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RWYMT (RUNWAY MICRO TEXTURE)

D1 – Report on the literature review

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SUMMARY

Problem area

A slippery wet runway is defined as a wet runway where the surface friction characteristics on a significant portion of the runway have been determined to be degraded. Investigations of various landing runway overruns on wet runway surfaces have concluded that the aeroplane wheel braking friction coefficients during the operations were significantly lower than those suggested by methods assumed in airworthiness regulations. Deficiencies in runway micro texture are believed to have contributed to these lower levels of wheel braking friction. This report considers methods that are currently used to determine either directly, or indirectly, runway friction levels. It was observed that none of these methods can be used to either establish minimum values for micro texture characteristics or develop procedures for determining, and monitoring, micro texture characteristics. The development of such a procedure is considered an integral element of a method for determining whether a runway condition is slippery wet, so that pilots can be given appropriate warning before their aeroplanes operate on such surfaces.

Description of work

As part of this study into Runway Micro Texture for EASA, NLR and ESDU performed a literature review of both the various methods that are used to assess runway friction and current research in the areas of runway and road friction. Runway friction is measured in most instances either by direct methods, in which the contact forces between either a tyre or a rubber block and the runway surface are recorded, or indirect methods, where the runway surface characteristics are evaluated. The functioning of, and parameters recorded by, a wide range of devices are described.

Results and Application

The literature review found that the runway friction assessment methods used currently by aerodromes do not evaluate the runway micro texture, a parameter that contributes significantly to the slippery wet runway condition. Hence, it is proposed that a procedure that evaluates micro texture be developed, which could be used to define when a runway is slippery wet.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
AC	Advisory Circular
AIP	Aeronautical Information Publication
ASTM	American Society for Testing and Materials
ATM	Air Traffic Management
CFME	Continuous Friction Measuring Equipment
EASA	European Union Aviation Safety Agency
ESDU	Engineering Sciences Data Unit
FAA	Federal Aviation Administration
FT	Fourier Transform
GRF	Global Reporting Format
ICAO	International Civil Aviation Organization
MFL	Minimum Friction Level
NASA	National Aeronautics and Space Administration
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Center)
NOTAM	Notice to Air Men
NTSB	National Transportation Safety Board
PANS	Procedures for Air Navigtion Services
RWYCC	Runway Condition Code
SFT	Surface Friction Tester
USAF	United States Air Force

1. Introduction

1.1 Background

Runway friction is assessed generally in two different ways.

(i) Directly, through the measurement of the contact forces between a tyre or rubber block and the runway surface. This can be done using runway friction testers, aeroplane-derived methods, or the use of devices such as the British Pendulum Tester.

(ii) Indirectly, through the measurement of the runway surface texture characteristics. This can be done by visual, tactile or non-contact methods, and by using volumetric measurement devices, laser scanners and image analysis techniques. Other methods can also be used, such as chalk-wear devices and Stylus tracers.These methods have been found to have a range of shortcomings, including poor repeatability, subjective assessment, unsuitability for use on some types of runway surface, and an inability to measure the runway micro texture.

The braking force acting on an aeroplane tyre is a function of several factors, two of which are the macro and micro texture characteristics of the runway surface. Macro texture is defined as the texture in a pavement with a wavelength ranging from 0.5 mm to 5 mm (Ballkwill, 2013). Micro texture is defined as the texture in a pavement with a wavelength of less than 0.5 mm. Most micro texture in pavements is manifest as texture on the individual stones and/or the finer sand in the asphalt mixture or concrete mortar (Ballkwill, 2013).

Runway macro texture can be measured using well-established techniques such as the sand patch method. At present there are no suitable methods for determining, and monitoring, runway micro texture characteristics.

In recent years aeroplane overruns have occurred on wet runways where the achieved braking performance was worse than that specified in accordance with EASA CS 25.109 (CS 25.109, 2021). Subsequent investigations demonstrated that the aircraft brake and anti-skid systems functioned as intended during these incidents. The macro texture depths of the runways were within the normal range and no evidence of significant rubber accumulation on the runway surface was found. Additionally, the runways were wet (not flooded). Deficiencies in the micro texture of the surface were believed to have contributed to the inferior braking performance.

A slippery wet runway is defined as a wet runway where the surface friction characteristics on a significant portion of the runway have been determined to be degraded (AMC 25.1591, 2021). A portion of runway in the order of 100 m long may be considered significant (GM1 41 (a), 2022). For a slippery wet surface, the braking level will be reported as RWYCC 3 by the aerodrome operator (AMC1 ADR.OPS.B.037(a), 2022).

An aerodrome is required to issue a NOTAM when a runway surface, or a portion of it, is identified as slippery wet. This should describe the location of the affected portion and remain in effect for as long as the surface friction remains sub-standard (ADR.OPS.A.065, 2022).

A runway surface with a smooth micro texture can produce slippery wet conditions. If such a surface has not been identified, pilots might not be forewarned of a potential degradation in surface friction when operating an aeroplane on a wet runway. This increases the risk of a runway excursion. Consequently, it is necessary to establish minimum values for micro texture characteristics to assist in defining a slippery wet runway and to develop a procedure for determining, and monitoring, micro texture characteristics.

1.2 Scope of report on the literature review

This report represents deliverable 'D-1' of the Horizon Europe Project: Runway micro texture. The work presented here is the output from 'Task 1'. Factors that are relevant to the performance of an aircraft tyre when it operates on a runway surface are outlined in Section 3. Section 4 comprises a summary of the current techniques, methods and criteria, which are used to assess runway surfaces, along with summaries of the current research projects in the road and aviation sector. Any applicable shortcomings in these procedures, with respect to identifying a slippery wet runway, are highlighted. The parameters used to define a mathematical model that determines the decelerating forces on an aircraft tyre for an aircraft operating on a runway are described in Section 5 and a slippery wet runway is considered in Section 6.

2. General Information

The project (EASA.2021.HVP.26), of which this literature review forms part, has been planned to consider the braked motion of aircraft on runways contaminated only by water. In particular, the project aims to identify which features of the surface contribute to the creation of a “slippery wet runway”.

Before embarking on a study of that situation, it is well to consider the superficially simpler case of the braked motion of aircraft on a dry runway. To that end, this review includes details of the various contributions to understanding of such a motion. Then, and only then, it is feasible to consider the effect on the braked motion of the aircraft when runways become damp, wet, or flooded.

Furthermore, because contact between runway and aircraft tyres depends on the performance of the tyres during braking, modelling is loosely founded in the physical chemistry of the consequences of contact between visco-elastic and elastic materials. However, such a study relies heavily on detailed knowledge of interactions at molecular level; the modelling underlying this project is, for ease of understanding, expressed in engineering terms.

2.1 Definitions

- Dry runway means a runway whose surface is free of visible moisture and not contaminated within the area intended to be used (Annex I of Regulation (EU) No 965/2012).
- Damp – Annex I of EU No 965/2012, 2012 states that a runway is considered damp when the surface is not dry, but when the moisture on it does not give it a shiny appearance. For performance purposes, a damp runway, other than a grass runway, may be considered to be dry (CAT.POL.A.105, 2012).
- Wet – a runway is considered wet when its surface is covered by any visible dampness or water up to and including 3 mm deep within the area intended to be used (Annex I of EU No 139/2014, 2022). Contaminated runway means a runway of which a significant portion of its surface area (whether in isolated areas or not) within the length and width being used is covered by one or more of the substances listed under the runway surface condition descriptors (Annex I of Regulation (EU) No 965/2012).

2.2 Contributing component

2.2.1 Runway

Runways are considered in Section 3. Ways and means of measuring the important parameters that are used to quantify braked motion are considered in the section.

2.2.2 Pneumatic tyres

Section 3 also summarises relevant aspects of braked-tyre performance.

2.2.3 Aircraft

Aerodynamic and system variables are considered in Section 5.2. The section also describes some means that may be used to augment information that is often incomplete from component suppliers.

3. Runway and tyres

3.1 General

Historically, the interaction between pneumatic tyres and paved surfaces has often been examined in isolation from detailed assessments of the physical-chemistry of such contacts. A major advance was made when Buehler, 2006 drew attention to the existence of a layer of low-strength material at the interface between a tyre footprint and a paved surface. That layer is perceived to be of molecular dimensions. Sills, Vorvolakos, Chaudhury, & Overney, 2007, amongst others, asserted that it was impossible to measure the mechanical properties of the layer. However, for engineering purposes, an adequate formulation is specified in ESDU TM 202, 2022 based on an analysis of data from Schallamach, 1952. That set of properties is the basis of the (algebraic) modelling summarised in Balkwill, 2022a.

3.2 Definitions

3.2.1 Elasticity

Elasticity is a property of a material to resist a distortion and to return to its original size and shape when the cause of distortion is removed (Treloar, 1975). Solid objects deform if sufficient loads are applied; if the material is elastic, the object returns to its initial shape and size after removal of load.

3.2.2 Viscosity

Viscosity is a property of a liquid or gas that determines resistance to flow (Massey, 2011). It is a consequence of internal friction.

3.2.3 Visco-elasticity

Materials that exhibit both viscous and elastic characteristics when being deformed are called visco-elastic. The response of a viscoelastic material to strain has both an elastic and a viscous component (Treloar, 1975). Energy is not dissipated when purely elastic materials are loaded and then unloaded. However, when a visco-elastic material is treated in the same way, energy is dissipated. In that case, the stress-strain curve forms a loop; the energy lost during the loading cycle is given by the area of the loop.

3.2.4 Cohesion

Cohesion is a bonding force between molecules of substances with similar molecular construction (Treloar, 1975). In the context of tyre-to-runway interaction, cohesion exists between tread material and interface layer; as well as between interface layer and a surface finished with an asphalt or any other visco-elastic material.

3.2.5 Adhesion

Adhesion is a bonding force between molecules of substances with dis-similar molecular structures (Treloar, 1975). In the context of tyre-to-runway interaction, adhesion exists between the interface layer and a surface finished with a concrete or any other purely elastic material.

3.2.6 Hysteresis

In the case of interaction between a pneumatic tyre and a paved surface, hysteresis is a source of energy loss in the interface material (Treloar, 1975). When the interface translates over a surface, the interface is stretched and released by asperities in a paved surface.

3.2.7 Macro texture

The definition and description for surface macro texture is taken directly from ISO 13473-2:2002 (ISO, 2002). The pavement macro texture is the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of 0,5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands including the range 0,63 mm to 50 mm of centre wavelengths). The texture wavelength quantity describes the horizontal dimension of the irregularities of a texture profile. This type of texture is the texture which has wavelengths of the same order of size as tyre tread elements in the tyre/road interface. Surfaces are normally designed with a sufficient macrotexture to obtain suitable water drainage in the tyre/road interface. The macrotexture is obtained by suitable proportioning of the aggregate and mortar of the mix or by surface-finishing techniques.

In principle, drainage capability of a surface is determined by the depth of the macro texture amongst others.

3.2.8 Micro texture

The definition and description for surface micro texture is taken directly from ISO 13473-2:2002 (ISO, 2002). The pavement microtexture is the deviation of a pavement surface from a true planar surface with the characteristic dimensions along the surface of less than 0,5 mm, corresponding to texture wavelengths up to 0,5 mm expressed as one-third-octave centre wavelengths. This type of texture is the texture which makes the surface feel more or less harsh but which is usually too small to be observed by the eye. It is produced by the surface properties (sharpness and harshness) of the individual chippings or other particles of the surface which come in direct contact with the tyres.

3.2.9 Sharpness

Surface sharpness (or roughness) is a feature associated with the state of the micro texture. In aviation practice, there is no generally used method to quantify the feature. Recent research (Balkwill, 2022b) has led to the formulation of an empirical statistic (F_1). Surface sharpness is a variable quality of a surface that is defined as a statistical quantity. It is argued in the reference that the range of the variable lies in the interval $0 \leq F_1 \leq \pi$. It is specified that for a perfectly rough surface $F_1 = 0$; for a perfectly smooth surface $F_1 = \pi$.

3.3 Tyre-runway interaction

As a pneumatic tyre moves over such an elastic surface as dry concrete, cohesive bonds between the interface layer and the bulk of the tread material as well as adhesive bonds between the interface layer and the surface are made and broken.

Likewise, as a pneumatic tyre moves over such a visco-elastic surface as dry asphalt, cohesive bonds between the interface layer and the bulk of the tread material are made and broken. In addition, adhesive and cohesive bonds between the interface layer and the surface are made and broken. In the process, energy is dissipated in the form of heat.

For each type of surface, hysteresis contributes to further losses in energy as the result of high-frequency interaction between the surface and the interface layer. The sum of all these losses results in a deceleration; the deceleration is attributed to the existence of a decelerating force; that force is perceived to be friction. It has therefore become the custom to represent the force as a fraction of the vertical load on the tyre and to name that fraction “coefficient of friction”.

4. Assessing Forces Acting on an Aircraft when Braked on a Paved Runway

4.1 Structure

In principle, there are four forces acting on an aircraft when it is moving, with brakes applied, over a paved runway.

- Aerodynamic drag and lift
- Net thrust
- Forces arising from impingement of spray (where applicable)
- Decelerating force generated by interaction between tyres and runway and the wheel braking system (anti-skid)

In practice it is assumed that these four sources of force are independent. Independence of net thrust and aerodynamics is generally achieved in modelling, by detailed thrust accounting (AGARDograph 237 MIDAP Study Group, 1979).

In this section, only the fourth contribution is considered. Furthermore, the customary usage is adopted, that the decelerating forces arising from tyre-to-runway interaction is attributable to "friction" and a friction coefficient.

Runway friction can be assessed in two different ways. Directly, through the measurement of contact forces between a tyre or rubber block and the runway surface; or indirectly, through the measurement of the runway surface texture characteristics. Direct measurements are compared to predefined values which are often supposed to form boundaries for when a wet surface may be slippery or not.

4.2 Direct measurement methods

4.2.1 Runway friction testers

Runway friction testers, also known as Continuous Friction Measuring Equipment (CFME), are used to monitor the friction levels of runways. The devices measure the braking friction using a tyre that is braked at a pre-defined slip ratio and a self-wetting system to wet the tyre footprint. Generally, the tyres fitted to CFME are smaller than those fitted to aircraft and are inflated to lower pressures than that on braked aeroplane tyres. Also, vertical loads are much lower. There are various manufacturers of runway friction testers which all have unique design characteristics. An example of runway friction tester is shown in Figure 4-1.

Friction measuring devices have been serving aerodromes for many years to monitor runway surface friction characteristics. For many years, countries have been following the guidance provided by ICAO. Measurements taken by runway friction testers are compared to defined thresholds for new runway designs, maintenance planning, and minimum friction level below which a runway may become slippery wet. A "slippery wet runway" may be issued whenever a significant portion of a runway drops below the Minimum Friction Level (MFL) as defined by ICAO or as determined by the State. However, these reference values have not been updated since their inception and are considered outdated as they no longer reflect levels which are considered unconditionally valid by ICAO. In ICAO Circular 355, the following statement is given: '*Doc 9137, Part 2, Table 3-1, has not been updated and reflects levels no longer considered unconditionally valid by ICAO*

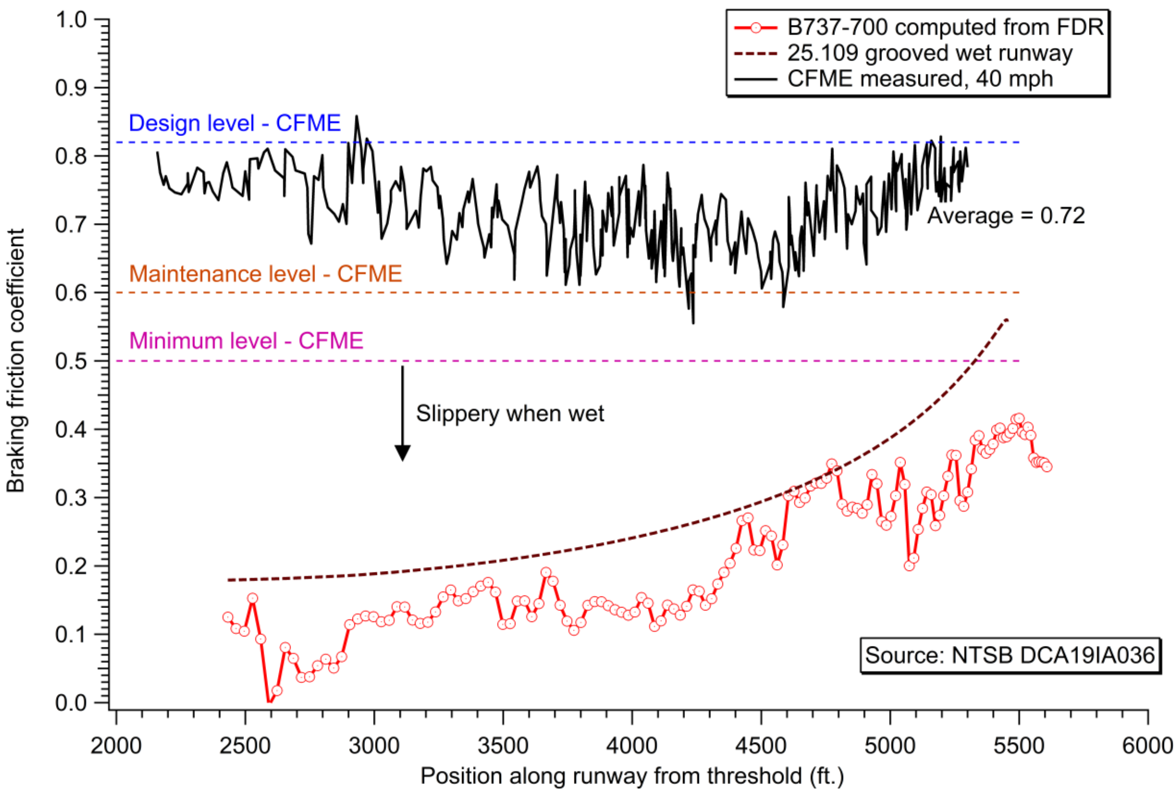
(“Design objective for new surface” and “Maintenance planning level”). The minimum friction levels in this table reflect historic levels for the individual friction measuring devices identified and are not adjusted according to more recent comparisons of these devices.’ Currently EASA maintaines the ICAO reference Table in the absence of any other reference.

Many researchers have tried to deduce a correlation between runway friction testers and full-scale braking data obtained with an aeroplane. In the United States much research was done on this topic by the FAA and NASA (Horne, Yager, Sleeper, & Merritt, 1977a), (Horne, Yager, Sleeper, & Merritt, 1977b), (Yager, Vogler, & Baldasare, 1990). The USAF also participated in these studies (Merritt, 1975). Organisations and equipment manufacturers from countries such as France, Norway, Sweden, Germany, the United Kingdom and Canada have also participated in similar research. (See, for example, Fristedt & Norrbom, 1980;Andrassy, 1999 Sugg, 1965; Sugg, 1968;Anon., 1974; and Meritt, 1975). These tests were designed to determine if a correlation between the aeroplane and friction measuring vehicles existed. Due to the large differences between the braking of an aeroplane and that of a runway friction tester, acceptable correlations were not found. The scatter was often too large to be meaningful in an operational aerodrome environment. ESDU has developed a more sophisticated approach in correlating runway friction testers and aeroplanes (ESDU 99015, 2010). ESDU developed a method for representing - and, if necessary, relating - the braking performances of aeroplanes and ground-test machines in wet conditions. The method is essentially statistical and implies that there is a clearly-defined level of probability that can be deduced from test runs of an aircraft (or ground-test machine) in a given set of wetness conditions on a particular runway.

Figure 4-1 Example of runway friction tester (Source: NASA)

Experience has shown that in a number of landing overruns the runway friction tester showed that the runway was complying with the minimum standards defined by ICAO or the State whereas the aeroplane was achieving much lower friction levels than expected by the regulatory models of EASA CS 25.109 (CS 25.109, 2021) or found during certification flight tests. An example is shown in Figure 4-2. This shows different braking friction coefficients as a function of the position along the runway. Both the measurements by the runway friction tester (CFME) as well as the friction level achieved by the aircraft are shown. Note that these two sources of friction data should not be compared directly with each other. The friction tester results reveal that the runway was well above the maintenance level defined by the FAA and far above the level which would require the runway to be classified as slippery when wet in a NOTAM. However, the wheel braking friction coefficients achieved by the aircraft are below those assumed by the regulatory models*. This would have justified a RWYCC of 3 (slippery wet runway) which proposes a much lower wheel braking friction coefficient for performance calculations.

Figure 4-2 Runway friction as function of position along the runway (source NLR, NTSB)



There are several reasons for runway friction testers sometimes giving results which are well above maintenance and minimum values, whereas aircraft decelerating forces are much lower than would justify a slippery wet warning. There are a few obvious explanations, such as the following.

* Results have been obtained from NTSB docket DCA19IA036. The operator in this overrun occurrence did not take credit for the grooved runway in their landing performance calculations. They assumed a smooth runway. The standard EASA 25.109(c) (CS 25.109, 2021) friction curve for a smooth runway does compare well with the achieved friction levels (not shown here). However, in this report the friction curves for a grooved runway are used to reflect the actual construction of the runway surface.

- No, or incorrect, calibration of the friction tester device.
- Improper inflation pressure of the test[†] or drive tyres.
- Worn test or drive tyres.
- Tests conducted far from the actual wheel tracks (where the runway surface is normally less worn or affected by rubber deposits).
- Worn axle bearings, wrongly aligned water delivery nozzle, and/or incorrect amount of water sprayed in front of the test tyre.
- Pavement temperatures can cause variation in measured friction coefficients (up to 20-25% between summer and winter season).

These factors can cause errors or variations in the measured friction values.

Some experiments showed differences of more than 30% between the same type of friction tester (poor reproducibility) which could be attributed to one or more of the aforementioned factors (Dardano, 2003), (Dardano, 2005). A worn test tyre or 7% variation in inflation pressure can result in a difference of more than 25-30% compared to results obtained with a new test tyre or a tyre inflated at the prescribed pressure (Gerthoffert & Laïmouche, 2013). A study conducted by Sydney Airport found that many airports were struggling with the poor repeatability[‡] of runway friction testers (Dardano, 2003). A variability of some 15% in the results has been recorded (Dardano, 2003). There are also reports that the manufacturer of the runway friction tester was unable to repeat the accuracy of measurements with the same device (Butterworth, 2010). Strict adherence to maintenance and operational requirements given by the manufacturer should help to improve the repeatability and reproducibility. As one manufacturer states “a badly maintained or wrongly calibrated runway friction tester is worse than no friction tester”. However, in practice poor repeatability and poor reproducibility are still experienced.

These aforementioned factors do not always explain some of the high, optimistic friction values measured by runway friction testers. Another explanation comes from the effect of rubber deposits on the surface texture. It is well-known that friction levels drop as rubber is built up on the runway. The rubber deposits tend to fill and smooth the pavement macro texture and micro texture; runway friction on wet surfaces is therefore reduced (Horne, 1975). Low friction values are often measured in the touchdown zone by runway friction testers. In this area the highest concentration of rubber deposits on the runway is found; both macro and micro texture are affected. In reality more rubber is deposited on the runway surface beyond the touchdown zone; aircraft tyres wear more during normal braking than during spin-up[§]. However, this rubber is more evenly spread and therefore often not clearly visible on the runway unlike in the touchdown zone. This rubber build-up usually has little influence on the macro texture unlike in the touch-down zone. However, the impact on the

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[†] Typically, this is 20 or 30 psi depending on the device and should stay within ± 0.5-1 psi for correct friction measurements. Some devices use test tyres inflated to 10 or 100 psi.

[‡] The ability of several different devices of type and configuration to report the same friction value for the same surface is called reproducibility. The ability of a friction measurement device to produce the same measured value of the same surface, when measurement runs are repeated under the same conditions, is called the repeatability (TP 14064E).

[§] The rubber deposition on runways is the result of wear of the tyre surface. Tyre wear depends largely on the amount of work done in skidding and is therefore influenced by the tyre slip and friction levels. An aircraft tyre spins up after contact with the runway in about 150 milliseconds. The work done in this very brief period is relatively small compared to that in the braked ground roll. Therefore, the rubber deposition is small. However, as aircraft all land in the same touchdown area, rubber builds up much quicker than on other areas on the runway as braking of the tyres will vary during the ground roll for each aircraft.

micro texture can be significant. Researchers (Chen, Huang, Chen, & Su, 2008) have measured the actual thickness of rubber deposits on a runway and correlated these results with measurements from a Surface Friction Tester (SFT) runway friction tester. The results are shown in Figure 4-3 together with the design, maintenance, and minimum level values specified by ICAO. Up to a rubber deposit thickness of 0.11 mm, the SFT measures friction values well above the ICAO maintenance level. This small amount of rubber is more than sufficient to affect the micro texture (which has amplitudes of typically less than 0.06 mm), making it much smoother. Even as the rubber deposit thickness is increased above 0.11 mm, friction values above the maintenance level were measured by the SFT. The results also show some significant scatter which is explained earlier in this paper. The reduction in friction measured by the SFT seems more likely be the result of a decreasing macro texture depth rather than a smoother micro texture. This might explain that in some cases results obtained by runway friction testers do not indicate that the runway could be slippery wet. Note that the braking friction force between a tyre and a rubber-contaminated surface in the dry contact zone is complex and not always well understood[**]. However, a plausible explanation is that the existence of cohesion in the dry contact zone could lead to higher friction values being measured by the runway friction testers. Because aircraft operate with speeds, loads, and inflation pressures which are significantly different from those of CFME, cohesion may be expected to play a lesser role in braking performance.

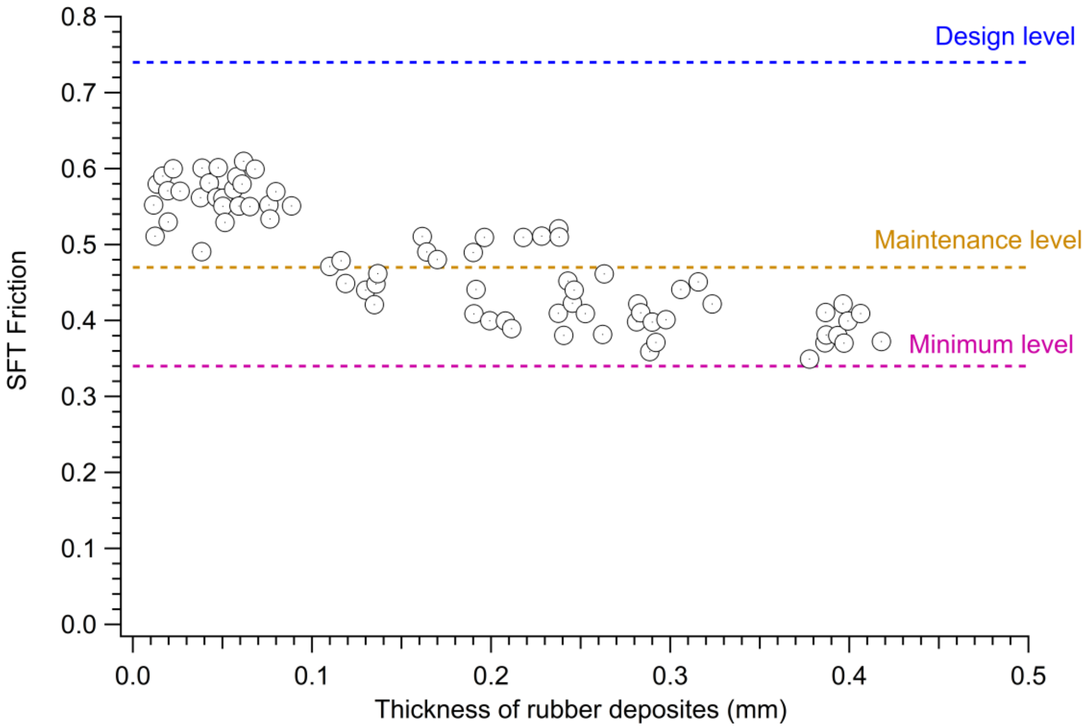
Finally there could also be a problem with the minimum friction levels provided by (see e.g. ICAO Doc 9137, 2015). In ICAO Circular 355, 2019, the following statement is given: 'Doc 9137, Part 2, Table 3-1, has not been updated and reflects levels no longer considered unconditionally valid by ICAO ("Design objective for new surface" and "Maintenance planning level"). The minimum friction levels in this table reflect historic levels for the individual friction measuring devices identified and are not adjusted according to more recent comparisons of these devices.' Simply, ICAO asserts that the minimum friction levels to which the recordings of runway friction testers are compared are no longer valid for the more recently produced devices of the same manufacturer listed in Part 2, Table 3-1 of ICAO Doc 9137, 2015. This table was (partly) developed from tests conducted at NASA's Wallops Flight Facility in 1989[††]. Many devices used in these tests are no longer in production and newer versions are available. Tests conducted during the NASA friction workshops[‡‡] showed that newer versions of a device can measure different friction levels than the older models on the same runway surface. Another issue arises from the sometimes poor repeatability of the results obtained with a friction tester. (See e.g. Figure 4-3.) The minimum friction levels provided by ICAO do not account for such issues. At present ICAO has withdrawn the table with minimum friction levels for different CFMEs. EASA still provides this table awaiting alternative methods.

[**] Dissimilar materials in the dry that are subjected to contact lead to friction forces due to adhesion and hysteresis. Friction forces between similar materials are subject to a further source of force – known as cohesion.

[††] According to ICAO, the minimum friction level (MFL) of a wet runway would be at which an aircraft using maximum wheel braking only would need twice the dry braked stopping distance during landing. However, a State could also define what minimum friction level it considers acceptable before a runway is classified as slippery when wet and should publish this value in the State's Aeronautical Information Publication (AIP).

[‡‡] The first annual NASA workshop was held in 1994 at NASA Wallops Flight Facility. There were six friction devices and six texture techniques on 18 different surfaces tested. At the eleventh annual workshop in 2004 there were 14 friction vehicles, five texture and five roughness measurement devices evaluating 33 different test surfaces. A database has been developed with all collected test data and distributed to several researchers. This database was used here.

➡ **Figure 4-3** Runway Relation between SFT friction tester results and thickness of rubber deposits on a runway (source NLR, Chen, Huang, Chen, & Su, 2008)



4.2.2 British Pendulum Tester

In 1952 attempts were made to develop a pendulum machine using the principle to measure the skid-resistant properties of roads. Experiments suggested the possibility of developing a machine with a low speed of sliding for testing road surfaces, as long as the shape and size of the rubber slider were such that the contact time was sufficiently short (Giles, Sabey, & Cardew, 1962). The portable skid-resistance tester that was developed by the Road Research Laboratory to fulfil these requirements is shown in Figure 4-4. The device is known as British Pendulum Tester and is specified in an ASTM standard (ASTM E303-22, 2022). This is a dynamic tester used to measure the energy loss when a rubber slider edge is propelled over a test surface at low speeds. The surface friction is determined by the energy loss in the pendulum, which is indicated by the height of the swing of the pendulum after it passes over the surface. To make a measurement, the pendulum, with the spring-loaded rubber slider attached to its foot, is passed across a pre-wetted surface by releasing the pendulum from a catch, which holds it in the horizontal position. A skid number known as the British Pendulum Number (BPN) is then read from the scale. This test method provides an indirect measure of the micro texture of hard surfaces as the tests are conducted at low speeds. More details on operating the British Pendulum Tester are found in the manual written by the Road Research Laboratory (TRRL, 1969). The disadvantages of the British Pendulum Tester method are that the results are not always generally reproducible, and they are subject to operator errors. Another issue arises from the initial setup of the Pendulum Tester. For each test the device must be setup correctly, which can introduce errors when not done properly. When properly used, the precision of test results is ±3 BPN (Works Central Laboratories, 1997). However, the same study found that British Pendulum Tester results can be affected when the surface is finished with large pieces of aggregate. The apparatus then responds inappropriately; the results may then vary by ±10 BPN (Works Central Laboratories, 1997). Runways are rarely finished with such aggregates.

Figure 4-4 Example of a British Pendulum Tester (Source: NLR)

From measurements made at skidding accident sites involving automobiles and motorcycles, the Road Research Laboratory has drawn up a table as a guide to the values of 'skid-resistance' required for different road layouts and traffic conditions (Giles, Sabey, & Cardew, 1962). This gives an indication of when a wet road surface may be classified as slippery. For runway surfaces such a table has not been developed.

Airport operators are not known to use the British Pendulum Tester. Neither the FAA and EASA, nor ICAO require its use by airports to monitor runways. Although the device has been used extensively during the runway friction workshops organised by NASA, operators have not recorded surface temperatures, hence analysis of such data is not possible.

4.2.3 Aeroplane derived friction

Using aeroplanes as sensors to estimate the runway braking friction level has recently become available as a commercial tool (AIRBUS, 2020), (US7797095, 2010), (Lopez Fernandez, 2022). The fundamental principle of the technology is to use data recorded in the aeroplane during its deceleration roll in landing to identify the wheel-braking forces. By using an aeroplane performance model, it is possible to differentiate the individual contributions to the total deceleration which arise from either aerodynamic forces, thrust reverse, or wheel-braking. Subsequently, the wheel-braking friction levels can be derived (post-landing). These braking friction levels can be compared to those assumed for different runway conditions in the Global Reporting Format (GRF) matrix RWYCC as set out in ICAO Annex 14, 2022. This new technology is already used by several airline operators in the world.

The technology has some drawbacks, such as the following.

- To obtain meaningful results the applied braking pressure to the main gear wheels should be such that a friction limited condition has occurred. This will often either not be the case or be experienced only for short periods of time, hence for only parts of the runway.
- Results can only be obtained for aeroplanes equipped with the required data recording or processing systems.
- The approach cannot account for the wetness of the runway surface. Although for performance analysis any runway surface that is wet up to 3 mm of water is relevant, higher water depths may have a different influence on wheel braking friction. Also, any drag force on the wheels arising from higher water depths and water spray impacting the airframe is not accounted for in the technology.
- The system needs rainfall conditions that are sufficient to wet the runway. During long periods of no rainfall, runway condition data are not collected. However, the runway surface could well be worn so that, when wet, it could be very slippery.
- During normal landing an aeroplane does not always use the full length of the runway and could therefore miss area's that are slippery wet.

As more aeroplanes are equipped with the technology, more data are collected which could aid the larger, busy aerodromes in identifying when wet runways become slippery. For smaller aerodromes, with less frequent landings, it usefulness could be limited as it could take too much time to collect sufficient data. Meanwhile the runway surface texture can change due to wear or weather influences.

4.3 Indirect measurement methods

Relevant literature that describes the methods to assess the surface texture have been reviewed. It was noted during the search that much of the literature published is a repetition of previous work done. These publications have been omitted from the survey unless they provided new insights.

4.3.1 Visual and tactile assessment

A simple method to assess the runway surface texture is by visual inspection or by touching the surface. This method is specified by ICAO (ICAO (PANS) - Aerodromes (Doc 9981), 2020), which states the following.

- Visual assessment will only give a very crude assessment of the macro texture. Extensive rubber build-up can be identified.
- Visual assessment will give a very crude assessment of the micro texture and to what degree it has been filled and covered by rubber.
- Assessment by touch can differentiate between degree of loss of macro texture but can not quantify this difference.
- Assessment by touch can identify if micro texture has been filled in/covered by rubber build-up.

Although rubber deposits are easily spotted in the touchdown zone, the build-up of rubber also occurs further down the runway; usually this is not visible to the naked eye. This can still have a significant impact on wet runway braking friction (van Es, 2021b). Visual inspections or touching the surface is very subjective and sub-standard surfaces cannot be identified this way. It is therefore very difficult to identify a slippery wet condition by visually inspecting or touching the surface.

4.3.2 Volumetric measurement

There are a variety of techniques for assessing pavement texture of which volumetric and non-contact measurements are the most common.

In volumetric types of tests, a known volume of test material is uniformly spread on the pavement in such a manner that the surface voids or texture are filled with just the asperity tips flush with the surface. The ratio of volume to area yields the average macro texture depth.

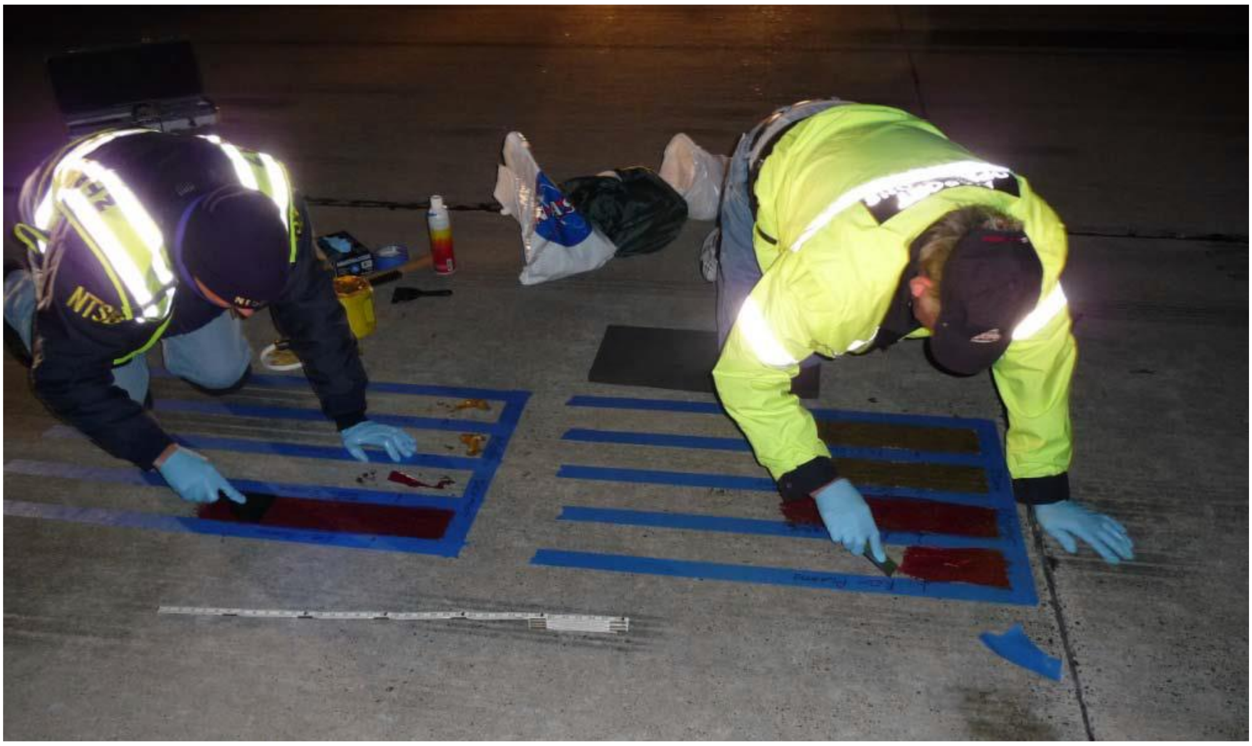
Three types of volumetric measurements are commonly used: grease smear, see Figure 4-5, the silicone putty test, and the sand patch test. A detailed description of these techniques is provided by Yager & Buhlmann, 1982. Tests conducted by NASA on different runway surfaces showed that all three methods gave very different results on the same runway surface (Yager & Buhlmann, 1982). The sand patch method is described in an ASTM standard (ASTM E965-15, 2019). Volumetric measurements are predominantly used as a technique to assess macro texture. These tests provide no information on the micro texture characteristics. Different regulatory bodies have published documents related to the assessment of runway surface macro texture and have defined minimum values. In particular ICAO and FAA have published information related to the runway surface macro texture. ICAO Annex 14, Volume I, (ICAO Annex 14, 2022) recommends that the average surface macro texture depth of a new surface be not less than 1 mm to provide good friction. FAA AC 150/5320-12C (AC 150/5320-12C, 1997) recommends a slightly higher texture depth of 1.14 mm. ICAO does not specify minimum macro texture depths for in-use runways. FAA AC 150/5320-12C (AC 150/5320-12C, 1997), on the other hand, recommends that the airport operator should initiate plans to correct the pavement when the average macro texture depth is below 0.76 mm, but above 0.40 mm. When the average texture depth measurement falls below 0.25 mm, the airport operator should correct the pavement texture deficiency within 2 months according to FAA AC 150/5320-12C (AC 150/5320-12C, 1997). Such detailed inspection specifications for the macro texture depth are not available for the micro texture. Both FAA and ICAO do not relate the macro texture depth directly to a slippery wet runway condition.

Sugg and others have stated that volumetric measurements have often shown poor repeatability (Sugg, 1979). Additionally, large differences in results between different operators are possible. Sugg also clearly showed that using macro texture as a single factor to identify runway friction is unsuitable. The lack of consideration of the micro texture is mentioned by Sugg as a reason for this. However, very low macro textured wet runway surfaces can experience low friction at high speeds. These surfaces could then be slippery wet. Following FAA AC 150/5320-12C (AC 150/5320-12C, 1997), a macro texture depth below 0.25 mm could be classified as a slippery wet runway surface even if this surface has a sharp micro texture. However, runways surface having a high average macro texture depth, on the other hand, could still be slippery wet due to a smooth micro texture of the surface. Therefore, using runway surface macro texture as a single factor to assess the slipperiness of a runway cannot always be used.

4.3.3 Non-contact measurements

Several non-contact methods to assess surface texture have been developed. All these methods use some form of mapping the surface using light sources or image capturing. A big advantage over the volumetric measurements is that these methods are more consistent and often more precise.

Figure 4-5 Example of conducting grease test (Source: NTSB)



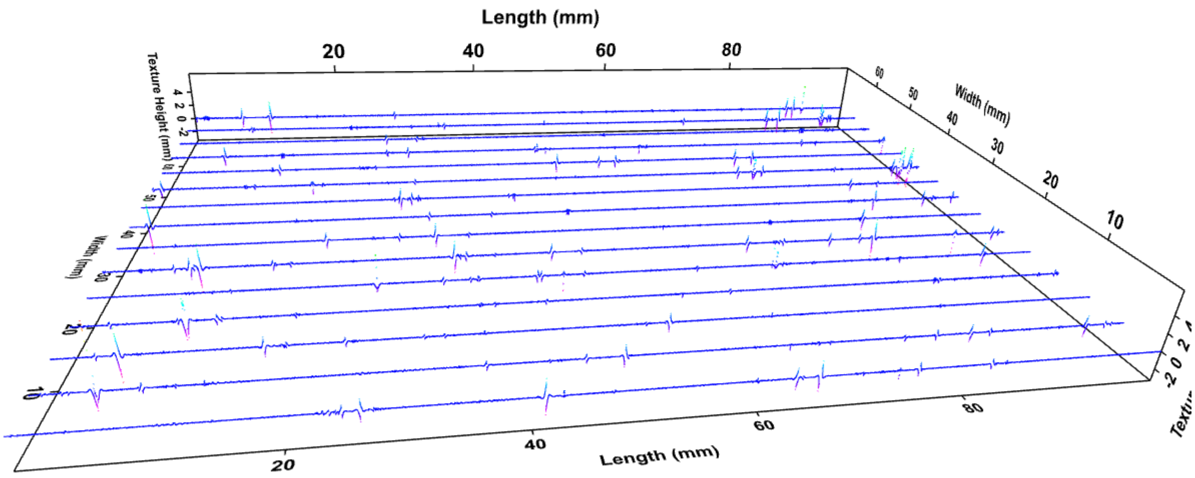
ISO 13473-1:2019, 2019 describes a test method for non-contact measurements using profilometers to determine the average depth of pavement surface macro texture by measuring the profile of a surface and calculating the texture depth from this profile. Modern profilometers in use are almost entirely of the contactless type (e.g. laser, light slit or light sheet, to mention a few) and ISO 13473-1:2019, 2019 is primarily intended for this type.

4.3.4 2D laser surface scanners

Laser surface scanners are the most commonly used profilometers. Several of these devices are commercially available. The majority of them are capable only of scanning the higher wavelengths associated with the macro texture of the surface. A few are also capable of scanning the lower wavelengths representative of the micro texture. The scanners typically scan multiple lines over a fixed area. (See, for example, Figure 4-6.)

Most profilometers, like volumetric measurement devices, can only determine the macro texture depth of a surface, which is not sufficient to assess the potential slipperiness under wet conditions. Devices that can scan at lower wavelengths to assess the micro texture characteristics are therefore of more interest. In 1986 the feasibility of measuring road surface micro texture by means of laser techniques was explored by the Swedish VTI (Samuels, 1986). Measurements were conducted by VTI on both known square wave and sawtooth wave surfaces and on a range of typical Swedish road surfaces. It was concluded, particularly on the basis of an analysis of the frequency spectral data, that the feasibility of the technique was demonstrated. Due to the continuous progress made in sensors, laser devices with higher resolution and sampling rate are now available. Recently, studies have been conducted into using high resolution surface laser scanners to assess both macro and micro texture characteristics. These lasers use triangulation to measure distance. A laser spot is projected onto the surface and its reflection from the surface is focused onto an optical detector. The height of the surface can then be calculated. Some of the more important studies on the use of laser scanners are discussed next.

Figure 4-6 Example of line scans made by a laser surface scanner (Source: NLR)



A number of significant studies were conducted by the Department of Civil, Architectural and Environmental Engineering, of the University of Texas at Austin Zuniga-Garcia & Prozzi, 2019), (Zuniga-Garcia & Prozzi, 2016), (Kouchaki, 2019), (Zuniga-Garcia, 2017), (Dong, Prozzi, & Fujian, 2019), (Serigos, Buddhavarapu, Gorman, Hong, & Prozzi, 2016). In these studies, a Line Laser Scanner was implemented to make an improved characterisation of the road texture, which included macro and micro texture description using different texture parameters. Different high resolution laser devices were used, including commercially available systems and laboratory setups. A Fourier Transform (FT) was used to convert the signal/data (texture profiles) from the space domain to the texture frequency (or wavelength) domain and to analyse the separate effect of each texture component. The researchers were successful in separating the measured line scans into a macro texture and micro texture component. A correlation could be established between British Pendulum Tester data[§§] and micro texture parameters derived from the line laser scans. All tests were conducted using a static setup in which the laser moved at very low speed along a fixed line. This meant that measurements could only be made at selected spots on a road or runway. Nowadays, equipment is available to measure macro texture at higher speeds allowing an assessment of larger sections of a road or runway surface in less time. The University of Texas research team is working on the measurement of micro texture at highway speeds. However, no results have been published yet. Measuring the micro texture characteristics while moving the scanning device at relatively high speeds puts significant requirements on the required laser frequencies. The sampling frequency of the laser should meet the requirement by the Nyquist sampling theorem, which means that the sampling frequency should be at least twice the highest frequency contained in the signal to avoid aliasing (ASTM STP1555, 2012). The studies conducted by the University of Texas did not look at slippery wet conditions, nor did they try to identify thresholds for the micro texture parameters. The collected data were used to derived empirical models to predict friction through improved surface texture characterisation.

[§§] Because the slip speed of the British Pendulum Tester is very low, the measured British Pendulum Number is mainly dependent on micro texture and therefore the BPN is often used as a surrogate for micro texture. However, macro texture can also have some influence on the British Pendulum Number.

Similar to the studies conducted by the University of Texas described above, other researchers studied the use of high resolution surface laser scanners to assess the surface texture in greater detail (Li, Yang, Wang, Zhan, & Wang, 2017), (Florková & L'ubomír Pepucha, 2017), (Kováč, Brna, & Decký, 2021), (Mahboob Kanaf, Kuosmanen, Pellinen, & Tuononen, 2015), (Dengab, Zhanab, Liuab, Qiuab, & Zhang, 2021), (Do, Zahouani, & Vargiolu, 2000), (Li, Noureldin, & Zhu, 2010). In most of these studies correlations were sought between the surface texture characterisation and some measured friction parameter. Comparable to the Texas University studies, these researchers applied similar techniques in analysing the scanned surface, such as power spectrum analysis and advanced filtering techniques, such as Butterworth's high-pass and low-pass filters, were applied to separate macro and micro texture components from the scanned surface profile. The surface texture characterisation results obtained with high resolution laser scanners were related to the slipperiness of roads or runways in any of these identified studies, including those conducted by the University of Texas.

In 2018, the National Aerospace Center (NLR) started testing a high resolution surface laser scanner to explore the possibility of assessing runway micro texture (van Es & van der Geest, 2019), (van Es, 2021a). The NLR studies explored the potential of using these high resolution scanners to determine the micro texture characteristics of runway surfaces. Algorithms were developed to separate both macro and micro texture from the traces. (See Figure 4-7.) Scans with the high resolution laser scanner were conducted on several (runway) surfaces and compared with a micro texture sharpness parameter derived from British Pendulum Tester tests on the same test spot. This statistic was developed by ESDU (Ballkwill, 2013). The statistic is explained as follows. Assume that the protrusions in the micro texture are triangular with the vertex upward. It may be supposed that a parameter is related in some way to the angle of that vertex. When the micro texture is completely smooth then the angle of the vertex is π radians. When the micro texture tends towards complete sharpness, then the angle of the vertex tends to zero. It is therefore asserted that the range of the parameter F_1 is such that $0 \leq F_1 \leq \pi$. This is in line with the analysis done by Sabey, 1958 and Moore, 1969. Different micro texture parameters derived from the laser scanner data were considered based on the work done by Forster, 1981. Most of them show a good correlation with the micro texture sharpness parameter. (See, for example, Figure 4-8.) It was concluded by the researchers that a high resolution laser surface scanner could be useful as a tool to assess runway micro texture characteristics. Some limited results obtained with full scale aircraft tests on wet runways were also analysed.

4.3.5 Image analysis

Image analysis has been used to assess the texture characteristics of surfaces. A number of important studies on this topic are reviewed next.

One of the more fundamental studies into the assessment of micro texture was conducted by Forster of the US Federal Highway Administration (Forster, 1989). This study was conducted to investigate the quantitative role played by micro texture in determining the skid resistance of a pavement. Specific objectives were to improve understanding of the micro texture's influence on skid resistance and to determine if optimal dimensions of micro texture exist that should be sought when designing a pavement or selecting aggregate materials. Measurements of micro texture profiles were obtained on a series of pavement cores using a non-contact image analysis system in the laboratory. This image analysis system used for micro texture measurements could only be used in a laboratory due to its size. It was also very time-consuming. (See Figure 4-9.) Correlations were determined between these measurements and British Pendulum Tester numbers obtained on the same cores. These friction measurements believed to be closely related to micro texture. Correlation coefficients of up to 0.70 were attained by Forster. Two micro texture parameters were measured directly, and a third is derived from these two in Forster's study. The average asperity (peak) height is defined as the sum of the vertical heights (above the "valley" immediately to the right of each asperity) of all asperities divided by the total number of asperities. The average asperity density is the total number of asperities divided by the profile length. The average shape factor, is calculated by multiplying the asperity height by the asperity density. The study found that this shape factor characterises the micro texture of pavement samples better than the other two parameters. Critical values of the shape factor that would identify a slippery wet condition were not identified nor sought in the study.

Figure 4-7 Example of separating raw laser trace in micro and macro texture parts (Source: NLR)

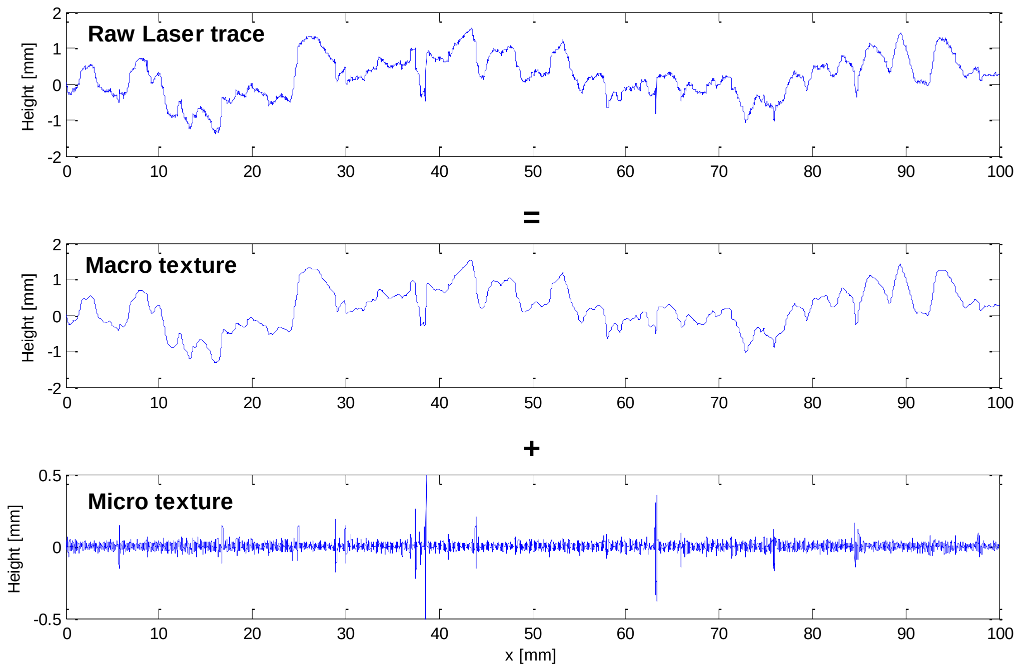


Figure 4-8 Correlation between power spectral micro texture depth and micro texture sharpness (source: NLR)

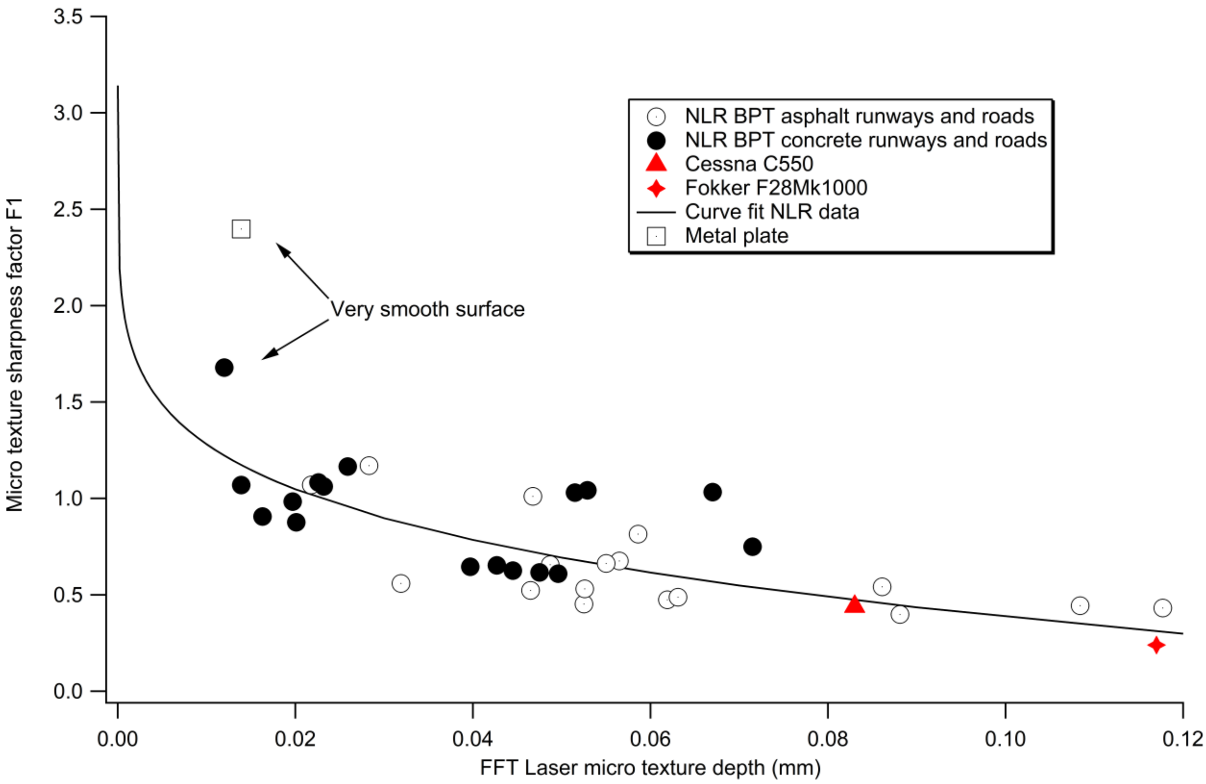
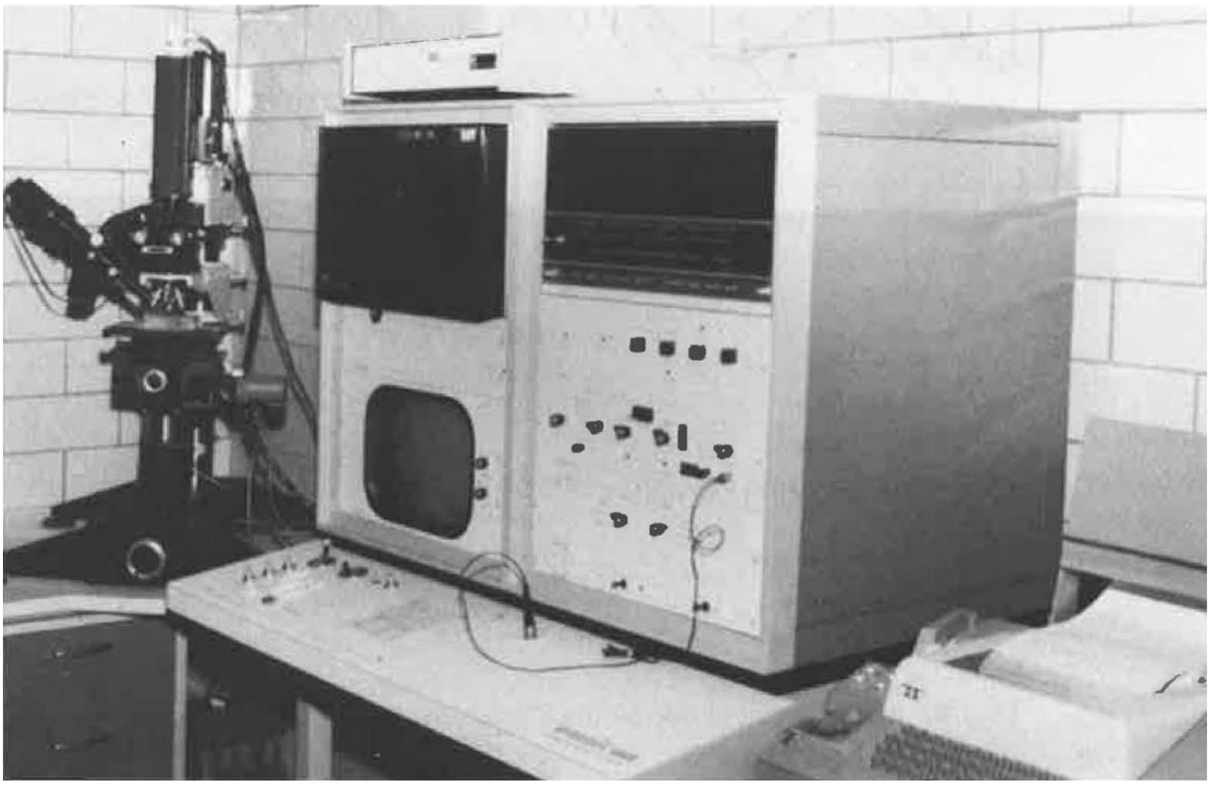


Figure 4-9 Image analysis system used for micro texture measurements by Forster, 1989



Another relevant study into image analysis was conducted by Schonfeld, 1974. The pavement surface texture classification method developed by Schonfeld is based on the concept that the pavement surface is a geometrical structure which can be expressed by six parameters: height, width, angularity, distribution, harshness of projections above the matrix from which they arise and harshness of the matrix itself. A 35-mm single-lens reflex camera with a focal length of 55 mm was used for taking pairs of stereophotographs of various hard surfaces. Pavement stereophotographs were viewed under a mirror-stereoscope or under a microstereoscope. The stereophotographic method is a comprehensive procedure. The parameters developed by Schonfeld related well with wet skid trailer test results. However the method is somewhat subjective and time consuming. The stereophotographic equipment used was described in ASTM Standard Test Method E770-80 (ASTM E770, 1985). This publication has been withdrawn. In 1976, a study conducted by the University of Edinburgh (Forde, Birse, & Fraser, 1976) compared British Pendulum Tester-based skid resistance evaluation with Schonfeld's photogrammetric procedure. The correlation between the two methods was low. However, the study concluded that the British Pendulum Tester on surfaces of irregular profile was unreliable which could explain the low correlation. The researchers claimed that Schonfeld's photogrammetric method has many practical and philosophical advantages over other methods of skid resistance evaluation.

In recent years numerous studies have been conducted that looked at more advanced image analysis of road surfaces to determine texture characteristics like the micro texture. The increase in computing power and more advanced digital systems have contributed to these developments. Examples include the photometric stereo techniques, 3D photogrammetry and 3D laser techniques (Labbate, 2001), (Slimane, Khoudeir, Brochard, & Do, 2005), (Lei, Chu, & Wang, 2009), (Ueckermanna, Wanga, Oesera, & Steinauera, 2014), (Chen, Xiong, Li, & Zhang), (Sarsam & Al-Shareef, 2015), (Jain, Venkatesh, & Das, 2022), (Jain, Das & Venkatesh, 2021), (Danzl, Helmli, & S., 2011), (Millar, 2013a), (Millar, 2013b) using microscopes and high-resolution cameras. Some of the research is more theoretical. The researchers are often focused on just experimenting with the new technologies rather than relating the results to slippery surfaces or finding practical techniques to be used on roads or runways. A big challenge is to find a balance between the scanned area and the resolution. Often only a very small area can be scanned at a resolution that is high enough to assess the micro texture. This would be a limitation for applying these techniques to actual road and runway surfaces.

4.4 Miscellaneous testing methods

4.4.1 Chalk wear test

In 1979, Mr. Burk of the USAF suggested a method for evaluating the micro texture of a pavement surface known as the chalk wear test (McKeen, Lenke, & Graul, 1984). This wear device consists of a wheeled cart with a swing arm and chalk holder. The chalk holder incorporates a threaded rod to adjust the amount of exposed chalk. The apparatus is machined out of aluminium to reasonable tolerances to ensure a precise normal surcharge on the pavement. The length of exposed chalk is measured prior to testing. The chalk cart is then pushed across the test surface causing the chalk to wear. The difference in chalk length divided by the length of travel yields a chalk wear coefficient. A prototype chalk tester was developed. The tester measured the wear of a piece of chalk per unit length while traveling at low sliding speeds on a pavement. The tester is pushed by the operator at a slow and uniform pace over a clean dry pavement. The normal load on the chalk produces contact pressures and corresponding shear forces that wear the bottom edge of the chalk. Since micro texture plays an important role in pavement friction, the tester ranks pavements by abrasion due to pavement micro texture. While the tester can be used on any surface with a hardness greater than the chalk, pavements with low micro texture due to polish may be difficult to test (McKeen, Lenke, & Graul, 1984). This limits its use to identify smooth microtextured surfaces correctly. There are no records of the chalk tester device being used operationally.

4.4.2 Outflow (drainage) device

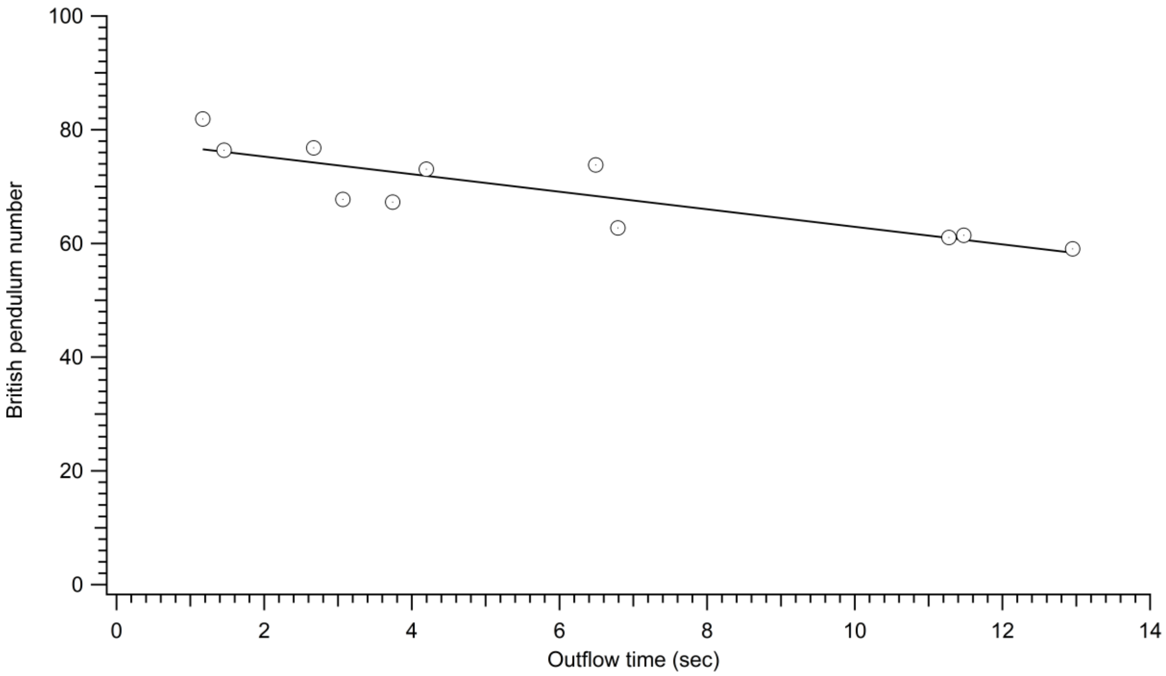
To evaluate surface texture, Moore developed a simple instrument called an outflow meter (Moore, 1966). The device measures the length of time required for a known quantity of water, under gravitational pull, to escape through voids in the pavement texture. In the use of the outflow meter, Moore developed a mathematical model to account for the effects of both macro and micro texture on outflow time. The timed outflow of water is indicative of the pavement macro and micro texture texture and porosity. The use of the outflow device has been standardised by the ASTM (ASTM E2380-05, 2005). An example of the outflow meter is shown in Figure 4-10.

The ASTM standard for the outflow device states that faster escape time indicates a thinner film of water may exist between the tyre and the pavement, thus more micro texture could be exposed to indent the face of the tyre and more surface friction available to the tyre. However, a detailed comparison of British Pendulum Tester data with outflow data, conducted by Yager and Buhlmann, showed a poor correlation (Yager & Buhlmann, 1982). This is attributed to the fact that surface micro texture has a greater influence on British Pendulum Tester results than does the combined effect of macro and micro texture as measured by outflow drainage time (Yager & Buhlmann, 1982). Unpublished test results obtained during the NASA runway friction workshops[***] showed that a correlation existed between British Pendulum Tester data with outflow data as shown in Figure 4-11. However, there is also an effect of the surface macro texture in this correlation. The surfaces tested during the NASA runway friction workshops with low British Pendulum Numbers also had a low macro texture depth. This clearly has an influence on the correlation as the outflow time increases on lowered macro-textured surfaces.

➨ **Figure 4-10** Water outflow meter (Source: NTSB)

[***] The first annual NASA workshop was held in 1994 at the NASA Wallops Flight Facility. There were six friction devices and six texture techniques on 18 different surfaces tested. At the eleventh annual workshop in 2004 there were 14 friction vehicles, five texture and five roughness measurement devices evaluating 33 different test surfaces. A database has been developed with all collected test data and distributed to several researchers. This database was used here.

➨ **Figure 4-11** Correlation between British pendulum test data (averaged values) with outflow data obtained during the NASA runway friction workshops (source NLR, NASA)



The separation of the effects of macro and micro texture from the outflow time test data is practically impossible. As both can have an influence on the measured outflow time, however, test data suggest that the macro texture dominates the outflow time. This is also confirmed by NASA specialists who derived empirical correlations between pavement macro texture measurements collected with the NASA grease tests and water outflow meter time (NTSB, 2012) irrespective of micro texture characteristics.

Thresholds to identify a slippery wet runway surface have not been defined for the outflow device, making the device not practical currently to identify such conditions. This is reflected by a comment made in the ASTM standard (ASTM E2380-05, 2005) that the outflow times measured are an indication only, and are not meant to provide a complete assessment of the pavement surface friction, or wet weather safety characteristics.

4.4.3 Stylus tracers

Stylus tracers are generally used to measure uniform textures on surfaces such as those found on finished metallic parts or floor tiles. In the 1970s the assessment of micro texture using such devices was explored with some limited success by the Texas Highway Department (Gallaway & Tomita, 1970). Correlations with the skid numbers obtained with a locked-wheel trailer at 40 mph were not high. However, it is questionable if this skid number is representative for micro texture. The researchers did not use a British Pendulum Tester which gives a better indication of the micro texture features of a surface. The researchers stated that the stylus tracer used in the study was built primarily to measure textures of uniform surfaces such as machined, ground, or sanded metallic parts. As such, the researchers found that the instrument has some undesirable features for measuring micro textures of pavement surfaces including the sensitivity to speed of tracing or of stylus movement, and the readings displayed on a dial gauge. The possible effects of these characteristics result in fluctuating readings and in obtaining unrealistic measures of micro textures.

The UK Health and Safety Laboratory conducted tests with a modern high-end stylus tracer and correlated the results with pendulum tests on natural and manmade stone flooring materials (Loo-Morrey, 2007). A favourable correlation was found between micro texture roughness parameters measured by the stylus tracer and the pendulum test data. The UK study also identified some thresholds for slippery conditions.

The sample length of a typical portable stylus tracer instrument is not more than 2-5 mm, which makes its use on non-uniform runway surface textures difficult. Also the application on macro-textured surfaces could be problematic due to the sensitivity to speed of the tracing or stylus movement.

4.5 Conclusions

Numerous techniques for assessing the friction of a hard surface like a road or runway have been reviewed. Some of these techniques have been used for many years, whilst others are still being developed. The classical method for assessing the slipperiness of wet runways is to compare results obtained with runway friction testers to defined thresholds provided by ICAO. Several overrun occurrences on wet runways have shown that this method does not always provide valid results. More recently, ICAO has indicated that the defined thresholds for the different runway friction testers are no longer applicable. Macro texture is an important parameter that contributes to runway friction. ICAO and FAA have defined thresholds for the macro texture depth. The macro texture depth can be measured using volumetric methods and profilometers. The profilometers give more consistent results than the volumetric methods. The macro texture cannot be used as a single parameter to identify a slippery runway unless it is very low. Micro texture needs to be taken into account and is generally the leading parameter in slippery wet runways. Several techniques have been developed to assess the micro texture characteristics of hard surfaces. The oldest micro texture measuring device is the British Pendulum Tester. It is assumed by researchers that this device provides an indication of the micro texture characteristics. The device is both simple to use and affordable. However, results obtained with the device can vary depending on the manner in which it is used and the accuracy of its calibration. A very promising technique to assess micro texture is based on a scan of the surface at the wavelength of the micro texture. High resolution profilometers using laser scanners have been successfully used by several researchers to identify the micro texture characteristics of road and runway surfaces. Other techniques use some form of image analysis using microscopes and high-resolution cameras. Some of these techniques are not easy to use, whilst others provide useful information only for a very small area. Using aeroplanes as sensors to estimate the runway braking friction level is a more recent method to assess the runway condition. This can help to identify slippery wet runways. However, this approach has some limitations but could be used in combination with other techniques – for example, laser scanners, to assess both macro and micro texture – to identify runways that perform poorly in wet conditions.

5. Aircraft Features

5.1 General

When defining a mathematical model for use in predicting ***operational*** data, it is customary to consider the motion of an aircraft on a paved runway in terms of three interdependent, but physically different, generators of force. Some aspects of this representation are considered in this section.

5.2 Aerodynamics and power units

Generally, the combination of aerodynamic and power units is treated as one (rigid) body; the details of the combination are usually based upon thrust/drag accounting methods similar to those described in (AGARDograph 237 MIDAP Study Group, 1979).

However, when research projects deal with test data collected at low power settings, caution must be exercised. Such settings as ground idle affect performance; it is not always possible to ensure that the setting on specific units is exactly that assumed in a brochure. Furthermore, deterioration of both engine and airframe do need to be quantified in order to avoid bias error. A method to compensate for deviations from a "fleet" model is specified in Balkwill, 2022d. If that method were to be adopted, then the deduced aerodynamic/engine model can be applied to the testing under consideration. Thus, effects of bias and imprecision can be minimised.

5.3 Tyres

Methods for calculating forces arising from the interaction of pneumatic tyres and paved runways are adapted by airframe suppliers from specifications provided by regulatory bodies. Many of these specifications are based on analyses by ESDU. Those analyses are in the process of modernisation to account for the recent research findings outlined in Section 3.

The intention that underlies the modelling scheme developed at ESDU is to produce an algebraically uncomplicated formulation for the performance of a single tyre in motion. It is emphasized that the model sought is for use in tyre performance, not for aid to tyre design. Such an intention implies the need to simplify for performance calculations. In particular, when designing a tyre, it is essential to account carefully for the rapid shape distortions that take place in the tread as the footprint moves around the circumference of the tyre. In modelling performance of a tyre, it is sufficient to suppose that the tyre is a rigid body and to account for distortions by allowing the centre of pressure in the footprint to migrate under the influence of speed and orientation to the direction of motion.

Following modern thinking, it is supposed also, that there exists a layer of low-strength material at the interface between a hard surface and a bulk of rubber. This layer is perceived to be of molecular thickness and has mechanical properties different from, but related to, those of the "parent" rubber. It is also supposed that decelerating force consists of two independent components: adhesion and hysteresis. This is a convenient simplification that is used to aid engineering modelling. In reality, it is probable that no such simple division exists. It is more likely that there is some dependence of the one on the other.

Furthermore, knowledge of the temperature of the surface on which a rubber compound moves is essential, not only to understanding the mechanisms involved in laying down the interfacial material, but to calculating decelerating forces. That temperature is often not recorded by experimenters; such an omission leads to difficulties in both analysis and synthesis. In studies at ESDU, it is presumed that temperature effects are most easily accounted by using (rebound) resilience as a parameter. This quantity is inversely dependent on the phase angle between stress and strain. It is to be noted that stress and strain are always in phase for elastic materials; for visco-elastic materials, strain lags stress. In the case of the interface membrane between a rubber and a hard surface, the phase difference depends on both temperature and bearing pressure.

The engineering nature of the ESDU approach cannot be over-emphasised. So, although attempts are made to minimise reliance on solely empirical relations, the physics and chemistry of the interactions involved are so complex that account is taken of only the most elementary aspects of such studies.

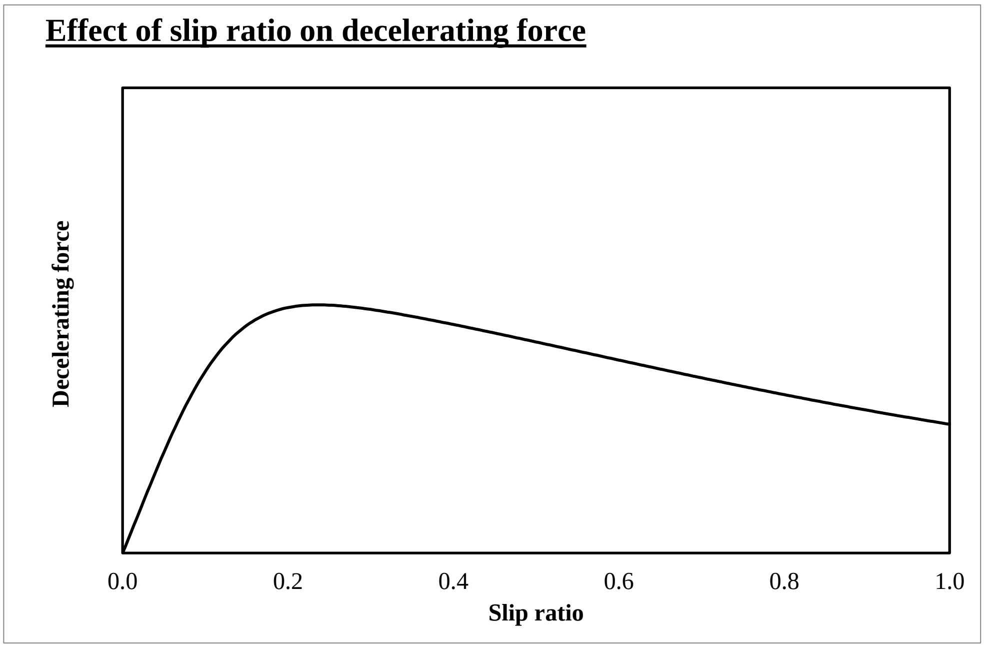
A much more detailed summary is given in Balkwill, 2022a.

5.4 Braking system

Braking systems designed for both military and (large) civil transport aircraft, are based on the control of slip ratio††† using a variety of means. In principle, decelerating force due to braking a pneumatic tyre is a function of

- Applied braking torque
- Angular velocity of braked wheel
- Angular acceleration of braked wheel
- Translation speed
- Inflation pressure
- Surface drainage and
- Surface sharpness (roughness)

Figure 5-1 Effect of slip ratio on decelerating force (typical)



††† Slip ratio is related to the angular velocity of a partially braked wheel and translation speed over a surface.

Figure 5-1 shows a typical variation of decelerating force with slip ratio. That force reaches a maximum at a slip ratio close to 0.2. Design of modern braking systems is therefor based on maintaining a slip ratio close to that value for all conditions likely to be encountered in operations.

It is not always possible to use design details to describe performance of any particular system. It is therefore common practice to use test results to identify either a braking efficienciency, or (better) an effective slip ratio that may be a function of speed and loading.

6. Slippery Wet

It is a commonplace that braking action deteriorates when runways are at all wet. In some cases, such a loss in braking action can be catastrophic; in other situations, the loss is barely more than an inconvenience. Finding ways and means to define the boundary between inconvenience and catastrophe has been the subject of research for decades. No satisfactory quantitative solution has been found.

A slippery wet runway is defined as a wet runway where the surface friction characteristics on a significant portion of the runway have been determined to be degraded (AMC 25.1591, 2021). EASA GM1 41 (a) – *Slippery wet runway* (GM1 41 (a), 2022) states that a portion of runway in the order of 100 m long may be considered significant. A slippery wet surface corresponds to a RWYCC of 3 in the RCAM (AMC1 ADR.OPS.B.037(a), 2022).

In 1981, the Air Navigation Commission agreed that the ICAO Secretariat should re-examine the criteria for the development of equipment for determining the friction characteristics of wet runways. Initially a maintenance level and, later, a minimum friction level was introduced. A link to the operational aspect was sought through an aeroplane stopping distance ratio between wet and dry of *two* (with maximum braking, no reverse thrust, normal landing configuration) and the introduction of the term "slippery wet".

A runway surface with a smooth micro texture can produce slippery wet conditions, hence a method of defining a level of micro texture that will result in a slippery wet runway surface would prove invaluable.

Research (Balkwill 2013) identified a statistic that showed promise in quantifying a feature of the micro texture, which is described as the micro texture sharpness parameter (F_1). Further studies (van Es 2019), (Balkwill 2022, b, c) using a British Pendulum to deduce F_1, have shown that there is promise of establishing a firm relationship between F_1 and aspects of the output from one type of laser scanning device.

When that promise is fulfilled, it is expected that a viable demarcation between runways will be possible by using readings from one or other of those devices. Slippery wet runways can then be distinguished from wet runways that are merely difficult, but not slippery.

7. Concluding Remarks

A review of current methods used to determine current runway friction characteristics has shown that the techniques currently used by aerodromes do not evaluate the runway micro texture, a key factor in the development of a slippery wet runway surface.

CFMEs have been used traditionally to identify a slippery wet runway. However, it has become clear that such devices have significant limitations in doing this correctly.

Automatic analysis of measurements taken during operational flights can provide insights in the actual braking friction levels that aeroplanes can achieve. This can be used to indentify a slippery wet runway condition. However, this technology has some drawbacks and is not always able to such runway conditions in time.

ESDU has developed a parameter for quantifying runway micro texture. Preliminary studies by NLR have shown that there is promise in establishing a firm relationship between this and aspects of the output from laser scanning devices.

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