Laboratory test methods for polishing asphalt surfaces and predicting their skid resistance

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LABORATORY TEST METHODS FOR POLISHING ASPHALT SURFACES AND PREDICTING THEIR SKID RESISTANCE

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ABSTRACT

In this paper, laboratory test methods reproducing phenomena affecting pavement skid resistance evolution are presented. Polishing tests are performed by Wehner/Schulze machine to simulate the polishing induced by traffic and the binder removal phase (typical for bituminous asphalt concrete). Accelerated ageing tests are performed by a weatherometer, operating conditions being adjusted according to local weather conditions, to simulate the binder ageing responsible for friction increase at early age. With respect to seasonal variations, a new test was developed to evaluate the effect of pollutants deposited on the road and the washing effect of rainfalls. Description of specimens and test procedures is given. Simulations are compared to observations to check their relevance.

A model is developed to combine, in a physical way, laboratory test results and give place to a prediction of the friction-polishing duration curve. Conversions are done to predict actual skid resistance variation from laboratory polishing curve. Predictions are compared to road data and results are discussed.

Key words: friction, evolution, polishing, ageing, modeling.

INTRODUCTION

Skid resistance of asphalt pavement continuously evolves due to traffic actions and climatic conditions. For infrastructure authorities and road companies, it would be valuable to dispose of tools to forecast such variation for whether new construction or existing road, in order to anticipate maintenance and optimize material use respectively. Long-term skid-resistance is usually assessed by means of PSV value of coarse aggregates *(1)*. This solution is not economical, since all quarries cannot provide this aggregate quality. In addition, performance of new mix design (for instance, sustainable solutions mixing aggregates whether of different PSV values or using recycled aggregates) cannot be assessed by means of the PSV. Without any appropriate laboratory test method, large-scale experiments are conducted to assess the feasibility of alternative solutions. This approach is expensive and time consuming and, by this fact, the number of solutions eligible for testing is limited.

Researches have been conducted at IFSTTAR since 2002 to see how a combination of quick laboratory tests and modeling can help to overcome the drawbacks listed above and to move toward a prediction of the variation of friction coefficient with time and traffic. This paper presents a state of progress after ten years of investigation. Results are extracted mainly from two Ph.D. theses *(2)(3)* and some related publications *(4)(5)(6)*.

BACKGROUND

Phenomena Affecting Skid Resistance Evolution

Skid resistance variation vs. time for a wearing course is due to at least four phenomena. They are listed below in the decreasing order of knowledge and understanding:

- Polishing. Tourenq and Fourmaintraux *(7)* demonstrated that two mechanisms can arise: “general polishing”, which removes materials and smoothes off coarse-aggregate edges, and “differential polishing”, which regenerates relief on aggregate faces between soft and hard minerals, the first ones being more attacked by wear than the second ones.
- Binder removal. Skid resistance of newly placed asphalt wearing courses is not high due the binder layer masking the road surface microtexture. As traffic gradually removes the binder, the skid-resistance increases and reaches a maximum when the binder is fully removed.
- Seasonal variations. Skid resistance generally records its lowest value at the end of summer and its highest during winter, with the variation approximating a sinusoidal function *(8)*. The actual cause of this variation is not well understood. According to the most widespread explanation, during the summer, it is presumed that dust is trapped between the tire and the road surface and accelerates the polishing, and during the winter, rainfall cleans the road surface and makes it rougher by microtexture recovering or chemical reactions.
- Ageing of the bitumen. This ageing phenomenon is due to climatic actions (temperature variations, oxidation, acid rain). The consequence of the ageing is not well documented.

Most developments of laboratory testing methods are dedicated to the simulation of polishing actions. In the following section, existing machines are briefly reviewed.

Polishing tests

Simulation of polishing action was first developed for aggregates in the 1950s by Transport Research Laboratory (TRL). The test method is now standardized and widely known as the PSV test (Polished Stone Value) *(1)*. The curve shape of PSV specimens make them unsuitable for asphalt testing. Other machines are then developed to polish asphalt specimens. The polishing principle is based mostly on the friction between rubber (wheels or pads) and asphalt surface. Two friction modes are employed: the sliding friction by pads, or the rolling friction by wheels, or equivalent supports, equipped with tires. References *(8)(9)* give two examples of machines applying respectively the two friction modes. Machines usually are prototypes and few results are found regarding the link between laboratory results and actual road observations.

Models Predicting Skid Resistance Evolution

Some prediction models are listed in Table 1. The main difference between Huschek model and the two other is that Huschek model does not display the aggregate PSV as an explanatory variable and the variation of friction coefficient depends on the sign of constant (b). It can be seen later that the direction of friction variation with time and traffic depends on the phenomena listed above and therefore its prediction needs a more comprehensive model.

TABLE 1 Models Providing Skid Resistance Evolution And Long Term Value

Authors	Model
Diringer et al. *(10)*	$\mu_{min} = c_0 \cdot \left(1 - e^{c_1 \cdot PV}\right) + c_2 \cdot PV$ where: PV = friction coefficient measured on PSV specimen after more than 10 hours of testing; and c_0, c_1, c_2 = constants to be obtained by fitting.
Roe et al. *(11)*	$\mu_{min} = a \cdot PSV - b.\ln(CVD) + c$ where: PSV = friction coefficient measured once the standardized test procedure is completed; CVD = number of light vehicles per day and per lane; and a, b, c = constants to be obtained by fitting.
Huschek *(12)*	$\mu = a \cdot (t+1)^b$ where: t = pavement age expressed in years; a = friction coefficient measured just after road construction; and b = constant to be obtained by fitting.

RESEARCH NEEDS

With respect to laboratory testing, there is a need to dispose of methods to simulate actions of phenomena affecting skid resistance evolution. Laboratory results have then to be linked to road data to see how simulations are close to the real world. As testing alone cannot reproduce the complexity of involved phenomena, mainly their interaction, modeling has to be performed in parallel to transform test results in predictions.

Researches carried out at IFSTTAR have been dedicated to the following aspects:

- polishing test for road materials;
- laboratory tests to better understand the effect of binder ageing and seasonal variations;
- predictive model.

Progresses achieved respectively in the three aspects, mainly the way they are linked one to the other, are reported the following sections.

POLISHING TEST FOR ROAD MATERIALS

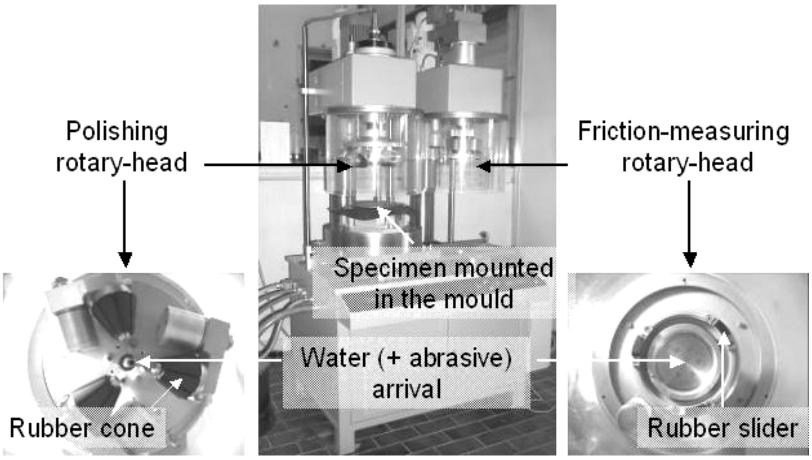
Details on the development of the polishing test can be found in *(2)(4)*. The following sections highlight the main findings.

Testing Machine

Polishing tests are performed by the Wehner/Schulze machine (Fig. 1) developed in Germany 40 years ago. The choice of this machine is based on visual observation of surface of polished specimens which looks like road surface subjected to traffic (surface covered by a black layer composed probably of tire wear debris, road debris and dust).

Specimens are circular discs of 225mm in diameter, thickness of which varying between 15mm and 45mm. They can be whether taken from pavements or laboratory-made slabs, or made of resin with the upper face composed of a coarse-aggregate mosaic (this type of specimens is dedicated to aggregate testing).

The machine has two rotary heads dedicated respectively to polishing and friction tests. Polishing is performed by means of three rubber cones (Fig. 1a) mounted on one rotary head and rolling on the specimen surface (rotation frequency: 500 rotations per minute; nominal pressure: 0.4 N/mm^2). A mix of water and abrasives is projected on the specimen surface during the test. The polished part is a circle of approximately 16cm in diameter and 6cm in width (Fig. 1b).

a)


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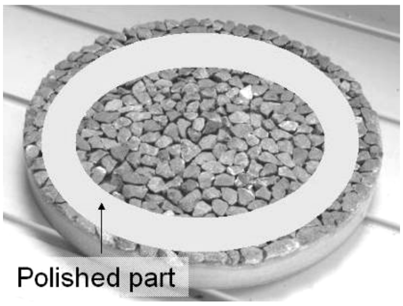


FIGURE 1 Wehner/Schulze machine (a: view of the machine and the two rotary heads; b: specimen and illustration of the polished part).

Friction test is performed by means of three rubber pads mounted on the second rotary head (Fig. 1a) (surface of each pad: 4cm^2; nominal pressure: 0.2 N/mm^2). The rotary head is accelerated until a speed of 100km/h is reached, the water-plus-abrasive mix being projected at 90km/h. The motor is then stopped and the head is lowered until the rubber pads touch the specimen surface. A braking curve is recorded from 100km/h until complete stop. Value of friction coefficient at 60km/h, expressed as μ_{WS}, is extracted for analyses. The speed value was chosen according to that of SCRIM devices, which are currently used for road monitoring in France.

Testing procedure

Polishing is stopped every 1,000 passes until 15,000 passes. Then stops are done at 20,000-50,000-90,000-180,000 passes; the end of the test procedure is conventionally fixed at 180,000 passes. Friction is measured at each stop. One single braking is performed to get the value of friction coefficient at a given polishing state. Example of results, expressed as the evolution of friction coefficient with number of passes, is shown in figure 3.

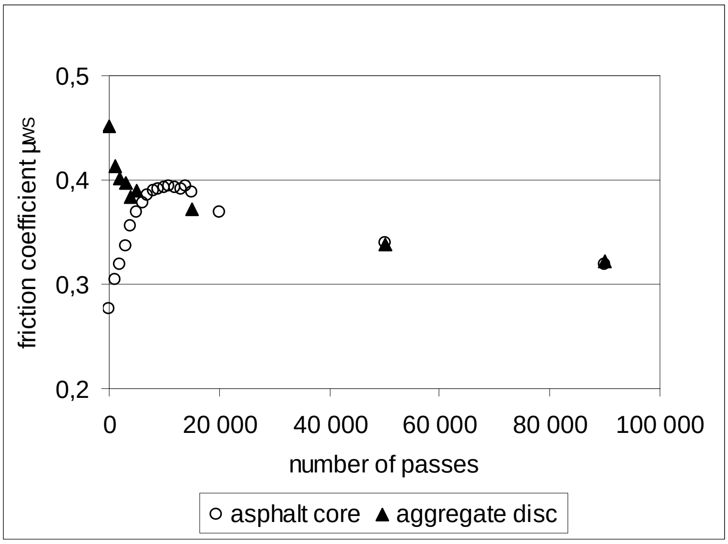


FIGURE 3 Friction evolution plot resulting from Wehner/Schulze polishing test.

Results for asphalt specimen clearly shows the two phenomena cited in the background section: binder removal induces an increase of friction coefficient from the original value to a maximum, then polishing induces a decrease of friction coefficient; this observation corroborates those made on actual roads. The aggregate plot starts logically from a maximum then joins, for this example, the asphalt plot.

Polishing test using Wehner/Schulze machine can replicate two major evolution mechanisms induced by mechanical actions. To deal with skid resistance variation in a comprehensive manner, other tests reproducing time-dependent evolutions have to be developed.

CONSIDERATION OF OTHER PHENOMENA

Binder ageing

Friction test performed on specimens left outside and not subjected to any mechanical actions shows a significant increase of friction coefficient (gain of 0.2 compared with the original value) with time (Fig. 4). This evolution is attributed to changes of binder properties and has to be taken into account for an accurate prediction. The graph in figure 4 shows that with natural ageing, one year at least is needed before the friction coefficient stabilizes. An accelerated laboratory test has then to be developed to simulate the ageing process. This work had been done extensively in *(3)* and synthesized hereafter.

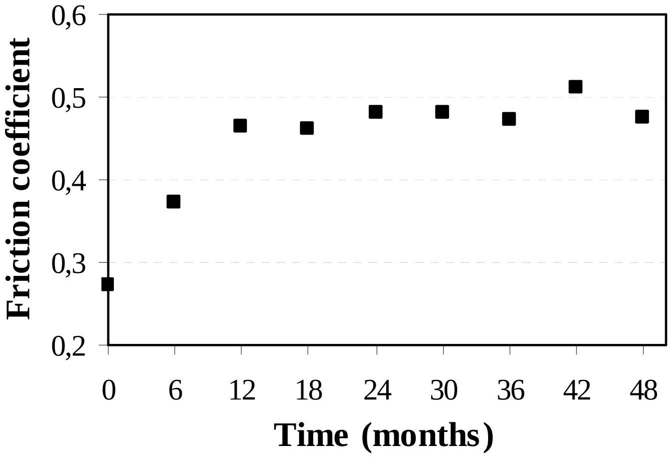
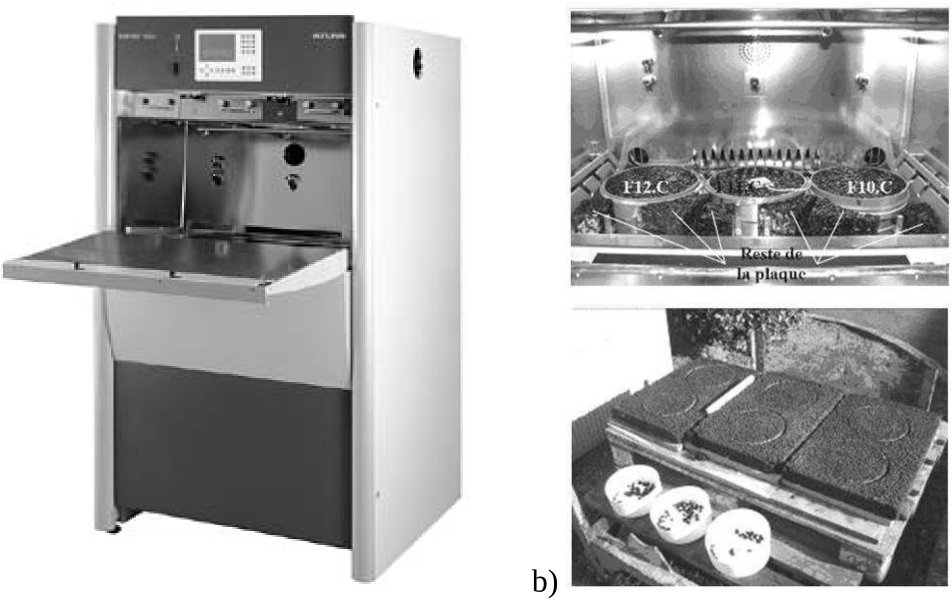


FIGURE 4 Evolution of friction coefficient due to natural ageing.

Ageing machine

The weatherometer (apparatus in which specimen materials can be subjected to artificial and accelerated tests which simulate natural weathering) SUNTEST XXL is used to accelerate the bitumen ageing process (Fig. 5). It is also possible to control the relative humidity and simulate rainfall with a wetting system.

The lighting system consists of three irradiators equipped with xenon lamps, specially designed to simulate natural sunlight. The radiation is absorbed by a quartz filter and is distributed by a curved reflector. A black panel with a temperature range of 45°C to 100°C, is used to control the temperature at the specimen surface. The humidification system allows varying the air relative humidity in the chamber between 20% and 95%. The watering system, present inside the chamber, can wet the specimens with an adjustable flow rate of up to 0.3 liters per minute.



a) b)

FIGURE 5 Ageing test (a: weatherometer for accelerated test; b: specimens artificially and naturally aged).

Accelerated ageing test procedure

The main goal of accelerated ageing tests is to bring answers to the following questions:

- Is the test representative of actual conditions of natural ageing?
- What is the equivalence between the durations of accelerated ageing and natural ageing?

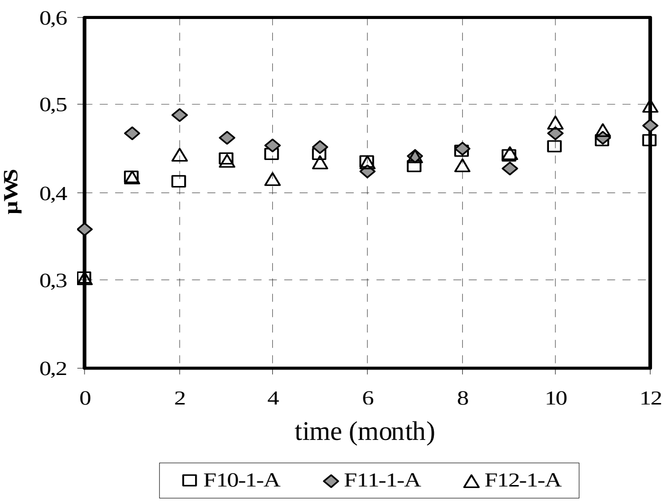
Weather conditions in Nantes region (data from Meteo France from 1961 to 1990) are used as reference to define the operating parameters of the machine. According to available data, one year of rainfalls in Nantes generates 820mm of water; the machine water flow is then set at 0.110 mm/min (12 wetting hours in total). Humidity of 81% is chosen (annual average humidity in Nantes). With respect to solar radiation (one of the main causes of ageing), in order to reach 215 MJ/m² in one year (average annual radiation in Nantes), the duration of exposure is 995 hours.

From the above estimates, 500 cycles of 2h are applied. Each cycle consists of 2 minutes of wetting and 118 minutes of drying under irradiation. Friction is measured every 24h using the Wehner-Schulze machine.

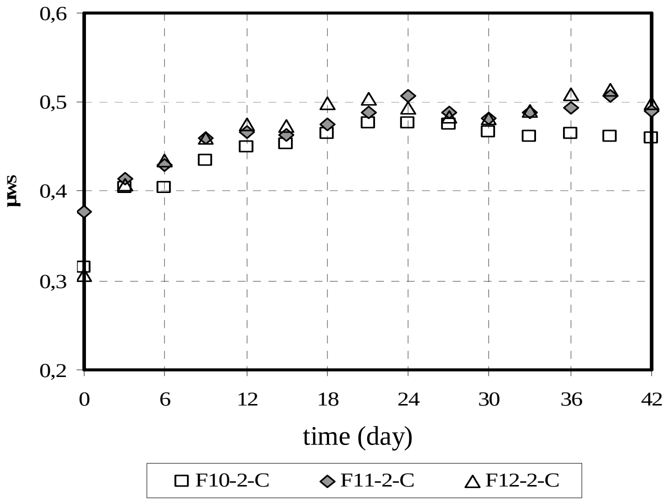
From laboratory accelerated ageing test to natural ageing prediction

Figure 6 shows comparisons of the evolution of friction coefficient for respectively naturally (Fig. 6b) and artificially (Fig. 6b) aged asphalt specimens. Characteristics of specimens can be found in *(3)*. For the natural sample ageing process, the samples were left outside (Fig. 5b, bottom) so as to expose them to the various climatic conditions.

It can be seen that for both forms of ageing, the friction coefficients of the three samples are very close. These observations clearly confirm the ability of reproducing the effect of natural ageing on pavement by the accelerated ageing protocol.



a)



b)

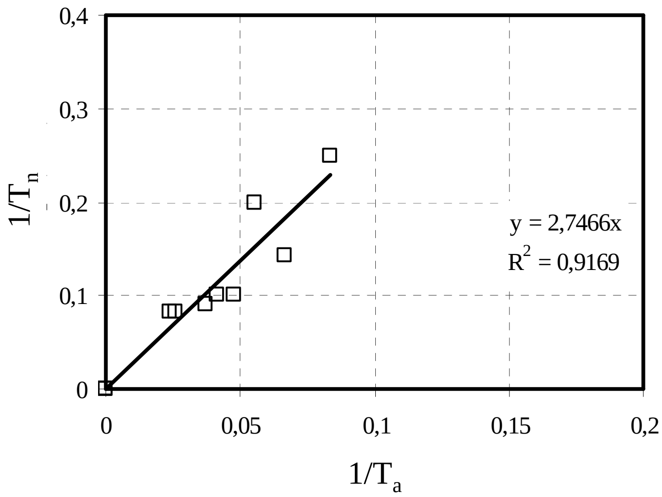
FIGURE 6 Comparison of evolution of friction coefficient due to natural/accelerated ageing.

To make a prediction of the evolution of friction coefficient, it is now necessary to establish a relationship between the "accelerated time" T_a, in days, and "natural time" T_n, in months. Simple linear relationship is used:

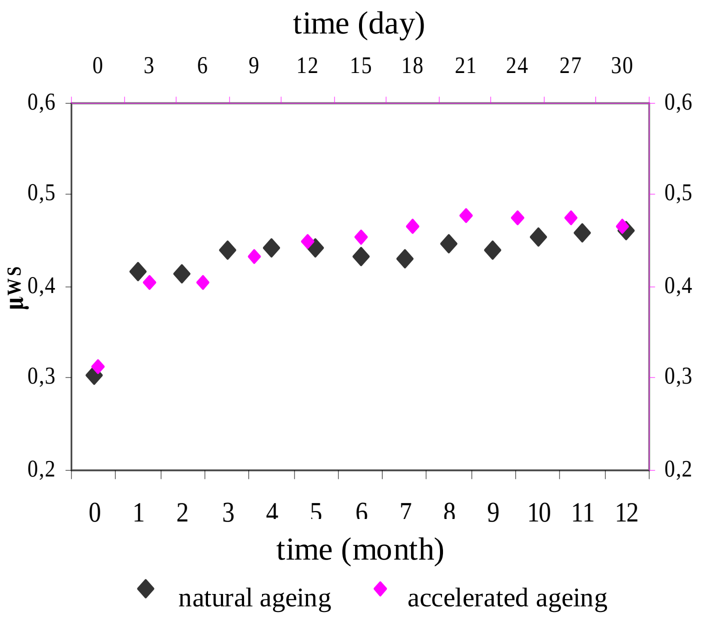
(1) $T_a = k_v T_n$

where: k_v = constant to be determined.

Determination of (k_v) can be done by fitting the graphs of figures 6a and 6b. Couples (T_a, T_n) for which difference between respective μ_{WS} values is less than 0.005 are plotted; figure 7a shows an example of $1/T_a$-$1/T_n$ plot. The slope of the regression line gives k_v. Figure 7b shows the evolution of friction coefficient by artificial/natural ageing after X-axis conversion with k_v. The quality of the superposition proves that the developed accelerated ageing test can reproduce natural ageing process.



a)



b)

FIGURE 7 Determination of (k_v) constant (a) and resulting superposition of accelerated and natural ageing plots (b).

To provide a physical explanation of binder ageing, another conversion method is developed in *(3)* and summarized hereafter. The degree of binder oxidation is used as a basis for comparison of the accelerated and natural ageing tests. Indeed, two chemical entities result from binder oxidation during the ageing process: sulfoxide and carbonyl. The increase in these chemical functions reflects the fact that ageing is accompanied by binder hardening. By measuring these chemical functions in samples subjected to both forms of ageing, the conversion factor k_v can be determined. A non-destructive technique was developed to determine the carbonyl index. For each asphalt specimen, two bitumen coated aggregates are extracted and immersed in a solvent. The mineral part is then separated from the organic – bitumen – part by centrifugation. The infrared absorption spectrum is then measured directly on the mixture solvent + bitumen from which the carbonyl index can be estimated *(3)*. Value of (k_v) can be determined from the following formula:

(2) $I_{ca} = k_{v,chem} I_{cn}$

where: I_{ca} = carbonyl index of bitumen subjected to artificial ageing; I_{cn} = carbonyl index of bitumen subjected to natural ageing; and $k_{v,chem}$ = constant k_v determined by chemical-based method.

It was proved in *(3)* that k_v and $k_{v,chem}$ values are similar. Even if the chemical-based method is more complex to use, it provides a satisfactory explanation of the binder ageing process and constitutes a relevant complement of the curve-fitting based method (formula (1)).

Seasonal Variations

In addition to the classical follow-up of friction coefficient (measurements performed every month), attempts are made to investigate the effect of pollutants deposited on the road (tire wear debris, road debris, dust, etc.) that might contribute to seasonal variations of skid resistance. Actually, in addition to temperature effect, low friction values during summer, or after long dry periods, can be due to the viscous lubricant created by a mix between pollutant particles and the very first water drops. During autumn or winter, rainfalls induce a washing effect and friction coefficient should increase and retrieve the value (minus probably a decrease induced in the meantime by polishing effect) before the pollutant deposit.

A test method is then developed to check the validity of the above explanation *(3)*. Sediments from runoff water are first collected directly at storage basins. Specimens are dried in laboratory and sieved; only particles smaller than 200µm are conserved. The test procedure is the following:

- mix sediment particles with water;
- pour the mix on the specimen surface and wait until drying is complete. Uniform distribution of sediments can be obtained by means of this method;
- perform friction measurements by means of the British Pendulum. For each run, fixed quantity of water – increment – is poured on the specimen surface; weighing is performed to determine the exact quantity (in grams). Friction coefficient is recorded from one swing.

Three water increments are tested (0.3g, 1.5g, 3g) to simulate respectively increasing rainfall intensities. Figure 9a shows an example of specimen prepared specifically for this test. The waterproof sheet is slightly raised, compared with the specimen surface, to retain the water-plus-sediment mix. Figure 9b shows the variation of friction coefficient with added water, expressed by weight.

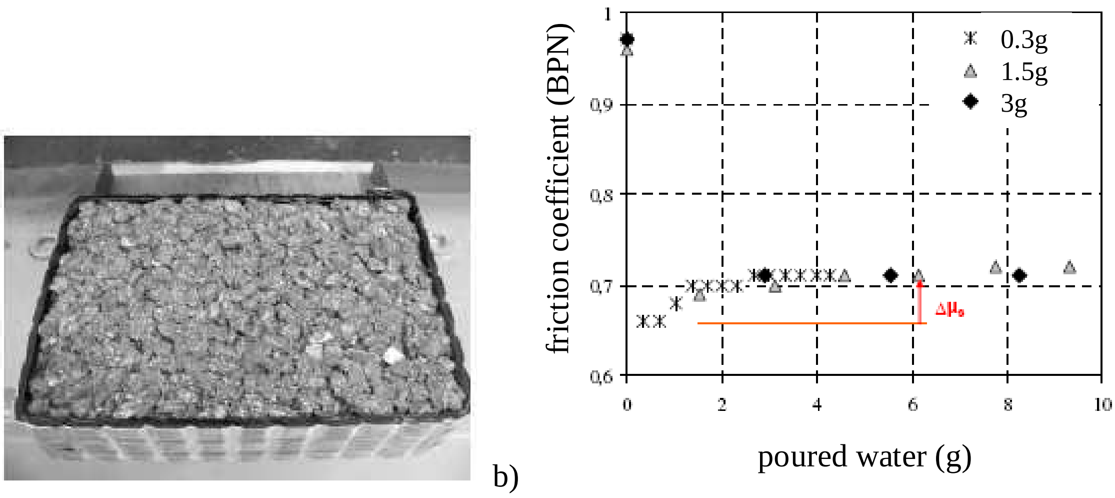
a)  b)

FIGURE 9 Test to evaluate the combined actions of pollutants and water (a: specimen; b: test results).

Friction drop as soon as water is added confirms the first assumption regarding the viscous nature of the water-plus-sediment mix. This drop is probably at the origin of the widely known “black ice” phenomenon in summertime. The slight increase ($\Delta\mu_0$ = 0.05, Fig. 9b)) confirms the washing effect. For 1.5g and 3g water increments, friction coefficient drops to a value lower than the “dry” one and remains stable afterward. The fact that friction coefficient stabilizes after a given quantity of poured water (2g) regardless of water increment values proves that once the sediments are washed out, the surface retrieves its skid resistance.

Protocol of the test above needs further improvement. However, this first attempt provides already further insight in the mechanisms causing seasonal variations. Beside the widely known temperature effect, care should be taken with respect to the presence of pollutants.

FROM TESTING TO PREDICTION

As it was said in "Research needs" section, laboratory tests help to understand and quantify effects of various phenomena. Results from these tests cannot be used separately to predict skid resistance variation. One approach can be using these results as explanatory variables in a statistical model. Approach adopted at IFSTTAR is different: the predictive model is developed from consideration of physical phenomena and the model parameters are determined from the laboratory tests described in previous sections. Details of theoretical development can be found in *(2)(6)* and summarized hereafter.

Predictive model

The friction coefficient measured on an asphalt surface can be written as:

(3) $$\mu = (1-d)\cdot\mu_B + d\cdot\mu_G$$

Where: μ = friction coefficient; μ_B = friction coefficient measured on the binder-covered part; μ_G = friction coefficient measured on the binder-removed part; and d = factor varying between 0 and 1.

Physically, the weight factor (d) represents the binder-removed surface fraction. The μ_B component is time dependent due to the time dependency of bitumen properties. Since the binder removal is traffic and climate dependent, the weight factor (d) varies with the number of vehicles and time. Actually, aggregates also evolve over time but, compared with the pavement lifetime (between ten and twenty years), their characteristics can be assumed to remain constant. Therefore, μ_G depends only on the number of vehicles.

The predictive model is written as:

(4) $$\mu = e^{\left(-\frac{N}{N_0}\right)}\cdot\left[\mu_0 + \mu_1\cdot\left(1-e^{\left(-\frac{t}{t_0}\right)}\right)\right] + \left(1-e^{\left(-\frac{N}{N_0}\right)}\right)\cdot a(N+b)^c$$

where μ_0 = friction coefficient of new asphalt road; μ_1 = friction gain due to ageing; and t_0, N_0, a, b, c = parameters to be determined by data fitting.

Individual functions ($\mu_B(t)$, $\mu_G(N)$ and $d(t,N)$) are easily identifiable by matching formulae (3)(4). Despite its rather complex form, due to the inclusion of three influential phenomena (polishing, binder removal and binder ageing), the model parameters can be simply identified by means of laboratory polishing tests on asphalt cores *(6)*. Indeed:

- μ_1 and t_0 are deduced from accelerated ageing test (in *(6)*, values were determined from fitting);
- five parameters are deduced from polishing Wehner/Schulze test: μ_0 is the starting point of μ_{WS}-N plot; a, b and c are deduced from fitting of the μ_G function to the decreasing part of μ_{WS}-N plot; and N_0 is deduced from a transformation involving μ, μ_0 and μ_G.

The most innovative point of this model is that it incorporates the binder-removal phase and mainly the climate effect, both responsible for the friction increase at early age. Most of existing models, as shown in Table 1, reproduce only the polishing process and theoretical curves describe only the decreasing part of the friction evolution.

Figure 10 shows a comparison between Wehner/Schulze polishing test data and theoretical predictions. Specimen was taken from newly constructed road (see *(4)* for details on experimental sites) and subjected to polishing test.

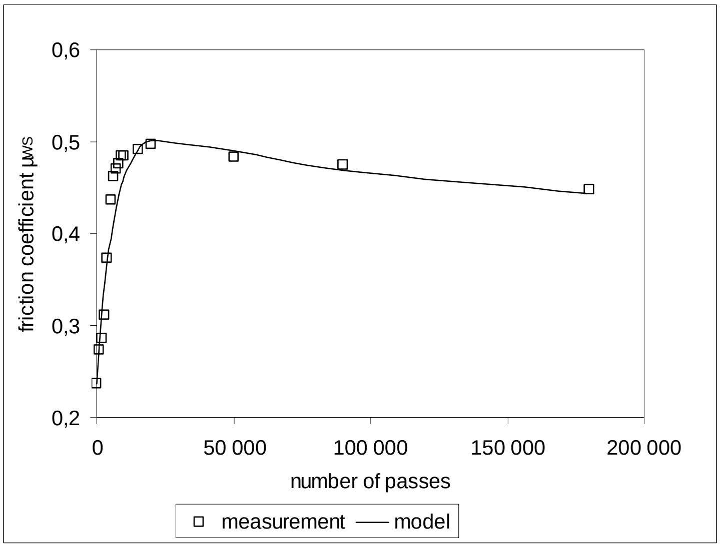


FIGURE 10 Comparison between Wehner/Schulze polishing curve and theoretical predictions.

From laboratory to road

The model presented in the section above is the first step toward the prediction. Skid resistance evolution is usually expressed as LFC/SFC-T, where: LFC/SFC = respectively longitudinal and side friction coefficients measured by friction monitoring devices; and T = traffic measurement expressed, in France, as the cumulated number of trucks. To make the prediction method complete, it is necessary to convert the laboratory μ_{WS}-N plot into the road LFC/SFC-T one. The simplest way is to perform two conversions: N into T, and μ_{WS} into LFC/SFC.

Relationship between laboratory polishing duration and road traffic

Since there is no literature about the relationship between the polishing duration (expressed as the number of passes) "N" and the traffic (expressed as the cumulated number of trucks) "T", the simplest relationship is investigated in this study, meaning that:

(5) $N = k.T$

The factor "k" is determined by minimizing (least-square method) the difference between μ_{WS}-N and μ_{WS}-T plots. These plots are obtained on the one hand from cores taken from the road side (not subjected to traffic) and subjected to Wehner/Schulze polishing test, giving μ_{WS}-N, and on the other hand from cores taken from trafficked lanes – together with traffic data at the moment where cores are taken – and subjected to Wehner/Schulze friction test, giving μ_{WS}-T. Within the scope of *(2)*, the best (k) value for all experimental sites is 0.024.

Relationship between Wehner/Schulze machine and other friction measuring devices

Few studies deal with the relationship between μ_{WS} and LFC/SFC. One reason is that before the regained interest for Wehner/Schulze machine in the 2000's, the last paper related to this machine was published in 1990 *(13)*. The only formula found in the literature is that proposed by Huschek *(12)*:

(6) LFC (80 km/h) = 1.04 μ_{WS} – 0.01

where: LFC = wet-friction coefficient measured by the German Stuttgart Friction Tester device travelling at 80 km/h and using a patterned tire.

Recent studies conducted at IFSTTAR test track by Cerezo *(14)* have produced the following relationship:

(7) LFC (40 km/h) = 1.15 μ_{WS} – 0.01

where: LFC = friction coefficient measured by the French ADHERA device (locked wheel, PIARC blank tire).

In the following sections, formula *(7)* is used as ADHERA was used as friction monitoring device.

Comparison road data/predictions

Data from roads followed-up during ten years (1997 to 2006) are used for the validation of the proposed prediction method. For each site:

- LFC/SFC measurements are collected, as well as traffic measurements (converted into equivalent cumulated number of trucks);
- cores are taken from the road side for Wehner/Schulze polishing tests; data are used to calibrate the model;
- friction coefficient-number of passes curve is calculated and converted into LFC-traffic curve using respectively formulae (7) and (5).

Example of comparison between road data and predictions is shown in figure 11.

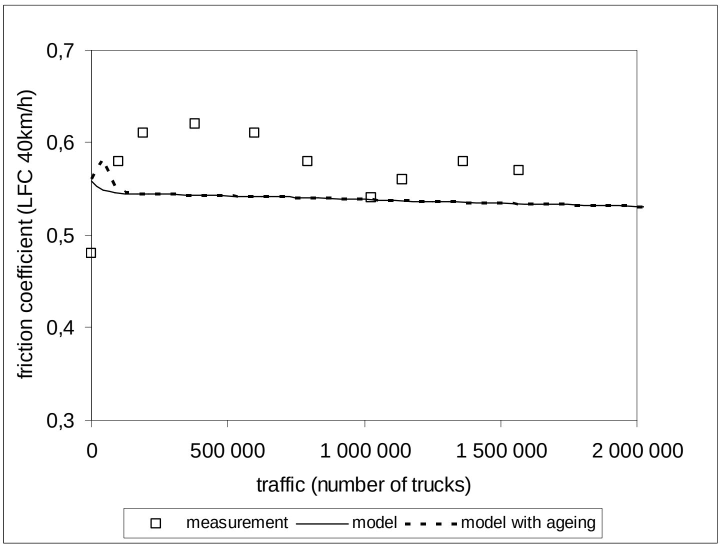


FIGURE 11 Comparison prediction/measurement of skid-resistance evolutions.

Since roads of the database were constructed long time ago (more than 15 years), it is not possible to evaluate the ageing effect by means of the accelerated test presented in previous sections. The (μ_B) term is then reduced to μ_0 (see formula (4)). The continuous line represents predictions without consideration of ageing effect. It can be seen that the predicted friction coefficient decreases and predictions are reasonable except at the first 500,000 truck passes. Attempts are then made to include the ageing effect: data obtained from new roads using roughly the same asphalt mix as that of figure 11, for which friction gain due to ageing effect can be quantified, are incorporated in the model to better estimate the (μ_B) term; results are shown in figure 11 (dotted line). It can be seen that predictions with/without ageing effect are identical, except at the early age where the consideration of ageing effect gives place to a slight increase of friction coefficient. However, the predicted binder removal phase (during which friction increases) is much shorter than the observed one.

The tentative introduction of ageing effect in the model for old roads is not very successful. However, it emphasizes the need to take this effect into account if the prediction of early-age skid resistance is sought.

CONCLUSIONS

In this paper, laboratory test methods reproducing phenomena affecting pavement skid resistance evolution are presented. Polishing tests using Wehner/Schulze machine can simulate the polishing induced by traffic as well as the binder removal phase (typical for bituminous asphalt concrete). Binder ageing, responsible for friction increase at early age, can be reproduced by weatherometer, operating conditions being adjusted according to local weather conditions; equivalence between accelerated (in day) and natural (in month) ageing times is established. With respect to seasonal variations, a simple test was developed to evaluate the effect of pollutants deposited on the road and the washing effect of rainfalls. Friction variation (drop due to water-plus-pollutant mix, then increase due to subsequently added water) reflects actual observations.

A model is developed to incorporate, beside the polishing, the binder-removal phase and mainly the climate effect, both responsible for friction variation at early age. The model can be calibrated by means of laboratory tests and used as a prediction tool. Simple conversions are performed on the one hand between polishing duration and real traffic, and on the other hand between laboratory and road friction measuring devices. Comparison between measurements and predictions is fair.

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