Health & Safety

A DESIGN APPROACH FOR LAB TEST SETUP FOR MEASURING WET GRIP OF TIRE RUBBER COMPOUNDS

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Abstract

Tire-pavement friction is a very important aspect of vehicle safety, especially in wet conditions. Tire manufacturers assess the wet grip of tires by conducting “ABS braking tests”, which is a realistic assessment but are expensive and time-consuming. Tire manufacturers are keenly interested to develop an economical and reliable test on a labscale, that can be used to quickly assess the wet grip during the development of rubber compounds. In this paper, we present a design approach for a lab test method, which can be used by the tire industry to test rubber compounds with greater precision. We discuss the actual wet grip tests which are conducted on purpose-built track with an ABS (Anti-Lock Braking System) equipped car; measuring stoppage distance as a performance parameter. In light of these tests, we present the tire-pavement friction concept in terms of roles played by pavement (skid resistance) and rubber (wet grip) to produce the traction during braking in wet conditions. Then we discuss skid resistance in terms of micro and macro scale contributions, elaborating on the environment that pavement creates for rubber to generate friction. Further, we present friction generation mechanisms of rubber that are present in a typical rubber/road contact. This study aims to present a design approach of a test method in a lab-scale, that has a good prediction capability of the wet grip of tires using a friction tester called “Linear Portable Friction Tester” (LPFT) in light of the knowledge of tire-pavement friction and contact patch dynamics. We present a dedicated test scheme and its results, to perceive the viability of LPFT, to be used as an effective wet grip friction tester. The outcome of the tests reveals some instrumental design insights (choice of rubber shapes, size, etc. and counter surface), that would help in reaching a right tribo-system to have a high correlation with actual wet grip performance.

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1. INTRODUCTION

The prime aspect of a passenger vehicle is the safety with which it can perform its function. 1.35 million people were reported to have died in 2018 in traffic according to WHO (World Health Organization) [1]. Not only these traffic-related incidents proved fatal for the passengers themselves but also the pedestrians, cyclists, and motorcyclists as well those happened to present in the vicinities of such accidents.

This traction comes from the frictional forces being generated between the tire/road contact and is produced during car maneuvering actions, like cornering, braking, and acceleration [2]–[4]. During wet conditions, the transmission of forces within the contact patch gets affected and the overall traction ability of the tires is greatly reduced [5], [6]. This leads to slippery situations during driving and cause accidents. Tire-pavement friction is therefore very crucial in terms of safety. For that reason, from a consumer point of view, it is of interest to know about the wet grip of the tires that they are purchasing. To communicate this, the European Commission has introduced a tire labeling system so that consumers are better informed about tire's environmental and safety performances [7]. The labeling regulation is by the name **EC 1222/2009 "**On the labeling of tires with respect to fuel efficiency and other essential parameters".

Tire industry and Road manufacturers are avidly working in their respective domains to increase the overall safety of the passengers on the road. While the tire industry focuses on the chemical aspect of rubber compounding recipes, the road industry plays a vital role in complementing the safety concept by making pavements with better skid resistance capabilities and improved structural integrity.

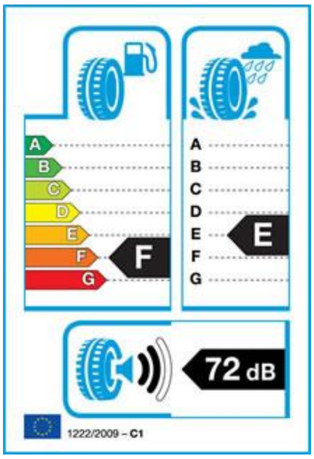


Figure 1: Tire label (EC 1222/2009).

Recently, it is noticed that actual wet grip tests (ABS Braking tests) have shown good repeatability (same test conditions = same tests results) but poor reproducibility (different test conditions within allowable testing conditions = different test results). It means if the test track is selected within allowable range to do test on, the wet grip label may change as well. The main contributors to this variation are the pavement temperature and skid resistance. While it needs to be improved, this creates room for an innovative test setup, which can predict a wet grip to a reasonable degree quickly and economically.

An in house lab test setup, which can predict the real wet grip performance of the tires will be of immense advantage due to two main reasons: First, it will help to reduce the costs and resources associated with real tire testing. Secondly, it will increase the research capabilities to improve the rubber compounds by quick pre-assessment of wet grip in the lab. This means faster product development and economic compound testing for wet grip.

In this paper, we present the design approach for a lab test setup for measuring wet grip using "Linear Portable Friction Tester". We start from the key concepts of tire-pavement friction by discussing the road and rubber contribution to produce friction, followed by an understanding of the tire/road contact patch during braking. In light of these understandings, a carefully designed test scheme is developed, which focus to realize the best design choices for creating a meaningful lab test setup for wet grip, whose results can correlate with actual ABS Braking tests (real tests). The results reveal the right sample shape, size, dimensions, the correct type of counter surface features and the test conditions, which provide key design insights in developing a full-fledged lab test setup with high wet grip prediction capabilities.

2. TIRE-PAVEMENT FRICTION

Tire-pavement friction is a process in which both, tires and pavement play its role. The overall friction is an outcome of two main contributions; Wet grip and Skid Resistance. "Wet grip" refers to the tire part, which is the ability of rubber compound to produce traction through friction generation mechanism offered by the unique viscoelastic behavior of rubbers. The second aspect of this friction is the skid resistance that is offered by the asphalt road. It is due to the multiscale texture of the road that enables rubber to produce friction.

For tire manufacturers, the wet grip of tires on the asphalt is one of the prime performance characteristics, which enables the vehicle to stop in shorter distances during emergency braking situations in wet conditions. Tire manufacturers test wet grip of tires according to ISO 23671 - "Method for measuring relative wet grip performance" on a purpose-built test track. This track has to meet certain specifications in order to qualify as the "test track" for measuring wet grip.

These tests include trailer tests and Vehicle Test using ABS brakes. The trailer test is conducted using a trailer towed by a vehicle that is fitted with one tire on a specific tool. The output of such a test is the "peak braking force coefficient". The vehicle test is conducted with a set of four tires mounted on a vehicle, equipped with an ABS system. The conditions of the tests are specified in ISO23671:2015, which explains the measurement of relative wet grip performance. The vehicle is decelerated from 80km/h to 20km/h and the braking performance is compared with the Standard Reference Test Tire (SRTT).

In this way, tire manufacturers assess the wet grip performance. These tests are expensive and time-consuming but are realistic assessments of wet grip with some inherent uncertainty as mentioned above.

3. ROAD MATERIAL AND SKID RESISTANCE

Road manufacturers and legislation institutes are busy in getting their road-roughness on a level that is safe for traffic under all conditions. The road-building sector employs road-roughness measurement equipment to be sure that their roads meet the demands of being safe regarding skid resistance [2].
Zooming into the skid resistance aspect of the road, it is visible that the texture of the road surface is composed of following distinguished texture types:

1- Microtexture, which consists of characteristic wavelength dimensions from 0 mm to 0.5 mm.
2- Macrotexture, which consists of larger characteristic wavelengths from 0.5 mm to 50 mm.
3- Mega texture, with characteristic wavelengths greater than 50 mm up to 500 mm.

For this work, only the micro and macrotexture will be focused on, as roughness on these levels are the most relevant ones in tire-pavement friction.

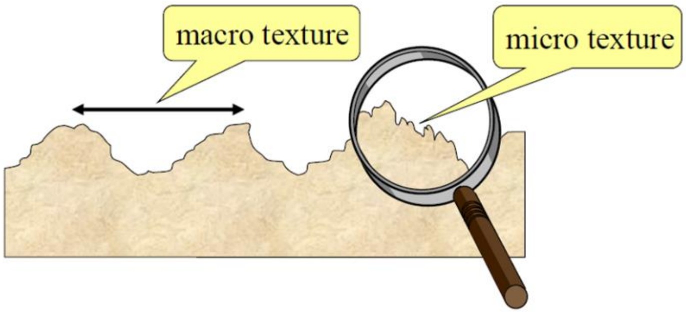


Figure 2: Macro and Microtexture depiction.

3.1 Origin of Skid Resistance

Based on the requirements, such as traffic loads, permeability, durability, and frictional properties, road manufacturers select the design of the pavement. By designing means the selection of aggregates (type, size, shape, etc.), type of binder (bitumen, Portland cement, etc.), and composition of materials (aggregate and binder composition). Based on the selected design, the main types of pavements are

- Stone Matrix Asphalt (SMA)
- Asphalt Concrete (AC),
- Porous Asphalt (PA)

Depends on the pavement design, the macro roughness is responsible for storing water in the pits so that the road can provide friction at high speeds and prevent aquaplaning. The microtexture of the road, which is roughness on the aggregate level, is responsible to break the water film and make contact with rubber to generate friction. This combination of both sums up the skid resistance characteristic of a pavement. Understanding the respective contribution leads to the right design choices for the lab wet grip test.

3.2 Skid Resistance evolution and discrepancy in real ABS Tests

It is important to mention that the skid resistance of pavement is an evolutionary process that changes with time. Skid resistance evolves during the lifetime of the pavement due to the polishing effect by the traffic load over the "wearing course". Due to this load, the aggregates get polished based on their mineralogy [3]. This characteristic of aggregates is gauged with "Polished Stone Value" (PSV), which is determined by a standardized accelerated polishing test conducted in a lab. It is preferred to use aggregates that are likely to retain microtexture and not easily polished.

The discrepancy in the real wet grip tests can be attributed to such changes in the pavement friction level over time. This means that the test tracks which are used for wet grip tests all over the world evolve differently, probably due to different aggregate mineralogy or different origin of aggregates. This is also because the allowable range of test track skid resistance (British Pendulum Number – BPN) is wide. So in theory, no matter if the test track falls in this standard range (42-60) but practically it is prone to yield different wet grip results.

3.3 Macrotexture

The macrotexture is mainly governed by aggregate size and arrangement, gradation of the aggregates, air void percentage, etc. There are several types of asphalt mixtures that offer different types of macrotexture based mainly on their gradation curves. The example of such gradation curves is shown in figure 3.
A short macrotexture of around 5mm reduces the noise level associated with tire-road interaction. But for wet grip, higher macrotexture is important due to its ability to store water and provide friction at higher speeds.

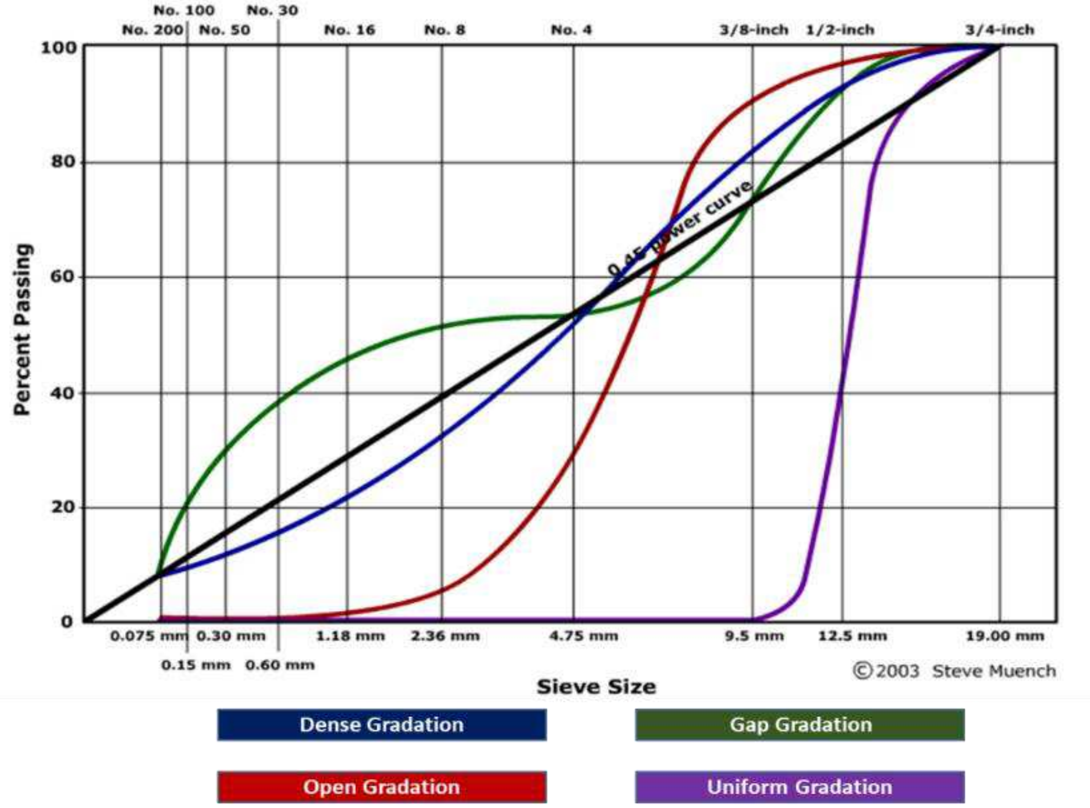


Figure 3: Example of Gradation curves [4]**.**

3.4 Microtexture

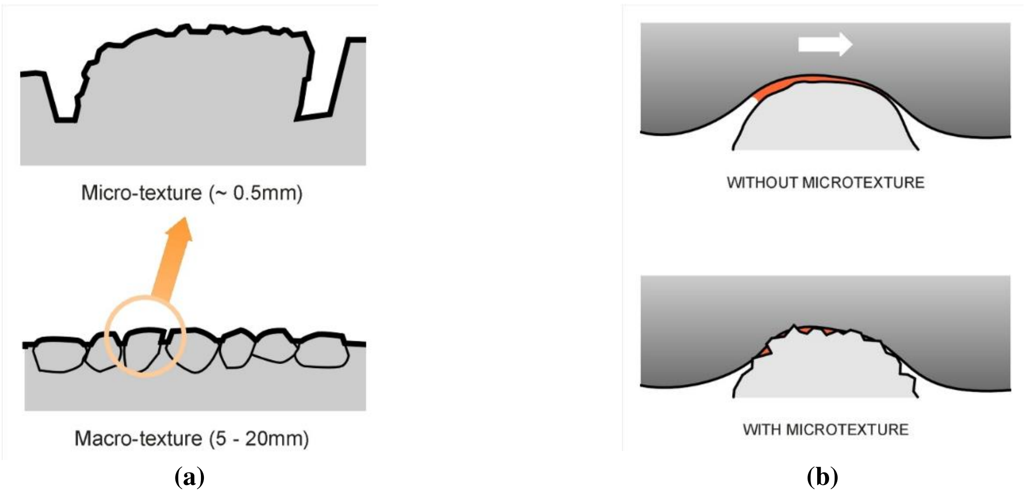


Figure 4: Macro and Microtexture (a). Microtexture breaking the water film and interacting with rubber to produce friction (b) [5]**.**

This is small scale roughness (0mm to 0.5mm) and related to the texture offered by the aggregates themselves. This microtexture is crucial to initiate the friction mechanisms in rubbers by breaking the water film and making real contact with rubber (fig. 4a). The overall skid resistance is measured by different tests like SCRIM (Sideway-Force Routine Investigation Machine), British Pendulum Tester, etc. which quantifies the frictional properties of pavement [6].

Understanding the role of macro/microtexture provides a logical basis for the selection of asphalt surfaces for the test scheme for this study.

4. THE WET GRIP

The ability of rubber to produce friction in wet conditions is called "wet grip". It is necessary to zoom into the mechanisms with which it creates friction. Understanding of this will help in reaching an optimum design of the samples for the test, so that, the actual ability of rubber to produce friction is gauged and all other non-frictional entities are reduced.

4.1 Mechanism for Rubber Friction

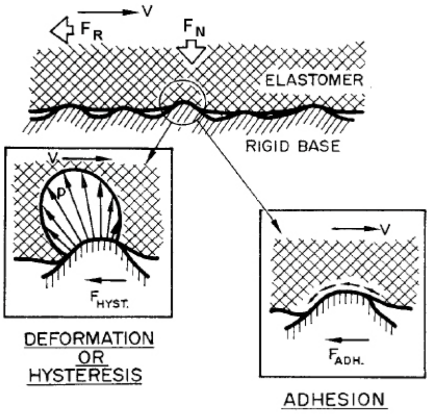


Figure 5: Mechanism of Rubber Friction [8]**.**

4.2 Hysteresis Friction: Road Roughness Effect

When rubber slips over a textured surface like a road, a frequency excitation in the rubber happens. For hysteresis friction, the typical frequencies range is ~ 10^2 to 10^6 Hz. Due to the viscoelasticity of the rubber, it exhibits hysteresis energy loss due to the penetration of road texture into the rubber material, which generates friction. The magnitude of surface texture varies from 1 cm to 1 µm. Figure 6 shows the asymmetric force field as a result of hysteresis, the "X" component of which opposes the motion; called hysteresis friction.

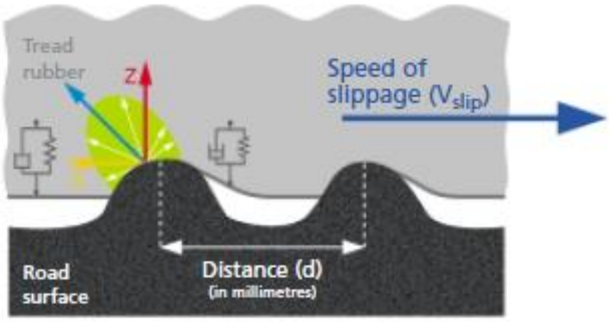


Figure 6: Hysteresis Friction mechanism by indentation by road texture [9]**.**

4.3 Molecular Adhesion:

This is the physical interaction of rubber with the road surface on a molecular level and this phenomenon functions at a scale of 1/100th of a micron (10^6-10^9 Hz). Rubber generates viscoelastic work by creating and breaking bonds with the road surface. This bond formation is due to weak Van der Walls forces.

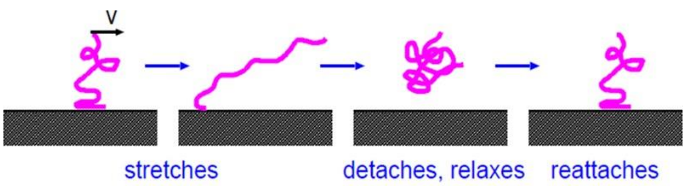


Figure 7: Stages of Molecular Adhesion of Rubber molecules with the counter surface [10]**.**

Due to wetness on the road, the indentation mechanism still plays its role in friction, however, adhesion is limited due to thin water film between the rubber and road, which limits the physical interaction.

4.4 Conclusion: Wet Grip

This section concludes the understanding of wet grip on a microscopic level which is crucial to select the counter surfaces, in terms of macro and microroughness features. These features govern the friction mechanism that prevails under ABS braking conditions. In simple terms, it is understood that during wet conditions, it is adhesion friction that gets affected, due to which the braking distance increases. The hysteresis friction, which depends on the excitation frequencies, provided by the texture, still present in wet conditions. For the lab wet grip test, we now understand what to gauge to predict the wet grip.

To understand the test dynamics (sliding speeds, contact pressures), we proceed to the third important aspect of the tire-pavement friction concept i.e. the contact patch during ABS braking.

5. THE CONTACT PATCH

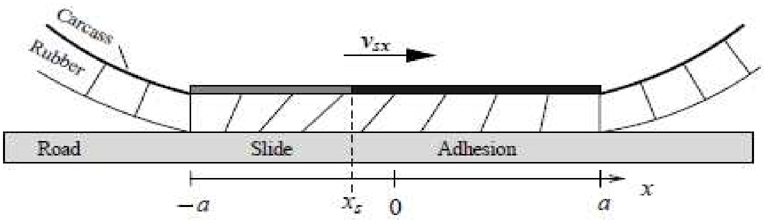


Figure 8: Illustration showing deformation of the rubber layer between tire carcass and road (brush model) during braking [11]**.**

Figure. 8 qualitatively illustrates the contact patch during a typical ABS Braking scenario. In the front part or "Adhesion" region, there exists a very small slip, called micro slip. Therefore, this region is dominated by adhesive friction. There comes a point within the contact patch after which the rubber tread blocks go into sliding (at point x_s). Therefore in the rear part, there is a momentary sliding (few cm/s) and hysteresis friction dominates. The contact pressure in the contact patch is ~0.25 MPa hence it is a good representation for the design test.

Looking into the contact patch dynamics, the sliding speeds for the lab test design are taken to be 100mm/s, 550mm/s and 1000mm/s which is representative of real ABS Braking case [12][13].

6. DESIGN OF EXPERIMENTAL SETUP

The above-mentioned concepts of skid resistance, wet grip, and contact patch form the basis of selecting design parameters for a lab-scale sliding test. For example, the rubber sample shape is to be like a tread block, with an appropriate size that ensures enough contact with the counter surface. The selected counter surface must have textural features, which provide the right environment for rubber to produce adhesive and hysteresis friction, without overheating the rubber during sliding. The selection of operating parameters like contact pressure, sliding velocity, choice of counter surface, etc. are such that friction remains the function of rubber's viscoelastic properties and not the abrasive wear (the tearing of rubber particles). The main challenge in the lab test design is to establish a tribo-system, which has minimal sources of error. These sources are identified to be the frictional heating effects during sliding, the jittering effects from mechanical interlocking and the abrasive wear. The interlocking effects will be discussed in detail later.

Knowing these concepts, the design choices (rubbers and counter surface) can now be made which can have a better correlation with the real situation. For the sliding tests, "Linear Portable Friction Tester" (LPFT) is used.

6.1 Linear Portable Friction Tester - LPFT

Linear Portable Friction Tester (LPFT) employs a linear sliding mechanism to measure the coefficient of friction. The idea of such a tester originates from the contact patch explained above. Figure 9 shows a free body diagram of LPFT. Rubber samples are slid in a linear motion. The contact pressure is maintained using weights in the normal direction. The sliding stator is moved along in a straight line with the help of a battery. A 3-D force sensor is placed as shown, which records the measured values of frictional force with a frequency of 10 kHz.

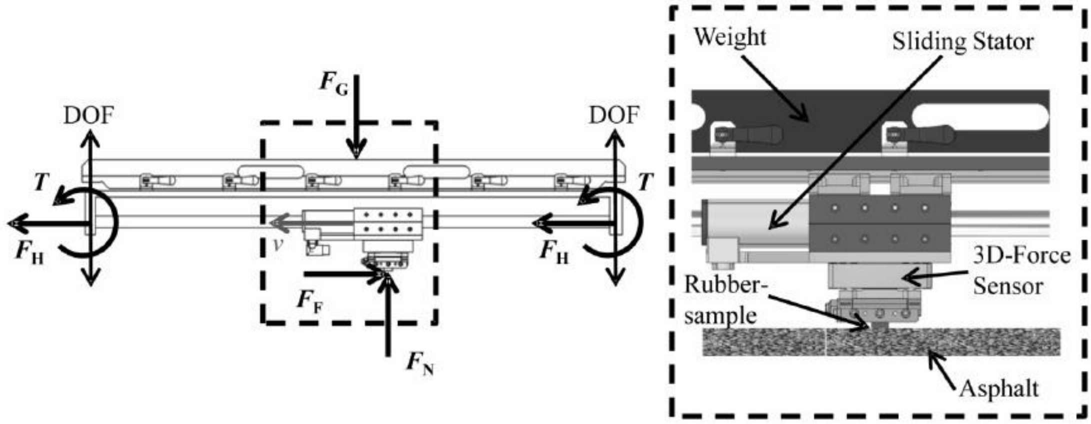


Figure 9: Free body diagram of the test rig [14].

6.2 Design of Test Scheme for LPFT

For the sliding tests, two different surfaces were selected, Asphalt Concrete (AC) and Stone Mastic Asphalt (SMA). The SMA has a maximum stone size of 8mm and AC has a maximum stone size of 5mm. The number of compounds, that were used are three, named Compound A, B and C. The tests are conducted with Linear Sliding Friction Tester (LPFT). The standard sample used normally is a small cuboid-shaped rubber sample, measuring 3.5 x 3.5 x 1 cm. The sample is slid across a length of 550 mm on the selected road surface. The LPFT has a data acquisition frequency of 10 kHz. Samples were made from each of the three rubber compounds, to assess the effect of

1- Frontal shape (straight or round)
2- Contact Area (smaller or bigger), to see if a bigger contact area is more feasible than a smaller one.
3- Shape of the sample (square or rectangular), to see the effect of “rectangularity” (long shape).

The experimental matrix is presented in the table below

Table 1. LPFT Test Matrix.

Compound A					
Sr. No.	**Name**	**dim. (cm)**	**Area (cm2)**	**shape**	**Type of Analysis**
1	A1s	3.5x3.5	12.25	straight	1- Effect of Frontal Shape 2- Effect of Contact Area 3- Effect of Sample Shape
2	A1r	3.5x3.5	12.25	round	
3	A2s	2x7.5	15	straight	
4	A2r	2x7.5	15	round	
5	A3s	2x6.125	12.25	straight	
6	A4s	3x4.1	12.25	straight	
7	A5s	3x5	15	straight	
Compound B					
Sr. No.	**Name**	**dim. (cm)**	**Area (cm2)**	**shape**	1- Effect of Sample Shape (Square and Rectangular)
1	B1s	3.5x3.5	12.25	straight	
2	B4s	3x4.1	12.25	straight	
3	B3s	2x6.125	12.25	straight	
Compound C					
Sr. No.	**Name**	**dim. (cm)**	**Area (cm2)**	**shape**	1- Effect of Contact Area
1	C1s	3.5x3.5	12.25	straight	
2	C6r	3x3	9	round	
3	C7r	2.5x4	10	round	
4	C1r	3.5x3.5	12.25	round	
5	C5r	3x5	15	round	

The three compounds used in the tests, named A, B and C are cut to different shapes, areas and frontal shapes. Each sample is given a name starting with the compound name. The next number shows the dimensions associated with that number and the last letter shows the frontal face of the sample, i.e. round or straight.

Also, the type of analysis within each compound category is also mentioned. For example,

- "A1s" is to be compared with "A1r" to see if the **round edge** has any effect on friction signal.
- "A1s" and "A1r" can be compared "A2s" and "A2r" to see the effect of the **contact area.**
- "A1s", "A3s" and "A4s" can be compared to see the **rectangular shape effect**.

Similarly, for B, the effect of the rectangular shape can be analyzed, while for C, the effect of the contact area is to be analyzed.
The experimental conditions selected were as follows

Table 2. Experimental Conditions of LPFT.

Parameter	Value	Comments/Reason
No. of Rubber Compounds	3 (named A, B, C)	For Comparison. Known wet grip (A<B<C)
Contact Pressure	~0.25 MPa	Real Tire/Road Contact Pressure
Sliding Velocity	100 mm/s, 550 mm/s, 1000 mm/s	Speed of tread block during braking
Depth of Water	~ 1mm	From Test Method ISO 23671
Ambient Temperature	16-18 C	Outdoor testing site temperature

6.3 Selection of Rubber Samples Design:

The existing standard rubber samples that are used with LPFT are a 3.5x3.5 cm rubber block with a thickness of 1cm, mounted on a steel plate. For this test scheme, rounded faced samples were also used to check the suspected mechanical interlocking effect, which is considered an error for our wet grip analysis.

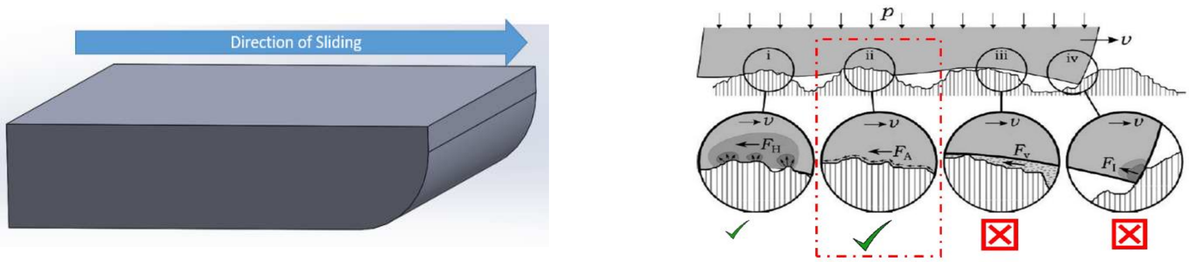


Figure 10: (left) The new adopted shape of the rubber sample for sliding test with LPFT. (Right) Potential Friction contributors using Linear Sliding Tests like LPFT.

Fig. Figure 10 (right) shows the sources of friction during a sliding test [15]. Case (iv) is the mechanical interlocking that is caused by the leading edge of the rubber samples. Although such interlocking is present in the real tire/road contact, for the LPFT sliding tests, it is suspected that these effects will cause a higher jittering (standard deviation) in friction signal. This limits the test's capabilities to distinguish between rubbers that have a close wet grip performance.

6.4 Selection of Counter Surface:

Figure. 11 shows the laser scan taken form a triangular laser asphalt scanner from Stemmer Imaging. The tests are conducted on SMA 8, and AC 5. Qualitatively, SMA 8 has a coarse macrostructure with a smooth microstructure, and AC has Fine macrostructure and rough microstructure.

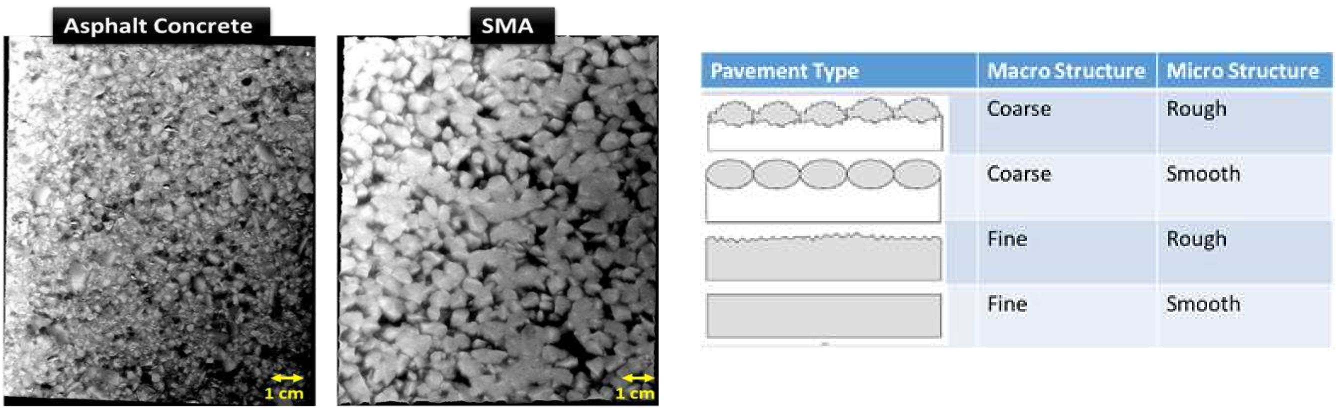


Figure 11: Asphalt Surface Macro scan of SMA and AC (left). Qualitative Characterization of road surfaces (right).

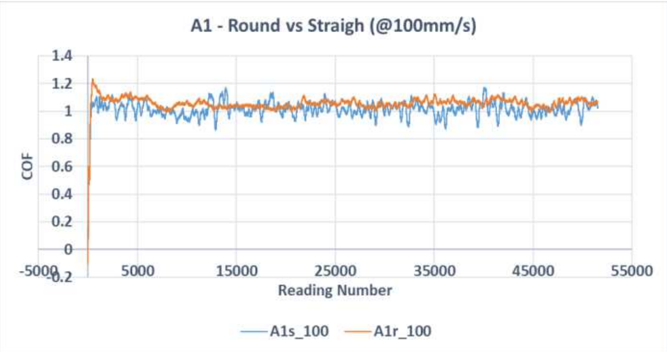
6.5 Water Level:

The water level is maintained at ~1 mm during the tests with the help of a portable pump. This level is selected to ensure that the rubber and road should have a physical interaction between them, without any viscous effects of water.

7. RESULTS AND DISCUSSION

7.1 Friction Signal Variation:

In figure 12 below, the friction signal for two speeds, 100mm/s, and 550mm/s are given for straight edge sample (blue) and round edge sample (orange). It is clearly seen that rounding the frontal edge has a definite effect on the friction signal. The important design consideration here is to use a round-faced sample to reduce the standard deviation of friction signal caused by the frontal edge interlocking. Such interlocking is present in real braking scenarios as well but due to the nature of contact dynamics of LPFT, it is a source of great error, which makes it hard to compare compounds, that have close wet grip properties.



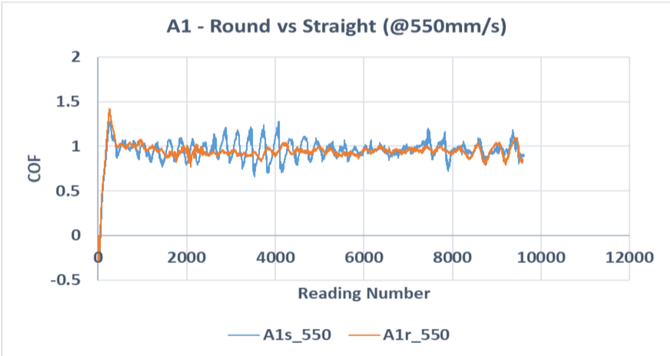


Figure 12: Friction signal during one sliding with LPFT.

7.2 Effect of Straight vs Round Edge.

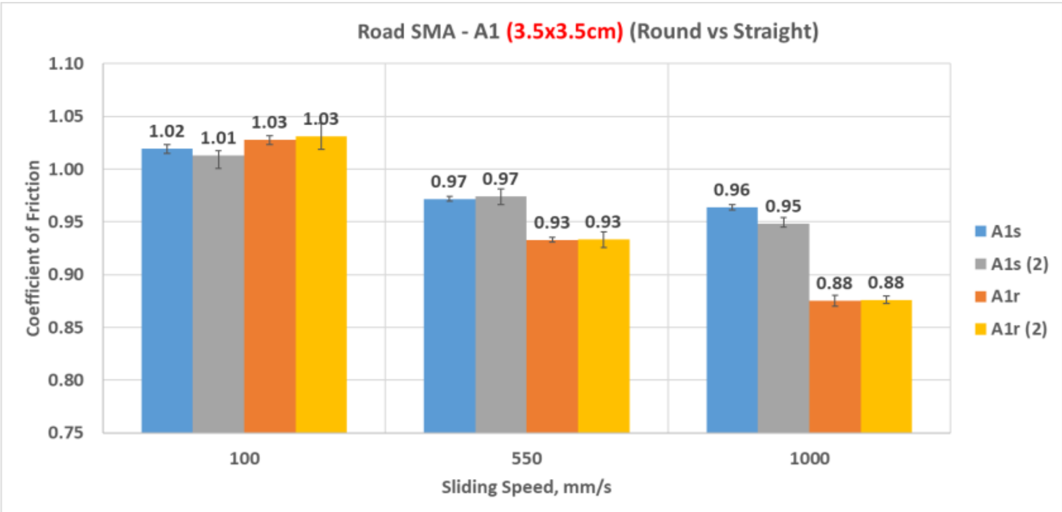
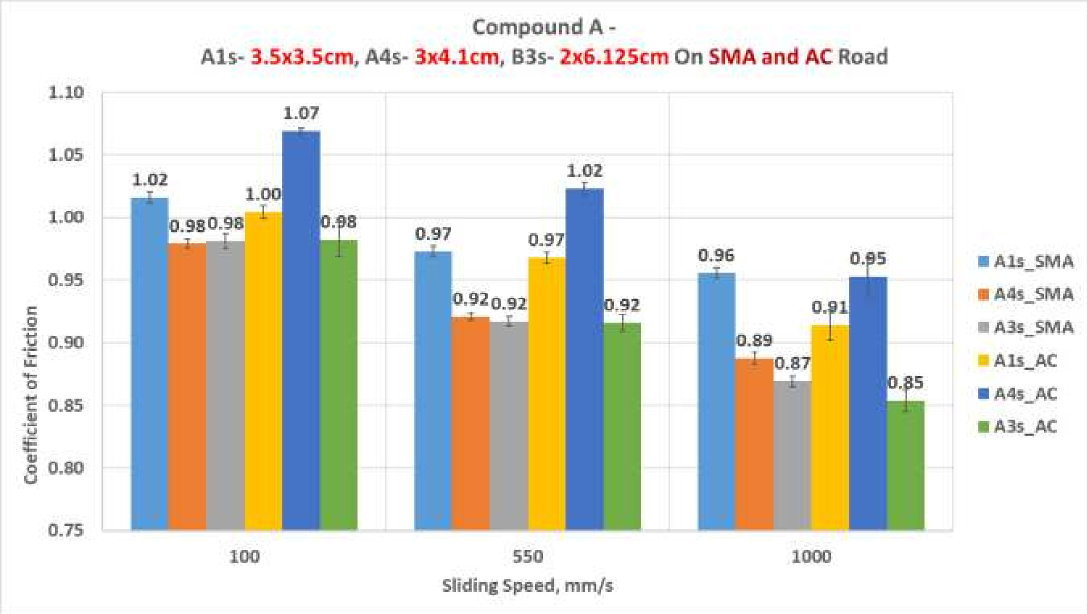


Figure 13: Coefficient of Friction, Straight vs Round edge.

Figure 13, shows the coefficient of friction of compound A with the same area. Ideally, there shouldn't be a difference in the value of the coefficient of friction, but here it is seen that the mechanical interlocking factor not only increases jitter in the friction signal, but it also has a significant contribution in overall friction force. The effect grows stronger for higher speeds.

Currently, the tire industry is using straight-edged samples for these kinds of tests. In light of above findings, one important suggestion will be to use round-faced samples to improve the output of these tests. secondly, using round sample help in comparing rubber compounds that have close wet grip properties.

7.3 Effect of Square and Rectangular shape.



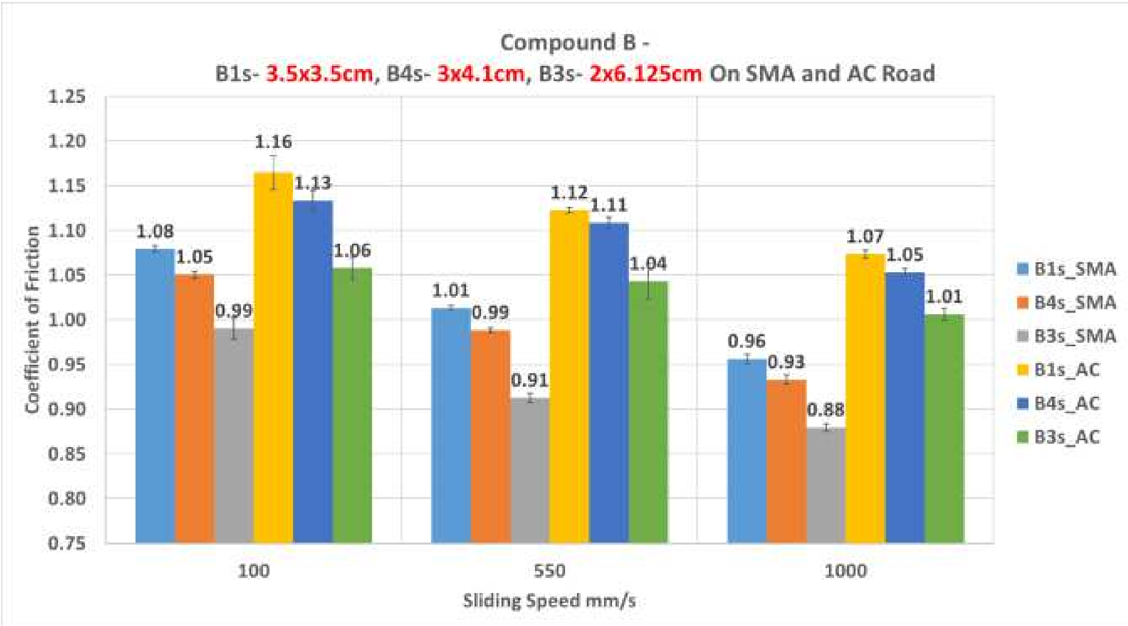


Figure 14: Compound wise comparison on SMA and AC with different rectangularity.

The above results show the coefficient of friction behavior of two different compounds, A and B on two different roads, i.e. SMA and AC. The results show that compound B shows consistency on both roads, but compound A does not. The “A4s” sample showed higher CoF for AC. This inconsistency is due to the different ability of rubber compounds to dissipate frictional heat within its bulk material. Therefore, we do not want to have heat development in contact with such tests. SMA offers round and smooth stones compared to AC, and hence a more realistic environment for wet grip tests.

This points out a choice of road that should be selected for such tests. In light of these studies, it is recommended to select a road that has a coarse macro and smooth microtexture (like middle-aged SMA). At this stage, this recommendation remains qualitative. The quantitative texture values for reaching even better test design remains a point of further research.

7.4 Effect of Contact Area

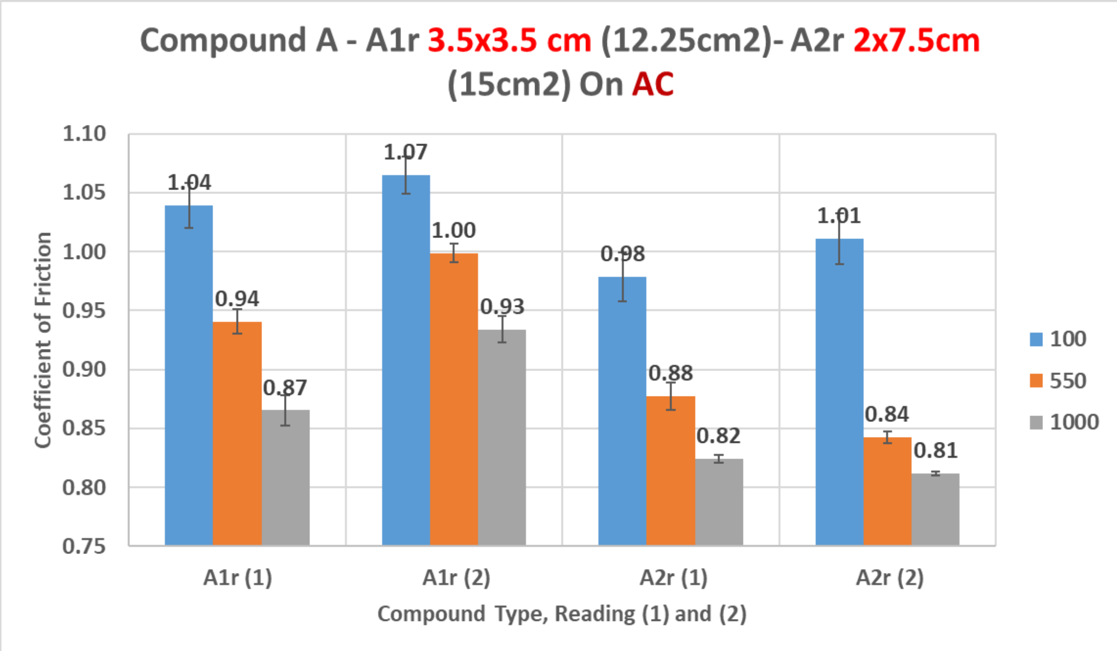


Figure 15: Coefficient of friction, small and large contact area.

Figure 16 shows the effect of having a small or large surface area. It is shown that the higher the contact area decreases the coefficient of friction. The most probable reason for this is the heat development within the contact due to the higher contact area. Therefore, the contact area is an important design consideration for tests with LPFT and must be selected in conjunction with the selected road. Higher stone size, higher areas are recommended. For 8mm SMA, 13 cm^2 seems to do a fine job.

8. CONCLUSION

In this paper, we started with the reasons the tire industry is interested in wet grip tests. Their aim is to develop safer rubber compounds for better wet grip. Then, we discussed the origin of skid resistance from the road perspective and how it contributes to the total friction. Then the rubber friction generation mechanisms are presented to develop an understanding of laboratory tester such as LPFT. We presented the LPFT test results on two different pavement types. In conclusion, there are identified patterns in all three different analyses. We found that rounding the sample shape can significantly reduce noise in the friction signal and also reduce the mechanical interlocking effect, which is a source of error in the measured results. Secondly, as the rectangularity increases (from square to a rectangle), the coefficient of friction progressively decreases and similar effects have been seen with bigger sample contact areas. This can be attributed to frictional heating in the contact. Therefore, lab test samples are recommended to have low rectangularity.
Also, we see that compound A responded differently than compound B with respect to the rectangularity. This is a piece of evidence that different rubbers behave differently to frictional heating produced in the contact, pointing out the importance of right contact dynamics for such tests. The main deduction out of this study is that to assess wet grip on a lab-scale, the contact conditions, sample size, sample geometry, sample shape and the choice of asphalt are very important. Conclusively, for a linear sliding test like an LPFT, it is recommended that rubber samples should be rounded and have medium rectangularity. Further, it is also recommended to select a road that has coarse macrostructure and smooth microstructure as it has a higher potential to correlate with ABS braking tests. This is because such a road will offer less harsh conditions and reduce the effect of frictional heating. This area of study is still in further research and better results are expected with more investigation of the rubber/road tribology in wet conditions.

9. REFERENCES

[1] "WHO | Global status report on road safety 2018," *WHO*, 2019.

[2] J. A. Cabrera, J. J. Castillo, J. Pérez, J. M. Velasco, A. J. Guerra, and P. Hernández, "A procedure for determining tire-road friction characteristics using a modification of the magic formula based on experimental results," *Sensors (Switzerland)*, vol. 18, no. 3, 2018.

[3] M. Kane, I. Artamendi, and T. Scarpas, "Long-term skid resistance of asphalt surfacings: Correlation between Wehner–Schulze friction values and the mineralogical composition of the aggregates," *Wear*, vol. 303, no. 1–2, pp. 235–243, Jun. 2013.

[4] "Gradation Test - Pavement Interactive." [Online]. Available: https://www.pavementinteractive.org/reference-desk/testing/aggregate-tests/gradation-test/. [Accessed: 24-Apr-2019].

[5] "Book : The Contact Patch." [Online]. Available: http://the-contact-patch.com/book/general/g3000-introduction. [Accessed: 18-Jan-2019].

[6] *Guide for Pavement Friction*. Washington, D.C.: Transportation Research Board, 2009.

[7] *Guide for Pavement Friction*. Washington, D.C.: Transportation Research Board, 2009.

[8] S. M. Bazlamit and F. Reza, "Changes in Asphalt Pavement Friction Components and Adjustment of Skid Number for Temperature," *J. Transp. Eng.*, vol. 131, no. 6, pp. 470–476, Jun. 2005.

[9] Société de Technologie Michelin, "The tire Rolling resistance," p. 120, 2003.

[10] B. Lorenz, N. J. Persson, G. Fortunato, M. Giustiniano, and F. Baldoni, "Rubber friction for tire tread compound on road surfaces," *J. Phys. Condens. Matter*, vol. 25, pp. 95007–95015, 2013.

[11] J. Svendenius and B. Wittenmark, "Brush tire model with increased flexibility," *Eur. Control Conf.*, no. 1, 2003.

[12] G. Heinrich and M. Klüppel, "Rubber friction, tread deformation, and tire traction," *Wear*, vol. 265, no. 7–8, pp. 1052–1060, 2008.

[13] T. V. Tolpekina and B. N. J. Persson, "Adhesion and friction for three tire tread compounds," *Lubricants*, vol. 7, no. 3, pp. 1–25, 2019.

[14] S. Mihajlovi, U. Kutscher, B. Wies, and J. Wallaschek, "Methods for experimental investigations on tire-road-grip at arbitrary roads," *Proc. 5th Expert Symp. Accid. Res.*, pp. 1–7, 2013.

[15] P. A. Ignatyev, S. Ripka, N. Mueller, S. Torbruegge, and B. Wies, "Tire ABS-Braking Prediction with Lab Tests and Friction Simulations," *Tire Sci. Technol.*, vol. 43, no. 4, pp. 260–275, 2015.