Lubricity Properties of Asphalt Binders Used in Hot-Mix and Warm-Mix Asphalt Pavements

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ABSTRACT

The more common science used in determination of a materials coefficient of friction is known as Tribology. Tribiology is defined as the science and technology of interacting surfaces in relative motion, including the study of friction, wear, and lubrication and is derived from the Greek tribo (to rub) and the Latin – logia (study or learning). The coefficient of friction of a material is empirical – it has to be measured experimentally, and cannot be calculated. Rough surfaces like hot-mix aggregates tend to have higher coefficients than smooth surfaces. Boundary fluids (like asphalt binders) can serve to reduce the coefficient of friction of aggregates during production of asphalt mixtures.

Reinke and Baumgardner first introduced the concept of testing asphalt binders in thin films and suggested lubricity and internal friction reduction as a potential explanation of the mechanism allowing production of asphalt mixtures at reduced temperature, warm-mix asphalt (WMA), at the warm-mix technical working group (WMA TWG) in Baltimore, MD, December 2007. Further work in this area was later reported by Hanz, Faheem, Hahmoud and Bahia at the 89th Annual Meeting of the Transportation Research Board, January, 2010.

This paper presents a continuation of the work of Reinke et al. and Hanz et al. moving from gap-dependent rheology to tribology utilizing a standard tribology fixture and new methods for testing asphalt binders with a dynamic shear rheometer. The work consists of evaluations of various asphalts used to produce hot-mix asphalt (HMA)mixtures and the effect they might have on friction characteristics, allowing production of warm-mix asphalt through non-chemical techniques such as foaming; and evaluation of Lubricity Optimized Asphalts™ (LOA) and the effect additives have on friction characteristics in asphalt mixtures produced with LOA asphalt binders.

Keywords: Warm Asphalt Mixture, Rheology, Tribology, Lubricity, Lubricity Optimized Asphalt

1. INTRODUCTION

Warm mix asphalt (WMA) is the generic title given to technologies developed for production and placement of hot-mix asphalt (HMA) at temperatures substantially lower than those conventionally accepted. WMA is typically produced at temperatures that are 20 to 55 C° (35 to 100 F°) lower than conventional HMA, and has been used successfully in all types of asphalt concrete, including dense-graded, stone matrix asphalt, porous asphalt and mastic asphalt over a range of layer thicknesses and traffic loadings [1]. Original speculation was that WMA technologies reduced the viscosity of the asphalt binder to provide complete coating of aggregates at lower temperatures. However, it has been shown that viscosity reduction is not the primary mechanism of WMA and that "lubricity" characteristics of asphalt binders may be the mechanism allowing for reduced asphalt paving temperatures [2,3,4,5,6]. This has prompted research and tribological testing of asphalt binders in thin films, less than 100 microns, as compared to typical bulk rheological binder specification testing thicknesses, of one millimeter and greater.

Tribology, is the science and technology of interacting surfaces in relative motion, including the study of friction, wear, and lubrication, is derived from the Greek tribo (to rub) and the Latin – logia (study or learning) [7]. Friction is the force that resists the relative motion of two solid surfaces in contact with one another. Surfaces of solids, even those that appear smooth are always microscopically irregular. When two such surfaces are in contact under pressure, the peaks, or asperities adhere to one another at an atomic level. When those surfaces move with respect to one another, friction arises from shearing of the adhered junctions, with the frictional force required to shear those adhesions varying dramatically depending on material involved. The ratio of frictional force to the load, known as the "coefficient of friction," is a constant that depends on the material that comprises the surfaces being contacted. The coefficient of friction of a material is empirical – it has to be measured experimentally, and cannot be calculated. Rough surfaces like hot-mix aggregates tend to have higher coefficients than smooth surfaces. Boundary fluids (like asphalt binders) can serve to reduce the coefficient of friction of aggregates during production asphalt mixtures. Relatively recent research has focused on asphalt binders as friction reducing media in asphalt mixtures at typical HMA mixing and compaction temperatures.

Reinke et al. introduced the term "lubricity" as it relates to asphalt binders and a thin film rheological test using a conventional dynamic shear rheometer (DSR) to evaluate the effectiveness of warm mix additives at reduced temperature [2,3,4,5]. The test incorporates modification of an improved tribo-rheometry test geometry for thin film testing developed by Chasen, Kavehpour and McKinley [8,9]. In the test a sample of binder sufficient to perform the thin film rheology test (≈ 1 gram for a 25 mm diameter plate) is placed in a stainless steel cup as shown in Figure 1. Depending on the binder grade being evaluated the test temperatures will vary. Typical test temperatures are on the order of 105°C (221°F), 115°C (239°F), 125°C (257°F) for typical straight run binders but can range as high as 160°C (320°F) for highly polymer modified binders. The cup assembly has been found to be the most utilitarian for this test because the high rotational speeds can spray small amounts of binder onto inner surfaces of the oven or Peltier enclosure. The binder sample is loaded into the cup and brought to the initial gap thickness. For screening purposes, generally four test gaps are used on the same sample for a single temperature. The initial gap is set at 500µm and the steady shear test is performed at rotational speeds of from 1 to 150 radians/sec (0 to 1433 rpm) and repeated at 100 µm, 50 µm and 25 µm gap settings.

Figure 1: Tribo-Rheometry testing fixture and sample loading

Data collected during a test consists of rotational speed (in radians/sec), viscosity (in Pa·s) and normal force (in Newtons). The test outcome for the "Control" binder in this study is shown in Figure 2. Observing Figure 2, it can be seen that as the rotational speed increases the normal force exerted by the binder increases along with resultant torque. The viscosity decreases exponentially with increasing rotational speed and the normal force reaches a peak value. When the temperature is decreased to 110°C there is a sharp breakpoint in the viscosity plot and sharp drop in the normal force and torque after achieving a maximum value. This occurs with most binders at some temperature and rotational speed and appears to be related to the upper plate breaking loose of the binder sample at some rotational speed. Two factors affecting binder performance appear to be the magnitude of rotational speed or shear rate that can be sustained before this slippage occurs and the magnitude of normal force produced by the binder at that shear rate.

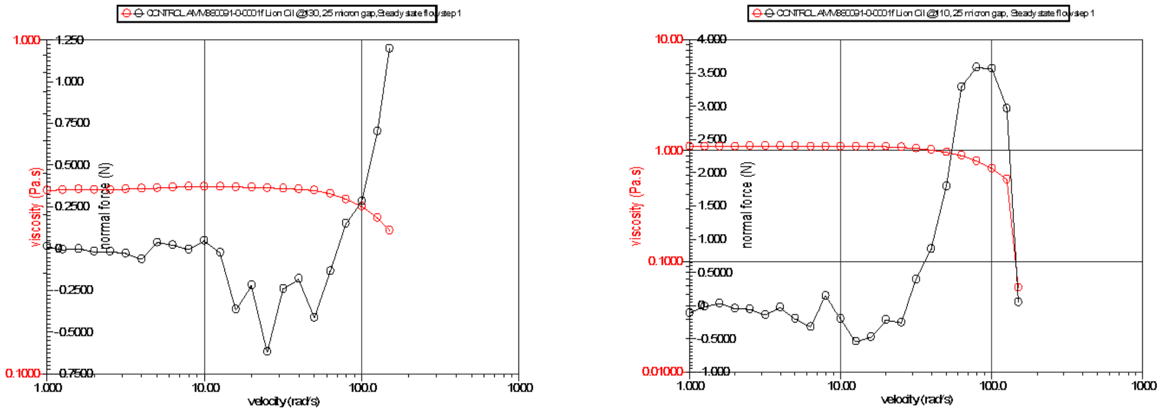

Figure 2: Thin film (25 µm) Tribo-Rheology plot for the "Control" binder @ 130°C (266°F) and @ 110°C (230°F) respectively, Viscosity and Normal Force

Hanz et al. [10], reported a four-ball asphalt lubricity test based on a modified version of an American Society for Testing and Materials (ASTM) test method commonly used to test lubricants [11]. As with [2,3,4,5] a thin film rheological test was employed using a conventional dynamic DSR with a specially designed testing fixture. The apparatus consists of three balls clamped in a cup, with a forth ball held in a chuck which is placed in contact with the three balls, with a sufficient amount of asphalt binder added to produce a film between the chuck and clamped assembly. The four-ball testing fixture is shown in figure 3.

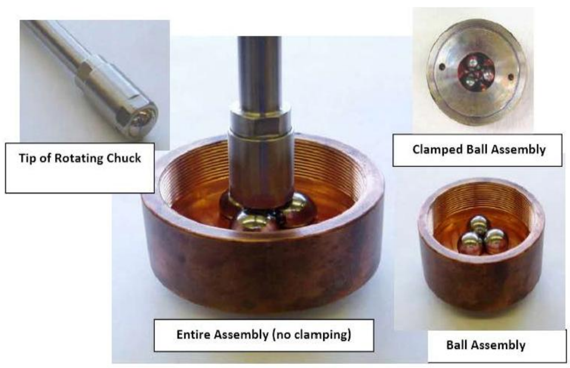

Figure 3: Asphalt Lubricity testing fixture (from Hanz, et al. [9])

The chuck is rotated at a constant shear rate of 50 rpm with the resistance provided by the fixed balls in the cup. The testing temperature ranged from 80 to 100°C (176 to 212°F) and two levels of normal force, 20N and 30N, were selected to ensure that sufficient force was present to maintain contact between the chuck and the clamped balls.

These two methods rely on gap based methods. With [2,3,4] gap dependence is the main variable due to the large contacting surface area of the rotating 25 mm (1 inch) plate and the stationary cup. The method employed by [10] is also gap dependent due to test temperature limitations of from 80 to 100°C (176 to 212°F), which is well below the operating temperature range for production of hot-mix asphalt and most warm-mix asphalt technologies. This paper presents a continuation of the early ground breaking work of [2,3,4,5] and the following related work of [10] by moving from gap-dependent rheology to tribology utilizing a standard tribology fixture and new methods for testing asphalt binders with a DSR.

2. EXPERIMENTAL

2.1 Rheometer

As with the work of [2,3,4,5] and [10] a DSR was used in this study as described by Heyer et al. [12]. An MCR 301 DSR from Anton Paar was used for all tests. The instrument controls the rotational speed and measures the resulting torque very accurately. In addition, torque-controlled measurements are possible by applying a torque and measuring the resulting speed. The normal force can be set and recorded during all tests. The instrument used features the following measurement ranges: rotational speed, 10^{-6} to 3000 rpm; torque, 10^{-7} to 0.2 Nm; normal force, 0.01–50 N.

2.2 Temperature Control

For tribological testing, temperature was maintained by a Peltier controlled bottom plate to which the cup fixture is affixed and an additional Peltier-controlled hood. Accurate temperature is therefore ensured by a combination of conduction and convection heating. The Peltier-controlled hood ensures a uniform temperature distribution within the sample over the whole measurement range. This is crucial since a temperature gradient within the sample will induce misleading results.

2.3 Tribology Fixture

The tribology set-up is based on the ball-on-three-plates principle (or ball-on-pyramid) consisting of a geometry in which a steel ball is held, a cup where three small plates can be placed and a bottom stage movable in all directions on which the cup is affixed. The ball-on-three-plates set-up was previously used by Stehr [13] in a dedicated device to measure static friction coefficients. Figures 4 depicts the tribometer fixture schematically, figure 5 presents photos of the fixture.

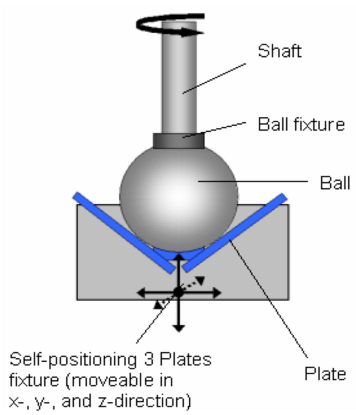

Figure 4: Schematic setup Tribology accessory

Figure 5: Cup and Plated assembly for the Tribology fixture.

Flexibility of the bottom plate is required to ensure that the normal force acts evenly on all the three contact points of the upper ball, the rotating sphere is adjusted automatically, and the forces are evenly distributed on the three friction contacts. An overload of one contact point would result in erroneous friction values. The ball, as well as the plates for the cup, can be exchanged so that the system can be adapted to desired material combinations such as aggregate types used in asphalt mixtures. The rotational speed applied to the shaft is producing a sliding speed of the ball with respect to the plates at the contact points. The resulting torque can be correlated with the friction force by employing simple geometric calculations. The axial force of the rheometer is transferred into a normal force acting perpendicular to the bottom plates at the contact points. The relations between the axial force (F_N) and the torque (M) of the rheometer to the normal force rectangular to the plates (F_L) and the friction force (F_F) experienced by the sample are:

$$F_L = 2(\cos\alpha)(F_N), \quad M = \sin\alpha(F_F)(r_{ball})$$

with r_{ball} being the radius of sphere and α the angle of the plates, respectively. The following dimensions have been used: $\alpha = 45$; $r_{ball} = 6.35$ mm (0.25 inch). Based on the geometrical dimensions, the tribological properties can be calculated:

$$\text{Normal force (N): } F_L = \sqrt{2} \cdot F_N$$
$$\text{Friction force (N): } F_F = M \cdot \sqrt{2}/r_{ball}$$
$$\text{Sliding distance (m) } S_s = 1/\sqrt{2} \cdot r_{ball} \cdot \varphi \; (\varphi\text{: deflection angle in rad})$$
$$\text{Sliding speed (m s}^{-1}\text{): } V_s = 1/\sqrt{2} \cdot r_{ball} \cdot \omega \; (\omega\text{: angular velocity in rad s}^{-1})$$

2.4 Sample Testing

A sample of binder sufficient to perform the tribology test (≈ 1 gram) is placed in a stainless steel cup as shown in Figure 5. As with [2,3,4,5], depending on the binder grade being evaluated, test temperatures may vary. Test temperatures used in the work being reported were 115°C (239°F), 130°C (266°F), 145°C (293°F) and 160°C (320°F). The cup assembly has a cover (not shown in figures) which provides protection from spray of binder onto inner surfaces of the Peltier enclosure at the higher rotational speeds. After the binder sample was loaded into the cup the upper ball was brought into contact with the cup and plate assembly and an applied normal force of 10 Newtons was maintained. The Peltier enclosure was lowered and temperature was allowed to equilibrate. A steady shear test was performed at rotational speeds of from 0 to 150 radians/sec (0 to 1433 rpm).

3. MATERIALS

The primary (control) asphalt binder used in this study was a PG64-22 supplied by Lion Oil Company, El Dorado, Arkansas. Additional binders were also selected from sources that would be considered to have considerably different chemistry and characteristics than the control binder. These binders consisted of a PG64-22 supplied by NuStar Asphalt, Savannah, Georgia, a PG64-16 from Shell Oil Company, Martinez, California and an AR4000 (PG64-16) from San Joaquin Refining, Oildale California.

4. MEASURMENTS AND DISCUSSION

Before discussing measurement results from asphalt binder tribology testing a brief discussion of lubrication and what the data from tribology testing represents will be helpful. This discussion is provided by Anton-Paar via an application note for DSR tribology testing [14]. The Stribeck curve [15] from tribology testing of lubricants can be divided into four areas, Figure 6. At low speeds, in the **boundary lubrication regime (1)** no hydrodynamic pressure has built up in the lubricant due to the movement. Boundary lubrication is lubrication by a liquid under conditions where the solid surfaces are so close together that appreciable contact between opposing asperities is possible. The friction in boundary lubrication is determined predominantly by interaction between the solids and between the solids and the liquid. The bulk flow properties of the liquid play little or no part in the friction behavior.

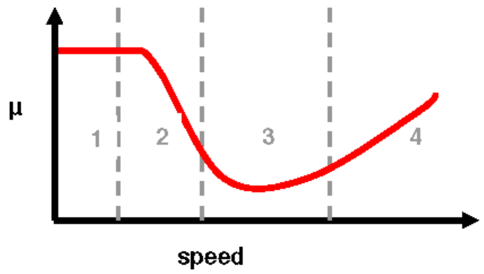

Figure 6: Friction Coefficient vs. Speed

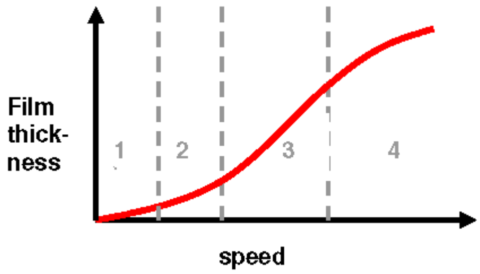

Figure 7: Film Thickness Dependency on Speed

At higher speed in the **mixed regime (2)** the lubricant (asphalt binder) builds up a hydrodynamic pressure so that direct contact between the two bodies is reduced. In the **elasto-hydrodynamic lubrication regime (3)** at intermediate speed a thin lubrication film has built up and at high speed the hydrodynamic pressure is in equilibrium with the normal load so that a thicker lubrication film has formed to separate the sliding bodies from each other Figure 7.

Figure 8 presents the friction characteristics of the steel ball in contact with the steel plates in absence of lubricant in the tribology fixture.

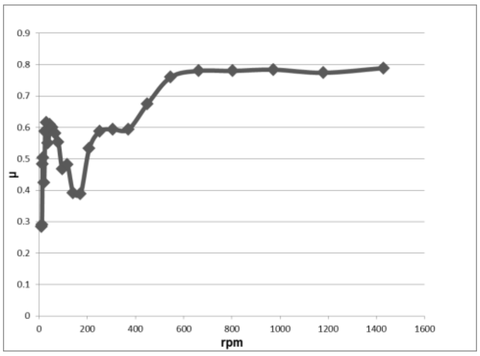

Figure 8: Coefficient of Friction, Steel Ball on Steel Plates

Figure 9 presents graphical data from testing of the control binder. These graphs reveal that the asphalt binder indeed behaves as described in the preceding discussion of expected tribology test results and that asphalt binder is considerably effective at reducing the coefficient of friction of steel surfaces in the testing apparatus. It is apparent from Figure 9 that the asphalt binder behaves primarily in the elasto-hydrodynamic lubrication regime. At the 160°C (320°F) test temperature the asphalt binder appears to show lubrication behavior predominantly in the boundary lubrication regime at the lower shear speeds from 0 to 600 rpm. As the test temperature is decreased the lubricity behavior at these shear speeds trends to the elasto-hydrodynamic regime which may be attributed to both increase of thickness in asphalt film due to shear speed and resultant normal force and an increase in film thickness due to temperature. This is most apparent at the 115°C (239°F) test temperature as the lubricity behavior is almost entirely in the elasto-hydrodynamic regime and may actually be a measurement of film viscosity or laminar flow in the binder as the binder behavior transitions from a lubricant to an adhesive media.

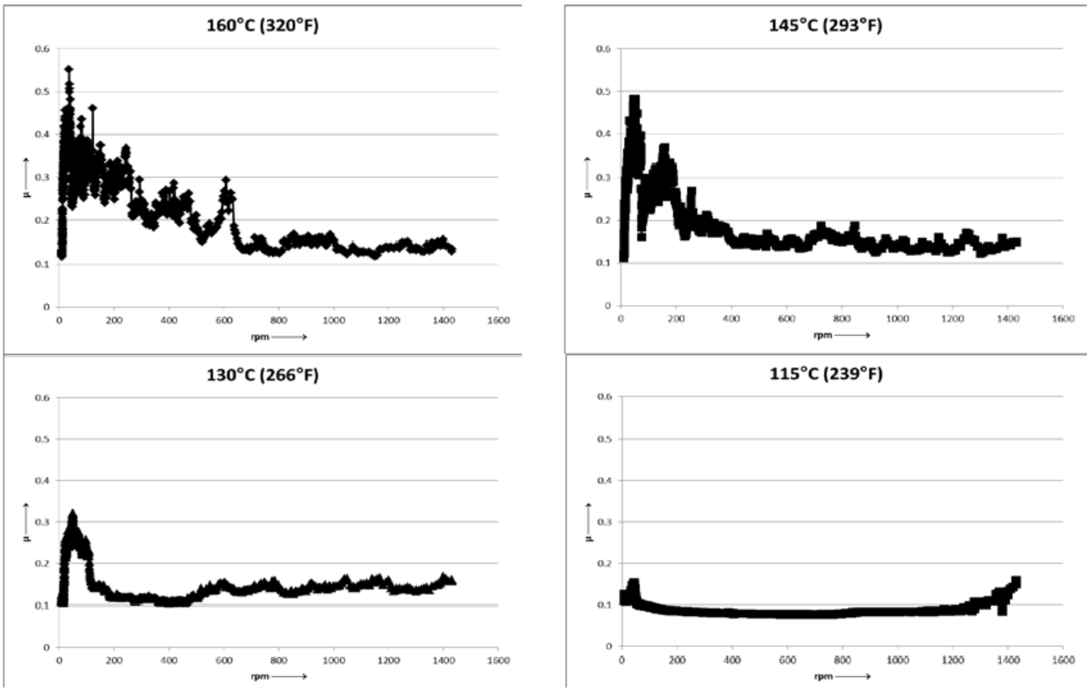

Figure 9: Tribology Results for Lion Oil PG64-22 (Neat) at 160°C, 145°C, 130°C and 115°C

These data are explanatory of WMA technologies that employ foamed asphalt binder as the method for production of WMA mixtures. It appears that foaming may not be the primary mechanism for producing WMA in the plus 135°C (275°F) range as even without foaming or additives the Lion Oil PG64-22 control asphalt or asphalt with similar properties could be used for successful production of WMA in that temperature range. The primary function of foamed asphalt binder may be limited to coating of the bulk aggregate structure. In US Patent 3,868,262, Karl Gunner Ohlson [16] reports a "sequential" mixing method for batch plant mixed asphalt mixtures that divides the bulk aggregate of the mixture into two portions which are coated in sequence of coating of the coarse fraction with the entire binder content with subsequent addition of the finer aggregate fraction for a mixture that shows improved aggregate coating. It should be noted that the aggregate is dry and no added water or damp aggregates are used in this process. Ohlson also reports improved coating of aggregates at bulk binder viscosities in the normal HMA range of 200-500 cSt depending on composition of mineral aggregate and at bulk binder viscosities of as high as 2000 cSt.. While Ohlson does not specifically refer to WMA in [16] it has recently been suggested by the Swedish Transport Administration [17] that the process reported in [16] does in fact enable reduction of mixture temperatures without foaming or the presence of moisture in the aggregates. Successful results applying this method to reduced temperature mixes were also reported by Howard et al. at the 90th annual meeting of the Transportation Research Board 2011 [18]. Methods and results reported by [16, 17, 18] all support that binder lubricity, not foaming, is the primary factor supporting these reduced temperature processes that do not employ additional WMA additives.

In practice, the sequential mixing and foaming approaches conducted at around 135° C (275°F) enable some reduction in mixing temperatures likely because both processes spread the asphalt more effectively than simply adding asphalt at 135°C (275°F) to aggregate and then attempting to get it to coat all of the particles (large and small alike). Since the asphalt is "cool" relative to normal hot mix temperature, coating coarse aggregate as in the sequential mixing process is fairly easy. At this point the elasto-hydrodynamic film is in place not due to shear rate but due to the thicker film of asphalt spread over the surface area of the coarse aggregate. In foaming processes, water injected into asphalt at 135-140°C (275-285°F) will tend to cool the asphalt as the water is converted to steam and the coarse aggregate is more readily coated than the fine aggregate, lack of agglomeration of the fine aggregate is probably indicative of this. Essentially the large aggregate being coated spreads the asphalt to a thick film while additional mixing in the drum enables the fines to coat more readily as they are sheared between the asphalt films on the coarse aggregate. Figure 9 helps make this case in that at 130°C (320°F) and 145°C (293°F) the untreated asphalt binder exhibits all of the lubrication phases. Consequently, asphalt films have to be thinner which is probably why untreated mixes cannot be easily compacted at reduced temperatures. Thicker film mixes (foam, sequential mixing) are lubricated by the thicker layer of asphalt on the coarse aggregate and therefore can be compacted at temperatures below those of normally produced HMA.

Figures 10, and 11 show results from the control binder modified with various WMA chemical additives, 0.5% Sasobit, and 0.5% of two different Evotherm 3G additives. Comparison of results from testing of binder without additives at 115°C (239°F) and 130°C (266°F) to the same binder modified with lubricating chemical WMA additives reveal the impact these WMA additives have on the lubricity characteristics of asphalt binders. It is readily seen that addition of WMA additives alters the lubricity charactistics of the treated binder as compared to those of the untreated binder at elevated HMA temperatures. Figure 10 shows the impact of chemical additives on the ability to provide a complete lubricating effect at 115°C (239°F), similar to the untreated asphalt at 160°C (320°F).

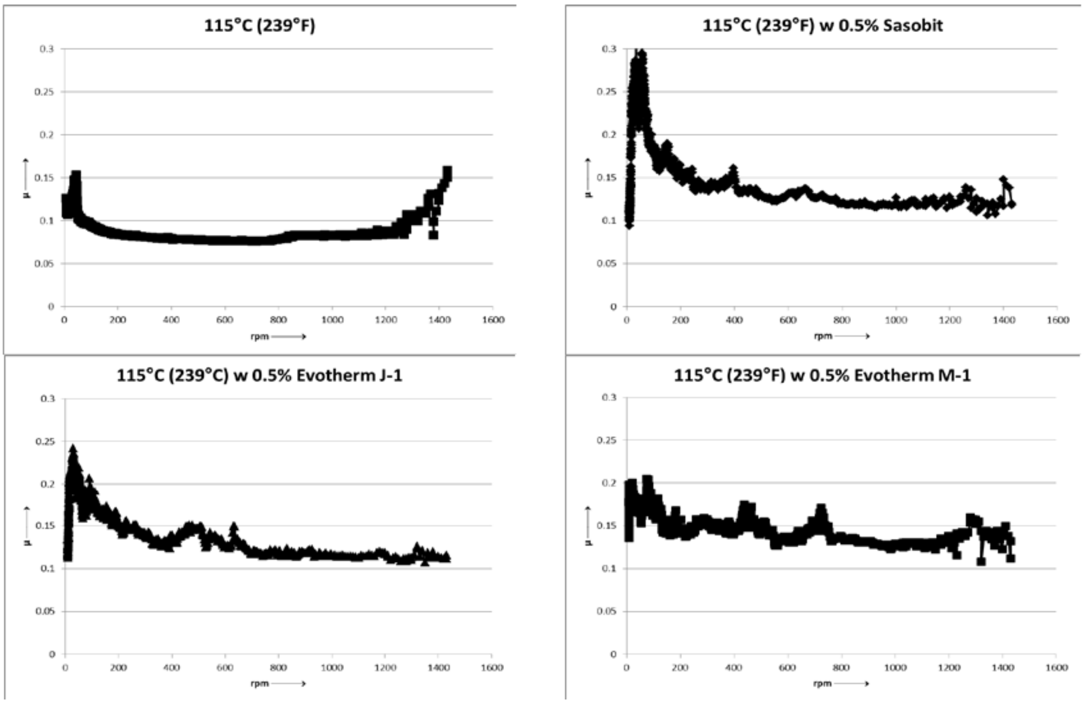

Figure 10: Tribology Results for Lion Oil PG64-22 at 115°C (239°F) Neat, Sasobit and Evotherm

Figure 12 shows the untreated asphalt at 130°C (266°F) with a narrow range of rotational speed when it is in the elasto-hydrodynamic regime and then it quickly move to the hydrodynamic regime at which point it might be very difficult to further coat and/or compact the aggregate particles. The additives evaluated, especially the Sasobit and Evotherm M-1 remain in the elasto-hydrodynamic regime through the end of the test with the Evotherm J-1 showing only a slight increase at the very highest rotational speed.

These data make it clear that while foaming and sequential mixing processes can enable mixing and compaction at reduced temperatures the reason (i.e. thick films on coarse aggregate) is mechanically much different than what appears to be occurring with the addition of chemical additives. Chemical additives, even at substantially reduced temperatures, enable the binder to exhibit the complete range of lubricating characteristics similar to those of the asphalt binder at elevated temperature. From this it is apparent that lubricity optimization or the concept of Lubricity Optimized Asphalt™ [LOA] provides additional improvement of WMA binders beyond that of simple foaming or sequential mixing. An expanded study by [18] on the concept of hot-mixed, warm compacted asphalt mixtures for disaster response is currently underway to evaluate the limits of LOA WMA asphalt mixtures.

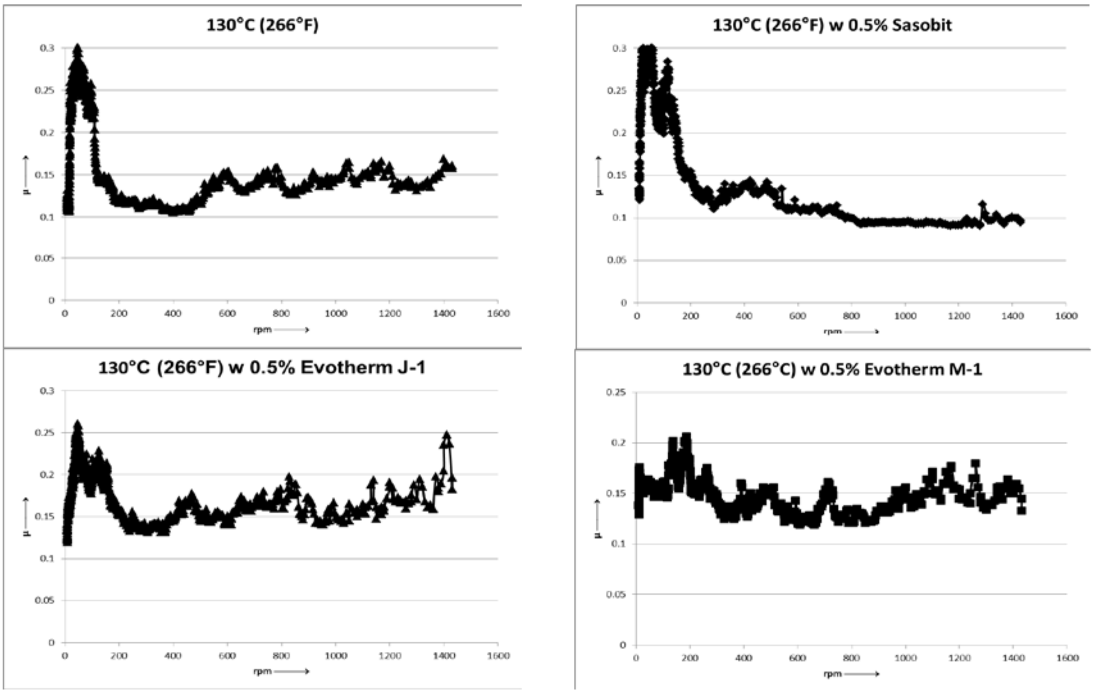

Figure 11: Tribology Results for Lion Oil PG64-22 at 130°C (266°F) Neat, Sasobit and Evotherm

This study focused applicability of tribology testing to primarily the control binder. It has been reported that binders from some sources perform well (with respect to lower WMA mixing and compaction temperatures) in additive WMA technologies but not as well in foamed WMA processes. This is considered to be due to binder source and the contribution the source chemistry may have on lubricity properties, therefore, additional binders from sources known to have different chemistry and performance characteristics in asphalt mixtures were also tested for their specific lubricity character. Figure 12 presents compartive graphs from tribology testing of four binders from this study tested at 130°C (239°F) and 115°C (266°F). These binders are all known to provide substantially lower temperature performance with chemical additive WMA technologies and typical low tempertures (≈ 135°C (275°F)) for foaming technologies, however, the NuStar binder does not generally perform as well in foaming technologies. From the data presented the Lion Oil, Shell Martinez and AR4000 are expected to provide lower compaction temperatures as compared to the NuStar binder. Considering that this binder, from a Venezualan source, is chemically different than the other three binders it is believed that binder source and composition play an apprecialble role in binder WMA performance and that binder chemistry with respect to lubricity is a topic that merits further study. It should be noted that the NuStar binder tends to perform better compared to most binders when chemical additive WMA technologies are utilized.

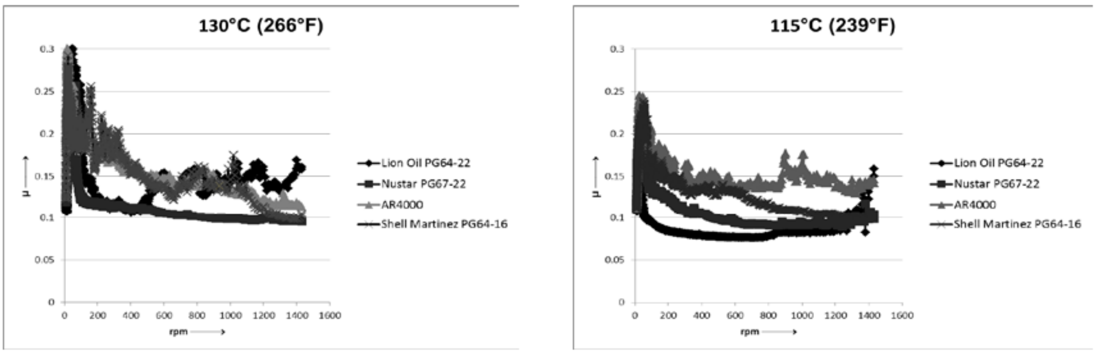

Figure 12: Tribology Results at 130°C (266°F) and 115°C (239°F) for Asphalt from Different Sources

6. SUMMARY AND CONCLUSIONS

Asphalt binder testing in bulk, thick films, is a common practice for grading purposes throughout the world but does not address binder performance in thin films common in asphalt mixtures. The advent and proliferation of WMA technologies has made understanding of asphalt binder performance in thin films necessary in order to understand the mechanisms of WMA binder performance. Thin film testing, tribo-rheology and tribology, has not been commonly used to evaluate asphalt binders. Reinke et al. first reported the concept lubricity and thin film tribo- rheology testing of asphalt binders in 2007, followed by Hanz et al. in 2010 with a method akin to tribological methods. This paper has presented results of a conventional tribology method and fixture, typically used in testing of lubricants, which can be applied to studying asphalt binders and additives used in HMA and WMA technologies.

The tribology procedure and fixture reported here refines and extends the ground breaking parallel plate gap based work of Reinke et al. and the testing temperature/gap dependent work of Hanz et al. Further this work provides a mechanistic explanation for the performance of reduced temperature technologies which rely on sequential mixing or water created foaming procedures in comparison to chemically enabled WMA production procedures. These results support the theory of binder lubricity as a factor in asphalt mixing and compaction at all applicable temperatures further demonstrating dependence on the technology being employed to produce the bituminous mixtures. The fixture described herein is fully adaptable to asphalt binder testing and provides tribological data useful in evaluating binder performance for binders used in asphalt mixtures. This valuable new tool is not only applicable WMA technology evaluation, but may also have merit in determination of mixture and compaction temperatures for asphalt binders used in all asphalt mixtures.

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