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# Investigation of Asphalt Mixtures Compaction Using a Novel Approach Based on Tribology

## Final Report

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Compaction is one of the most important factors that affects the durability of asphalt pavements. Many studies have been focused on developing methods to improve compaction. Previously, the authors found that the addition of small percentages of Graphite Nanoplatelets (GNPs) significantly increase the compactability of asphalt mixture. Traditional viscosity test results show that the increase in compactability is not a result of viscosity reduction, which implies that other mechanisms are responsible for the increase in compactability of GNP modified mixtures. This study investigates the lubricating behavior of the binder. A new test method, referred to as a tribological test, is conducted to evaluate the lubricating behavior of binders modified with different percentages of GNP (0%, 3%, and 6%). To better simulate the roughness of the aggregate surface, the tribological fixture is modified using textured contact surfaces instead of smooth ones. The results of rough surface tribological tests show that the addition of GNPs increases the lubrication behavior of the thin film binder between rough surfaces. It is hypothesized that the increase in compactability can be attributed to the increase in the lubricating behavior of the binder due to the addition of GNP.

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# INVESTIGATION OF ASPHALT MIXTURES COMPACTION USING A NOVEL APPROACH BASED ON TRIBOLOGY

## FINAL REPORT

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# TABLE OF CONTENTS



# LIST OF FIGURES

## LIST OF TABLES

# EXECUTIVE SUMMARY


This study investigates the effect of graphite nanoplatelets (GNPs) on the lubricating behavior of asphalt. Traditional viscosity test results show that the increase in compactability of asphalt mixtures modified with GNP is not a result of viscosity reduction, which implies that other mechanisms, such as lubrication, are responsible for the increase in the compactability of GNP modified mixtures.

Chapter 1 provides a brief background of asphalt mixture compaction and the use of additives to reduce compaction effort.

The mechanism of friction and lubrication is discussed in Chapter 2, and testing methods and a method of analysis based on the Stribeck curve are also presented.

In Chapter 3, the materials evaluated and the test method used are described in detail. Asphalt binders with three different fractions of GNP (0%, 3%, and 6% by weight) are investigated, and both viscosity and tribological tests are conducted. In the tribological testing, both smooth and rough substrates are used. The use of rough surfaces is a novel approach to investigating the lubrication properties of asphalt materials.

The test results are analyzed and discussed in Chapter 4. It is observed that the viscosity of binder increases with the addition of GNP, which confirms previous observations that the increase in compactability of a GNP modified mixture is not related to a reduction in viscosity. The tribological tests on rough substrates show that that the addition of GNP increases the lubrication of binders. This effect is not observed in tribological tests using smooth surfaces that cannot be increased by GNP. It is hypothesized that GNP can improve lubricity through a mending effect, in which GNPs fill the asperities present on the rough substrate and create a smooth film.

# CHAPTER 1: INTRODUCTION

The majority of pavements built in the US are asphalt pavements. The hot mix asphalt (HMA) used to build asphalt pavements is produced in a hot mix plant where aggregates of various sizes are heated and mixed with hot liquid asphalt binder and then moved to the site using trucks. Once the hot mix is poured and leveled per requirements using specialized equipment, it is then compacted to a target air void around 7%. The compaction process is greatly affected by the viscosity of the binder, which increases with a decrease in temperature. In field conditions, the temperature of the HMA drops significantly, thus making the compaction process impossible when the temperature drops below 175$^{o}$F.

To achieve better compaction under field conditions, various additives have been proposed and tested. Le and Marasteanu (2016) observed that the addition of small percentages of graphite nanoplatelets (GNPs) can significantly reduce the compaction effort required to densify HMA. It was thought that the increase in compactability was caused by the decrease in viscosity of binder due to the addition of GNP, while the experiments showed the opposite trend. Adding GNP actually increased the viscosity of binder. This observation implies that a different mechanism should be responsible for the increase in compactability caused by adding GNPs. Le and Marasteanu (2016) concluded that the traditional approach, based on rheological analysis, was not sufficient to fully understand the compaction process of asphalt mixtures. During compaction, the aggregates reorient thus leaving a thin film of asphalt between aggregates. Previous work of Kavehpour and McKinley (2004) has showed that rheology does not apply for thin films. Also, Kavehpour and McKinley pointed out the necessity of using tribology, which deals with friction and lubrication and wear of contact surfaces in relative motion, to investigate thin film behavior. Furthermore, recent work by Professor Canestrari’s research group at Università Politecnica delle Marche in Italy, in collaboration with Nynas, the largest Swedish manufacturer of specialty naphthenic oils and bitumen products, has shown that tribology provides a more complete picture of the binder properties, which helps the understanding of the role of binder in compaction.

The objective of this study is to investigate the lubricating behavior of asphalt binders with GNPs. The goal is to determine if the enhanced workability observed in GNP mixtures is related to binder lubricity. Both viscosity and tribological tests are conducted on asphalt binders modified with GNP to achieve this goal. he tests were performed at the University of Minnesota and at Nynas asphalt binder laboratory in Sweden by a graduate student from the Università Politecnica delle Marche in Italy.

# CHAPTER 2: MECHANISM OF FRICTION AND LUBRICATION

According to the science of tribology, the lubricating properties of a material placed between two solids in relative motion can be described through the so-called Stribeck curve (Figure 2.1(a)), which shows the evolution of the coefficient of friction $\mu$ as a function of the sliding speed (Canestrari et al., 2017; Ingrassia et al., 2018). The variation of the coefficient of friction is due to the change in the thickness of the lubricating film, as shown in Figure 2.1(b). The Stribeck curve can be divided into four regions, corresponding to different regimes of lubrication (Canestrari et al., 2017; Ingrassia et al., 2018):

- the boundary regime (1), that occurs when the lubricating film is thin and therefore a high $\mu$ is determined by the strong interaction between the asperities of the solids;
- the mixed regime (2), in which a reduction of $\mu$ is caused by the increased thickness of the lubricating film, that reduces the direct contact between the solids;
- the elasto-hydrodynamic regime (3), which occurs when the thickness of the lubricating film is able to completely separate the solid surfaces, allowing to reach the minimum $\mu$;
- the hydrodynamic regime (4), where the film is so thick that the variation of $\mu$ depends on the viscous drag of the lubricant.

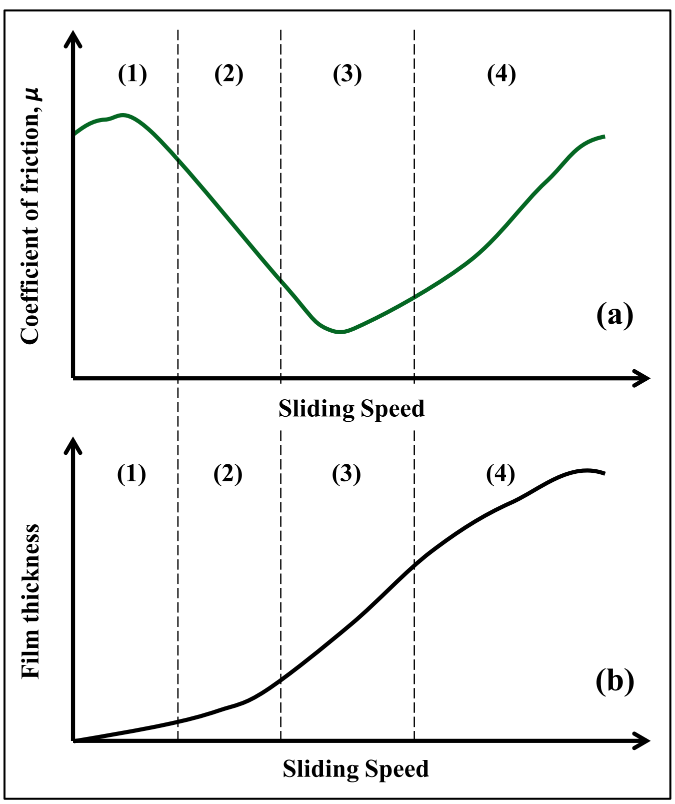


**Figure 2.1 Stribeck curves. (a): coefficient of friction as a function of the sliding speed; (b): film thickness as a function of the sliding speed.**

However, the phenomenon is not governed only by the sliding speed, but also by other important parameters. Friction is not an intrinsic property of the material but of the overall system, which means that it strongly depends also on the nature, surface roughness and wear of the solids in contact (Canestrari et al., 2017; Ingrassia et al., 2018). Such factors may be extremely crucial especially when the lubricating film is not thick enough to separate all solid asperities. Moreover, the thickness of the lubricating film is influenced by the normal load between the two solids and, for thermo-dependent materials such as bitumen, by temperature (Ingrassia et al., 2018).

## 2.1 MECHANISM OF NANOPARTICLES

Although the use of nanoparticles to improve the lubricity of asphalt mix is new to asphalt paving materials, it has been in use in the lubrication industry for decades. Extensive research has been conducted to study the effect of use of nanoparticles, such as graphite as additives to improve the lubricity of lubricants. Various forms of graphite nanoparticles such as nanotubes, flakes, nanofibers, and nanoplatelets continue to be investigated. In the present study, the focus is on graphite nanoplatelets (GNP), and therefore, only previous research on the possible effect of carbon-based nanoparticles, specifically GNP, on lubricity, were reviewed.

The role of nanoparticles in friction reduction has been widely investigated and the mechanism involved can be described as follow: rolling effect (Chinas-Castillo, & Spikes (2003); Wu, Tsui, & Liu (2007), protective film (Zhou, Yang, Zhang, Liu, & Xue (1999); Hu et al. (2002); Rastogi, Yadav, & Bhattacharya (2002), mending effect (Liu, Li, Qin, Xing, Guo, & Fan, 2004) and polishing effect (Tao, Jiazheng, & Kang, 1996). The first two mechanisms belong to the direct effect of nanoparticles on lubrication improvement. The spherical nanoparticles are likely to roll between the frictional surfaces and play the role of ball bearings (Figure 2.2(a)). In addition, the nanoparticles form a thin protecting film on the surface thereby reducing the friction between two surfaces (Figure 2.2(b)). The other two mechanisms are the secondary effect of nanoparticles on surface enhancement. The nanoparticles deposit on the frictional surface forming a tribo-film to compensate for the loss of mass known as mending effect (Figure 2.2(c)). Also, the roughness of the rubbing surfaces is reduced due to the abrasiveness of the hard nanoparticles known as polishing effect (Figure 2.2(d)).

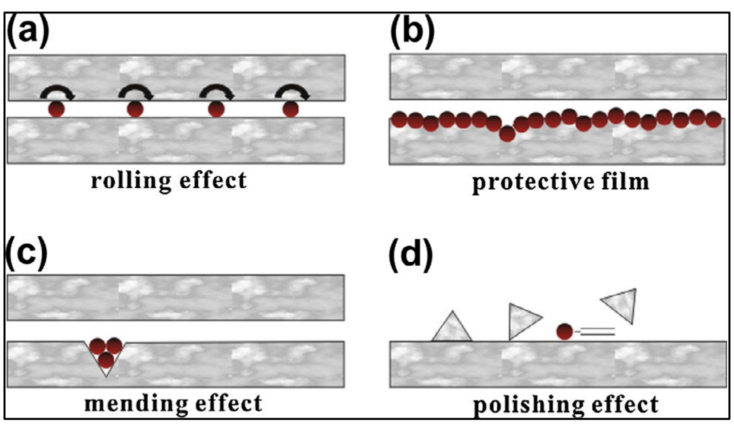


**Figure 2.2 Lubrication mechanisms of nanoparticles: (a) rolling effect, (b) protective film, (c) mending effect, and (d) polishing effect (Lee et al., 2009)**

## 2.2 GRAPHENE & GRAPHITE NANOPLATELETS

Graphene is an atomically smooth two-dimensional material consisting of a single layer of sp2 bonded carbon atoms, i.e., one atomic layer of graphite. Multilayer graphene possesses well established impressive mechanical, thermal, and electrical properties. Also, due to its low surface energy, multilayer graphene has gained popularity as lubricant behavior (Berman, Erdemir, & Sumant, 2014). Its inertness, extreme strength, and easy shear capability and its densely packed and atomically smooth surface are the main reasons for its impressive tribological behavior (Berman et al., 2014). In a test by Berman, Erdemir, & Sumant (2013) on sliding steel surface, they showed that presence of few layer graphene (2-3 layers) between the sliding steel surfaces decreased the coefficient of friction between the surfaces. They attributed the reduction in friction to the formation of a stable tribolayer.

Graphite Nanoplatelet (GNP) are multi-layer particles consisting of 10-30 sheets of graphene (Figure 2.3) that display properties similar to single layer particle properties (Choi et al, 2010 as cited in Nieto, Lahiri, & Agarwal, 2012). When used as an additive to conventional lubricants, even in small amounts it can significantly improve lubricating properties. (Lin, Wang, & Chen, 2011).  Lin et al. (2011) modified GNP to obtain better dispersion of GNP in base oil. They attributed the improvement of lubricating property to small diameter and extremely thin laminated structures which allow GNP to easily enter the contact area and form a protective film preventing contact between the rough surfaces.

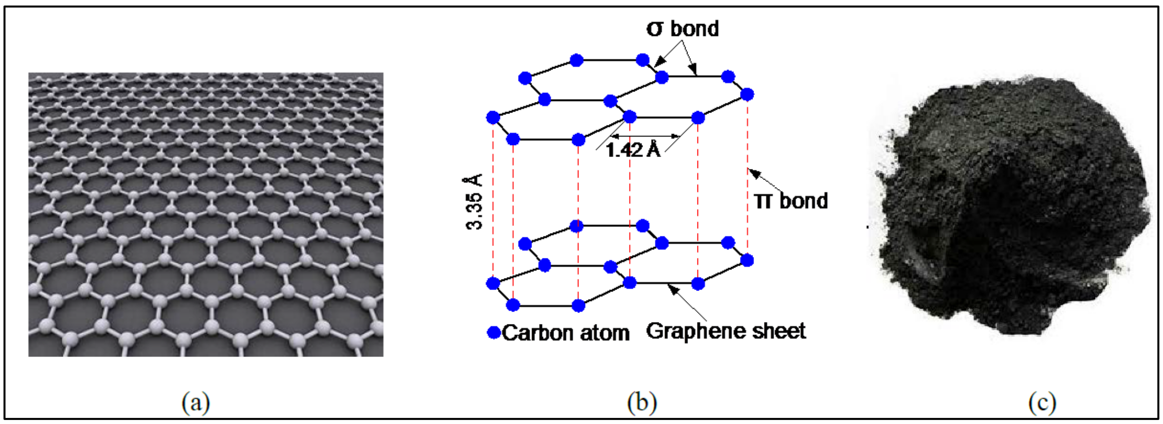


**Figure 2.3 Graphene and graphite nanoplatelet (GNP): (a) graphene sheet, (b) atomic structure of GNP, and (c) as received GNP materials.**

## 2.3 GRAPHITE NANOPLATELETS IN ASPHALT MIXTURES

As mentioned above, previous studies have shown that GNP has excellent lubricating properties when used in lubricating oil. The superior lubricating performance of GNP is attributed to the formation of a tribo-layer between the substrates. GNP can also improve lubricity through a so-called mending effect, by filling the asperities present on rough substrates and creating a smooth tribo-film. It is expected that GNP will behave similarly when added to asphalt binders at mixing and compaction temperature. Previous results obtained by Le & Marasteanu (2016) showed that indeed the addition of small percentages of GNP reduce compaction effort.

# CHAPTER 3: EXPERIMENTAL INVESTIGATION

## 3.1 MATERIALS

In this study, a plain PG58-28 bitumen was used as base binder. GNP made of a synthetic graphite material with 99.66% carbon and 0.34% ash, characterized by an enhanced surface area equal to 250 $m^2/g$ and labeled as “4827”, was added to PG58-28 in two amounts: 3% and 6% by weight of the binder. It is worth emphasizing that the cost of GNPs is comparable to the cost of common polymer modifiers, such as styrene-butadiene-styrene (SBS) (Le et al., 2016).

The control (0%), 3% and 6% blends were prepared at the University of Minnesota using a high shear mixer, and then were stored in 3 oz. cans. Half of the cans were shipped to Nynas in Sweden to be tested and the other half was kept and tested at the U of M.

## 3.2 EXPERIMENTAL METHOD

Tribological tests were performed on the base bitumen and base with GNP binders through a ball-on-three-plates fixture mounted on a Dynamic Shear Rheometer (DSR), as schematized in Figure 3.1. As for the principle of the measurement, the coefficient of friction $\mu$ is determined according to Equation (1):

$$\mu = \frac{F_{F-TOT}}{F_{N,tribo-TOT}} \tag{1}$$

where $F_{F\text{-}TOT}$ and $F_{N,tribo\text{-}TOT}$ are, respectively, the total friction force and the total normal force experienced by the specimen, calculated as in Equations (2) and (3):

$$F_{F-TOT} = 3 \cdot \left( \frac{T}{3 \cdot r_{ball} \cdot \sin\alpha} \right) = \frac{T}{r_{ball} \cdot \sin\alpha} \tag{2}$$

$$F_{N,tribo-TOT} = 3 \cdot \left( \frac{F_N}{3 \cdot \cos\alpha} \right) = \frac{F_N}{\cos\alpha} \tag{3}$$

where $F_N$ is the axial force of the DSR, $T$ the torque, $r_{ball}$ the radius of the ball and $\alpha$ the angle between the plates and the horizontal plane (equal to 45° for the ball-on-three-plates fixture, as in Figure 2.2). As the geometry of the fixture is known, in order to determine the coefficient of friction, it is sufficient to impose the axial force and the rotational speed while simultaneously measuring the resulting torque value.

The experimental investigation also included viscosity tests, which were performed in Sweden using a DSR with a cone-plate fixture, characterized by a radius of 20 mm and a slope of 2°, and at U of M using a Brookfield viscometer.

## 3.3 EQUIPMENT

All tests were carried out using a steel ball and steel plates as substrate. New ball and plates were used for each specimen, in order to avoid the possible influence of wear and therefore, reduce the variables involved in the experiments. During the tests, the axial force was kept constant and equal to 10 N, while the rotational speed was logarithmically increased from 0.1 to 1433 rpm. These testing conditions were selected based on previous experimental work done by others (Baumgardner et al., 2012; Ingrassia et al., 2018). The tribological tests were performed in Sweden using an Anton Paar DSR equipment, and at the University of Minnesota using an AR 2000 DSR, made by TA Instruments.

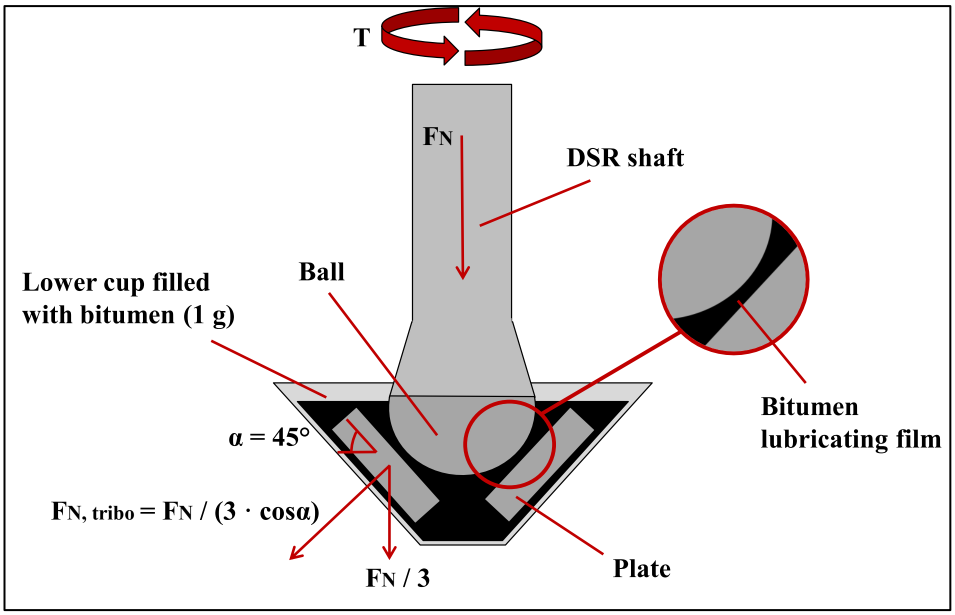


**Figure 3.1. Scheme of the tribological fixture.**

The ball-on-three-plates fixture used in the tribological testing at the University of Minnesota is based on the same concept as the one presented in Figure 3.1 (Canestrari et al., 2017), but the parts are slightly different as shown in Figure 3.2 (a) & (b). The fixture has five different components: a lower cup, three steel plates, a steel ball, a shaft, and a ring to attach the ball to the shaft. The lower cup holds the three plate at angle of 45° and the asphalt sample. The steel ball is attached to the shaft which then gets attached to the DSR head. The same principles discussed above are used to measure the coefficient of friction between the ball and the plates under the presence of binder with and without GNP added to the binder.

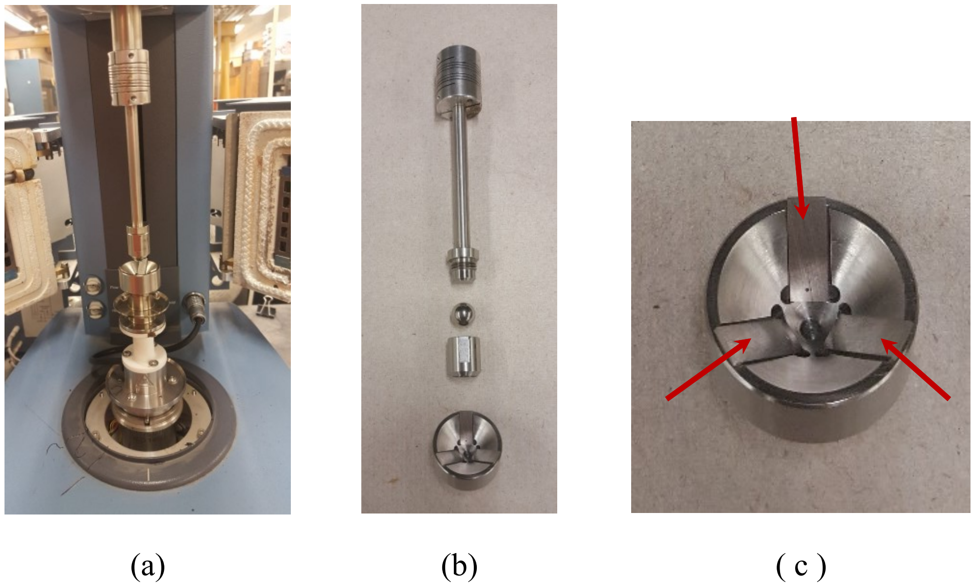


**Figure 3.2 (a): Tribology fixture set up at University of Minnesota pavement lab; (b): components of the tribology fixture; (c) testing plates**

During the first part of this study, the original manufactured geometry was used on both DSR devices, which consists of ball and plates that have shiny and smooth surfaces. All binder samples were tested at 110°C, 130°C and 150°C.

Since the smooth surfaces do not realistically represent the rough surface of actual aggregates in asphalt mixtures, the authors investigated the possibility of obtaining rougher surfaces for the components of the testing fixture. After a number of trials, it was decided to use a simple method that provided relatively consistent results. In this method, the ball and plate were immersed in hydrochloric acid for 3 days. Hydrochloric acid corroded the surface of the parts and made it rougher as seen in Figure 3.3; Figure 3.3 (a) and (b) show the original smooth ball and plate, and Figure 3.3 (c) and (d) present the ball and plate after they were removed from the acid.

All rough surface samples were tested at 130°C. The rationale of conducting the test at 130°C was that this the closest temperature at which the asphalt mix is typically compacted. New ball and plates were used for each specimen for each set of substrates to avoid the possible influence of wear on the experiments. During all of the tests, the axial force was kept constant and equal to 10±0.1 N, while the rotational speed was logarithmically increased from 0.01radian/sec (≈ 0.1 rpm) to 150 radian/sec (≈ 1433 rpm).

The tests were performed according to the protocol previously developed by Ingrassia et al. (2018), which is summarized below. Some modifications were made to accommodate the difference between the DSR at the University of Minnesota and the one used by Ingrassia et al. (2018).

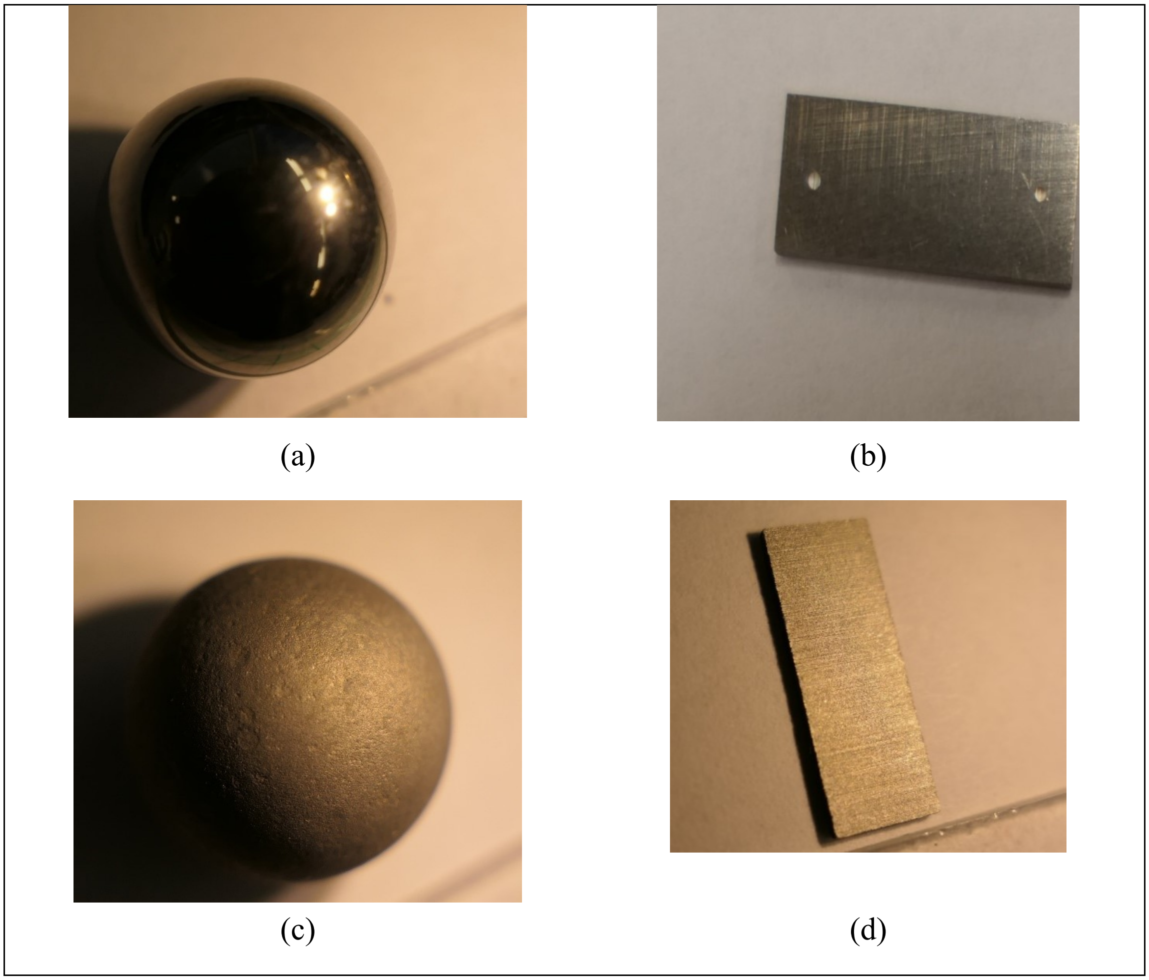

Figure 3.3 (a): smooth ball; (b): smooth plate (used); (c): rough ball; (d): rough plate

The tests were performed according to the following protocol:

1) Turn on the DSR and set the testing parameters and the testing temperature.
2) Pour a specimen of bituminous binder of 1 g in the lower cup with plates already in it.
3) Mount the lower cup and the shaft with the steel ball on the DSR.
4) Keeping the axial force equal to zero, lower the shaft and the hood of the DSR and maintain this condition for about 10 minutes to stabilize the temperature.
5) Gradually increase the axial force until reaching the testing value.
6) Leave the specimen for 1-2 minutes keeping the axial force equal to the testing value to relax the stresses produced by the applied load.
7) Perform the test by increasing the rotational speed within the testing range.
8) Rest the specimen for 1-2 minutes and then start a new replicate on the specimen (as described in phase 6);
9) Repeat four more times phase 7, for a total of six replicates on the specimen.
10) Two specimens should be tested for each binder.
11) At the end of the test, dismount and clean the ball, the plates, the shaft and the lower cup.

# CHAPTER 4: EXPERIMENTAL RESULTS AND ANALYSIS

## 4.1 VISCOSITY RESULTS

Viscosity measurements were performed using two different methods: Brookfiled viscometer equipped with the standard SP 27 spindle (University of Minnesota) and DSR cone and plate geometry (Nynas).

Figure 4.1 shows the viscosity results obtained with the Brookfield Viscometer. The shear rate, in $s^{-1}$, is calculated as the RPM multiplied by 0.34, according to the manual of operation. All samples were tested at 110°C, 130°C, and 150°C, respectively. As expected, viscosity decreases with the increase in temperature. The addition of GNP increases viscosity at all temperatures compared to the base binder, which, without considering other mechanisms, would indicate an increase in compaction effort, which is the opposite of what was observed.

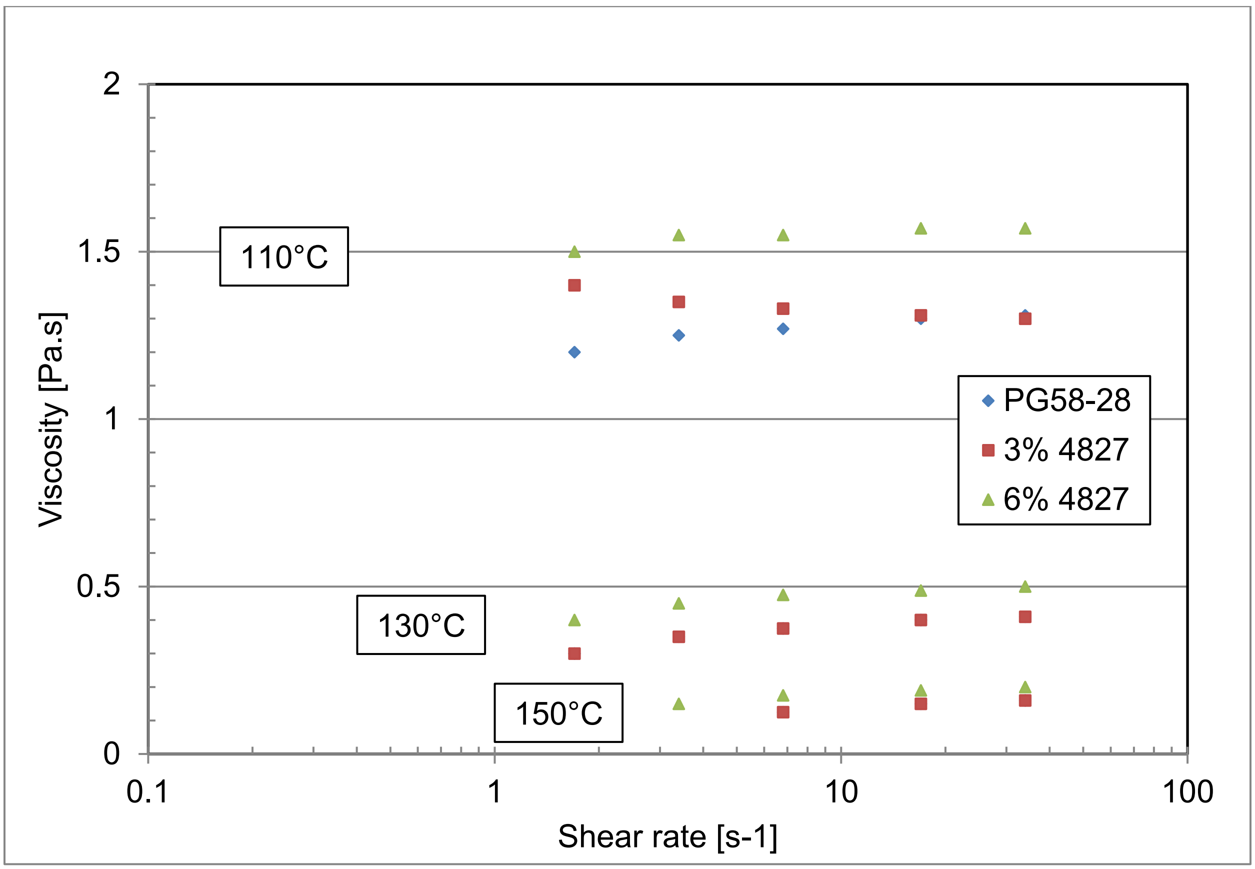


**Figure 4.1 Brookfield viscosity of binders tested**

Figure 4.2 shows the results of the viscosity tests performed with the cone and plate geometry. Similar trends with the Brookfield data are observed.

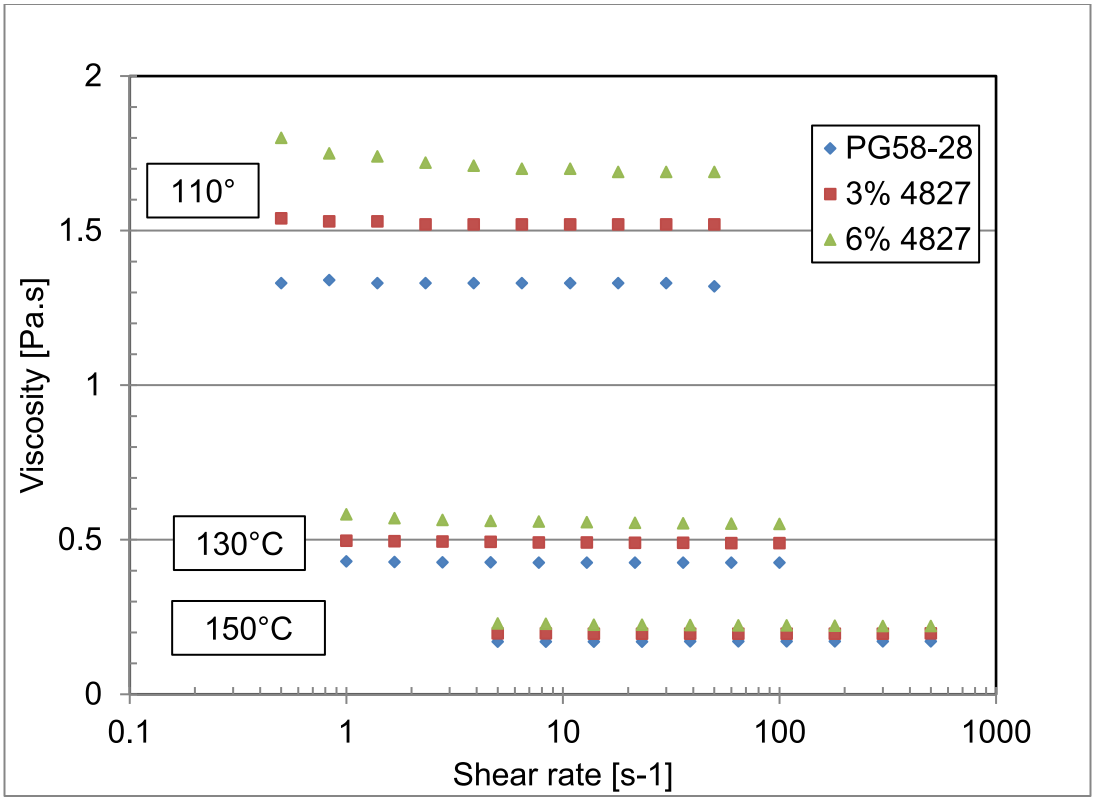


**Figure 4.2 Cone and plate viscosity of the binders tested.**

Table 4.1 summarizes the average viscosity values at 110°C, 130°C and 150°C, at which Newtonian behavior could be broadly assumed for all binders. The addition of GNPs leads to an increase in viscosity with respect to the base bitumen, which is approximately equal to 15% and 30% for the binders with 3% 4827 and 6% 4827, respectively, at all testing temperatures. These results indicate that the improvement in the workability of GNP mixtures, observed by Le & Marasteanu (2016), cannot be explained by a viscosity reduction.

**Table 4.1 Average viscosity values of binders tested [Pa.s].**

| Temperature [°C] | PG58-28 (control) | | 3% 4827 | | 6% 4827 | |
|---|---|---|---|---|---|---|
| | Brookfield | Cone & plate | Brookfield | Cone & plate | Brookfield | Cone & plate |
| 110 | 1.28 | 1.32 | 1.35 | 1.52 | 1.57 | 1.69 |
| 130 | 0.375 | 0.43 | 0.4 | 0.49 | 0.48 | 0.55 |
| 150 | 0.155 | 0.17 | 0.16 | 0.20 | 0.19 | 0.22 |

## 4.2 TRIBOLOGY RESULTS USING SMOOTH SURFACES

The tribological tests results are shown in Figure 4.3,Figure 4.4Figure 4.5Figure 4.6Figure 4.7Figure 4.8, where data were obtained as the average of at least eight replicates, namely four consecutive replicates on each specimen tested. Specifically, according to the protocol by Ingrassia et al. (2018), the first replicate on the specimen was considered as a "pre-run" to allow the formation of the lubricating film (see Figure 2.2) and therefore was discarded. At 110°C, the boundary (1), mixed (2) and elasto-hydrodynamic (3) regimes are identified at very low, intermediate and high speeds, respectively (Figure 4.3). As the temperature increases, the same lubrication regimes are observed for progressively higher values of speed (Figure 4.4 Figure 4.5), because of the lower viscosity of the binder. Moreover, an obvious lubrication improvement is achieved by the decrease in temperature, since the values of $\mu$ are between 0.08 and 0.22 at 110°C, between 0.06 and 0.18 at 130°C, and between 0.05 and 0.16 at 150°C.

Similar trends were observed from U of M test data. Figure 4.6, Figure 4.7, andFigure 4.8 show the results at 110, 130, and 150°C, respectively.

As for the comparison between the binders, a general increase of the coefficient of friction is observed for all temperatures and lubrication regimes after the addition of GNPs. Specifically, the binder with 3% 4827 tends to exhibit intermediate values of $\mu$ between the control bitumen and the binder with 6% 4827. These trends indicate that, for the testing conditions considered, GNPs do not seem to improve the lubricating properties of the base bitumen. It is worth noting that, in general, the differences between the binders seem to be reduced by the increment of temperature. Furthermore, at 150°C, all binders tend exactly to the same value of $\mu$ for low speeds, probably because under these conditions the lubricating film is so thin that friction is almost entirely determined by the substrate.

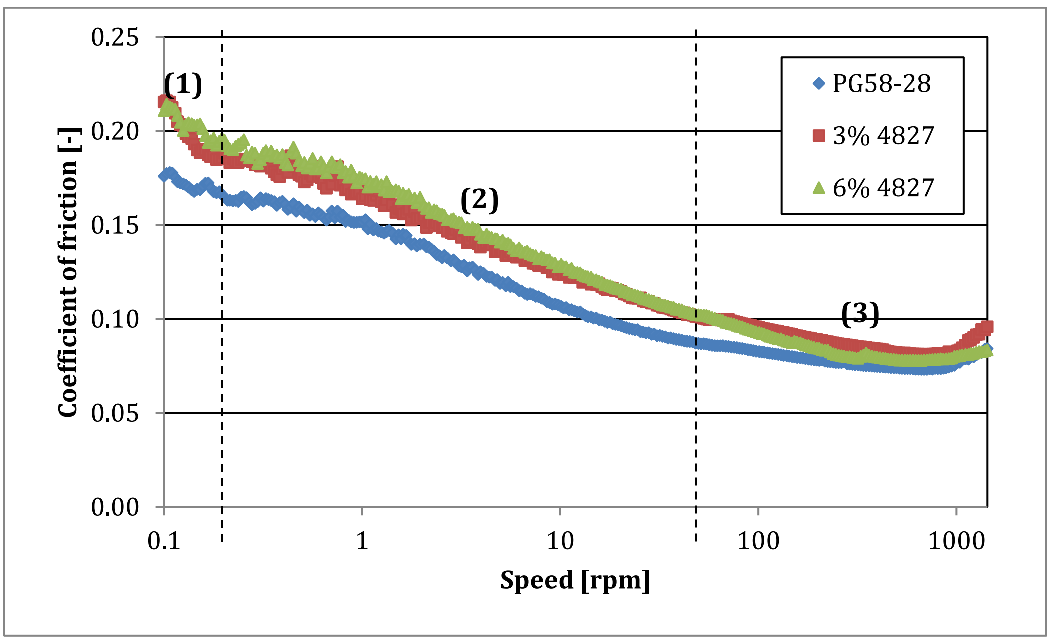


**Figure 4.3 Tribological results at 110°C.**

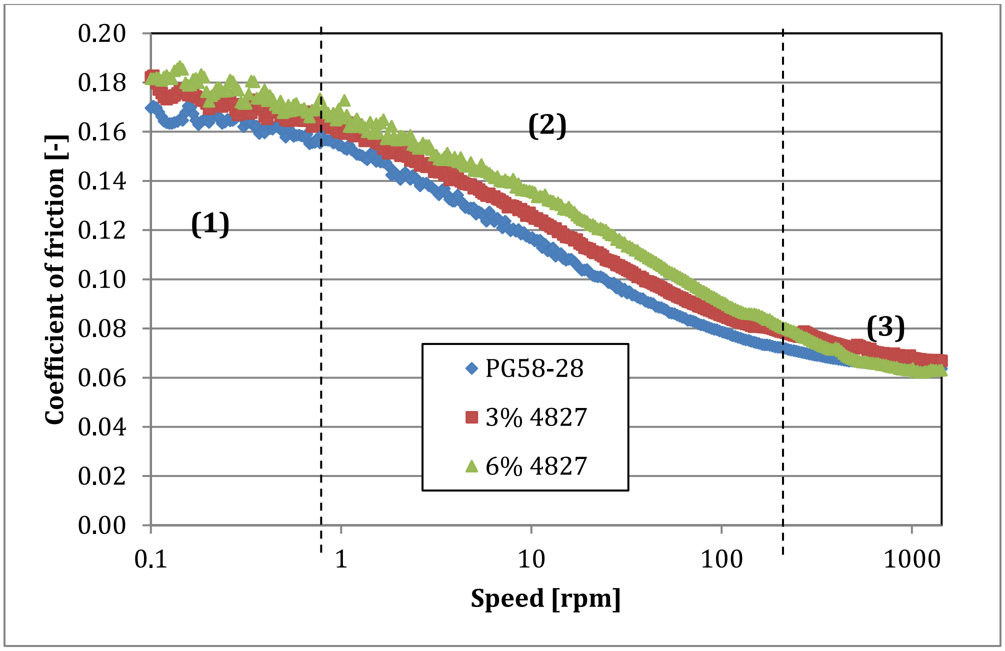


Figure 4.4 Tribological results at 130°C.

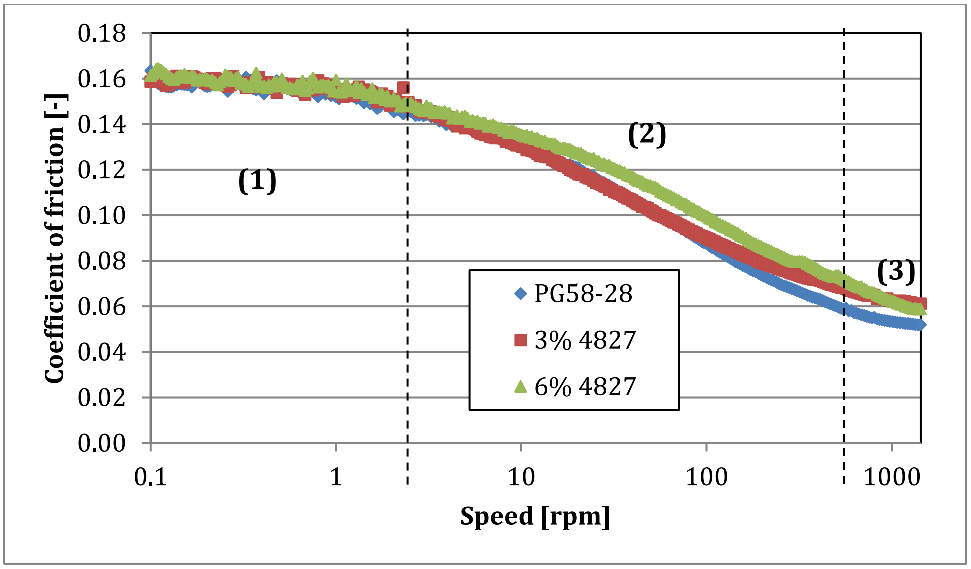


Figure 4.5 Tribological results at 150°C.

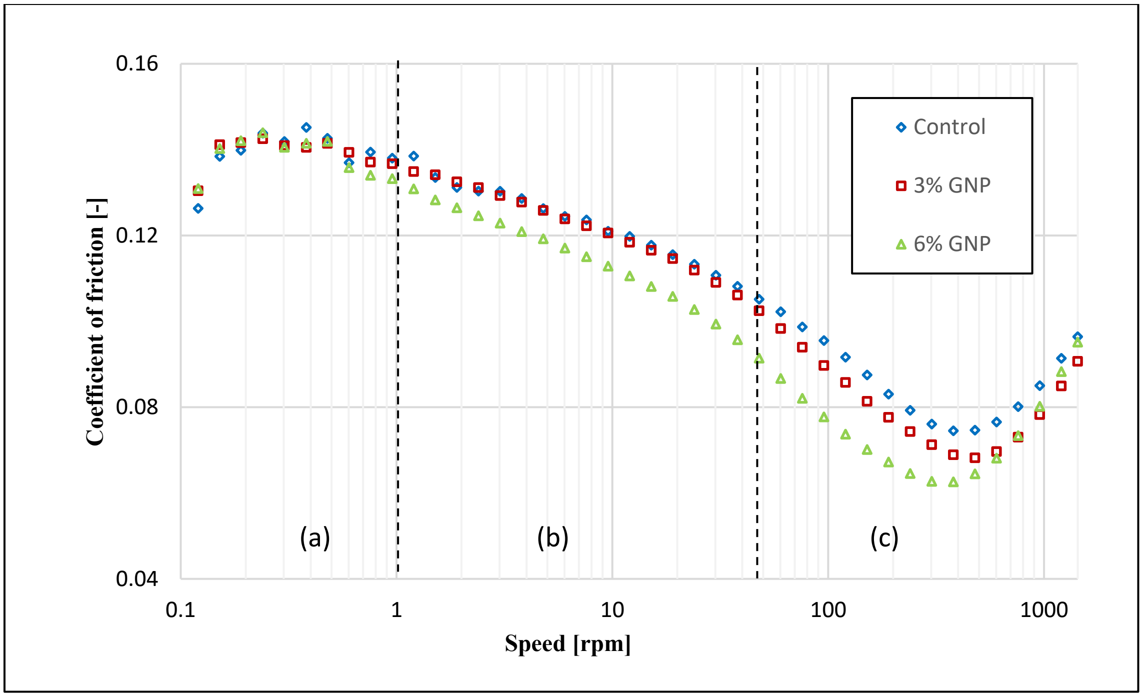


**Figure 4.6 Tribological results at 110°C (U of M)**

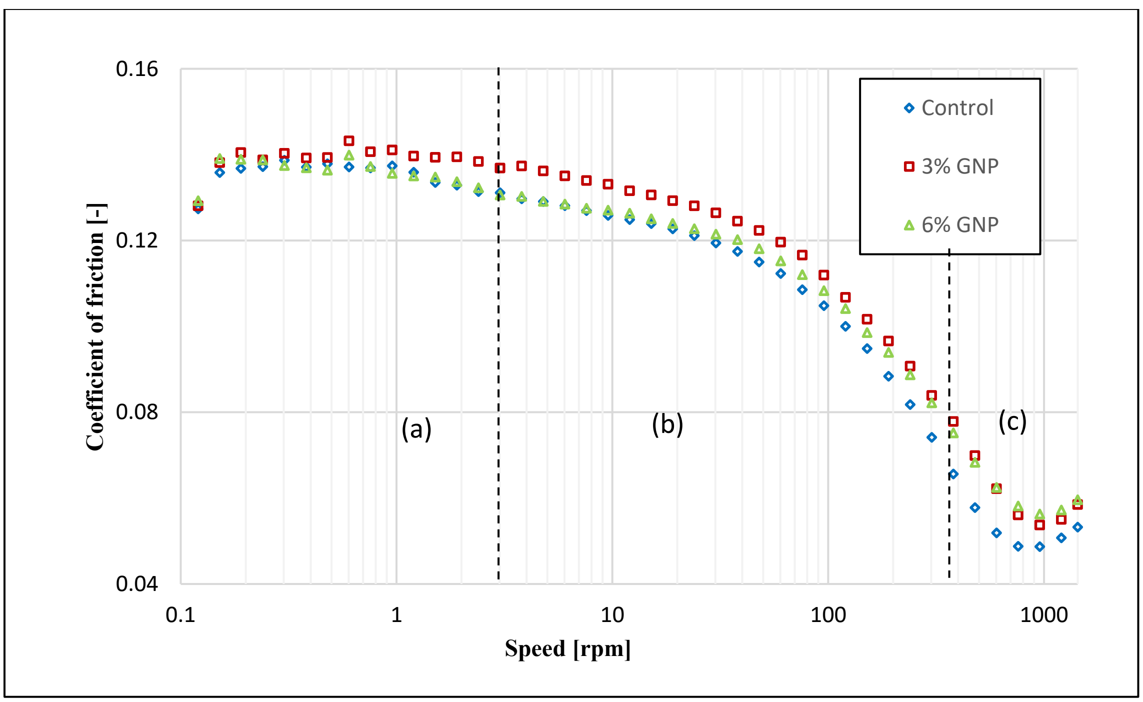


**Figure 4.7 Tribological results at 130°C (U of M)**

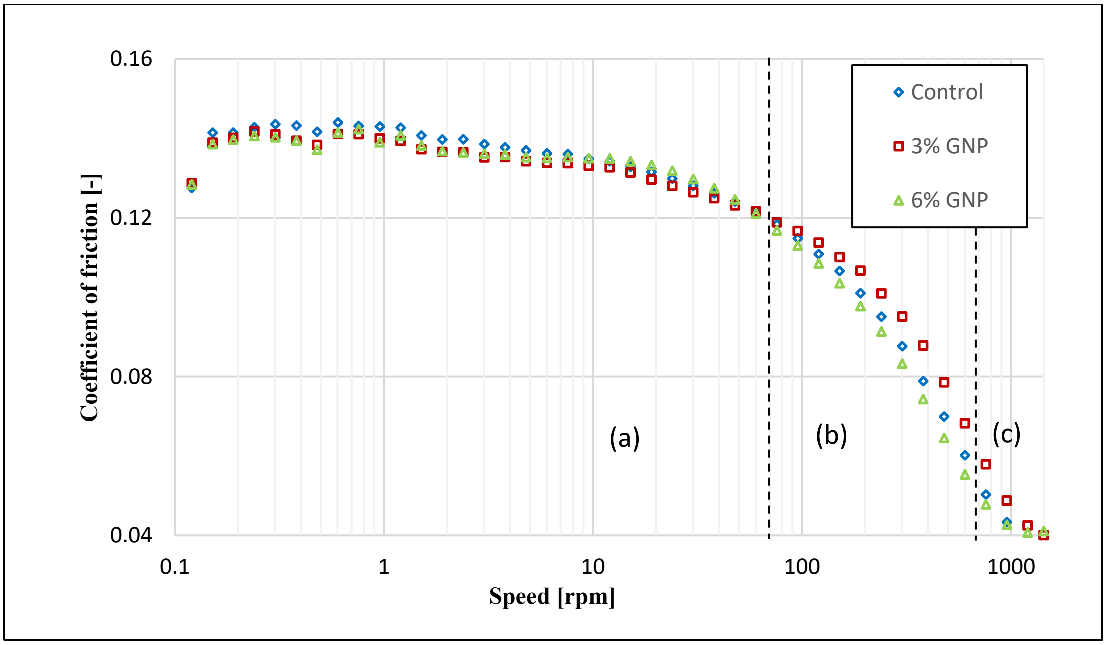


**Figure 4.8 Tribological results at 150°C (U of M)**

Figure 4.9 shows the correlation between the viscosity and the minimum coefficient of friction measured in the elasto-hydrodynamic regime (3) for all binders and testing temperatures. The high value of the coefficient of determination $R^2$ indicates that in the elasto-hydrodynamic regime (3) the lubricating behaviour of the material is mainly determined by its viscosity, in accordance with previous results by Ingrassia et al. (2018). Therefore, given the viscosity values obtained for the binders tested (Figure 4.1, Figure 4.2 and Table 4.1), the potential lubrication improvement provided by GNPs cannot occur in this regime. Moreover, it is unlikely that during mixing and compaction a thick film of bitumen completely separates aggregates, because of the high working temperatures.

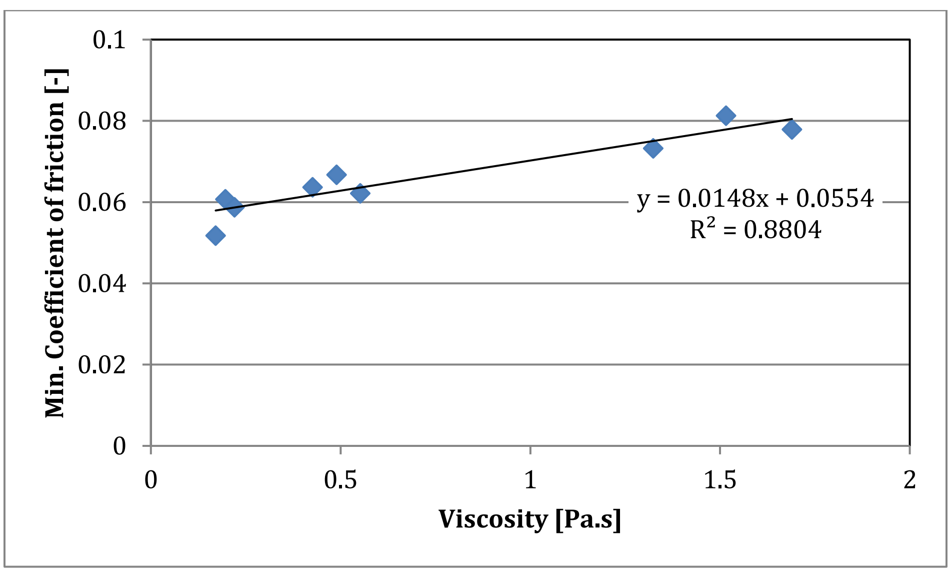


**Figure 4.9 Correlation between minimum coefficient of friction and viscosity**

For these reasons, a possible reduction of friction due to GNPs should be sought in the boundary (1) and mixed (2) regimes of lubrication, in which, the influence of the substrate is considerable.

## 4.3 TRIBOLOGY RESULTS USING ROUGH SURFACE

To simulate the rough aggregate surfaces, tribological tests with rough substrates were performed at U of M. Different trends were shown in these test compared with the smooth substrates tests. As shown in Figure 4.10,Figure 4.11, andFigure 4.12, at all of the three temperature levels, the coefficient of friction was reduced for the binders mixed with GNP during the boundary and mixed regime, and it was the same for all mixes once the shear velocity increased to elasto-hydrodynamic regime.

That can be explained by the lubrication mechanism of nanoparticles (presented previously in Chapter 2), and at the same time elucidates the significantly reduced compaction effort observed in the GNP modified mixtures.

During the compaction process, the aggregates move with a small relative speed, which is comparable to the boundary and mixed velocity regime of this test. As a result, the nanoparticles stored on the aggregates' rough surface which mended the roughness and thus improves the compaction properties of the hot mix asphalt.

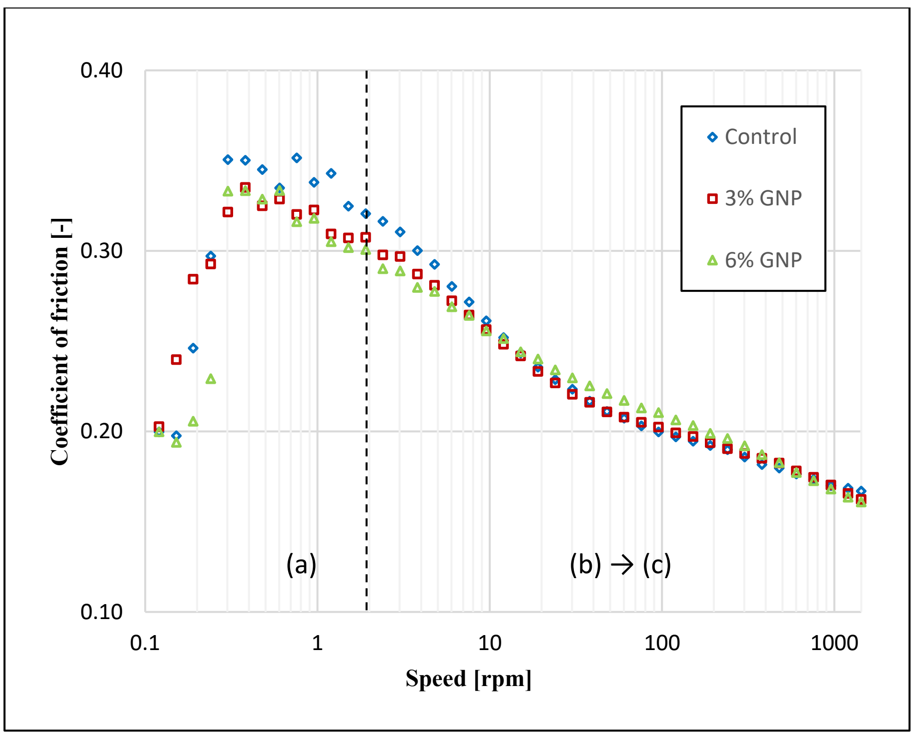


**Figure 4.10 Comparison with rough substrate at 110°C**

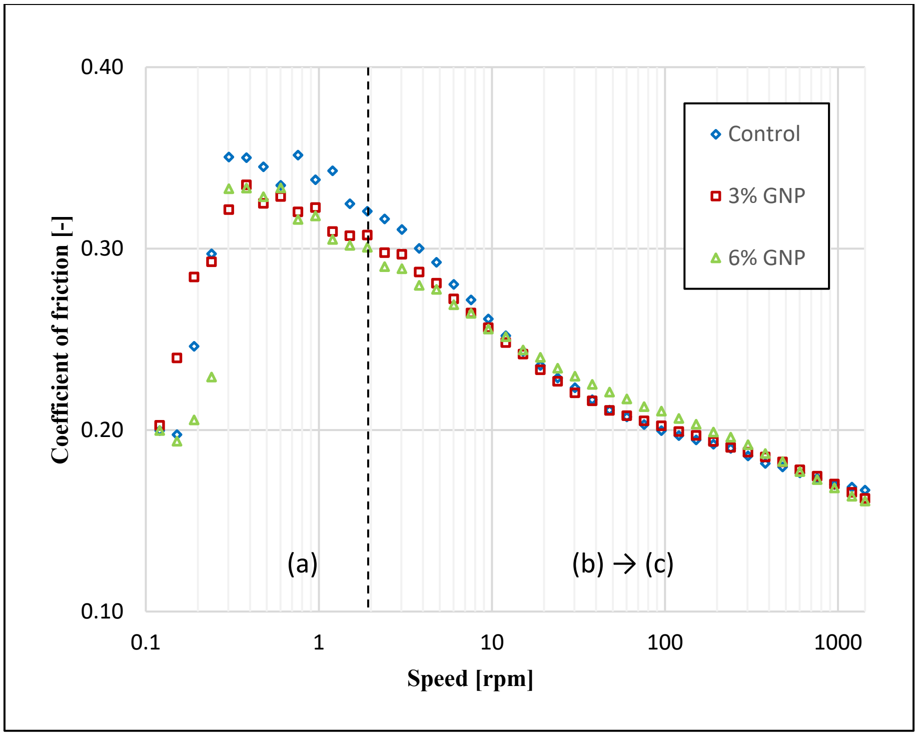


**Figure 4.11 Comparison with rough substrate at 130°C**

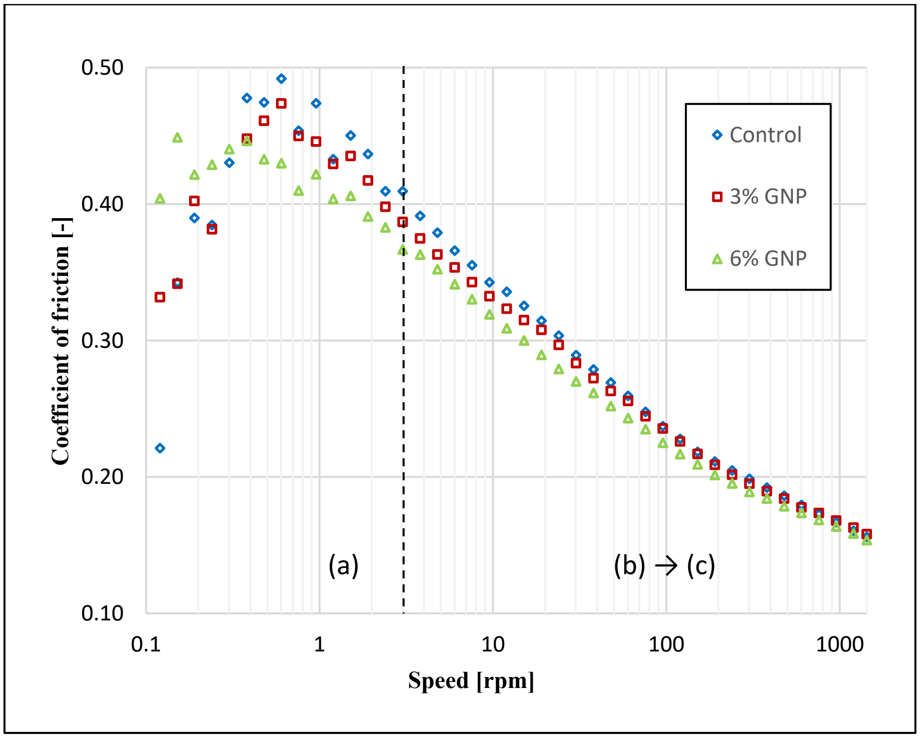


**Figure 4.12 Comparison with rough substrate at 150°C**

# CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to examine the effect of GNP on the lubrication property of asphalt binder in an attempt to correlate the lubrication property of asphalt binder with the enhanced compactability observed in GNP-modified mixtures (Le et al., 2016). Binders with three different fractions of GNP (0%, 3%, and 6% by weight) were investigated. Both viscosity and tribological tests were conducted to study the viscous and lubricating behavior of binder, respectively. In the tribological tests, both smooth and rough substrates were investigated.

It was observed that the viscosity of binder increases with the quantity of GNP. This observation confirms the hypothesis that the increase in the workability of the GNP-modified mixture cannot be attributed to the reduction in viscosity. The tribological tests on smooth substrates showed that the lubricating behavior of the binder between smooth surfaces does not improve with the addition of GNP. However, the tribological tests on rough substrates showed that GNP can increase the lubricating behavior of binder between rough surfaces. Given that the rough substrates better simulate the surface of actual aggregates used to produce asphalt mixtures, the enhanced compactability of GNP-modified mixture can be attributed to the improvement in the lubricating behavior of asphalt binder between rough surfaces caused by the presence of GNP.

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