting rotational speed may lead to evaluating different lubricational regime for the same binder tested at different temperatures. Another drawback is a limitation to one substrate type – chromed steel balls.

4.2.2 Materials and Methods – Methods - Asphalt Lubricity Test using Anton Paar Measuring Cell

The Asphalt Lubricity Test was also performed using the Anton Paar Tribology measuring cell (Figure 18, Figure 19, Figure 20, Figure 21). The cell works on principles similar to the Asphalt Lubricity Test apparatus.

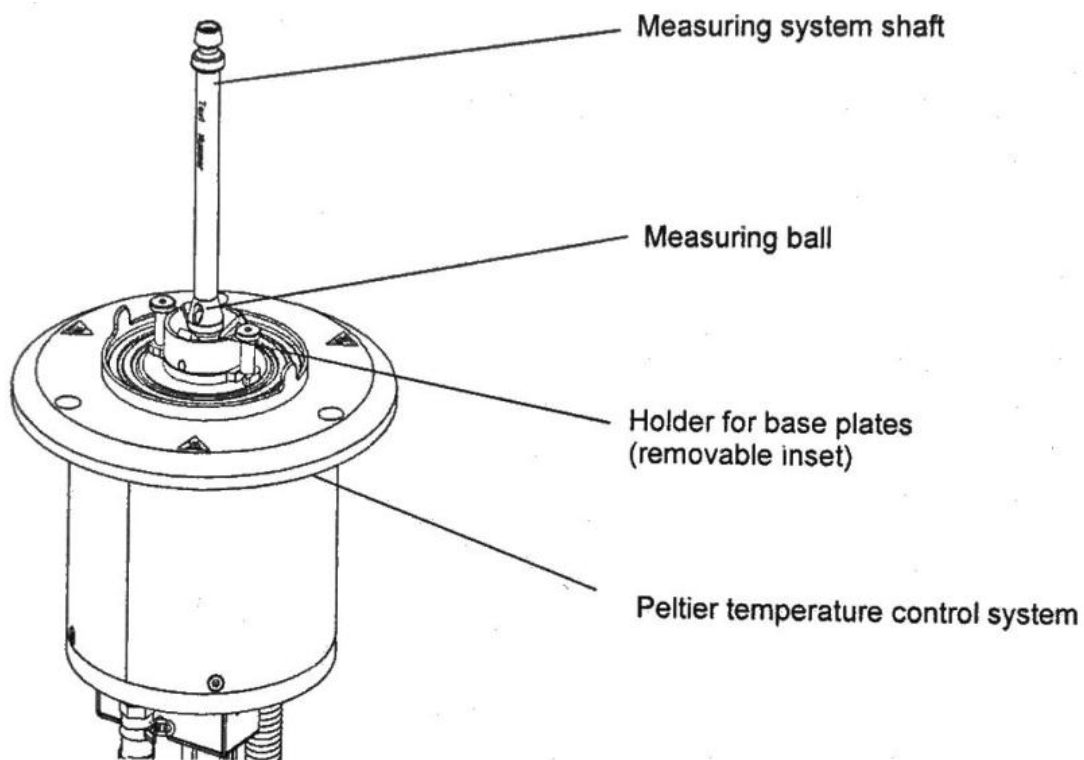


Figure 18 *The Anton Paar tribology measuring cell with the measuring system (Anton Paar Germany GmbH 2009)*

The major difference between the Asphalt Lubricity Test apparatus and Anton Paar cell are the flat plates on the bottom portion of the cell (holder for base plates) rather than balls. However, there are still three contact points between the top ball and the three plates, through which the load is

transferred. Anton Paar supplies the cell with two types of removable insert plates: steel and Teflon. The cell also features Teflon measuring balls for the measuring shaft system. This allows for testing coefficient of friction of a particular lubricant on different substrates. The coefficient of friction is calculated based on the same principle as in the Asphalt Lubricity Test apparatus, with the difference being the geometry constant: three plates make contact with the top ball at different inclination angle causing differences in the amount of load transferred from the top ball. The results presented in this study come from tests run at 100 RPM at 85°C and 21 N normal force.



Figure 19 Anton Paar tribology measuring cell – photograph of chromed steel ball attached to measuring system shaft and holder for base plates. The whole assembly is ready for sample placement.



Figure 20 Anton Paar tribology measuring cell – photograph of holder for base plates. The holder in the photograph has metal surface plates installed in the three holding spots. The metal plates can be easily replaced with Teflon plates using Allen wrench.

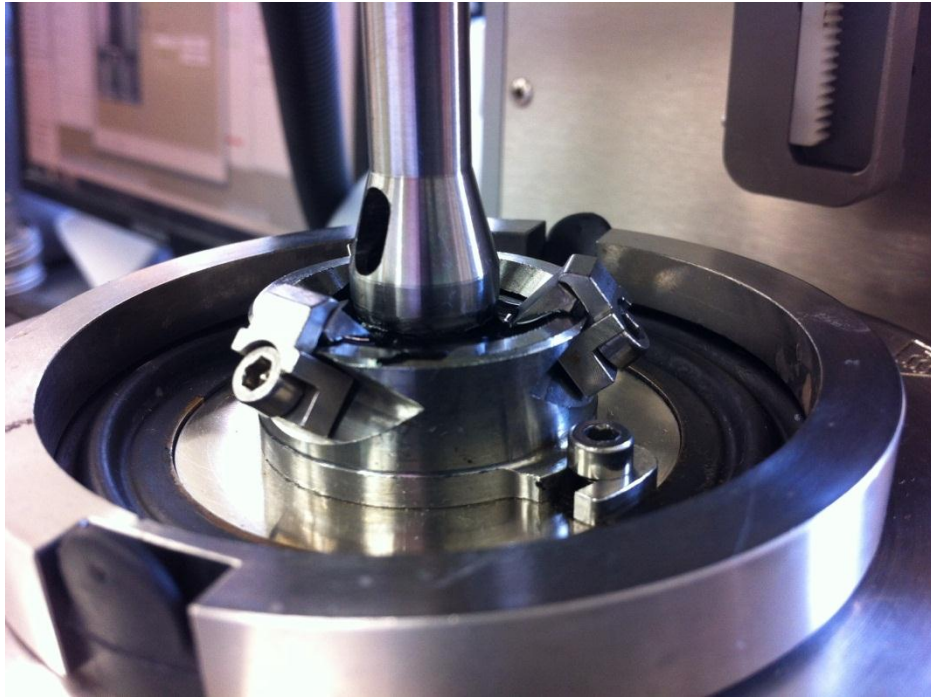


Figure 21 Anton Paar tribology measuring cell – the whole assembly with asphalt binder sample placed inside.

4.2.3 Materials and Methods – Methods - Stribeck Curve Test

The Stribeck Curve test is designed to test lubricants through varying rotational speeds, from very slow to very fast, in order to create a Stribeck curve for given lubricant. The rotations begin at 0.01 RPM and are ramped logarithmically to 3000 RPM. The test is performed using Anton Paar Tribology Cell. Typically, as the rotational speed increases, thin film of binders begins to build up through viscous drag causing initial decrease in coefficient of friction because asperities become separated. However, the continuous speed increase eventually results in increasing viscous drag. The higher the viscous drag, the larger the coefficient of friction. Figure 22 illustrates the effect of increasing the rotational speed on coefficient of friction for an unspecified lubricant.

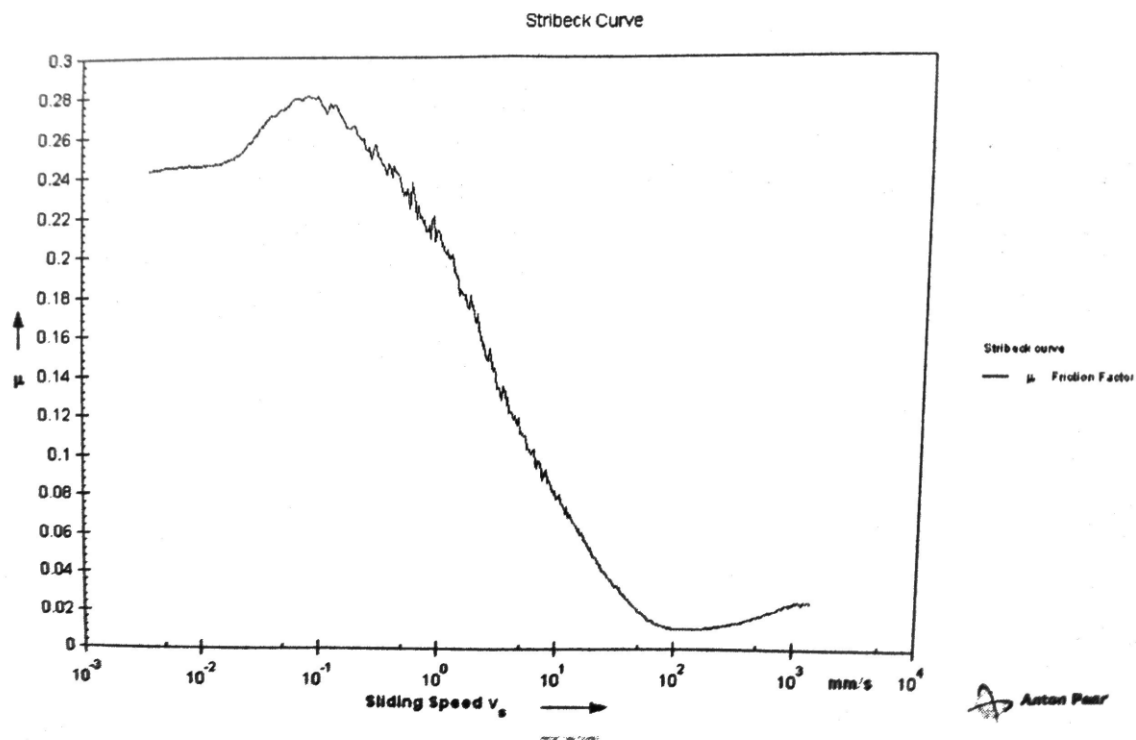


Figure 22 Example of Stribeck Curve test for unspecified lubricant. (Anton Paar Germany GmbH n.d.)

The Stribeck Curve test allows for examining binder lubricating properties through different lubricating regions. For this study the test was conducted at three different temperatures (85, 115 and 145°C). All Stribeck Curve tests were performed using chromed steel ball and steel insert plates setup.

Anton Paar Tribology cell offers a wider selection of substrate types than the Asphalt Lubricity Fixture. However, the selection of substrates is still limited to materials offered by the manufacturer. Also, the cell is very expensive.

4.2.3 Materials and Methods – Methods - Asphalt Boundary Lubrication Test

The Asphalt Boundary Lubrication test was developed as part of this thesis in response to the shortcomings of the previously described tests. The test will be described in detail in subsequent parts of this document.

Chapter 5: Preliminary Results

5.1 Preliminary Results - Asphalt Lubricity Test

The results of the Asphalt Lubricity Test in terms of coefficient of friction for various WMA modified binders were compared to corresponding mixture % air voids at N design (Figure 23) (The data is a courtesy of Andrew Hanz and Pouya Teymourpour). The premise of testing for coefficient of friction is that the binders with lower coefficient of friction should allow for better mixture compactability, hence leading to lower % air voids at N design.

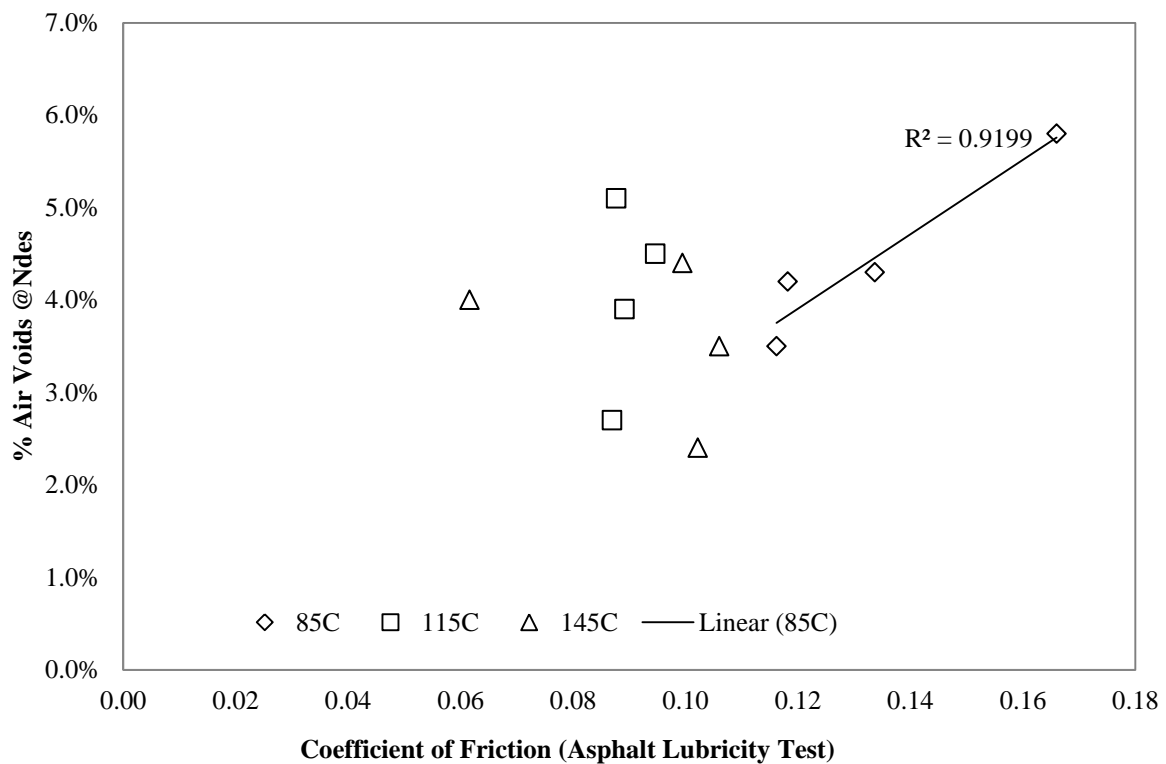


Figure 23 Scattered plot of coefficient of friction measured by Asphalt Lubricity Test vs. % air voids at N design for corresponding mixtures.

In Figure 23 it is visible that there is a correlation between % air voids at N design and coefficient of friction at 85°C ($R^2=92\%$). However, as the testing temperature in the Asphalt Lubricity Test rises, the trend between coefficient of friction and % air voids at N design disappears (115°C, 145°C).

The poor relationship between mixture % air voids at N design and coefficient of friction at higher testing temperatures is caused by change of lubrication regime tested in the Asphalt Lubricity Test. At the low testing temperature (85°C) the binders are tested in hydrodynamic lubrication regime due to relatively high fluid viscosity (Hanz 2012). However, as the testing temperature is increased,

low fluid viscosity combined with high stress due to normal force applied causes a shift towards the elasto-hydrodynamic lubrication regime (Hanz 2012).

The premise of the Asphalt Lubricity Test is that improved compaction is partially caused by improved lubrication, realized through lower coefficient of friction, in the hydrodynamic regime (Hanz 2012). Therefore, the Asphalt Lubricity Test can be thought of in terms of a thin film viscosity test. Asphalt binder in such a test is subject to high loads and high shearing. However, the metal balls, assuming the hydrodynamic regime, never contact each other. Instead all the stresses are transferred through the thin film of binder.

The hydrodynamic regime is governed by previously mentioned Sommerfeld number, which is a function of fluid viscosity, applied load, and sliding speed. Viscosity of a thin film, such as one present in the Asphalt Lubricity Test, may be very different from typical viscosity measured at low shear rates due to non-Newtonian behavior. Therefore, testing asphalt binders for coefficient of friction in the hydrodynamic regime using the Asphalt Binder Lubricity Test is very useful.

Additionally, under the assumption that asphalt mixture compaction is influenced by binder hydrodynamic lubrication, the Asphalt Lubricity Test constitutes a useful binder measurement tool. (See the correlation at 85°C presented in Figure 23)

However, as it is shown in Figure 23, as the testing temperatures rise, the trend visible for 85°C disappears. As Hanz pointed out, at that stage the Asphalt Lubricity Test starts capturing boundary interactions among the chromed steel balls in the fixture. Figure 25 and Figure 26 provide the direct relationship between coefficient of friction measurements and testing temperatures. It is observed that at 115 and 145°C the relative trend in terms of coefficient of friction among the four binders shifts away from the one presented at 85°C.

It is important to note that even though the lubrication regime changes from hydrodynamic towards the elasto-hydrodynamic or mixed regime, the values of coefficient of friction decrease. This is caused by much lower viscous drag being close to the Stribeck curve minimum. Figure 24 illustrates such a possibility with a Stribeck curve for which hydrodynamic coefficient of friction at specific point indicated by line #1 is higher due to viscous drag than the coefficient of friction indicated by line #2 for which there is some asperity contact. The results of the Stribeck Curve contained in the next section offer an experimental explanation of the schematic representation in Figure 24

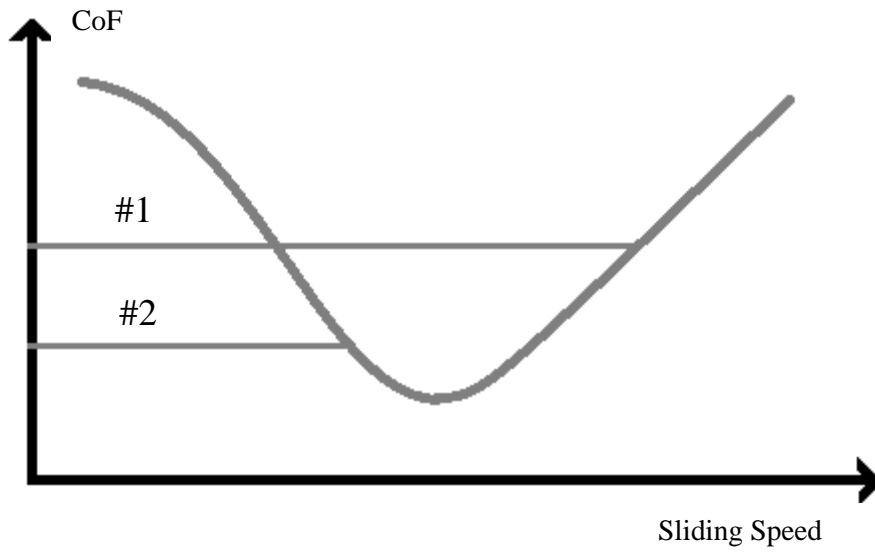


Figure 24 Schematic of a Stribeck curve.

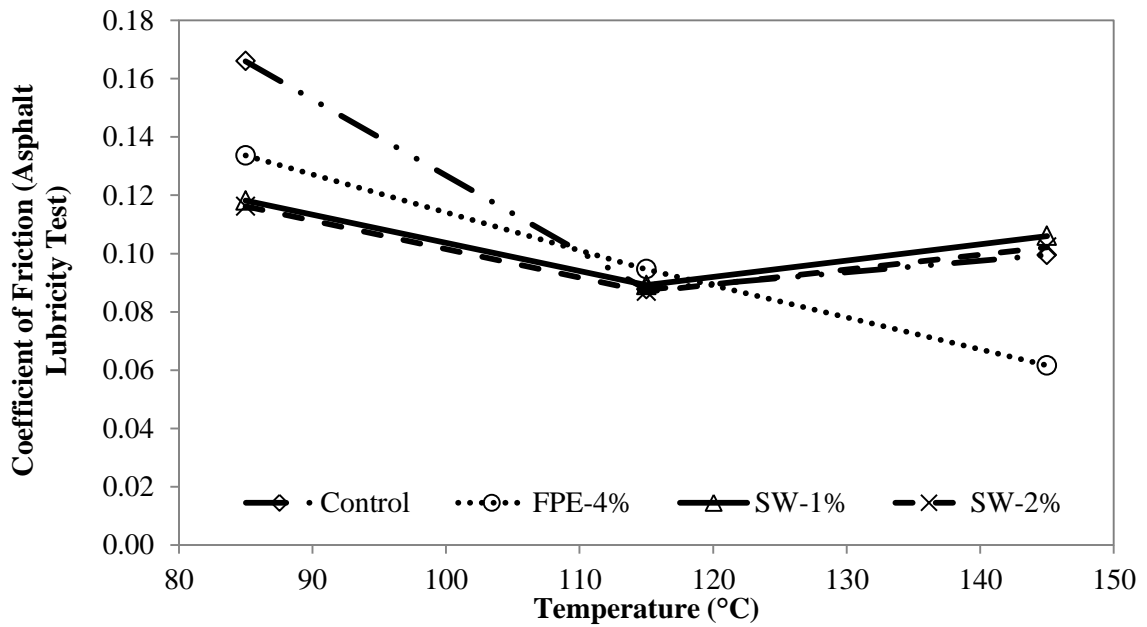


Figure 25 Coefficient of Friction measurements from Asphalt Lubricity Test (Hanz 2012).

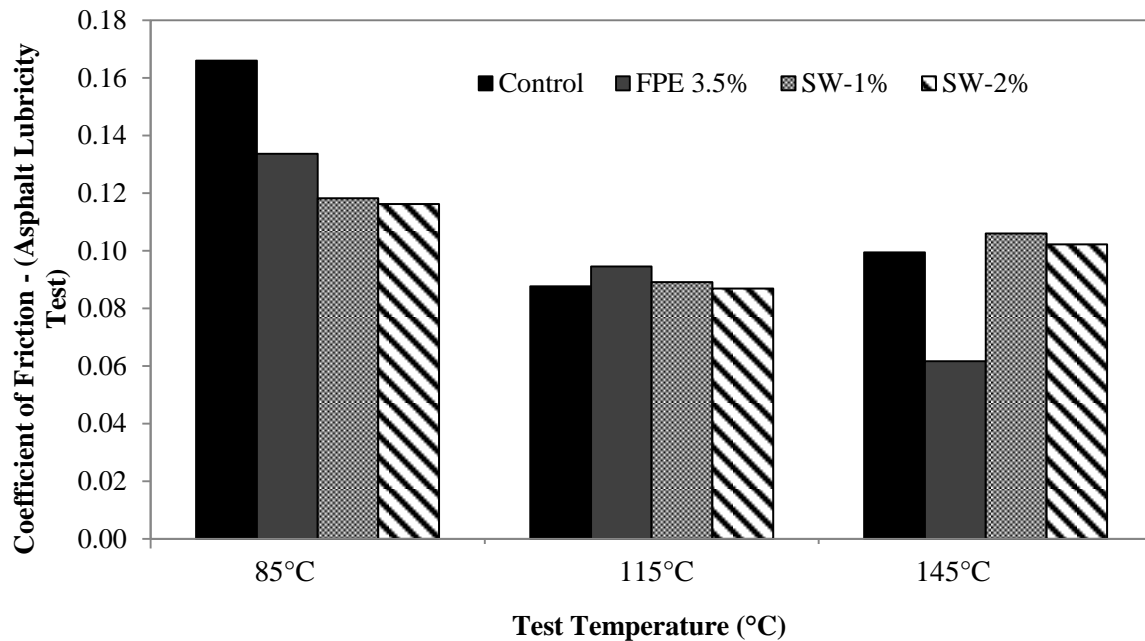


Figure 26. Coefficient of Friction measurements from Asphalt Lubricity Test (Hanz 2012).

In order to obtain a better insight into lubrication process of mixtures at higher compaction temperatures it is necessary to investigate the boundary lubricating properties of the binders and their relationship to volumetric results of compacted mixes.

5.2.1 Preliminary Results - Asphalt Lubricity Test – Comment on the WMA additive performance

At 85°C test temperature, there is a clear improvement trend in terms of coefficient of friction for all WMA additives tested as compared to control binder. The improvement occurs in the hydrodynamic lubrication region, suggesting that Rediset at 1 and 2% (SW-1,-2%) as well as the functionalized polyolefin polymer (FPE) lower thin film, high shear rate viscosity.

The results of tests at 145°C signify that the effect of hydrodynamic lubrication is diminishing, as the lubricating thin film possesses lower stress support strength due to lower viscosity. At that temperature the author speculates that lubrication is in the elasto-hydrodynamic or mixed regime where there is a sizable amount of solid asperity contact. The positive effect of Rediset visible in the pure hydrodynamic regime is not visible at 145°C. However, the FPE additive shows improved coefficient of friction. Such results indicate that FPE may possess boundary lubricating properties, giving it an advantage in lubrication when asperities come in contact.

5.1 Preliminary Results - Stribeck Curve Test (Anton Paar Tribology Cell)

The Stribeck Curve Test was used to investigate lubricating properties of the binders used in this study across all lubricating regimes. The following binders were used in the test:

- NuStar PG64-22 Control,
- NuStar PG64-22 SW-2%,
- NuStar PG64-22 FPE-3.5%.

All binders were tested at 85, 115 and 145°C using three replicates.

5.2.1 Preliminary Results - Stribeck Curve Test (Anton Paar Tribology Cell) - Test Objective 1

The first objective was to identify distinct lubricating regimes using control binder. Figure 27 shows test results for NuStar PG64-22 control binder samples tested at the three temperatures.

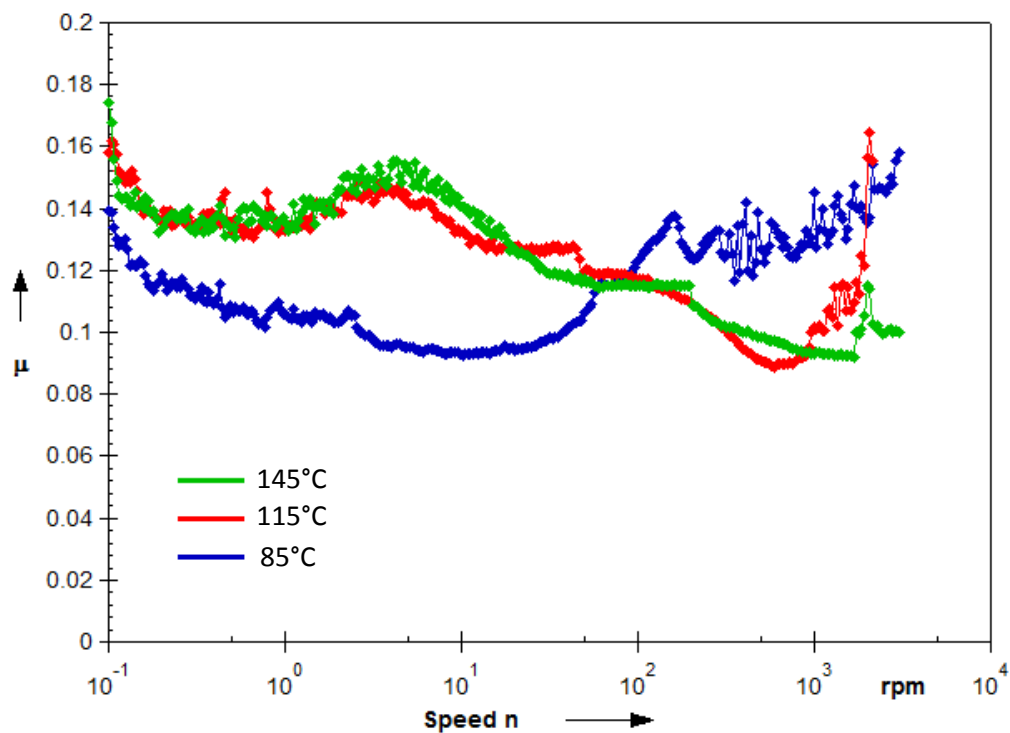


Figure 27 Stribeck curves generated at different testing temperatures.

Figure 27 demonstrates a clear distinction in transition from boundary to mixed regimes, and the hydrodynamic regime can be observed for each curve, except at 145°C, which never reached the hydrodynamic regime. At lower speed it is visible that machine readings of CoF are scattered due to asperity contact. However, as speeds increase the points become uniform. This indicates that the

asperity contact is nonexistent, and the entire load between the solids is carried by a thin film of binder.

Another observation regarding the large scatter in points observed at the end of the curves is clear from Figure 27. At very high rotational speeds, the lubricating film cannot be sustained, causing increasing scatter in the results and eventual dramatic increase in coefficient of friction.

There is a large difference in shape between control binder tested at 85°C and the other two temperatures. The binder tested at 85°C performed slightly better than when tested at 115°C or 145°C in the boundary regime, or at speeds close to 10^{-1} RPM. This is speculated to be due to higher shear strength of film at that temperature. Shear strength of lubricant is an important property in the boundary lubrication regime (Bhushan 2002).

Also, in the test run at 85°C the binder transitioned to the mixed and hydrodynamic regimes much faster than when tested at 115 or 145°C. It is a result of higher viscosity, allowing for much faster buildup of hydrodynamic lubricating film.

The results of the Stribeck test also explained the results obtained in the Asphalt Lubricity test. Looking at Figure 27 and a rotational speed of 100 RPM, control binders tested at 115°C or 145°C are still in the mixed lubrication regime. However, the binder tested at 85°C is already well within the hydrodynamic lubrication regime.

5.2.2 Preliminary Results - Stribeck Curve Test (Anton Paar Tribology Cell) - Test Objective 2

The second objective of the Stribeck Curve Test was to detect relative differences between the warm mix additives used across the lubrication regions.

The data in Figure 28, Figure 29 and Figure 30 represent Stribeck curves generated for PG 64-22 Control, 2% SW and 3.5% FPE binder. In order for Stribeck curves to show results of all replicate tests, the plotted data points represent the averages for all three replicates at the given rotational speed. The average data points were sampled every decade on the logarithmic horizontal scale in order to make the curves easier to interpret.

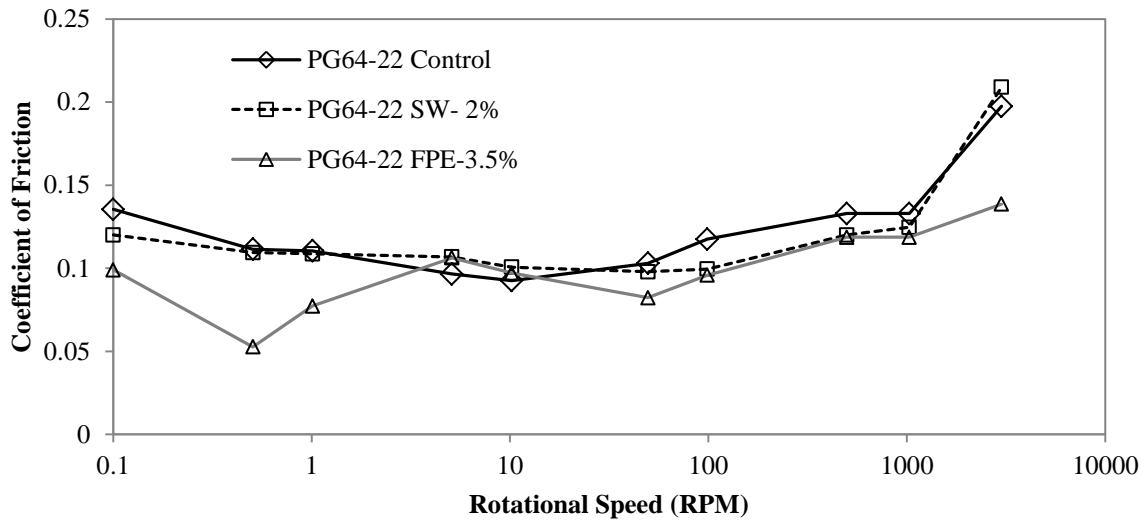


Figure 28 Stribeck curves generated using Anton Paar Tribology Cell at 85°C.

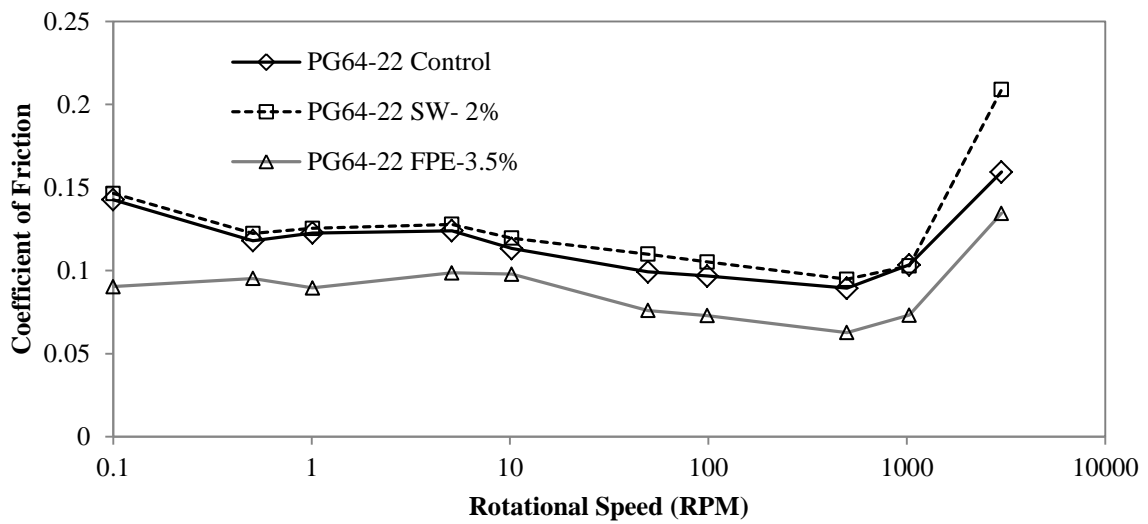


Figure 29 Stribeck curves generated using Anton Paar Tribology Cell at 115°C.

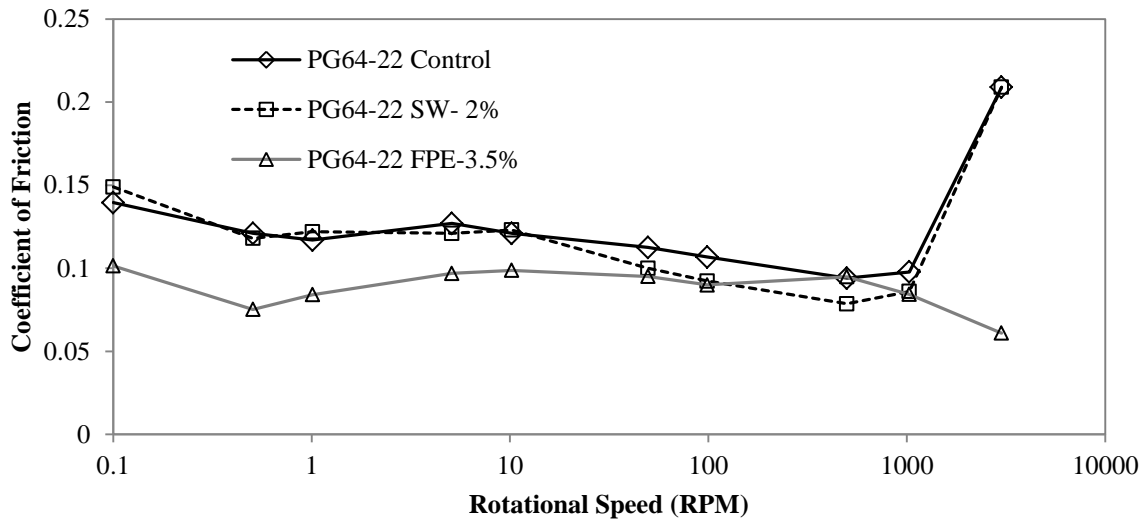


Figure 30 Stribeck curves generated using Anton Paar Tribology Cell at 145°C.

While SW-2% additive does not show significant improvement in terms of CoF at any region of the curve or testing temperature, the FPE-3.5% does. The advantage of using FPE is especially visible in the boundary lubrication regime, or at low speeds. The CoF recorded is on average 30% lower than the CoF of control or SW-2%. The result indicates that FPE is capable of developing a protective film on the solid asperities providing improved CoF in regions where asperity contact is of concern (Boundary and Mix regimes).

At 115°C the FPE additive performed better across the entire Stribeck curve, while at 145°C it was able to maintain low CoF at terminal parts of the curve, at which the other two binders were not able to sustain the film anymore.

5.3 Preliminary Results - Asphalt Lubricity Test using Anton Paar Tribology Cell

The Anton Paar Tribology cell was also used to conduct the Asphalt Lubricity Test. The test was conducted using different combinations of top ball and bottom insert plates to investigate the effect of substrate on binder lubrication. All binders were tested at 100 RPM, 85°C at 21 N normal load. Stribeck Curve tests were run at same temperature and load conditions and it was determined that at 100 RPM all binders were in the hydrodynamic lubrication region. There was a total of three different solid substrate combinations:

- 1) Ball: Chromed Steel
Plates: Teflon
- 2) Ball: Chromed Steel
Plates: Steel
- 3) Ball: Teflon
Plates: Teflon

The results of the test presented in Figure 31 indicate a strong influence of solid substrate on the lubricating effectiveness of particular WMA additive as observed based on coefficient of friction measured. For instance the SW-2% additive for chromed steel-steel combination shows no improvement in terms of CoF as compared with the control binder. However, for the chromed steel-Teflon combination the SW-2% relatively improves lubrication. The trend is opposite for FPE-4%.

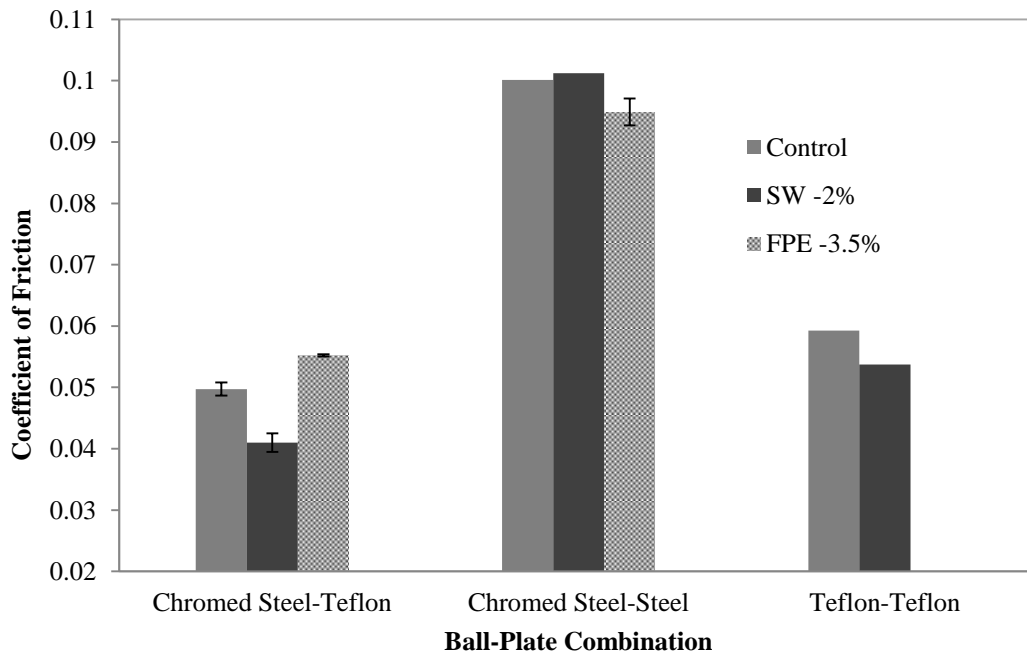


Figure 31 Results of the Asphalt Lubricity test using Anton Paar Tribology cell. Note that each value in the figure below is an average of three measurements and the standard deviation for neither of the reported averages exceeded 0.001. Teflon-Teflon tests for 3.5% FPE were not conducted due to limited cell availability. Error bars represent one standard deviation for the averages presented.

5.4 Preliminary results - Conclusions

The following conclusions can be drawn from the preliminary binder tests:

- Binders behave like lubricants; they can be characterized in terms of the Stribeck Curve

- Warm Mix Additives affect binder lubricating properties
- Coefficient of Friction as measured in the Asphalt Lubricity Test using apparatus for TA DSR at 85°C is a good indicator of mixture density (% air voids at N design) compacted at the same temperature given all other mixture properties constant (i.e. gradation);
 - Hydrodynamic lubrication seems to play a role in compaction at low temperatures
- In the boundary lubricating regime, as measured in the Stribeck Test, the FPE additive showed significant lubricational improvement, relative to control binder.
 - *FPE additive is capable* of providing boundary lubrication film protecting solid substrate's asperities.
- In boundary lubricating regime, as measured in Stribeck Test, the SW additive showed no lubricational improvement, relative to control binder.
 - *SW additive is not capable* of providing boundary lubrication film protecting solid substrate's asperities.
- As shown in the Asphalt Lubricity Test using different substrate materials, the type of substrate material affects the lubricating effectiveness of WMA modified binders.
 - SW additive showed improvement relative to control binder, when tested using chromed steel-Teflon setup, while FPE did not. The trend was reversed for chrome steel-steel setup.

5.6 Preliminary results - Discussion

The preliminary test results highlight the potential of using binder hydrodynamic lubrication properties at low temperatures to help explain improved WMA mixture compaction. Nonetheless, the mixture compaction data show that at high temperatures the WMA additives also allow for improved compaction (Hanz, Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance 2012). These results, however, were not captured in the conducted binder lubrication tests. In addition the SW additive did not show improvement when tested in Anton Paar tribology cell at any of the lubrication regimes (Stribeck Curve test) using standard chromed steel-steel configuration. Yet, relative gain to control binder was observed for SW additive when chromed steel-Teflon Teflon and Teflon-Teflon substrate combinations were used.

Since WMA additives are shown to improve the compaction process at high temperatures, where the lubrication mechanism is speculated to involve a significant amount of asperity contact due to low binder viscosity, it was determined necessary to test binders in boundary lubrication regime. Also, since there is a visible effect the substrate type on effectiveness of lubrication it is speculated

that the effect of SW or surfactant additive could not be captured due substrate-additive incompatibility. Therefore, testing binders at pure boundary lubrication regime using actual aggregate substrate utilized in the mixes seemed to be the best solution to investigate the additive effect on high temperature lubrication.

Chapter 6: Asphalt Boundary Lubrication Test

6.1 Asphalt Boundary Lubrication Test - Introduction

The shortcoming of the preliminary binder results with respect to observed mixture compaction results necessitated an alternative tool for evaluating WMA modified binder lubrication:

- asphalt binders need to be tested in the boundary lubrication region to evaluate their boundary lubrication properties,
- effect of interaction between WMA additives and aggregates needs to be accounted for.

In response to the listed needs a new testing apparatus was developed.

6.2 Asphalt Boundary Lubrication Test - Design and Manufacture of the Apparatus

The task of creating an apparatus capable of testing aggregate for frictional properties is not easy due irregular aggregate shapes. The Four-Ball geometry is not feasible due to the inability of making spherical aggregate specimens. Instead, an alternative testing geometry had to be utilized. After conducting literature review on different types of setups for testing friction, the pin-on flat geometry offered the most optimal approach Figure 32.

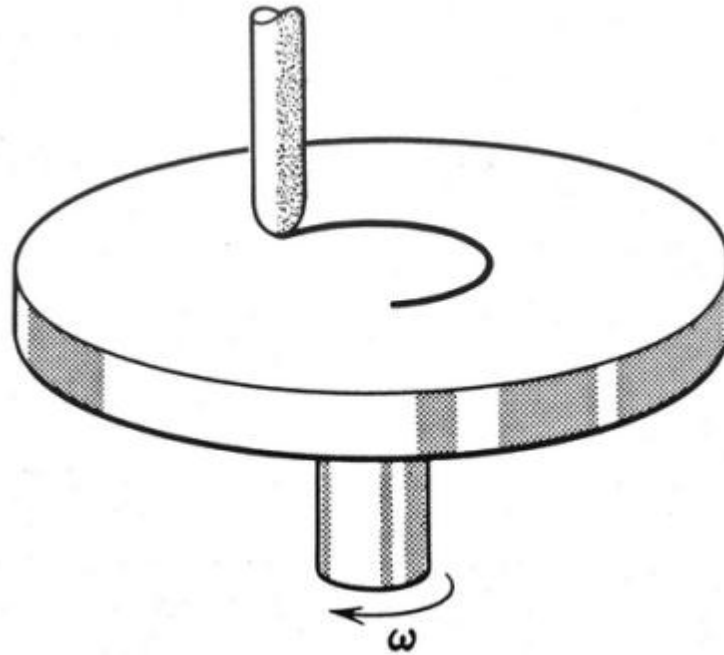


Figure 32 *Pin-on-flat testing geometry.* (Rabinowicz 1995)

The pin-on-flat type of geometry is suitable for development of a new apparatus for two important reasons:

- The apparatus must be compatible with Dynamic Shear Rheometer in order to apply normal load, rotation, and measure torque. Therefore, the circular-type motion utilized in pin-on-flat geometry is suitable.
- Fabricating aggregate disks through coring rocks and slicing them to specific dimensions is a fairly simple process

However, the geometry presented in Figure 32 cannot be used without modifications:

- Fabricating a pin (or semispherical aggregate) is a hard process. Instead of pin end, a flat rectangular shape was deemed more useful due to simplicity of fabrication. In addition a flat contact area allows for controlling pressure in addition to normal load exerted on flat disk.
- Using only one pin creates a bending moment on the load applying shaft. In order to overcome the issue, two symmetrically distributed pins were used.

The following Figure 33 illustrates model of the Asphalt Boundary Lubrication apparatus. Detailed drawings can be found in the appendix. The apparatus was developed for a TA AR-2000 Dynamic Shear Rheometer. It features the following characteristics:

- Load application through the Dynamic Shear Rheometer shaft (up to 50N)
- Control over contact pressure between pins and aggregate disk due to finite measurable pin surface area
- Swing system to provide constant equal pressure contact between pins and the disk
- Exchangeable Aggregate-Pin arrangements to test various aggregate types
- TA AR-2000 Dynamic Shear Rheometer features thermal chamber enclosing the apparatus to control testing temperature with $\pm 0.1^{\circ}\text{C}$ precision
- Thermo-Epoxy attachment of pins to swing pin platform and disk to DSR shaft for quick assembly

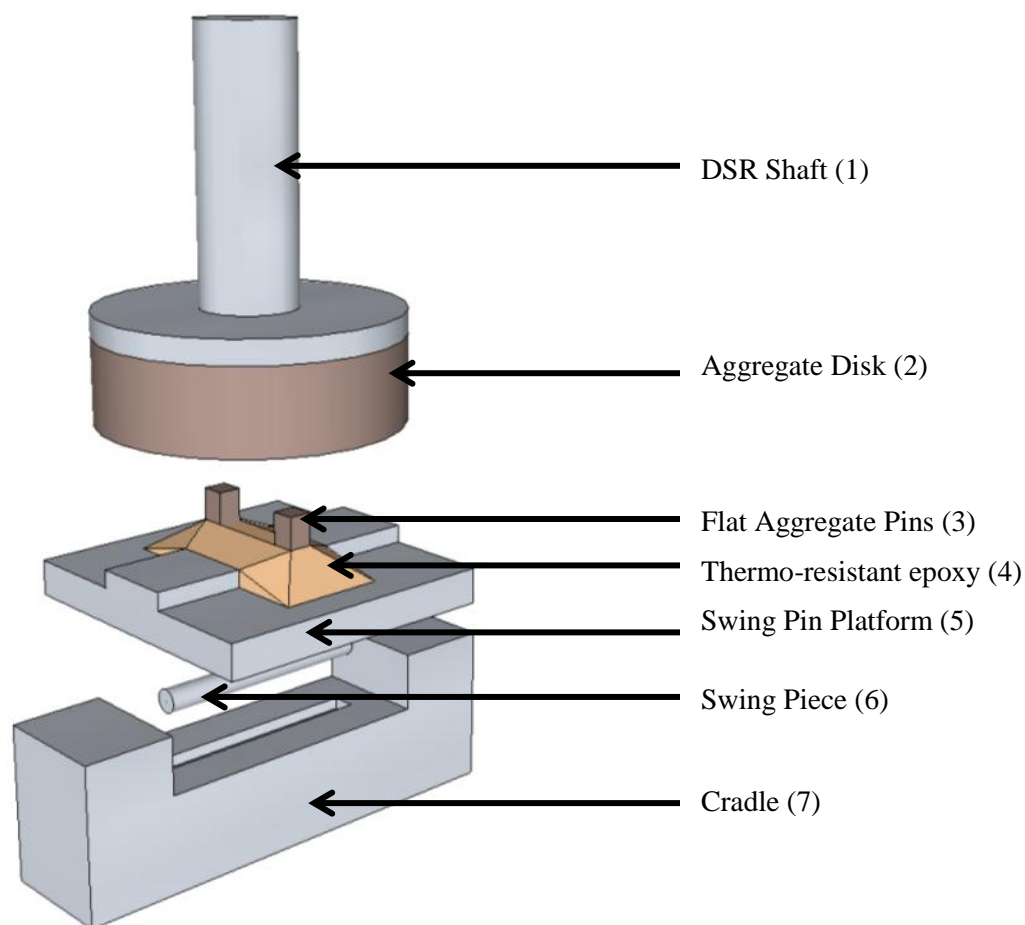


Figure 33 Asphalt Boundary Lubrication Test apparatus for TA AR-2000 Dynamic Shear Rheometer. Sketchup Model.

The swing pin platform (5) and the cradle (7) were manufactured using aluminum due to low cost and high metal workability. The swing piece (6) was cut from commercially available steel pins. The aggregate disk (2) and flat aggregate pins (3) were made using a coring machine and low-speed diamond blade saw. Thermo-resistant epoxy glue was used to cement the aggregate pieces to the metal parts. It was necessary to use thermo-resistant epoxy due to high testing temperatures ($>100^{\circ}\text{C}$).

Figure 34 illustrates the manufactured exchangeable Aggregate-Pin arrangements: Limestone, Granite and Aluminum. Limestone and Granite were sourced from South-Central Wisconsin. Figure 35 illustrates the manufactured Asphalt Boundary Lubrication test apparatus installed into the DSR with the granite Aggregate-Pin arrangement. An asphalt binder sample is also visible in the figure.



Figure 34 Exchangeable Aggregate-Pin arrangements (from left: limestone, granite, aluminum).



Figure 35 Asphalt Boundary Lubrication Test apparatus with binder sample present.

To ensure that the apparatus can measure boundary lubrication, a series of tests at different pressures and rotational speeds were performed. The following Figure 36 shows an example of such test performed at 90°C at 500kPa using granite Aggregate-Pin arrangement.

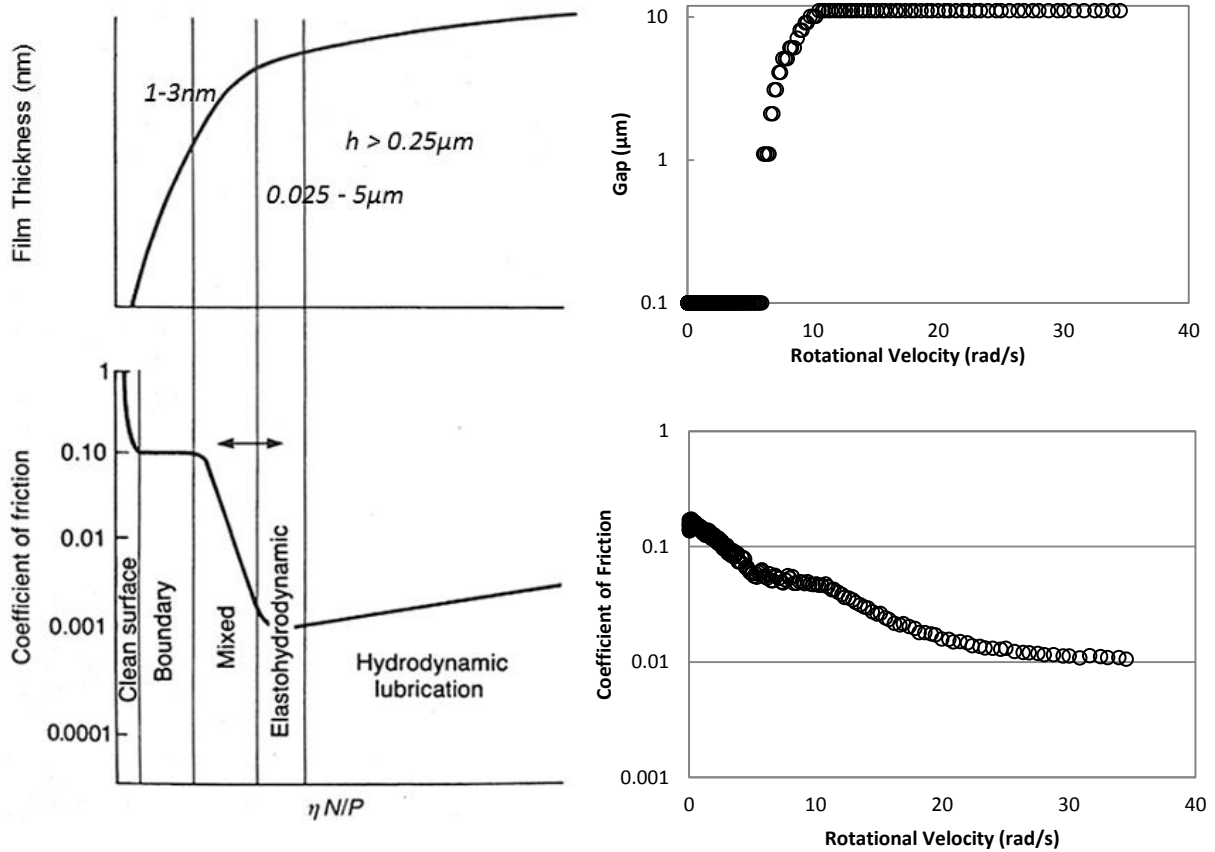


Figure 36 Determination of lubricating region for the test (Bhushan 2002)

Based on the relationship between film thickness and Stribeck Curve a testing speed of 0.05 rad/s was determined to ensure boundary lubrication regime. Since 90°C is the lowest testing temperature, the boundary lubrication requirement will be met for higher testing temperatures.

Figure 37 shows sample DSR output for normal force and torque from which coefficient of friction is calculated according to the following formula:

Equation 10 Equation for calculation of boundary coefficient of friction in the Asphalt Boundary Lubrication test.

$$\mu = \frac{T}{P \times d'}$$

Where:

μ = Coefficient of Friction,

T = Torque (N.m),

P = Normal Force (N),

d' = distance between centroids of the top surfaces of two pins (m). d' is Aggregate-Pin arrangement specific

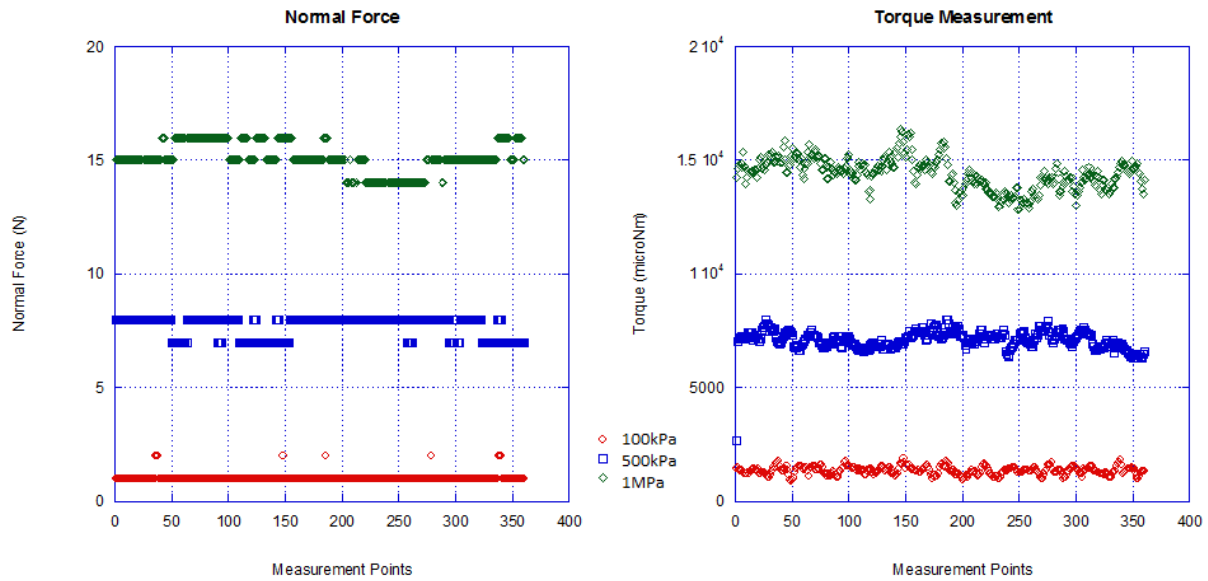


Figure 37 Normal force and torque apparatus output.

6.3 Asphalt Boundary Lubrication Test - Test Procedure

Based on the screening measurements performed during the development of the apparatus, the following testing conditions were determined for the Asphalt Boundary Lubricity test:

- Testing Temperatures: 90°C, 115°C, 145°C
- Stress levels: 100kPa, 500kPa, 1MPa

The three temperatures were selected to represent asphalt mixture compaction temperatures used to compact mixes utilized in the study. It was also recognized that during compaction asphalt binders are subject to stresses at aggregate-aggregate contact points, that range from very low to extremely high. In order to account for such stress variation during compaction process, the three stress levels were selected. They do not necessarily correspond to any modeled or measured stresses that can be found during mixture compaction. However, they were selected based on sensitivity and limits of the testing equipment and are meant to represent arbitrary high, medium and low stress levels.

The Asphalt Boundary Lubrication test procedure is as follows:

- 1) Prepare asphalt binder sample in 8-mm DSR mold. Sample weight should be ~0.1g.
- 2) Condition the apparatus in DSR at desired application temperature for 20 min. For all tests this was done at 150°C to avoid confounding the application temperature effect.
- 3) Detach the top spindle with the aggregate disk attached to it. Put the asphalt sample onto the disk and let it melt and cover the disk area. Melting typically takes 10 seconds.

- 4) Attach the top spindle with the aggregate disk back into the DSR.
- 5) Lower the spindle towards the swing pin platform and stop when asphalt binder just touched the aggregate pins.
- 6) Close the thermal chamber and condition the sample for 20 minutes at 145°C before performing the test using the pre-test procedure.
- 7) After 15 minutes the testing procedure will apply consecutively increasing pressure and begin CoF measurements followed by decreasing the temperature and repeating the stress application and CoF measurement until all three stress levels and temperature levels are covered. Total of 360 measurement points are collected per stress-temperature level.

6.4 Asphalt Boundary Lubrication Test - Results

General observations regarding boundary Coefficient of Friction measurements:

- Since CoF is a system property, the same asphalt binder results in a different CoF when the Aggregate-Pin arrangement is changed
- For a given applied stress, there is a binder specific pattern regarding the change in CoF due to change of testing temperature. Certain binders become more effective at higher temperatures, while the others do not.

Observations regarding additives:

The results of the Asphalt Boundary Lubrication test provided new insight into WMA lubricating properties.

- It was discovered that the effectiveness surfactant type additives (SW, CRT) in boundary lubrication heavily depend on the type of Aggregate-Pin arrangement, i.e. interaction with the substrate. (See Figure 39)
- SW additive resulted in significant boundary lubrication improvements relative to the control binder across all stress levels and test temperatures when tested with granite Aggregate-Pin arrangement. When tested using limestone Aggregate-Pin arrangement the effect of SW additive became much less pronounced.
 - The effectiveness of SW additive depended on concentration: 3%-SW performed better than 2%-SW when tested using granite substrate. 2%-SW performed better than 1%-SW.

- CRT additive had an effect opposite to the SW with better performance observed using limestone Aggregate-Pin arrangement. However, 0.7%-CRT performed worse than control binder for granite substrate at 100kPa.
- FPE additive was the most effective across all stresses and temperatures (with a few exceptions) in terms of improving lubrication. Its effectiveness was also observed in the preliminary Stribeck Curve tests capturing the boundary regime. Such results suggest that FPE creates an excellent lubricating film regardless of the substrate type, as measured in the Asphalt Boundary Lubrication test.
- SBS polymer by itself was not observed to improve lubrication. However, in combination with FPE it resulted in improved boundary CoF. The improvement, however, seems to be an exclusive contribution of FPE since pure FPE samples performed very similarly to the hybrid in terms of boundary CoF.
- There is a distinct difference between two sources of control binder (NuStar and Flint Hills) in terms of CoF measured for both control binders. The difference may be derived from different binder composition, which depends on crude oil source and the refining process.

The following tables illustrate relative binder ranking for different combinations of testing temperature and stress. It can be observed that there is typically a slight shift in ranking when stress level increases from 100kPa to 500kPa or 1MPa. This trend is especially visible for NuStar PG64-22 binders tested using granite Aggregate-Pin arrangement. Such trend may indicate sensitivity of boundary lubrication film to the stress level.

Table 4 Ranking of NuStar PG64-22 binders tested using granite Aggregate-Pin arrangement.

Temperature (°C)	Stress	NuStar PG64-22 Control	NuStar PG64-22 + SW-1%	NuStar PG64-22 + SW-2%	NuStar PG64-22 + SW-3%	NuStar PG64-22 + CRT-0.7%	NuStar PG64-22 + FPE-3.5%
145	100kPa	6	3	4	2	5	1
	500kPa	5	4	3	2	6	1
	1MPa	5	4	3	2	6	1
115	100kPa	6	4	3	2	5	1
	500kPa	5	4	3	2	6	1
	1MPa	5	4	1	2	6	3
90	100kPa	6	3	4	2	5	1
	500kPa	6	3	2	1	5	4
	1MPa	6	3	2	1	5	4

Table 5 Ranking of Flint Hills PG64-22 binders tested using granite Aggregate-Pin arrangement

Temperature (°C)	Stress	Flint Hills PG64-22 Control	Flint Hills PG64-22 + SBS-3.5%	Flint Hills PG64-22+ FPE-4%	Flint Hills PG64-22 + SBS 3.5% + FPE-4%
145	100kPa	3	4	1	2
	500kPa	3	4	1	2
	1MPa	4	3	1	2
115	100kPa	3	4	1	2
	500kPa	4	3	1	2
	1MPa	3	4	1	2

Table 6 Ranking of NuStar PG64-22 binders tested using limestone Aggregate-Pin arrangement

Temperature (°C)	Stress	NuStar PG64-22 Control	NuStar PG64-22 + SW-2%	NuStar PG64-22 + CRT-0.7%	NuStar PG64-22 + FPE-3.5%
145	100kPa	3	4	2	1
	500kPa	4	3	2	1
	1MPa	4	3	2	1
115	100kPa	4	3	2	1
	500kPa	4	3	2	1
	1MPa	4	3	2	1
90	100kPa	4	3	2	1
	500kPa	4	3	2	1
	1MPa	4	3	2	1

The following figure is a typical graphical representation of boundary coefficient of friction value measured during Asphalt Boundary Lubrication test. The error bars represent one standard deviation of total of three replicate samples. Figures representing all tests results can be found in the Appendix

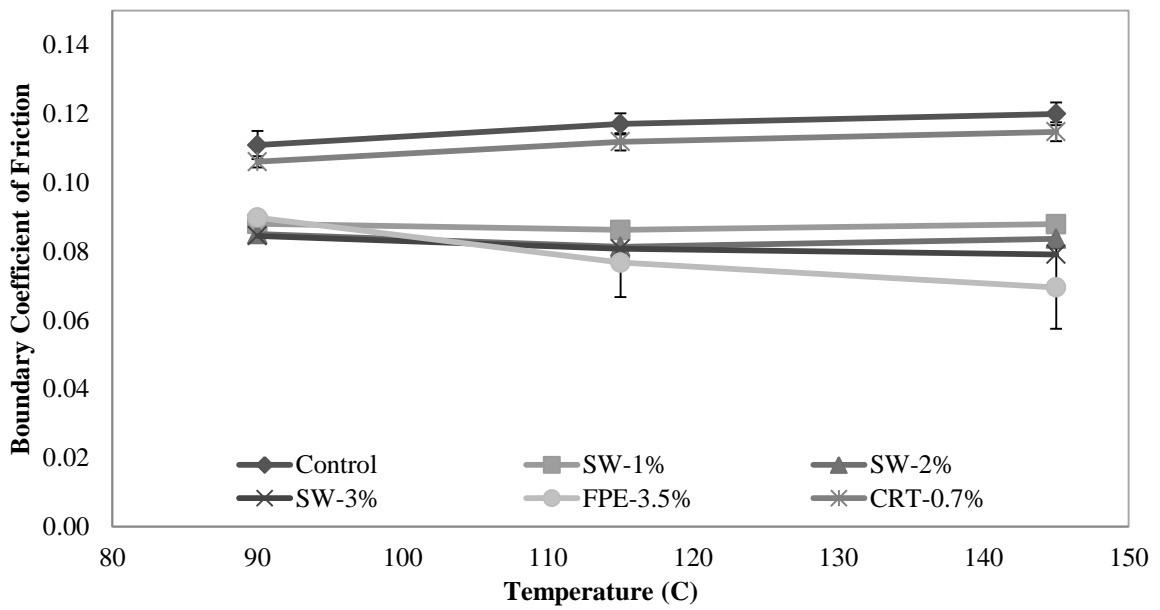


Figure 38 500 kPa Granite - PG64-22 NuStar (error bars represent 1 standard deviation).

The following figure shows relative difference of WMA chemical additives due to different substrates (granite and limestone).

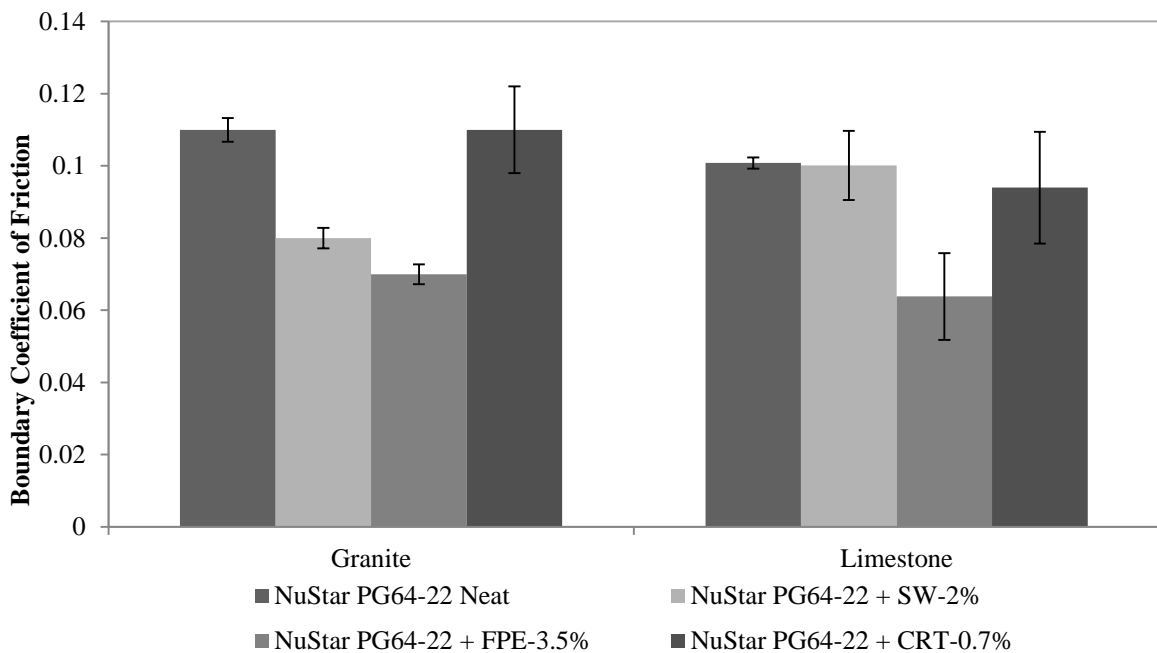


Figure 39 PG64-22 NuStar boundary coefficient of friction data at 500 kPa Granite for granite and limestone substrates (error bars represent 1 standard deviation).

6.5 Asphalt Boundary Lubrication Test - Statistical Analysis

6.5.1 Asphalt Boundary Lubrication Test - Statistical Analysis - Statistical Model

In order to evaluate the statistical significance of the results generated by the Asphalt Boundary Lubrication test an Analysis of Variance (ANOVA) two-way layout involving two treatment factors with fixed levels was implemented.

The linear model for the two-way layout is (Wu and Hamada 2009):

Equation 11 *Linear model for the two-way ANOVA layout (Wu and Hamada 2009)*

$$y_{ijl} = \eta + \alpha_i + \beta_j + \omega_{ij} + \epsilon_{ijl}$$

Where:

y_{ijl} = observation for the l th replicate of the i th level of factor A and j th level of factor B,

α_i = i th main effect for factor A,

β_j = j th main effect for factor B,

ω_{ij} = (i,j)th interaction effect between A and B,

ϵ_{ijl} = independent errors distributed as $N(0, \sigma^2)$,

$i=1, \dots, I$,

$j=1, \dots, J$,

$l=1, \dots, n$.

The two-way ANOVA layout allows for statistical evaluation of main effects of two factors and their interaction using the F test on null hypothesis (Wu and Hamada 2009). The F test rejects null hypothesis, or hypothesis assuming no difference among different factor levels, at level α if the F statistic.

Equation 12 *F test on null hypothesis for two-way ANOVA layout (Wu and Hamada 2009).*

$$F = \frac{SS_A/(I-1)}{SS_R/IJ(n-1)} > F_{I-1, IJ(n-1), \alpha}$$

where SS_A and SS_B are sums of squares for factors A and B (Wu and Hamada 2009).

5.5.2 Asphalt Boundary Lubrication Test - Statistical Analysis – Data Analysis

The sensitivity of Asphalt Boundary Lubricity test was evaluated using the PG64-22 NuStar binder test results with three replicates for each combination. Due to presence of four factors

(aggregate substrate type, temperature, stress level, effect of additive) it was decided to utilize the following two-way ANOVA designs:

- 1) Factor A: Additive
 Factor B: Temperature
 Fixed: Stress level, Aggregate substrate type

Design repeated six times (2 aggregate types x 3 stress levels) times to take into account all three stress levels and two aggregate substrate types

- 2) Factor A: Additive
 Factor B: Stress Level
 Fixed: Temperature, Aggregate substrate type

Design repeated six times (2 aggregate types x 3 stress levels) times to take into account all three testing temperatures and two aggregate substrate types.

Table 7 and

Table 8 provide collapsed ANOVA tables for the two designs across all levels. The tables were reduced to show only F statistic and p value. Highlighted are the values indicating significance of the factor or interaction between two factors for a given combination.

Table 7 2-way ANOVA with 3 replicates. Factors: additive, temperature.

ANOVA Table						
	100 kPa, Limestone		500 kPa, Limestone		1 MPa, Limestone	
Source of Variation	F statistic	p	F statistic	p	F statistic	p
Additive	28.91	<0.0001	28.89	<0.0001	35.35	<0.0001
Temperature (°C)	17.44	<0.0001	1.15	0.3339	0.18	0.837
Additive x Temperature (°C)	0.46	0.8327	0.4	0.8723	0.82	0.568
	100 kPa, Granite		500 kPa, Granite		1 MPa, Granite	
Source of Variation	F statistic	p	F statistic	p	F statistic	p
Additive	101.83	<0.0001	140.57	<0.0001	164.62	<0.0001
Temperature (°C)	7.37	0.0032	0.17	0.8419	6.42	0.0059
Additive x Temperature (°C)	6.06	0.0006	7.62	0.0001	10.62	<0.0001

Table 8 2-way ANOVA with 3 replicates. Factors: additive, stress level.

ANOVA Table						
Source of Variation	90°C, Limestone		115°C, Limestone		145°C, Limestone	
	F statistic	p	F statistic	p	F statistic	p
Additive	36.46	<0.0001	26.87	<0.0001	29.17	<0.0001
Stress Level (kPa)	13.96	<0.0001	2.06	0.1499	3.33	0.053
Additive x Stress Level (kPa)	1.5	0.2214	0.3	0.9323	0.35	0.9019
Source of Variation	90°C, Granite		115°C, Granite		145°C, Granite	
	F statistic	p	F statistic	p	F statistic	p
Additive	194.32	<0.0001	163.31	<0.0001	108.11	<0.0001
Stress Level (kPa)	106.74	<0.0001	18.23	<0.0001	26.28	<0.0001
Additive x Stress Level (kPa)	23.99	<0.0001	1.64	0.1786	3.59	0.0112

6.5.3 Asphalt Boundary Lubrication Test - Statistical Analysis – Comments

- The presence of additive resulted was strongly significant with p values always less than 0.0001 for every design combination. This outcome corresponds with observed changes in mixture % air voids for binders with different WMA additives.
- Stress level was significant for all results utilizing granite substrate. Tests utilizing limestone substrate yielded stress level significant only at 90°C test temperature. The differences in significance of stress level for limestone and granite may be caused by lower stiffness of limestone. Stress level controls thickness of lubricational film between the rocks.
- Temperature level was statistically significant only for at 90°C. It is possible that at that temperature viscosity of binder surrounding the rock contact area, but not being subject to friction, slightly confines the fixture rotational movement.
- At 1MPa using granite substrate, interaction effect of additive type and temperature was significant. Correspondingly, for granite at 90°C the interaction effect of additive and stress level was significant. This interaction effect seems to be an artifact of testing method. It is not expected to have any practical implications.

6.6 Asphalt Boundary Lubrication Test - Mixture Comparison

6.6.1 Asphalt Boundary Lubrication Test - Mixture Comparison - Boundary Coefficient of Friction- Air Voids Ranking

Since binder viscosity does not capture the surface effects of Warm Mix Asphalt modification, boundary coefficient of friction for lubricated aggregate surfaces is meant to provide an explanation of improvements for such binders as seen in mixture compactability. It is recognized that viscosity, while not being able to provide a good correlation with mixture air voids for some cases, does have influence of mixture compaction. Therefore, boundary CoF results, however, are not presented as correlation with mixture % air voids at N design, rather than relative ranking. Table 9 and

Table 10 provide a ranking for NuStar and Flint Hills binders in terms of CoF at different stress levels and mixture % air voids at N design for three temperature levels.

6.6.1.1 Boundary Coefficient of Friction- Air Voids Ranking – NuStar Binder Type

Boundary coefficient of friction resulting from boundary lubrication provides a relatively good ranking when compared with mixture % air voids at N design. For the NuStar binder series, the control binder ranked the lowest across all temperatures in terms of both CoF and % air voids at N design. However, there is a discrepancy between mixture and binder data for relative ranking of FPE and SW modified binders: While FPE modified binder provides boundary CoF lower than SW, it does not lead to lower % air voids at N design when compared to SW. This discrepancy could be attributed to viscosity effect not captured in boundary lubrication test, but captured in mixture compaction. SW has a viscosity reducing effect.

Table 9 Boundary Coefficient of Friction- % Air Voids Ranking – NuStar Binder Type.

Temperature (°C)	Variable	NuStar PG64-22 Control	NuStar PG64-22 + FPE-3.5%	NuStar PG64-22 + SW-1%	NuStar PG64-22 + SW-2%
145	Air Voids Ndes	4	3	2	1
	100kPa	4	1	2	3
	500kPa	4	1	3	2
	1MPa	4	1	3	2
115	Air Voids Ndes	4	3	2	1

	100kPa	4	1	3	2
	500kPa	4	1	3	2
	1MPa	4	2	3	1
85	Air Voids Ndes	4	3	2	1
	100kPa	4	1	2	3
	500kPa	4	3	2	1
	1MPa	4	3	2	1

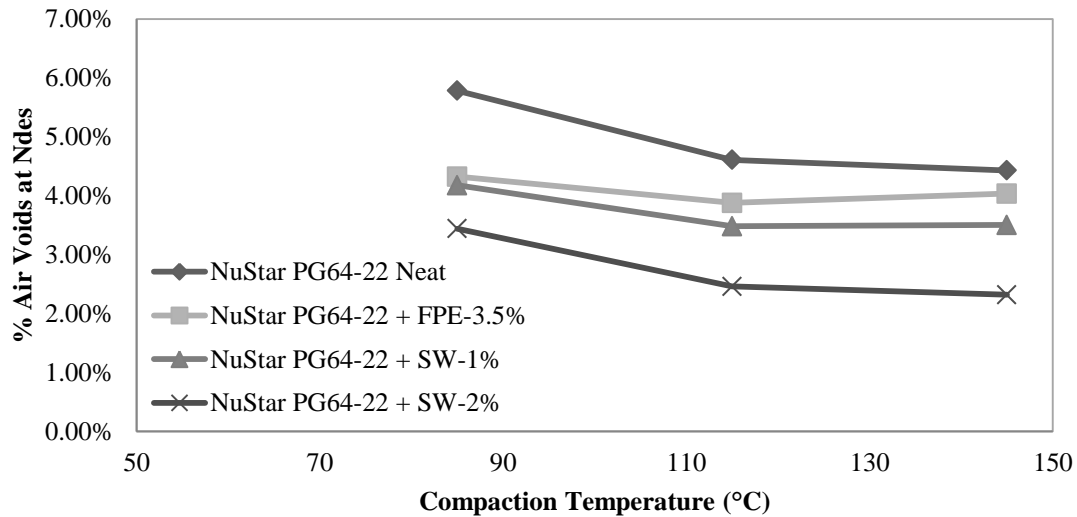


Figure 40 % Air Voids at Ndes vs. Compaction Temperature (°C) for NuStar mixes.

6.6.1.2 Boundary Coefficient of Friction- Air Voids Ranking – Flint Hills Data

For the Flint Hills binder series the ranking between % air voids at N design and boundary CoF is good at 145°C testing temperature. The mixture and binder data are similarly ranked and the improvident in compaction can be attributed to the presence of FPE polymer as the boundary coefficient of friction was only improved for binders containing the polymer. As the testing temperature is decreased the ranking becomes worse due to increasing effect of viscosity on mixture compaction. For the Flint Hills set of mixtures the binders were additionally tested in the Asphalt Boundary Lubrication test at 65°C temperature in order to correlate with mixture compaction data. However, the test results do not coincide with mixture results: the binder test at such low temperature seems to be out of boundary lubrication zone due to increasingly high binder viscosity causing thick film buildup in the apparatus.

Table 10 Boundary Coefficient of Friction- Air Voids Ranking – Flint Hills Binder Type.

Temperature (°C)	Variable	Flint Hills PG64-22 Control	Flint Hills PG64-22 + SBS-3.5%	Flint Hills PG64-22+ FPE-4%	Flint Hills PG64-22 + SBS 3.5% + FPE-4%
145	Air Voids Ndes	4	3	2	1
	100kPa	3	4	1	2
	500kPa	3	4	1	2
	1MPa	4	3	1	2
115	Air Voids Ndes	1	4	2	3
	100kPa	3	4	1	2
	500kPa	4	3	1	2
	1MPa	3	4	1	2
65	Air Voids Ndes	3	1	2	4
	100kPa	1	4	2	3
	500kPa	1	4	2	3
	1MPa	2	3	1	4

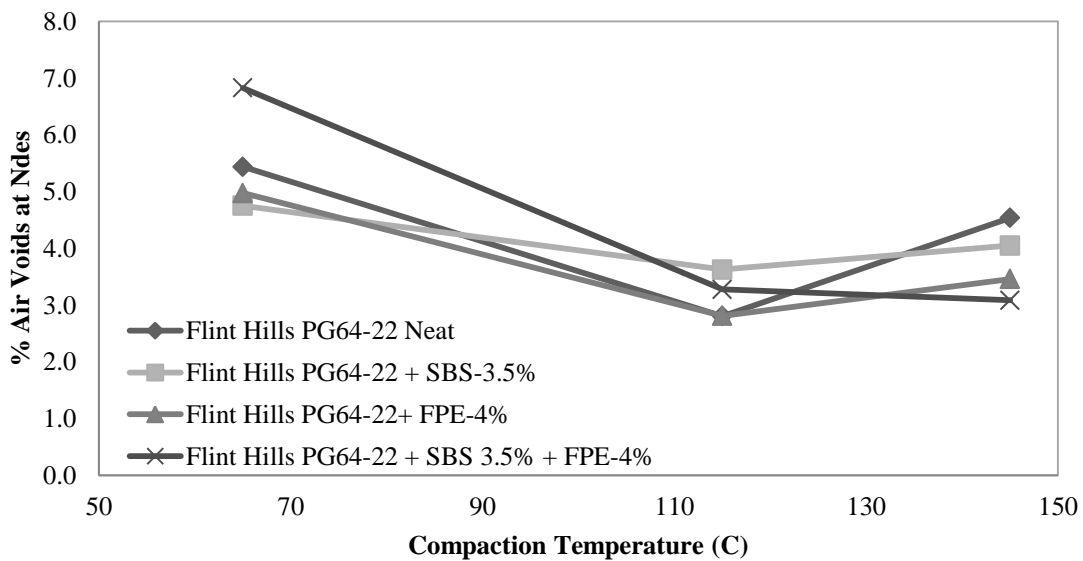


Figure 41 Air Voids at Ndes vs. Compaction Temperature (°C) for Flint Hills mixes.

6.6.2 Asphalt Boundary Lubrication Test - Mixture Comparison - Mastic Viscosity Model

Using only asphalt binder viscosity or boundary lubrication coefficient of friction to estimate % air voids after compaction for a fixed-gradation mixture has obvious shortcomings: viscosity does not capture the surface lubrication effects of WMA additives, while the boundary coefficient of

friction does not capture the binder viscosity effect. It is known that they both have quantifiable effects on compaction. Therefore, it would be useful to combine the binder viscosity and boundary effects of WMA additives to evaluate their combined effect on compaction.

In their recent work Roohi et al. showed the importance of considering mastic viscosity in mixture compaction (Roohi, Teymourpour and Bahia 2013). Asphalt mastic is a combination of asphalt binder and aggregate material passing sieve #200. It has been shown that there was a good correlation between low shear mastic viscosity and aggregate structure (total contact length) formation in asphalt mixtures as measured at 145°C. At initial stages of compaction, the increased ability of aggregate particles to reorient will increase their total contact length parameter or improve the asphalt mixture interlock. Roohi et al. showed that there is a correlation between low shear mastic viscosity and the ability of particles to reorient for larger amount of time during Superpave gyratory compaction, leading to better structure. Their assumption is that mastics of higher low shear viscosity provide better lubrication for large aggregate particles.

Figure 42 provides a correlation between % air voids at N design and mastic low shear viscosity for Flint Hills mixtures and mastics at 115°C and 145°C testing temperatures. Internal structure data for the mixtures was not available; hence the author decided to use % air voids at N design instead. Only one type of mixture was used for the correlation.

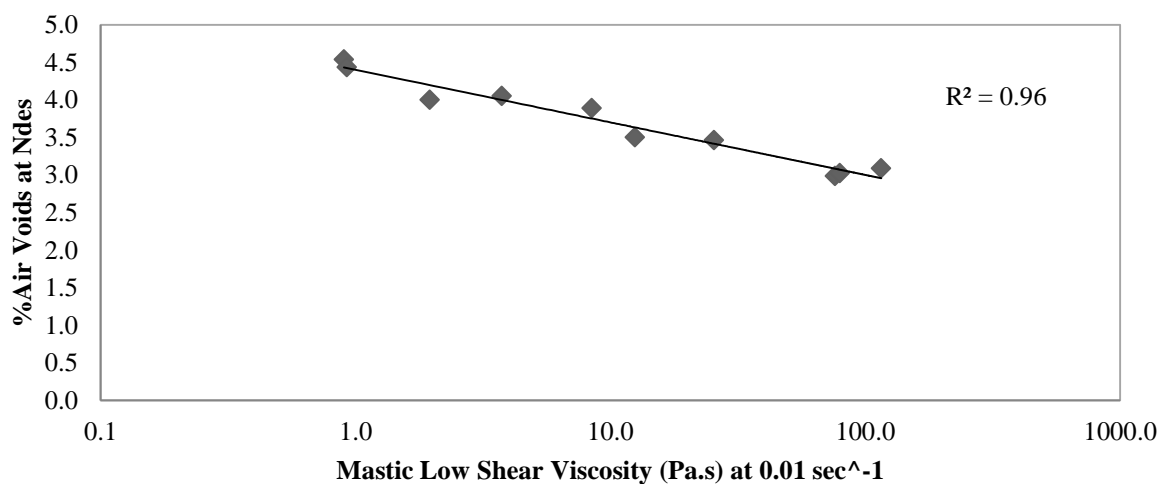


Figure 42 % Air Voids at N design vs. Mastic Low Shear Viscosity (Pa.s) at (0.01 sec⁻¹).

Roohi et al. did a comparison between mastic and binder viscosity at 145°C resulting in poor correlation. This indicates that there is an effect of particle filler on mastic viscosity. It was shown by Clopotel and Faheem that particle contact plays an important role in characterizing mastic rheology (Faheem 2009) (Clopotel 2012). Therefore, it is speculated that the particle contact in mastics can be

accounted for by the boundary coefficient of friction. Figure 43 provides a correlation between boundary coefficient of friction and mastic viscosity at 115°C and 145°C. The resulting R² value is only 65%. Therefore, boundary coefficient of friction does have high degree of influence on mastic viscosity at mentioned testing temperatures. However, the remaining 35% of results are not accounted for.

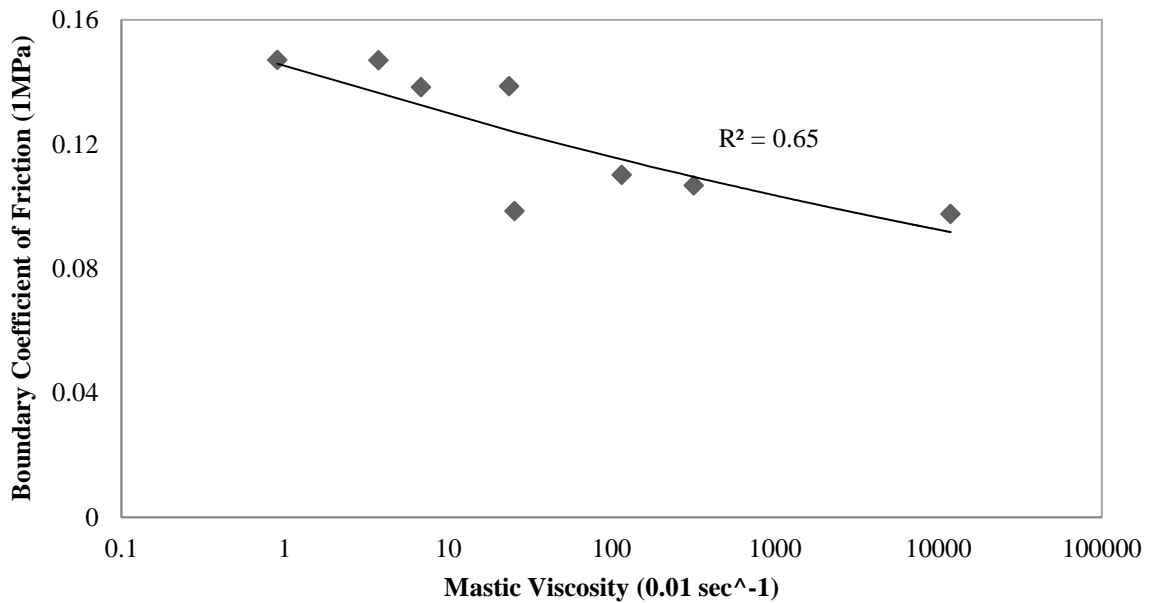


Figure 43 Mastic Viscosity –vs. Boundary Coefficient of Friction (1 MPa).

In order to take into account the effects of both boundary coefficient of friction and binder viscosity on the mastic viscosity, a best subsets regression was used. A model for predicted mastic viscosity based on binder viscosity and mastic viscosity was generated:

Equation 13 Best Subset Regression model for predicted mastic viscosity based on binder and boundary coefficient of friction.

$$\text{Log(Mastic Viscosity)} = 5.234 + 0.829 \times \text{Log(Binder Viscosity)} - 32.989 \times \text{Boundary CoF}$$

Table 11 Attempts for best subsets regression model utilizing various combinations of predictors (binder viscosity, boundary coefficient of friction at 1MPa and a product of the two predictors. X's signify which predictors were used for a given attempt.

Attempt	R-Sq	R-Sq(adj)	Cp	S	Binder Viscosity	COF @ 1 MPa	Viscosity*COF
1	63.5	56.2	8.7	0.578		X	
2	29.1	15	19.7	0.805	X		

3	90.3	85.4	2.1	0.333	X	X	
4	88.8	83.3	2.6	0.357		X	X
5	90.6	81.3	4	0.378	X	X	X

Table 12 Chosen model for mastic viscosity prediction with *p* values for each predictor.

Predictor	Coeff.	SE Coeff.	T	P
Constant	5.2336	0.8455	6.19	0.003
Binder Viscosity	0.8295	0.2497	3.32	0.029
COF @ 1 MPa	-32.989	6.577	-5.02	0.007

The model was chosen from five different attempts (Table 11) considering different combinations of predictors (bulk binder viscosity, boundary coefficient of friction at 1MPa and a combination of the two factors) based on the highest adjusted R^2 value and lowest C_p value. Based on those criteria, attempt 3 yielded the best results. Table 12 shows details coefficients for each factor along with *p* significance values. From the best subsets regression model it can be observed that boundary coefficient of friction is an important factor highly influencing the low shear mastic viscosity.

The model for low shear mastic viscosity considering the boundary coefficient of friction and the bulk binder viscosity provides much better relationship with the measured low shear mastic viscosity (Figure 44). Therefore, it can be concluded that asphalt mixture compaction at high temperatures is mostly governed by mastic viscosity. Mastic viscosity, however, is a function of binder viscosity and boundary lubricating efficiency of binder, as measured by the Asphalt Boundary Lubrication test. It is important to note that coefficient of friction is a system property: It depends not only on binder, but also the substrate type and cell geometry. Therefore, the presented model is only valid for the boundary lubricating efficiency measured by the presented Asphalt Boundary Lubrication fixture.

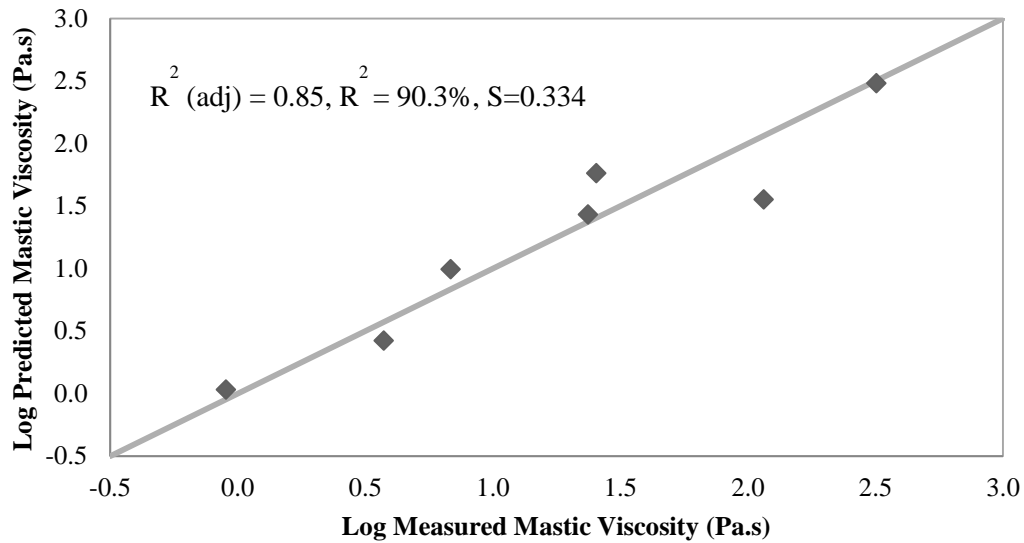


Figure 44 *Measured vs. Predicted Mastic Viscosity.*

7. Conclusions and Recommendations

7.1 Conclusions and Recommendations - Conclusions

The objective of this thesis was to evaluate the effect of Warm Mix Asphalt additives on mixture compaction through evaluation of their lubricational properties. As it was shown in the preliminary results, surface lubrication is a complex phenomenon, which depends on the conditions of solid surface contact and external conditions (ex. temperature). As it was shown by Hanz, at low temperatures of compaction (85°C) the hydrodynamic lubrication effect is predominant. However, the hydrodynamic behavior of binders did not explain the trends observed for compaction at high temperatures.

During preliminary lubrication tests it was discovered that at high binder temperatures the solid-to-solid interaction became an important factor differentiating various WMA additives. This discovery led to development of the Asphalt Boundary Lubrication test. The results of the test offered insight into the mechanism by which the tested WMA additives lubricated the aggregates in boundary conditions. The most important findings of the test were:

- There are two different lubrication regimes that should be considered to evaluate effect of WMA additive on mixture compaction: Hydrodynamic and Boundary lubrication.
- WMA additives are capable of aiding mixture compaction through aggregate surface lubrication.

- The effect of WMA additives on boundary lubrication coefficient of friction depends on aggregate substrate type. Therefore, aggregate surface should be represented in measuring effect of WMA additive lubrication.
- For a particular aggregate substrate, the effectiveness of improving frictional characteristics depends on the amount of WMA additive.
- WMA additives typically improve the boundary lubricational characteristics when compared to control binder.
- Certain WMA additives improve the boundary lubricational characteristics regardless of the aggregate substrate type.
- Statistical analysis of asphalt mixture compaction results (% air voids at N design) shows that mastic viscosity is the best material parameter to predict % air voids. Mastic viscosity is a function of boundary lubrication and binder viscosity.
- In this study it is found that measuring boundary lubrication in the presence of aggregate surface is possible, but not practical. Therefore, measuring mastic low shear viscosity could be a more practical and reliable method to evaluate WMA additive's need and effectiveness.

7.2 Conclusions and Recommendations - Recommendations

- The comparison to mixture data in this study was limited to granite aggregate. It is recommended that further comparison be made to aggregate mixtures of limestone gradation.
- Additionally, the Asphalt Boundary Lubrication test results should be expanded to encompass a larger number of WMA additives and binder modifiers not necessarily classified as WMA additives to gain further insight into binder boundary lubrication properties.
- Also, it is recommended that future studies evaluate the effect of PG grade on boundary lubricating properties.
- In addition, it is well known that rocks of the same type vary in mineralogy. It is recommended that different types of aggregates, including different mineralogies of the same type of rock be included in future boundary lubrication testing.
- Another important implication of lower boundary coefficient of friction during compaction is potentially less wear and fewer aggregate fractures. This may lead to better long term mixture durability. Therefore, a study comparing boundary coefficient of friction with mixture durability should be conducted.

8. References

- Anton Paar Germany GmbH. "Tribology Measuring Cell T-PTD200 - Instruction Manual." Ostfildern: Anton Paar Germany GmbH, August 2009.
- Anton Paar Germany GmbH. *Tribology-Measurement-of-Friction-Lubrication-and-Wear*. n.d. http://www.anton-paar.com/Tribology-%E2%80%94-Measurement-of-Friction-Lubrication-and-Wear/Tribology/60_Corporate_en?product_id=385 (accessed November 11, 2012).
- ASTM_D6425-05. "Measuring Friction and Wear Properties of Extreme Pressure Lubricating Oils Using SRV Testing Machine." *Annual Book of ASTM Standards*. American Society for Testing Materials, 2005.
- Bennert, Thomas, Gerald Reinke, Walaa Mogawer, and Karissa Mooney. "Assessment of Workability and Compactability of Warm-Mix Asphalt." *Transportation Research Record*, 2010: 36-47.
- Bhushan, Bharat. *Introduction to Tribology*. New York: John Wiley & Sons, 2002.
- Binder Selection Guideline Project*. Preliminary Final Report., Madison: Wisconsin Department of Transportation, 2004.
- Biresaw, Girma. "Surfactants in Lubrication." In *Lubricant Additives: Chemistry and Applications*, by Leslie Rudnick, 399-418. Wilmington: CRC Press, 2009.
- Blankenship, P, K Mahboub, and G Huber. "Rational Method for Laboratory Compaction of Hot Mix Asphalt." *Transportation Research Record*, 1995: 144-153.
- Bonaquist, Ramon. *Mix Design Practices for Warm Mix Asphalt*. NCHRP 691, Washington D.C.: Transportation Research Record, 2011.
- Chadbourn, Bruce A, David E Newcomb, Vaughan R Voller, DeSombre, James A Luoma, and Timm. *An Asphalt Paving Tool for Adverse Conditions*. Minneapolis: University of Minnesota, 1998.
- Cho, Dong-Woo, Hussain U Bahia, and Nabil I Kamel. "Critical Evaluation of Use of the Procedure of Superpave Volumetric Mixture Design for Modified Binders." *Transportation Research Record*, 2005: 114-125.
- Clopotel, Cristian. *Filler Reinforcement Mechanisms in Asphalt Mastic*. PhD thesis: University of Wisconsin-Madison, 2012.
- Coenen, Kutay, and Bahia. "Aggregate Structure Characterization of Asphalt Mixtures Using 2-Dimensional Image Analysis." *International Journal of Road Materials and Pavement Design*, 2011.
- Crawford, C. "The Rocky Road of Mix Design." *National Asphalt Pavement Association, Hot Mix Asphalt Technology* (National Asphalt Pavement Association, Hot Mix Asphalt Technology), 1989.

- D'Angelo, John, et al. *Warm-Mix Asphalt: European Practice*. FHWA-PL-08-007, Alexandria: US Federal Highway Administration, 2008.
- Damm, K-W, J Abraham, T Butz, G Hildebrand, and G Riebeschl. "Asphalt Flow Improvers as 'Intelligent Fillers' for Hot Asphalts - A New Chapter in Asphalt Technology." *Journal of Applied Asphalt Binder Technology*, 2002: 36-69.
- De Sombre, Rachel, David E Newcomb, Bruce Chadbourn, and Vaughn Voller. "Parameters to Define the Laboratory Compaction Temperature Range of Hot-Mix Asphalt." *Association of Asphalt Paving Technologists*, 1998: 125-142.
- Delgadillo, Rodrigo, and Hussain U Bahia. "Effects of Temperature and Pressure on Hot Mixed Asphalt Compaction: Field and Laboratory Study." *Journal of Materials in Civil Engineering ASCE*, 2008: 440-448.
- Epps, et al. "Influence of Mixture Variables on the Flexural Fatigue Properties of Asphalt Concrete." *Association of Asphalt Paving Technologists*, 1969: 423-464.
- Faheem, A. *Modeling of Asphalt Mastic in Terms of Filler-Bitumen Interaction*. PhD thesis: University of Wisconsin-Madison, 2009.
- Gonzalez Leon, Juan Antonio, Lionel Grampre, and Gilles Barreto. "Warm-Mix Asphalts with Low-Dosage Chemical Additives." *Transportation Research Record*, 2009.
- Hansen, Kent R, and David E Newcomb. "Asphalt Pavement Mix Production Survey on Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, and Warm-mix Asphalt Usage: 2009-2010." National Asphalt Pavement Association, November 2011.
- Hanz, Andrew. "Quantifying the Impacts of Warm Mix Asphalt on Constructability and Performance." *PhD Thesis*. Madison: University of Wisconsin – Madison, 2012.
- Hanz, Andrew, Ahmed Faheem, Enad Mahmoud, and Hussain U Bahia. "Measuring Effects of Warm Mix Additives Using a Newly Developed Asphalt Binder Lubricity Test for the DSR." *Transportation Research Record*, 2010: 85-92.
- Hanz, Andrew, Enad Mahmoud, and Hussain U Bahia. "Asphalt Lubricity Test Evaluation and Relationship to Mixture Workability." *Transportation Research Record*, 2011.
- Hurley, Graham C, and Brian D Prowell. *Evaluation of Evotherm For use in Warm Mix Asphalt*. NCAT 06-02, 2006.
- Hurley, Graham C, and Brian D Prowell. *Evaluation of Sasobit For Use in Warm Mix Asphalt*. NCAT Report 05-06, Auburn: National Center for Asphalt Technology, 2005.
- Jost, P. "Lubrication (Tribology) - A report on the Present Sosition and Industry's Needs." HMSO, London: Department of Science and Education, 1966.
- Kandhal, and Koehler. "Placement and Compaction of ASphalt Mixtures." *ASTM STP 829*, 1984: 93-106.
- Kandhal, Prithvi Singh. "Warm Mix Asphalt Technologies: An Overview." *Journal of the Indian Roads Congress*, 2010: 143-152.

- Kari, W. "Mix Properties as They Affect Compaction." *Asphalt Paving Technology*, 1967: 295-309.
- Kenbeck, Dick, and Thomas Bunemann. "Organic Friction Modifiers." In *Lubricant Additives: Chemistry and Application*, by Leslie Rudnick, 195-209. CRC Press, 2009.
- Kennedy, Thomas W, Freddy L Roberts, and Robert B McGennis. "Effects of Compaction Temperature and Effort on the Engineering Properties of Asphalt Concrete Mixtures." *ASTM STP 829*, 1984: 48-66.
- Khatri, Arif, Hussain U Bahia, and Doug Hanson. "Mixing and Compaction Temperatures for Modified Binders Using the Superpave Gyratory Compactor." *Association of Asphalt Paving Technologists*, 2001: 368-395.
- Kristjánsdóttir, Ólöf, Stephen T. Muench, Larry Michael, and Gloria Burke. "Assessing Potential for Warm-Mix Asphalt Technology Adoption." *Journal of the Transportation Research Board*, 2007: 91-99.
- Lenz, Russel W, P.E., Director, Construction Division. "Pavement Design Guide Manual." Austin: Texas Department of Transportation, January 1, 2011.
- Linden, Mahoney, and Jackson. "Effect of Compaction on Asphalt Concrete Performance." *Transportation Research Record*, 1989: 20-28.
- Logaraj, Sundaram, and Angelo Almeida. "Surface-active bitumen additive for Warm Mix asphalt with adhesion promoting properties." *AkzoNobel*, 2010.
- Ludovic, Bertrand. Vibratory compactor having vibrationally tuned frame. United States of America Patent 5,397,198. November 3, 1999.
- Mamlouk, Michael S., Zaniewski P. John. *Materials for Civil and Construction Engineers*. Upper Saddle River: Pearson, 2011.
- McLeod, N W. "Influence of Viscosity of Asphalt-Cement on Compaction of Paving Mixtures in the Field and Discussion." *Highway Research Board*, 1967: 76-115.
- Meadwestvaco. *Evotherm Warm Mix Asphalt*. n.d.
<http://www.meadwestvaco.com/mwv/groups/content/documents/document/mwv006575.pdf>
 (accessed October 10 , 2012).
- Mitsui, Akira, and Kristian John Guard. Vibratory Pneumatic Tire Roller. United States of America Patent 5,788,408. August 4, 1998.
- Moraes, Raquel. "Validation of the Bitumen Bond Strength Test Using Surface Energy Measurements." *Master Thesis Dissertation*. Madison: University of Wisconsin-Madison, 2011.
- Mortier, and Orszulik. *Chemistry and Technology of Lubricants*. New York: VCH Publishers, Inc., 1992.
- MWV Evotherm. *Evotherm Chemistry Episode 2 - Surfactant Chemistry*. March 28, 2011.
<http://www.youtube.com/watch?v=cdKlyofu0Xw&feature=related> (accessed October 25, 2012).

- Nijboer, L. "Plasticity as a factor in the design of sense bituminous road carpets." *Elsevier*, 1948.
- Pell, and Taylor. "Asphaltic Road Materials in Fatigue." *Association of Asphalt Paving Technologists*, 1962: 371-422.
- Rabinowicz, Ernest. *Friction and Wear of Materials*. New York City: John Wiley & Sons, Inc., 1995.
- Richter, Elk. Finisher To Lay And Compact Asphalt Layers And Method For Operating Same. United States of America Patent 6,514,007 B2. February 4, 2003.
- Roberts, Freddy L, Prithvi S Kandhal, E Ray Brown, Dah-Yinn Lee, and Thomas W Kennedy. *Hot Mix Asphalt Materials, Mixture Design, And Construction*. Lanham: National Asphalt Pavement Association Research and Educational Fundation, 1996.
- Roohi Sefidmazgi, Nima. "Defining Effective Aggregate Skeleton in Asphalt Mixture Using Digital Imaging." *Master Thesis*. University of Wisconsin-Madison, 2011.
- Roohi, Tashman, and Bahia. "Internal Structure Characterization of Asphalt Mixtures for Rutting Performance Using Imaging Analysis." *Association of Asphalt Pavement Technologies*, 2012.
- Roohi, Teymourpour, and Bahia. "Effect of Particle Mobility on Aggregate Structure Formation in Asphalt Mixtures." *Road Materials and Pavements Design*, 2013.
- Sampath, Anand. "Comprehensive Evaluation of Four Warm Mix Asphalt Mixture Regarding Viscosity, Tensile Strength, Moisture Sensitivity, Dynamic Modulus and Flow Number." *Master Thesis Dissertation*. University of Iowa, 2010.
- Scherocman, J A. "Guidelines For Compacting Asphalt Concrete Pavment." *Better Roads*, 1984.
- Schmidt, Kari, Bower, and Hein. "Behavior of Hot Asphaltic Concrete Under Steel-Wheel Rollers." *Highway Research Bulletin No. 251*, 1959: 18-37.
- Sowers, George. *Introductory Soil Mechanics and Foundations*. New York: Macmillen, 1970.
- Stribeck, R. "Characteristics of Plain and Roller Bearings." *Zeit. Ver. Deut. Ing.*, 1902: 1341-1348.
- Wang, L, and Frost J. "Dissipated strain energy method for determining preconsolidation pressure." *Canadian Geotechnical Journal (C)*, 2004: 760-768.
- Wang, Linbing. *Modeling of Asphalt Microstructure and Micromechanics*. New York: The McGraw-Hill Companies, Inc., 2011.
- Wang, Linbing, Bing Zhang, Dong Wang, and Zhongqi Yue. "Fundamental Mechanics of Asphalt Compaction Through FEM and DEM modeling." *The Symposium on the Mechanics of Flexible Pavements*. Boulder: American Society of Civil Engineers, 2007. 45-63.
- Wu, Jeff C. F., and Michael S. Hamada. *Experiments Planning, Analysis, adn Optimization*. Hoboken: john Wiley & Sons, Inc., 2009.
- Yue, Bekking, and Morin. "Application of Digital Image Processing to Quantitatively Study of Asphalt Concrete Microstructure." *Transportation Research Record*, 1995: 53-60.

8. Appendix

8.1 Asphalt Boundary Lubrication test results

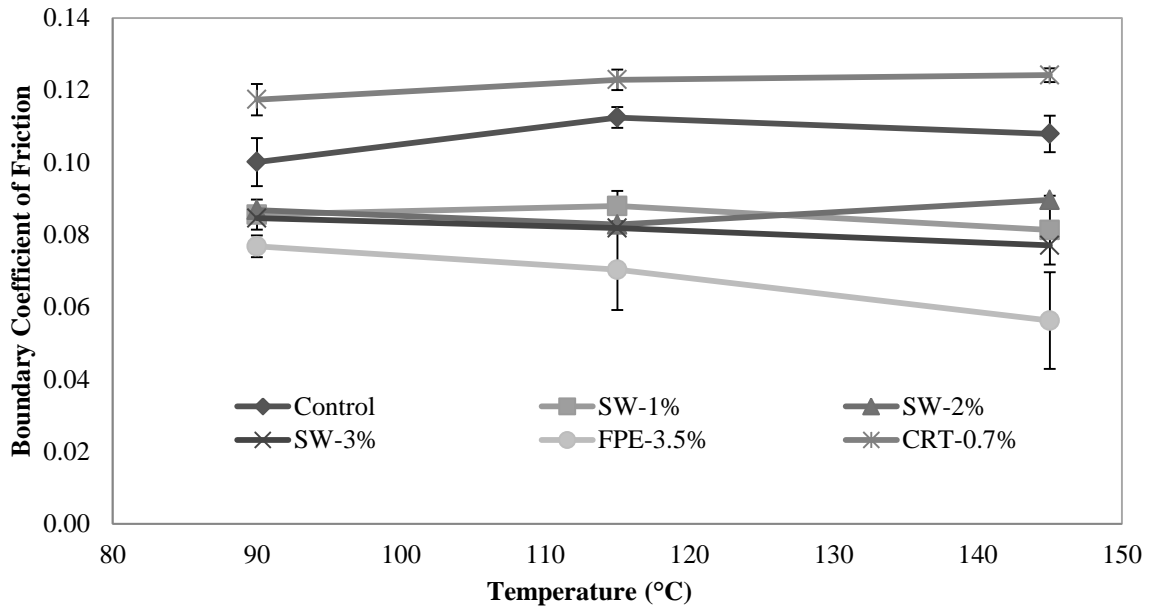


Figure 45 100 kPa Granite - PG64-22 NuStar (error bars represent 1 standard deviation).

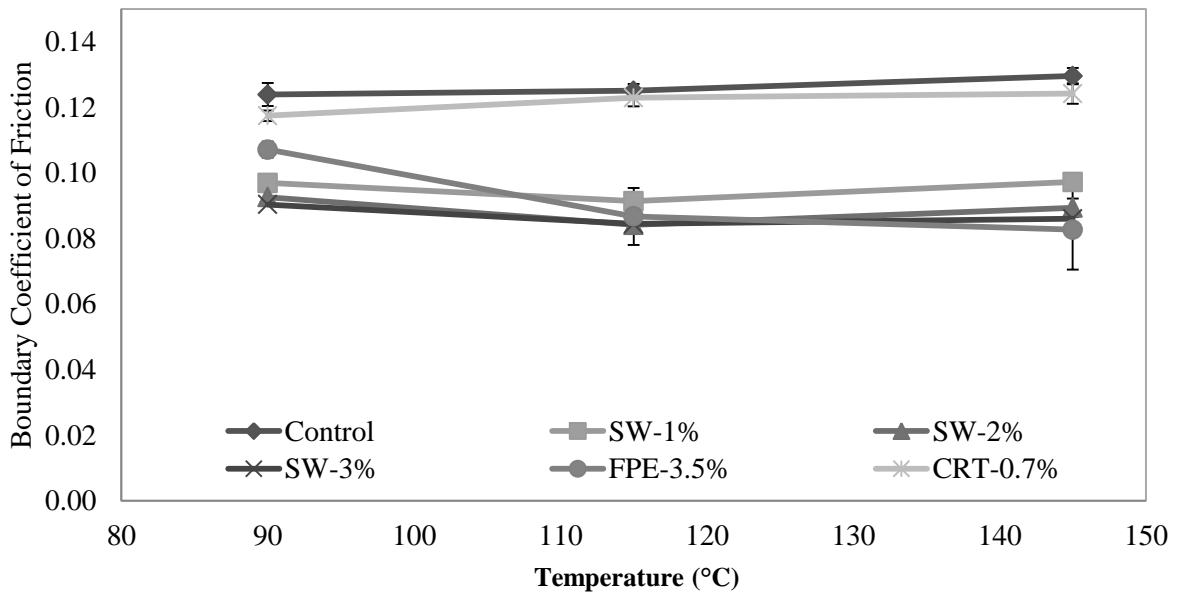


Figure 46 1 MPa Granite - PG64-22 NuStar (error bars represent 1 standard deviation).

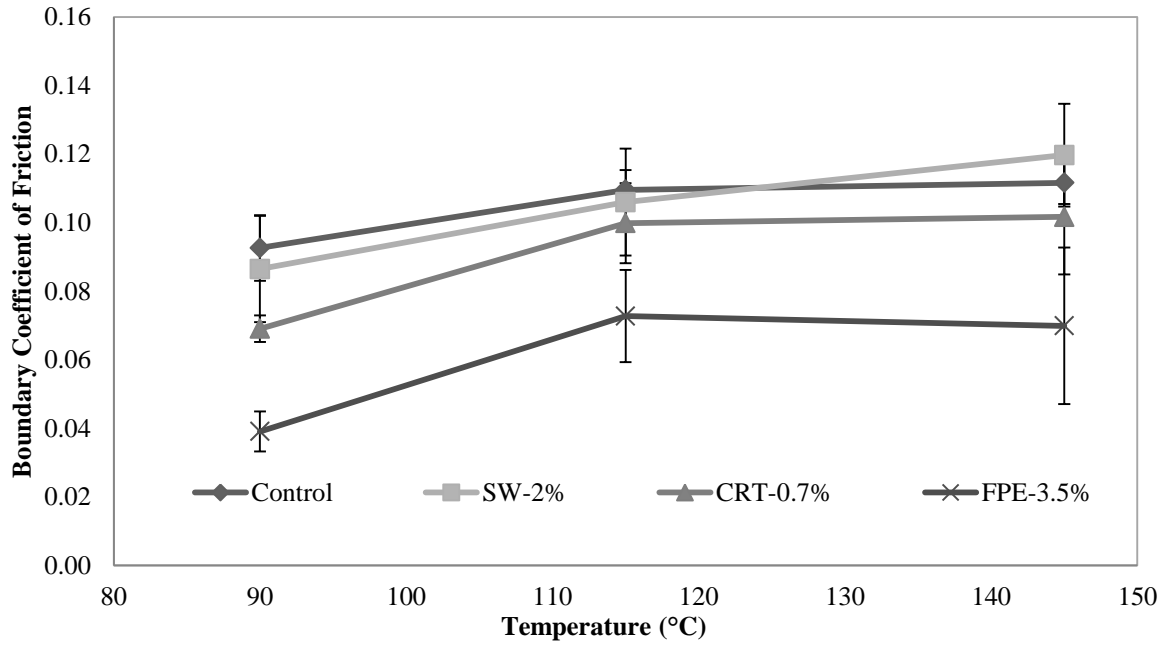


Figure 47 100 kPa Limestone - PG64-22 NuStar (error bars represent 1 standard deviation).

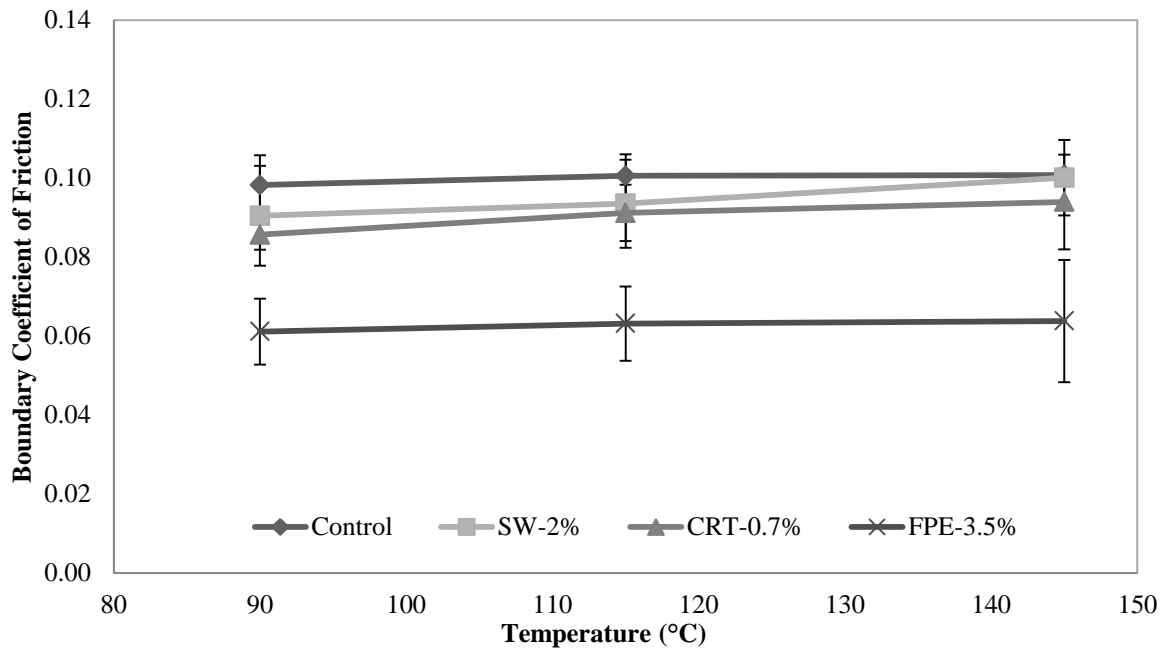


Figure 48 500 kPa Limestone - PG64-22 NuStar (error bars represent 1 standard deviation).

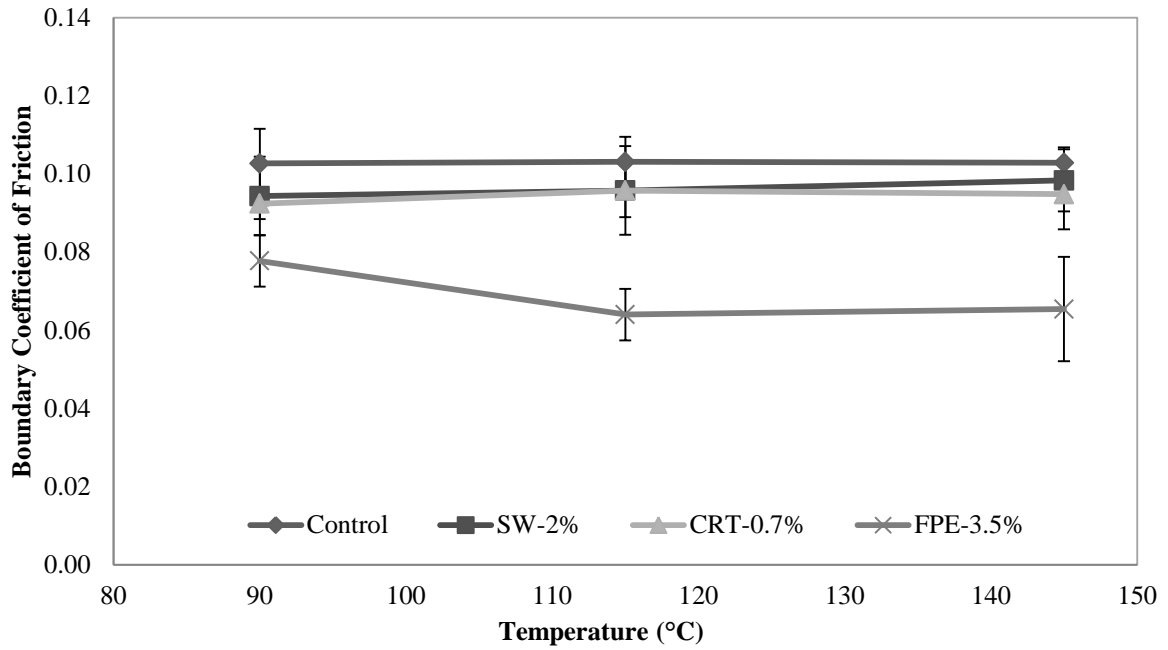


Figure 49 1 MPa Limestone - PG64-22 NuStar (error bars represent 1 standard deviation).

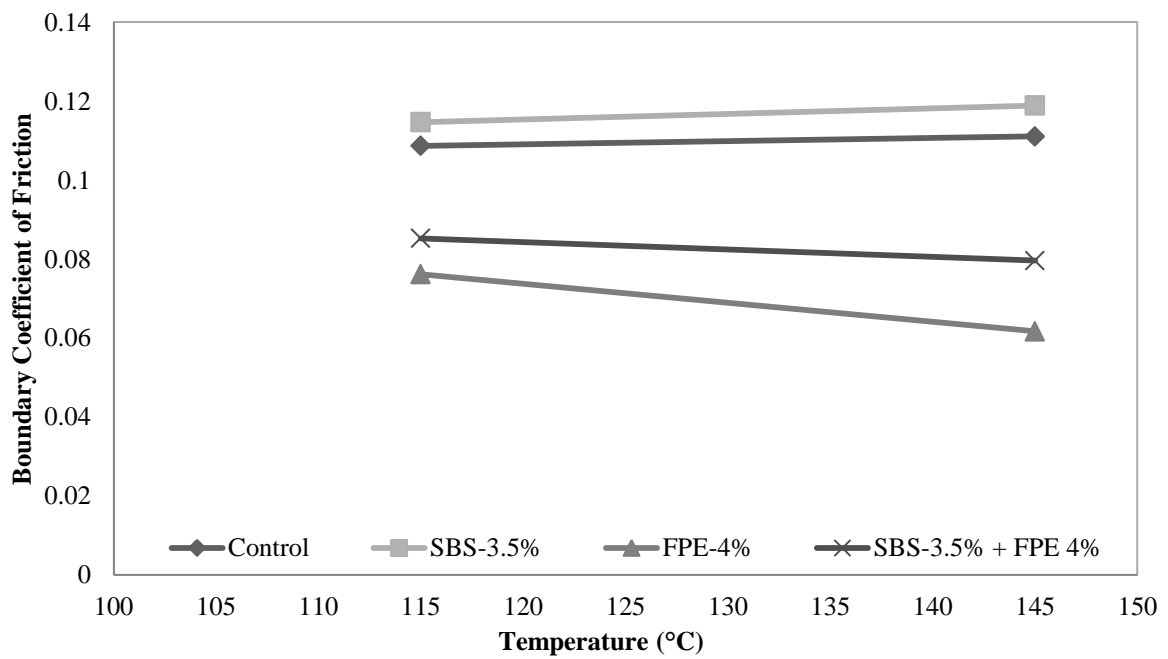


Figure 50 100 kPa Granite - PG64-22 Flint Hills

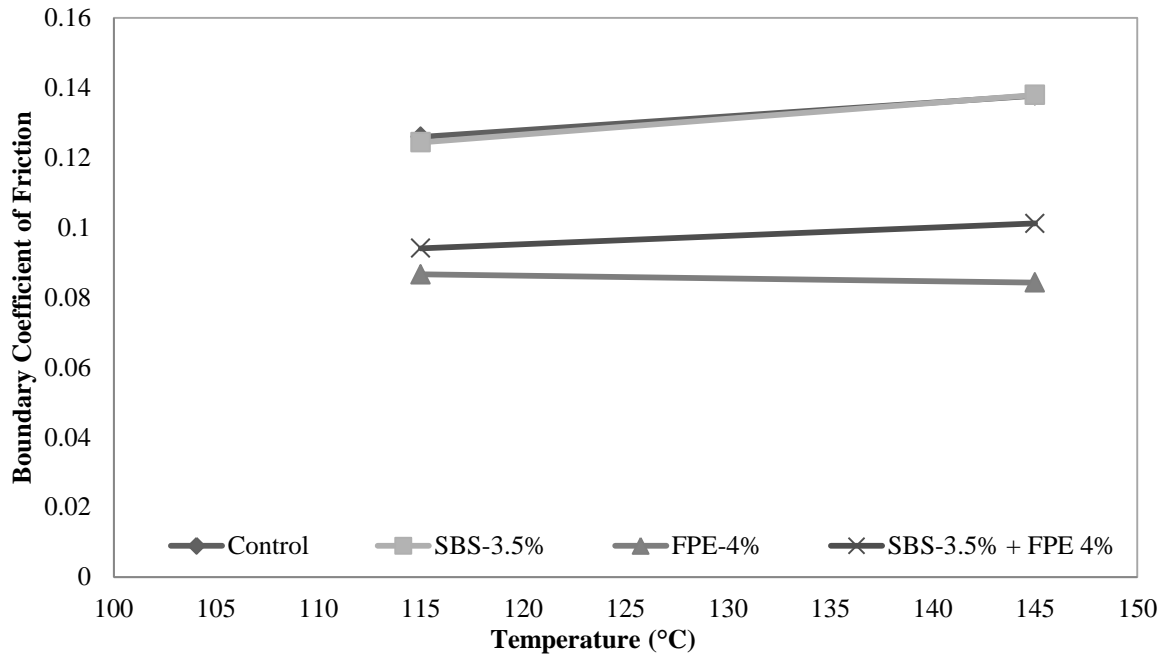


Figure 51 500 kPa Granite - PG64-22 Flint Hills

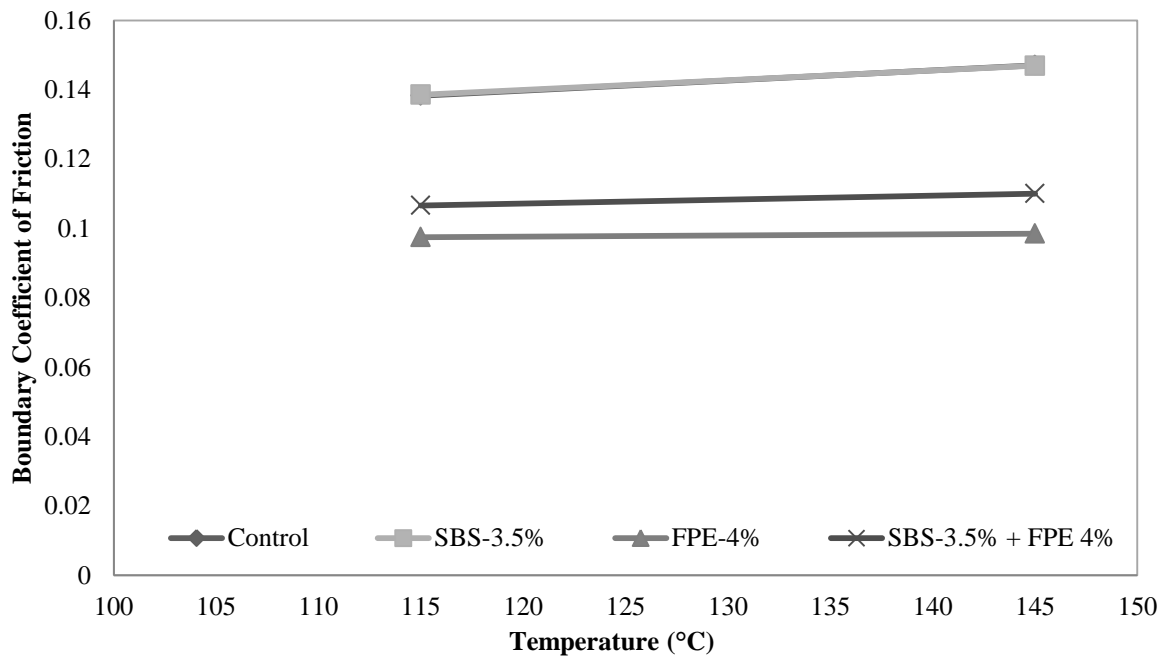


Figure 52 1 MPa Granite - PG64-22 Flint Hills

8.2 Detailed drawings of Asphalt Boundary Lubrication cell.

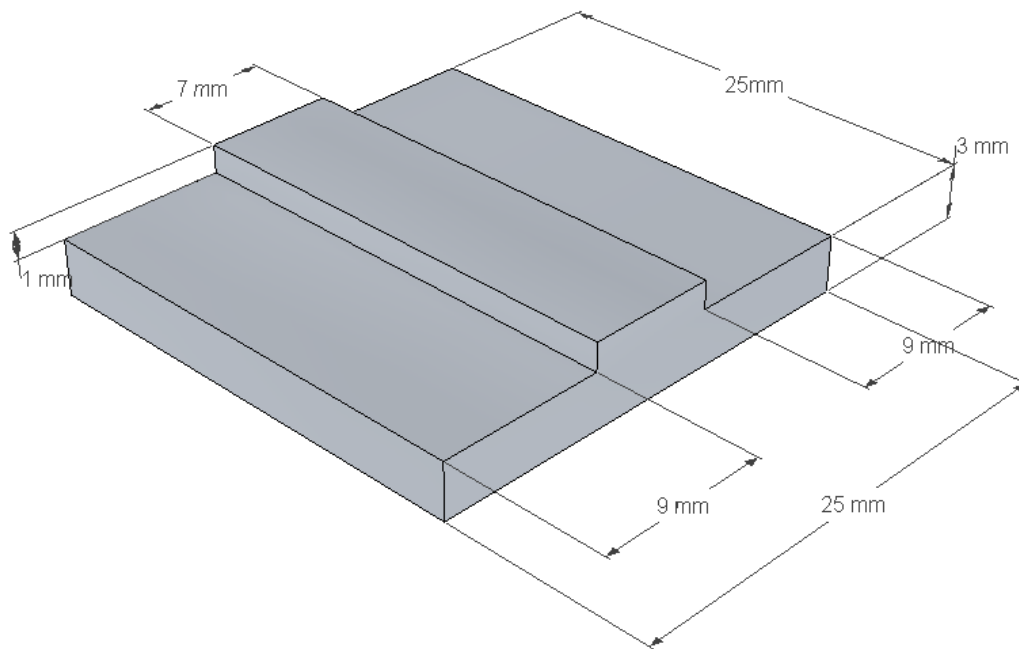


Figure 53 *Swing Pin Platform - Detailed drawing 1*

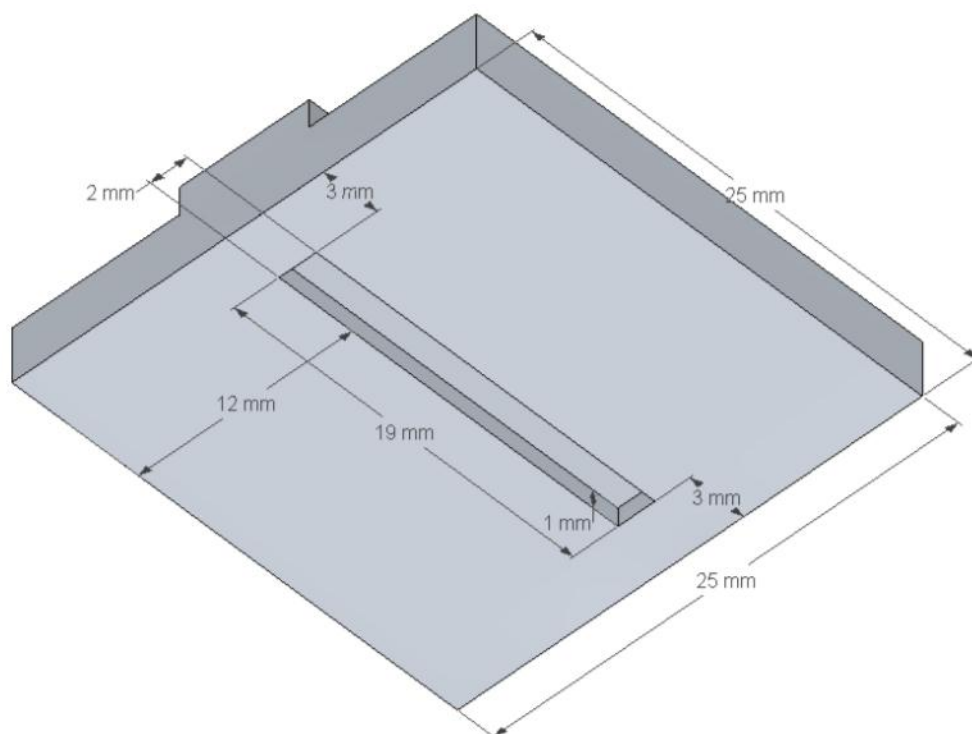


Figure 54 *Swing Pin Platform - Detailed drawing 2*

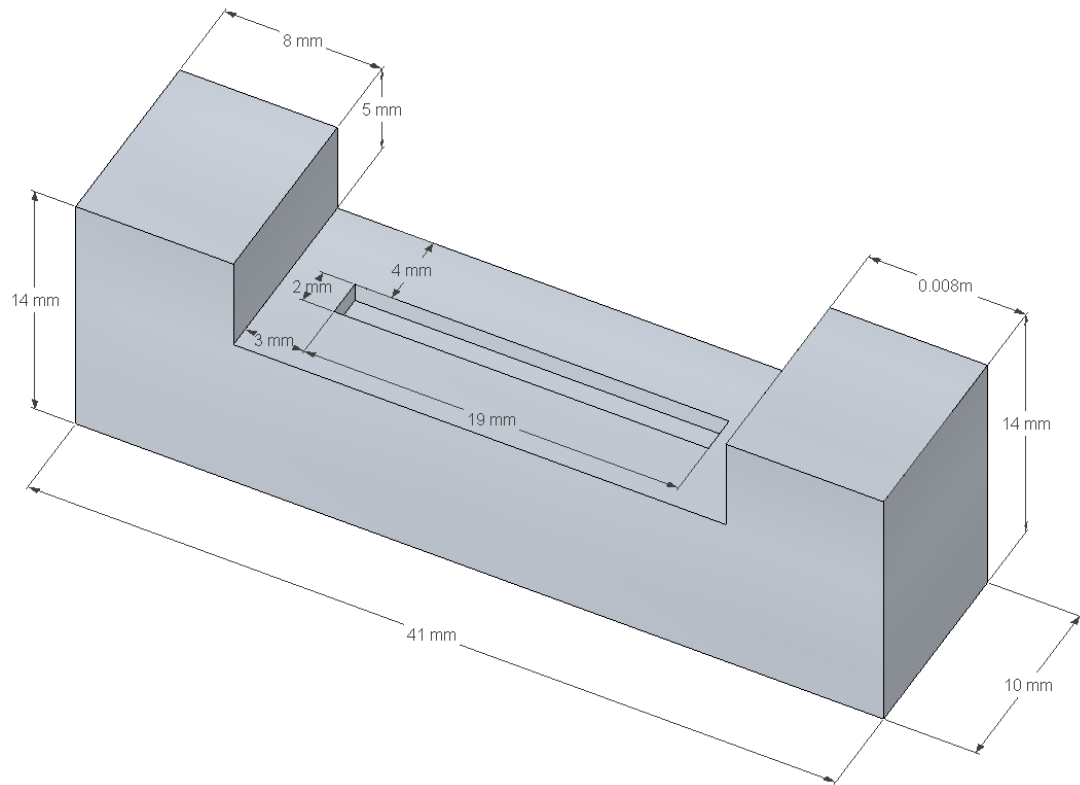


Figure 55 Cradle - Detailed drawing 1

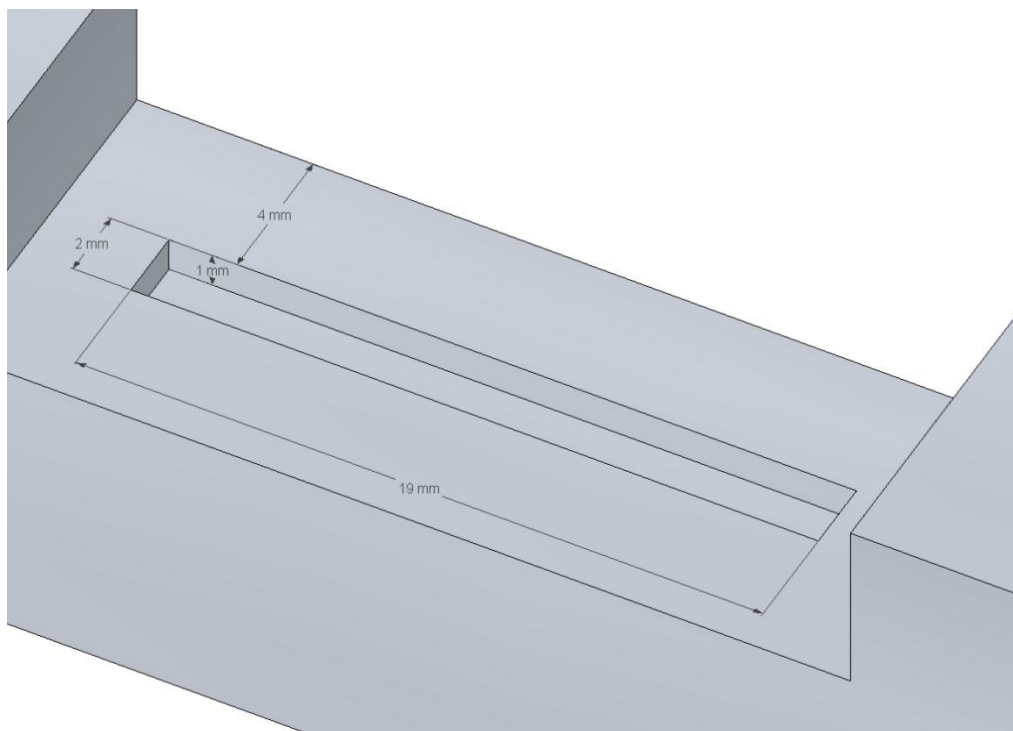


Figure 56 Cradle - Detailed drawing 2

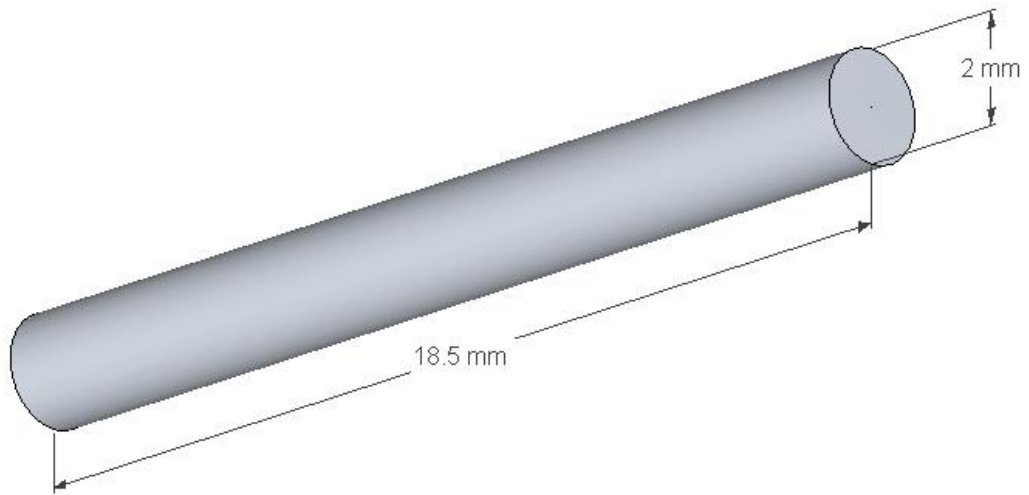


Figure 57 *Swing Piece - Detailed drawing*