Universidad Politécnica de Madrid

Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos

Skid resistance of asphalt pavements: Laboratory measurements and model assessment

Doctoral Thesis

Wouter van Bijsterveld

Civil Engineer (M.Sc.), Delft University of Technology, The Netherlands

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Foreword

At the beginning of this century, I was offered the possibility to develop a doctoral thesis at the Delft University of Technology. A combination of circumstances, amongst which my young age, lead to the early abandonment of this project. Eight years later, through my new employer GEOCISA, I enrolled in the European research project SKIDSAFE, which brought a new opportunity to write a thesis. The present document is the proof that this time, although it took many years, I finished the task. Thank you, Tom Scarpas, for all your support and confidence.

Of course I would also like to thank the partners in the SKIDSAFE project, who made their data available to me and gave permission to use their results for this thesis. In particular, Tom Scarpas and Mirella Villani from Delft University of Technology, Arian de Bondt and Radjan Khedoe from Ooms Civiël (now Strukton Civiël), Malal Kane and Véronique Cerezo from IFSTTAR, Ignacio Artamendi from Aggregate Industries and Andreas Loizos from National Technical University of Athens.

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To my parents and family in the Netherlands: I know you have really looked forward to this moment and it fills me with joy to share this with you.

To Lucía, Sofía and Isabel: thank you for your love, support and patience. You gave me the time and energy to continue.

Summary

For a car to be able to brake, accelerate or change direction, it needs a sufficient level of friction between its tyres and the pavement surface. The tyres play an important role, but road authorities are only responsible for an adequate level of skid resistance of the pavement surface. The skid resistance of a pavement changes over time due to various processes, such as polishing, wear and weathering, but also temporary effects such as temperature or dust accumulation.

Road authorities perform skid resistance measurements on a regular basis in order to be able to plan and perform timely maintenance to restore skid resistance. There are only in Europe 14 skid resistance measurement devices with different working principles and different technical characteristics, such as the type of tyre, the measurement speed, the type and amount of wheel slip, the vertical load, etc. These differences make that the measurements are comparable, but there is no unique correlation, since the response to changes in the friction conditions are different for each measurement device, and especially for each type of rubber used for the testing wheels.

In the meantime, significant advances are made in the optical techniques to measure the pavement texture with a higher resolution and precision than the current practice. Pavement texture is currently characterised by macrotexture, which is in the wavelength range of 0.5 mm to 50 mm. Current laser profilers can measure with resolutions smaller than 0.1 mm and in static laboratory setups resolutions in the order of 10 μm can be reached. A more detailed description of pavement texture is expected to improve correlation with skid resistance.

In this thesis different texture characterisation parameters have been described, analysed and tested on different pavement surfaces and profiler methods. Some of the parameters provide a detailed description of the shape of the asperities of the surface, which then can be treated statistically. Also a fractal approach is described which allows for a characterisation of the texture profile over the complete range of wavelengths. It is shown that the profile pre-processing has a significant influence on the results. Procedures are proposed which can be used in future standardization documents.

All texture parameters have been determined on different types of asphalt and rock specimens in order to investigate possible correlations with the polishing level of the specimens and later on with friction measurements.

The tyre rubber can be characterised by the Dynamic Shear Rheometer (DSR). In this test a rubber sample is subjected to a periodical shear rotation at a range of frequencies and temperatures. It is shown that by using the Arrhenius equation for time-temperature equivalence, the material's complex shear modulus, storage modulus, loss modulus and phase angle can be represented adequately by potential functions a function of the reduced frequency. With this result it is shown that the SLS- or Zener model is a poor representation of the visco-elastic material.

Within the research project SKIDSAFE, co-financed by the 7th Framework Programme of the European Commission, a new laboratory testing device, named Skid Resistance Interface Testing Device (SR-ITD), was developed to measure skid resistance on asphalt specimens. The device was designed specifically to measure the forces that are generated in the tyre-

pavement contact area, under controlled skid conditions. The SR-ITD device has been essential in the development of the thesis.

There are two main testing protocols for the SR-ITD: a braking test and a polishing procedure. In the braking test the tangential speed of the rotating specimen is reduced from 80 km/h to 0 while a locked rubber test wheel is pressed to the surface with a predefined force. During the test the forces on the wheel and the temperature inside the rubber are measured. It is observed that the temperature in the rubber tyre rises very sharply in the 6 to 8 seconds of the duration of the test. The vibration during the test and the fast changing test conditions (speed and temperature) make it extremely difficult to obtain stable friction measurements. The polishing test on the other hand was not designed to measure friction but to accelerate polishing and wear of the asphalt surface under representative conditions. The side-way force principle is used to generate friction with a 5° slip angle, and a speed of 20 km/h. Under these test conditions, the temperature of the wheel remains stable even during several hours of testing, in which a significant deterioration of the pavement surface is generated. Because of the long duration of the test, long-term averages of the measured forces do show stable friction measurements, which are sensitive to the polishing level of the specimens.

Despite the detected shortcomings of the testing protocols, procedures for the post-processing are proposed in this thesis to obtain as good as possible friction measurements. A dataset was elaborated with results from the braking tests on different asphalt mixtures, with two different rubber types and several vertical force levels. The polishing tests were also performed on the three different asphalt types, but all tests were performed at the same speed, temperature, slip angle and vertical force.

Finally, the thesis explores the possibility that, given an adequate characterization of the pavement surface and a physical quantitative model describing the generation of friction between a rubber body and a rough surface, a reasonably accurate prediction of skid resistance can be made. The model proposed by Klüppel and Heinrich (2000) is analysed and assessed by comparing it to the experimental dataset. A simplified mathematical formulation of the model is presented, which qualitatively reproduces the typical speed-friction curve within a certain range of the input parameters. The range of temperature and speed in which the model produces significant friction values is narrower than the range found in the experimental data. Moreover, the quantitative difference between the theoretical and experimental results can be of two orders of magnitude. This suggests that the hypotheses of the Klüppel and Heinrich model need to be adapted to the scale of the observed phenomena.

Resumen

Para que un automóvil pueda frenar, acelerar o cambiar de dirección, necesita un nivel suficiente de fricción entre los neumáticos y la superficie del pavimento. Aunque la influencia de los neumáticos es importante, los gestores de las carreteras son responsables de mantener un nivel adecuado de resistencia al deslizamiento de la superficie del pavimento. Ésta cambia con el tiempo debido a diversos procesos, como el pulido por la acción de los neumáticos y el desgaste por la exposición a la intemperie, pero también debido a circunstancias cambiantes como la temperatura o la acumulación de polvo.

Los gestores de las carreteras realizan mediciones de la resistencia al deslizamiento de manera regular para poder planificar y realizar un mantenimiento adecuado para, en su caso, reestablecer la resistencia al deslizamiento. Tan solo en Europa existen 14 dispositivos distintos para su medición, cada uno con diferentes principios de funcionamiento y diferentes características técnicas, como el tipo de neumático, la velocidad de medición, el tipo y la cantidad de deslizamiento de la rueda, la carga vertical, etc. Estas diferencias hacen que aunque las mediciones son comparables, no exista una correlación unívoca, ya que la respuesta a los cambios en las condiciones de fricción es diferente para cada dispositivo de medición y especialmente para cada tipo de caucho utilizado en las ruedas de medida.

Mientras tanto, se realizan avances significativos en las técnicas ópticas para medir la textura del pavimento con una mayor resolución y precisión que la que de la técnica actual. La superficie del pavimento se caracteriza evaluando su macrotextura, que se encuentra en el rango de longitud de onda de 0,5 mm a 50 mm. Los perfilómetros láser actuales pueden medir con resoluciones inferiores a 0,1 mm y en configuraciones de laboratorio estáticas se pueden alcanzar resoluciones del orden de 10 μm . Se espera que una descripción más detallada de la textura del pavimento mejore la correlación con la resistencia al deslizamiento.

En esta tesis se han descrito, analizado y probado diferentes parámetros para la caracterización de la textura en diferentes superficies de pavimento con distintos métodos perfilométricos. Algunos de los parámetros proporcionan una descripción detallada de la forma de las asperezas de la superficie, que luego pueden tratarse estadísticamente. También se describe el uso de fractales que permite una caracterización del perfil de textura sin limitar el rango de longitudes de onda. Se demuestra que el preprocesado del perfil tiene una influencia significativa en los resultados. Se proponen procedimientos que puedan usarse en futuros documentos de estandarización.

Todos los parámetros de textura se han determinado en diferentes tipos de muestras de asfalto y roca para investigar posibles correlaciones con el nivel de pulido de las muestras y más tarde con las medidas de fricción.

Para la caracterización del caucho se han realizado ensayos con el reómetro dinámico de corte (DSR). En este ensayo se somete una probeta a una deformación cíclica de torsión en un amplio rango de temperaturas y frecuencias. Aplicando el principio de equivalencia de tiempo y temperatura mediante la ecuación de Arrhenius se demuestra que el ángulo de desfase, el módulo de almacenamiento y el módulo de pérdidas solo dependen de la frecuencia reducida y su relación de dependencia se puede expresar mediante sendas ecuaciones potenciales. Este resultado pone de manifiesto que el modelo de Zener de

material viscoelástico no se ajusta correctamente al comportamiento de los cauchos caracterizados.

Dentro del proyecto de investigación SKIDSAFE, cofinanciado por el 7º Programa Marco de la Comisión Europea, se desarrolló un nuevo dispositivo de ensayo de laboratorio, denominado *Skid Resistance Interface Testing Device* (SR-ITD), para medir en el laboratorio la resistencia al deslizamiento en probetas de mezcla bituminosa. El dispositivo fue diseñado específicamente para medir las fuerzas que se generan en el área de contacto entre pavimento y la rueda, en condiciones controladas de deslizamiento. El equipo SR-ITD ha sido fundamental en la realización de esta tesis.

Hay dos protocolos de ensayo principales para el SR-ITD: un ensayo de frenado y un procedimiento de pulido. En la prueba de frenado, la velocidad tangencial de la probeta se reduce de 80 km/h a 0, mientras que una rueda de caucho bloqueada está apoyada en la superficie con una fuerza vertical predefinida. Durante la prueba se miden las fuerzas ejercidas sobre la rueda y la temperatura dentro del caucho. Se observa que la temperatura en el neumático de caucho aumenta muy rápidamente en los 6 a 8 s de duración de la prueba. Las vibraciones y las condiciones cambiantes durante el ensayo (velocidad y temperatura) hacen que sea extremadamente difícil realizar mediciones de fricción estables. El ensayo de pulido, por otro lado, no fue diseñado para medir la fricción, sino para acelerar el desgaste de la superficie del asfalto en condiciones representativas. El principio del rozamiento transversal se usa para generar fricción con un ángulo de deslizamiento de 5 ° y una velocidad de 20 km/h. Bajo estas condiciones, la temperatura de la rueda permanece estable incluso durante varias horas, en las cuales se genera un desgaste significativo de la superficie del pavimento. Debido a la larga duración de la prueba, los promedios temporales de las fuerzas medidas proporcionan valores de fricción estables, que son sensibles al nivel de pulido de las probetas.

Las deficiencias detectadas en los protocolos de ensayo no impiden que esta tesis proponga procedimientos de postproceso de datos para obtener las mejores medidas de fricción posibles. Con este fin se ha generado un gran número de datos basado en los resultados de las pruebas de frenado combinando diferentes mezclas de asfalto con dos tipos de caucho y varios niveles de fuerza vertical. Las pruebas de pulido también se realizaron con tres tipos diferentes de asfalto.

Finalmente, la tesis explora las posibilidades de que, con una caracterización adecuada de la superficie del pavimento y un modelo cuantitativo físico que describa la generación de fricción entre un cuerpo de caucho y una superficie rugosa, se pueda hacer una predicción razonablemente exacta de la resistencia al deslizamiento. El modelo propuesto por Klüppel y Heinrich (2000) se analiza y sus predicciones se contrastan con los datos experimentales. El modelo reproduce cualitativamente la relación entre fricción y velocidad dentro de determinados rangos de los parámetros de entrada, aunque en el caso de la velocidad y la temperatura es un rango más estrecho el encontrado en los datos experimentales. Además, las diferencias cuantitativas entre los valores teóricos y experimentales llegan hasta los dos órdenes de magnitud, lo que sugiere que las hipótesis del modelo de Klüppel y Heinrich necesitan ser adaptadas a la escala del fenómeno estudiado.

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Symbols and acronyms

α	in texture profile analyses: summit angle of an asperity
β	in texture profile analyses: the angle formed by the lines connecting three subsequent peaks in the profile in friction model: roughness exponent $\beta = 2H + 1$
α_T	shift factor for time-temperature superposition according to Arrhenius
H	Roughness or Hurst-exponent. ($0 \leq H \leq 1$)
δ	Dimension of the Euclidian embedding space ($\delta = 2$ for cross sections, $\delta = 3$ for 3D representations)
D	Surface fractal dimension. $D = \delta - H$
$\bar{d}$	mean penetration depth
E^*	Dynamic Modulus
E'	Storage modulus
E''	Loss modulus
$\xi_{ }$	<i>Xi parallel</i> , Correlation length parallel to the surface
$\xi_{\perp}$	<i>Xi perpendicular</i> , Correlation length perpendicular to the surface
$\tilde{\sigma}^2$	Variance, i.e. the root mean square of the fluctuations around the mean height
λ	Wavelength
C_z	Height correlation function
$2L$	Asperity width, defined as the length between two subsequent valleys
R_q	The root mean square value of the ordinate values of a profile
R_{peak}	Radius of the asperity peak
θ	relative height between two consecutive asperities, expressed as the angle of the line connecting two peaks with the horizontal
E_e	spring constant of the spring parallel to the spring and dashpot in the Zener or SLS-model
E_m	spring constant of the spring in series with the dashpot in the Zener or SLS-model
τ_z	relaxation time of the dashpot, defined as the viscosity of the dashpot divided by E_m
η	viscosity of the dashpot in the Zener or SLS-model
v	speed
R	universal gas constant

ΔH	activation energy
μ or μ_H	friction coefficient or horizontal friction coefficient μ may also be used to indicate the average value of a population
T, T_s	temperature, reference temperature (20°C or 293,15 K)
t	time
$\bar{\sigma}_z$ or σ_0	average vertical stress in the tyre-pavement contact area σ may also be used to indicate the standard deviation of a population
F_z	vertical force
f, f_{red}	frequency, reduced frequency
${}_2F_1$	hypergeometric function
$\tilde{E}_\infty$	dimensionless expression for rubber parameters: $\tilde{E}_\infty = \frac{E_\infty}{E_0}$

SR-ITD	Skid Resistance-Interface Testing Device
MPD	Mean Profile Depth
PA	Porous Asphalt
BBTM	Beton Bitumineux Très Mince (Very thin asphalt concrete layer)
AC	Asphalt Concrete
DSR	Direct Shear Rheometer
SMA	Stone Mastic Asphalt
DFT	Dynamic Friction Tester
H&K model	Friction model proposed by Heinrich and Klüppel (Klüppel and Heinrich, 2000)
ABS	Anti-loc braking systems
PSV	Polished Stone Value
ACV	Aggregate Crushing Value
LA	Los Angeles test or value
TPF	Ten Percent Fines
AIV	Aggregate Impact Value
MD	Micro-Deval
AAV	Aggregate Abrasion Value
WLF	Williams-Landel-Ferry
SKM	Seitenkraft-Messverfahren
SFC	Sideway-force coefficient

LFC	Longitudinal Friction Coefficient
BFC	Breaking Force Coefficient

Chapter 1 Introduction

This introductory chapter will describe the problem statement of the thesis, the backgrounds that have led to the development of the thesis, the framework in which the research has been carried out and its research objectives, identifying the novel and original contributions of the research to the state of the art. It describes the methodology that was followed during the development of the research and finally will present the structure of the thesis.

1.1 Problem statement

Skid resistance is one of the most important functional properties of a pavement surface. It determines the interaction between the pavement and the vehicle and therefore the ability to control the vehicle. A lack of skid resistance of the pavement leads to a loss of braking power and steering capability of the vehicle, which may lead to accidents and loss of lives.

Road agencies carry out skid resistance measurements for approval of new surface layers and subsequently on a regular basis (e.g. yearly or biennially) to ensure sufficient levels of skid resistance during its service life.

Even though skid resistance is such an important characteristic of pavements, it is not a design parameter during the mix design process. This can be deduced from the fact that no mention is made to skid resistance in the European Standard EN 13108-1:2006 regarding the material specification of asphalt concrete, nor in the definition of the CE-marking. Moreover, at the initiation of this thesis in 2012, no laboratory method was mentioned in the EN 12697 series regarding the determination of skid resistance of asphalt mixtures. For completeness it should be mentioned that the British pendulum is standardized in the EN-13036 series for test methods for road and airfield surface characterization. This test however is, just like other skid resistance measuring devices, intended to be used on laid-down (asphalt) pavements. In 2014 the European Standard EN 12697-49 "Determination of friction after polishing" was published, describing a way to measure skid resistance in the laboratory.

In November 2009 a research project started under the title SKIDSAFE: Enhanced Driver Safety due to Improved Skid Resistance (<http://www.skidsafe.org>). This project, co-financed by the European Commission under the 7th Framework Programme for Research and Development, developed a laboratory test to measure skid resistance on asphalt specimens, with the aim of obtaining material parameters which could be used in finite element modelling of tyre-pavement interaction. In parallel, these finite element models for the analysis of the interaction between a tyre and a pavement were developed and tested.

The complexity and cost of these computational analyses make it practically unfeasible that these techniques be used in the everyday engineering practice. There is a need for a simplified and faster model, which shall be able to predict the in-field performance of skid resistance of asphalt mixtures based on relatively simple material parameters and surface geometry measurements. Thereby taking into account that the tyre pavement friction is affected by transient external conditions, such as weather or surface contamination.

1.2 Research objectives

This study pursues progress towards the following high-level objective:

- Adaptation and validation of a friction model to estimate the potential skid resistance of an asphalt mixture based on its composition, specifically its surface geometry or texture.

In the following paragraphs, more detailed objectives are presented.

1.2.1 Parametrisation of laboratory and field measurements

The SKIDSAFE project proposed a number of innovative methods to measure and characterise functional properties of road materials. One of the objectives of this thesis is to analyse these methods to characterise these properties and wherever necessary propose new or improved ways of parametrising the obtained laboratory, field or simulation data, in such a way that they represent a fundamental functional material property that can be used in a mechanics-based model according to the main objective.

- a) Parametrisation of aggregate properties
 - Petrological characterization of aggregates
 - Microtexture data of stones and aggregates

- b) Parametrisation of texture of asphalt mixtures

- Texture data of asphalt mixtures

The objective of this task is to utilize an approach for the characterization of texture as a whole, eliminating the arbitrary division between macro- and microtexture.

- c) Interpretation of laboratory skid resistance measurements

- Laboratory Skid Resistance Interface Testing Device (SR-ITD) measurements on stone samples
- Laboratory SR-ITD measurements on asphalt samples

This task involves the analysis of the influence of temperature, slip speed, rubber properties and pressure.

- d) Interpretation of field skid resistance measurements

- Field measurements of longitudinal friction coefficients

In this part of the study the different test configurations will be analysed and special attention will be paid to external conditions that may have affected the measurements.

1.2.2 Assessment of a physical friction model for skid resistance

The main objective of this thesis will be the assessment and adjustment of a model which allows the estimation of friction between a rubber tyre sliding over a pavement surface, based on the characterisation of the pavement's surface texture, the properties of the tyre and the prevailing test conditions, e.g. speed and temperature. The model shall represent physically relevant parameters and behaviour. Further fundamental tasks will be the interpretation of experimental data and the correlation of the influence factors with the parameters in the model.

1.3 Scope limiting

There is an almost infinite variety in the combination of pavement surfaces, tyre configurations, rubber compositions, temperature and speed conditions, etc. The analyses presented in this thesis are limited to the laboratory test data available from the SKIDSAFE project. This implies that the pavement surfaces are reduced to three types of asphalt surfaces obtained from laboratory prepared specimens. The tyre is represented by a smooth solid rubber wheel, for which the interaction with the pavement should strictly be denoted as rubber-pavement interaction. The rubber properties are those obtained from two different test tyres, typically used in friction measurements. These rubber types are not necessarily comparable with the rubber properties of commercial vehicle tyres.

The choice of texture parameters and friction model is based on the literature study. The most promising combination of model and parameters are studied in detail in this thesis.

1.4 Research methodology

The methodology for this study is illustrated in the scheme shown in figure 1.1, an explanation of which is presented in the following paragraphs. The alphanumeric codes next to the scheme items will be used in the text as reference.

Figure 1.1 Methodology scheme

A: Friction model

The heart of the scheme is the friction model developed by Klüppel and Heinrich (2000), which is described in detail in paragraph 6.3. The model has a limited number of input

parameters, which will be briefly described subsequently, and finally one output parameter which is a friction coefficient of a uniform piece of rubber on a rough surface, such as a pavement. The main input parameters of the model should be physically relevant and measurable. The original paper by Klüppel and Heinrich proposes various ways of defining the input parameters. Depending on the available data, the most suitable implementation of the model must be determined.

B: Basic model input parameter

B.1 Surface geometry

The friction model requires a characterisation of the geometry of the pavement surface. The input parameters are based on detailed profile data, within the range of microtexture and macrotexture. In this thesis the characterisation of the surface is done by means of the fractals theory, in which the resulting parameters provide information on the wavelengths and amplitudes of the profile. The advantage of this approach is that it provides with a few parameters a description of the surface profile over the full range of wavelengths. The basic surface geometry is the one formed by the aggregates and bitumen in a specific mixture composition and is measured by high resolution laser scans. On a given moment in time, the profile may be altered by transient or reversible phenomena, such as accumulation of other materials, like dust, rubber and detritus. The surface characterisation is discussed in Chapter 3.

B.2 Speed

The parameter speed should be handled in two different ways. In the first place, as input parameter of the friction model, speed represents the sliding speed of a piece of rubber over a rough surface. The speed is important, because the mechanical response of a viscoelastic material such as rubber is to a harmonic loading so not proportional but frequency dependent. To this effect, the speed in combination with the different wavelengths and amplitudes in the surface geometry yields the loading frequencies of the rubber piece which slides over this surface. In the scheme in figure 1.1 the effect of speed on the rubber behaviour (B.3) is considered through the Friction model (A).

On a higher level, the speed of the rubber tyre, in combination with the tyre geometry, determines the amount of water that remains present between the pavement surface and the tyre, thereby altering the surface geometry. Moreover, the speed has an influence on the tyre temperature, due to the energy dissipation involved in viscoelastic deformation.

B.3 Rubber properties

The input parameter for the friction model related to the rubber properties is the dynamic modulus as a function of the loading frequency and temperature. Additional parameters which are not included in the friction model are the material strength properties, the temperature dependency of strength and stiffness properties and thermodynamic properties. Beforehand, given the importance of the rubber properties in the development of friction, these omissions in the model leave room for significant improvement, if necessary.

B.4 Contact pressure

The vertical force on a wheel or on a piece of rubber, results into a vertical pressure in the area of contact between the tyre (or rubber) and the pavement. In most engineering applications, the average pressure (vertical force divided by the enveloping contact area) is used and is commonly denominated as contact pressure. On macro- and microtexture level, the contact pressure between a rubber block and the asphalt surface determines the penetration depth of the rubber into the surface cavities (or vice versa, the penetration of surface asperities into the rubber material). This means that the actual contact stress on each asperity of the surface is different and depends on the height and shape of the asperity. The contact pressure itself, depends on the tyre geometry, the inflation pressure and loading conditions.

C: Data for model calibration

For the development and calibration of the models, various data sets are available coming from laboratory and field measurements. In the scheme the following blocks are distinguished:

C.1 Rubber characterisation

Rubber properties are expected to have a significant influence in skid resistance. The viscoelastic properties of rubber are dependent from the temperature. Data from the dynamic shear rheometer testing of rubber samples are processed and used in this work to obtain the rubber viscoelastic characteristics.

C.2 Texture scans

Pavement surface texture is the main pavement related parameter in the model. Texture scans on aggregates and asphalt samples, obtained with different methods and resolutions are available from the SKIDSAFE test programme. The development of procedures for pre-processing and filtering, as well as the procedures for the calculation of the texture parameters, is part of the research objectives of this thesis.

C.3 Laboratory friction measurements

Laboratory friction measurements have been carried out on three different asphalt mixture compositions and three different aggregates. Different types of rubber have been tested and slip speed and vertical pressure were varied. These data are used to adapt and calibrate the friction model (A.). The test data are described and analysed in Chapter 5 as a contribution of this thesis. The laboratory test set-up was specifically developed for this purpose. The processing and interpretation of the test data is therefore part of the research activity.

C.4 Field friction measurements

Friction measurements have been carried out with two different measurement devices within the SKIDSAFE project, on various pavement surfaces, under various climatic conditions, speeds and water flows. These data are used in this thesis to calibrate the overall functioning of the model under “real life” conditions.

D: External agents for in-time evolution

This block includes the effect of external agents, such as traffic loading and weather (moisture damage, frost-defrost, UV-radiation, ...) on the surface geometry: in the first place to complement macrotexture measurements with information on the microtexture based on the aggregate type, and in the second place to be able to predict the in-time evolution of these properties.

D.1 Aggregate nature

Chapter 4 deals with the characterisation of aggregates regarding the mechanical characteristics, such as strength and resistance to abrasion and polishing. The mineral composition has an influence on the mechanical characteristics but also on the behaviour under different climatic conditions (weathering, water susceptibility, frost-thaw damage,...). These aspects are not directly incorporated in the friction model, but they have an influence on the deterioration of the surface geometry. In this thesis the effect of polishing on different types of aggregates and asphalt mixtures is shown through the change of the texture parameters.

D.2 Traffic loading

The traffic loading on a pavement has a strong influence on the deterioration rate of its surface characteristics. Because the model considers a unit block of rubber under a certain vertical pressure, the actual traffic loading can be approached by a summation of combinations of contact surface and contact pressure.

D.3 Climatic conditions

The field skid resistance measurements are used to quantify the influence of climatic conditions on skid resistance measurements.

E: Instant external factor on model parameters

In this block a number of essential parameters in the tyre-pavement friction are mentioned for completeness.

Temperature is a key parameter in rubber friction, as the rubber mechanical properties strongly depend on temperature. Moreover, friction is by definition a process of energy dissipation, where kinematic energy is transformed into heat. This, combined with the fact that rubber has a very low heat conductivity, causes the temperature to rise locally to very high values, altering the material properties or even leading to direct failure (skid marks on the road are well-known indicators of this).

The effect of temperature on rubber properties can relatively easily be determined in the laboratory with a standardised test. However, the way temperature develops during a rolling or skidding process, with or without the presence of water, is a more complex process, in which the tyre geometry, air and water flow, air and water temperature and the amount of dissipated energy play a role.

The effect of tyre geometry is used in the analysis of the friction measurement results. This is however an atypical tyre geometry. The influence of the tyre geometry of a ribbed pneumatic tyre is not taken into account in this thesis.

The influence of the presence of water is not a variable in this study. In the laboratory test, the abundant presence of water was necessary to avoid a too high temperature built-up. In this respect the presence of water was a constant test condition.

F. Result

The output of the model is a single friction coefficient (μ) for a unit piece of rubber on a pavement surface.

1.5 Structure of the thesis

Following the methodology, the structure of the thesis is as follows. In Chapter 2 the current state-of-the-art and background for this thesis is described including a review of relevant literature. More detailed background from literature is included elsewhere in the thesis where this is relevant for the development of the contents of the chapters. Chapter 3 describes the texture characterisation carried out in this thesis. It includes the calculation of parameters on limited subsets of pavement texture profiles, in order to illustrate the sensitivity of the results to some of the configuration options in the calculation procedures. Once the texture parameters are defined and the calculation procedure is established, the results of the texture parameter determination are presented in Chapter 4. This chapter also includes a detailed description of the aggregates and asphalt mixtures used in this study. In Chapter 5, the laboratory test set-up developed to measure rubber-pavement friction is described in detail and a critical evaluation of its design features is presented. The testing protocols are also analysed and the post processing procedures, developed for this thesis are presented. As the test wheels are part of the testing device, the characterisation of the rubber of the test wheel is also described in this chapter. Chapter 5 is closed with the results of the test programme and a description of the obtained data.

In Chapter 6 the rubber-pavement friction model is described in detail. A critical evaluation of the model and a sensitivity analysis of the parameters is presented. Modifications of the model are proposed, primarily in order to incorporate the temperature sensitivity and to simplify some of the terms of the model. Finally the predictive potential of the model versus the experimental data coming from the laboratory friction measurements is presented.

Chapter 7 shows the field skid resistance measurements and the correlation of these measurement data with the texture based predictions of the friction model.

Finally, Chapter 8 includes the conclusions, recommendations and guidance for future research derived from this thesis.

Chapter 2 Literature review

A brief literature review is presented in order to indicate the state of the art and/or the state of the practice regarding the different aspects of this study and to set the starting point. At the end of this chapter the intended progress beyond this point is outlined. In the subsequent chapters of the thesis, additional sources will be reviewed when relevant and duly introduced for the specific topic of that chapter.

2.1 Tyre – pavement friction

2.1.1 Basic concepts

Friction is defined as the resistance to relative motion between two bodies in contact, the frictional force being the force acting tangentially in the contact area. Friction is therefore by definition a phenomenon that is dependent on two bodies, which means that one cannot determine the "friction of a pavement". It is therefore that the European Standards on pavement surface characteristics use the term skid resistance, which is defined as follows:

"Characterisation of the friction of a road surface when measured in accordance with a standardised method".

As the skid resistance of a pavement surface reduces when the surface is wet, skid resistance is practically always measured on a wet surface. For this reason, from here onward, wet skid resistance shall be assumed when skid resistance is mentioned. Dry skid resistance shall be explicitly mentioned as such.

The friction between a rubber tyre and a pavement surface is determined by three physical mechanisms: adhesion, hysteresis and abrasion.

Adhesion is caused by the attraction between molecules, the so called Van der Waals forces. The Van der Waals forces are rather weak and need a very close contact to develop (Lessel et al., 2013). This means that on rough surfaces, such as a pavement, the contribution of adhesion is low. In the presence of water or other surface contaminations, the adhesion forces tend to zero.

Abrasive friction occurs under extreme conditions of high contact load and high temperature of the rubber, where the material of the bodies in contact is actually being disintegrated, when sliding takes place. Skid marks on the road show that these conditions actually occur, however, the focus of this thesis is on (wet) skid resistance measurements, in which excessive abrasion and high temperatures are avoided.

The hysteresis component of friction is determined by the internal damping of the rubber material. The rubber of the tyre deforms as the asperities of the pavement surface indent the rubber material or when the rubber tyre penetrates into the cavities of the pavement surface. The viscoelastic properties of the rubber cause an energy loss, which can be attributed to an effective friction force.

2.1.2 Braking cars

Under normal driving conditions, the wheels of the car are rolling with no slip between the rubber and the pavement surface. In this situation the stress situation can be considered as the classical friction example of a block of rubber at rest on a horizontal surface with a vertical force. Only when an external horizontal force is applied, the block will deform slightly which creates a counterforce. If the horizontal force is taken away, the block will return to its initial shape. During this process, the block has not moved from its initial position. Only when the horizontal force exceeds a specific limit, the block will start moving and sliding over the surface. Normally, the horizontal force to start the sliding process is somewhat higher than the force needed to continue sliding. The energy dissipation in a normal, controlled braking process is almost entirely in the braking system, due to the sliding friction between the braking disc and the braking pads. Notice that when the wheel stops rotating, the brakes no longer dissipate energy. In case of an emergency brake, it may happen that the horizontal force in the tyre-pavement contact area exceeds the limit and the tyre starts to slide over the pavement. In this situation the peripheral speed of the wheel due to its angular velocity is lower than the overall speed of the vehicle. The difference to unit of the ratio between these two speeds is the slip ratio. There is consensus in literature that the maximum friction in the braking system under slip conditions is generated at a slip rate between 15% and 25%. At higher slip rates, the braking force reduces and flattens out to a minimum value up to the ratio of a 100% (full slip). For this reason, the anti-lock braking systems (ABS) are designed to maintain the slip ratio within the range of maximum friction.

2.2 Skid resistance measurements

2.2.1 The need for skid resistance field measurements

On most part of the modern highways in the developed countries, with a reasonable level of maintenance, skid resistance is the property of a pavement surface with the highest influence on road safety, as it determines the interaction between the pavement and the vehicle and therefore the ability to control the vehicle. A lack of skid resistance of the pavement leads to a loss of braking power and steering capability of the vehicle, which may lead to accidents.

Skid resistance becomes critical only under extreme conditions, which include a wet pavement, high speeds and the necessity of high horizontal forces due to strong braking or steering actions. Unlike other distresses such as cracking, longitudinal unevenness or rutting, the loss of skid resistance cannot be detected visually nor perceived under normal driving conditions. It is therefore essential to measure the skid resistance of a pavement in order to assure a correct level.

Skid resistance measurements are carried out for different purposes and therefore with different requirements:

- **Routine measurements on network level:** Road agencies measure systematically the skid resistance level on the road network. The purpose of the measurements is to monitor the evolution of the skid resistance of the network in order to predict the maintenance needs in the upcoming years. Moreover, if skid resistance values below a certain limit are detected, a detailed investigation is necessary in order to determine the

appropriate measure to be taken. Measurements are usually carried out at a specific time of the year in order to minimize variations in the measurements due to seasonal changes in the conditions. The accuracy of the measurements is not very important, because on a network level, small variations in skid resistance within a road section will filter out in the mean values and in case of measuring below the threshold (investigation level), a detailed inspection will follow.

- **Quality assessment of new pavement surfaces:** New pavement surfaces shall meet a number of specifications in order to ensure a minimum level of quality. Most of the properties can be determined in laboratory on specimens of the asphalt mixture. However, so far, skid resistance needs to be measured in situ. On new pavements, the minimum threshold is much higher than the investigation level of in-service roads. Some asphalt mixtures show a lower initial skid resistance because of the presence of the bitumen film. Measurements are carried out when the paving works are finished, which can be at any time of the year. Therefore, the weather conditions, especially temperature, may have an influence. The precision and reliability of the measurement is very important in this case, because the contractor may face a financial penalty if the minimum threshold value is not reached or even may have to repeat the paving works.
- **Quality control for contract compliance:** The maintenance of roads is often externalised to specialized companies, either through concessions (toll roads) or through long-term maintenance contracts, in which the contractor is responsible for maintaining adequate levels of pavement performance. The contractor shall prove on regular time intervals, by means of measurements carried out by an independent organization, that the minimum levels of the established pavement performance indicators are met. In some cases, the remuneration of the contractor depends on the level of the performance indicators. The road administration usually checks the measurements carrying out contrast measurement randomly on parts of the road network.

It is obvious that in the last two applications, the repeatability and reproducibility of the measurements is extremely important. Any time the result of a measurement implies a financial consequence far higher than the cost of the measurement, the validity of the measurement is disputed.

2.2.2 Measuring principles

In Europe alone, at least 14 different devices for routine field measurements are operative (Do & Roe, 2008). The main differences between the different devices can be grouped by:

- the slip conditions
- the testing tyre
- the vertical load
- the wetting system

The amount of friction generated in the contact area between a tyre and a wet surface depends on each of these factors.

Regarding the slip conditions, measuring devices are usually divided into two groups

1. Devices operating according to the side-way force principle (SFC - Side-way Force Coefficient): e.g. SCRIM, SKM and μ -meter.
2. Longitudinal friction devices (LFC – Longitudinal Friction Coefficient): e.g. GripTester, Adhera and Viafriction.

The so-called sideways-force devices have a test wheel derived at an angle to the longitudinal axis of the vehicle. When the wheel is dragged along the surface, the friction between the tyre and the pavement generates a horizontal force perpendicular to the rotation plane of the wheel, which is measured.

Currently there are two groups of SFC devices: devices with one or two measuring wheels located within a carrying vehicle, with each of the measuring wheels generating a value of the generated horizontal force. The measuring wheels are located within the wheel path of the road. The second group of devices are trailers with two wheels set at an angle and where the force is measured between both wheels as shown in figure 2.1. A third wheel is provided to the trailer for stability.

Figure 2.1 Measuring principle of two-wheeled SFC friction trailers (source: Douglas Equipment Ltd)

This device is normally used on airport runways. On roads it is not possible to locate both measuring wheels in the wheel path, which has two important drawbacks (Henry, 1986): the resulting measurement is the average of two friction values measured on two pavement surfaces with potentially different skid resistance properties. If there is a difference in friction between the two measuring wheels, the device generates a friction force in the third wheel, which is not measured. For these reasons, these trailer devices are not and shall not be used on European roads. They can be used on surfaces where there are no clear and narrow wheel paths, such as airfields.

The advantage of side-way force measurements is that they are highly representative for the friction conditions under steering actions. Considering that the majority of fatal accidents are lane departure crashes (including head-on collisions and run-off-road collisions) caused by loss of control of the vehicle, these conditions are highly relevant.

The second group of devices, for measuring the longitudinal friction coefficient, has a large number of different measuring machines.

Some devices use a fully locked wheel to measure the skid resistance. The advantage of a fully locked wheel is that the conditions are the most unfavourable for friction, so a low and stable level of friction is measured. The downside is that the conditions are not representative for normal driving and steering conditions, as anti-lock braking systems (ABS) are mandatory on all new cars sold after 1 January 2004. Moreover, for measurements on longer road sections, excessive and irregular wear may develop in the tyre and temperature may rise to levels which alter the rubber properties.

Most of the longitudinal slip devices create a fixed slip ratio by means of a gear system which forces the test wheel to rotate slower than the transport wheels. Some devices aim for the slip ratio that yields the highest friction results. This makes the measurement more sensitive for small variations in the test conditions. On the other hand it provides better information on the friction potential of the pavement, under realistic slip conditions. Moreover, since the wheel keeps rotating, excessive wear and temperature build up is prevented. The device relies on the transport wheels to generate sufficient friction to induce the slip ratio. With the devices that control the amount of slip in the contact area and measure the generated horizontal force, only the friction force generated by slip is measured. This is why in the classical graphs of slip ratio versus horizontal force, the horizontal force is zero at zero slip speed. Especially at low slip ratios, this has no relation at all with the braking force potential.

A second sub-group of longitudinal friction devices uses a braking system to control the slip ratio. The system can be configured to maintain a fixed slip ratio throughout the test, or it may use braking cycles gradually increasing the braking force until reaching a 100% slip. In the first case the systems must respond to changes in the friction properties of the pavements, which may result in unstable measurement conditions. In the case of using braking cycles, different braking conditions are applied during a single measurement. The advantage of these systems is that they are the most representative of a braking action of a vehicle.

All dynamic measuring systems use a pneumatic rubber test tyre for the measurements. The properties of these tyres are a very important factor in the process of generating friction. The standards or technical specifications of these devices prescribe either a standardized tyre, such as the ASTM tyre or the PIARC tyre, or they define a device specific tyre, which usually is provided by the manufacturer of the device only. The most relevant properties of the tyres are the size (radius and width, which determine the contact area), the inflation pressure (which also influences the contact area and the contact pressure), the profile of the tyre (smooth or ribbed) and the rubber composition (specifically the rubber hardness and resilience).

The vertical load on the test tyre is another differentiating factor amongst the skid resistance measuring devices. The vertical load on the test wheels varies from 250 N to 3500 N. The vertical load determines the contact surface and the contact pressure. On a more detailed level, the vertical load causes a closer contact between the two materials, when asperities of the pavement surface penetrate into the rubber material. A vertical load of less than 1500 N per wheel (equivalent to approximately 600 kg as the total mass of the car) can hardly be considered representative for modern cars, not to mention for trucks or buses. Even a typical motorcycle of approximately 150 kg with driver (70 kg) supports approximately 1100 N per wheel, and significantly more under braking conditions when the weight is transferred mainly to the front wheel.

The pavement wetting system is an essential part of the system, but when some minimum requirements are complied with, small differences appear to have little influence on the measurement results. Most devices apply the amount of water to create a theoretical water film thickness of 0.5 mm or 1.0 mm. In order to reduce the water consumption (and therefore increasing the production of the measurements), the trend is to reduce the water film thickness to 0.4 mm and limit the wetted area to the contact area of the measuring tyre. Research carried out by Beautru et al. (2012) with the Dynamic Friction Tester (DFT), shows that the effect of increasing water film thickness beyond 0.4 mm has a limited influence on the measurement (figure 2.2).

Figure 2.2 Influence of water film thickness on DFT measurements (Beautru et al., 2012)

It should be noted though that the water film thickness is a theoretical value based on the assumption that the surface is smooth and flat. It is most likely that on porous and discontinuous surface courses it is impossible to obtain a high water film thickness with a standard wetting system of a measuring vehicle. This effect can be seen in figure 2.3 where the influence of the theoretical water depth on porous asphalt and on the discontinuous asphalt concrete for thin layers, is practically non-existent.

Figure 2.3 Influence of water film thickness (measurements with the Adhera device, Beautru et al., 2012)

In general it can be concluded that as long as the water film thickness is sufficient to break the adhesion component of friction, but not thick enough to cause hydroplaning, the effect on the measurement is small. Moreover, it should be taken into account that the water also acts as a coolant for the tyre, and the tyre temperature does have a high influence on the friction results. The effect of temperature will be treated in paragraph 2.3.

Finally, static tests such as the British Pendulum and Dynamic Friction Tester (DFT) can also be used for friction measurements on pavements. This is usually done on very short road sections or in special situations such as bends with a very low radius of curvature. The aforementioned static devices will be shortly described in section 2.5.

2.2.3 Harmonisation trials

An internal report by the Swedish National Road and Transport Research Institute (VTI, 1971) in which various devices for skid resistance measurements are evaluated, concludes that *"... any numerical consistency between the results of the various devices cannot be expected, and should such correlation by chance be found, it must be considered to be coincidence"*. Many efforts have been done and are under way to prove this conclusion wrong.

In the 1990s the working group on "Surface characteristics" within the CEN Technical Committee on "Road Materials" (TC227 WG5) was entrusted with the task to provide harmonised test methods to measure skid resistance. The request was motivated by the need for assessing the skid resistance of recently-laid pavement surfacings, primarily for contract compliance or production control.

WG5 encountered a situation where each country had its own preferred method(s) and device(s) and the different methods rely on different principles, as described in the previous section. The need for harmonisation had already been recognized by the World Road Association (PIARC), who organised in 1992 an international experiment which comprised

comparative testing between many different devices and resulted in the definition of the International Friction Index – IFI (Wambold et al., 1995). The resulting harmonisation equations however were not considered sufficiently reliable to be used in European standards, as they relied on individual equations for individual machines and took no account of the feasibility of maintaining an entire fleet of vehicles calibrated and on how the harmonisation equations would maintain stable over time.

A consortium of six European countries, under the umbrella of the Federation of European Highway Research Laboratories (FEHRL), continued the work on the IFI, reducing the number of devices included and proposing a methodology to maintain a stable European Friction Index (later called SRI, Skid Resistance Index) and a methodology by which (national) fleets can be calibrated to the new index.

In 1999 the HERMES project was carried out by six member states and additional participants in the field experiments, again coordinated by FEHRL. The complicated and much debated interpretation of the results delayed the publication of a final report to 2006 (Descornet et al., 2006). Although the calibration process proved practical and the coefficients were reasonably stable, the harmonisation process did not work well for devices of very different operating principles and the precision was uncertain or not good enough to be used in a European Standard. Furthermore, the lack of operating procedures resulted in marked differences between devices of the same family.

A technical specification (CEN/TS13036-2: “Assessment of the skid resistance of a road pavement surface by the use of dynamic measuring systems”) was published (CEN, 2010a), describing the calculation of the SRI and a calibration procedure, based on the outcomes of the HERMES project. However, till date this standard has not been put into practice and the fundamental problems detected in HERMES have not been resolved.

According to the technical specification the estimate (*sic*) of the SRI is calculated by means of the equations 2.1 and 2.2:

$$SRI = BFe^{[(S-30)/S_0]} \quad (\text{eq. 2.1})$$

With S_0 being a speed constant in km/h which depends on the pavement texture and is defined as follows:

$$S_0 = aMPD^b \quad (\text{eq. 2.2})$$

Furthermore:

F is the measured friction coefficient at slip speed S

S = the slips speed (km/h)

MPD = mean profile depth as defined by ISO standard 13473-1 (ISO, 1997)

a , b and B are parameters specific to the friction measuring device used

The device-specific parameters are determined in the course of a calibration exercise involving several (at least three) skid resistance measuring reference devices.

As becomes apparent from equation 2.2, the SRI includes the effect of pavement texture by means of the parameter Mean Profile Depth (MPD) as defined in ISO-13473-1. Through a conversion formula, also the Estimated Texture Depth, related to the parameter Mean Texture Depth (MTD) obtained by the volumetric method (EN13036-1, CEN, 2010b), is allowed. The ISO standard for MPD has been under revision for several years in order to

resolve the ambiguities which have led to a poor reproducibility in MPD measurements. Probably because of the poor reproducibility of both MPD and MTD measurements, the correlation of MPD and MTD/ETD is subject of continuous discussion (Esteban et al., 2008; China and James, 2011; Parra and Yanguas, 2013).

Moreover, texture depth does not provide a complete evaluation of all texture properties, as will be described more extensively in section 2.4.

A questionnaire to national road administrations, about four years after the publication of the technical specification of the harmonized standard, revealed that the methodology has not been implemented anywhere in Europe and that calibration trials will not be carried out unless specific research funds are made available for this purpose. The main reason is the increase in measurement uncertainty when using different devices on a common scale and the cost and organizational aspects of the calibration exercises.

Since 2013, CEN TC227 WG5 is working on a new attempt of harmonizing the measurements of skid resistance by using three different scales: a side-way force skid resistance index, a longitudinal high slip skid resistance index and a longitudinal low slip skid resistance index.

Results of correlation trials carried out in the ROSANNE project (Haider et al., 2016) are used to test this new approach. Preliminary results show an improvement of the reproducibility as compared to the HERMES trials.

2.3 Variations in skid resistance measurements

Skid resistance measurement variations over time have been a subject of study ever since measurements began almost a century ago. The study by TRRL between 1958 and 1968 (Hosking & Woodford, 1976a) established a consensus that skid resistance measurements are subject to seasonal variations.

Figure 2.4 Seasonal variation in pendulum measurements (graph reproduced with data from Hosking & Woodford, 1976a)

The authors state that the differences in the values obtained cannot only be explained by temperature difference; the effect of a 10°C temperature difference on the same day is much more limited than a 10°C temperature difference between early spring and mid-summer. Polishing, wear and weathering are suggested as possible explanations, as they change the pavement surface texture, with the climatic conditions determining which of these phenomena predominates. It should be noted that the measurements in these studies were taken with the British pendulum and not with a dynamic measurement device. Also the type of bituminous mixtures used in the 1960s is significantly different from those currently in use. More recent publications, e.g. Gothié (2005) using high performance equipment point to similar trends (see figure 2.5), although no details are given on the processing of the data.

Figure 2.5 Seasonal variations in high performance measurements according to Gothié (2005)

Review of the literature seems to indicate neither a consensus on the quantification of seasonal variations nor on the background or real causes. The following phenomena contributing to in-time skid resistance variations are identified by various authors:

- Polishing of the aggregate: this affects the microtexture and reduces friction. The polishing effect is directly related to traffic intensity, especially heavy vehicle numbers (Oliver et al., 1988). Some authors suggest that the absence of rain causes dust and other small particles to accumulate, accelerating the polishing effect, whereas in wet periods polishing reduces significantly due to the absence of abrasive material (Sanjuán and Gutiérrez-Bolívar, 2003).
- Weathering of aggregate: this phenomenon is little studied. Sanjuán and Gutiérrez-Bolívar (2003) observed that on roads where traffic intensity decreased significantly due to changes in the network (e.g. the opening of a by-pass), the friction values increased over time. This latter observation may reinforce the hypothesis that aggregate weathering increases the road surface's skid resistance. Kane et al. (2013) report increased surface friction caused by asphalt mixture ageing (in the absence of traffic loads).
- Accumulation of dust, detritus, rubber or other substances that may act as a lubricant, especially in the presence of water (Oliver et al., 1988).

The influence of temperature has been quantified in various studies. For SCRIM and SKM measurements, temperature corrections are established in the corresponding national standards. In case of the SCRIM, the temperature correction is based on the pavement surface temperature, whereas in case of the SKM, the correction is based on both pavement surface temperature and the water temperature. Oliver et al. (1988) suggested that it is mainly the tyre temperature that influences the skid resistance, because of the viscoelastic nature of the rubber material. In practice it is very difficult to measure the rubber temperature of a wet tyre, because the presence of the water film makes non-contact measurements imprecise and heat built up within the tyre structure because of energy dissipation is hard to measure. For this reason, indirect correlations with pavement

temperature are commonly used. In this respect, the use of water temperature is an interesting approach as it has a significant influence on the tyre temperature as well.

Studies into the correlation of pavement temperature and skid resistance in general show rather weak correlations or temperature correction factors that depend strongly on the specific site conditions (Van Bijsterveld and Del Val, 2016; Jahromi et al., 2011).

Srirangam et al. (2013) and Anupam et al. (2013) in a paper in two parts, present a very interesting approach for the prediction of the tyre operating temperature. In the first paper, a finite element model of a standardized test tyre is made and its structural response is validated by laboratory measurements. With the finite element model, the temperature development in the tyre is simulated, as a function of the pavement temperature, the ambient temperature and the temperature in the air chamber of the tyre. A temperature increase is caused by the deformations of the rolling tyre under the vertical load. In an iterative process, the rubber properties are updated taking into account the temperature of the tyre. In the next paper the results of a parametric study of finite element analyses with the tyre temperature model under different friction conditions is presented. The results confirm that the influence of pavement temperature depends on the type of surface course. Unfortunately, the model does not include the presence of water, for which the applicability to wet skid resistance measurements is limited.

2.4 Pavement surface texture characterisation

Pavement surface texture is a key parameter for all surface characteristics. The surface geometry determines the water evacuation capacity and the tyre-pavement contact area (Do and Cerezo, 2015), and consequently the correlated surface properties such as noise generation and/or absorption, skid resistance and rolling resistance, as shown in figure 2.6.

Figure 2.6 Texture wavelengths and their effect on pavement-vehicle interaction (ISO, 1997).

Currently there are two standardized measurement methods for pavement texture characterization: the volumetric method (formerly known as the sand patch test), according

to the European Standard EN13036-1 (CEN, 2010b) or ASTM E965-15 (ASTM, 2015a) which yields the mean texture depth (MTD), and the profilometric method according to the ISO standard EN-ISO 13473-1 (ISO, 1997) providing the mean profile depth (MPD).

Both parameters are well established and widely used. The MTD since the middle of the 20th century and the MPD since the 1990s, due to the introduction of high-speed laser profilometers (Wambold et al., 1995). The main drawback of the volumetric method, nowadays performed with glass beads of 0.18 mm to 0.25 mm in diameter, is its low productivity, poor reproducibility and the high accident risk for operators on in-service roads. Moreover, on porous road surfaces the particles will sink down into the lower cavities which are no longer representative for surface texture, resulting in unrealistically high MTD values. For this reason, sometimes a predetermined volume of grease is used instead, especially on airfield surfaces. This practice is included in the ASTM standard, but not in the European standard.

The MPD is a texture parameter developed for high speed profilometers. It is essentially a very simple parameter: from two halves of a 100 mm long segment, the highest peak values are determined and the average of these two values is the Mean Segment Depth (MSD). The MPD is typically calculated for 10 m long sections, which means that it is the average of 1000 MSD values. Despite this average filter, a rather complex pre-processing procedure for the raw profile is needed, including peak filters and high and low-pass Butterworth filters, to obtain harmonized results with various types of profilometers (Losa and Leandri, 2011). Moreover, it is surprising that this indicator for macrotexture, whose wavelength is between 0.5 mm and 50 mm, may be determined with profiles with a sampling distance of 1 mm.

It should be acknowledged that both standards clearly indicate the limitations of each method. The ASTM standard literally states: *"This test is not meant to provide a complete assessment of pavement surface texture characteristics"*, and this statement indicates the need for further developments in this field.

One of the short-coming of the MPD and MTD is that different surface shapes may yield similar texture depth values. Although it is not included in the macrotexture standards, distinction can be made between positive and negative texture (see figure 2.7), where positive texture refers to a surface characterized by peaks and pointed asperities and negative texture describes a flattened surface with peaks pointing downwards in the pavement (Rasmussen et al., 2008).

Figure 2.7 Schematic representation of positive (above) and negative (below) texture (Source: Rasmussen et al., 2008)

Izevbekhai and Voller (2013) describe a method to quantify the skewness of a profile and therewith the orientation (positive or negative) of the surface profile. The definition is based on the mean cube value of the ordinate values divided by the cube of the root-mean-square value of the same ordinate values through a specific sample length. By using cube values, the higher amplitudes, and therefore longer wavelengths, become predominant. This means that the sample length must be carefully chosen and that the indicator is insensitive to microtexture.

Traditionally an arbitrary distinction is made between macrotexture and microtexture. Well accepted indicators for macrotexture exist, but this is not the case for microtexture even though it is commonly accepted that microtexture is determining for aspects such as dry skid resistance.

Microtexture is defined as irregularities deviating less than 0.5 mm from a true planar surface, both in wavelength and amplitude. The ISO standards regarding pavement texture (ISO, 2002) state that the amplitude considered in microtexture is in the range of 0.001 mm to 0.5 mm. To be able to capture wavelengths less than 0.5 mm by means of surface profiles, the distance between samples needs to be less than 0.25 mm. Currently available laser texture profilers for field measurements at traffic speed do not offer higher resolutions than 1 sample per 0.5 mm.

Recent developments are aiming for contactless estimations of skid resistance, where the pavement related parameters are only related to texture in the range from macrotexture to microtexture (Villani et al., 2011; Ueckermann et al., 2014; Kane et al., 2015). On the short term, these friction models can be used to quantify the effect of temperature on traditional skid resistance measurements involving a rubber measurement tyre, thereby improving the reliability of these measurements. Moreover, the improved texture characterisation, including microtexture measurements, will allow for the determination of changes in texture due to polishing, weathering or wear.

Image-based detection of surface deterioration (Mathavan et al., 2014) is not considered here for two main reasons: high resolution image acquisition is much more costly than laser profiles and the image analysis does not provide a quantification of texture which could be used in response models.

2.5 Skid resistance laboratory measurements

2.5.1 Introduction

Meanwhile for field measurement there are about thirty different measuring devices for skid resistance on roads, the number of different machines for the measurement in laboratory of friction properties of paving materials can be counted on one hand.

Probably the strongest reason for this is that there has been since the 1940s a well-accepted functional measuring device on the market, which can be used both in laboratory as in the field.

A secondary reason may lie in the question whether measurements on laboratory specimens can be considered representative for the conditions in the field (Vojtěšek, 2006). The texture of a pavement surface depends on the method of extending and compacting the asphalt mixture.

New laboratory measurements were only invented when accelerated wear of the pavement surface was envisioned, or when a need for better control of the test conditions was detected. Moreover, the development of new laboratory compaction methods, that closely simulate the compaction by a roller compactor, has increased the possibilities of testing skid resistance on laboratory prepared specimens (Georgiou and Loizos, 2014).

2.5.2 Skid Resistance Tester or British Pendulum

The reference device for measuring skid resistance on samples of pavement surfaces is the Skid Resistance Tester, also known as the British Pendulum.

The apparatus, originally developed at the Road Research Laboratory, consists of an adjustable pendulum arm, and a spring loaded rubber slider mounted on the end of the arm. During operation the pendulum is raised and then allowed to swing freely, allowing the edge of the rubber slider to skid across the surface of the road or sample. The pendulum can be used on flat surfaces, but also on curved specimens as is done in the test to determine the PSV value of aggregates or similar tests (Ramírez, 2017).

The standard procedures, as described in EN 13036-4:2011 (CEN, 2011), establishes that the test shall be performed on wetted surfaces. The standard also specifies two types of rubber sliders with different hardness and establishes temperature corrections for each of the sliders. The temperature to be measured for the corrections is the temperature of the slider, before and after the test.

Figure 2.8 Skid Resistance Tester or British Pendulum (EN 13036-4:2011)

2.5.3 Dynamic Friction Tester

The Dynamic Friction Tester (DF Tester) is a portable instrument for measuring pavement surface friction as a function of speed and under various conditions. The measuring unit consists of a disc made to rotate horizontally at a specified velocity before being lowered onto a wetted test surface for measurement of friction. The torque-generated by the resistance between the test surface and spring-loaded rubber "sliders" attached to the underside of the rotating disc-is continuously monitored and converted to a measurement of friction (Saito et al., 1996).

Figure 2.9 Rotating disc of the Dynamic Friction Tester

The device provides the coefficient of friction as a function of speed during a full braking cycle from the target speed to the full stop. As the name of the device already indicates, this means that the measuring conditions are variable throughout the test, especially the temperature of the rubber sliders. Usually the friction is reported at certain speeds (f_{80} , f_{60} , f_{40}).

Figure 2.10 Measurement cycle of the dynamic friction tester (Saito et al., 1996)

Considering that the friction is measured with a rotating disc, there are two important limitations to the device, especially when used in the field on in-service roads. First of all, the surface to be measured has to be flat in order to have a constant contact pressure between the sliders and the pavement surface. The second, most important issue is that skid resistance is dependent on the texture orientation. This is obvious for mechanically textured pavements, especially when grooves are applied, but the direction of asphalt laying and compaction, as well as the action of traffic influences the orientation of the aggregates of the surface, which yields different friction values according to the direction of measurement. Tests carried out in the opposite direction to trafficking averaged about 0.04 units of SFC higher than in the direction of trafficking (Hosking and Woodford, 1976b). More recent investigations have shown differences of up to 0.07 units of SFC depending on the direction of measurement (Berenguer et al., 2015). The DFT by design gives an average value of the friction in all directions.

2.5.4 Friction after Polishing test or Wehner Schulze

In the 1960s a new device to measure the polishing of aggregates, commonly known as the Wehner Schulze machine, was developed at the University of Berlin. Over the years the machine was further developed by the company Freundl and is now commercialized under the name "Wehner Schulze Freundl Apparatus". In 2014 the method became adopted as a harmonised European Standard test method and is now known as the Friction after Polishing (FAP) test (CEN, 2014).

Figure 2.11 Wehner Schulze device, with details of the polishing unit and the measurement unit

The machine consists of two parts: the first part is a rotating head with three conical hard rubber blocks which, under controlled pressure and speed conditions, provide a polishing action on a flat specimen. During the polishing water is sprayed on the surface and additionally, a polishing agent (sand or similar) can be added. After a polishing cycle the specimen is moved to the second part of the machine, where the friction is measured following a similar procedure as with the Dynamic Friction Tester. The reference value is the friction measured at 60 km/h.

2.5.5 Skid Resistance Interface Testing Device (SR-ITD)

Within European research project SKIDSAFE, co-financed by the 7th Framework Programme, a new laboratory testing machine was developed to simulate the surface deterioration caused by traffic and to measure skid resistance properties under a wide range of measuring conditions (Van Bijsterveld et al., 2015). A detailed description of the device and its principles is presented in 0, since data obtained with this device are used for the development of this thesis.

Figure 2.12 Skid Resistance Interface Testing Device (SR-ITD)

2.6 Tyre-road interaction modelling

2.6.1 Tyre modelling

Modelling of tyre-road interaction has been focussed on the tyre part for many years. The tyre industry is highly competitive and the design of the tyre has by far the most influence on grip, rolling resistance, noise, vibrations and durability of the tyre. A tyre manufacturer needs to find the right balance between these characteristics, according to the requirements of the tyre. Numerical modelling is a cost-effective tool for this purpose, only if the results are reliable enough.

One of the most mentioned tyre- model is the so called Magic Formula (Pacejka and Bakker, 1992). The model provides a set of mathematical expressions from which the forces and moment acting from road to tyre can be calculated at longitudinal and transverse slip conditions, which may occur simultaneously. The model aims at an accurate description of measured steady-state tyre behaviour, which is referred to by the authors as a "pure slip" model. The coefficients of the basic formula represent typifying quantities of the tyre characteristics. The model can be considered as a regression model, were the regression parameters are related to physical properties of the tyre.

A different approach is initiated by a group of researchers related to the German tyre and rubber industry, namely Heinrich, Persson and Klüppel based on previous works from Grosch. More recently, also the University of Aachen (Ueckermann and Oeser) and the University of Delft (Villani and Scarpas) have contributed to this approach. The fundamental idea consists of a model of a rubber block sliding over a rough surface, which is characterised

following a fractals approach. A viscoelastic model of the rubber material defines the stiffness of the rubber material and the hysteretic damping, which defines the amount of dissipated energy (Klüppel and Heinrich, 2000). In this model, the surface properties of the pavement become relevant and the characterisation of texture, especially microtexture is needed.

2.6.2 Pavement-tyre interaction

With the development in laser profiler techniques and 3D-imaging, the measurement of microtexture in the field may become a possibility in the near future. Dunford et al. (2008) already explored the possibilities of field microtexture measurements to be developed into contactless friction measurements.

Some studies have established correlations between (micro-)texture parameters and friction measurements (Kane et al., 2015, Kane et al., 2013). Although a qualitative explanation is given for the correlation, it cannot be considered a physical model. Studies into correlation of macrotexture and skid resistance, though numerous, are not included here, since it is already commonly accepted that even though a correlation exists between macrotexture and skid resistance, macrotexture is not sufficient to calculate friction.

Pinnington (2006) explored models for hysteretic friction, describing different approaches to the contact and slip conditions, frequency dependent rubber response models and the response to periodic arrays, in which the pavement texture is characterised as such. Ueckermann (2006) describes a model for the tyre rubber pavement interaction response, without specifying the characterisation of the pavement surface, focussing only on the development of the rubber model as a linear, isotropic viscoelastic material.

The uniaxial relaxation function $E(t)$ increases with the loading frequency and decreases with increasing temperature. This effect is the William, Landel and Ferry (WLF) transformation. However, the so called Payne effect describes a behaviour in which the shear storage modulus G' decreases with increasing strain level.

Typical tyre rubber behaviour shows a constant maximum value of the elastic modulus E_0 and a minimum value, the glass modulus or E_∞ . Ueckermann chose to describe this material behaviour with a model consisting of 21 Maxwell elements and one spring in parallel, whose storage modulus is described by the following equation:

$$E'(\omega) = E_\infty + \sum_{i=1}^{21} E_i \frac{(\tau_i \omega)^2}{1 + (\tau_i \omega)^2} \quad (\text{eq. 2.3})$$

The proposed model shows a very good fit with the experimental data provided by a tyre manufacturer (Continental), but the model has a practical drawback, which is the large computational time, as the matrix to resolve the differential equation becomes very big.

Kane and Cerezo (2015) use a similar approach in which the dynamic friction test is modelled as a set of Kelvin-Voigt elements, which are subjected to deformation induced by a rough pavement surface. As the DFT measures on a small area, the full (micro-)texture profiles was used to simulate the sliding of the rubber pads over the surface. A reasonable correlation on different surfaces was found with a relatively simple response model. For routine measurements on road networks, it is most likely unpractical to use the full microtexture profile.

Villani et al. (2011) applied the Heinrich and Klüppel (H&K) model to predict the friction properties of stone surfaces. The study focusses mainly on the characterization of texture using a height difference correlation function. Parameters of the H&K model are determined in order to obtain a qualitative fit of the model to the theoretical frictional properties of different rock specimens. Experimental data for an exact calibration were not yet available. In her Ph.D. thesis, Villani (2015) extended this approach to the characterisation of asphalt properties for friction modelling purposes.

Ueckermann et al. (2014) measured texture at microtexture scale and applied a power spectral density analysis to characterize the surface. A model for rubber friction by Persson is used to model the friction, in which the elastic and storage modulus of the rubber material are the main parameters. The time-temperature dependency is introduced via mastercurves based on WLF-transformations. A significant observation is that the level of strain in a rubber tyre under slip conditions is in the order of 8%.

The calibration of the model is done with laboratory measurements (Wehner-Schulze) on eight different asphalt and cement concrete pavement materials, and on five different asphalt concrete road sections by means of a longitudinal friction measurement device (Viafriction). The fit between the measurements and the model is very good. It should be noted though that the authors used the same rubber response model for the Wehner-Schulze and the Viafriction device, and that the rubber properties used in the model are not based on any measurement on the rubber of these devices. This means that the rubber properties have been used as a calibration factor. Moreover, the rubber temperature is assumed (and not measured) for both devices separately (47°C for the Viafriction and 57° for the Wehner-Schulze). This means that temperature has also been used as a calibration factor. Further investigations are needed to determine whether these assumptions are valid.

2.6.3 Finite element modelling

Finite element models are a powerful tool to simulate complex mechanical and physical problems. Once the material behaviour is properly described for each of the boundary or loading conditions it is subjected to, simulations of complex structures and combinations of loads can be done in order to determine the coupled response of the entire structure. Provided the availability of sufficient computational power and time, parametric runs to determine the influence of each of the external conditions can be performed. Especially in the field of determining the stresses in the contact area between the tyre and the pavement, finite element models have provided very usable results (Wang and Roque, 2010; Wang et al., 2012, Anupam et al. 2013, Srirangam et al., 2013).

Figure 2.13 Example of a finite element model for tyre contact on wet pavements (Srirangam et al., 2013)

2.7 Conclusions and observations

Skid resistance is a subject that is equally important and complex. Depending on the specific objectives of each researcher, different aspects of skid resistance are highlighted and (partially) explained. The engineering approach of the pavement engineering community has simplified the problem by developing measurement methods which reproduce tyre pavement interaction under slip conditions in order to be able to evaluate the skid resistance of pavements.

The tyre-pavement contact conditions depend on many factors, amongst which:

- vertical load;
- vehicle speed;
- slip ratio / slip angle;
- braking/acceleration force;
- presence of water or other surface "contaminations";
- tyre tread design;
- tyre rubber properties;
- pavement surface texture;
- temperature.

Moreover, during the braking process, factors like vehicle speed, slip ratio, braking forces and temperature are variable. In addition to this, the variables are not all independent, since the rubber properties are strain rate and temperature dependent.

Practically the only undisputed observation made by all authors is that pavement texture, in the complete spectrum from macrotexture to microtexture is the most important pavement property for tyre-pavement friction. Since laboratory measurements of microtexture are already feasible, it is a matter of time that optical devices will become available which are able to measure microtexture in the field. It is therefore the right time to establish parameters that effectively characterise the texture of pavement to the extent that is relevant for friction.

A reliable tyre-pavement friction model is needed to be able to make the conversion from traditional empirical skid resistance measurement to pavement texture indicators.

Important advances have been made in texture characterisation. Also interesting developments have been published on rubber pavement friction models. Moreover, finite element analyses have been able to provide information on the influence of physically coupled variables, such as temperature and contact stresses.

The key to resolving the puzzle of tyre-pavement friction lies in the effective characterisation of the rubber properties and, most important, the correct definition of the slip/contact conditions.

Chapter 3 Characterisation of texture for modelling purposes

Texture is an influential characteristic of pavement surfaces and determinant in the road-vehicle interaction in many aspects. Traditionally an arbitrary distinction is made between macrotexture and microtexture. Well accepted indicators for macrotexture exist, but this is not the case for microtexture. In this chapter, new approaches to texture characterisation will be presented, amongst which a methodology based on the theory of self-affinity of rough surfaces, which makes it particularly suitable for numeric modelling. Moreover, methodologies to obtain high resolution profiles are described and the influence of profiling methods on the parameter determination procedures is analysed.

3.1 Methods for (aggregate) microtexture characterisation

3.1.1 Introduction

Microtexture is defined as the deviation less than 0.5 mm from a true planar surface, both in wavelength and amplitude. The ISO standards regarding pavement texture (EN ISO 13473) state that the amplitude considered in microtexture is in the range of 0.001 mm to 0.5 mm. To be able to capture wavelengths less than 0.5 mm by means of surface profiles, the distance between samples needs to be less than 0.25 mm.

Obviously the amount of data required to obtain representatives microtexture profiles is enormous and the profiles itself do not provide directly useful information. The French Highway Research Laboratory IFSTTAR (former LCPC) developed indicators to characterise microtexture, determining some typical aspects of the surface geometry (Do, 2005; Do et al., 2009). The focus of the indicators is on the shape of the asperities¹ found on the surface.

3.1.2 Microtexture parameters

Depending on the setup of the texture profile scanner, the reference plane may vary for example with the thickness of the specimen. Moreover, the specimen may have a slope which would influence in the average value of the profile. For this reason, profiles are subdivided into sections of 1000 mm, on which slope suppression is applied. This method consists of performing a linear regression on the profile and subtracting the regression line from the scanned profile. This results into a profile with a constant slope and an average value of 0 for the z-coordinates. If the scanning length is less than 1000 m, slope suppression is applied on each section and various profiles are concatenated after truncating at the first and last intersection with the x-axis.

The following parameters are used to characterise the microtexture of different types of surfaces:

- R_q – Root mean square value of the profile height
- 2α – summit angle
- β – peak to peak summit angle

¹ IFSTTAR named the asperity shape indicators “indenter parameters”, which is derived from the French word “indenter”, related to the action of the teeth of a tooth-wheel.

- 2L – asperity width

The R_q parameter is the root-mean-square value of the ordinate values z_i .

$$R_q = \sqrt{\frac{1}{N} \sum_{i=0}^n z_i^2} \quad (\text{eq. 3.1})$$

By taking the squared value of the ordinate values of the corrected profile, an indicator is obtained for the amplitude of the peaks and valleys of the profile. Moreover, the root-mean-square value represents to some extent a weighted average in which the higher amplitudes are considered more relevant, which is in line with general considerations on friction, as these are the points that first get in contact with the rubber tyre surface.

The asperity shape parameters provide information about the height, shape and density of a profile. The profile analysis method and the asperity shape parameters are described as follows:

- the profile local maximum (peak) and minimum (valley) are first defined (see figure 3.1);
- the line connecting a peak and two adjacent valleys forms an asperity;
- the summit angle of an asperity, denoted as 2α , where α is calculated as the average value of the approach and leave angles (eq. 3.4). This parameter characterizes the profile sharpness;
- the relative height between two consecutive asperities, characterized by the angle θ characterizes the profile relief (height parameter, eq. 3.2). This parameter is relevant if it is considered that an object sliding over the surface moves from peak to peak, bridging the valleys;
- the line connecting all peaks and valleys (green line) constitutes the profile roughness scale;
- the line connecting the profile peaks (red line) represents the wavelength of the profile (also referred to as "undulation scale");
- the distance between two valleys is denoted as the asperity width 2L.

Figure 3.1 Definition of the asperity shape parameters

The angle θ is calculated by means of the following equation (3.2):

$$\theta = \tan^{-1} \left| \frac{z_{p+1} - z_p}{x_{p+1} - x_p} \right| \quad (\text{eq. 3.2})$$

where (z_p, x_p) are coordinates of the p^{th} peak.

The original concept of θ is not quite clear; there is no difference in positive and negative angles and the reference plane is arbitrary. Alternatively a similar definition as 2α is proposed, defined as the angle formed by 3 subsequent peaks (instead of valley-peak-valley). In this case, the physical meaning is clearer as it describes the asperity of a contact surface, considering that a tyre would roll from peak to peak. Mathematically, there is not much difference as the formulation of the new definition could be written as equation 3.3:

$$\beta = \pi - \theta_p - \theta_{p+1} \quad (\text{eq. 3.3})$$

The definition of the new β parameter is illustrated in figure 3.2.

Figure 3.2 Definition of the roughness scale angle β

Equation 3.4 is used to calculate α :

$$\alpha = \frac{1}{2} \left\{ \tan^{-1} \left| \frac{x_p - x_v}{z_p - z_v} \right| + \tan^{-1} \left| \frac{x_{v+1} - x_p}{z_{v+1} - z_p} \right| \right\} \quad (\text{eq. 3.4})$$

where (z_v, x_v) are coordinates of the v^{th} valley.

The asperity width, denoted as $2L$ is the horizontal length between two valleys of the profile:

$$2L = x_{v+1} - x_v \quad (\text{eq. 3.5})$$

Depending on the profiling equipment, a completely flat surface may occur in the scanning data. Given the high resolution of the scan, this phenomenon is most-likely to be due to a scanning error, which would distort the calculation of the asperity parameters. Therefore the following procedure for flat sections is applied:

- Flat sections of more than three points are not considered in the analysis. This means that the first point of the flat section will be considered as the endpoint of the profile, and the last point of the section as the first point of a new profile. The intermediate points are ignored, which means that the effective length of the scanned profile is reduced. The total number of points (or the total length of flat sections) shall be reported.
- If two consecutive points present the same ordinate value, the following cases can occur:
 - The flat section is included in an otherwise increasing or decreasing line. In this case no special treatment is given to the flat section.
 - The flat section is a peak or a valley. In this case the first point is considered to be the peak or the valley and the second point is considered as a decreasing or increasing value respectively.

3.1.3 Peak descriptors

In contact modelling, the peaks of the surface profile are very important. The shape and the density determine the penetration and the contact force.

The peak density is defined as the number of detected peaks (local maximums) divided by the area. However, in practise, 2D texture profiles are used for the texture analysis. Real 3D profiles with a resolution in the microtexture range are so far unavailable. It is obvious though that not all detected peaks on a 2D profiles are absolute maximums on a 3D profile. The actual surface peak density is lower than the profile peak density.

The profiles obtained at IFSTTAR were obtained by scanning 15 parallel profiles with a distance between profiles of 0.5 mm and a scanning interval (horizontal resolution) of 0.01 mm. Although this is not the same scanning density, this 3D scan can be used to determine the 3D peak density and the 2D peak density on the individual linear profiles. The result on a greywacke rock specimen was a total of 7 670 peaks on a 76 mm x 7 mm surface, which is a

density of 14.4 peaks/mm². Whereas each of the 15 line scans of 76 mm length had 1810 peaks on average. This is a density of 23.8 peaks/mm.

However, when the 3D surface data are filtered in order to obtain a homogeneous resolution in the x and y directions (of 0.5 mm), the results are the following:

On a 76 mm x 7 mm surface a total of 122 3D peaks are detected, which is a density of 0.23 peaks/mm². On each of the 15 profile lines, a minimum of 28 and a maximum of 37 peaks are detected (32.6 on average, 490 in total). The average peak density on the linear profile is 0.43 peaks/mm.

From this analysis it becomes clear that the scanning resolution has a large influence on the number of peaks that can be detected. The peak density on a 3D surface can be roughly estimated by calculating the linear peak density and dividing it by 2 (1 peak/mm $\approx$ 0.5 peak/mm²).

In the tyre pavement contact models, the penetration depth of the peaks of the profiles has to be determined. As will be explained later on, this will be done by representing each peak of a profile as a semi-circle with a radius that represents the sharpness of the peak. For this reason, the radius R is calculated for each peak by fitting a cubic spline function ($z = f(x)$) through the profile and applying the following equation:

$$R_{peak} = -\frac{(1 + f'^2)^{\frac{3}{2}}}{f''} \quad (\text{eq. 3.6})$$

3.2 Fractal approach to texture characterisation

Fractal analyses are commonly used for objects exhibiting random properties and it is often assumed that these objects exhibit self-affine properties in a certain range of scales. In tribology the roughness characterization by means of fractal geometry parameters is described by various authors (Villani et al. 2011; Klüppel and Heinrich 2000). Self-affinity refers to a fractal surface that exhibits an invariant behaviour under anisotropic dilation in vertical and horizontal directions. According to this concept, the shape of asperities and cavities of the surface is self-similar (approximately similar to a part of itself), only the size of the shape is variable. The analysis of the self-affine properties of a profile consists in determining the boundary limits of the wavelength in which the shape of the irregularities is self-similar. For practical reasons and in accordance with the definitions of micro and macrotexture in ISO 13473-2:2002, the length scale over which texture is analysed should be from 0.001 mm to 50 mm. However, due to limitations of the equipment used for this study, the full range of microtexture could not be covered and the lower boundary is set to 0.05 mm. The upper range of the macrotexture wavelength (50 mm) is generally not limiting the fractal characterisation as the self-affinity usually ends before reaching this wavelength.

The techniques used for the characterization of fractals are not limited by the boundaries of micro- or macrotexture. The difference and advantage with the profilometric and volumetric indicators is that they take into account the shape, considering not only the amplitude but also the wavelength, in a way similar or comparable to spectral analysis. This is relevant to the extent that the response model for friction in which the rubber of a tyre is excited by the asperities of the pavement surface and the strain-rate dependency of the rubber.

In order to define the fractal parameters of a surface, we consider a surface profile $z(x)$ without overhangs, which means that every value of x corresponds to a unique value of z , where z is the height and x is the distance along the profile. To characterise the fractal characteristics of a profile, a number of parameters are defined. The fractal dimension D is a quantitative measure of the surface irregularity; the rougher the surface, the higher the fractal dimension D . The Hurst exponent H is in principle an independent index that indicates how a time series will evolve in the long term. H assumes values between 0 and 1. By definition, on self-affine surfaces, the Hurst exponent and the fractal dimension are related according to the following equation:

$$D = \delta - H \quad (\text{eq. 3.7})$$

in which δ is the dimension of the Euclidean embedding space. As in this work we will consider two dimensional cross-sections (profiles), δ is equal to 2.

Two further parameters are necessary to characterise a self-affine surface: the correlation length $\xi_{\parallel}$ parallel to the surface and the variance σ^2 of the z coordinates, i.e. the root mean square of the variations around the mean value of z :

$$\sigma^2 = \langle (z(x) - \langle z \rangle)^2 \rangle \quad (\text{eq. 3.8})$$

This variance can also be expressed as the correlation distance perpendicular to the surface:

$$\sigma^2 = \sqrt{\frac{1}{2} \xi_{\perp}^2}.$$

The three surface descriptors, the fractal dimension D , $\xi_{\parallel}$ and $\xi_{\perp}$, can be obtained by correlation functions of the surface. The function chosen in this study is the height difference correlation function:

$$C_z(\lambda) = \langle (z(x + \lambda) - z(x))^2 \rangle \quad (\text{eq. 3.9})$$

For self-affine surfaces, two different parts of the graph can be identified, as shown in figure 3.3. For small values of λ the correlation function follows a power law, while after the horizontal cut-off length of the profile, self-affinity breaks down and the correlation function is constant.

$$C_z(\lambda) = \left(\lambda / \xi_{\parallel} \right)^{2H} \xi_{\perp}^2 \text{ for } \lambda < \xi_{\perp} \quad (\text{eq. 3.10})$$

$$C_z(\lambda) = \xi_{\perp}^2 \text{ for } \lambda > \xi_{\perp} \quad (\text{eq. 3.11})$$

Figure 3.3 Height difference correlation function for a self-affine surface with corresponding set of descriptors

Once the height difference correlation function is calculated for a specific data set, the parameters $\xi_{\parallel}$, $\xi_{\perp}$ and H can be calculated by means of the procedure described below.

Note that in the graph in figure 3.3 the axes are on a log-scale, for which equation 3 represent a straight line with a slope of $2H$.

The first step is to obtain the limit value of the curve which represents $\xi_{\perp}^2$.

On log-log scale, equation 3 can be rewritten as follows:

$$\log(C_z(\lambda)) = \log\left(\xi_{\perp}^2 \cdot \left(\frac{\lambda}{\xi_{\parallel}}\right)^{2H}\right) \quad (\text{eq. 3.12})$$

$$= 2\log\xi_{\perp} + (\log(\lambda) - \log(\xi_{\parallel})) \quad (\text{eq. 3.13})$$

$$= 2\log\xi_{\perp} + (\log(\lambda) - \log(\xi_{\parallel})) \cdot 2H \quad (\text{eq. 3.14})$$

$$= 2(\log(\xi_{\perp}) - H\log(\xi_{\parallel}) + H\log(\lambda)) \quad (\text{eq. 3.15})$$

$$= \log\left(\frac{\xi_{\perp}^2}{\xi_{\parallel}^{2H}}\right) + 2H * \log(\lambda) \quad (\text{eq. 3.16})$$

By means of a linear regression, we obtain an equation of the type:

$$y = a \cdot \log(\lambda) + b \quad (\text{eq. 3.17})$$

Once we obtain the constants a and b , we can calculate $2H$ and $\xi_{\parallel}$.

$$2H = a \quad (\text{eq. 3.18})$$

$$\log\left(\frac{\xi_{\perp}^2}{\xi_{\parallel}^a}\right)=b \quad (\text{eq. 3.19})$$

$$\frac{\xi_{\perp}^2}{\xi_{\parallel}^a}=10^b \quad (\text{eq. 3.20})$$

$$\xi_{\parallel}^a=\frac{\xi_{\perp}^2}{10^b} \quad (\text{eq. 3.21})$$

$$\xi_{\parallel} = \sqrt[a]{\frac{\xi_{\perp}^2}{10^b}} \quad (\text{eq. 3.22})$$

The procedure described above has been implemented in computer algorithms to be able to process automatically large amounts of data.

3.3 High resolution profile sampling systems

3.3.1 Introduction

Common profile measurement systems in pavement engineering practice take measurements in the range from macrotexture to evenness with typical horizontal sample distances of 1 mm up to 100 mm for the latter and a vertical resolution in the range of 0.05 mm to 0.1 mm. Measurement at higher resolutions, in the range of microtexture, are made for research purposes by means of static laboratory equipment. Systems for routine measurements of microtexture on roads are so-far unknown.

In the following paragraphs three different systems are described which have been used to obtain microtexture data for this thesis.

3.3.2 Confocal microscopy

High resolution texture measurements can be carried out using confocal microscopy with extended field. The measurement principle is shown in figure 3.4. A white light is projected by the objective lens on the focus point (M) on the surface. Backscattered light passes back through objective lens and is then directed towards the detector by a beam splitter. The pinhole, located at the image of the focus point produced by the lens, plays an essential role in this configuration as it stops light coming from all points except the focus point, in particular points located on the optical axis, above or below the focus point.

The next step is decoding of the collected light in order to extract the information about the z-coordinate of the point M. This may be realized by spectral analysis. After its passage through the pinhole, the light beam is directed towards a diffraction grating which deviates each wavelength at a different direction. When the linear optical sensor intercepts the light coming out of the diffraction grating, the position of the intensity maximum on the optical sensor is directly correlated with the position (z-coordinate) of the focus point.

A view of the system as used at IFSTTAR is shown in figure 3.5. The sensor is fixed while the specimen is moved by translation in the horizontal plane by means of a set of two orthogonally placed linear actuators. The characteristics of the system are:

- Vertical measuring range: 3.0 mm
- Maximum error: 0.3 μm
- Resolution: 9 μm

Figure 3.4. Principle of confocal microscopy with extended z-axis field (source: IFSTTAR)

Figure 3.5. View of the IFSTTAR profile measurement system (source: IFSTTAR)

3.3.3 Texture profiler through laser triangulation

Within the framework of the SKIDSAFE project, the company Geocisa developed a static laser texture profiles, based on laser triangulation (Van Bijsterveld, 2011). The setup consists of a pair of orthogonally positioned linear actuators which support a Selcom laser scanner, typically used for macrotexture measurements on pavement surfaces on the road. The system setup is shown in figure 3.6.

Figure 3.6 Static laser profiler system setup

The set of arms can translate the scanner over a range of 500 mm in the x-direction and 400 mm in the y-direction. The encoder allows a horizontal resolution of 50 μm , whereas the laser scanner provides a vertical resolution of 10 μm .

The scanner is designed to detect erroneous readings due to secondary reflections and also registers the intensity of the laser reflection. This information is stored numerically in a text-file, together with the 3D coordinates of each measured point on the surface. With the post-processing software 3D-images can be generated, as well as linear profiles.

3.3.4 SR-ITD laser line scanner

The Skid-Resistance Interface Testing Device (SR-ITD) developed by Ooms Civiël (Van Bijsterveld et al., 2015), incorporates a texture measurement system based on a laser line scanner which uses the triangulation principle for a two dimensional acquisition of a height profile of a target surface. By using special lenses, a laser line is generated and projected onto the target surface. A high-quality optical system projects the diffusely reflected light of this laser line back onto a highly sensitive sensor matrix. In addition to the calibrated distance information (z-axis), the controller, integrated into the sensor head, uses this matrix image to calculate the position along the laser line (x-axis). This generates calibrated matched measurement values (x, z) which are then output as a precise line profile. Regardless of the position or angle, the profile data are absolute calibrated data sets in a two dimensional coordinate system that is fixed with respect to the sensor. By rotating a

cylindrical specimen (figure 3.7) underneath the scanner, a set of concentric profiles is obtained.

Figure 3.7 Specimen for the SR-ITD

The scanner, used in the system is a type 2750-25 from the company Micro-Epsilon. This device emits a beam like a familiar bar code scanner. The device can measure the distance of the target object with a precision of $4\text{ }\mu\text{m}$ at each of 640 points along the laser line it draws on the target object. In figure 3.8 the beam can be seen projected onto a cardboard box during software testing. The scanning width is between 22 and 29 mm depending on the offset, yielding a horizontal resolution in the range between $35\text{ }\mu\text{m}$ and $45\text{ }\mu\text{m}$. A complete scan on a specimen consists of 360 concentric profiles (one per degree of rotation).

Figure 3.8: Laser beam projected onto a cardboard box during software testing (source: Ooms Civil)

The concept of this scanning device is particularly interesting as it is a promising technique for field measurements. Because the profile is measured instantly within a line, it is in theory not sensitive to vehicle movements.

3.4 Influence of profile sample characteristics on fractal analysis

3.4.1 Sample length for height correlation functions

High resolution scans are typically made on laboratory specimens and with equipment with a limited horizontal measuring range, as described in the previous paragraphs. Considering the purpose of taking these techniques on to routine field measurements, it is important to define a representative sample length for determining the fractal parameters.

First of all the length over which the height correlation function (eq. 3.9) is calculated shall be established. As described in paragraph 3.2, the parameters can be derived by fitting a potential equation on the small wavelengths and a horizontal (constant) on the larger wavelengths. The transition point from the increasing trend to the constant line defines the parameter $\xi_{||}$. The experience shows that this transition takes place at wavelengths between 1 mm and 5 mm. The value of $\xi_{\perp}$ is related to the value of the constant on a log-log scale. Furthermore it is taken into consideration that the range for macrotexture is up to 50 mm. It is therefore considered appropriate to choose the range from 0.001 mm to 50 mm as the range for calculating the height correlation function. Note that the lower limit can never be lower than the horizontal resolution of the sampled profile.

In the case where individual samples do not reach a length of 50 mm, e.g. in the case of the SR-ITD scanning system, samples can be concatenated. In this process, care should be taken that the concatenation does not introduce irregularities with relevant wavelengths for the profile analysis. In paragraph 4.4.3 the procedure for pre-processing surface profiles, including slope suppression and height adjustment, is described.

3.4.2 Sample length for parameter determination

Given the chosen sample length for the height correlation function, a value of each parameter can be calculated for every 50 mm of the profile. This would yield about 20 000 values per km. Apart from the consideration that this amount of data may be impractical, one should be aware that due to the nature of paving equipment and practices, surface characteristics are fairly constant over lengths up to 20 m to 100 m. Also the braking length of a vehicle driving at normal speeds is in the order of tens to over a hundred of metres. On the other hand, currently, the mean profile depth (MPD) is calculated on samples of 100 mm, whereas average values are reported over sections of 1 m.

A parametric study has been carried out calculating the fractal parameters of a scan with a total length of 8400 m, varying the evaluation length from 100 mm to 1000 mm. For each evaluation length the average values and the standard deviations are calculated and presented in table 3.1.

Table 3.1 Average values and standard deviation for fractal parameters versus evaluation length

Section length	2H		$\xi_{ }$		$\xi_{\perp}$	
	μ	σ	μ	σ	μ	σ
mm	-	-	mm	mm	mm	mm
100	1.47	0.0667	1.93	0.306	0.271	0.0479
200	1.47	0.0515	1.95	0.273	0.274	0.0430
500	1.47	0.0370	1.96	0.202	0.276	0.0353
1000	1.47	0.0371	1.96	0.152	0.276	0.0271

The data in table 3.1 indicate that the stability of the parameters increases with increasing evaluation length. For practical reasons, an evaluation length of 1000 mm is considered appropriate and will be used by default in further analyses, unless explicitly indicated otherwise.

3.4.3 Influence of sample distance (resolution)

In paragraph 3.2 the definition of the fractal parameters was explained, illustrated by figure 3.3. The parameter 2H is determined by fitting a straight line through the height difference correlation curve, plotted on a log-log scale. If the surface were truly self-affine, the data of the curve would be on a straight line and a further increase of the resolution would not add more information. However, the curves are slightly curved and the transition from increasing trend to the constant value is not sharp. Although this does not invalidate the data or the fractal parameters, it does imply that the choice of the sections of the graph used to determine the parameters does influence the outcome.

At the same time, the sample distance also becomes a relevant factor of influence in the outcomes of the parameter determination procedures. It was mentioned that the transition from the increasing trend to the constant value takes place approximately between 1 mm and 5 mm. The more data points are available on the left side of this point, the more exact is the estimation of 2H. On a log scale, this means that to gain an additional data point on the left-hand side, a reduction of the sample distance by a factor 10 is needed.

To study the influence of this parameter, a high resolution profile scan on a granite SR-ITD sample, with a resolution of 43.75 μm was taken as reference. Subsequently, the profile was resampled at the following sample distances: 87.5 μm , 0.219 mm, 0.438 mm and 0.875 mm (2, 5, 10 and 20 times the original sample distance). Moreover, two different sections were used to determine 2H: from the sample distance up to 1 mm and secondly up to 2 mm. In the case of 1mm sample distance, no results are reported for the sample distance of 0.875 as there is only one point available.

The results are presented in table 3.2 and graphically represented in figure 3.9. The values were obtained on a profile with a total length of more than 8 m.

Table 3.2 Influence of sample distance on fractal parameters (average values)

Range	up to 2 mm			up to 1 mm		
Sample distance (mm)	2H (-)	$\xi_{\parallel}$ (mm)	$\xi_{\perp}$ (mm)	2H (-)	$\xi_{\parallel}$ (mm)	$\xi_{\perp}$ (mm)
0.04375	1.39	2.44	0.300	1.55	1.95	0.300
0.0875	1.36	2.48	0.300	1.51	2.01	0.300
0.21875	1.27	2.69	0.302	1.43	2.17	0.302
0.4375	1.20	2.83	0.304	1.33	2.42	0.304
0.875	1.06	3.18	0.305

Figure 3.9 Influence of sample distance and parameter determination procedure on fractal parameters

Regarding table 3.2 and the graph in figure 3.9, the following observations are made:

- The sampling distance of 0.875 mm yields results for the parameters 2H which are 25% below the value obtained with the highest resolution. In the case of $\xi_{||}$ the values are more than 30% higher. Together with the observation that a sampling rate of 0.875 mm is not representative for microtexture, these data should be disregarded. This conclusion has serious consequences for texture measurements carried out in the field, as most of the field data have a sampling distance of 0.7 mm or 1.0 mm.
- The influence of the range of wavelengths on which the parameter determination is performed is also very significant. The case of $\xi_{||}$ is especially significant with a difference of 25%. In order to look further into the stability or representativeness of the data, we analyse the standard deviation on the data obtained on a single specimen and a total length of 8 m (table 3.3). The variation in the data is less in the case where the fitting is performed up to a wavelength of 1 mm. Moreover, it is considered that the lower wavelengths are more representative for the friction model.
- The parameter $\xi_{\perp}$ is stable at all sample distances considered in this study

Table 3.3 Influence of sample distance on fractal parameters; standard deviations

Range	up to 2 mm			up to 1 mm		
Sample distance (mm)	2H (-)	$\xi_{ }$ (mm)	$\xi_{\perp}$ (mm)	2H (-)	$\xi_{ }$ (mm)	$\xi_{\perp}$ (mm)
0.04375	0.034	0.342	0.042	0.042	0.266	0.042
0.0875	0.034	0.345	0.042	0.039	0.259	0.042
0.21875	0.029	0.417	0.043	0.031	0.313	0.043
0.4375	0.034	0.451	0.044	0.039	0.35	0.044

To illustrate the above, in figure 3.10 the height correlation functions calculated on the profiles with different sample distances are presented. It shows clearly that for the higher values of λ , the curves are identical. On the left-hand side, each curve ends at its sampling interval.

Figure 3.10 Height correlation functions for different sample distances

In the following graph (figure 3.11) the curve for the sample distance 0.4375 mm is shown and its corresponding regression lines, extrapolated to the original sample distance of 0.04375. Additionally, the regression line to the original data with the 0.04375 mm sample distance is shown. The figure illustrates that due to the curve fitting on a log-log scale, the parameter determination is rather sensitive.

Figure 3.11 Influence of sample distance on parameter determination

3.5 Correlations with other texture indicators

Given the fact that all linear profile based texture indicators depend on purely geometric characteristics, it is likely that strong correlations exist between those indicators. If two indicators have a strong linear correlation, there is no added value to the new indicator.

In the following graphs (figure 3.12) correlations between the asperity shape parameters, the fractal parameters and MPD are shown.

In this study various new parameters are evaluated for their added value compared to the MPD. If a parameter shows a strong and linear correlation with MPD, a priori, it has no added value, unless the parameter shows a better stability (e.g. less variance) or if the parameter has a clear physical meaning which makes it more useful and intuitive for modelling purposes. If a parameter shows no correlation with the MPD values on a relevant range of MPD values, it possibly provides additional information on the texture. In this case also the sensibility is a critical parameter: if the parameter shows no variation between different surfaces, obviously there is no good correlation with the MPD but there is also no added value to these data.

For the analyses different surfaces with a texture range expressed as MPD between 0.2 mm and 2.0 mm are used. MPD is calculated according to the revised ISO standard in its second version as Committee Draft (ISO, 2015). The surfaces are made of different materials: two specimens are made of rock (greywacke and granite) and three specimens are made of asphalt concrete (AC10, PA10 and SMA10). The texture of the asphalt specimens has been measured several times during a testing procedure which includes wear and polishing by rubber tyres.

In figure 3.12, the correlation with MPD of the six most relevant new texture parameters described previously is shown. In all cases the MPD values are on the abscissa and the new parameters on the y-axis.

In the case of $\xi_{||}$ there is no clear correlation with MPD. The SMA sample gives higher values of $\xi_{||}$ than PA, which would even change the ranking of these materials. On the contrary $\xi_{\perp}$ shows a strong linear correlation with the MPD, which is surprising given the completely different way of calculating both parameters. The case of 2H is somewhat different. Theoretically it can vary between 0 and 2. All values except one are between 0.83 and 0.95, which indicates that the sensitivity of this parameter is not very strong. The α and θ parameters show a weak linear trend with respect to the MPD. The deviations from these trend lines are sufficiently large to be able to contain additional information on the texture characteristics.

The wavelength-related parameter 2L appears to be rather insensitive, except for the SMA sample. It should be noted that the profiles obtained on the SMA samples contained many invalid or spurious readings which were deleted. This may have affected negatively the reliability of the parameters obtained on this sample, but especially the parameter 2L as the original value-peak-value sequence may be distorted.

To evaluate the stability of the parameters, the standard deviation for each parameter determination is calculated and the coefficient of variance is determined. The fractal parameters are the most stable, probably because the evaluation length is 1 m long. The coefficient of variation is on average 15% with 34% as maximum for both $\xi_{||}$ and $\xi_{\perp}$. H has even less variation with 13% as maximum. The asperity shape parameters show more

variation: α has an average variation coefficient of 34% (44% maximum) whereas θ and $2L$ show coefficients of variation of well over 100%, which indicates that the precision of these indicators is rather low.

Figure 3.12 Correlation of various texture parameters with MPD

3.6 Conclusions and recommendations

This chapter has dealt with the characterisation of pavement surface texture for modelling purposes. A total number of eight parameters have been defined, five of which are related to the asperity shape and density and three parameters to describe the fractal parameters of a surface.

Three different techniques for texture measurements within the range of microtexture have been described; two are strictly used in a static set-up which implies a restriction to

laboratory use. The third method, although to date has only been applied in laboratory, is expected to produce similar results in the field.

In this stage of the research a limited dataset has been analysed to investigate the influence of sample distance and the sensitivity of the parameter determination procedure. A significant influence of the sample distance was found on the microtexture related parameters ($2H$ and $\xi_{||}$). Also the choice of the part of the height difference correlation curve to be used for the parameter determination has a significant influence on the outcomes. These observations lead to the recommendation to establish a maximum sample distance length of 0.5 mm and to determine the fractal parameters on the wavelengths up to 1 mm. In any case, these conditions shall always be reported in order to enhance the reproducibility of the method.

Chapter 4 Texture characterisation of road materials

In this chapter the surface texture properties of three types of aggregates used in asphalt mixtures and three types of asphalt mixtures are analysed. First of all the influence of the geological and mineralogical properties on skid and polishing resistance is explained. An overview is given of petrographic characterisation methods in use. The most important part of this chapter will be dedicated to the (micro-)texture of stone surfaces, laboratory prepared asphalt specimens and texture measurements on a test track. The characterisation is done as described in the previous chapter.

4.1 Description of the selected aggregates

In this study three types of aggregates are used: greywacke, granite and limestone. All aggregates were selected, produced and supplied by Aggregate Industries in the United Kingdom for use in the SKIDSAFE project. The selected aggregates are commonly used products in the UK and in the Netherlands. The asphalt mixtures used in this study are prepared with greywacke and granite. Limestone not included in the asphalt mixture testing, since it is rarely used in surface layers where skid resistance is an important parameter. Because of the different properties, limestone has been included in the texture analysis for comparison of texture indicators.

Within the generic classification of aggregates, such as greywacke, granite and limestone, the exact structure and composition of the rocks depends on its origin, age and environmental conditions. A brief description of the aggregate sources is given hereafter.

Greywacke aggregate was sourced from Haughmond Hill Quarry near Shrewsbury in Shropshire, England. The rocks of Haughmond Hill date from the Upper Pre-Cambrian age. These are some of the oldest rocks in England and were formed from sediments laid down in shallow waters along the margins of a continental shelf, over 600 million years ago.

Granite aggregate was sourced from Croft Quarry near Leicester, England. The rock quarried at Croft was formed about 500 million years ago from molten igneous materials deep in the earth's crust. Croft Quarry lies within the Ordovician 'South Leicestershire diorites' and it is generally referred to as a quartz-diorite due to the lack of alkali feldspars.

Limestone aggregate was sourced from Topley Pike quarry near Buxton in the Peak District, Derbyshire, England. Topley Pike is found on the outcrop of the Carboniferous Limestone series referred to locally as the Derbyshire Dome. The central part of the dome is characterised by massive and chemically pure limestone of several hundred metres total thickness. The limestone is a typically thinly bedded, fine grained, dark grey limestone with thin shaley partings, which are interbedded with paler grey, medium grained, fossiliferous limestone.

4.2 Standard characterization of aggregates

4.2.1 Introduction

A series of standard empirical tests were carried out to characterise the aggregates, regarding the shape, the strength and the resistance to wear, abrasion and polishing. Many of these tests are currently used in the specifications for aggregates. A short description of the tests, carried out by Aggregate Industries, and the results are presented in the following paragraphs.

4.2.2 Shape indicators

The flakiness index indicates whether the aggregates have a rather cubic shape or a more elongated or flattened shape. Aggregates with a high flakiness may negatively influence the compactibility of the asphalt concrete, flaky aggregates break more easily under high loads, such as the roller compactor, and moreover, the flat surface may have a negative influence on skid resistance. Layered sedimentary rocks are more susceptible to have higher flakiness, although in this case, the greywacke has a lower value than the granite. Flakiness is especially relevant for larger sized aggregates.

Table 4.1 Flakiness index

	Flakiness index (%)		
	6.3/14 mm	4/10 mm	2/6.3 mm
Greywacke	7	13	19
Granite	12	14	17
Limestone	10	13	15

4.2.3 Strength parameters

A number of standard tests to determine the strength of aggregates have been done, which include Los Angeles (LA), aggregate crushing value (ACV), ten per cent fines (TPF) and aggregate impact value (AIV).

The Los Angeles test is a measure of the resistance of coarse aggregate to fragmentation resulting from a combination of actions including abrasion or attrition, impact and grinding. The test method is described in EN 1097-2 and is widely used to characterise aggregate for road applications.

The aggregate crushing value (ACV) gives a relative measure of the resistance of an aggregate to crushing when subjected to a compressive load gradually applied to a maximum value of 400 kN in a prescribed time. The test method is described in BS 812-110.

The 10 % fines value (TPF) gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. The test method is described in BS 812-111. The test is similar to the ACV test, but the increase in force stops when 10% of the original material has passed the sieve after being crushed. The TPF test gives more accurate results for weaker aggregates.

The aggregate impact value (AIV) test gives a relative measure of the resistance of an aggregate to sudden shock or impact. The test procedure is described in BS 812-112.

The strength related tests, indicate that the granite and the limestone have similar strength characteristics. These tests also show that the greywacke is by far the strongest material in terms of resistance to fragmentation, crushing and impact.

Table 4.2 Aggregate strength parameters

	LA (%)	ACV (%)	TPF (kN)	AIV (%)
Greywacke	23	10	410	9
Granite	28	20	180	27
Limestone	31	24	180	25

4.2.4 Abrasion and wear

Micro-Deval (MD) and aggregate abrasion value (AAV) are, on the other hand, related to the abrasion and wear characteristics of the aggregates.

The Micro-Deval test consists of measuring the wear produced by friction between the aggregates and an abrasive charge in a rotating drum. The sample is normally tested in the presence of water but it may also be carried out in a dry condition. The test method is described in EN 1097-1.

Two test samples, each consisting of 500 g of 10/14 mm aggregate, are placed in two separate drums with 2.50 l of water and 500 g of steel balls. After 12 000 revolutions at 100 rpm, the percentage of each test specimen passing a 1.60 mm sieve is determined, and the average is reported. A low percentage indicates a high resistance to wear.

The aggregate abrasion value (AAV) gives a measure of the resistance of aggregate to surface wear by abrasion. The test procedure is described in EN 1097-8 (Annex A).

In this test, two specimens are first prepared by embedding selected 10/14 mm aggregates in a resin. The specimens are then positioned and pressed, using 2000 g weights, against the surface of a steel disc rotating in a horizontal plane, while adding sand. The loss of weight of the original specimen is reported. In limestone samples before and after the test are shown.

Figure 4.1 Samples of the AAV test, before (left) and after testing (right)

Results indicate that the greywacke and granite aggregate have similar resistance to abrasion and wear. The limestone is the least resistance to abrasion and wear.

Table 4.3 Resistance to abrasion and wear

	MD (%)	AAV (%)
Greywacke	10	3.2
Granite	9	4
Limestone	17	9.4

4.2.5 Polishing

The polished stone value (PSV) is a relative measure of the resistance of an aggregate to the polishing effect of vehicle tyres under conditions intended to simulate those of traffic acting on a road surfacing. The test was developed in the UK more than 60 years ago and is still in use. The test method is described in EN 1097-8.

The test is carried out on aggregate passing a 10 mm sieve and retained by 7.2 mm grid sieve. Test specimens are prepared by embedding aggregate in resin in a curved-shaped mould. Prepared specimens are polished in an accelerated polishing machine (see figure 4.2 on the left). Two of the specimens are not polished in order to make the comparison stone. The degree of polishing of the specimens is then measured by means of the pendulum friction tester (see figure 4.2 on the right).

Figure 4.2 Polished Stone value – test setup (source: Aggregate Industries)

PSV values corresponding to the three types of aggregates types indicate that the greywacke and granite aggregates have good polishing resistance characteristics. The polishing resistance of the limestone is, however, rather poor.

Table 4.4 Results PSV test

	PSV
Greywacke	60
Granite	58
Limestone	32

4.2.6 Summary of the standard test

The values of the shape parameter flakiness are very similar between the three aggregates, especially if we consider the range of sizes that is used in the asphalt mixtures in this study (0/10).

The greywacke aggregate has a high strength and resistance to crushing. The resistance to abrasion and wear is high, although granite presents an even better result in the Micro-Deval test. The greywacke aggregates have the highest resistance against polishing.

The granite aggregate has a significantly lower strength and resistance to crushing than the greywacke. The results of the strength tests are in fact very similar to the limestone. However, the resistance to abrasion and wear is amongst the highest value and much better than the limestone. Also the PSV value is close the greywacke and much better than the limestone.

Finally, the limestone is clearly the weakest aggregate in all aspect, even though the strength is at the same level of the granite aggregate.

4.3 Mineral composition

4.3.1 Introduction

Elaborate petrographic analyses of the aggregates have been carried out, including chemical analyses, scanning electron microscopy and X-ray techniques. For the purpose of this study, the full mineralogical composition does not appear to be relevant. However, the basic composition and structure of the stone have an influence on the microtexture and its resistance to polishing and wear.

Bagampadde et al. (2005) investigated the influence of moisture on the mechanical behaviour of asphaltic mixtures, based on the chemical and mineralogical composition of aggregates. The susceptibility of the mixture to moisture damage was determined by means of the resilient modulus and the tensile strength ratios. It was concluded that aggregates with a high sodium or potassium content are highly moisture sensitive. Aggregates with calcium, magnesium and iron are resistant to moisture damage. Stripping was generally high for aggregates with quartz and alkali feldspars, although one aggregate of practically 100% quartz showed a low moisture sensibility. The type of moisture inflicted damage will mainly lead to loss of aggregate, which affects mainly the macrotexture and on the long term the pavement roughness.

A study by Van de Wall (1992) determined influential factors in the polishing resistance of aggregates, which are summarized in table 4.5.

Table 4.5 Influence factors in the polishing resistance of aggregates (source: Van de Wall, 1992)

Contributing to polishing	Preventing polishing
Single mineral composition	Multimineral composition
Equal hardness of the minerals	Differential hardness of the minerals
Highly crystalline structure	No crystalline structure
Strong adherence between minerals	Low adherence between minerals
Homogeneous density	Heterogeneous density
Closed texture	Open texture
Virgin stone	Weathered stone

4.3.2 Greywacke

Petrographic examination of greywacke aggregates showed that the aggregates are comprised of several mineral grains that were present in the pre-crushed sample, namely quartz, mafic minerals and feldspars. The actual grain size was in the region of 100 μm to 400 μm . All fine and course particles showed a multi-mineral composition with a rough surface finishing. Mono-mineralic particles were only found with a size less than 70 μm (dust). The mineral composition is given in table 4.6

Table 4.6 Mineral composition of greywacke aggregates

Mineral	Weight (%)	Grain size (μm)	Grain shape
Quartz	48	70-300	Angular
Feldspar	15	100-300	Angular
Chlorite	20	20-100	Elongate
Biotite	9	100-300	Elongate
Opauques	8	70-150	Angular to rounded

The feldspatic materials have suffered weathering. The aggregates have a low porosity and do not show any cracks or veins in the structure. Regarding the influence factors in polishing resistance (table 4.5), the multi-mineral composition and the presence of weathered material contribute to a high polishing resistance.

4.3.3 Granite

Petrographic examination of granite aggregates showed that the typical aggregate size was in the region of 5 mm to 10 mm. Examination of the aggregates clearly showed that the aggregates comprised of several interlocked mineral grains, namely quartz, weathered amphibole and orthoclase feldspars. The actual grain size was in the region of 100 μm to 2 mm, which shows a wider distribution of grain size than the greywacke.

The mixed nature of the minerals was prevalent down to the finest grain size of the aggregates. Only where individual grains were present (i.e. grain size of the dust was less than 70 μm) were the grains mono-mineralic. The overall mineral composition of the aggregates together with grain size and shape are presented in table 4.7.

Table 4.7 Mineral composition of granite aggregates

Mineral	Weight (%)	Grain size (μm)	Grain shape
Quartz	25	50-200	Rounded anhedral
Orthoclase feldspar	46	100-2000	Angular euhedral
Amphibole	18	100-2000	Angular euhedral
Biotite	5	100-300	Elongate euhedral
Opakes	6	70-150	Angular to rounded

Examination of the amphibole grains indicates that the rock has been or is undergoing weathering by the alteration of the parent amphibole grains to chlorite. There is no evidence of cracking of the parent rock or the inclusion of mineral veins within the rock.

Also in the case of granite, the multi-mineral composition and the presence of weathered material contribute to a high polishing resistance

4.3.4 Limestone

The typical aggregate size of the limestone aggregates was in the region of 5 mm to 10mm. Examination of the aggregates clearly showed that they comprised exclusively of limestone (calcite) grains. The detailed mineral composition showed only calcium oxide and carbon dioxide (which would be integrated in the calcium oxide as calcium carbonate).

Depending on the crystal structure, different types of calcite can be discerned.

Table 4.8 Mineral composition of limestone aggregates

Mineral	Weight (%)	Grain size (μm)	Grain shape
Calcite sparite	48	50 - 1100	Rhomboid to irregular
Calcite micrite	15	< 5	N/A
Calcite ooid	20	100-300	Rounded
Terrigenous material	9	100-300	Rounded

Based on the assumptions mentioned in the introduction, a poor polishing resistance can be expected for this aggregate, as has been shown in the PSV results presented in table 4.4.

4.4 Microtexture of aggregates

4.4.1 Samples for aggregate microtexture determination

The first question before measuring the surface texture of aggregates is on which surface it should be measured. An important restriction is that the profiling equipment needs a more or less horizontal surface and a minimum length that exceeds the typical aggregate size. Several approaches have been tested in this research. The first option is to measure on the surface of a rock specimen taken from the quarry, before crushing it into aggregates. It should be taken into account that the breaking process of these blocks is different from the aggregate crushing procedure, for which the surface texture may be different. Stones with a more or less flat surface have been selected for the scanning. Scans were made on different

locations and in two directions. In the forthcoming, these specimens will be referred to as *rock specimens*; two examples are shown figure 4.3

Figure 4.3 Rock specimens (greywacke and granite)

The second option is a specimen composed of aggregates embedded in a resin, similar to the specimens for the PSV-test. In this case though, the specimen is a flat cylinder-shaped specimen. These specimens will be referred to as *mosaic specimens*.

Figure 4.4 Mosaic specimens (greywacke and granite)

In figure 4.4 two mosaic specimens are shown. The advantage of these specimens is that the microtexture of the stone surfaces is most representative for the aggregates in an asphalt mixture. The downside is that the scans are disturbed by the spacing between stones, which because of its uniform gradation is not representative for a normal pavement surface.

The third option arose from the intention to perform friction measurements on stone surfaces with the SR-ITD. For this purpose, cylindrical specimens with a reasonably flat surface where needed. These specimens are obtained by taking cores from large rocks and

then cutting or slicing these cylindrical cores to the required thickness. The specimens obtained by this procedure will be referred to as slice specimens.

Figure 4.5 Production of slice specimens from limestone.

The surface texture of these specimens is, however, very smooth due to the cutting process. The specimens therefore require further treatment to reproduce the microtexture of a crushed aggregate. In order to modify the texture of the rock specimens a shot blasting technique known as wheel blasting has been adopted. In wheel blasting, a wheel uses centrifugal force to propel steel balls (in this case with a diameter of 2 mm) onto the surface of the specimen.

The result is shown in figure 4.6. Tests by Villani et al. (2011) showed that the shot blasted slice specimens approached reasonably well the fractal parameters of the rock specimens.

Figure 4.6 Shot blasted slice specimens

In any case, one should be aware that this method is proposed in order to be able to test the friction characteristics of the original rocks. The shot blasting is meant to reasonably represent the texture of the aggregates, but cannot be considered as a way to characterize the original surface properties.

4.4.2 Laboratory prepared asphalt specimens

Three different asphalt mixtures for wearing courses would originally be tested in the SKIDSAFE test program: Stone Mastic Asphalt (SMA), Porous Asphalt (PA) and Thin Surfacing (BBTM). A maximum aggregate size of 10 mm was chosen for all mixtures in order to obtain an even surface and to reduce the thickness of the specimens, while obtaining a correct compaction level. Probably due to these restraints, the difference between the SMA and the BBTM mixtures appeared not to be significant. For friction testing, the BBTM was replaced by a conventional dense asphalt concrete, AC10. The BBTM has been used for texture characterization though.

The final three different asphalt mixtures thus are:

1. SMA 10: Stone Mastic Asphalt with granite aggregate
2. PA 10: Porous Asphalt with greywacke aggregate
3. AC 10 surf : Dense Asphalt Concrete with granite aggregate

The density and void content of the obtained specimens is given in table 4.9.

Table 4.9 Density and void content of the asphalt mixtures

		AC 10 surf	SMA 10	PA 10
Density [kg/m ³]	μ	2358	2335	2111
	σ	13.6	10.7	25.6
Void Content [%]	μ	3.3	4.2	18.2
	σ	0.6	0.4	1.0

4.4.3 Profile measurements and pre-processing

Most of the profile measurements have been carried out at the laboratory of IFSTTAR by means of confocal microscopy, as described in paragraph 3.3.2.

Zones composed of 15 parallel profiles, regularly spaced every 0.5 mm, were measured. Profiles were 76 mm long and sampled every 10 μ m. The microtexture parameters as defined in 3.1.2 can be determined on each of the 15 profiles of 76 mm. For the fractal parameter determination, however, a minimum profile length of 1 m is needed. For this purpose the 15 profiles are concatenated "snake-wise", that is, the even numbered profiles are considered in the reverse direction, forming one longitudinal profile of approximately 1140 mm.

A typical result of this concatenation process is shown in figure 4.7, where it is shown that this procedure provides a profile without discontinuities, although in this case one of the seaming edges is clearly recognizable.

Figure 4.7 Typical profile for microtexture analysis on a rock specimen

The profiles can contain spurious measurements, which read zero, whereas the rest of the profile contains positive values. The zero-values are replaced with interpolated values.

In case of the measurements performed with the scanning system of the SR-ITD, described in paragraph 3.3.4, all profiles obtained on the specimen are concatenated and filtered for detectable errors.

4.4.4 Results on rock specimens

Texture profiles were measured on two rock specimens of each type; greywacke (GW), granite (GT) and limestone (LS). The individual specimens are indicated by the two-letter code and a number. On each specimen 3 zones (samples) were measured. These samples are indicated with S1, S2 and S3.

Table 4.10 Texture indicators on greywacke rock specimens

	Greywacke rock specimens					
	GW1 S1	GW1 S2	GW1 S3	GW2 S1	GW2 S2	GW2 S3
R_q (mm)	0.36	0.44	0.44	0.72	0.42	0.39
θ (°)	4.9	5.8	6.1	4.9	5.1	5.8
α (°)	72	71	70	72	73	71
2L (mm)	0.32	0.32	0.31	0.32	0.35	0.34
β (°)	163	162	161	163	163	162
$\xi_{ }$ (mm)	27.0	20.3	12.0	119.6	23.3	16.1
$\xi_{\perp}$ (mm)	0.62	0.77	0.68	1.23	0.68	0.65
2H	1.26	1.37	1.43	1.17	1.32	1.36
R_{peak} (mm)	0.012	0.012	0.011	0.012	0.014	0.012

The data in the table reveal that some of the parameters have a high variability within the specimen. R_q for example varies between 0.36 and 0.72, whereas α , β and 2L have rather constant values. The sample GW2 S1 presents rather different values on all parameters, which may indicate that this profile is not representative.

Table 4.11 Texture indicators on granite rock specimens

	Granite rock specimens					
	GT1 S1	GT1 S2	GT1 S3	GT2 S1	GT2 S2	GT2 S3
R_q (mm)	0.48	0.36	0.35	0.39	0.40	0.26
θ (°)	9.2	8.2	9.3	12.0	10.8	11.3
α (°)	61	65	62	53	53	54
2L (mm)	0.20	0.26	0.22	0.13	0.12	0.13
β (°)	156	158	156	149	151	150
ξ (mm)	15.5	8.6	8.2	8.6	25.1	4.9
ξ_⊥ (mm)	0.71	0.59	0.56	0.60	0.65	0.39
2H	1.28	1.39	1.32	1.22	1.08	1.19
R_{peak} (mm)	0.010	0.013	0.011	0.007	0.007	0.007

The same observation as above can be made with the data from the granite rock specimens. In this case, a clear difference can be observed between specimen GT1 and GT2, especially regarding the α , β and 2L parameters.

Table 4.12 Texture indicators on limestone rock specimens

	Limestone rock specimens					
	LS1 S1	LS1 S2	LS1 S3	LS2 S1	LS2 S2	LS2 S3
R_q (mm)	0.45	0.50	0.51	0.65	0.28	0.68
θ (°)	13.1	12.3	11.8	10.9	12.6	17.0
α (°)	57	58	58	58	55	49
2L (mm)	0.18	0.18	0.19	0.17	0.16	0.15
β (°)	149	149	150	154	151	142
ξ (mm)	12.8	15.8	16.8	28.6	8.9	21.0
ξ_⊥ (mm)	0.73	0.83	0.78	1.02	0.41	0.84
2H	1.14	1.18	1.17	1.23	1.03	1.01
R_{peak} (mm)	0.010	0.010	0.010	0.009	0.008	0.007

The differences between the three types of rocks are most pronounced with the β parameter.

4.4.5 Results on mosaic specimens

On the mosaic specimens only two profile samples were taken on each specimen. The tables 4.13, 4.14 and 4.15 contain the results of the parameter determination on the mosaic specimens of greywacke, granite and limestone respectively.

Table 4.13 Texture indicators on greywacke mosaic specimens

	Greywacke mosaic specimens			
	GW3 S1	GW3 S2	GW4 S1	GW4 S2
R_q (mm)	0.64	0.69	0.68	0.72
θ (°)	10.0	12.3	15.9	16.0
α (°)	65	64	59	58
2L (mm)	0.49	0.49	0.40	0.35
β (°)	157	155	152	152
$\xi_{ }$ (mm)	1.72	2.28	2.51	3.00
$\xi_{\perp}$ (mm)	0.86	0.92	0.89	1.17
2H	1.46	1.48	1.40	1.41
R_{peak} (mm)	0.015	0.015	0.014	0.013

Table 4.14 Texture indicators on granite mosaic specimens

	Granite mosaic specimens			
	GT3 S1	GT3 S2	GT4 S1	GT4 S2
R_q (mm)	0.76	0.74	0.75	0.70
θ (°)	12.8	14.1	15.8	14.9
α (°)	63	61	61	60
2L (mm)	0.39	0.45	0.44	0.37
β (°)	153	151	152	152
$\xi_{ }$ (mm)	2.90	2.34	2.07	2.01
$\xi_{\perp}$ (mm)	1.00	0.99	0.98	0.92
2H	1.40	1.51	1.46	1.39
R_{peak} (mm)	0.013	0.013	0.014	0.014

Table 4.15 Texture indicators on limestone mosaic specimens

	Limestone mosaic specimens			
	LS3 S1	LS3 S2	LS4 S1	LS4 S2
R_q (mm)	0.80	0.74	0.83	0.72
θ (°)	10.5	10.4	9.7	9.4
α (°)	65	65	67	67
2L (mm)	0.47	0.44	0.49	0.43
β (°)	156	156	158	159
$\xi_{ }$ (mm)	2.22	2.59	3.15	2.27
$\xi_{\perp}$ (mm)	1.07	0.98	1.16	0.94
2H	1.50	1.43	1.49	1.47
R_{peak} (mm)	0.014	0.014	0.015	0.015

4.4.6 Results on slice specimens

The texture scans on the slice specimens were performed with the laser scanner on the SR-ITD. As described before, the resolution and accuracy of these scans is lower than the previous scans. Each column in table 4.16 contains the results of a subsection of 1000 mm of the total concatenated profile. In case of the greywacke specimen, due to a large amount of erroneous readings, only one valid subsection was left over after filtering.

Slice specimens of limestone turned out to be too fragile for testing in the SR-ITD. For this reason the texture was not measured on these specimens.

Table 4.16 Texture indicators on granite slice specimens

	S1	S2	S3	S4	S5	S6	S7	Average
R_q (mm)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
θ (°)	6.6	8.5	8.6	8.7	8.6	8.5	8.6	8.3
α (°)	77	75	75	75	75	75	75	75
2L (mm)	0.67	0.67	0.68	0.69	0.67	0.68	0.71	0.68
β (°)	167	163	163	163	163	163	163	163
$\xi_{ }$ (mm)	1.7	1.6	1.6	1.8	1.7	1.7	1.7	1.7
$\xi_{\perp}$ (mm)	0.26	0.25	0.25	0.30	0.28	0.31	0.27	0.27
2H	1.5	1.5	1.5	1.4	1.4	1.4	1.5	1.5
R_{peak} (mm)	0.31	0.30	0.31	0.29	0.29	0.28	0.3	0.30
MPD (mm)	0.35	0.39	0.39	0.45	0.40	0.48	0.42	0.41

Table 4.17 Texture indicators on greywacke slice specimens

R_q (mm)	0.22
θ (°)	2.7
α (°)	85
2L (mm)	0.70
β (°)	175
$\xi_{ }$ (mm)	1.9
$\xi_{\perp}$ (mm)	0.14
2H	0.9
R_{peak} (mm)	0.18
MPD (mm)	0.14

4.4.7 Conclusions on aggregate texture characterization

In each of the graphs in figure 4.8 the triangular markers represent the average values of one of the texture parameters. The vertical line marks the range between the average value plus and minus one standard deviation. The first three values are obtained on rock specimens and the second group of three values come from the mosaic specimens.

Figure 4.8 Average values and standard deviation for texture shape parameters

The first observation to be made is that the difference between the different types of specimens (rock vs. mosaic) are very different, which indicates that the macrotexture scale is well described by all these parameters. Secondly, if the values are ranked from low to high within the same specimen type, the ranking of the different types of rock are different.

The limestone specimens show the highest variation within the results on all parameters. The standard deviations are lowest on the mosaic specimens, especially the specimen with granite aggregates.

The graphs in figure 4.9 represents in the same way as above the results of the fractal parameters and the peak radius.

Figure 4.9 Average values and standard deviation of fractal parameters and peak radius

The standard deviations on the limestone rock specimens are extremely high for the fractal parameters. If we ignore these values, the similarity and the ranking within the group of specimen types is more similar than with the previous groups of parameters. This could indicate that they are more sensitive to microtexture.

In general it must be concluded that the influence of the specimen configuration has a high influence on the texture parameters. In this respect, aggregate texture characterisation is not very effective, as the parameters will change significantly after incorporating the aggregates in an asphalt mixture.

4.5 Texture parameter determination on asphalt surfaces

4.5.1 Introduction

The traditional division between macrotexture and microtexture, although arbitrary, has a practical explanation. Macrotexture is determined by the aggregate size and gradation, whereas microtexture is dependent on the nature of the aggregates, as described before. The bitumen, filler and sand play an additional role in the texture of the asphalt mixture. Especially in laboratory prepared specimens the presence of bitumen on the surface is likely to influence the microtexture. The measurement data are taken on new asphalt specimens and the measurement are repeated after several polishing cycles in the SR-ITD.

Furthermore, texture measurements taken on asphalt surfaces on the IFSTTAR test track are analysed. The measurements, however, have a horizontal resolution of 0.7 mm, for which the microtexture is not considered.

4.5.2 Results on laboratory prepared asphalt specimens

In the following tables the results of the texture parameter determination are presented. In this case the scans are made with the laser measurement system of the SR-ITD as described in section 3.3.4. All scans are performed on one specimen of each asphalt mixture and each specimen is subjected to a polishing procedure, which is described in detail in 5.2.1. The heading of each column indicates the level of polishing represented by the time the specimen was subjected to the polishing process.

Scans may be repeated at the same polishing level. In between braking tests have been performed which may have slightly altered the surface texture.

Table 4.18 Scans on AC10 laboratory specimens

Polishing time (h:mm)	0:00	1:00	2:00	3:00	6:00	6:00	6:00	6:00	11:00	11:00
R_q (mm)	0.44	0.42	0.40	0.43	0.40	0.39	0.40	0.31	0.47	0.44
θ (°)	19.6	18.0	17.1	17.1	16.5	16.6	16.1	12.9	18.4	19.6
α (°)	57	58	59	59	60	60	60	66	58	57
2L (mm)	0.85	0.40	0.43	0.40	0.41	0.42	0.46	0.44	0.39	0.85
β (°)	141	144	146	146	147	147	148	154	143	141
$\xi_{ }$ (mm)	1.7	1.6	1.6	1.6	1.7	1.6	1.7	1.9	1.7	1.7
$\xi_{\perp}$ (mm)	0.55	0.58	0.55	0.59	0.56	0.53	0.53	0.43	0.64	0.55
2H	0.9	0.8	0.9	0.9	0.8	0.8	0.9	0.9	0.9	0.9
R_{pk} (mm)	0.046	0.049	0.055	0.056	0.057	0.057	0.064	0.067	0.048	0.046
MPD	0.59	0.54	0.52	0.51	0.55	0.52	0.50	0.42	0.63	0.59

Table 4.19 Scans on PA laboratory specimen

Polishing time (h:mm)	0:00	1:00	2:20	3:20	6:50	8:50	12:50	12:50	15:50	17:50	24:10
R_q (mm)	1.25	1.22	1.15	1.13	1.05	1.04	1.08	1.03	1.03	1.06	0.90
θ (°)	27.1	25.4	25.1	24.2	24.1	23.6	24.7	23.1	24.4	23.7	21.7
α (°)	49	52	53	53	53	53	52	53	53	53	55
2L (mm)	0.62	0.64	0.56	0.58	0.58	0.59	0.58	0.63	0.57	0.57	0.61
β (°)	126	129	130	131	132	133	131	134	131	132	137
$\xi_{ }$ (mm)	2.4	2.6	2.5	2.6	2.6	2.6	2.4	2.5	2.5	2.5	2.4
$\xi_{\perp}$ (mm)	1.78	1.67	1.56	1.58	1.46	1.63	1.46	1.35	1.42	1.40	1.20
2H	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
R_{peak} (mm)	0.036	0.042	0.044	0.044	0.044	0.041	0.041	0.044	0.045	0.045	0.046
MPD	1.93	1.71	1.56	1.68	1.57	1.55	1.59	1.38	1.44	1.62	1.30

Table 4.20 Scans on SMA laboratory specimens

Polishing time (h:mm)	0:00	1:00	1:00	1:00	4:00	7:00	10:00	13:00	29:00
R_q	0.46	0.51	0.48	0.58	0.57	0.61	0.54	0.57	0.58
θ (°)	23.2	22.4	13.9	20.8	21.2	17.6	22.9	23.7	17.2
α (°)	54	52	64	55	55	61	49	52	62
2L (mm)	1.79	1.69	0.79	0.97	0.87	0.49	2.01	1.30	0.47
β (°)	134	135	152	138	138	145	135	133	146
$\xi_{ }$	2.7	2.8	2.7	2.5	2.7	2.6	2.8	2.7	3.1
$\xi_{\perp}$	0.58	0.71	0.66	0.85	0.82	0.85	0.69	0.84	0.83
2H	0.9	0.9	0.9	0.8	0.8	0.9	0.9	0.9	0.8
R_{peak} (mm)	0.043	0.046	0.064	0.047	0.049	0.065	0.041	0.041	0.088
MPD (mm)	0.68	0.84	0.68	0.76	0.77	0.86	0.78	0.81	0.98

In the following graphs, the evolution of each of the parameters with the increased polishing level is shown for all three asphalt mixtures. It should be noted that the AC mixture was only submitted to almost 9 hours of polishing, whereas the PA and SMA specimens were polished for 24 and 29 hours respectively.

The parameter R_q shows a clear decreasing trend on the porous asphalt mixture, whereas on the SMA and AC mixtures (both with significantly lower values) the values are more stable (figure 4.10). This could indicate that the porous asphalt specimens suffer an initial alteration of the surface, for example a reduction of the depth of the pores.

Figure 4.10 Evolution of R_q with increased polishing level

In the case of θ , the values show a decreasing trend on the asphalt concrete specimen, whereas the porous asphalt shows a more constant behaviour. The parameter determination on the SMA specimen proved rather spurious. As indicated before, an alternative definition based on θ , called β , is theoretically more meaningful. As can be seen in figure 4.12, the results for parameter β are similar.

Figure 4.11 Evolution of θ with increased polishing level

Figure 4.12 Evolution of β with increased polishing level

The parameter α shows more similar values on the different mixture types and an equal ranking as with the β parameter.

Figure 4.13 Evolution of α with increased polishing level

The indicator 2L, which indicates the distance between peaks in the profile, does not show significant evolution over time. Apparently, the number of peaks does not change, at most the shape and height. Again, the results on SMA show excessive variation.

Figure 4.14 Evolution of 2L with increased polishing level

The $\xi_{||}$ parameter shows consistent behaviour, with low variation with polishing, but a clear distinction between the AC10 and the open graded mixtures.

Figure 4.15 Evolution of $\xi_{||}$ with increased polishing level

The results of $\xi_{\perp}$ are very similar to R_q , showing a strong decrease on the porous asphalt and less variation on the SMA and AC mixtures.

Figure 4.16 Evolution of $\xi_{\perp}$ with increased polishing level

The last fractal parameter, $2H$, does not seem to add much information. The variations of the parameter within one type of specimen are larger than the difference between the various specimen types. Theoretically, $2H$ can obtain values between 0 and 2, whereas in this case all values are within the range 0.84 to 0.94.

Figure 4.17 Evolution of 2H with increased polishing level

The parameter representing the sharpness (the radius) of the peaks, also shows a consistent behaviour. Differences between the mixture types can be observed, as well as a small variation with the polishing level.

Figure 4.18 Evolution of R_{peak} with increased polishing level

4.5.3 Conclusions on asphalt texture characterization

The texture scans are performed on the specimens at different phases of the SR-ITD testing. This means that in the first stages the bitumen film is worn off the surface and polishing and wear of the pavement surface takes place. In most parameters a certain evolution with the polishing level can be observed. The results on the SMA specimens show a high variability, which makes it impossible to observe a clear evolution.

The parameters α and β show very similar results, although on a different scale, with β providing a higher distinctiveness. The results of θ look different, but are related to β . From these three parameters, β appears the most useful.

The same occurs with the parameters R_q and ξ_L , which appear to represent the same characteristics of the texture. ξ_L is the preferred parameter as it has a higher distinctiveness.

The parameter $2H$ doesn't seem to be of much value, as it produces similar results for all mixtures at all polishing levels.

The parameters $2L$ and R_{peak} do not appear to very sensitive to changes in the surface texture caused by polishing. However, the parameters can be determined correctly and they are theoretically relevant in the tyre-pavement interaction modelling.

4.6 Application to field texture data

The testing facilities at IFSTTAR in Nantes, France, were used to perform skid resistance measurements. The results of these measurements will be described in Chapter 7. The tests were performed on five different pavement surfaces, each having a length of approximately 200 m, except for the last section which is an artificially smooth surface and has a length of 100 m.

The characteristics of the pavement surfaces are provided in table 4.21. The denomination of the asphalt mixtures, the size of the aggregates, the void ratio (if available) and the year of construction are indicated. Moreover, an approximate value of the MPD (Mean Profile Depth) which characterizes the macrotexture level is given on each test track.

Table 4.21 Description of the pavement surfaces on the test site (photos by IFSTTAR)

Code	Mix type	MPD (mm)	Photo
A	Porous Asphalt (PA) Gradation: 0/6 Void content 22.4% Constructed in 2006	2.90
E1	Asphalt Concrete (AC) Gradation 0/10 Constructed in 2006	0.66

E2	Asphalt Concrete (AC) Gradation 0/10 Void content 8.1% Constructed in 2002	0.82	<p>Planche E2 - Béton bitumineux 0/10 semi-grenu ancien</p>
M1	Asphalt concrete (AC) Gradation 0/10	1.3	<p>Planche M1 - Béton bitumineux 0/10</p>
M2	Very thin asphalt concrete (BBTM) Gradation 0/6 Void content 10.2% Constructed in 2005	1.00	<p>Planche M2 - Béton bitumineux très mince 0/6</p>
F	High friction surfacing Epoxy-based binder with 9 kg/m ² calcined bauxite aggregate (gradation 1/3)	1.17	<p>Planche F - COLGRIP (haute adhérence)</p>

L1	Epoxy Resin (very smooth surface)	0.12
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The results of the scans are shown in table 4.22. Except for the epoxy surface, which has an exceptional high smoothness, all parameters can be reasonably established. Except of the R_q and $\xi_{||}$ parameter, the values are of the same magnitude as in the microtexture measurements.

Table 4.22 Texture parameters on test tracks

	A	E1	E2	F	L1	M1	M2
R_q (mm)	69.1	69.9	69.1	65.9	n/a	66.7	65.8
θ (°)	11.19	5.27	8.30	11.51	n/a	15.28	11.42
α (°)	70.2	80.1	74.9	70.0	n/a	66.2	70.4
2L (mm)	4.43	4.01	4.28	3.95	n/a	5.07	4.74
β (°)	158	169	163	157	n/a	149	157
$\xi_{ }$ (mm)	2.06	2.18	2.80	2.15	22.44	2.85	2.36
$\xi_{\perp}$ (mm)	1.18	0.84	0.99	1.00	0.24	1.76	1.40
2H (-)	1.50	1.48	1.59	1.46	1.05	1.59	1.55

Chapter 5 Laboratory testing of friction interfaces

A new laboratory test has been developed in order to characterise the interface properties of rubber on stone and asphalt surfaces. The purpose of this new development is to obtain skid resistance measurements under controllable and measurable stress conditions. This is essential for the assessment of physics-based friction models in this study. In this chapter the working principle of the interface testing device will be described and the results of the testing programme will be analysed. A methodology to characterise the results of the tests in terms of physical and engineering parameters is presented.

5.1 The Skid Resistance Interface Testing Device (SR-ITD)

5.1.1 Motivation and requirements for the design of a new device

The skid resistance interface testing device was developed by the research and development department of Ooms Civiel (Van Bijsterveld et al., 2015) within the SKIDSAFE project. It was designed for the purpose of scientific research into constitutive models for skid resistance measurements of a rubber wheel on a pavement surface. It was considered that existing devices, such as the Wehner-Schulze machine, measure friction properties, but do not allow for variations of slip conditions, nor (relative) speed, nor rubber compound. For this reason, a laboratory test set-up was needed which satisfies the following conditions:

- suitable for asphalt specimens that can be fabricated with standard laboratory equipment or which can be obtained from the road by coring
- possibility to test other types of pavement materials, such as rock samples or cement concrete
- controlled vertical force representative for field conditions
- controlled speed and slip speed representative for field conditions
- possibility to introduce a slip angle
- speed and contact pressure representative for field conditions
- dry and wet friction testing
- pavement surface polishing under realistic conditions
- continuous measurement of vertical and horizontal forces on the wheel

It was foreseen to compare laboratory test results with field test measurements with SCRIM and GripTester. For this reason, the design concept was to reproduce on a smaller scale the testing conditions of these methods. The size of the specimen was chosen based on the largest standard size drill for coring specimens from asphalt pavements or out of rock, which is 390 mm.

The decision to design and build a new testing device adjusted to the specific needs for the research, included the risk of technical difficulties that needed to be resolved.

5.1.2 Specimen holder

In the initial design concept, the SR-ITD consists of two main parts. The first part has maintained practically unchanged since the first design concepts and consist of a metal

cylindrical pan, with an internal diameter of 390 mm and a height of approximately 50 mm, which is connected to an electrical motor able to make the pan spin, like a turntable, at speeds up to 1200 rpm. The outer track on the sample is located at 174 mm from the rotation center, which means that at the maximum rotating speed, the test wheel can reach 78.7 km/h, whereas the inner and intermediate track can reach speeds of 42.5 km/h and 60.6 km/h respectively. Considering the dimensions and a specific weight of 2350 kg/m³ for a typical asphalt sample, a test specimen weighs approximately 13 kg.

The motor has a power of 5 kW in order to maintain speed even when a (limited) external braking force is applied. The specimens to be tested can be cored out of asphalt slabs produced with standard laboratory equipment. The specimen is allocated in the cylindrical pan, which supports the specimen in horizontal and vertical direction, and allows for the evacuation and circulation of excess water.

Figure 5.1 Specimen holder (pan) and specimen layout

In the design drawings of the pan, studs were foreseen to prevent the specimen from slipping. However, when testing with rock specimens, the studs were likely to have caused the cracking of the specimen. For this reason, in the final version, the studs were taken out and the bottom of the pan is flat. The specimen is fixed with a plastic ring and a metal clamp bolted down. During the test reference marks are made on the ring and specimen in order to verify that the specimen has not moved (figure 5.2).

Figure 5.2 Reference marks to check for movements of the specimen

5.1.3 Wetting and cooling system

During the test, water can be sprayed on the specimen at a controlled flow rate. There is an individual spraying nozzle for each wheel. The standard flow rate is set at 3 l/min at each wheel. A closed water circuit with a basin is used, provided with a system for heating and cooling in order to maintain a the water at a constant temperature throughout the test.

5.1.4 Loading frame

The second part of the machine is the part where one or more wheels are pushed against the surface to measure friction at different loading conditions and also to simulate the polishing effect. The design principle was a three legged star frame with a free rotating wheel on each leg in such way that the distance to of the wheel to the rotation centre of the specimen could be adjusted (figure 5.3). Each wheel support was provided with sensors to measure the acting forces in three directions. The vertical force on the frame is controlled by a dynamic load cell. In order to create wheel slip, the wheels can be set at an angle relative to the tangent of the circular wheel track or one or more wheels can be blocked.

Figure 5.3 Initial design of the loading frame

The generation of friction by applying a slip angle is mechanically very convenient, because it is easy to adjust and it doesn't generate additional friction or wear to any component of the test setup, other than the rubber wheel. However, problems occurred during the testing with the skewed wheel: the tyres would run off the rims and strong vibrations were generated in the setup, which produced measurements with a high noise level. This led to the conclusion that the test with high friction forces would only be carried out using a locked wheel and without any slip angle. During the polishing cycles, the contact forces are kept relatively low and the force measurements are not relevant. This made it feasible to set a slip angle of 5° on the wheels. Moreover, it became also clear that temperature is a predominant influence factor in tyre-pavement friction, especially when testing under high friction forces. Rubber temperature rises quickly to values that alter the mechanical properties. It was therefore deemed essential to measure rubber temperature during the friction measurements. Due to the relatively small dimensions of the wheels, this is only possible with wired sensors, which makes it inevitable to have a fixed (non-rotating) wheel. Non-contact measurements of the tyre temperature were discarded because of the presence of water.

By using three wheels, three different wheel paths or tracks could be tested simultaneously. Track 1, Track 2 and Track 3 are respectively at 94 mm, 134 mm and 174 mm distance from the rotation centre. However, the difference in radii implies different speeds, different friction conditions and a different vertical force distribution. So even though it was mechanically possible to test on different tracks, the best data were obtained with all wheels acting on the most outside track. The bigger the radius of the track, the closer it resembles to a straight path.

Each wheel is mounted on an individual triaxial load cell, which measures the vertical force, and the horizontal force components parallel and perpendicular to the axle of the wheel.

The initial tests showed that the high speed combined with the surface irregularities and the relatively small wheels gave rise to strong vibrations in the measuring system, leading to

excessive noise in the measuring instruments. The loading frame was modified adding a spring and damper at the end of each of the three support arms, as illustrated in figure 5.4. This new configuration reduces the vibrations, but also modifies the force distribution over the three wheels. There is now less control over the total force applied on the frame through the load cell since there are three springs and dampers in parallel. This means that part of the energy is dissipated by the damper system and therefore it is not clear how much energy is supplied to the wheels to begin with.

Figure 5.4 Final version of the SR-ITD with suspension system

5.1.5 Testing wheels

The test wheels are made of solid rubber and have an external diameter of 100 mm and a width of 25 mm. Two types of rubber were used: one is the rubber of the ASTM standard test tyre (ASTM, 2015b) and the other was produced by the provider of the tyres of the SKM testing device (CEN, 2009). During braking tests a thermocouple is embedded in the rubber at 4 mm from the contact surface. The actual contact surface and stress distribution will vary during the braking tests because of the wear changing the tyre geometry. In figure 5.5 a new wheel is shown on the left whereas in the middle the flat areas due to the wear are clearly visible. The damaged tyre on the right shows the result of an experimental braking test with insufficient cooling. It is shown to demonstrate the high temperature developments and its devastating effect on the rubber tyre, although during regular testing this situation is avoided by reducing the duration of braking tests and by supplying sufficient cooling water.

Figure 5.5 Different stages of wear/damage on the test wheels

Preliminary static tests were carried out on new wheels before testing, in which a vertical load was applied on a test wheel, while this one was resting on a pressure sensitive measurement film. This is a sheet of paper that indicates applied pressure differences as red colour density variations. These tests are helpful to obtain the gross contact area and estimate the effective pressure. In figure 5.6 the contact surface is plotted as a function of the vertical force.

Figure 5.6 Contact surface as a function of the vertical force on the wheel

The width of the tyre is 25 mm. This means that in the tests shown above, assuming that the width won't change significantly, up till 400 N the rectangular contact area is shorter than 25

mm in the direction of movement. At higher vertical forces, the contact length becomes larger than 25 mm: up till 36 mm approximately.

Next, the average contact pressure is calculated by dividing the vertical force by the contact surface and a potential curve was fitted to relate the contact pressure with the vertical force (figure 5.7).

Figure 5.7 Contact pressure as a function of the vertical force on the wheel

The relation between contact pressure and vertical force can be expressed as equation 5.1.

$$\bar{\sigma}_z = 0.014F_z^{0.6319} \quad (\text{eq. 5.1})$$

Where $\bar{\sigma}_z$ is the average contact pressure in MPa and F_z is the vertical force in N on one wheel.

Obviously this correlation is only valid for this tyre geometry and rubber characteristics.

5.1.6 Rubber characteristics

Two types of rubber have been used for the tyres on the SR-ITD. The first rubber type is the material used for the production of the ASTM standard test tyre according to ASTM E 524 (ASTM, 2015b). According to the specifications, the Shore hardness of this rubber should be between 53 and 57. The second rubber type is the material used to produce the tyres for the skid resistance measuring device for field measurements called SKM (Seitenkraft-Messverfahren) according to CEN Technical Specification 15901-8 (CEN, 2009). The hardness of this type of rubber is specified as the Shore hardness according to ISO standard 7619 (ISO, 2010), which should be between 65 and 69.

In order to determine the rheological properties of the two rubber types, samples of both materials have been submitted to the Dynamic Shear Rheometer (DSR) test. In this test a cylindrical rubber specimen of 8 mm in diameter and 2.45 mm thickness is glued between two plates and submitted to a torsional movement, by making on plate oscillate in a small rotational movement whereas the other is fixed. The principle of the test is illustrated in figure 5.8.

Figure 5.8 Dynamic shear rheometer test setup

The dynamic shear modulus $|G^*|$ is derived from the complex shear modulus G^* of the rubber, which is a temperature dependent complex function of the rotational frequency ω . The real and imaginary part, defined as the shear storage modulus G' and the shear loss modulus G'' can be derived according to the equations 5.2 to 5.4. The argument δ of the dynamic shear modulus G^* is the phase angle.

$$|G^*| = \sqrt{(G')^2 + (G'')^2} \quad (\text{eq. 5.2})$$

$$G(\omega) = G'(\omega) + iG''(\omega) \quad (\text{eq. 5.3})$$

$$G'(\omega) = G^*(\omega) \cdot \cos(\delta) \quad (\text{eq. 5.4})$$

$$G''(\omega) = G^*(\omega) \cdot \sin(\delta)$$

Two types of tests were carried out. In the temperature sweep test the frequency is constant and set at 1 Hz, while the temperature is varied from -20°C to 160°C . The test is strain controlled (which means that the rotation speed and the maximum and minimum rotation angle are constant) and the maximum torque in each cycle is registered, as well as the phase angle, which represents the rotated angle during the time lag between the maximum strain and the maximum torque.

From figure 5.9 we can clearly see that at temperatures above 100°C a change in the material behaviour takes place. The same occurs at temperatures below 10°C . Since the focus of this study is on wet skid resistance we can assume that the temperature range for the rubber tyre is within this range.

Figure 5.9 Loss modulus and phase angle of two rubber types

The results of the frequency sweep tests for the two types of rubber are presented in the following figures. Figure 5.10 represents the complex shear modulus $|G^*|$ of the SKM rubber and figure 5.11 the phase angle. The values of $|G^*|$ and δ for the ASTM rubber are shown in figures 5.12 and 5.13. It can be observed that both materials have similar values of the complex shear modulus. In both materials the stiffness at the lowest temperature and highest frequency is about 18 times higher than the stiffness at the highest temperature and lowest frequency.

Figure 5.10 Frequency sweep results for $|G^*|$ of SKM rubber

Figure 5.11 Frequency sweep results for δ of SKM rubber

Especially the data of the phase angle show consistently low values of approximately 9° to 15° in the range between 20°C and 80°C . At higher and lower temperatures, the phase angle is much higher and shows stronger variations. This holds for both materials, although the SKM rubber is a little bit less sensitive to temperature.

Figure 5.12 Frequency sweep results for $|G^*|$ of ASTM rubber

Figure 5.13 Frequency sweep results for δ of ASTM rubber

Given the above observations and taking into consideration that the temperature of the test wheels is in the range between 20 °C and 80 °C, the dataset is reduced to this temperature range. In order to create a mastercurve for the dynamic shear modulus ($G^*=G^*(\tilde{\omega})$), we combine the frequency and temperature scale into one combined scale, called the *reduced frequency*, applying the Arrhenius equation (eq. 5.5 and 5.6).

$$\tilde{\omega} = \alpha_T \cdot \omega \quad (\text{eq. 5.5})$$

where $\tilde{\omega}$ is the reduced (angular) frequency, ω is the frequency and the shift factor α_T is defined as in equation 5.6. The WLF transformation mentioned in paragraph 2.6.2 is a particular case of equation 5.5, but with a different definition of the shift factor:

$$\alpha_T = e^{\left(\frac{\Delta H}{R}\right) \cdot \left(\frac{1}{T} - \frac{1}{T_s}\right)} \quad (\text{eq. 5.6})$$

in which ΔH (J/mol) is the activation energy, R is the universal gas constant (8.314 J/(mol·K), T is the temperature (K) and T_s is the reference temperature (293.15 K).

By means of an iterative process the parameter ΔH is determined at the same time that an equation for the dynamic shear modulus and the phase angle as a function of the reduced frequency is fitted to the data. With both materials a good fit could be obtained with a linear function on log-log scale (eq 5.7), which can also be expressed as a potential function as shown in equation 5.8.

$$\log(|G^*|) = p \cdot \log\left(\frac{\tilde{\omega}}{\omega_0}\right) + \log(q) \quad (\text{eq. 5.7})$$

$$|G^*| = q \cdot \left(\frac{\tilde{\omega}}{\omega_0}\right)^p \quad (\text{eq. 5.8})$$

where $\omega_0 = 1$ Hz.

The curve fitting parameters for both materials are represented in table 5.1. The most significant difference between the two materials is in the value of ΔH , which results in a much larger range of the reduced frequency for the SKM rubber.

Table 5.1 Curve fitting parameters for SKM and ASTM rubber stiffness mastercurves

	ΔH (kJ/mol)	$ G^* $		δ	
		p	q (MPa)	p	q (°)
SKM	275	0.0480	3.34	0.0133	12.4
ASTM	179	0.0516	3.12	0.0306	13.0

Figure 5.14 and 5.15 show the individual mastercurves for the complex, storage and loss modulus for SKM and ASTM rubber respectively, including the experimental data as a function of the reduced frequency. Due to the small phase angle, the data for the complex modulus and the storage modulus overlap. The R^2 -values are over 0.96 for all regressions.

Figure 5.14 SKM Complex modulus mastercurve

Figure 5.15 ASTM Complex modulus mastercurve

The fit of the mastercurves for the phase angle is not as good in the case of the complex modulus, but with a value for R^2 of 0.74 for SKM and 0.91 for ASTM it can still be considered as acceptable. Notice also that in the following graphs the y-axis is linear and not on logarithmic scale as in the previous figures.

Figure 5.16 SKM phase angle mastercurve

Figure 5.17 ASTM phase angle mastercurve

To transform from dynamic shear modulus to dynamic modulus E^* , we apply the same relation as in equation 5.9 for an incompressible viscoelastic material.

$$E^*(\omega) = 3G^*(\omega) \quad (\text{eq. 5.9})$$

In the H&K friction model, the Zener model (or Standard Linear Solid (SLS) model, figure 5.18) is used as the simplest representation of a viscoelastic solid material. We can determine the parameters E_e , E_m and τ_z , where $\tau_z = \eta/E_m$, from equation 5.10, by fitting the experimental results of figures 5.14 to 5.17 to the dynamic modulus of the Zener material.

Figure 5.18 Zener or SLS-model definition

$$E^*(\omega) = \frac{E_e + (E_m + E_e)\omega^2\tau_z^2}{1 + \omega^2\tau_z^2} + i \frac{E_m\omega\tau_z}{1 + \omega^2\tau_z^2} \quad (\text{eq. 5.10})$$

The storage and dissipation moduli respectively are the real and imaginary parts of $E(\omega)$:

$$E'(\omega) = \text{Re}\{\hat{E}(i\omega)\} = E_e + E_m \frac{\omega^2\tau_z^2}{1 + \omega^2\tau_z^2} \quad (\text{eq. 5.11})$$

$$E''(\omega) = \text{Im}\{\hat{E}(i\omega)\} = E_m \frac{\omega\tau_z}{1 + \omega^2\tau_z^2}$$

Figures 5.19, 5.20 and Table 5.2 show the result of the fitting procedure, the temperature effect having been taken into account by using the reduced frequency. The shape of the Zener model for the storage modulus is a constant low value for the low frequencies and a constant high value for the higher frequency. A smooth transition between the high and low value is obtained in the frequency range from 10^{-5} Hz to 10^{-3} Hz. The fit is not too bad (R^2 equals 0.69 for ASTM and 0.72 for SKM), but it does not adequately reflect the actual material behaviour. The fit of the loss modulus is completely out of range. However, due to the low values of the phase angle, the contribution of this part of the complex modulus is minor.

All in all, the Zener model does not seem to be an appropriate choice for modelling the behaviour of the SKM and ASTM rubber.

Table 5.2 Zener model parameter determination

	SKM	ASTM
E_e (MPa)	0.839	1.14
E_m (MPa)	0.969	0.883
τ_z (s)	2.98E+06	9.31E+03

Figure 5.19 Zener model approximation of the SKM experimental data

Figure 5.20 Zener model approximation of the ASTM experimental data

For a modified approach, explicitly including the temperature effects, the material constants of the Zener model can be expressed as follows (see figure 5.21):

$$\begin{aligned} E_e &= E_0 \\ E_m &= E_0 - E_\infty \\ \tilde{E} &= \frac{E_\infty}{E_0} \end{aligned} \quad (\text{eq. 5.12})$$

$$\tau_z = \tau_T = \alpha_T \tau_{20} \quad (\text{eq. 5.13})$$

When combined with equation 5.13, equation 5.10 yields:

$$E^*(\omega) = \frac{E_e + (E_m + E_e)(\omega \alpha_T \tau_{20})^2}{1 + (\omega \alpha_T \tau_{20})^2} + i \frac{E_m \omega \alpha_T \tau_{20}}{1 + (\omega \alpha_T \tau_{20})^2} \quad (\text{eq. 5.14})$$

and the storage and dissipation moduli become:

$$E'(\omega) = \text{Re}\{E^*(\omega)\} = \frac{E_e + (E_m + E_e)(\omega \alpha_T \tau_{20})^2}{1 + (\omega \alpha_T \tau_{20})^2} \quad (\text{eq. 5.15})$$

$$E''(\omega) = \text{Im}\{\hat{E}(i\omega)\} = \frac{E_m(\omega \alpha_T \tau_{20})}{1 + (\omega \alpha_T \tau_{20})^2} \quad (\text{eq. 5.16})$$

Where τ_{20} is the relaxation time τ_z of the Zener model at the reference temperature $T_s = 20^\circ\text{C}$ of equation 5.6.

Equation 5.6 can be rewritten as:

$$\alpha_T = e^{\left(\frac{c}{T} - \frac{c}{T_{20}}\right)} \quad (\text{eq. 5.17})$$

In which c is the material constant $\Delta H/R$ to be determined and $T_{20} = T_s = 293$ K. This means that the temperature T should also be expressed in Kelvin.

Figure 5.21 Zener or SLS-model for the definition of dimensionless model parameters

For the ASTM and SKM rubber, the following parameters have been determined from equation 5.9 and the mastercurves of figures 5.19 and 5.20:

Table 5.3 Model parameters for SKM and ASTM rubber

	SKM	ASTM
G_0	4.21 MPa	4.43 MPa
G_∞	0.80 MPa	1.12 MPa
τ_{20}	2.45 s	3.12 s
$\tilde{E}_\infty$	0.190	0.252
c	33 076 K	21 529 K

5.2 Analysis of SR-ITD test results

5.2.1 Testing protocols

Testing was performed using two different testing protocols: the brake test protocol and the polishing protocol. In the following paragraphs the protocols are described and analysed.

The polishing protocol was designed to submit the specimen for an extended period of time to rubber friction forces which reproduce the wear and tear a pavement suffers by the passage of cars. Equilibrium had to be found which allows for an accelerated deterioration of the tested pavement surface while maintaining a relatively constant and low rubber temperature to preserve the testing wheel. The side-way force method, in which a free rotating wheel is set at an angle with respect to the direction in which it is advancing, is the ideal option, since the friction forces are generated in the tyre-pavement contact area. As the wheel keeps rotating, the heat can dissipate and its wear occurs evenly distributed.

Following the polishing protocol, the three test wheels are set at an angle of 5° with respect to the tangent of the pavement specimen in the outer wheel track. All wheels can rotate

freely, for which temperature measurements in the rubber cannot be performed. The rotation speed is set at 300 rpm, which corresponds to a wheel speed of 20.1 km/h. A vertical force is applied which theoretically corresponds with a contact pressure of 0.3 MPa. However, considering the average vertical force and the estimation of the true contact stress according to equation 5.1, the contact stress is approximately 0.54 MPa. Water is sprayed directly at the contact interface of each wheel at a rate of 3 l/min. The duration of the polishing test starts with 1 h. Depending on the observed results the polishing time is further increased. Sessions of 3 to 6 hours are common. In one case, polishing was performed during 16 h continuously.

The braking protocol was designed to measure the pavement-rubber friction properties on different pavement surfaces with an increasing level of polishing. During this test, two wheels are rolling freely in the normal direction. A third wheel is locked and thermocouples are installed inside the rubber of this wheel; one at 4 mm from the initial rubber surface and two at 8 mm. The tri-axial force measurements on the wheel supporting structure are used for the data interpretation.

The test duration must be controlled in order to prevent excessive temperature rising in the rubber material of the locked wheel.

With the test wheels hanging freely above the surface (without contact), the specimen is accelerated in 3 s up to 1200 rpm, corresponding with a speed of approximately 80 km/h at the outer wheel track. The test may also be initiated with the specimen already spinning at the desired speed, in which case no acceleration is needed. In the next 6 s the speed is maintained constant while the loading frame with the wheels is pressed to the specimen surface with the specified theoretical contact pressure. This means that as soon as the wheels are in contact with the surface, friction is generated, although the rotation speed of the specimen is maintained constant by the motor that drives it. In the next 5 s approximately, the speed is reduced linearly to zero. The speed and pressure during a braking test are shown in figure 5.22.

Figure 5.22 Representation of the braking protocol, based on actual measurement data

It is important to stress that the speed is actively controlled by the SR-ITD. If the braking force generated by the locked wheel is too low, which is generally the case, the motor forces the reduction of the rotating speed. If the generated friction by the test wheel would be too high, the motor would counteract the braking in order to maintain the deceleration rate. Typically, the small rubber tyres do not have sufficient braking capacity to dissipate the kinetic energy of the rotating specimen, especially since only one of the wheels is blocked. This aspect is considered a design flaw, especially since the torque delivered by the motor is not monitored, for which no energy dissipation analysis is possible.

During the test, water is sprayed at the contact interface of each wheel at a flow rate of 3 l/min. Moreover, the rubber temperature at the start of the test shall not exceed 25 °C.

5.2.2 Measurement sensors and parameters

The rotation speed of the specimen is determined by the rotation speed of the engine (motor). This speed is given in rpm (revolutions per minute) and can only be regulated in steps of 47 rpm. This can be considered the resolution of the devices' speed control. If we consider that, at a radial distance of 176 mm from the specimen centre 1200 rpm corresponds to 80 km/h, the resolution of the speed data is 3.1 km/h.

The sensors to measure the track induced rotating speed of the test wheels appear to be less robust, as can be seen in figure 5.23. It consists of an induction sensor which detects when a groove in the wheel passes in front. If the groove is filled with water it will not be detected, which explains the high number of downward peaks. The reason for the time lag in the speed reduction between motor speed and wheel speed is less apparent. It could happen that the wheel starts slipping on the wet surface, resulting in a lower wheel speed than the track speed.

Figure 5.23 Measurement of the rotation speed

During the braking test, the wheel speed is irrelevant, since the measuring wheel is blocked. However, it could be interesting to know the actual wheel speed in the case of the polishing test according to the side-way force principal. Since the wheel is derived at an angle of 5° of

the "travelling direction", there may be a difference with the rotating speed of the specimen due to the slip that occurs.

Between each wheel and the loading frame, a triaxial load cell is mounted which measures the forces in three directions: vertical and, in the horizontal plane, parallel and perpendicular to the axis of the wheel.

5.2.3 Vertical load distribution

The vertical force on the wheels during the test is an important test factor. It needs to be controlled and monitored. Due to the vibrations in the system, the force measurements are not very stable. In all the work done by Villani (2015), the friction μ is calculated as the quotient of the horizontal force and the vertical force and the noisiness of both force measurements is further aggravated when calculating the quotient. In order to reduce the noise, in this thesis a moving average filter on five consecutive measurements is applied covering a time span of 1 s. The friction values are then calculated with the filtered force values. This approach is by default also used on the SCRIM measurements.

The vertical load is applied and distributed by a metal frame to the three wheels. In figure 5.24 the red line indicates the load applied and registered by the load cell of the pneumatic piston that provides the vertical force on the frame. The output of the load cell is in units of pressure. The blue line indicates the sum of the vertical forces registered by each of the three load cells mounted on the wheels. The other three lines express the vertical force on each wheel. In this case there is a certain unbalance and the load fluctuations during the test are significant, especially considering that already a moving average filter has been applied to these data. As mentioned before, the external damping system influences the force distribution during the test and is not monitored. This makes the control of the vertical force on the wheels not very accurate. However, the fact that the individual triaxial load cells on each wheel provide the most accurate measurement of the forces (horizontal and vertical) occurring in the tyre-pavement contact face, the measurements are absolutely valid and useable. It is important though to use the forces measured at the wheels in the friction calculations and not the target load set by the main load cell on the frame.

Figure 5.24 Vertical force and pressure distribution

5.3 Asphalt mixture friction testing

5.3.1 Testing programme

As already mentioned, the testing programme for asphalt mixture friction testing with the SR-ITD includes 3 asphalt mixtures and 2 different types of rubber. For each asphalt type, only one specimen has been fully tested at different levels of polishing. This means that although two different types of rubber have been used, there is no full data set with both types of rubber at all polishing levels.

The following test results are available and have been reprocessed according to the methodology developed for this thesis.

Table 5.4 SR-ITD testing programme

Asphalt	Rubber	Braking tests	Polishing levels	Texture scans
AC	ASTM	19	5	9
	SKM	10		
PA	ASTM	47	10	12
	SKM	9		
SMA	ASTM	53	6	10
	SKM	15		
Total		153	21	31

5.3.2 Data post-processing

Each test file provides measurements over a period of approximately 8 seconds in which a target load is applied on the loading frame while the speed in the test track is reduced from 80 km/h to 0. In the processed data file the following parameters are included for each timeframe of approximately 0.2 seconds:

- time;
- average vertical force on each of the three wheels;
- triaxial forces on the locked wheel;
- track speed;
- temperature at 4 mm deep from the surface of the wheel;
- temperature near the rim.

After the post-processing, the reported forces are moving average values over the five previous data points. The speed value is the mean value of the 5 previous data points. The friction values are calculated with the filtered horizontal and vertical force values.

The results of one specific braking test, which is considered representative for the dataset, are described here in detail.

The purpose of the test is to measure a friction coefficient under braking conditions. In figure 5.25 the horizontal force in the direction of movement (F_y) is plotted versus the vertical force (F_z). The plot shows a point cloud with a rather unclear correlation. Assuming

that the regression line should pass through the origin, a friction coefficient of 0.47 can be derived, whereas the average of all individual F_y/F_z data points would yield an average μ of 0.52.

Figure 5.25 Relation between horizontal and vertical forces

The reasons for the high variance in the force data can be many. In the first place, the force measurements are not very stable. The vertical force is supposed to have a more or less constant value, corresponding to a vertical pressure of, in this case 0.3 MPa. However, the measured vertical force shows variations between 100 N and 200 N, approximately, which can only partly be explained by the unequal force distribution between the three wheels. It can be observed in figure 5.26 that the vertical force on the locked wheel is higher than the average of the three wheels, but it shows that similar fluctuations in the force occur on all wheels simultaneously. On the vertical force there is no clear trend visible, whereas on the horizontal force an increase with time can be observed. It is unavoidable that the quotient of two noisy signals also yields a noisy output.

Figure 5.26 Measured triaxial forces during a braking test as a function of time

Friction is assumed to be speed dependent. In figure 5.27 the friction coefficient obtained from the blocked wheel is plotted against the speed of the specimen in the wheel track where the measurement is performed. This speed is equal to the slip speed and its decrease with time is linear. This is an imposed condition by the testing protocol as described in 5.2.1. The overall friction coefficient shows an increasing trend, however with large variations. Most tests show an increasing trend in the last three seconds of the test, although in some cases higher friction values are measured in the first five seconds.

Figure 5.27 Speed dependency of the friction coefficient

The temperature is another important factor in the measurement results. In figure 5.28 the measured in the rubber tyre at 4 mm from the surface is shown in the same graph with the friction coefficient. It can be observed that the rubber temperature increases in eight seconds from below 20°C till almost 60°C. At higher contact pressures, the temperature can increase up to 140°C.

Figure 5.28 Rubber temperature dependency

It becomes apparent that the highly variable conditions during a very short time lapse make the interpretation of the measurements troublesome.

5.3.3 Results of the braking tests

In the following three graphs, the results of 153 braking tests are shown. Figure 5.29 shows the results of the tests on asphalt concrete, figure 5.30 on porous asphalt and, lastly, in figure 5.31 the test results on SMA are presented. Each of the data points is a single μ -value obtained from a braking test as described in the previous paragraph and illustrated in figure 5.25.

The friction coefficients are plotted against the level of polishing, expressed in number of polishing cycles. This refers to the number of rotations of the specimen during the polishing protocol, bearing in mind that during each cycle, three wheels pass over the surface.

Figure 5.29 Results of braking tests on asphalt concrete (AC10)

Braking tests were performed at three different target levels of the contact pressure. However, as explained in previous lines, the actual vertical force on the wheel is measured and used to calculate the friction index. Finally, different markers are used for the two types of rubber used during the tests. The SKM rubber tyres have not been used at all polishing levels.

In the AC results, there is hardly any trend visible. Up to 108 000 cycles a decreasing trend may be observed. The SKM tyres appear to be more sensitive to the pressure level and show therefore both higher and lower values at all polishing levels. Taking this into account, a decreasing trend up to 250 000 cycles can be observed on porous asphalt and SMA, after which the friction level appears to remain more or less constant.

Figure 5.30 Results of braking tests on porous asphalt (PA10)

Figure 5.31 Results of braking tests on stone mastic asphalt (SMA10)

Nevertheless, the results show a large scatter, even when tests are repeated under the same conditions, which can be seen on PA at 435 000 cycles or on SMA at 180 000 cycles.

5.3.4 Results of the polishing tests

The polishing protocol was developed only to create an accelerated deterioration of the specimen surface under realistic conditions, as described in paragraph 5.2.1. Although data were acquired from the sensors, they have not been processed or analysed before this thesis.

The advantage of this test is that the minimum duration is one hour and the testing conditions are designed to maintain a constant operating temperature of the tyre. Friction is generated by the side-way force principle, which ensures a constant slip speed throughout the test and with that, a rather constant energy dissipation rate. Even though the measurements are noisy, the long term average allows a fairly reliable estimation of the friction coefficient to be obtained.

The disadvantage of this data set is that there are no reliable measurements of the rubber temperature and there is no variation in the (slip) speed or in the contact pressure. Moreover, only one type of wheel is used for the polishing.

An additional potential disadvantage is that the slip angle of 5° is very low. According to research on the SCRIM device (Hosking, 1976b), the maximum skid resistance potential of a surface is measured at an angle of 20°. At lower slip angles, the actual skid resistance level is likely to be underestimated. The experimental results from the research (see figure 5.32) show the measured side-way force coefficient at three different pavements as a function of the slip angle. The measurements on the pavement with the highest skid resistance potential are indicated with squares and the measurements on the pavement with the lowest skid resistance with triangles. The measurements at 5° slip angle produce the lowest value on the pavement with the highest skid resistance potential, so the ranking of different mixtures can be erroneous at low slip angles.

Figure 5.32 Influence of the slip angle on the measurement results (Hosking, 1976b)

The polishing data files are processed in the following manner. The average of the horizontal and vertical force on 10 data points (2 s) is calculated. The total duration of the polishing

session is divided into 6 or more intervals, which can vary between 10 and 60 minutes approximately. The horizontal and vertical forces, averaged every 2 s, are plotted for each interval separately. A typical result is shown in figure 5.33, in which the value series obtained for the first, the second, the third and last interval are shown. In general, the first interval shows much more variation than the subsequent intervals. This can be explained by the fact that the constant operating temperature of the tyre has not been reached yet. For this reason, in the further analyses the first interval of each new test start is ignored.

Figure 5.33 Representation of the vertical and horizontal forces during polishing

Next, on each of the intervals a linear regression line, through the origin of the graph is calculated, and the resulting slope is reported as μ . The result of the first hour of polishing on the AC10 specimen is shown in figure 5.34. A clear and steady decrease of the friction coefficient with polishing time is observed.

Figure 5.34 Polishing test results on AC10

As the polishing increases, the point cloud becomes more concentrated and the decrease of the friction coefficient becomes practically zero, as can be seen in figure 5.35. Notice that the scales of figure 5.34 and 5.35 are identical.

Figure 5.35 Test results after 7 to 12 hours of polishing

If all the friction coefficients resulting from the regression lines are plotted versus the polishing level (in this case expressed in hours of polishing), we obtain the graph from figure 5.36.

Figure 5.36 Evolution of μ vs polishing time for asphalt concrete (AC10)

The decreasing trend in the data, which stabilizes over time, is clearly visible. The irregularities in the curve may be explained by the initiation of a new test (although the first interval of the test data is always left out), or by the change of the polishing wheels, which obviously suffer deterioration.

The irregularities in the data are more pronounced in the tests on porous asphalt, as can be seen in figure 5.37.

Figure 5.37 Evolution of μ vs polishing time for porous asphalt (PA10)

The evolution of friction on SMA appears to be slightly different, with a less pronounced initial descend, and on the long term a descend in friction which has not stabilized after almost 30 hours, but with significantly higher friction values than the AC and PA mixtures.

Figure 5.38 Evolution of μ vs polishing time for stone mastic asphalt (SMA10)

5.4 Conclusions

Laboratory tests are ideally designed in such a way that the input parameter of interest is varied over a certain interval while the output parameter is measured and all other influencing factors are maintained constant. The design of the SR-ITD braking test did not achieve this situation, because the following parameters show strong variations during the test:

- slip speed

- temperature
- vertical force

Moreover, due to the damping system and the active braking/accelerating of the engine, the amount of dissipated energy is unknown.

Luckily, the first three parameters are monitored, which means that the data can be used with caution.

On the other hand, the polishing test, which was not meant to be used for measuring the friction coefficient, is much closer to a steady-state approach. The registered force data of the test can be used to determine friction coefficients on different pavement surfaces. However, in the available data set no variation of contact stress or speed was introduced and no significant temperature change occurred.

Chapter 6 Texture based friction models

In this chapter models are presented correlating the parameters derived from the available data sources. The models should be useable for software tools for the engineering practice and be physically correct. This means that mathematical formulations are preferred over statistical relations and regression techniques.

6.1 Introduction

Skid resistance measurements are influenced by many factors. Many studies have determined correlations between skid resistance and external factors, such as macrotexture or temperature. The validity of purely statistical correlations is limited to the range of conditions under which the data were obtained. The holy grail of skid resistance modelling is a perfect physically correct model that describes the tyre-pavement interaction. Not only is there a lack of generally accepted theoretical models, there is moreover a lack of means to measure the parameters included in the models. In this chapter, modifications of an existing rubber-friction model are proposed which aim to result into a physical quantitative model, with a limited number of measurable parameters. This type of model may probably be classified as a mechanistic-empirical model as are commonly used in road engineering, especially in the USA, in which a number of correlation factors are introduced in a theoretically correct model. The correlation factors are to be determined for each dataset obtained under certain conditions.

In the following paragraphs, first the single parameter correlations of each of the texture indicators with friction are described. Next, a sophisticated theoretical friction model is described and analysed, after which modifications of the model are proposed. Lastly, the correlation of the model with the measurement data is presented.

6.2 Friction – texture correlations

6.2.1 Introduction

After having analysed separately the results of the texture parameter determination in Chapter 4 and the friction measurements in Chapter 5, now the direct correlation between the selected texture parameters and the friction measurements are studied in this chapter.

It should be noted that there are many factors influencing the friction measurements, such as the type of rubber and the contact pressure. When only two variables are represented in a graph, e.g. friction versus a texture parameter, variations can be expected due to the fact that other variables in the testing programme, like the vertical load, speed or polishing level, are not constant.

6.2.2 Braking tests vs texture parameters

As explained in the previous chapter, braking tests include two different rubber types and three different vertical pressure levels, which introduce variations in the friction measurement results. In the next graphs, all friction measurements are plotted against the

selected texture parameters. The graph on the left contains all data points, the graph on the right contains the measurements taken at a vertical target contact pressure of 0.8 MPa and the ASTM rubber tyre.

Whereas in the graphs on the left, no significant trends can be observed from the point clouds, in the case of $\xi_{||}$ (figure 6.2), $2H$ (figure 6.4) and β (figure 6.7) a weak correlation can be discerned. In the case of $\xi_{\perp}$ (figure 6.1) it is mostly the results on the SMA that disturb the trend, and this is also the case if we use the quotient of $\xi_{\perp}$ and $\xi_{||}$. The results on PA are unexpected on the $2L$ parameter (figure 6.6). The peak radius appears to have the least significance (Figure 6.5).

Figure 6.1 Braking force coefficient vs $\xi_{\perp}$

Figure 6.2 Braking force coefficient vs $\xi_{||}$

Figure 6.3 Braking force coefficient vs $\xi_{\perp}/\xi_{||}$

Figure 6.4 Braking force coefficient vs $2H$ Figure 6.5 Braking force coefficient vs R_{peak} Figure 6.6 Braking force coefficient vs $2L$

Figure 6.7 Braking force coefficient vs β

6.2.3 Sideway-force coefficients vs texture parameters

As opposed to the braking tests, the friction data obtained during the polishing tests were only obtained at one target contact pressure, one slip speed and with one type of wheel. Due to the conditions of the test, also the temperature variations are much smaller than in the braking tests.

Unfortunately, also in this case there are no clear correlations in the data. It is to be highlighted that even though the PA and AC specimens yield very similar values of friction, the shape parameters are very different. This may be caused by the low slip angle, which yields similar friction values as long as the maximum friction potential is not reached, as has been explained in paragraph 5.3.4 and shown in figure 5.32. Also, an unexpected observation is that the variation of the shape parameters of the SMA as a function of the polishing cycles is much larger than with the AC and PA mixtures, even though the reduction of friction due to increased polishing is the smallest in the SMA sample.

With the fractal parameters similar results were obtained, as shown in the graphs in figures 6.8 to 6.1. In this case, it is noticeable that the values of the parameters $\xi_{||}$ and $\xi_{\perp}$ of the SMA and AC specimens are very similar and the values for the PA specimen are much higher, whereas the friction results on PA and AC are similar and significantly higher for SMA.

Figure 6.8 Sideways-force coefficient vs $\xi_{\perp}$

Figure 6.9 Sideway-force coefficient vs $\xi_{||}$

Figure 6.10 Sideway-force coefficient vs $2H$

Figure 6.11 Sideway-force coefficient vs R_{peak}

Figure 6.12 Sideway-force coefficient vs $2L$

Figure 6.13 Sideway-force coefficient vs β

6.3 Rubber – surface friction model

6.3.1 Description of the rubber friction model

The skid resistance of pavements is essentially determined by the friction of rubber on a rigid rough surface. Klüppel and Heinrich (2000) presented a model to quantify the relation of friction with the viscoelastic and thermal behaviour of rubber and the roughness² characteristics of the surface. One objective of this research is to assess the predictive capacity of such a model, to the extent to which it could be able to relate the engineering approach to the friction phenomenon in the road traffic with the basic physical quantities that can be determined in laboratory at material level, both for the tires and the pavements.

² In this context roughness is used in its most generic denotation as the opposite of smooth, and is not limited to the definition in road engineering which defines roughness as unevenness with a wavelength between 0.5 m and 50 m.

In literature generally two mechanisms are identified to contribute to rubber friction. The first is the adhesive interaction originated from the disruption of intermolecular bonds and characterised by the free surface energy. It is assumed that this mechanism is predominant where a close contact between the two materials is possible, i.e. dry friction on a clean and smooth surface such as glass or ice. The second mechanism is the hysteretic energy loss arising from the rubber deformation on the surface asperities, which is assumed to be the predominant one on rough surfaces. It is this second mechanism that will be the basis of the model assessment carried out in this investigation.

The current culmination of the different models addressing this issue is that developed by Klüppel and Heinrich (2000). In their model the roughness of the surface is characterised by a specific spectral analysis of a surface profile, applying a fractal approach as described in section 3.2. In this way, the deformation of the rubber and its initial strain rate are obtained for the various wavelengths, given the speed at which the rubber moves over the surface.

The first step for the Klüppel and Heinrich model (K&H-model) is the characterization of self-affine surfaces which is described in chapter 3. In the following paragraphs the model for the rubber friction response will be described.

Persson (1998) underlines that because of the low elastic modulus of rubber, adhesive interaction makes rubber deform and fill out the cavities of the pavement surface on the nanoscale. For low sliding velocity this means that the adhesion induces some friction by forcing the rubber to follow the short wavelength surface roughness profile. In wet conditions, the adhesion component of the total friction is drastically reduced, whereas the hysteresis friction remains largely unaffected. This means that for wet surfaces, the friction coefficient is mainly dependent on the hysteresis friction. The latter is directly related to the energy dissipated by hysteresis. The long-term dissipated power $\dot{w}$ per unit volume in a linear viscoelastic material under uniaxial harmonically cyclic strain ε of angular frequency ω and amplitude ε_0 is:

$$\varepsilon = \varepsilon_0 \cos(\omega t) \quad (\text{eq. 6.1})$$

$$\dot{w} = \frac{\varepsilon_0^2}{2} \omega E''(\omega) \quad (\text{eq. 6.2})$$

$E''(\omega)$ being the loss modulus as given by equation 5.4 and 5.9. When strain consists of the superposition of harmonic functions of time with different frequencies and amplitudes, the power dissipated by the rubber per unit volume is the sum of the values given by equation 6.1 for each harmonic component of the strain. As will be seen later, a case of particular interest is that of the discrete series of harmonic functions known as the Weierstraß-Mandelbrot fractal function, whose frequencies follow a geometrical progression rather than the arithmetical progression of the conventional Fourier series:

$$\varepsilon = \varepsilon_0 \sum_{n=0}^{n=\infty} \frac{\cos(\omega_{min} t \gamma^n)}{\gamma^{nH}} \quad (\text{eq. 6.3})$$

$$\dot{w} = \frac{\varepsilon_0^2}{2} \sum_{n=0}^{n=\infty} \frac{\omega_{min} \gamma^n}{\gamma^{nH}} E''(\omega_{min} \gamma^n) \quad (\text{eq. 6.4})$$

where ω_{min} is the lowest angular frequency of the series, and ε_0 , H and γ are constants of the series with $0 < \gamma, H < 1$. The summation that provides the corresponding dissipated power per unit volume can be approached by the integral in equation 6.5 (KlÜppel and Heinrich, 2000):

$$\dot{w} = \frac{\varepsilon_0^2}{2 \ln \gamma} \int_{\omega_{min}}^{\infty} E''(\omega) \left(\frac{\omega}{\omega_{min}} \right)^{-2H} d\omega \quad (\text{eq. 6.5})$$

Pavement texture measurements can be considered as self-affine profiles described by the roughness exponent H and the correlations lengths $\xi_{||}$ and $\xi_{\perp}$, respectively parallel and perpendicular to the mean plane of the pavement surface. The sliding between the tire and the pavement makes the rubber penetrate the surface cavities in such a way that the tire experiences local strains proportional to the pavement vertical profile. For a skid speed v , the strain due to a profile height initially at distance x of the tire occurs at a time $t=x/v$ later (figure 6.14).

Figure 6.14 Relation between speed and vertical strain in the rubber according to the Zener model

Consequently, the induced strain in the rubber is a function of time as given by equation 6.3, with the angular time frequencies ω resulting from the spatial wavelengths of the pavement profile. Since the extreme values of these are λ_{min} (to be treated later on) and $\xi_{||}$, ω ranges between:

$$\omega_{min} = \frac{2\pi v}{\xi_{||}} \quad (\text{eq. 6.6})$$

$$\omega_{max} = \frac{2\pi v}{\lambda_{min}} \quad (\text{eq. 6.7})$$

whereas the strain amplitudes of equation are determined by

$$\varepsilon_0 = \frac{1}{2\pi} \frac{\xi_{\perp}}{\xi_{\parallel}} \sqrt{H \ln \gamma} \quad (\text{eq. 6.8})$$

The power of the friction force is assumed to be dissipated through the hysteretic response of the tire rubber taking place in a prismatic volume whose base and height respectively are the contact area A and the mean penetration depth $\bar{\delta}$ of the rubber into the pavement. Accordingly, when skidding takes place at speed v under a normal contact force N , the friction coefficient μ between the pavement and the tire shall read:

$$\mu N v = A \bar{\delta} \dot{w} \quad (\text{eq. 6.9})$$

Replacing equation 6.5 and 6.8 in equation 6.9 yields:

$$\mu = \frac{A \bar{\delta}}{N v} \frac{H}{8\pi^2} \frac{\xi_{\perp}^2}{\xi_{\parallel}} \int_{\omega_{\min}}^{\omega_{\max}} E''(\omega) \left(\frac{\omega}{\omega_{\min}} \right)^{-2H} d\omega \quad (\text{eq. 6.10})$$

In the K&H-model the mean compression stress (N/A) transmitted from the pavement to the tire and the mean penetration depth $\bar{\delta}$ are assumed to be in agreement with the Hertz theory of contact between a rigid plane and a Hookean spherical body (figure 6.15). The elasticity modulus and the radius of the spherical body are respectively replaced by the storage modulus of the rubber $E'(\omega_{\min})$ at the minimum angular frequency contributing to the tire strain, and by the minimum curvature radius of the longest harmonic contribution to the pavement profile.

Figure 6.15 Concept of penetration depth and contact forces in the tyre pavement contact area

After some theoretical calculation it is numerically shown (KlÜppel and Heinrich, 2000) that the two quantities are proportional because their quotient is independent of the distance between the rubber surface and the mean line of the pavement profile:

$$\frac{N}{A} = \frac{E'(\omega_{\min})}{\pi \xi_{\parallel}} \bar{\delta} \quad (\text{eq. 6.11})$$

Substitution of equation 6.11 in 6.10 leads to the friction coefficient predicted by the K&H-model:

$$\mu = \frac{H \xi_{\perp}^2}{8\pi E'(\omega_{min})} \int_{\omega_{min}}^{\omega_{max}} E''(\omega) \left(\frac{\omega}{\omega_{min}} \right)^{-2H} d\omega \quad (\text{eq. 6.12})$$

To obtain the minimum wavelength λ_{min} of the pavement profile and the maximum angular frequency of strain ω_{max} (equation 6.7), the following equation can be derived from the estimation given by the K&H-model:

$$\frac{E'(\omega_{max})\omega_{max}^{3-3H}}{E'(\omega_{min})\omega_{min}^{3-3H}} \cong \frac{1}{0.09\pi} \frac{4 - 2H}{2 - 2H} \frac{\xi_{\parallel}}{\xi_{\perp}} \quad (\text{eq. 6.13})$$

For the Zener viscoelastic material (figure 5.18), the integral in equation 6.11 can be expressed in terms of the hypergeometric function ${}_2F_1(\cdot)$, with the aid of the auxiliary velocities v_1 and v_2 :

$$v_1 = \frac{\xi_{\parallel}}{2\pi\tau_z} \quad (\text{eq. 6.14})$$

$$v_2 = \frac{\lambda_{min}}{2\pi\tau_z} \quad (\text{eq. 6.15})$$

$$\begin{aligned} \mu_H = \frac{E_m}{E_e} \tau_z^3 \frac{\xi_{\perp}^2}{\xi_{\parallel}^2} \frac{H}{8(H-1)} \frac{v}{v_1} \\ \cdot \left\{ \left(\frac{v_1}{v_2} \right)^{2-2H} {}_2F_1 \left(1, 1-H, 2-H, \frac{-v^2}{v_2^2} \right) \right. \\ \left. - {}_2F_1 \left(1, 1-H, 2-H, \frac{-v^2}{v_1^2} \right) \right\} \end{aligned} \quad (\text{eq. 6.16})$$

This formula is scarcely operative to assess the predictive capacity of the K&H-model when a lot of data concerning all the testing variables (temperature, skid velocities and pavement fractal parameters) have to be managed in order to check the dependence of the test results on them. To overcome this difficulty, an alternative formulation of equation 6.16 is presented in this thesis.

The new formulation consists in rewriting equations 5.15 and 5.16 with the constants of the Zener model of figure 5.21 and equation 5.12, together with a new variable θ defined as:

$$\tan\theta = \omega\alpha_T\tau_{20} \quad (\text{eq. 6.17})$$

As a consequence, equations 5.15 and 5.16 transform into:

$$E'(\omega) = \left(\frac{1 + \tilde{E}_{\infty}}{2} - \frac{1 + \tilde{E}_{\infty}}{2} \cos 2\theta \right) E_0 \quad (\text{eq. 6.18})$$

$$E''(\omega) = \left(\frac{1 - \tilde{E}_{\infty}}{2} \sin 2\theta \right) E_0 \quad (\text{eq. 6.19})$$

And equations 6.12 and 6.13, once particularized for the Zener material, become:

$$\mu = \frac{9H}{8 \cdot 2^{3/4}} \frac{\xi_{\perp}^2}{\xi_{\parallel}^2} \frac{(1 - \tilde{E}_{\infty})(\tan\Theta_1)^{2H-1}}{1 + \tilde{E}_{\infty} - (1 - \tilde{E}_{\infty})\cos 2\Theta_1} \int_{\Theta_1}^{\Theta_2} (\tan\Theta)^{1-2H} d\Theta \quad (\text{eq. 6.20})$$

The value of Θ_1 is given by the following equation, which includes the speed and the temperature dependency.

$$\tan\Theta_1 = \frac{2\pi v \alpha_T \tau_{20}}{\xi_{\parallel}} \quad (\text{eq. 6.21})$$

Tan Θ_1 is equivalent to a non-dimensional reduced speed, which integrates slip speed, temperature, pavement texture and delayed deformation of tyre rubber.

Once Θ_1 is obtained, Θ_2 can be determined by means of the relation between Θ_1 and Θ_2 as presented in equation 6.21.

$$\frac{(1 + \tilde{E}_{\infty} - (1 - \tilde{E}_{\infty})\cos 2\Theta_2)(\tan\Theta_2)^{3-3H}}{(1 + \tilde{E}_{\infty} - (1 - \tilde{E}_{\infty})\cos 2\Theta_1)(\tan\Theta_1)^{3-3H}} = \frac{1}{0.09\pi} \frac{4 - 2H}{2 - 2H} \frac{\xi_{\parallel}}{\xi_{\perp}} \quad (\text{eq. 6.22})$$

This formulation shows that skid velocity and temperature have an influence on the friction coefficient μ of the K&H-model, coupled with the longitudinal correlation length of the pavement $\xi_{\parallel}$ and the rubber constant τ_{20} as given by the right hand of equation 6.21. The remaining two rubber constants only influence μ through the ratio $\tilde{E}_{\infty}$, directly as given by equation 6.20 and conditioning the value of $\tan \theta_2$ in equation 6.22.

The transverse correlation length and the roughness exponent H of the pavement do not influence μ in a coupled way. The observed coupling facilitates the contrast between the experimental results and the theoretical predictions in order to assess the predictive capacity of the K&H-model.

6.3.2 Parameter analysis

The predictive capacity of the models will be assessed with the dataset described in Chapter 5. Table 6.1 shows the range of the main input parameters for the models from the data set.

Table 6.1 Range of input parameters

Parameter	unit	min	max
$\xi_{\parallel}$	mm	1.59	3.08
$\xi_{\perp}$	mm	0.53	1.78
H	-	0.42	0.47

v	m/s	0.28	23.8
T	K	286	393

The following parameters depend on the speed and temperature.

Table 6.2 Range of speed dependent parameters

Parameter	unit	min	max
α_T	-	$3.3 \cdot 10^{-13}$	16
$\tan(\Theta_1)$	°	$1.56 \cdot 10^{-8}$	$1.37 \cdot 10^5$

The reduced speed $\tan \Theta_1$ was calculated for the available test data of the braking tests described in paragraph 5.3.3. Figure 6.16 shows a histogram of $\log(\tan \Theta_1)$, which shows that the SKM data are spread out over a range of 10^{13} , whereas most of the ASTM data are within a range of 10^8 .

Figure 6.16 Histogram of reduced frequency of SR-ITD measurement data

In the following tables (6.3 to 6.7) the reduced speed $\tan \Theta_1$ is presented for various combinations of asphalt types (AC, PA and SMA) and the two rubber types (ASTM and SKM). The values presented in the table represent $\log(\tan \Theta_1)$ as a function of the rubber temperature and the slip speed. The colour scheme in the table indicates in green the range of $\tan \Theta_1$ in which the model yields the highest friction values (>75% of the maximum value). The yellow area indicates the range in which friction values between 25% and 75% of the maximum value are found. Lastly, the values of $\tan \Theta_1$ in the red areas yield very low friction values, less than 25% of the maximum value.

These tables show that according to the model there is an optimal range of tyre temperatures in which the friction values due to hysteresis is relevant. At higher speeds, a higher temperature is admissible. Unfortunately, in the friction tests according to the polishing protocol, the temperature remains below 35°C, which implies that the model does

not predict relevant friction values. In the braking tests the tests start at low temperature and high speed and end at a low speed and high temperature. This is opposite to the optimal range of temperature and speed according to the model. Nevertheless, a significant amount of data points are within the effective range of the model.

Table 6.3 Values of $\log(\tan \Theta_1)$ on AC with ASTM rubber

ASTM - AC		Rubber temperature (°C)													
		40	45	50	55	60	65	70	75	80	85	90	95	100	105
speed (km/h)	3.6	2.0	1.5	1.1	0.7	0.2	-0.2	-0.6	-1.0	-1.4	-1.7	-2.1	-2.4	-2.8	-3.1
	7.2	2.3	1.8	1.4	1.0	0.5	0.1	-0.3	-0.7	-1.1	-1.4	-1.8	-2.1	-2.5	-2.8
	14.4	2.6	2.1	1.7	1.3	0.8	0.4	0.0	-0.4	-0.8	-1.1	-1.5	-1.8	-2.2	-2.5
	21.6	2.8	2.3	1.9	1.4	1.0	0.6	0.2	-0.2	-0.6	-1.0	-1.2	-1.2	-2.0	-2.3
	28.8	2.9	2.4	2.0	1.6	1.1	0.7	0.3	-0.1	-0.5	-0.8	-1.2	-1.2	-1.9	-2.2
	36	3.0	2.5	2.1	1.7	1.2	0.8	0.4	0.0	-0.4	-0.7	-1.1	-1.1	-1.8	-2.1
	43.2	3.1	2.6	2.2	1.7	1.3	0.9	0.5	0.1	-0.3	-0.7	-1.0	-1.4	-1.7	-2.0
	50.4	3.2	2.7	2.2	1.8	1.4	1.0	0.6	0.2	-0.2	-0.6	-0.9	-1.3	-1.6	-2.0
	57.6	3.2	2.7	2.3	1.9	1.4	1.0	0.6	0.2	-0.2	-0.5	-0.9	-1.2	-1.6	-1.9
	64.8	3.3	2.8	2.3	1.9	1.5	1.1	0.7	0.3	-0.1	-0.5	-0.8	-1.2	-1.5	-1.9
	72	3.3	2.8	2.4	2.0	1.5	1.1	0.7	0.3	-0.1	-0.4	-0.8	-1.1	-1.5	-1.8
	79.2	3.4	2.9	2.4	2.0	1.6	1.2	0.7	0.4	0.0	-0.4	-0.8	-1.1	-1.4	-1.8
	86.4	3.4	2.9	2.5	2.0	1.6	1.2	0.8	0.4	0.0	-0.4	-0.7	-1.1	-1.4	-1.7
	93.6	3.4	3.0	2.5	2.1	1.6	1.2	0.8	0.4	0.0	-0.3	-0.7	-1.0	-1.4	-1.7

Table 6.4 Values of $\log(\tan \Theta_1)$ on PA with ASTM rubber

ASTM - PA		Rubber temperature (°C)													
		40	45	50	55	60	65	70	75	80	85	90	95	100	105
speed (km/h)	3.6	1.8	1.4	0.9	0.5	0.0	-0.4	-0.8	-1.2	-1.5	-1.9	-2.3	-2.6	-3.0	-3.3
	7.2	2.1	1.7	1.2	0.8	0.3	-0.1	-0.5	-0.9	-1.2	-1.6	-2.0	-2.3	-2.7	-3.0
	14.4	2.4	2.0	1.5	1.1	0.6	0.2	-0.2	-0.6	-0.9	-1.3	-1.7	-2.0	-2.4	-2.7
	21.6	2.6	2.1	1.7	1.3	0.8	0.4	0.0	-0.4	-0.8	-1.1	-1.5	-1.8	-2.2	-2.5
	28.8	2.7	2.3	1.8	1.4	1.0	0.5	0.1	-0.3	-0.6	-1.0	-1.4	-1.7	-2.1	-2.4
	36	2.8	2.4	1.9	1.5	1.0	0.6	0.2	-0.2	-0.5	-0.9	-1.3	-1.6	-2.0	-2.3
	43.2	2.9	2.4	2.0	1.6	1.1	0.7	0.3	-0.1	-0.5	-0.8	-1.2	-1.5	-1.9	-2.2
	50.4	3.0	2.5	2.1	1.6	1.2	0.8	0.4	0.0	-0.4	-0.8	-1.1	-1.5	-1.8	-2.1
	57.6	3.0	2.6	2.1	1.7	1.3	0.8	0.4	0.0	-0.3	-0.7	-1.1	-1.4	-1.8	-2.1
	64.8	3.1	2.6	2.2	1.7	1.3	0.9	0.5	0.1	-0.3	-0.7	-1.0	-1.4	-1.7	-2.0
	72	3.1	2.7	2.2	1.8	1.3	0.9	0.5	0.1	-0.2	-0.6	-1.0	-1.3	-1.7	-2.0
	79.2	3.2	2.7	2.3	1.8	1.4	1.0	0.6	0.2	-0.2	-0.6	-0.9	-1.3	-1.6	-1.9
	86.4	3.2	2.7	2.3	1.9	1.4	1.0	0.6	0.2	-0.2	-0.5	-0.9	-1.2	-1.6	-1.9
	93.6	3.3	2.8	2.3	1.9	1.5	1.0	0.6	0.3	-0.1	-0.5	-0.9	-1.2	-1.5	-1.9

Table 6.5 Values of $\log(\tan \Theta_1)$ on PA with SKM rubber

SKM - PA		Rubber temperature (°C)													
		40	45	50	55	60	65	70	75	80	85	90	95	100	105
speed (km/h)	3.6	0.7	-0.1	-0.8	-1.4	-2.1	-2.7	-3.4	-4.0	-4.5	-5.1	-5.7	-6.2	-6.7	-7.2
	7.2	1.0	0.2	-0.5	-1.1	-1.8	-2.4	-3.1	-3.7	-4.2	-4.8	-5.4	-5.9	-6.4	-6.9
	14.4	1.3	0.5	-0.2	-0.8	-1.5	-2.1	-2.7	-3.4	-3.9	-4.5	-5.1	-5.6	-6.1	-6.6
	21.6	1.4	0.7	0.0	-0.7	-1.3	-2.0	-2.6	-3.2	-3.8	-4.3	-4.9	-5.4	-5.9	-6.5
	28.8	1.6	0.8	0.1	-0.5	-1.2	-1.8	-2.4	-3.1	-3.6	-4.2	-4.8	-5.3	-5.8	-6.3
	36	1.7	0.9	0.2	-0.4	-1.1	-1.7	-2.4	-3.0	-3.5	-4.1	-4.7	-5.2	-5.7	-6.2
	43.2	1.7	1.0	0.3	-0.4	-1.0	-1.7	-2.3	-2.9	-3.5	-4.0	-4.6	-5.1	-5.6	-6.2
	50.4	1.8	1.1	0.4	-0.3	-0.9	-1.6	-2.2	-2.8	-3.4	-4.0	-4.5	-5.1	-5.6	-6.1
	57.6	1.9	1.1	0.4	-0.2	-0.9	-1.5	-2.1	-2.7	-3.3	-3.9	-4.5	-5.0	-5.5	-6.0
	64.8	1.9	1.2	0.5	-0.2	-0.8	-1.5	-2.1	-2.7	-3.3	-3.9	-4.4	-4.9	-5.5	-6.0
	72	2.0	1.2	0.5	-0.1	-0.8	-1.4	-2.1	-2.7	-3.2	-3.8	-4.4	-4.9	-5.4	-5.9
	79.2	2.0	1.3	0.6	-0.1	-0.8	-1.4	-2.0	-2.6	-3.2	-3.8	-4.3	-4.9	-5.4	-5.9
	86.4	2.0	1.3	0.6	-0.1	-0.7	-1.4	-2.0	-2.6	-3.2	-3.7	-4.3	-4.8	-5.3	-5.9
	93.6	2.1	1.4	0.7	0.0	-0.7	-1.3	-1.9	-2.5	-3.1	-3.7	-4.2	-4.8	-5.3	-5.8

Table 6.6 Values of $\log(\tan \Theta_1)$ on SMA with ASTM rubber

ASTM - SMA		Rubber temperature (°C)													
		40	45	50	55	60	65	70	75	80	85	90	95	100	105
speed (km/h)	3.6	1.8	1.3	0.9	0.5	0.0	-0.4	-0.8	-1.2	-1.6	-1.9	-2.3	-2.6	-3.0	-3.3
	7.2	2.1	1.6	1.2	0.8	0.3	-0.1	-0.5	-0.9	-1.3	-1.6	-2.0	-2.3	-2.7	-3.0
	14.4	2.4	1.9	1.5	1.1	0.6	0.2	-0.2	-0.6	-1.0	-1.3	-1.7	-2.0	-2.4	-2.7
	21.6	2.6	2.1	1.7	1.2	0.8	0.4	0.0	-0.4	-0.8	-1.2	-1.5	-1.9	-2.2	-2.5
	28.8	2.7	2.2	1.8	1.4	0.9	0.5	0.1	-0.3	-0.7	-1.0	-1.4	-1.7	-2.1	-2.4
	36	2.8	2.3	1.9	1.5	1.0	0.6	0.2	-0.2	-0.6	-0.9	-1.3	-1.6	-2.0	-2.3
	43.2	2.9	2.4	2.0	1.5	1.1	0.7	0.3	-0.1	-0.5	-0.9	-1.2	-1.6	-1.9	-2.2
	50.4	3.0	2.5	2.0	1.6	1.2	0.8	0.4	0.0	-0.4	-0.8	-1.1	-1.5	-1.8	-2.2
	57.6	3.0	2.6	2.1	1.7	1.2	0.8	0.4	0.0	-0.4	-0.7	-1.1	-1.4	-1.8	-2.1
	64.8	3.1	2.6	2.1	1.7	1.3	0.9	0.5	0.1	-0.3	-0.7	-1.0	-1.4	-1.7	-2.1
	72	3.1	2.6	2.2	1.8	1.3	0.9	0.5	0.1	-0.3	-0.6	-1.0	-1.3	-1.7	-2.0
	79.2	3.2	2.7	2.2	1.8	1.4	1.0	0.5	0.2	-0.2	-0.6	-1.0	-1.3	-1.6	-2.0
	86.4	3.2	2.7	2.3	1.8	1.4	1.0	0.6	0.2	-0.2	-0.6	-0.9	-1.3	-1.6	-1.9
	93.6	3.2	2.8	2.3	1.9	1.4	1.0	0.6	0.2	-0.2	-0.5	-0.9	-1.2	-1.6	-1.9

Table 6.7 Values of $\log(\tan \Theta_1)$ on SMA with SKM rubber

SKM - SMA		Rubber temperature (°C)													
		40	45	50	55	60	65	70	75	80	85	90	95	100	105
speed (km/h)	3.6	0.6	-0.1	-0.8	-1.5	-2.1	-2.8	-3.4	-4.0	-4.6	-5.2	-5.7	-6.2	-6.8	-7.3
	7.2	0.9	0.2	-0.5	-1.2	-1.8	-2.5	-3.1	-3.7	-4.3	-4.9	-5.4	-5.9	-6.5	-7.0
	14.4	1.2	0.5	-0.2	-0.9	-1.5	-2.2	-2.8	-3.4	-4.0	-4.5	-5.1	-5.6	-6.2	-6.7
	21.6	1.4	0.7	0.0	-0.7	-1.4	-2.0	-2.6	-3.2	-3.8	-4.4	-4.9	-5.5	-6.0	-6.5
	28.8	1.5	0.8	0.1	-0.6	-1.2	-1.9	-2.5	-3.1	-3.7	-4.2	-4.8	-5.3	-5.9	-6.4
	36	1.6	0.9	0.2	-0.5	-1.1	-1.8	-2.4	-3.0	-3.6	-4.2	-4.7	-5.2	-5.8	-6.3
	43.2	1.7	1.0	0.3	-0.4	-1.1	-1.7	-2.3	-2.9	-3.5	-4.1	-4.6	-5.2	-5.7	-6.2
	50.4	1.8	1.0	0.3	-0.3	-1.0	-1.6	-2.2	-2.9	-3.4	-4.0	-4.6	-5.1	-5.6	-6.1
	57.6	1.8	1.1	0.4	-0.3	-0.9	-1.6	-2.2	-2.8	-3.4	-3.9	-4.5	-5.0	-5.6	-6.1
	64.8	1.9	1.2	0.5	-0.2	-0.9	-1.5	-2.1	-2.7	-3.3	-3.9	-4.4	-5.0	-5.5	-6.0
	72	1.9	1.2	0.5	-0.2	-0.8	-1.5	-2.1	-2.7	-3.3	-3.9	-4.4	-4.9	-5.5	-6.0
	79.2	2.0	1.2	0.5	-0.1	-0.8	-1.4	-2.1	-2.7	-3.2	-3.8	-4.4	-4.9	-5.4	-5.9
	86.4	2.0	1.3	0.6	-0.1	-0.8	-1.4	-2.0	-2.6	-3.2	-3.8	-4.3	-4.9	-5.4	-5.9
	93.6	2.0	1.3	0.6	-0.1	-0.7	-1.4	-2.0	-2.6	-3.2	-3.7	-4.3	-4.8	-5.4	-5.9

6.4 Model correlation with measurement data

6.4.1 Model correlation on the full dataset

The ultimate goal of the skid resistance model is to obtain a good prediction of skid resistance purely based on the input parameters of the model, such as described above.

With the available dataset it proved impossible to obtain a reasonable fit on the complete dataset, which includes three types of asphalt surfaces, two types of rubber and two types of tests (braking and side-way force).

In the following paragraphs a detailed comparison is presented of the obtained results, analysing the differences in response.

Figure 6.17 shows the results of more than 1000 data points from braking tests, performed at temperatures varying from 13 °C to 120 °C, and speed from 80 km/h to 0 km/h in comparison with the friction value calculated through the model, based on the texture parameters and test conditions.

Figure 6.17 Comparison of predicted μ values versus SR-ITD measurements (all braking test data)

The obtained fit is very poor. As mentioned earlier on, the model predicts very low friction values. The higher friction values are calculated for the texture data of the PA specimen.

In the following graphs the influence of the main model parameters on the outcomes are shown. In figure 6.18 the red squares represent the measured friction values grouped by the corresponding values of ξ_L . The first observation is that for each of the values of ξ_L a wide range of friction values were measured: from less than 0.1 to more than 1.1. The variation can be reproduced by the model to some extent, although the higher friction values are not reached for the lower values of ξ_L .

Figure 6.18 Influence of ξ_L in the measurement data and in the model

The highest friction model output values are obtained for values for $\xi_{||}$ of 2.4 to 2.5. The $\xi_{||}$ parameter shows less variation, and similarly to the previous parameter, there is a large range of friction values possible with the same value of $\xi_{||}$ (figure 6.19). In the model however for the values above approximately 2.6, only low friction values are obtained.

Figure 6.19 Influence of $\xi_{||}$ in the measurement data and in the model

With the parameter $2H$ the situation is also similar. The only trend visible in the measured data is that the range of friction values increases with an increase of $2H$. This trend is also visible in the model, up to 0.91, after which the trend is lost.

Figure 6.20 Influence of $2H$ in the measurement data and in the model

Speed is the driving parameter of the friction model. The bulk data do not reflect clearly a relation with speed, but individual results do show an increase of friction with a decrease of the speed, as presented in figure 5.27 in section 5.3.2. As was discussed there, the temperature increases rapidly during the braking test, changing the rubber response.

Figure 6.21 Influence of speed in the measurement data and in the model

The modification introduced in the original model intends to resolve this issue by using the time-temperature superposition principle as described in paragraph 6.3. Figure 6.22 shows the effect of combining speed and temperature in a new variable called "reduced speed". The distribution of the data is now different, with a steep increase of friction at low speeds and a gradual descend to a lower limit value (notice the log-scale on the x-axis). The friction model obviously shows this as well, although overall the values are too low.

Figure 6.22 Influence of the combined speed-temperature in the measurement data and in the model

6.4.2 Correlation on individual braking tests

For every combination of the fractal parameters $\xi_{\parallel}$, $\xi_{\perp}$ and H and the rubber parameters $\tilde{E}_{\infty}$ and τ_{20} a friction curve can be calculated as a function of $\tan \theta_1$ (which depends on speed and temperature according to equation 6.21).

As described before, each of the three asphalt mixtures was tested at various polishing levels and with two different rubber types. This yields six different graphs, in which the curves for the different polishing levels are presented. The three graphs for AC, PA and SMA tested with SKM rubber are shown in figures 6.23, 6.24 and 6.25.

The curves obtained for the ASTM rubber are identical in shape, but the values are 22% lower. For this reason, these graphs are not included here. The maximum peak value of μ is 0.128 and the minimum 0.018 with the SKM rubber. These values are much lower than the experimental values obtained on asphalt surfaces.

Figure 6.23 Friction curve for the AC specimen and SKM rubber at various polishing levels

Figure 6.24 Friction curve for the PA specimen and SKM rubber at various polishing levels

Figure 6.25 Friction curve for the SMA specimen and SKM rubber at various polishing levels

When applying the model to the experimental results, the friction value depends on the range of θ_1 , which depends on the speed and temperature. The maximum friction value is obtained at $\tan \theta_1 \approx 0.25$, whereas the values higher than 10% of the maximum value are found in the range 0.0065 and 3.8.

The experimental data of the braking tests contain 1014 data points, each with a specific combination of speed and temperature. When calculating $\tan \theta_1$ for each data point, about 28% of the values are within the range of $\tan \theta_1$ of the curves where μ is bigger than 10% of the maximum friction value. As a consequence, the calculated friction values are much lower than the measured values and the time and speed dependency is also less than should be expected.

In the following figures, the experimental data from braking tests on asphalt specimens with a specific polishing level and a given rubber type are combined in one graph with the theoretical friction curve as a function of $\tan \theta_1$. Notice that the order of magnitude for the model results is 10 times lower than the experimental results.

Figure 6.26 Model results vs experimental values for the PA 9 specimen

An improved fit could be obtained by adding adjustment factors. Specifically the amplitude could be increased by multiplying the end result and the shift factor α_T could be modified in order to shift the curve horizontally. However, since the adjustment factors would be different for each individual case, it was chosen to present the model results without modifications.

In total there are 23 unique combinations of rubber and texture parameters, with data of at least one braking test. All braking test results performed on one of these 23 test cases are plotted together in one graph. The data within one graph include various braking tests, which may have been performed at different vertical pressures and temperatures.

In the following graphs, test results for three of the 23 test conditions are shown. In figure 6.27 one example of an AC specimen is shown. In all cases, the model underestimates the range of speed/temperature ($\tan \theta_1$) in which significant friction occurs

Figure 6.27 Adjusted model results for a test on an AC specimen with ASTM rubber

Figure 6.28 shows test results on a PA sample. The model predicts higher friction values for the PA specimen as compared to the AC specimen, which is in line with the experimental data.

Figure 6.28 Adjusted model results for a test on a PA specimen with ASTM rubber

In figure 6.29 the results for a SMA sample are shown. In this case, the model underestimated the friction potential of the sample.

Figure 6.29 Adjusted model results for a test on an SMA specimen with ASTM rubber

In general it can be observed that the experimental data appear as a cloud of points without a clear pattern or trend. Even when the model passes through the point cloud, it still cannot be considered a good fit.

Annex A includes the results of all 23 test cases.

Chapter 7 Skid resistance field measurements

Field measurements have been carried out on different types of asphalt pavement surfaces. The measurements were carried out through a period of at least 2 years by SCRIM and Adhera measuring devices under various climatic conditions, speeds and wetting states. The aim of this chapter is to properly analyse these data in order to be able to use them for calibration of the skid resistance model. This should also result in recommendations for the correction of the measurements for seasonal influences on skid resistance.

7.1 Purpose of the skid resistance measurements

Skid resistance field measurements have been carried out with two different skid resistance measuring devices. From these test, two specific datasets have been selected for this study. One set was set up specifically to study seasonal variations in skid resistance measurements and will be described in section 7.2. The second set has been devised to serve as a calibration set for the skid resistance models and is described in 7.3.

7.2 Description of the seasonal variations data set

7.2.1 Device used for the elaboration of the dataset

The data set for the seasonal variation study has been collected by means of the SCRIM (Sideway-force Coefficient Routine Investigation Machine). SCRIM uses a sideway force method of measuring resistance to skidding. The primary element is a test wheel known as the SCRIM wheel, mounted on a secure framework attached to the test vehicle. During test runs, the wheel is lowered so that it is in contact with the road surface. The wheel carries a constant load induced by a dead weight of 200 kg and is derived at an angle of 20° to the longitudinal axis of the vehicle. The angle causes a horizontal force perpendicular to the plane in which the wheel is rotating, which is sensed by a load cell force transducer. The ratio of sideway force and vertical load on the SCRIM wheel is the Sideway-force Coefficient or SFC.

The SCRIM used for the testing (see figure 7.1) is a single sided machine, which means that it contains one measurement wheel on the right-hand side of the vehicle.

During the measurements a constant flow of water is applied to the road surface forward of the wheel to provide wet road conditions during testing. At the designated test speed a theoretical water film thickness of 0.5 mm is obtained.

Figure 7.1 SCRIM vehicle operated by the company Geocisa

The SCRIM is operated according to the Technical Report UNE 41201:2010-IN, issued by the Spanish national standardization body AENOR. This Report is based on the European Technical Specification EN/TS 15901-6 with some additional (more restrictive) clauses. These clauses include the specification of the pavement wetting system and the speed correction.

The necessary water flow is calculated by means of the following formula:

$$F = t \times a \times V \quad (\text{eq. 7.1})$$

where:

F = water flow

t = theoretical water film thickness (i.e. 0.5 mm)

a = width of the wetted zone in meters (at least 0.12 m)

V = speed of the SCRIM vehicle

Measurements are carried out at 50 km/h. Typically, at higher speeds a lower skid resistance value is obtained. Therefore, the following correction formula should be applied:

$$SFC_{50} = SFC_{\text{measured}} + ((v_{\text{meas}} - v_{\text{ref}}) * 0.0025) \quad (\text{eq. 7.2})$$

Where v_{ref} is the reference speed of 50 km/h and v_{meas} is the actual speed during the measurement.

These corrections are allowed for deviations from the target speed of not more than 10 km/h. The British design manual for roads and bridges (Highways England, 2015) allows for speed correction in the range from 25 to 85 km/h with the following formula:

$$SFC_{50} = SFC_{\text{measured}} \cdot (-0.0152 \cdot (v_{\text{meas}})^2 + 4.77 \cdot v_{\text{meas}} + 799) / 1000 \quad (\text{eq. 7.3})$$

Figure 7.2 Speed corrections for a measured SFC value of 0.5 at different speeds

7.2.2 Results of the analysis for seasonal variations

The study into the seasonal variations in skid resistance measurements is fully described by the author in a journal paper (Van Bijsterveld and Del Val, 2016). Seasonal variations include many different factors, such as the presence of surface contaminants during dry periods, weathering and polishing of aggregates. Temperature is however one of the most important factors, especially because it is measurable.

Although the correlations are not very strong, still a significant temperature effect can be observed. The air and water temperatures cause the SFC to decrease at rates of 0.007 and 0.0077 per °C respectively (Figures 7.3 and 7.4).

Figure 7.3 Influence of air temperature on SFC (Van Bijsterveld and Del Val, 2016)

Figure 7.4 Influence of water temperature on SFC (Van Bijsterveld and Del Val, 2016)

On SCRIM measurements, no temperature corrections are applied, but the technical specification EN/TS15901-8 (CEN, 2009) of the German measuring device SKM establishes a water temperature correction of 0.0012 per °C of pavement surface temperature and 0.002 per °C of water temperature difference. This is significantly less than the correlations found in figure 7.3 and 7.4. However, it must be noted that in the standard, both corrections are applied at the same time, whereas the correlations presented before are determined individually.

7.3 Description of the IFSTTAR data set

7.3.1 Device used for the elaboration of the dataset

Adhera is a skid resistance measuring device developed at IFSTTAR in France, which measures a Longitudinal Friction Coefficient (LFC) with a blocked wheel on a wet pavement. The device is composed of a towing vehicle and a trailer, where the test wheel is located.

The structure of the trailer is very similar in its dynamics to a quarter of an average light vehicle (figure 7.5):

- static mass of 250 kg on the test wheel to generate the vertical load,
- ratio of suspended to non-suspended mass in the region of five,
- proper wheel frequency and proper body frequency close to those of a light vehicle.

The test consists of running the equipment at the required speed, wetting the surface, locking the measurement wheel and recording the force required to drag it along. This drag force divided by the vertical load on the wheel gives the braking force coefficient.

Figure 7.5 Principle of the Adhera device (source: IFSTTAR)

The water flow is adjusted to the vehicle speed, in order to obtain the theoretical water depth, assuming a smooth surface.

Standard tests are performed with a special smooth standard tyre PIARC 98 (see figure 7.6). For the current dataset also a commercial ribbed tyre (see figure 7.7) was used in order to obtain results as close to real life conditions as possible.

Figure 7.6 Adhera trailer with the smooth PIARC test wheel (source:IFSTTAR)

Figure 7.7 Real tyre used in the tests (source: IFSTTAR)

The test speed ranges between 40 and 90 km/h. Since the test is done with a blocked wheel, excessive wear and heating of the tyre can be expected on long measurement distances. For this reason, at 40 and 60 km/h, the wheel is blocked over a distance of 20 m, and the value of LFC is calculated by averaging the frictional force over a distance of 10 m. At 90 km/h the wheel is locked over 25 m (1 second) and measurements are also taken over 10 m. This procedure, in combination with the application of sufficient water keeps the temperature during the measurement within an acceptable range.

IFSTTAR carried out in-situ skid resistance measurements on asphalt pavements surface mixes, as described below, utilizing the Adhera device under various speed and moisture conditions. The sections are located on the test track of IFSTTAR in Nantes (described in paragraph 4.6), which means that they are not affected by traffic, apart from the scarce movements of testing vehicles.

The surfaces are described in 4.6. Measurements were carried out on 6 months intervals during 2 years.

7.3.2 Multiple linear regression of measurement data

The first step in the data analysis is to perform a multiple linear regression analysis to detect the parameters that are influencing the results. For each of the six sessions a dataset is prepared that contains a time variable (t), the pavement temperature (T) and the speed (v), which shall act as predictor values, and the Longitudinal Friction Coefficient (LFC) values which are the responses.

The regression equation that is assumed is:

$$LFC = \beta_1 + \beta_2 \cdot v + \beta_3 \cdot t + \beta_4 \cdot T + \varepsilon \quad (\text{eq. 7.4})$$

To improve the quality of the linear regression, time, speed and temperature are expressed in units such that their values are of the same order of magnitude. Specifically, the time is

expressed in months (by dividing the number of days between 30), the speed in m/s and temperature in degrees Celsius.

Table 7.1 Regression parameters of LFC values

	PA	BBTM	AC	AC old)	SD
β_1	0.7469	0.6991	0.9292	0.7182	1.1549
β_2 (s/m)	-0.0043	-0.0077	-0.0173	-0.0138	-0.0226
β_3 (1/month)	-0.0059	-0.0042	-0.0069	-0.0025	-0.0077
β_4 (1/°C)	-0.0044	-0.0022	-0.0042	-0.0019	-0.0099
R^2	0.904	0.862	0.964	0.963	0.762

Notice that in this dataset temperature causes the LFC to decrease at a rate ranging from 0.0019 to 0.0099 per °C (average 0.0045). This is in the same order of magnitude as in the SCRIM dataset. The LFC decrease rate due to speed, ranges from 0.0012 to 0.0063 per km/h (0.0036 average), which is in accordance with the standardized correction of 0.0025 per km/h for SFC (equation 7.2).

Figure 7.8 shows a representation of the regression function of equation 7.4 for the PA surface.

Figure 7.8 Representation of the regression function for porous asphalt ($R^2 = 0.90$)

7.3.3 Skid resistance measurements for model correlation purposes

With the available texture parameters, reported in paragraph 4.6 a prediction of the skid resistance level is made with the rubber friction model. The temperature and speed during the measurement are input values for the model.

Also in this case, it is impossible to obtain a good correlation of the measurement results with the model predictions on all asphalt surfaces.

Figure 7.9 Overall correlation of LFC field measurements with model predictions

An individual adjustment of the correlation parameters yields better results for each surface type. Figures 7.1 to 7.14 represent the best possible fit on the five different surfaces.

Figure 7.10 Model correlation on asphalt concrete

Figure 7.11 Model correlation on "old" asphalt concrete surface

Figure 7.12 Model correlation on very thin asphalt concrete (BBTM)

Figure 7.13 Model correlation on porous asphalt

Figure 7.14 Model correlation on an epoxy low friction surface dressing

Chapter 8 Conclusions and recommendations

When the results of a research are not as gratifying as expected, the point at which it can be concluded is not clearly defined. In this chapter, conclusions on texture and rubber characterisation, the procedures for laboratory skid resistance measurements and friction models are presented and the contributions of this thesis to the state of the art are highlighted. The research gives rise to recommendations for the practical use of the results and for further research to progress further towards the initial goals of the research.

8.1 Conclusions regarding the research work

The primary objective of this research was to perform an interactive assessment of the most advanced experimental techniques and the most elaborated theoretical models concerning a critical issue in pavement engineering: the accurate determination of the friction coefficient of the tyre-pavement interaction.

The work presented in this study towards this objective includes the definition and analysis of pavement texture indicators, based on contactless measurements of texture and control of the influence factors. Three different techniques for texture measurements within the range of microtexture have been applied; two are strictly used in a static set-up which implies a restriction to laboratory use. The third method, although to date has only been applied in laboratory, is expected to produce similar results in the field.

A dataset with texture measurement from different instruments has been analysed to investigate the influence of sample distance and the sensitivity of the parameter determination procedure. A significant influence of the sample distance was found on the microtexture related parameters ($2H$ and $\xi_{||}$). Also the choice of the part of the height difference correlation curve to be used for the parameter determination has been shown to have a significant influence on the outcomes. These observations lead to the recommendation to establish a maximum sample distance length of 0.5 mm and to determine the fractal parameters on the wavelengths up to 1 mm. In any case, these conditions shall always be reported in order to enhance the reproducibility of the method. This type of seemingly arbitrary limits call for standardization.

Data from an experimental laboratory testing system, the Skid Resistance-Interface Testing Device (SR-ITD), have been used for the assessment and calibration of the friction model. A thorough analysis of the devices concepts and the output data has brought to light shortcomings which affect the usability of the measurement data for model calibrations.

Laboratory tests are ideally designed in such a way that the parameter of interest is varied and measured over a certain interval, while all other influencing factors are maintained constant. In the design of the SR-ITD braking test protocol, the choice of reproducing realistic full skid breaking conditions, implies that not all the influencing factors can be controlled. The following parameters show therefor strong variations:

- slip speed,
- temperature,
- vertical force.

Moreover, the damping system and the active braking/accelerating of the engine do not allow the amount of dissipated energy to be measured.

Luckily, the first three parameters (speed, temperature and force) are monitored, which means that the data can be used with caution. Due to the fast changing conditions, most data show strong variations with unexpected peaks. Filtering procedures have been applied to obtain smoother curves.

A second testing protocol, the polishing test, which was not meant to be used for measuring, creates measuring conditions that are much more stable regarding speed and temperature. The registered force data can be used to calculate friction coefficients on different pavement surfaces, and a significant decrease of the friction values was shown to occur increasing the level of polishing and wear. These results confirm the existing hypothesis. However, within the available dataset, no variation of contact stress, speed and temperature was imposed, which limits the possibilities to use it for model calibration.

The contribution of the tyre rubber in skid resistance is at least as important as the pavement texture. To characterize the rubber, samples were tested in the Dynamic Shear Rheometer. Mastercurves for the complex shear modulus, the storage modulus, loss modulus and the phase angle have been elaborated for the different types of rubber by using the frequency-temperature superposition principle of visco-elastic materials. In this way, the frequency and temperature dependent behaviour of the rubber material can be analytically described approaching the mastercurves by potential functions. The parameters a Standard Linear Solid model or Zener model were also obtained, although it appeared that this model does not represent the material behaviour accurately.

The most advanced models for pavement-rubber friction originate from research promoted by the rubber industry. The model proposed by Heinrich and Klüppel is a sophisticated model, based on the fractal characterisation of the surface and the interaction with the tyre rubber assumed to have a viscoelastic behaviour. The data used originally for calibrating these models were slow moving rubber blocks on a dry artificial surface (e.g. glass). The conditions of the SR-ITD tests are fundamentally different. First of all because of the type of surface: asphalt specimens have a much wider roughness scale. Secondly, the slip speed is much higher than in the tests used in the rubber industry. The most important side effect is that the temperature increases rapidly during a full slip test, altering the isothermal rubber behaviour. In the tests where no full slip is imposed, but a slip angle instead, a lower slip speed is generated and high temperatures are avoided as the wheel keeps rotating. The rotating wheel ensures that the region of the tyre where the energy dissipation takes place is replaced continuously as the wheel rotates. Consequently, the temperature rise of the rubber is less. However, the correct slip speed must be taken into account by particularizing the model not for the actual overall forward speed of the axis of the wheel, but for the effective slip speed, which is much lower.

The original model does not explicitly include temperature effects. The implementation of the time-temperature equivalence principle for the rubber stiffness allows introducing temperature into the model. Even though the overall fit of the model is not satisfying, the inclusion of temperature does make an improvement.

Given these considerations, the following conclusions can be drawn:

1. Fractal parameters provide a means of characterising texture of pavement surfaces over the full range of microtexture and macrotexture.
2. The current state-of-the-art in laser line scanning does not yet allow for full microtexture measurements on wet or moist asphalt surfaces at traffic speed. As shown in this research, this limitation can be overcome by using data from static profilers and texture processing algorithms developed here.
3. However, texture processing entails subjective decisions like filter properties, sampling or resampling distances and wavelength cut-offs, that have a significant influence on the results. Standardization is needed.
4. The braking test protocol of the Skid Resistance Interface Testing Device does not serve the purpose of obtaining measurement data for the assessment and calibration of predictive friction models substantiated on the interactions tyre-pavement. This is due to intrinsic reasons external to the testing design:
 - The duration of the test is too short to obtain stable measurements of forces and temperature.
 - The high speeds, the irregularities of the surface and the "three wheels on a specimen" set-up, lead to a large scatter of the experimental results because of high vibrations and noise in the measurements.
 - The use of dampers and an engine-controlled deceleration of the specimen makes it impossible to establish the energy dissipation rate in the tyre-pavement contact interface.
 - According to the friction model, the involved values of traffic speed and pavement roughness produce dynamic loading of the tyre contact area at frequencies beyond the limits of rubber characterisation from the conventional testing.
5. The polishing protocol, which was conceived to polish and wear the pavement surface and not specifically to perform measurements, takes out some of the short-comings of the braking protocol, but also has some disadvantages:
 - The polishing protocol establishes a constant slip rate and speed and the test is performed during long periods of time (typically 1 hour or more). This allows for averaging measurements over hundreds of measurements points. This is the simplest and least arbitrary way of filtering data.
 - The sideways-force set-up is a relatively simple mechanism in which the friction is generated in the tyre-pavement interface, due to the skewed position of the wheel, without the need for external braking forces. Due to the continuously rotating wheel, no excessive wear and localized damage occur in the contact interface.
 - The temperature of the rubber reaches after a run-in period, a fairly constant operating temperature, so that the testing conditions can be considered isothermal.
 - Due to the rotating wheel under wet conditions, it was impossible to measure accurately the rubber temperature.
 - The slip speed is very low due to the limited slip angle. Higher slip angles would lead to instability of the test tyre and an excessive temperature built up. However, in the friction model, the low rubber temperatures result into high values of the reduced speed $\tan \Theta_1$ which in turn yield low friction values.
 - Due to the fact that in the test programme it was foreseen to use the braking tests for the determination of the friction behaviour of the specimens, no variations were introduced in the test conditions of tests performed under the polishing protocol; specifically speed, contact pressure and rubber properties. This means that although

the quality of the obtained data under this protocol is better, the usability for model calibration is limited.

6. The friction model proposed by Klüppel and Heinrich is able to reproduce the typical theoretical and empirical friction – speed curve, within a certain range of the rubber properties, surface texture and speed. The complexity of the model and the apparently large number of parameters involved gives it a considerable amount of degrees of freedom, so that any experimental curve with a similar shape can be reproduced by the model.

Regardless the scatter of the experimental results, the model does not allow a reasonable fit to the measured data on the three different asphalt surfaces, two different types of rubber and a variable vertical force. The model was unable to predict the variation of the experimental results.

Moreover, it appears that the influence of the rubber properties is much stronger in the model than the texture properties. This result is consistent with the basic assumption of identifying the power dissipated by the friction force with the anelastic internal power developed by the stresses of the rubber in the contact area of the pavement surface: the model was developed by the tyre industry and, as mentioned before, the type of surfaces used for the calibration were smooth compared to a typical pavement surface.

7. A simpler mathematical formulation based on the paper by Klüppel and Heinrich (2000) for the engineering applications of the model has been developed in this thesis. With this formulation the variables determinant of friction are clearly identified, as well as the existing relations between them for producing equivalent effects on the friction coefficient. The physical basis on which the model relies, becomes more evident; temperature is incorporated as an independent variable and the mathematical reproducibility simplifies. Further, the characterisation of the rubber material has shown to be one of the weaknesses for the application of the model to laboratory tests involving skid speeds which are representative for automotive applications. However, despite the observation that the adjustment of the model on the SR-ITD data is poor, the results indicate that the model is easier to adjust with fewer calibration factors without qualitatively changing the basic assumptions.

8.2 Contributions to the state of the art

Despite the limited success rate in reaching the initial research objectives, a number of relevant contributions to the state of the art have resulted from this study:

1. First of all a full procedure was developed to pre-process texture profiles and calculate texture indicators based on 2D profile measurements. The procedures for filtering, spike detection, interpolation and concatenation of short profiles can be used for standardized calculation processes.
2. A comprehensive review and evaluation of the SR-ITD testing protocols has been performed, showing possibilities for improvement that were not detected during the SKIDSAFE project. A detailed analysis of the polishing protocol has revealed an interesting source of experimental data. New protocols have been developed for a systematic and comprehensive interpretation of the SR-ITD measurement data.

3. The friction model proposed by Heinrich and Klüppel has been analysed and checked for usability on SR-ITD measurements. Causes for the lack of adjustment have been identified and modifications to the model have been suggested.
4. A different mathematical formulation of the Heinrich and Klüppel model has been developed and fully described. This approach is mathematically less complicated and physically more comprehensive. The usability of this formulation is more promising, because of its enhanced adjustability.

8.3 Recommendations for practical implementations

The practical implementations from this study are limited to the characterisation of pavement surface texture, since the friction prediction has been shown to be beyond the scope of the available models. Nevertheless, some promising outcomes for the adjustment of the models have been found. It is recommended to calculate the proposed texture indicators on a large scale in order to obtain more experience about the in-time evolution of these parameters and the range of normal values for different types of surfaces. The indicators give additional information to the current MPD (Mean Profile Depth) values and a texture database is helpful for the further development of texture based skid resistance properties.

The findings resulting from the analysis of the laboratory friction measurements can be used to improve the SR-ITD and its testing protocols.

Lastly, the method of incorporating the influence of temperature on friction by coupling it with speed in accordance with the thermomechanical behaviour of the tyre rubber may be further developed for standardization purposes.

8.4 Recommendations for further research

As a result of this research a number of shortcomings in the measurement data concerning the tyre-pavement friction have been identified. Further research and developments on the following topics are essential for the development of predictive friction models with pavement and tyre design purposes:

- Viscoelastic characterisation of tyre rubber under significant conditions, strain level, loading frequency and temperature.
- Measurement of tyre temperature during friction laboratory and field testing. The temperature of the rubber in the contact interface has a large influence on the rubber's viscoelastic properties, hence on friction. Contactless measurements on the surface are not reliable enough due to the presence of water. Embedded sensors in the tyre rubber could be a solution.
- Development and testing of high speed and high resolution texture profilers for field measurements. Measurements within the microtexture range have been performed on rotating asphalt specimens at traffic speeds. On most of the tested materials the results were useable for the determination of texture parameters, but on black and shiny surface with a more open texture the results are more error prone. The continuous developments in the field of laser scanners are likely to produce reliable high resolution texture scans in field measurements.

- With more reliable and high resolution texture scans, in combination with a better characterisation of the rubber properties, it is worthwhile to investigate an improved model according to the contact conditions during skid resistance field measurements.
- In the texture characterisation procedures a number of arbitrary decisions were made, regarding the minimum sample distance and the wavelength limits that were set to determine the fractal parameters. It cannot be discarded that with different settings of some of the influencing parameters a better correlation with the model output could be obtained.

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Annex A Model versus experimental data

Asphalt Concrete specimen (AC)

Porous Asphalt specimen (PA)

Stone Mastic Asphalt specimen (SMA)