Influence of thin water film on skid resistance

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ABSTRACT

Most of past researches on the skid resistance/road wetness relationship deal with thick water depths (> 1mm). Questions remain as to the variation of skid resistance with thin water films and the transition between the dry state and the so-called "damp" or "humid" state at which the skid resistance drop can be as high as 30-40%. This paper deals with a theoretical and experimental assessment of the friction/water depth relationship. The main objective is to estimate local water depths trapped between the tire and the road asperities and to define a so-called "critical" water depth which can be used for driver assistance systems.

Tests are performed in laboratory and on test tracks. It was found that the friction-water depth curves have an inverse-S shape and present an initial constant-friction part before decreasing to a minimum value. A "critical" water depth, defined as the water depth above which the friction coefficient collapses significantly, is determined from observed friction-water depth curves. Influence of test speed and road surface texture on critical water depth is discussed.

1 INTRODUCTION

It is well known that tire/road friction decreases when the road surface is wet. Moore [1] showed that water acts as a lubricant and reduces the fraction of the tire/road contact area where friction forces are generated. Despite this widely accepted explanation, few works have dealt with the relationship between the water depth and the tire/road friction. Based on friction tests using a vehicle equipped with trailer, Veith [2] showed that the friction coefficient is independent of water depth at low speeds (up to 50 km/h) but it is strongly influenced by water depth at high speeds (96 km/h or greater). It was found that the friction coefficient varies as the logarithm of water depth. Water depths greater than 0.12 mm were studied.

Models were also published on the calculation of the so-called “hydroplaning speed” [1][2] defined as the speed above which the driver can no more act on his vehicle to control its trajectory [3]. The related situation called “hydroplaning” – or aquaplaning – occurs on flooded roads.

Even if the abovementioned works have contributed significantly to the reduction of hydroplaning risk, knowledge is still needed regarding the effect of thin water film on tire/road friction. This situation occurs after rainfalls or during drizzles where the damp aspect of the road surface provides a safety feeling; driving speeds are then as high as those practiced on dry roads. Nevertheless, experimental studies [4] showed that friction at a “damp” state can already be significantly lower than that at a “dry” state. This drastic drop of friction coefficient explains why accident records are generally high after rainfalls. The tire/road contact loss on damp road surfaces is sometime referred to as “viscoplaning” in order to emphasize the viscous effect of thin water depths.

The single paper dealing with thin water depths is based on works conducted by Kulakowski and Harwood [5]. Using a dedicated laboratory device, they performed friction tests at different water depths and found that the relationship between the friction coefficient and the water depth can be approximated by an exponential function (Fig. 1):

$$\mu = \Delta\mu \cdot e^{-\beta \cdot h} + \mu_F \quad (1)$$

Where
- μ: friction coefficient;
- h: water depth;
- μF: “final” friction coefficient;
- Δμ: difference between μ(0) (μ at h = 0) and μF;
- β: parameter of the model.

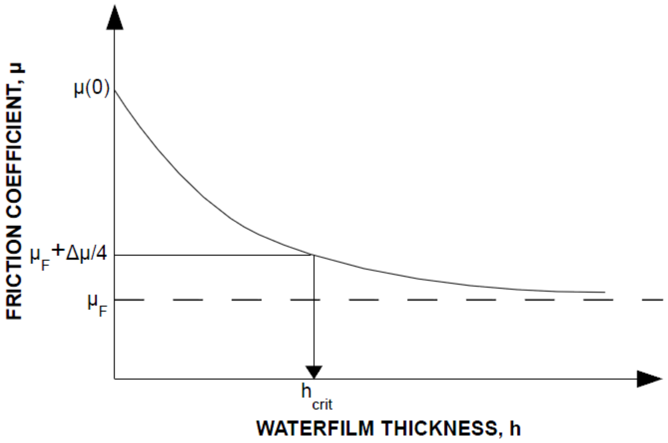


Figure 1 – Relationship between tire-pavement friction and water-film thickness [5]

Actually, Kulakowski and Harwood [5] supposed that the friction coefficient reaches a level – that is μF – at which there is no more variation with increasing water depths. These authors defined a critical water depth hcrit as the depth at which the dry friction μ(0) has lost an equivalent of 75% of Δμ (Fig. 1). The 75% threshold was chosen arbitrarily. Field tests were conducted at 64 km/h to study the influence of the asphalt formulation and the tire on the induced critical water depth. Results indicate that critical water depth lies between 0.025 and 0.23 mm for different combinations of pavement surfaces and tire types. It is important to notice that the tested pavement surfaces are representative of a wide range of roads and results show that, for each test configuration, very thin water film thickness can decrease significantly the friction coefficient. The wide range of values of critical water depth points out the significant influence of both surface texture and tire.

2 RESEARCH NEEDS AND METHODOLOGY

From the brief review presented above, it can be said that research on the effect of thin water depths on tire/road friction is still needed to get a more comprehensive understanding of lubricated tire/road contact. In addition to scientific interests, results of this research can be useful for road authorities looking for a way to inform road users about slip risks under bad weather conditions. Applications can also be developed by car and tire manufacturers to assist drivers unaware of slippery road.

Within the frame of the European project SKIDSAFE (7th Framework Program) dedicated to the modelling of tire/road friction at different scales (materials, tire, vehicle), Ifsttar has initiated a research aiming at developing a model predicting the onset of visco- and hydroplaning from the knowledge of road materials, tire characteristics and tire/road contact conditions (speed, wheel slip, water depth, etc.). The work presented in this paper is part of the Ph.D. carried out by the first author and focused on the viscoplaning aspect. It is composed of three parts:

- in the first part, friction tests, both in-laboratory and on-site, at different water depths from dry to flooded states are presented;
- in the second part, the shape of the friction-water depth plot is presented;
- in the third part, definition of a critical water depth is derived in a more physical way than it has been done up to now. Analyses are then conducted to assess the influence of various test conditions on the critical water depth.

3 FRICTION TESTS

3.1 In laboratory

3.1.1 Dynamic Friction Tester machine

The Dynamic Friction Tester (DFT) is widely used in North America, Asia and Oceania; the first DFT copy in France was acquired by Ifsttar in 2009. The machine is composed of a measuring unit (Fig. 2) and a control unit. The measuring unit consists of a horizontal fly wheel and disc which are driven by a motor. Three rubber sliders are attached to the disc by leaf springs. They are pressed on the test surface by the weight of the device and are loaded to 11.8 N each.

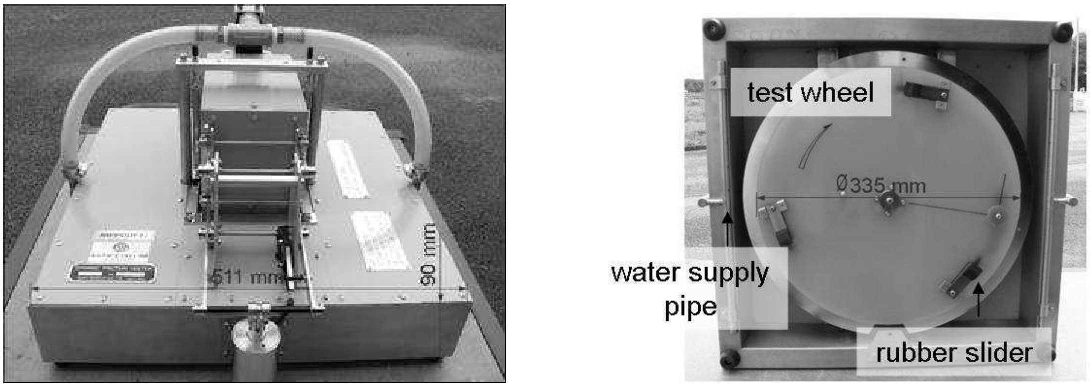


Figure 2 – Dynamic Friction Tester (DFT)

The slider (Fig. 3) is a rubber pad, whose dimensions are 6 mm × 16 mm × 20 mm, bonded to a steel plate. The rubber pad is shaped to provide a contact pressure of 0.15 MPa. Full sliding conditions occur in the contact area between the DFT sliders and the test surface. The slider dimensions as well as the contact condition might then simulate tire tread rubber blocks sliding during a locked-wheel braking.

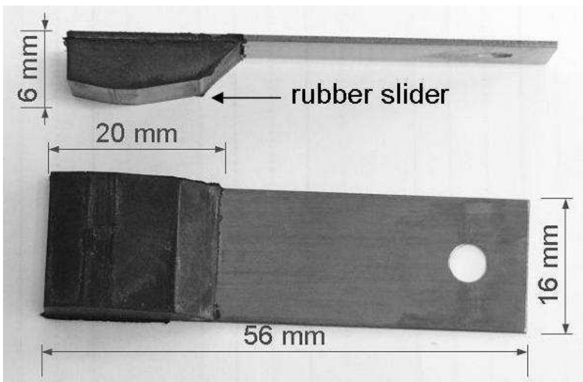


Figure 3 – DFT rubber slider

The test procedure is standardized by ASTM [8]. The test wheel (Fig. 2) is accelerated until it reaches a linear speed of 80 km/h. Water, provided by a water supply, is projected on the test surface by means of two pipes. The water depth is 1 mm by the time the test wheel speed reaches 80 km/h and the measurement is initiated. The motor is then stopped and the test wheel is dropped. When the rubber sliders are in contact with the test surface, the wheel rotational speed decreases due to the friction generated between the sliders and the surface. Due to the forces on the rubber sliders, displacement occurs in a spring balance. This displacement is then converted into an electrical signal. The speed of rubber sliders is measured from the output of a rotational speed dynamo.

The measurement output is a braking curve from 80 km/h to complete stop (Fig. 4). Values of the friction coefficient, typically at 20, 40 and 60 km/h, are extracted, recorded and displayed on the screen of the control unit.

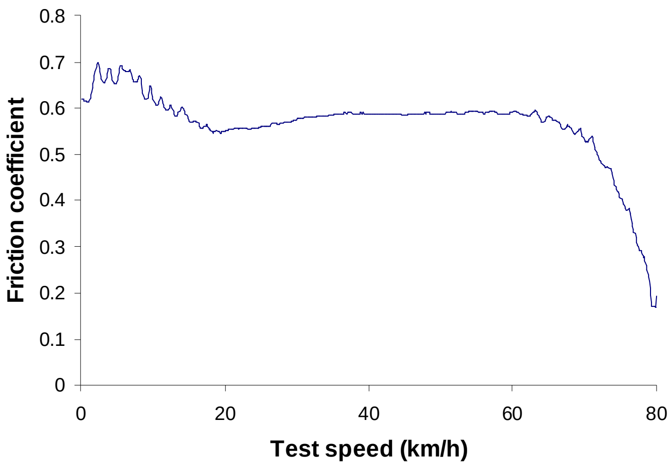


Figure 4 – Typical DFT braking curve

3.1.2 Measurement of water depths

There are different ways to define a water depth; two of which are shown below (Fig. 5).

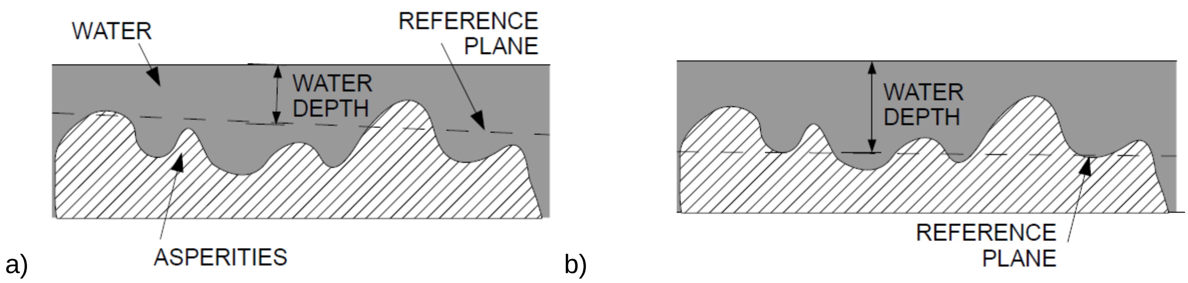


Figure 5 – Definitions of water depth (a: above-asperity; b: centreline-average) [2]

The water depth above asperity summits can be measured by means of devices equipped with needles (usually two conducting electrodes moving vertically). The main drawback of this method is that the measurement is local and cannot represent the mean water depth on the surface unless measurements are done at many locations. Non-contact optical water depth sensors can be used too. Unfortunately, devices available at Ifsttar cannot measure water depths less than 1 mm – range of interest for this study.

Thereby, a more basic method was chosen to evaluate the wetness of the surface. A spray was used to wet the surface. Before and after each friction measurement, the spray is weighed to know the amount of water sprayed on the test surface (Fig. 6). Dividing the volume of water by the wetted area, an average water depth can be calculated. This method takes into account the fact that water can fill voids in case of a rough surface. The derived water depth corresponds then to the second definition given in the figure 5.

The calculated water depth is called the “initial equivalent water depth” as it is the thickness of the water film before the friction test is performed. Actually, when the test wheel is in contact with the surface and spins, the water film thickness becomes non uniform. The determination of actual depths is complex and can be done only by models such as the one developed by Moore [9]. In the present study, the “initial equivalent water depth” is used for further analyses and referred to as, for the sake of simplicity, “water depth”.

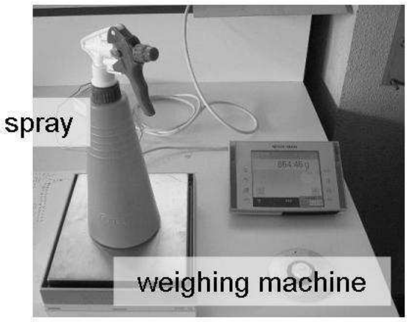
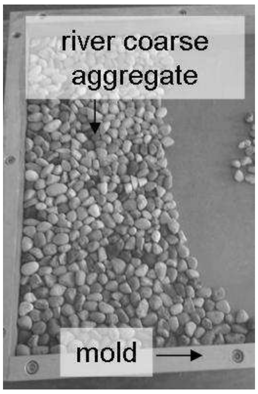


Figure 6 - Spray weighing

3.1.3 Specimens

Specimens are 520 mm × 375 mm × 30 mm slabs. Four slabs are produced in laboratory: a very thin asphalt concrete (VTAC) 0/6 (the numbers indicate the size range, in millimeter, of coarse aggregates); a semi-coarse asphalt concrete (SCAC) 0/6; a sand-asphalt and a mosaic composed of river coarse aggregates. Moreover, to study the effect of surface microtexture, the aggregate mosaic is sandblasted using 590µm corundum particles to simulate a microtextured surface. Actually, the sandblasting roughens the aggregate surface and, by consequent, modifies only the surface microtexture. VTAC and SCAC are representative of asphalt formulations used for main and secondary roads in France. Asphalt slabs are made by means of Ifsttar compactor. The mosaic is made by placing coarse aggregates in a mold (Fig. 7a) then covering the bottom with sand and resin.

a) 

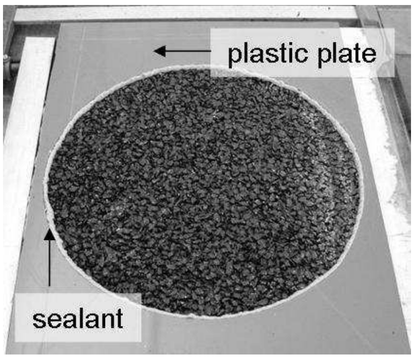
b) 

Figure 7 - (a) Preparation of the mosaic; (b) VTAC specimen prepared for friction tests

3.1.4 Test procedure

The wetted surface is delimited by a plastic plate, in which a circle of 345 mm of diameter was cut (Fig. 7b), affixed to the specimen slab. The edge of the circle is filled with a sealant to avoid water flowing from the test area. Finally, the slabs are covered, except on their upper face, by a layer of waterproof material in order to prevent the water from flowing out of the sample. The spraying operation can be considered reasonably accurate with the specimens used for the tests. Actually, when 6 g (average sprayed quantity before each friction measurement) is sprayed on 0.1 m² ($\approx \pi \times \left(\frac{0.345}{2}\right)^2$) and, assuming that 10% of this amount of water is sprayed outside the measurement area, it implies an error of only 0.006 mm on the estimated water depth.

For each friction test, new sliders are used to ensure that slider wear does not affect results. The test surface is leveled and free of any contamination. The DFT is placed above the slab using visual markers to ensure that it is always placed at the same location. Compared with the ASTM standard [8], the test procedure is modified to study the influence of water depth on friction coefficient. Actually, the machine is programmed to run tests with no water from the supply unit; water is then added uniquely by the spray. After a first measurement performed on a perfectly dry surface, the following procedure is repeated 12 times:

- Wetting of the slab surface by nine sprayings (≈ 6 g of water);
- A friction measurement is performed;
- Weighing of the spray.
- At the end of the procedure, a test using the standard procedure for the DFT is performed.

3.2 On site

3.2.1 ADHERA device

The Adhera device (Fig. 8) measures a Longitudinal Friction Coefficient (LFC) with a slip ratio of 100% (blocked wheel). The LFC is defined as the ratio between the horizontal force (F_H) due to the friction in the tyre/road contact and the vertical load (F_V). The static value of F_V corresponds to the load of the system (2 500 N). The speed of the vehicle can vary from 20 to 130 km/h and the water thickness in front of the test wheel ranges from 0.25 mm to 3 mm. Both standardized test tyres as smooth PIARC tyres and commercial tyres from 155x65x15 to 205x45x16 can be tested.

Figure 8 – ADHERA device

3.2.2 Measurement of water depths

The water depth provided by the ADHERA device is a standard value determined by considering the road surface as a smooth surface. The water film thickness is obtained by regulating the water flow of the water pump. The water flow depends on the vehicle speed. The theoretical values of water depth are given in figure 9.

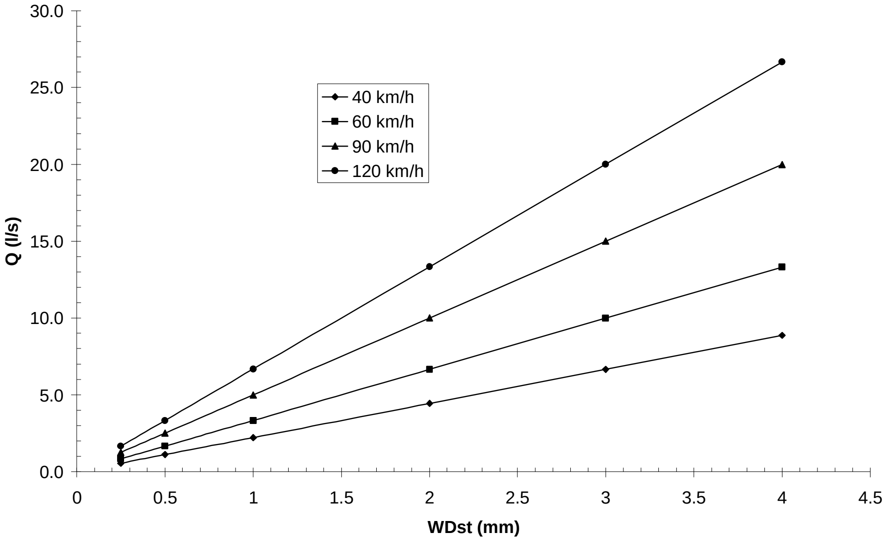
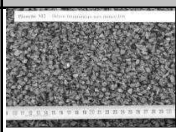
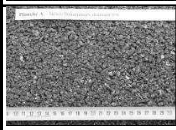
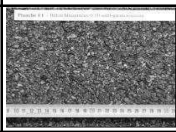
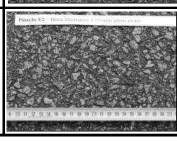


Figure 9 – Water film thickness versus speed

3.2.3 Test tracks

Tests are performed on Ifsttar test tracks. Various pavement surfaces are considered in this study. The characteristics of the mixes, which represent actual pavement surfaces in France, are given in Table 1. A wide range of microtexture and macrotexture is covered.

Table 1: Tested surface pavements characteristics

Type of pavement	Size of aggregates (min/max)	Acronym	Photography	SFC	MPD (mm)
Very Thin Asphalt Concrete	0/6	VTAC 0/6		0.56	1.00
Very Thin Asphalt Concrete	0/10	VTAC 0/10		0.71	1.30
Porous Asphalt Concrete	0/6	PAC 0/6		0.65	2.90
Surface Dressing	0.8/1.5	SD 0.8/1.5		0.90	0.45
Semi-coarse Asphalt Concrete (old)	0/10	SCAC 0/10		0.73	0.66
Semi-coarse Asphalt Concrete (new)	0/10	SCAC 0/10		0.59	0.82

3.2.4 Test procedure

The on-site tests aimed at representing the variation of LFC with water depth on various pavement surfaces at different test speeds.

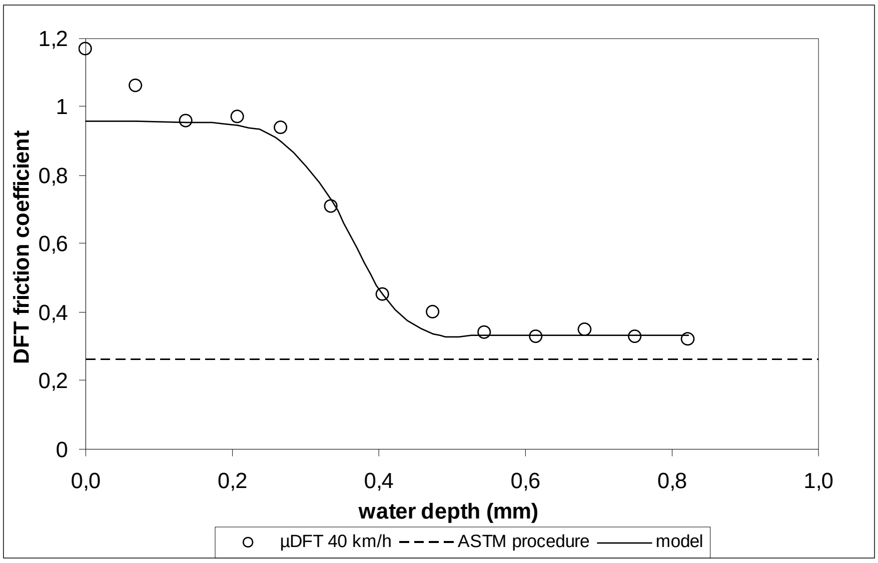
Three speeds are considered: 40, 60 and 90 km/h. For each speed, the device adapted automatically the water flow. The water pipe is opened few seconds before arriving on the testing area to obtain a stabilized water flow and a water depth as uniform as possible behind the tire.

Tests are performed with six water depths: 0.1 – 0.25 – 0.50 – 0.75 – 1 – 1.5 mm. The operators let few minutes between two successive measurements to avoid water accumulation on test tracks.

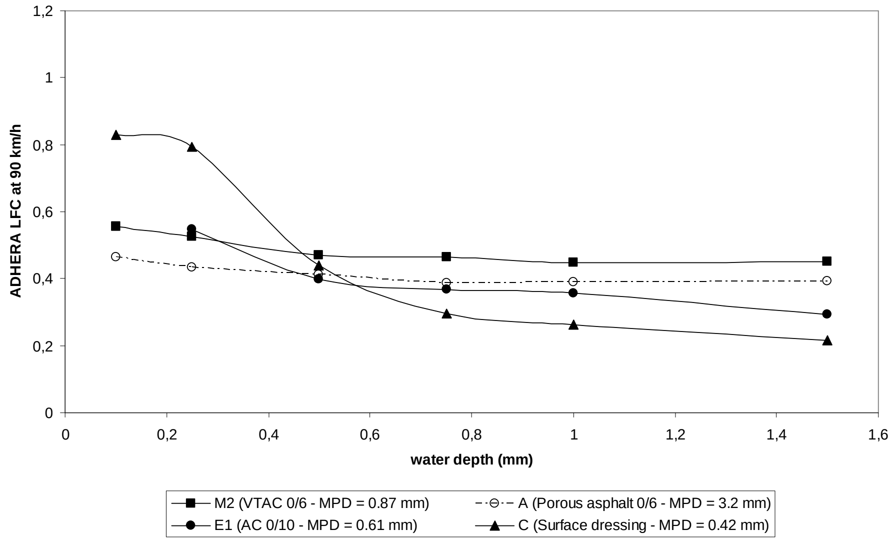
4 FRICTION/WATER DEPTH PLOT

4.1 Shape of the friction/water depth curve

Examples of friction/water depth plots derived respectively from in-laboratory and on-site test data are shown in figure 10. The X-axis represents the water depth. The Y-axis represents respectively the DFT friction coefficient (Fig. 10a) and the ADHERA LFC (Fig. 10b). For the DFT plot, friction coefficient obtained by applying the ASTM procedure [8] is also shown.



a)



b)

Figure 10 - Example of the variation of friction coefficient versus water depth (a: in-laboratory; b: on-site)

The observed shape is different from that found in previous works where an exponential variation of friction with water depth is observed [2][5]. During the first tests (unpublished) aiming at developing an appropriate test procedure, water was sprayed on the primarily dry surface until it appears wet. This procedure induced actually an exponential variation of friction with water depth. The difference between the figure 10 and published results can then be attributed to the water quantity sprayed on the dry test surface to obtain the first wet state. If too much water is sprayed, the transition from “dry” to “wet” can be missed.

The shape of the curve derived from our experiments is similar to that of the well-known Stribeck curve (Fig. 11) although the X-axis is not the same.

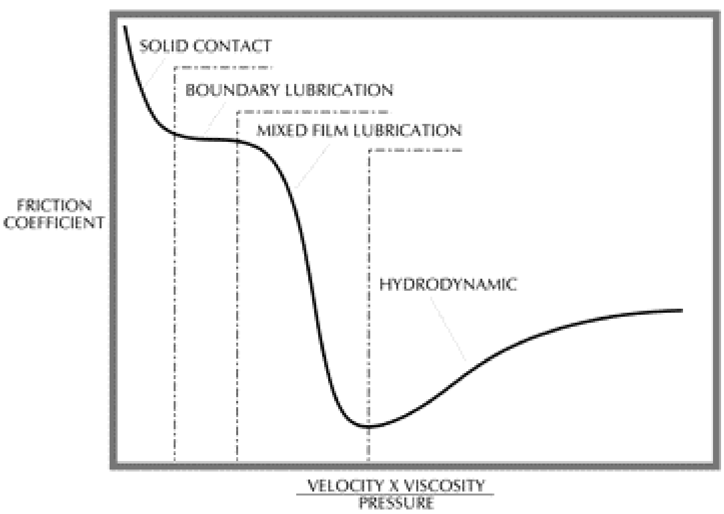


Figure 11 - Stribeck curve [10]

The Stribeck curve relates relative velocity (V), fluid viscosity (η) and pressure (p), using the number ηV/p, to friction coefficient. Schipper [11] proved that there exists a relationship between the lubricant depth (h) and ηV/p in the case of elasto-hydrodynamic lubrication:

(2) $$h \propto \left(\frac{\eta V}{p}\right)^{0,7}$$

Based on Schipper results, it can reasonably be said that the obtained friction/water depth curve exhibits the same lubrication regimes as those identified in a Stribeck curve (Fig. 11): boundary, mixed and hydrodynamic. It means that the understanding of tire/wet road friction mechanisms, and consequently their modeling, can be enhanced by taking benefit of existing knowledge acquired in tribology. Actually, the graph in figure 10a exhibits also a solid-contact phase. This phase is not considered in the following analyses as it occurs only on few surfaces – surfaces covered by a relatively thick binder layer or smooth river coarse aggregates – where water drops do not “stick” to the test surface during the first sprays and then some adhesions might occur.

Figure 10a shows that the DFT friction coefficient measured by the ASTM procedure represents the lowest friction value that can be expected.

Comparison between figures 10a) and 10b) also shows that in-laboratory and on-site observations are similar. The laboratory is more complete in terms of lubrication regimes. A plausible explanation is that water spray is more easily controlled in laboratory than on site and, by consequence, it is easier to follow the variation of friction with water depth in laboratory. As variations are similar, analyses presented in the following sections will be focused on laboratory results only.

4.2 Modeling of the friction/water depth curve

A model was developed to fit the shape of the friction/water depth curve derived from our experiments:

(3) $$\mu = \Delta\mu \cdot e^{\left(-\frac{h}{h_0}\right)^{\alpha}} + \mu_F$$

Where μ: friction coefficient;
h: water depth;
μ_F: final friction coefficient;
$\Delta\mu$: difference between $\mu(0)$ (μ at $h = 0$) and μ_F;
h_0, α: constants.

The new model is similar to that proposed by Kulakowski [5] but can simulate other shapes than the exponential one. Actually, if $\alpha = 1$, an exponential variation can be found. For $\alpha \neq 1$, other shapes can be found. The continuous line in figure 9a shows how the model (3) fits experimental data.

5 CRITICAL WATER DEPTH

5.1 Definition

The word “critical” is used by road authorities to decide whether warnings must be sent to road users or not. The same word can be used by car manufacturers to activate driver assistance systems. In the context of warning or driver assistance on wet roads, people look for a critical water depth, which can be measured or estimated in real time, above which something must be done. Based on the shape of the friction/water depth curve, it appears that the most critical phase is the transition from boundary to mixed lubrication regimes where friction can drop drastically even if the road surface still displays an apparent “safe” aspect.

Dividing the friction/water depth curve into three parts: boundary, mixed and hydrodynamic lubrication, each part of the friction-water depth curve is linearized as shown in the figure 12: a horizontal line to represent the stable friction level during the boundary lubrication phase (BL), a sloped line to represent the mixed lubrication phase (ML), and again a horizontal line to represent the hydrodynamic lubrication phase (HL). Actually, friction should increase slightly during the hydrodynamic phase due to drag forces. However, within the experimental set up, no variation curve experienced such a tendency; a horizontal constitutes then a good approximation.

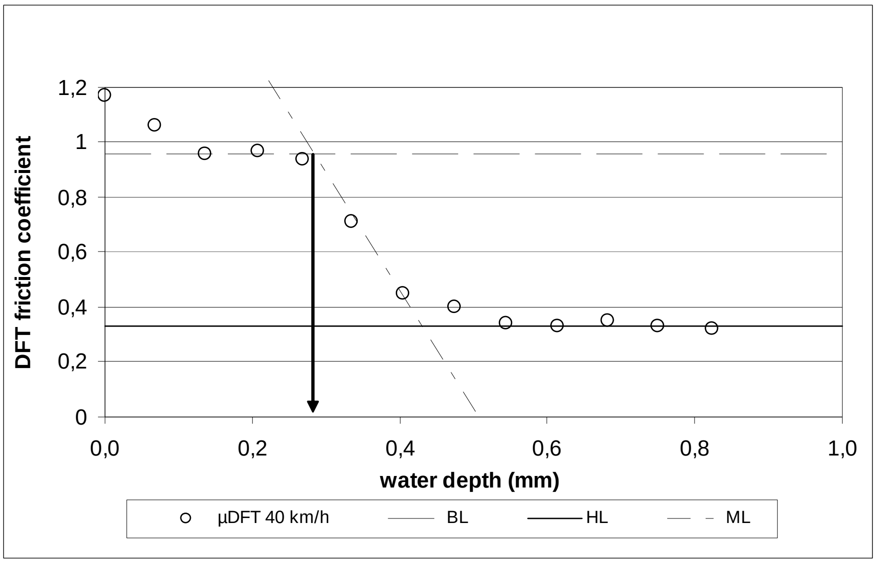


Figure 12 - Linearization of the friction/water depth curve

The critical water depth is then defined as the amount of water obtained at the intersection between the boundary lubrication and mixed lubrication lines (arrow in figure 12). From this point, a small additional amount of water is sufficient to degrade significantly the friction coefficient. Within the frame of our experiments, critical water depths lower than 1 mm were found. Such critical water depths can also determine the onset of viscoplaning as discussed in the introduction.

The remaining of the paper focuses on the critical water depth and highlights how it is affected by factors related to the tire/road contact such as speed or road surface texture.

5.2 Influence of the test speed

Figure 13 shows the variation of the critical water depth with the test speed. The very thin asphalt concrete specimen (VTAC) is considered.

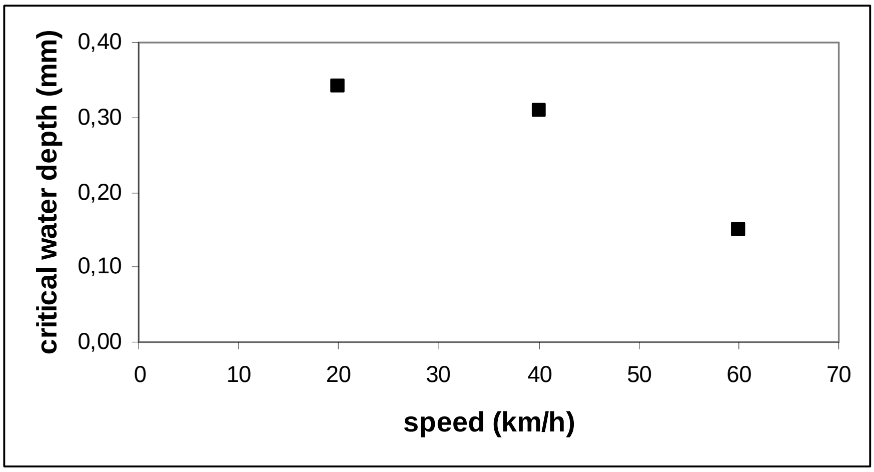


Figure 13 – Variation of critical water depth with speed

Critical water depth tends to decrease with test speed. This tendency is logical since increasing speed leaves less time to evacuate water from the tire/road contact area and, consequently, induces a rapid transition to the mixed lubrication regime. It can be seen that critical water depths are similar at 20 and 40 km/h (0.34 and 0.31 respectively) and higher than that at 60 km/h (0.15). It suggests that the effect of speed on the critical water depth is only significant above a certain speed. This confirms observations made by Veith [2].

5.3 Influence of the surface microtexture

Since the present study deals with thin water films, it is thought that the influence of road surface microtexture is the most preponderant. Microtexture is conventionally defined as surface irregularities with wavelengths under 0.5 mm and peak-to-peak amplitudes from 1 to 0.5 mm [14]. It is a function of the surface properties of the aggregate particles contained in the asphalt. It assists in squeezing thin water films in order to provide effective contact between road and tire.

The influence of the surface microtexture can be assessed by comparison of results obtained from the aggregate mosaic before – smooth – and after – rough – sandblasting. Figure 14 shows that when the surface is dry, the smooth surface exhibit higher friction value than the sandblasted surface does. This is due to the fact that dry friction depends on available contact area, which is larger on smooth surfaces. However, the friction coefficient of the mosaic before sandblasting, called “smooth” in figure 14, drops rapidly as soon as the surface is wetted. In contrast, the sandblasted mosaic displays a more stable variation of the friction coefficient with the water depth. Also, it can be seen that, even if both surfaces experience friction decrease with water depth, the sandblasted curve is always above the initial-state curve. These observations corroborate those made by Moore on smooth and roughened spheres [1].

Figure 14 clearly highlights the role of the surface microtexture to mitigate the risk of a brutal degradation of wet pavement skid-resistance while maintaining a high friction level. When the surface is wetted, asperities, mainly sharp ones, are needed to squeeze out the water film. Otherwise, as it happened with the smooth mosaic, water, even at very thin thicknesses, can penetrate very quickly in the tire/road contact area and causes contact loss between the tire and the road.

The above analysis is a first attempt to assess the influence of microtexture on the onset of viscoplaning. A more rigorous analysis, using quantitative microtexture descriptors derived from surface profiles, is underway.

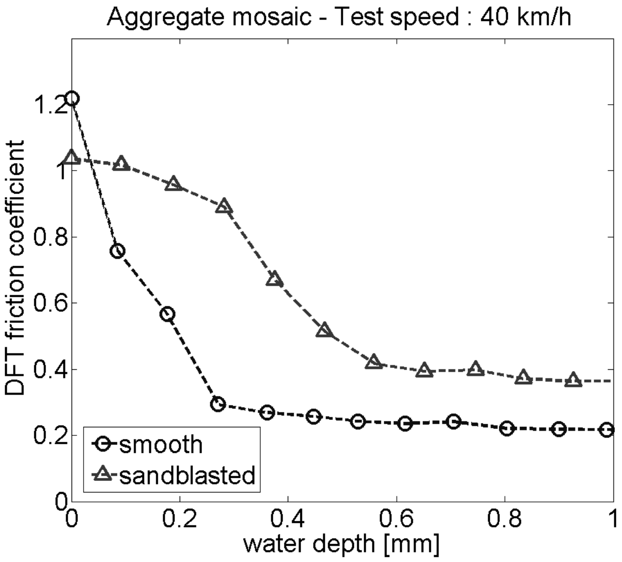


Figure 14 – Influence of surface microtexture on friction coefficient

6 CONCLUSIONS

In this paper, study of tire/wet road friction was presented. Focus was made on the effect of thin water films (< 1 mm) which occur after rainfalls or during drizzles. Despite the apparent safety feeling provided by a damp aspect of the road surface, thin water films can alter already significantly the available road friction and reduces contact between the tire and the road.

In the first part, friction tests both in laboratory and on site were presented. Using a basic method to wet the surface and estimate the average water depth, due to the absence of sensors to measure accurately thicknesses of tenth of millimeter on road surfaces, friction/water depth curves were obtained. Different in shape from previously published curves, the new curves are similar to the well-known Stribeck curve. It was then possible to identify different lubrication regimes occurring at the tire/road interface. Using a simple mathematical function to represent the observed results, a so-called “critical water depth” was derived. It represents the water depth at which transition between the boundary and the mixed lubrication regimes occurs. This new definition, compared with the few ones found in existing literature, is more physical and can be used to determine the onset of viscoplaning.

Further analyses were made to assess the influence of some factors on the critical water depth. It was found that critical water depth decreases with speed, mainly above 60 km/h within the frame of our experiments. Observations are logical and can be explained by considering the way by which the water penetrates the tire/road contact area. The influence of road surface microtexture has been clearly demonstrated: friction coefficient on wet microtextured surfaces is maintained at a level comparable to that of a dry surface until a critical water depth is reached, whereas friction coefficient on smooth surfaces drops as soon as the surface is wet. Surface microtexture is then needed to prevent a brutal degradation of skid resistance. Our results corroborate those from previous studies. Progress has been made because our observations have been made on actual road surfaces whereas those found in the literature are derived from modeled surfaces (spheres, cones, etc.). Efforts, mainly by means of modeling, are still needed to better assess the conditions of viscoplaning onset.

7 ACKNOWLEDGEMENTS

The authors gratefully thank the financial support of the SKIDSAFE project (Enhanced Driver Safety due to Improved Skid Resistance). Technical support of Mr. Patrick Maisonneuve for laboratory tests is highly appreciated.

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