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in

CONTEXT SENSITIVE DESIGN IN TRANSPORTATION INFRASTRUCTURES

A CLASSIFICATION OF ASPHALT SURFACING TEXTURES BASED ON 3D IMAGERY

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INDEX

INTRODUCTION

Analysing many years of research it becomes apparent that “texture”, both that of the road surface and that of tyres, and the way that they combine in the contact patch, is the most important broad factor which needs to be understood for optimising tyres and road surfaces. This factor, on all its scales, influences the interaction between tyre and road to develop friction; it plays a significant role in noise generation or attenuation and, potentially in tyre rolling resistance.

There are also other aspects of road surfaces and tyres, such as the impacts that construction techniques might have on the surface properties that show gaps in current knowledge.

In many areas, the knowledge gaps are associated with inadequate or inconsistent measurement techniques. For example, our understanding of texture and its influence is limited by what can currently be measured and the ability to measure characteristics. For this reason other methods of analysis are required and so it’s useful to consider the problem in three dimensions rather than two. It would enable different or new parameters to be defined that would better predict or explain behaviour. The problem of measurement limitations restricting understanding also applies to surface construction characteristics such as interconnected voids, which may influence noise, water dispersal in the skid resistance context and the durability of performance.

Lack of well-defined measurement techniques is also a serious limitation of understanding the rolling resistance of tyres, especially on real road surfaces. Similarly, differences in ways of assessing passenger-car and truck tyres and their performance are not always well understood.

Over the years there has been a great deal of research relating to the optimization of skid resistance, rolling resistance and noise emissions, and work in this area is continuing. However, the research typically is driven by the different perspectives and interests of various involved groups: the road construction industry, the tyre manufacturing industry, road users and road agencies. Consequently, in individual research projects, optimization has tended to be focused on either road surfaces or tyres but seldom on both. The optimisation of road surfaces was not really affected by the optimisation of tyres and vice versa. Road surfaces are always tested with specified test methods for the individual properties; tyres are tested on specified surfaces (particularly in accordance with ISO10844).

Therefore, road surfaces are designed to perform optimally in relation to the specific test methods and tyres are optimised to perform on their specified test surfaces.

In practice, interaction between roads and tyres and the factors that affect them are influenced in their turn by road geometry, general traffic levels and the speeds and loads of vehicles.

However, some environmental factors, such as particulates and seasonal effects, have specific impacts on the three surface properties that are also associated with knowledge gaps requiring research to fill them and these are shown in the next chapters.

Currently, texture is measured in one of two basic ways. One of these, the historic approach, is to use a volumetric technique to fill the voids in the surface to provide an estimate of the space available in the texture (the texture depth) which, it is thought, has a primary function of draining water from the tyre/road interface. However, a limitation of this technique is that it does not access all the voids in the surface from this perspective and says little about the smaller component of texture near to the surface that actually makes contact and interacts with tyres.

Over the last 25 years there has been a trend towards measurement of a two-dimensional surface profile of the road surfaces, typically using lasers. However, this technique requires algorithms to convert the discreet height measurements in the profile into parameters to represent the texture and these are proving inadequate to enable researchers and engineers to properly understand the texture. It may be much more helpful not only to improve the profile measurement technique but to extend it to make laminar texture measurements of road surfaces provided that this can be done with the necessary resolution and acceptable speed.

This would allow the different texture wavelengths, texture depth, texture form and their relationships with the three surface properties to be assessed.

Potentially, microtexture, which currently is not measured directly at all, could also be included. The contact patch of the tyre on the surface, and therefore the interaction of the tyre with the surface occurs in three dimensions, not only one line (2D). A 3D approach to measurement and assessment of road surface texture could lead not only to an improved measuring technique but would also follow on to the development and assessment of new parameters to represent aspects of texture that cannot be suggested at the moment because they cannot be measured adequately, if at all.

How tyres respond to the road surface texture is also a significant knowledge gap; it is likely that many other factors could be involved here which currently are not known or well understood. These might include size of the contact patch, localised pressures due to different road surface textures or tyre characteristics and the way the tyre shapes itself to the surface, specific tyre characteristics, vehicle size and mass. Such factors, deriving from both road surfaces and tyres, may have different influences in relation to the three properties which could then be complicated further when differences between wet and dry conditions are taken into account. [1]

In this thesis has been considered how the interaction of a tyre and an asphalt surfacing may be investigated in the laboratory to assess a range of properties ranging from aggregate and mix type, grip, texture, noise and rolling resistance.

The interactive properties of any vehicle / tyre / road surfacing combination are constantly changing. The holistic relationship between the many different variables is extremely difficult to model and predict. With unlimited funding and time the interaction between vehicles and the different types of asphalt road surface could be assessed over many years using full scale road trials. However, this ideal is now totally unrealistic.

Laboratory based research needs to relate to observable and measureable performance in the field. Whilst there is a need for the fundamental approach, improved understanding needs to be based on accelerated simulated conditions to provide meaningful data, something that most standardised test methods cannot do as they do not adequately consider how materials and properties change with time. This thesis describe how new types of data might be measured in the laboratory that either relates to or effects the interaction of a tyre and an asphalt surface. The measurements considered include skid resistance, interface mapping and texture.

Moreover, the use of 3D models allows much greater insight into surface textures. For example, it may generally be used to highlight areas of a surface potentially at risk due to water entrapment, and the use of software, such as ArcGIS, can help us in predicting the effect of water and of other parameters on durability of asphalt surfacing materials, better than a simple estimation of texture depth could give. [15]

CHAPTER 1:

TYRE/ROAD INTERACTION: SKID RESISTANCE AND ROAD TEXTURE

1.1 INTRODUCTION:

Acting together, roads and tyres make a vital contribution to road safety but in the process they also have an impact on the environment. The interaction between the tyre and the road surface, provides grip to allow vehicles to manoeuvre, but the same process can also give rise to rolling resistance, with a potential increase in fuel consumption and CO_2 emissions. The interactions also generate noise both in vehicles and in areas close to the road. There are also safety implications for rolling resistance and noise, although these are not related to vehicle control. Vehicle emissions and noise levels have a potential influence on the health of drivers and those living or working near major roads. If road/tyre noise is very low there might be risks to vulnerable road users such as pedestrians who might not be alerted to the approach of a vehicle. This chapter introduces the known main factors associated with road surfaces and tyres that influence skid resistance and road texture. [1]

1.2 FRICTION AND SKID RESISTANCE

Clearly, the provision of adequate grip between tyres and roads is vitally important in helping drivers to be able to travel safely, a fact recognized in the earliest days of research as motor traffic began to increase.
There are three particular situations in which the forces transmitted through the tyres are increased and so the adhesion provided needs to be adequate for a vehicle to be driven safely:

• ***Under power***, when a reaction force between the tyre and the road is needed for the vehicle to accelerate or maintain speed.

• ***In braking***, when forces are developed between the tyre and the road that react against the action of the brakes so that the vehicle slows down.

• ***While cornering***, when reaction against side forces generated in response to steering action enables the vehicle to follow around the curve.

These forces are generated as a result of friction between the tyre and the road. In normal circumstances, the contact patch, the area of the tyre in direct contact with the road, is instantaneously stationary.

However, if the forces required by the manoeuvre exceed the available friction, the contact patch will start to slide over the road surface, a condition known as “slipping”. If too much power is applied when accelerating, the powered wheels may spin freely; if the force on the brakes is too great the wheels may lock, leading to a skid; if lateral acceleration is too great when cornering, the tyre will slide sideways. If acceleration or, braking, are combined with cornering then the combined forces must be “shared” with the available friction, increasing the likelihood of grip being reduced.

Once the tyre is slipping or skidding, full control is lost. In many situations control cannot be recovered in time, if at all, and a crash of some kind is the inevitable result.

When a road surface is dry, the coefficient of friction between a tyre and the road is normally high and adequate for most vehicle manoeuvres. However when the road is wet, the tyre/road friction decreases significantly and becomes much more dependent on the properties of the road surface and the tyre. When the road is wet, friction is not only reduced but also decreases as speed increases. Importantly, sliding friction on a wet road is typically much lower than the friction available just before the tyre starts to slip. It is also important to note that a damp road may also show a marked reduction in tyre/road friction even though it may no longer be raining.

It is important to appreciate the differences between these two concepts since they are often used interchangeably and this can sometimes lead to confusion.

The following convention, widely used in the context of road surface characteristics, is therefore used to distinguish between the meanings of "friction" and "skid resistance".

Friction, in the context of tyres and roads, represents the grip developed by a particular tyre on a particular road surface at a particular time. The coefficient of friction is a measure of this, defined as the ratio of the load, the force applied in the vertical direction, to the traction, the force resisting movement in the horizontal direction.
Friction is influenced by a large number of parameters relating to the road and the tyre but it is also affected by other influences that may not be directly attributable to them, such as the vehicle suspension, ambient conditions, speed and the presence of localized contaminants (including water).

Skid resistance describes the contribution that the road makes to tyre/road friction. Essentially, it is a measurement of friction obtained under specified, standardized conditions, generally chosen to fix the values of many of the potential variable factors so that the contribution that the road provides to tyre/road friction can be isolated.
In the context of a crash, or situation that might lead to one, it is the coefficient of friction available at the time and place of the incident that matters. However, for the purposes of building and maintaining roads, it is the initial designed properties of the surfacing and, subsequently, the general condition of the road surface in service that are important. [1]

1.3 PRINCIPLES OF FRICTION GENERATION

The mechanisms of tyre/road friction are not fully understood, but it is widely recognized that there are two main mechanisms involved: molecular *adhesion* and *hysteresis losses*, and so the overall friction between tyre and road surface is the sum of these two components.

Adhesion is a surface phenomenon that occurs at the interface between the tyre tread rubber and the road, so this contribution depends on the actual contact area.

Some theories have described adhesion as a thermally activated molecular stick-slip process. During sliding between a rubber and a hard surface, the separate chains on the two surfaces attempt to link together, thus forming a local bond. Sliding causes these bonds to stretch, rupture and relax before new bonds are made. The contribution of adhesion to friction is the sum of the inter-facial shear tension between the tread rubber and the road surface by different islets on the overall contact area, which depend on surface roughness at the microscopic scale.

The hysteresis contribution comes from energy losses due to damping in the rubber bulk when this is deformed as it passes over the aggregate particles in the surface. The internal damping in the rubber opposes its own movement upstream of aggregates and its shape recovery downstream of aggregates, creating an asymmetric pressure distribution on aggregate surfaces. This contribution depends on roughness of the surface at the macro scale.

Figure 1.1 illustrates these two concepts of adhesion and hysteresis.

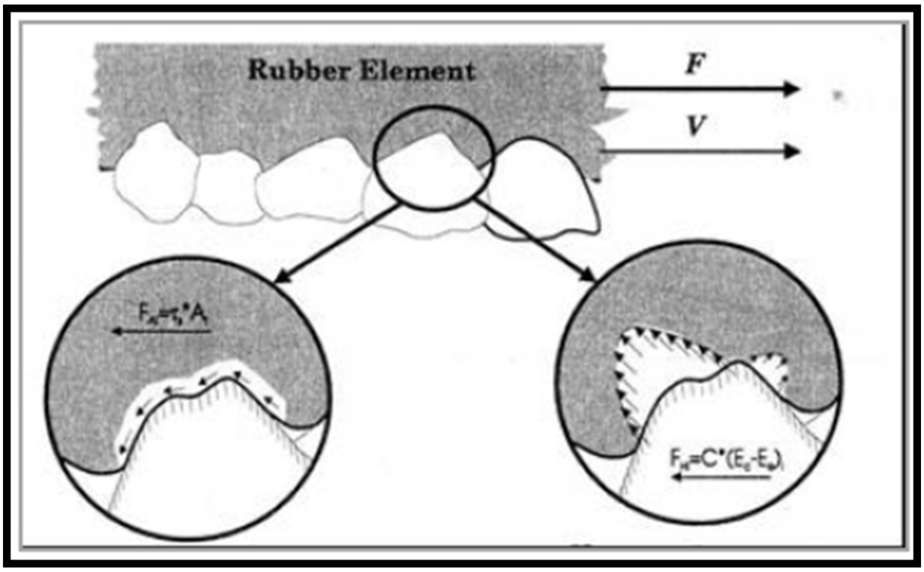


Figure 1.1 – Adhesion and Hysteresis

To be effective, the adhesion component needs close contact and thus a clean surface, while the hysteresis component needs cyclic deformation of the rubber and a rough surface. It is argued that, on rough and lubricated surfaces, the friction force derives primarily from the hysteresis contribution, whereas adhesion is dominant when rubber slips on a smooth and clean surface.

There is a slightly different interpretation by Yandell, which is based on the assumption that adhesion does not play a significant part in tyre-road friction, rather that the observed effects can be entirely explained in terms of hysteresis.

In this theory, the texture of the road surface is separated into components with different scales. Hysteresis is generated on each of these scales and the total friction is obtained from the sum of the individual contributions.

Yandell and his colleagues showed that predictions based on this analysis, together with measurements of the damping factor of the tread rubber, agree well with locked wheel and sideways force measurements on concrete and bituminous surfaces. [1]

1.3.1 LONGITUDINAL FRICTION PRINCIPLE

For a vehicle travelling in a straight line, when the driver applies the brake, a torque is applied to the vehicle wheels via the braking system. A reacting force develops in the tyre/road contact area. Provided that grip is maintained, the angular speed of the wheels decreases and the vehicle slows down as kinetic energy is absorbed in the braking system.

However, as the braking torque increases, the wheel speed may reduce below the vehicle speed and consequently the tyre slips on the road, generating friction forces in the contact area, due to adhesion and deformation processes, to slow down the vehicle.

In the extreme, the wheel may cease to rotate, known as the “locked” condition, and one area of the tyre slides or skids over the road surface. Longitudinal friction measuring devices try to simulate part of this process, typically by controlling the rate at which the wheel rotates relative to the road speed. This leads to the idea of the “slip ratio” and it is important to appreciate how the longitudinal friction coefficient varies with the slip ratio.

The tyre slip ratio G is defined by the formula:

$$G = \frac{(V - R\omega)}{V}$$

where:

ω: angular speed of the wheel;

R: wheel radius;

V: vehicle speed.

G varies between 0 and 1. For skid-resistance measuring devices, G is generally expressed as a percentage.

Thus, for G = 0%, the tyre speed is equal to the vehicle speed and the wheel is freely rotating; for G = 100%, there is no rotation and the wheel is locked.

The longitudinal friction coefficient LFC varies with the tyre slip ratio as illustrated in Figure 1.2:

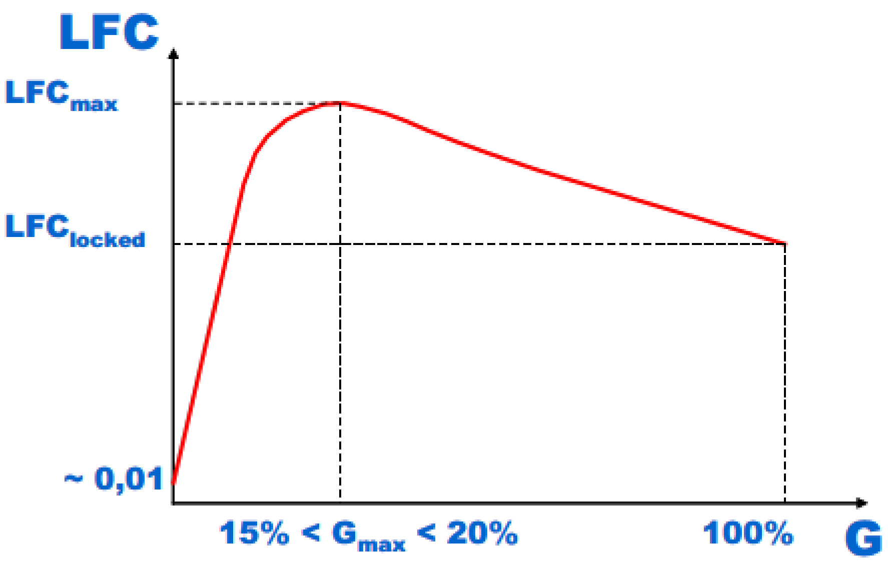


Figure 1.2 - Illustration of LFC – G curve

It can be seen that, initially, friction increases as the slip ratio increases but it reaches a maximum value before decreasing as the slip ratio continues to increase until the locked wheel state is reached.

This variation can be explained by the movement of the tyre treads in the tyre/road contact area changing from a largely shear phase to a mainly slipping phase.

The maximum value of LFC denoted by Gmax, sometimes known as “peak friction”, typically occurs at a slip ratio between 15% and 20%. [2]

1.3.2 TRANSVERSE FRICTION PRINCIPLE

In a bend, the driver uses the steering system to turn the vehicle’s front-wheels so that there is a difference between the vehicle direction and the wheel rotation-plane.

The induced angular difference is known as the slip angle. It induces tyre/road friction, which in turn generates a centripetal force opposing the centrifugal force exerted on the vehicle in the bend, allowing the vehicle to follow round the curve. Just as with longitudinal friction, when as the braking force increases the wheel starts to slip over the road surface, so in the transverse friction situation if the centrifugal force exceeds the friction force available, the tyre will slip sideways, even though it continues to rotate.

Transverse-friction skid resistance measuring devices try to simulate this process. This leads to the concept of the “slip angle” and it is important to appreciate how the transverse, or sideway, friction coefficient varies with the slip angle. The slip angle is the angle formed by the wheel’s plane of rotation and the tangent to the wheel’s path. On a skid resistance test device the wheel’s path normally follows the direction of travel of the test vehicle.

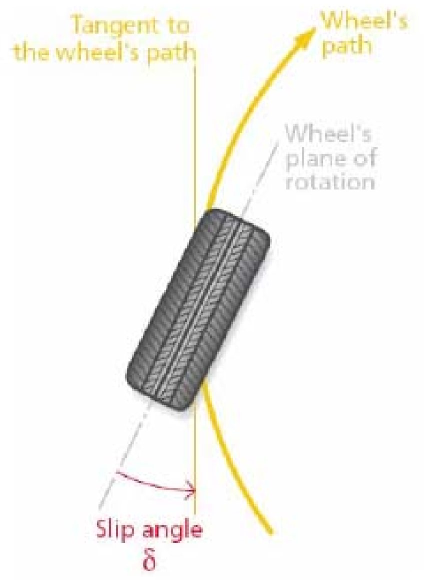


Figure 1.3 - Illustration of slip angle

The sideways friction coefficient SFC varies with the tyre slip-angle as illustrated in Figure 1.4:

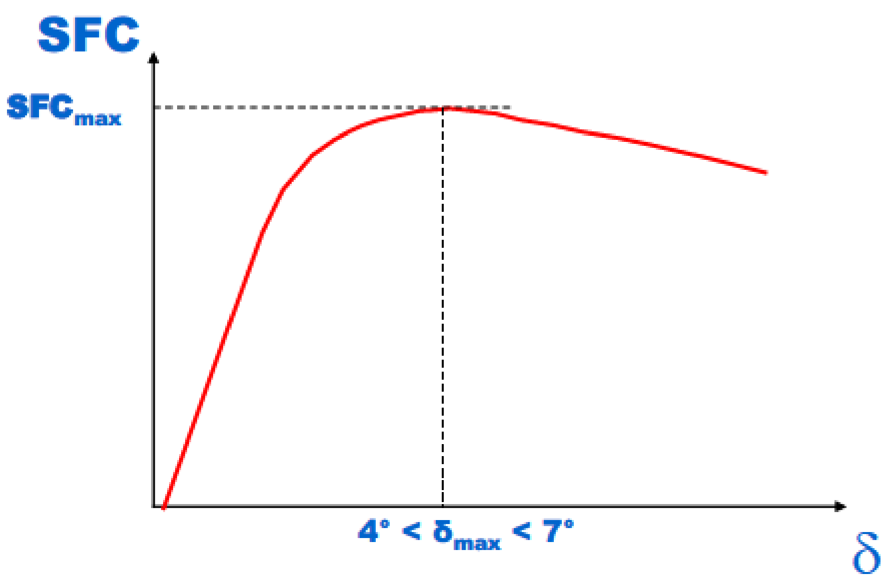


Figure 1.4 - Illustration of SFC – δ curve

It can be seen that the friction increases at first as the slip angle increases, reaching a maximum before decreasing as the slip angle continues to increase. This process is analogous to the variation observed in longitudinal braking, as the tyre tread in the tyre/road contact area moves from a shear phase to a slipping phase.

Typically, the maximum value of SFC occurs at a slip angle, denoted by δ_{max}, between 4° and 7° for a light vehicle, and between 6° and 10° for a truck. [2]

1.4 IMPORTANT PARAMETERS FOR ROAD SURFACE

As we have seen, the interactions between the tyre and the road that affect skid resistance, rolling resistance and noise emission all derive from the way in which different parts of the tyre deform to make intimate contact with the road, and then are released again as the tyre rotates further or moves on.

The surface profile of a road with which tyres interact is often described in terms of its “surface texture”. In order to describe the components of texture, [1] that is defined as the deviation of actual surface from an ideal reference plan, in relation to the factors that they influence, [3] the profile is divided into different texture scales, based on wavelength ranges. Figure 1.5 illustrates the “irregularity ranges” that are typically used to describe these texture scales and the different factors, including skid resistance, rolling resistance and noise that are influenced by them.

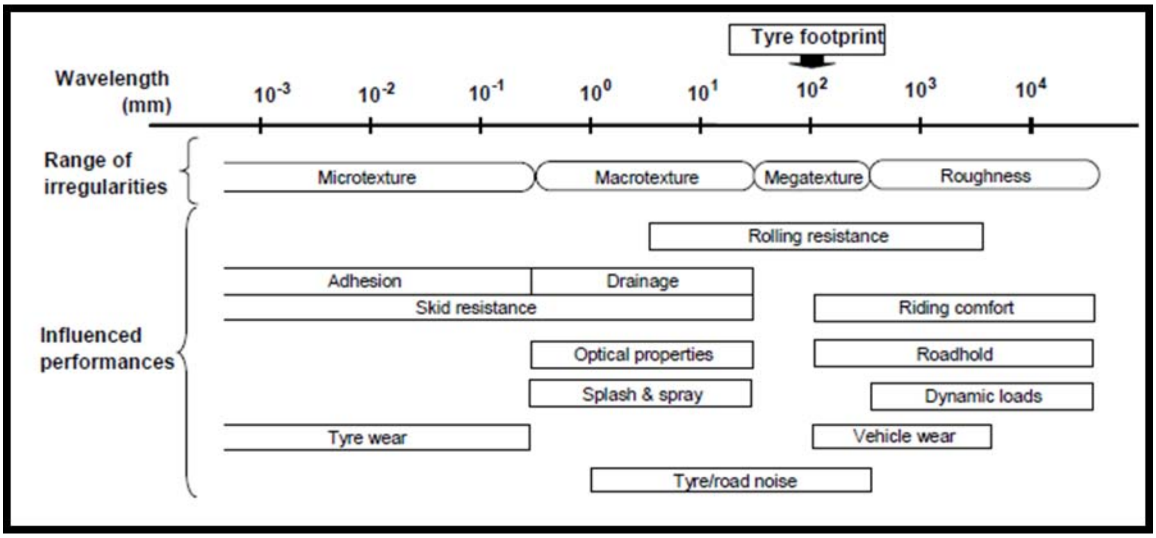


Figure 1.5 - Texture wavelength influence on tyre-road interactions

Although their influence varies, it can be seen that essentially there are just three main parameters relating to the road surface that affect the three main factors in this study. They are:

• ***Microtexture***, which is formed by the microscopic asperities on the surface of aggregate particles and fine grains in the road surfacing material. [1] It's constituted by wavelenght values inferior to 0,5 mm and profile peak-to-peak width values between 1 μm and 0,2 mm, which is the result of roughness of individual aggregate items used in road surface material and is therefore tightly connected to the mineralogical composition of an aggregate. [3]

• ***Macrotexture***, which is formed by the shape of and spaces between the larger aggregate particles (or grooves formed in concrete) at the surface of the road. [1] It's constituted by wavelenght and peak-to-peak width values between 0,5 mm and 50 mm and 0,2 and 10 mm, respectively, depending on mixture size range. [3]

• ***Megatexture***, which arises from variations in the surface profile on a larger scale. It often appears as waviness and includes wavelengths between 50 and 500 mm and peak amplitudes from 0.1 to 50 mm. These wavelengths are of the same order of size as the length of the tyre/road contact area.

There are no boundaries between these categories; one merges into the next. Figure 1.6 illustrates the range of textures that could be encountered on roads. It is macrotexture and microtexture that have the greatest influence on skid resistance and tyre/road friction. [1]

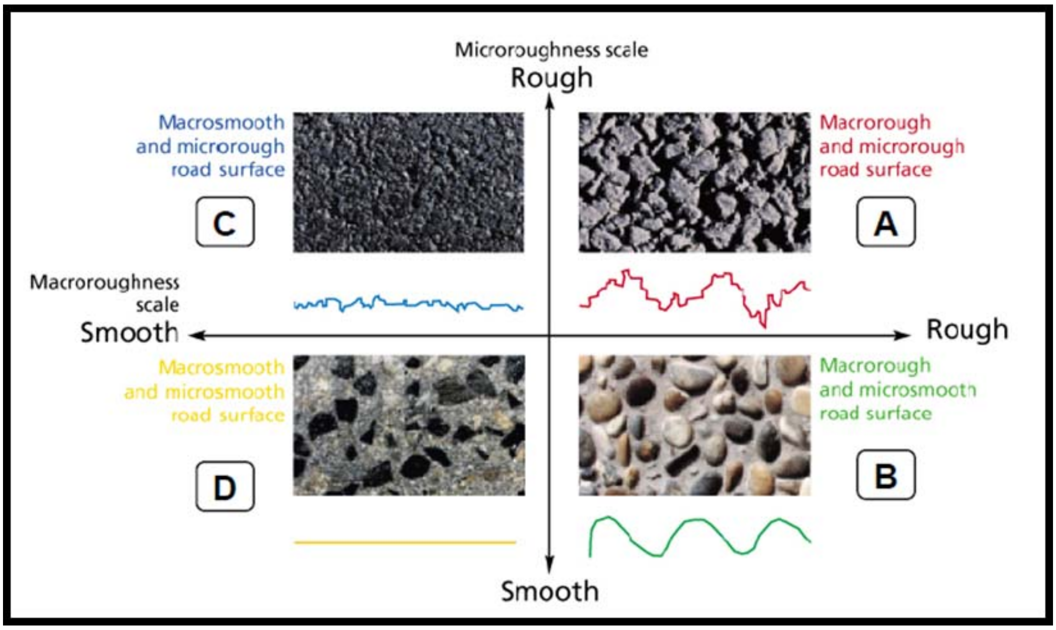


Figure 1.6 – Texture

1.4.1 INFLUENCE OF TEXTURE ON SKID RESISTANCE

The effects of texture scales on the two basic mechanisms of tyre/road friction can be summarized as the adhesion component being highly sensitive to microtexture, whereas the hysteresis component is mostly sensitive to macrotexture.

Although skid resistance is generally high on dry and clean road surfaces, in wet conditions road surface texture on both the micro- and macro-scales is essential.

The surface must provide sufficient macrotexture to assist effective drainage of water from the road/tyre interface and increase the zone of potential dry contact at the rear of the tyre/road contact patch. However, drainage alone is not sufficient to provide good skid resistance; the water film can only be broken if the road surface has a good microtexture on which localized high pressures are built up.

The texture of the surface also influences how skid resistance varies with speed. As is normal practice in studies of skid resistance, a standardized smooth tread tyre was used in the tests to separate the effect of road characteristics from those of the tyre, such as tread pattern and depth. A smooth tyre represents the worst case in practical terms.

It can be seen from the results of many studies that all texture scales have a significant effect on tyre/road friction. Both the microtexture and the macrotexture of a road surface should be high in order to increase adhesion, hysteresis and water drainage.

Microtexture affects friction over the range from almost zero up to the maximum possible friction and is important at all speeds. Macrotexture has some influence on friction at low speeds, albeit to a much lesser extent than microtexture, but is the dominant factor at higher speeds on wet roads.

However, as yet there are limitations to the reliable modelling of the influence of macrotexture, partly due to the ways in which this factor is quantified and measured.

Microtexture currently cannot be measured quantitatively. Work is in hand at many institutes to study this but measurements made with low-speed devices such as the pendulum tester or dynamic friction tester are often used as surrogates. [1]

1.5 THE INFLUENCE OF SURFACING MATERIALS

In order to produce road surfacings with effective texture, it is necessary to know how the composition of the asphalt or concrete influences the development and maintenance of skid resistance.

Parameters of the surfacing material that will influence the texture and therefore the skid resistance include:

1) Aggregates.

2) Bitumen.

3) Void content.

4) Paving and compaction of asphalt surfaces.
5) Texturing of concrete surfaces.
6) The types of surfacing - Asphalt / Concrete .

As well as providing appropriate levels of microtexture and macrotexture when new, it is important that the surfacing can maintain appropriate levels during its service life. This will depend on various factors, including:

• The aggregates' ability to resist polishing and the associated loss of microtexture when trafficked.

• Resistance to wear that could lead to reduced macrotexture as surface aggregate particles are worn down or concrete brush-marks are worn away. Microtexture may also be affected as aggregate particles in the body of the surfacing material with less polishing resistance become exposed at the surface.

• The ability of the surface to maintain its structural integrity and hence macrotexture. This is important on modern asphalt materials in which loss of some aggregate particles from the surface can lead to a gradual degradation of the surrounding material as unsupported particles are broken away. Deformation or flushing of bitumen could lead to the embedment of surface chippings with loss of macrotexture (or even, in the extreme, the covering of microtexture). [1]

1.5.1 AGGREGATES

The shape of the various asperities on the road must be taken into account in order to explain the main differences in the friction performance of different types of road surfacing materials. Depending on how the surface is made, patterns of texture can vary widely, both at the micro- and macrotexture scales.

On asphalt surfaces these may range from closely-packed small particles through larger individual chippings spaced out from one another with relatively smooth asphalt mortar in the spaces between them. The aggregate particles may be orientated differently, with pyramidlike angles or, conversely, essentially flat surfaces uppermost. The natural properties of the aggregate after crushing and grading will have an influence on these factors. A high proportion of naturally-flaky particles, for instance, will tend to present flatter faces to the surface, whereas more cuboid particles are more likely to present an angled edge. On concrete surfaces the ways in which grooves and ridges are formed can create a different range of texture patterns, including repeating patterns that may be transverse or longitudinal compared with the direction of traffic movement.

In relation to microtexture and, in particular, its ability to break through a water film, it is reasonable to assume that aggregates with sharp asperity peaks produce higher localized pressures in the contact patch and that these are likely to be more efficient at breaking the last slight water film than aggregates with rounded asperities. Another advantage of sharp
asperities is that the total load on a tyre could be carried on quite a small area; thus, only a small area need be cleared of water before much of the load is supported upon a dry road surface.

The shape of the aggregates used can be assessed by the shape index or flakiness index.

Flaky aggregates tend to lie flat during the paving process and so make a relatively small contribution to macrotexture. For this reason, it is better to use coarse aggregates with a low shape or flakiness index and this is often taken into account in different national regulations or specifications.

Angularity of the aggregates is only relevant for the sand (0.063 – 2 mm) within the mix, because for the coarse aggregates in surface layers crushed materials have to be used. This property of the sand is determined by the flow coefficient. Crushed sand gives a higher value of the flow coefficient and the friction coefficient increases with the crushed sand content. This is currently taken into account in different national regulations.

As well as being affected by particle shape, macrotexture is controlled to a certain degree by the size of the aggregate particles. On surface dressings and most asphalt surfacings, the macrotexture, in particular the drainage paths, is determined by the spaces between the particles at the surface, the so-called “positive” texture. On porous asphalt and Stone Mastic Asphalt (SMA) thin surfacings, macrotexture is produced by voids between adjacent particles below their upper surfaces, so-called “negative texture” and is controlled by the way the particles pack together in the mix.

The size of aggregates used in surfacings influences skid resistance, with smaller sizes giving greater skid resistance. This has been observed in a number of experiments. For example it has been shown that increasing the percentage of crushed faces increases the skid resistance, and is important for high-speed skid resistance while chip grade is more important at low speeds.

In controlled environmental conditions, skid resistance at any time is primarily a function of the geological properties of the aggregates and the traffic loads placed upon them. The type of aggregate used will determine the microtexture of the surfacing and its ability to maintain that microtexture under loading from traffic and as a result of weathering.

Under traffic loading high stresses are developed at the tips of the asperities which combined can cause the individual particles to polish, particularly if fine surface detritus is also present. Thus the main engineering quality required from an aggregate to be used in a pavement surfacing is to be resistant to the polishing and abrasive actions of traffic. Rocks, which contained minerals of sufficiently different hardness or which were friable, consisting of grains rather insecurely cemented together, were found to give high polishing resistance.

The microtexture on an aggregate that is exposed in the surface of a road is affected by the following factors:

- Polishing.
- Differential wear.
- Weathering.

The term “polishing” describes any general smoothing of an aggregate, including rounding that takes place by abrasion. This phenomenon tends to smooth aggregates by reducing their angularity and microtexture and is caused by the action of tyre carrying detritus and grinding away material from the exposed aggregate. The severity of the abrasive action is related to the density of the traffic and the petrographic characteristics of the aggregates:

- Degree of hardness and proportion of hard minerals.
- Proportion, orientation and distribution of cleaved minerals.
- Grain size

- The nature of the inter-granular bond.
- Degree of liability to chemical alteration of the mineral content.

Where aggregate particles consist of agglomerations of several minerals with different resistance to wear, rough texture can remain as the particles are worn by traffic. Some minerals remain in high relief, whilst others are worn down to a lower level. This phenomenon can be expected where the minerals are of different hardness or toughness.

This will tend to prevent general smoothing by recreating a microtexture.

The aggregate used in a road surfacing has a progressively greater influence on skid resistance as the surfacing ages. The aggregates start with good microtexture but this is lost over time and aggregates with good resistance to polishing can be expected to provide higher levels of equilibrium skid resistance. In order to help in the selection of appropriate aggregates, accelerated polishing tests have been developed that can be used in the laboratory to assess likely performance. The most widely-used of these is the Polished Stone Value (PSV) test. [1]

1.5.2 INFLUENCE OF TRAFFIC LOADING

On opening a surface to traffic, the skid resistance can alter for the first year or two as a result of traffic action before settling to an equilibrium value around which the skid resistance will fluctuate slightly. Once equilibrium has been reached, the skid resistance at any time may vary as a result of seasonal variation and a significant change in traffic level may alter the equilibrium level.

On a new asphalt surface, the microtexture can be masked by bitumen when the surface is initially laid and for a period afterwards until the effects of trafficking and weathering remove the excess bitumen to expose the microtexture. This phenomenon, often referred to as “early life skid resistance”, has been investigated in some depth in recent years.

The rate at which skid resistance changes in this period depends upon the type of surfacing material, the trafficking and climatic conditions.

Particularly on more lightly-trafficked roads, the process can sometimes dominate the skid resistance performance of a surfacing throughout its life.
After the initial period, the aggregates are gradually exposed and actual polishing of the aggregate particles begins, gradually reducing skid resistance to the equilibrium level. [1]
The effect of trafficking can be evaluated in laboratory conditions using the Road Test Machine (RTM) apparatus.

1.5.3 BITUMEN/BINDER

The amount of bitumen used in the asphalt mix can also have some influence on skid resistance. High binder contents will tend to produce a low void content, which could lead to bleeding: this may have resulting negative effects on skid resistance as a result of loss of microtexture, as the bitumen covers the aggregate, and on macrotexture as the filling of surface voids reduces macrotexture.
There is no evidence that suggests that the type of bitumen used in the asphalt mix has a noticeable effect on skid resistance. However, for carriageways with heavy traffic it is better to use bitumen with higher viscosity to ensure the durability of the surface and therefore, indirectly, its skid resistance.
Practical experience shows that the use of polymer modified bitumen (PMB) tends to produce higher levels of skid resistance compared to standard bitumen. This could be due to the higher viscosity of PMB and therefore a higher ring-and-ball softening point, resulting in a pavement that has a higher resistance to permanent deformation at high temperatures.
In contrast, however, if bitumen with higher viscosity or polymer modified bitumen is used, it may take much longer for the bitumen to be removed from the aggregate in the initial period after laying, especially if there is less traffic. This can have two influences: one is adverse, in which the bitumen blinds the microtexture and reduces skid resistance, especially as speed increases; the other is favourable because the presence of the bitumen can delay the onset of the polishing of the aggregate so better microtexture is maintained for longer. [1]

1.5.4 VOID CONTENT

The void content and other volumetric values of the asphalt mixture are only relevant for dense rolled asphalt.
Different studies and practical experience show that, with lower 'void content' (V) and therefore rising 'voids filled with bitumen' (VFB) at the surface, the skid resistance tends to fall because of loss of micro and macro texture. A critical range of V is about 2 Vol.-% and VFB about 90%. [1]

1.5.5 PAVING AND COMPACTION OF ASPHALT SURFACES

The appropriate usage of the paver and the roller compactor could avoid negative effects on skid resistance of paving and compaction to the surface. The effects are likely to vary depending on the specific material being laid, but examples found in some countries could include segregation in the horizontal direction caused by inappropriate use of the paver and in the vertical direction by the selection of an inappropriate use of the roller. [1]

1.5.6 TYPE OF SURFACE

Asphalt

There are many different types of asphalt surfacing, as well as applied treatments such as surface dressings, used on European roads. These can have markedly different characteristics in the ways in which micro- and macro-texture are provided at the surface. Therefore, the skid resistance that a road will provide is affected by the type of surfacing. The finished surface will have different proportions of coarse and fine aggregate exposed at the surface to interact with tyres through which the skid resistance forces are transmitted. Studies have shown that for asphalt mixtures with a high proportion of fines in the contact area, such as some Asphalt Concrete materials, the fines themselves contribute to microtexture, and hence skid resistance. In surfacings in which coarse aggregate predominates in the contact area, high-PSV aggregate (typically, PSV > 50) is needed to provide and maintain microtexture. In some countries, in the UK for example, that generally use surfacings with a high proportion of coarse aggregate at the surface, different levels of PSV are used to deliver different levels of skid resistance depending on expected traffic levels. Nevertheless, in surfaces which are not gap-graded, it is necessary to use coarse aggregate with adequate PSV since both coarse and fine materials contribute to microtexture.

Concrete

Portland cement concrete surfaces behave differently from asphalt surfaces in the way in which microtexture and macrotexture, and hence skid resistance are developed initially and how this changes over time. The actual composition of the concrete has a relatively small impact on skid resistance at first because the running surface is created by the mortar on the surface and the way in which that has been formed to provide texture. However, as the surfacing wears over time, this initial texture can change.

In the worst cases, the internal structure may be exposed at the surface and consequently influences skid resistance.

The microtexture of a concrete surface is provided initially by the sand grains in the mortar. These are naturally at the microtexture scale and the polishing resistance can be important, especially if crushed-rock fines are used.

Over time, the upper surface can wear away to expose the coarse aggregate in the bulk of the material and the polishing resistance of the aggregate then becomes of great significance in terms of skid resistance, especially if this is associated with a naturally-low texture depth.

The macrotexture of concrete roads is determined by their structure, which can be broadly divided into two categories:

• *Isotropic*, in which the macrotexture is formed by aggregate particles deliberately exposed at the surface (e.g. exposed aggregate concrete, porous concrete).

• *Anisotropic,* where the macrotexture is formed by ridges or grooves applied to the surface, either while the cement is still wet or plastic or after it has hardened.

In Germany, for example, where the composition of cement concrete surfaces can vary more than elsewhere in Europe, it has been found that using a higher stability concrete does not necessarily lead to greater durability of the texture produced. Furthermore, a loss of texture geometry does not have to lead to a loss of skid resistance, provided that the mortar layer contains a high proportion of fine aggregate and is of suitable thickness, perhaps 0.5 to 1.0 mm. However it has also been found that as well as the composition of the mortar, its consistency can also have an impact on measured skid resistance. [1]

1.6 THE ROLE OF TYRES IN SKID RESISTANCE

Skid resistance is described as the “Characterization of the friction of a road surface when measured in accordance with a standardized method” and does not therefore relate to the contribution that different tyre types or properties make to road/tyre friction.

The ability of a tyre not to skid on a surface is sometimes referred to as “wet traction” or “wet grip”. Tyres are a rotationally symmetric composite that consists of a complex rubber compound with about 200 constituent parts which is reinforced by different layers of textile or steel fabric. Tyres have to support wheel loads but they also transfer torques that enable the vehicle to accelerate and decelerate and transfer lateral forces in order to steer.

There are different types of tyre design but the predominant type for cars and many trucks is the radial tyre. Radial tyres are built on a carcass of steel cords running radially from bead to bead. A stabilizing belt of crossed steel cords surrounds the carcass. The rubber tread, which is the part of the tyre that is contact with the road surface, is bonded to the belt and sculpted with a tread pattern.

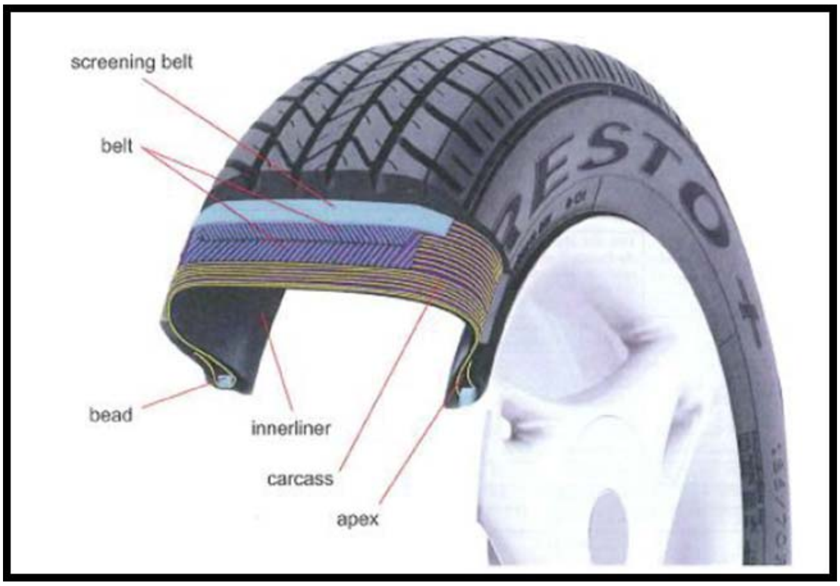


Figure 1.7 – Tyre section

The two parts of the tyre that have the main influences on skid resistance, rolling resistance and noise are the carcass and the tread. The design of the carcass, its inflation pressure and aspect ratio all have an influence on the way in which the tyre rolls over the surface and responds to changes in surface characteristics such as megatexture, or changes in driving pattern such as braking or cornering.

In the case of the tread, which is the part of the tyre through which frictional forces are transmitted and which is distorted by the road surface, there are a number of particular aspects that influence our main topics in different ways. [1]

1.6.1 TREAD PATTERN

We have seen that a major contribution that road surface macrotexture makes to road/tyre friction is removal of water from the contact area. The tyre also contributes to this through its tread pattern. This provides channels for water to escape, with the aim of establishing some localized dry contact between the tread and road surfaces. The role of the tread pattern is extremely important on surfaces that have low drainage capacity, i.e. low macrotexture.

Today, there are many different designs of tread pattern but most consist of circumferential and zigzag rib patterns. Investigations were undertaken in the

1960s to determine whether particular tread patterns produce better performance on wet surfaces, but at that time no one pattern design seemed to show significantly better performance than others. [1]

1.6.2 TREAD DEPTH

The effect of tread depths on skid resistance has also been studied. From these various studies, it appears that on surfaces with relatively high macrotexture, the influence of tread depth on the tyre is less important until water depths become high.

Studies, have demonstrated clearly that macrotexture is important but that increasing it markedly beyond a certain level, about 1.2 mm TD has been suggested gives no additional benefit. Therefore, on road surfaces that are already above this level in macrotexture terms, the contribution of tyre tread is small in terms of increased grip. However, on surfaces with inherently low texture depth, the contribution made by the tyre tread becomes a much more significant component of the tyre/road friction process, especially at higher speeds with greater water depth.

However, on wet surfaces, an increase in tread depth resulted in higher friction values. [1]

1.6.3 TREAD COMPOUND

Tread rubber is a viscoelastic material. The term viscoelasticity is applied to materials which are neither ideal elastic solids nor viscous liquids but posses characteristics which are typical of both. On a stress against strain curve, the loading and unloading parts of a cycle have different slopes that are due to energy loss in rubber with changes in the storage and loss modulus of the rubber; this is what gives rise to the hysteresis effect.

It is established that a large part of friction between rubbers sliding over a rough lubricated surface comes from energy losses in the rubber and that the lower the rubber resilience is, the greater the tyre wet grip is. [1]

1.6.4 INFLATION PRESSURE

It is clear that changes in loading and inflation pressure will alter the dimensions and shape of the contact area. This is potentially important since this will determine the duration of the contact between each element of the tyre and the road, and so will have an effect on the water film variation. However, tests carried out in normal conditions, with patterned tyre and textured surface, showed that relatively large changes in inflation pressure had hardly any effect on tyre/road friction; its effect was low compared with road macrotexture and tyre tread depth.

Other investigations have shown the same for wet surfaces, where the inflation pressure has no effect on friction value, even if the tread depth increases.

However, on dry surfaces the friction value rises, when the inflation pressure decreases, even with an increase in the tread depth, and this reduction in friction value can be explained by the reduced contact area that results from a higher inflation pressure, which leads to higher contact pressure.

On wet surfaces, however, it seems that the influence of the changes of the inflation pressure and therefore the inhomogeneous contact pressure are in balance. This may occur because on wet surfaces the dry area through which the contact pressure acts to develop adhesion is already a relatively small part of the tyre contact patch and so is less sensitive to the overall change in contact area as a result of inflation pressure changes. [1]

1.6.5 TYRE TYPE

Tyres are essentially of two general types: heavy goods vehicle (HGV) tyres and passenger car tyres. Car tyres can also be divided into summer and winter tyres, with different rubber compounds and tread patterns chosen to reflect the different conditions. Winter tyres are not always used in countries that do not experience great extremes between summer and winter conditions or in which the extreme conditions are not over prolonged periods.

Heavy vehicles use different tyres on different axles according to their purpose. Tyres on the drive axles usually have a traction profile to give grip for power transmission, whereas tyres on the steering axles have a longitudinal profile.

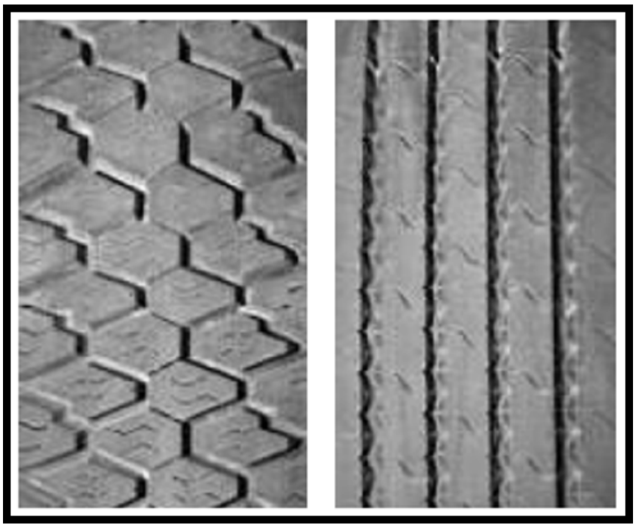


Figure 1.8 – Tyre types

The different tyres on HGVs, with their various profiles, influence the braking distance of these types of vehicle. The tyres on the power transmission axles with a traction profile have approximately the same braking distance as the tyres on the steering axles with a longitudinal profile. However, the behaviour of braking distance in relation to the tyre width is inconsistent; sometimes the braking distance rises and sometimes it falls with an increase in tyre width. [1]

1.7 EXTERNAL ENVIRONMENTAL INFLUENCES

1.7.1 RAINFALL AND THE INFLUENCE OF WATER FILM

When a road is clean and dry, high levels of tyre/road friction are generated whatever the vehicle operating conditions; it is water on the surface during and after rainfall that is the main factor leading to reduced friction. Various factors relating to the road and the tyre and other influences such as vehicle speed then affect the actual level of friction achieved in a particular situation.

The role of the water itself is primarily as a medium that separates the rubber of the tyre from the microtexture of the road by acting as a lubricant.

A wedge angle is created between the tyre and water ahead the contact area. This occurs because of the change in momentum of the water as it is pushed ahead of the tyre by the rolling surface of the tyre.

This phenomenon creates a hydrodynamic pressure that increases with the square of the vehicle speed. A tread element which comes into contact with the road as the tyre is rolling must first squeeze out the film of water ahead of the contact area before it can make contact with the road surface asperities in the remainder of the contact patch. The real areas of contact between tread elements and the road occur only towards the rear of the contact patch. At any moment during the tyre movement, the tyre load is supported partly by the water trapped in the contact patch and partly by the road surface asperities that are in direct contact with the tyre tread. The greater the proportion of dry contact, the greater the tyre/road friction will be.

The contact patch can be divided into three zones with different proportions that range from wet to almost dry. These zones are generally explained as follows:

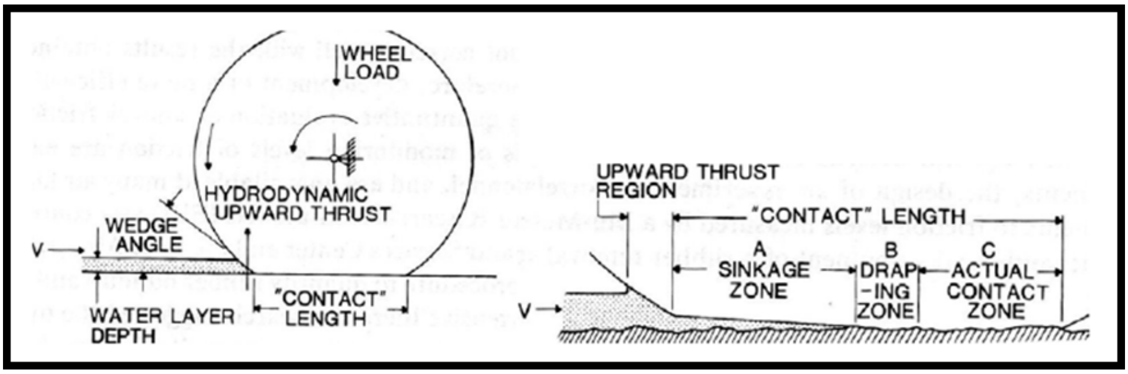


Figure 1.9 - Three zones in the tyre/road contact patch

• **Squeeze-film zone (or Sinkage zone or Zone A):** Under wet conditions, the forward part of what would normally be considered the contact area under dry conditions floats on a thin film of water, the thickness of which decreases progressively as individual tread elements traverse the contact area. Since the tyre, water film, and the road surface have virtually no relative motion in the contact area, the tread elements in effect attempt to squeeze out the water.

• **Transition zone (or Draping zone or Zone B):** The transition zone begins when the tyre tread elements, having penetrated the squeeze-film, commence to drape over the major asperities of the surface and to make contact with the lesser asperities.

• **Actual contact zone (or Dry zone or Zone C):** This is the region where the tyre tread elements, after draping, have attained an equilibrium position vertically on the surface. This zone occupies the rear portion of the contact area.

The lengths of these regions depend on vehicle velocity and relate to water drainage time. At low speeds, the contact time is long, and there is ample time for water film to be expelled, thus allowing a large actual contact zone to develop with a resulting high level of friction.

When speed increases, the time available for water to be expelled from the interface becomes shorter and consequently the expulsion of water is less complete, the actual contact zone is smaller and friction is lower.

Increasing speed will decrease the available drainage time so much that the squeeze-film zone is extended, ultimately to the point where it occupies the whole contact length. This situation corresponds to the viscous hydroplaning limit. At such a speed, the hydrodynamic pressure is less than the wheel load. Further increase in speed moves the situation to the point that corresponds to dynamic hydroplaning, where the hydrodynamic pressure balances the normal wheel load and the water occupies the whole contact area. In this extreme situation the tyre is effectively lifted off the road and all grip and steering control are lost. However, normal road surface are never smooth, so the contact area is usually broken up into discontinuous areas, either by the texture of the road or by the texture of the tread pattern of the tyre. This increases the speed needed for hydroplaning to occur. Nevertheless, in practice, it is not at all necessary to have a flooded road surface for viscous hydroplaning to occur, and the slightest film of water may be sufficient to make skidding possible.

Instead of determining water drainage time, Horne and Buhlmann proposed an alternative method for determining the available friction at any speed that takes the road texture directly into account. This method describes the water removal rate in the squeeze film and transition zones. The relative drainage times from both zones are expressed in terms of pavement drainage coefficients, Cmac and Cmic. It is Cmac that determines the percentage of the tyre footprint in the squeeze-film zone. Since in this area the dynamic effect of water predominates, the removal rate is dependent upon bulk channel flow, which is determined by the amount of road surface macrotexture in the case of a smooth test tyre.

Cmic determines a percentage of the tyre footprint that set the relative size of the transition zone. Unlike the squeeze-film zone in which bulk water is removed, fluid viscous forces prevail in this region. Since localized high contact pressures are required to penetrate and break this viscous film, this coefficient depends on the road surface microtexture.

The film thickness decreases rapidly with time as soon as it enters in contact with the tyre. Thus, the differences in the initial thickness of the water films are small importance. Experimental investigations at the Road Research Laboratory in the UK in the late 1960s confirmed that the main skidding problem on roads is the lubricating effect of a relatively thin water film, of about 3 to 4 mm. Based on experimental investigations, Bohdan et al proposed a mathematical relationship between water film thickness and skid resistance with a form that responds in the same sense as the RRL results.

1.7.2 OTHER EXTERNAL FACTORS INFLUENCING TYRE/ROAD INTERACTION

There are also other external environmental factors that also have an influence in the real world of in service roads and tyres travelling on them.

Over time, microtexture is polished by the action of the repeated passage of vehicle tyres, especially those of heavy vehicles. This leads to a gradual reduction in skid resistance as the road ages until an equilibrium value is reached. The extent to which a surface will polish, and hence the equilibrium skid resistance achieved, depends on both the level of traffic and the ability of the aggregate to resist polishing. The effect is also influenced by other stresses such as braking and cornering forces, so an aggregate may provide different levels of skid resistance depending on where it is used.

Generally, the greater the polishing resistance of the aggregate, the better the microtexture and the better the skid resistance will be. Conversely the greater the traffic level, the greater the polishing and the lower the skid resistance will be.

On very lightly trafficked roads, it may take many years for the equilibrium skid resistance to be reached. On heavily trafficked roads this may happen in as short a time as six months to a year.

It has been found that, especially in temperate climates such as in much of western and central Europe, there is a marked variation in skid resistance (and consequently in road/tyre friction) throughout the year and from one year to the next. Typically, skid resistance is at its lowest in summer and higher in winter.

This cyclical effect is known as “seasonal variation and this process can be explained as follows. Initially, the skid resistance on a new road is high because the aggregate is unpolished. During the summer period, fine deposits on the surface act as a polishing medium, leading to a reduction in the microtexture. However, in winter, frost action and more frequent rainfall mean that the deposits are coarser and so the microtexture is roughened. Initially, the polishing process dominates and the skid resistance gradually falls to the equilibrium level. Once reached, the skid resistance will remain at this same general level but, depending on the balance between summer polishing and winter roughening, it will vary from year to year. A change in traffic will also alter the balance of the polishing cycle and the equilibrium level may then increase (lighter traffic) or decrease (heavier traffic).

While seasonal variation is a significant phenomenon in the study of skid resistance, and must be taken into account in any standards for roads based on skid resistance measurements, it is not strictly a parameter of either the road or the tyre. Rather, it reflects in part the way in which the road responds to the effects of traffic and weather over time.

The presence of ice and snow on the road surface primarily impacts on tyre/road friction. By covering the surface of the road with a slippery film, the normal frictional characteristics of road surfaces are masked and the tyre has to interact with ice.

If the ice or snow has a water film on its surface then clearly it becomes very slippery indeed. However, when it is dry, for example on recently-fallen snow, reasonable levels of grip may be available.

Salt or other de-icers may be spread on the road during winter maintenance operations to counteract the effects of ice formation. Some of these might have an adverse effect on skid resistance but recent research in the UK suggests that the effects, if any, are negligible and preferable to an icy road.

During long, hot, dry spells, especially in summer, deposits of dust, oil and rubber can build up on the road. When it next rains, at first these deposits create a slippery film on its surface that has a worse effect on friction than water alone. Once sufficient rain has fallen, the deposits are washed from the surface but for a short time they are potentially hazardous. This is an important factor of which drivers need to be aware but it has little directly to do with the properties of road surfaces and tyres.

Temperature itself does not directly influence the skid resistance of roads but high summer temperatures and frosty conditions can have an influence on the deterioration mechanisms of road surfacing materials that then affect their performance characteristics.

There are also small effects due to temperature changes that can influence tyre rubber characteristics and consequently affect friction, or skid resistance measurements. [1]

CHAPTER 2:
TESTS TO ASSESS SKID RESISTANCE AND TEXTURE DEPTH

2.1 TEST TO ASSESS SKID RESISTANCE

2.1.1 ***BS 7941-2:2000 - Surface friction of pavements - Part 2: Test method for measurement of surface skid resistance using the GripTester braked wheel fixed slip device***

This British Standard describes a method for determining the skid resistance of a surface using the GripTester continuous reading braked wheel fixed slip device.

The method is applicable to the following:

- highways: surfacings;
- highways: horizontal signs;
- airport runways;
- flight decks;
- footways;
- pedestrian precincts;
- test panels of surfaces intended for any of the above.

The method is for measurement of skid resistance along a continuous surface on external paved surfaces or indoors. Test speeds can vary from 5 km/h to 130 km/h depending on the application. The measured values can be affected by the test speed.

The GripTester is a device developed by Findlay Irvine Ltd in the United Kingdom, initially for use on helipads but now widely used in many countries on airfields and roads. The device operates on the longitudinal friction principle and is a trailer with two running wheels, called the “drive” wheels, and a single small test wheel.

The wheel dimensions are similar to those of a “go-kart” wheel (Figure 2.1). It can also be configured to be pushed manually for low speed operation in confined areas.

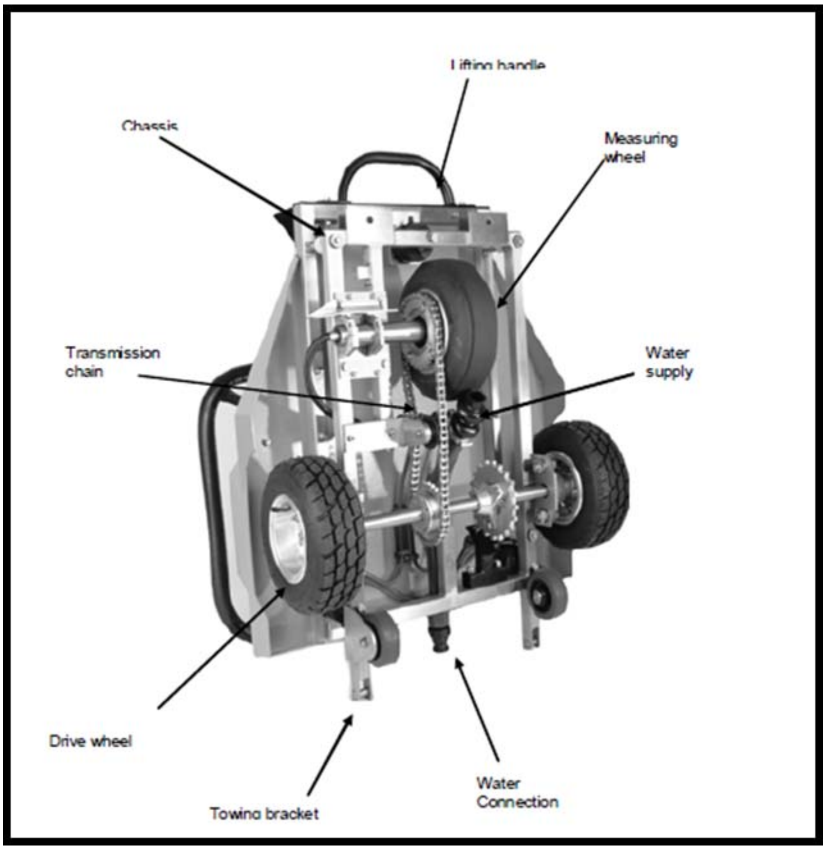


Figure 2.1 – Grip Tester

GripTester measures LFC using a small test wheel operating at fixed slip ratio of 15%.

The test wheel is mounted on a stub axle and is mechanically braked by a fixed gear and chain system linking it to the drive wheel axle.

The wheel slips as it is towed along the wetted pavement surface at a constant speed and the slipping force and vertical load are both measured. The static load on the test wheel is (250 ± 30) N when towed or (260 ± 30) N when used in push mode. In the latter case a small water container is mounted on the device itself, adding to the load.

During operation, the stub axle becomes elastically deformed by the horizontal drag and vertical load forces acting on the test tyre. Two strain gauge bridges on the stub axle continuously measure the horizontal drag and vertical load forces. The two drive wheels are mounted on the main axle, which also carries a toothed wheel. A proximity sensor generates signals for distance recording.

For normal wet road testing, water is deposited in front of the test tyre from a water tank fitted with a control valve. A water nozzle is mounted directly in front of the test wheel delivering a controlled amount of water to the road surface. In towing mode, water flow rate is further controlled by a pump and may be monitored with a flow meter.

The standard test-conditions for the GripTester are listed in Table below: [2]

air temperature	> 4 °C
pavement temperature	> 5 °C and < 50 °C
pavement status	no pollution
test wheel	smooth ASTM-tyre 254 mm in diameter inflated at 0.14 MPa
method	constant slip ratio, 15 %
static wheel load	250 ± 20 N
operating speed	5 km/h to 100 km/h
theoretical water film thickness	0.5 mm
minimum recording length	Optional, typically 10 m or 20 m.
wheel path	Normally nearside wheel path or as required

Table 2.1 - The standard test-conditions for the GripTester

2.1.2 *BS 7941-1:2006* - Methods for measuring the skid resistance of pavement surfaces – Part 1: Sideway-force coefficient routine investigation machine

This British Standard describes a method for determining the wet-road skid resistance of a surface using the sideway-force coefficient routine investigation machine (SCRIM). The method provides a measure of the wet-road skid resistance properties of a bound surface by measurement of sideway-force coefficient at controlled speed. The method has been developed for use on roads but is also applicable to other paved areas such as airport runways.

The SCRIM was originally designed in the UK by the then Road Research Laboratory and has been manufactured under licence by WDM Limited since the 1970s. The device operates on the transverse friction principle and uses special narrow test wheel which set at an angle to the direction of travel. The wheel is lowered on to the road surface under the action of a static load.

The test wheel is mounted to the side of a tanker lorry between the front and rear axles of the truck so that it runs in the vehicle wheel path. SCRIM is used widely across Europe with many countries operating more than one machine. There is a wide variety of truck chassis and bodywork in use, ranging from small units for use on local roads to very large three-axle trucks for long-distance main highway work.

Figure 2.2 shows the measuring wheel assembly on a SCRIM built for UK main road use, with its test wheel on the left side of the truck. European mainland machines normally carry the test wheel on the right side and some machines are fitted with two test wheels.

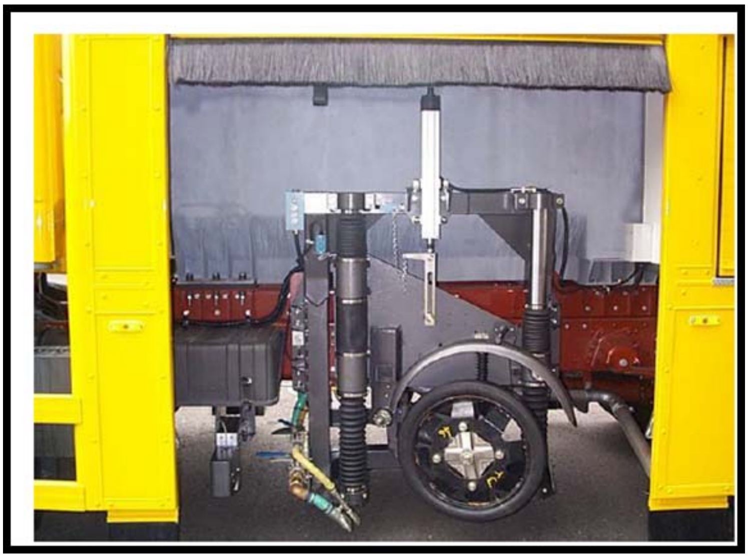


Figure 2.2 – SCRIM

SCRIM measures SFC using an angled wheel. Some machines are also fitted with laser sensors to measure macrotexure.

These have been estimated from data from the 2008 annual comparison trial in the UK involving fourteen machines operating on seven different test surfaces. Reproducibility values may vary in other countries depending on whether the machines have been maintained and compared with the UK fleet.

A freely rotating wheel fitted with a special pneumatic, smooth, rubber tyre, is mounted midmachine in line with the nearside wheel path and set at an angle to

the direction of travel of the vehicle. The wheel is lowered on to the road surface under the action of a static vertical load defined by the mass of the wheel assembly, which is able to move freely up and down on vertical linear guides. The force acting along the axle of the test wheel is measured and used to calculate the SFC. On some machines, particularly those operating in the UK, the dynamic vertical load is also simultaneously measured and used in the computation of SFC.
The standard test conditions for the SCRIM are listed in Table 2.2. [2]

air temperature	> 4 °C
pavement temperature	> 5 °C (testing season: April till November) and < 50 °C
pavement status	no pollution
test wheel	smooth tyre 76/508 mm inflated at 0.35 MPa
method	constant slip ratio from slip angle
slip angle	20°
static wheel load	1960 N
operating speed	Varies from country to country. Typically 50 km/h is used as a reference speed but other speeds are sometimes used in operation for safety reasons with measurements corrected to the reference speed.
theoretical water film thickness	0.5 mm
length for the mean value	Minimum typically 10 m but other options available
wheel path	Normally nearside wheel path or as required

Tabel 2.2 - The standard test conditions for the SCRIM

2.1.3 ***BS EN 13036-4:2011 - Road and airfield surface characteristics — Test methods. Part 4: Method for measurement of slip/skid resistance of a surface: The pendulum test***

This European Standard describes a method for determining the slip/skid resistance of a surface using a device which remains stationary at the test location. The slip/skid resistance is measured by means of a slider mounted at the end of a pendulum arm, either in the field or in the laboratory.
This method measures the slip/skid resistance of a small area of a surface (approximately 0,01 m^2). This should be considered when deciding its applicability to a surface which may have non-homogeneous surface

characteristics, e.g. containing ridges or grooves, or is rough textured (exceeding 1,2 mm mean texture depth).

As the results from this test are taken at one small location, the results cannot be compared with results from devices e.g. mobile devices, that measure the slip/skid resistance over a long length of a surface.

Measurements in the field

- The test surface shall be brushed free of loose particles and flushed clean with water, unless the test is to include for the contamination of the surface.
- Place the Pendulum Tester upon a firm surface with the pendulum swinging in the direction of traffic. The surface shall not have gradient in excess of 10 %. Where this is not possible, the test may be carried out at any angle to the direction of traffic to enable the gradient criterion to be satisfied. On surfaces bearing a regular pattern such as ridged or brushed concrete, grooved asphalt or paving blocks, tests should be made with the slider operating at an angle of approximately 80° to the ridges, grooves or joints in pavers.
- Measure and note the temperature of the test surface and the slider to the nearest whole number. The test cannot be carried out if the temperature of the wet surface and/or slider temperature are outside the range 5 °C to 40 °C.
- Measure and note the temperature of the water used for wetting the surface to the nearest whole number. The test cannot be carried out if the water temperature differs more than 15 °C from air temperature.
- Wherever possible the readings shall be taken on the C scale using the wide slider. This determines the PTV directly. On non-homogeneous surfaces where a plane test surface can only be achieved of sufficient size to use the narrow slider, this may be used reading on the F scale. An estimation of the PTV can be obtained by calculation.

Measurements in the laboratory

- Flat laboratory test specimens shall have minimum dimensions of not less than 100 mm × 150 mm. Where the specimens are initially smaller then this specimens may be cut and glued together on a backing panel to provide a plane surface of sufficient size to test. Curved specimens for the Polished Stone Value test shall have a test surface as described in EN 1097-8.
- The appropriate slider assembly with either a slider 57 or slider 96 shall be selected as required.
- Specimens cut from a surface shall use a method of cutting or coring to ensure the surface to be tested remains undamaged.
- Specimens manufactured in the laboratory shall have the texture and material type on the surface specified in the relevant European Standard or as specifically detailed.
- Specimens may be tested as taken from the site, as prepared in the laboratory (unpolished) or after a polishing regime.
- Laboratory specimens shall be clean and free from contamination or loose particles and held rigidly so as not to be moved by the passage of the slider.
- The water for wetting the surface, the pendulum tester, and the slider shall be kept in a room where the temperature is controlled at (20 ± 2) °C for at least two hours before the test begins and for the duration of the test.
- Laboratory tests shall be carried out with the specimens held for a minimum of 30 min at (20 ± 2) °C before testing and for the duration of the test.

Test procedure

The pendulum test equipment, illustrates in Figure 2.3, shall be transported in the box supplied with the equipment. Carry out a visual check of the pendulum tester to ensure that it has been assembled correctly and there is no obvious damage that requires repair prior to use. Swing the pendulum arm to see if there are any obvious mechanical defects.

Figure 2.3 - Skid Resistance Tester (SRT)

In the field, check the surface temperature when wet at each test location. If a pyrometer is used to measure the slider surface temperature it shall be orientated perpendicular to the direction of the surface.
Set the pendulum up over the surface to be tested such that the pendulum swings over the particular area that is required for testing. When testing samples in the laboratory, set the pendulum upon a rigid surface that includes a suitable means of restraining the test sample in a horizontal position and support it solidly. The adjustable feet are used in conjunction with the built-in spirit level to ensure that the frame of the instrument is horizontal. It is important that the bubble lies exactly in the centre of the spirit level.
Raise the axis of suspension of the pendulum so that the arm swings freely, and adjust the friction in the pointer mechanism so that when the pendulum arm is released from the right-hand horizontal position the pointer comes to rest at zero position on the test scale. Repeat twice more for confirmation. If the pointer swings past the zero position, screw the rings up a little more tightly. If the pointer does not reach zero, unscrew the rings a little. Ensure that the locking ring is tight before further use.
Adjust the height of the pendulum arm so that in traversing the surface the slider is in contact with it over the whole width of the slider and over the length

below and wet the surfaces of the specimen and the slider rubber with a copious supply of water.

Set the sliding length of the slider (the distance between two points where the sliding edge of the rubber touches the test surface) by gently lowering the pendulum arm while using the vertical screw after unclamp the head of the pendulum until the slider just touches the surface, first on one side of the vertical, and then on the other. The sliding length shall be between (126 ± 1) mm for the wide slider and (76 ± 1) mm for the narrow slider. This is normally accomplished as follows in a series of small steps, using one of the gauges for 126 mm sliding length or a special scale for the narrow slider with a sliding length of 76mm.

Move the pendulum foot to the right and lower the head so that the slider starts to contact the test surface with its rear corner (aluminium backing) level with the right mark on the gauge. Manually hold the gauge in that position.

Raise the slider with the slider lifting handle and move the pendulum foot to left hand side sufficiently to ensure the slider is clear of the surface when the slider is lowered. Allow the pendulum foot to gently drop back so that the slider contacts the test surface.

The rear edge (aluminium backing) of the slider shall coincide with the left hand mark of the gauge. If not, then raise or lower the Pendulum head so that the slider moves about 50 % of the distance towards the correct setting.

Reclamp the head, reposition the gauge so that the corner of the slider is level with the left hand gauge mark and then move the pendulum foot over to the right hand side and check if it lines up with the right hand gauge mark. If not, repeat the process, backwards and forwards until the pendulum head is set at the correct height to give the required sliding length. Alternatively use a gauge or scale and measure directly at the contact points of rubber and test surface. If the sliding length is okay return the pendulum arm to its rest horizontal position.

Wet the surfaces of the specimen and the slider rubber with a copious supply of water, being careful not to disturb the slider from its set position.

Generally on surfaces typical of those found on roads, at least 100 ml of water may be required to be applied to the surface and the slider rewetted prior to each swing to ensure the wet slider is passing over the wet test surface.

Applying too little water will have a significant effect on the results if any part of the swept length is dry.

Release the pendulum arm and pointer from the horizontal position using the release mechanism (knob), catch the pendulum arm on the early portion of the return swing and record the position of the pointer on the scale to the nearest whole number. Return the pendulum arm by raising the slider using the lifting handle and pointer to the release position.

Perform this operation five times, re-wetting the surface and slider copiously just before releasing the pendulum and recording the result each time. If the first five readings differ by more than three units, repeat until three successive readings are constant and record this value.

Calculations

Now it's possible to calculate the Pendulum Test Value as the mean of five swings using the formula:

$$PTV = \frac{\sum(\,v1 + v2 + v3 + v4 + v5)}{5}$$

Where v_1 to v_5 are individual values for each swing; or:

$$PTV = v_j$$

Where v_j is the constant value achieved by the final three swings if the initial swings are too variable.

Where testing in the field, correct Pendulum Test Value for temperature using the nearest temperature from the Table below:

Measured slider temperature °C	Correction to measured value
36 to 40	+3
20 to 35	+2
23 to 29	+1
19 to 22	0
16 to 18	-1
11 to 15	-2
8 to 10	-3
5 to 7	-4
NOTE The temperature correction can be affected by the texture of the surface.	

Table 2.3 – correction factor for PTV due to the temperature

The measured slider temperature shall be the mean of the temperatures of the wetted slider before and after testing. Report the temperature corrected *PTV* value as *PTV*Corr to the nearest whole number. The *PTV* for a location is the mean of three individual *PTV* determinations.

Precision

The reproducibility of the measuring method has been examined on the basis of a round-robin test in which eleven different European laboratories participated. This involved testing twelve different material surfaces, whereby each laboratory tested the relevant material surfaces under laboratory conditions, using a slider 57 as well as a slider 96. Testing was done in the “wet” condition. The materials were tested in two opposite directions and the average value was examined. The standard deviations found were as follows:

- Slider 96: From 1.5 to 4.5 *PTV* units, depending on the nature and the surface characteristics of the material, with an average standard deviation of 2.4 *PTV* units.
- Slider 57: From 1.4 to 3.9 *PTV* units, depending on the nature and the surface characteristics of the material, with an average standard deviation of 2.6 *PTV* units.

2.2 TEST TO ASSESS TEXTURE DEPHT

2.2.1 BS EN 13036-1:2010 - Road and airfield surface characteristics — Test methods. Part 1: Measurement of pavement surface macrotexture depth using a volumetric patch technique

This European Standard specifies a method for determining the average depth of pavement surface macrotexture by careful application of a known volume of material on the surface and subsequent measurement of the total area covered. The technique is designed to provide an average depth value of only the pavement macrotexture and is considered insensitive to pavement microtexture characteristics.

This test method is suitable for field tests to determine the average macrotexture depth of a pavement surface. When used in conjunction with other physical tests, the macrotexture depth values derived from this test method can be used to determine the pavement skid resistance capability, noise characteristics and the suitability of paving materials or finishing techniques. When used with other tests, care should be taken that all tests are applied at the same location.

Test method

The standard materials and test apparatus consist of a quantity of uniform material, a container of known volume, a suitable wind screen or shield, brushes for cleaning the surface, a flat disc for spreading the material on the surface, and a ruler or other measuring device for determining the area covered by the material. A laboratory balance is also recommended to ensure consistent amounts for each measurement sample.

The test method involves spreading a known volume of material on a clean and dry pavement surface, measuring the area covered, and subsequently calculating the average depth between the bottom of the pavement surface voids and the tops of surface aggregate particles.

In spreading the material specified in this test method, the surface voids are completely filled flush to the tips of the surrounding aggregate particles.

Pavement aggregate particle shape, size and distribution are surface texture features not addressed in this method. The method is not meant to provide a complete assessment of pavement surface texture characteristics. In particular, care should be exercised in interpreting the result if the method is applied to porous surfaces and to deeply grooved surfaces.

The method can be applied to a wide range of surfaces. Its validity range is 0,25 mm to 5 mm, expressed in Mean Profile Depth, MPD.

Material and apparatus

The essential elements of the apparatus, shown in Figure 2.4, consist of the following:

1) portable wind screen
2) spreading tool
3) surface cleaning brushes
4) sample cylinder
5) ruler

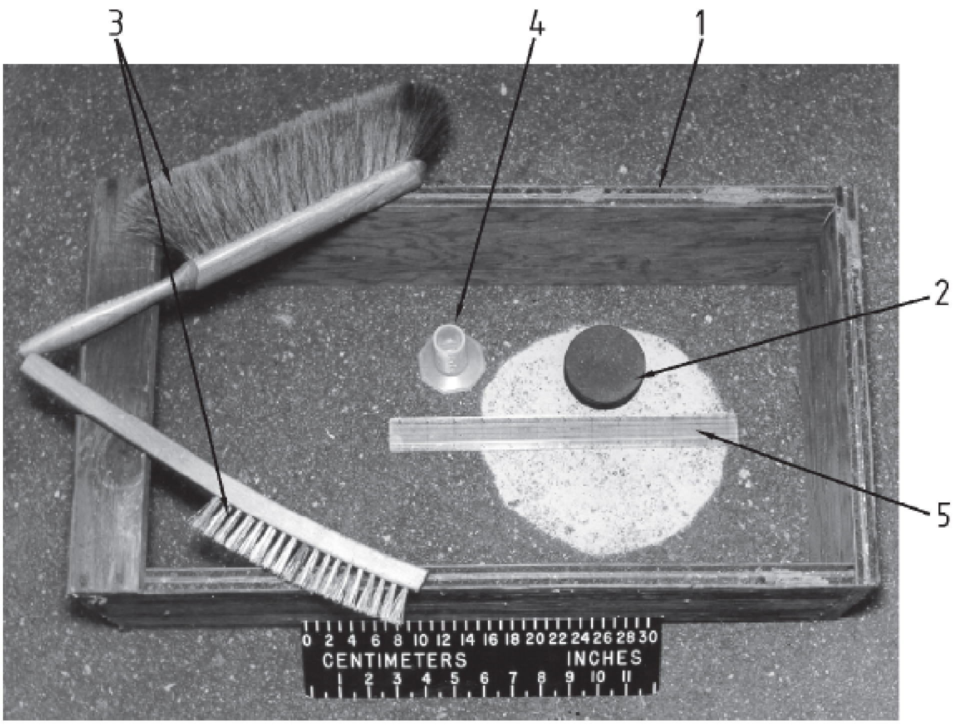


Figure 2.4 — Apparatus for measuring surface macrotexture depth

Procedure

Inspect the pavement surface to be measured and select a dry, homogeneous area that contains no unique, localized features such as cracks and joints. Thoroughly clean the surface using the soft bristle brush to remove any residue, debris or loosely bonded aggregate particles from the surface. Position the portable windshield around the surface test area.

Material sample

Fill the cylinder of known volume with dry material and gently tap the base of the cylinder several times on a rigid surface. Add more material to fill the container to the top, and level with a straightedge. If a laboratory balance is available, determine the mass of material in the container and use this mass of material sample for each measurement.

Determination

Pour the measured volume or mass of material on to the dry and cleaned test surface. Carefully spread the material into a circular patch, with the disc tool, rubber-covered side down, filling the surface voids flush with the aggregate particle tips. Use a slight pressure on the hand, just enough to ensure that the disc will spread out the material so that the disc touches the surface aggregate particle tips.

Measure and record the diameter of the circular area covered by the material at a minimum of four equally spaced locations around the sample circumference. Calculate and record the average diameter.

Number of test measurements

The same operator should perform at least four, randomly spaced measurements on a given test pavement surface type. The arithmetic average of the individual values shall be considered to be the average surface texture (macrotexture) depth of the tested pavement surface.

Calculation of surface mean texture depth

Calculate the mean texture depth, *MTD*, using the following equation:

$$MTD = 4V / \pi D^2$$

Where:

- *MTD* is the mean texture depth, expressed in millimeters (mm);
- *V* is the sample volume (i. e. internal cylinder volume), expressed in cubic millimeters (mm3);
- *D* is the average diameter of the area covered by the material, expressed in millimeters (mm).

Precision of the method

Controlled tests have been conducted on laboratory specimens having a range of macrotexture depth 0,5 mm to 1,2 mm.

The standard deviation of repeated measurements by the same operator on the same surface can be as low as 1 % of the average texture depth.

The standard deviation of repeated measurements by different operators on the surface can be as low as 2 % of the average texture depth.

The standard deviation of the site-to-site variations may be as large as 27 % of the average texture depth. Here, site defines a randomly selected location within a nominally homogeneous pavement section. This means that a large number of measurement observations would be necessary to estimate the average texture depth reliably for given pavement types with large variations in texture, despite the fact that the method is highly repeatable and not subject to large operational influences.

2.3 TEST TO ASSES ASPHALT WEAR: ROAD TEST MACHINE (RTM)

The Road Test Machine was built by what is known as the TRL in the 1930's to research the properties of asphalt road materials. The equipment was located from TRL to the University of Ulster in 2004. [4]
The RTM was originally designed over 70 years ago and was subsequently at what is now known as the TRL for many years. [5]
Actually, it is used to assess the wear characteristics of High Friction Surfacing system for use in the United Kingdom, and it has also used at the University of Ulster to investigate the wear characteristic of asphalt materials.
The same methodology as used for High Friction Surfacing, was used in this laboratory investigation to assess the change in SMA characteristics.
The machine, shown in Figure 2.5, consists of a 2.1 m diameter table that rotates at 10 rpm. Up to ten 305mm x 305mm x 50mm test specimens can be mounted on this table.
Two vertically mounted tyres rune freely on the table applying a load approximately 5 kN. New tyres are fitted prior to testing a new set of test specimens.
During testing the tyres track back and forth across the width of the test slab. The RTM is enclosed in a temperature controlled room where testing is carried out at 10+/-2C. Both the number of rotations and temperature are recorded automatically. The RTM can be programmed to stop after a specified number of rotations. [4]
The use of this machine allows to reach three main objectives:

- To determine the effect of nominal aggregate size on wet skid resistance and texture depth.
- To determine how these properties developed with simulated trafficking.
- To assess the importance of contact area on wet skid resistance and texture depth. [5]

Figure 2.5 – Road Test Machine

CHAPTER 3

3D TECHNIQUES FOR THE EVALUATION OF TEXTURE DEPTH

3.1 INTRODUCTION

Characterization of surface texture is very important for pavement management applications, because it can affect road characteristics and vehicle performance in the areas of tire wear, rolling resistance, tire and road friction, noise in vehicles, exterior road noise and discomfort. [3]
Characterization of pavement surface texture has significant effects on ride comfort and road safety. It is typically reported as a single attribute, such as mean profile depth, root mean square roughness or hydraulic radius, which limits the usefulness of information extracted from texture measurements. [7] Although mean profile depth was correlated with friction and noise, it is not the only contributing factor, and for this reason, methods that characterize pavement texture in three dimensions are requested. [3]
The main objective of these methods is to recover the 3D heights of the pavement surface. Also, the validation of the proposed image-based texture indicators is examined. Results show that image-based techniques can be successfully applied to recover the 3D heights of pavement surface textures and provide substantial information on the friction and noise characteristics of the surface.
Pavement texture characteristic is a common indicator for evaluating the performance of road pavements In the wavelength ranges of macrotexture (0.5–50 mm), the most significant impacts of texture are in the areas of rolling resistance, tyre-road friction and noise.
The ability to characterize highway surfacing textures is essential to better understanding their performance. Traditional volumetric methods such as sand patch produce data based on estimation of a single geometry and offer little insight to early life deformations of bitumen coatings, changes in aggregate shape or longer term performance of the asphalt. Durability of an asphalt surfacing is a function of its ability to withstand static and dynamic contact

stresses applied during its life. The asphalt surface / tyre interaction governs properties such as grip, noise generation, rolling resistance and durability. These properties cannot be viewed or studied on their own. This requires a holistic approach, that is extremely difficult to predict. There is the need for laboratory testing to assess not only the aggregate, or the bitumen, but to evaluate the asphalt mix to accelerated simulated trafficking conditions and consequently relate these tests to observable and measurable performance in-situ. Most standard test methods offer little insight in this regard as they do not fully address how material performance and properties vary with time. [10]

3.2 THE CONTACT BETWEEN A TYRE AND THE ROAD SURFACE

Before analyzing the different 3D techniques, is interested to focus our attention on the knowledge of the contact patch between a tyre and the road surface. This is essential to improve understanding of surfacing properties. It was found that the contact area enveloped between tyre and surface is an ellipse; it’s directly proportional to wheel load and inversely proportional to tyre pressure. Siegfried and Douglas found stress due to a tyre rolling over a road surface to be highly concentrated. This concentration would then exploit any weaknesses in the aggregate or asphalt surface. A simple circular configuration is typically assumed in structural design. Figure 3.1 shows the ellipsoid model proposed by Tielking and Roberts to explain how the tangential motion between tyre friction and the pavement is inwards towards the centre of the tyre contact patch.

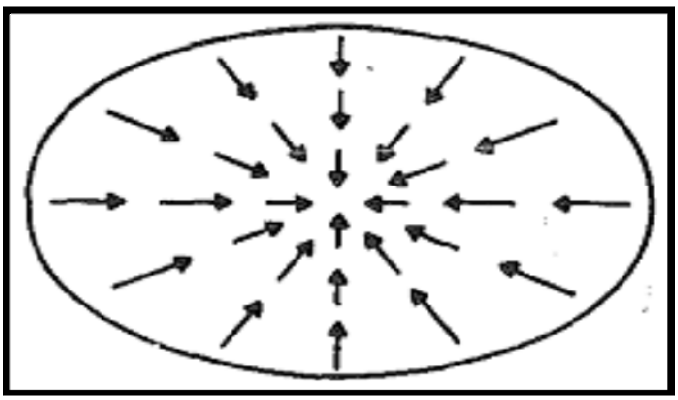


Figure 3.1 - Tyre deforming due to vertical contact

Millar showed that close range stereo photogrammetry could be used to monitor accelerated wear of asphalt concrete surfaces. Figure 3.2 shows a high resolution contact pressure map generated by a worn smooth Findlay Irvine Griptester tyre placed statically on a high resolution (1x1mm) XSensor pressure mat; this is a simplification of what actually happens.

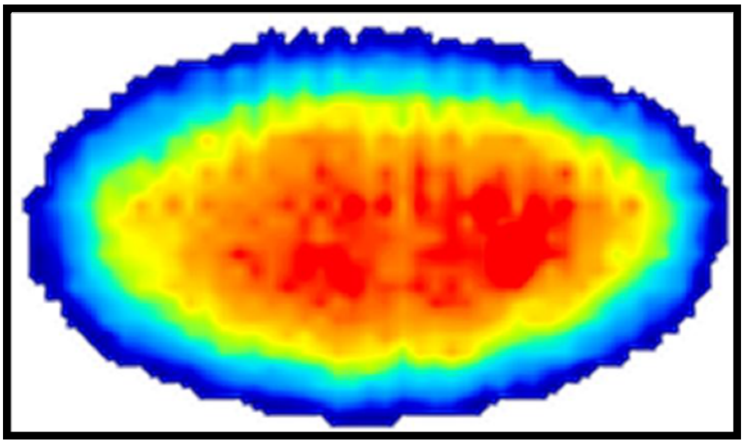


Figure 3.2 - Ellipitcal contact footprint measured using a high resolution XSensor pressure pad

Although wheel load is important to pavement structural design, tyre inflation pressure is more related to road / tyre interfacial phenomena. The distribution of contact stress within the contact patch is not uniform and changes frequently as a vehicle travels down a road. [8]

This interaction may be investigated in the laboratory to assess a range of properties ranging from aggregate and mix type, grip, texture, noise and rolling resistance, and this holistic relationship between tyre, road surface and vehicle is extremely difficult to model and predict.

3.2.1 LABORATORY EXPERIENCE

A new approach was developed to measure static and dynamic tyre / asphalt surface contact properties. It complements existing test methods such as the Noise and Rolling Resistance Indices and uses roller compactor slabs subjected to accelerated trafficking using the Road Test Machine (RTM) to show development of surface properties with time. This test in based concerns a modification of a Wessex dry wheel tracker to cause the asphalt test specimen to move under a loaded tyre in a controllable manner.

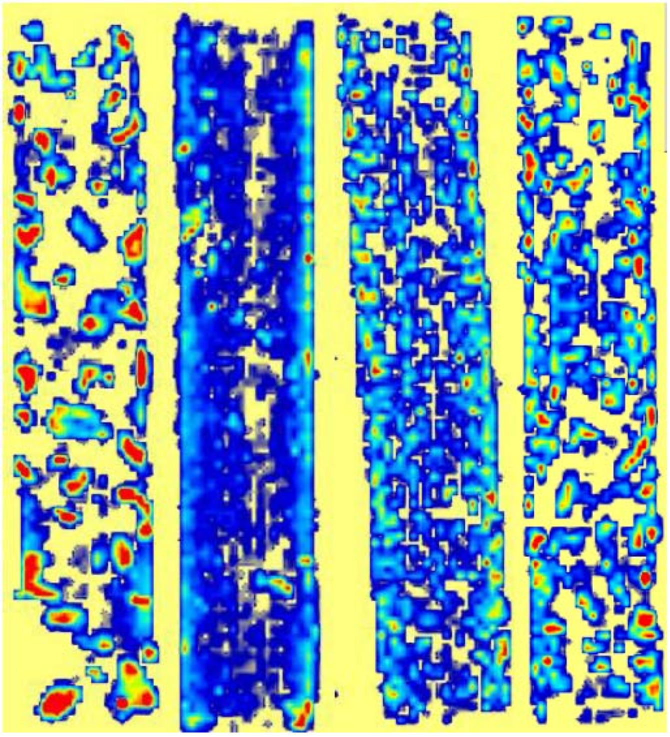


Figure 3.3 Example contact pressure maps for (left to right) chipped HRA, unchipped HRA, 6mm SMA and 14mm SMA

Highway surfaces are vulnerable to the potentially damaging effects of protracted exposure to wet weather or melting snow and ice containing de-icing salts. Cyclic freeze/thaw mechanisms and hydraulic pressures can subject a surface to significant stresses exacerbated by pockets of entrapped standing water. The ability to identify and rank surface vulnerability is another area of growing importance. Millar and Woodward noted that the extent to which water can accumulate on and within highway surfaces leads inevitably to consideration of surface texture.

Methods of characterizing surface texture range from the simple sand patch method for static spot testing to high speed laser based dynamic systems. However such methods based on estimation of a single geometry offer little direct insight of processes occurring at the tyre surface interface. The use of TIN datasets generated within a spatial information system from digital images can improve this. Millar found mean texture depth estimated from 3D models based on stereo images correlates well with sand patch method.

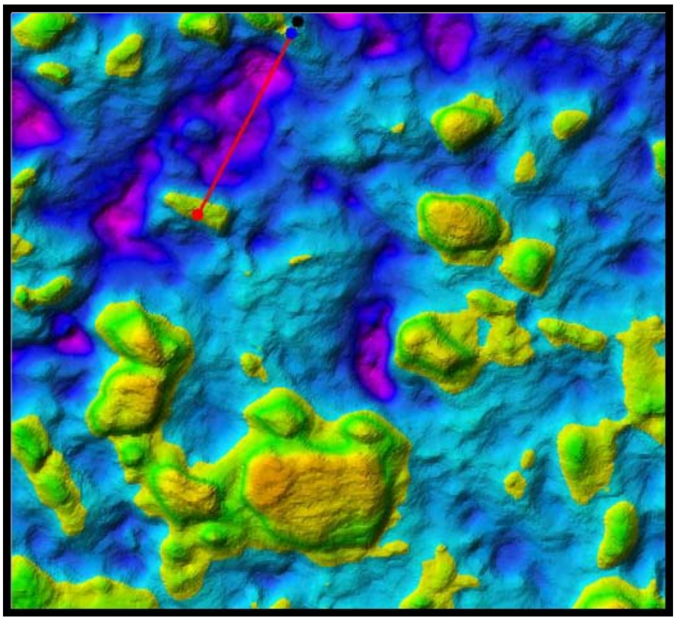


Figure 3.4 – Representation of depth using ArcGIS

This figure illustrate an example of ArcGIS depth classified surface showing potential areas of water entrapment, as areas of purple. Low textured surfaces may show high risk whilst a highly textured surface may have a relatively low risk of water entrapment. For this purpose, a simple estimation of texture depth alone gives a limited indication of a surface's capacity for surface water retention. This is an area that offers potential for predicting the effect of water on durability of asphalt surfacing materials. It's also very important to consider the effect of rain on aggregate wear and how aggregate wear is assessed. Simple in-situ conditions such as rain and the use of salt can have significant effects on the aggregate which in turn affects contact area and which in turn affects properties such as skid resistance, noise and raveling. It's possible to use pressure mapping to help explain the growth of a pothole due to a weaker aggregate, as shown in Figure 3.5 in which is illustrated a pressure distribution of a tracked asphalt slab test specimen where a single coarse aggregate particle is missing. This allow to consider the increased contact stressing around the hole in the and to monitoring his evolution after trafficking.

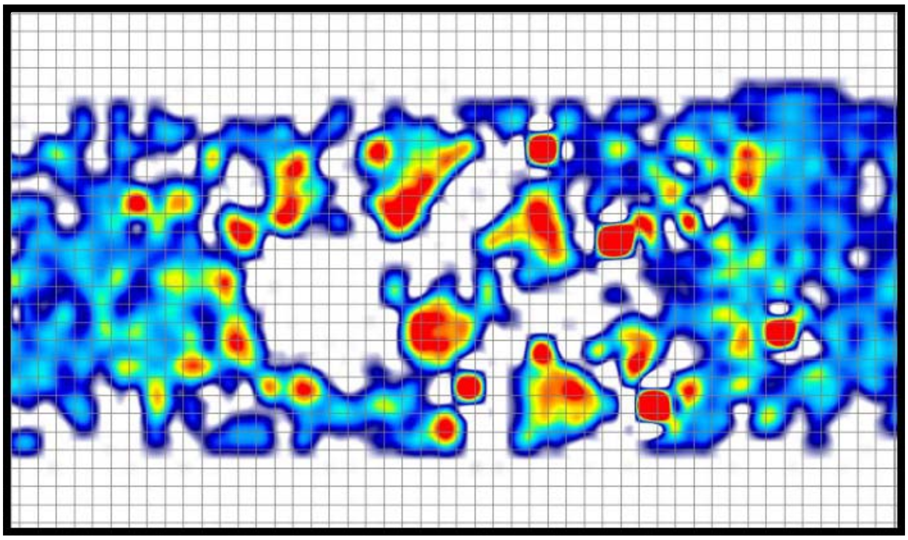


Figure 3.5 - Pressure map showing concentrated contact around a missing piece of coarse

3.3 CHARACTERIZATION OF TEXTURE USING 3D LASER SCANNER

The potential of a laser-scan 3-D technique is examined for the detection of road pavement macro- and micro-texture. Triangulation laser devices are based on forward intersection topographical principle and are therefore able to determine the position of one point within the instrumental reference system space. it is provided with:

- an emitting source allowing to scan the reference area by rotating at α emission angle;
- a reception sensor acquiring the ray reflected from surface at β incidence angle, determining the point coordinates at a given distance.

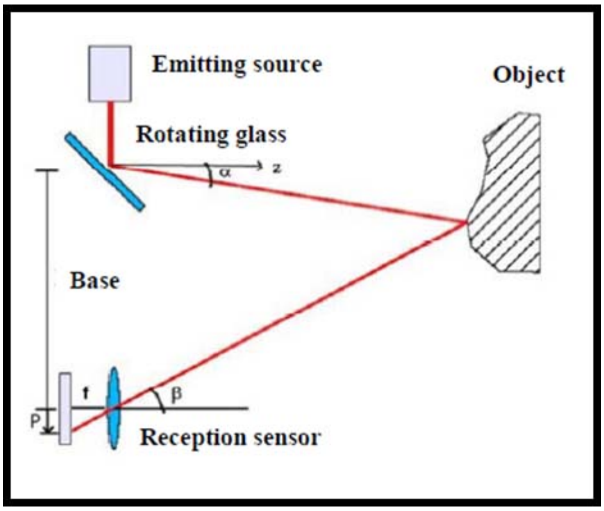


Figure 3.6 - Service drawings of a triangulation laser device

In addition to geometrical data, the instrument also allows to catch radiometric data. The device allows operating at Macro and Wide operating modes, differing in terms of accuracy, working distance and scanning surface size on one object. Acquisition speed is about 50,000 points/sec with an average delay of 90 seconds for each scan.

Laser datum acquisition is usually performed in both Macro and Wide modes. The scanner has to be set for individual scans at the best quality available, with an acquisition delay time of 120 sec approximately. In order to acquire an image of the whole surface with a single scan, samples need to be placed at about 40 cm when scanned in Wide mode. Scan data have to be user-filtered in order to remove both image portions of sample stands and any outlayers, that is rough mistakes in point determination. Mesh objects are linked to a single local reference system and once aligned, they need to be consolidated in a single mesh object describing the whole sample surface. In order to do so, it’s required that redundant points are removed along with triangulation faults resulting from:

• “non manifold” mesh conditions (3 surfaces are in the same side) (figure 3.7, n^{o} 1);

• Overlapping faces (some sides intersect) (figure 3.7, n^{o}. 2);

• Face redundancy (figure 3.7, n^{o}. 3);

• Inverted mesh normal (figure 3.7, n^{o}. 4).

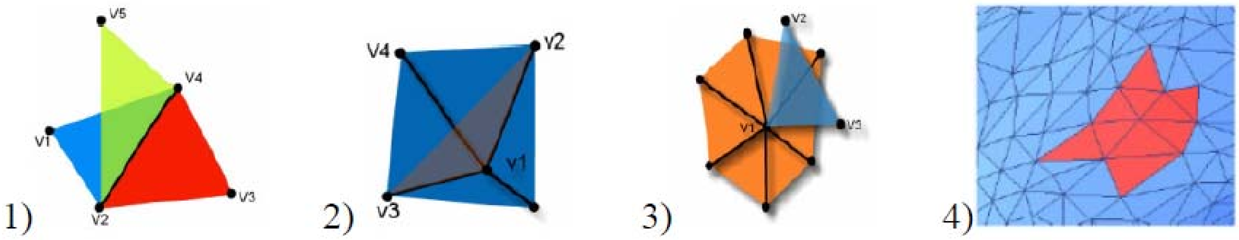


Figure 3.7 - Triangulation faults

After these stages, a final DSM (Digital Surface Model) is obtained representing sample orography. Figure 3.8 shows an example of this:

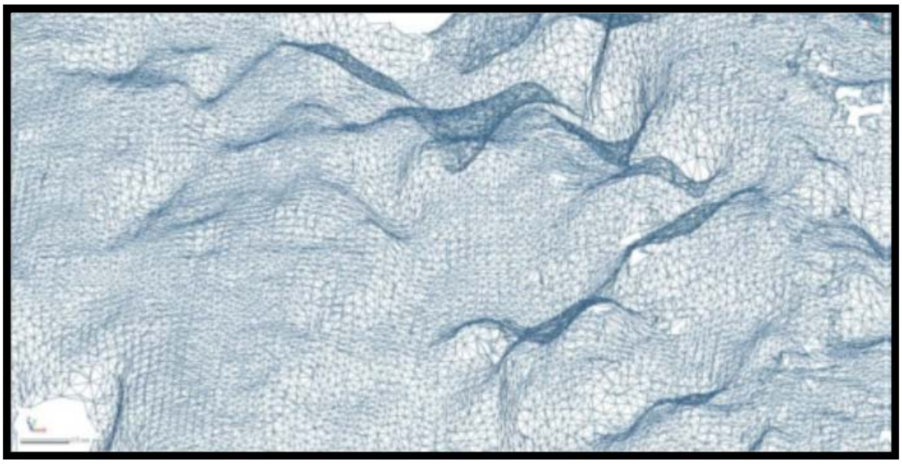


Figure 3.8 - Wireframe surface representation

In order to determine which data acquisition system would better suit the exam application, surfaces obtained through Wide and Macro modes must be compared along with the relevant deviations for each analysed sample.

Wide operating mode generally allows to obtain a morphologically representative image with one single scan, with a smaller number of dropouts, and processable with no particular mesh filtering operations. Opposite, the surface appears smoothed compared to Macro mode, since points spacing does not allow for a perfect detection of micro-roughness. In order to have a better understanding of his potentiality, it’s useful compare results obtained through laser scanner with indicators conventionally used in order to measure adherence. In particular, the indicators usually considered, are listed below and represented in Figure 3.9 and 3.10:

- ***HS value***, assessing surface roughness mean height as the between a given sand volume and the relevant covered area;
- ***Mean Profile Depth (MPD)***, determining profile mean depth as the difference between arithmetic mean of two peaks and mean level on a 100 mm baseline;
- ***average roughness (Ra)***, that is the average value of absolute deviations with reference to mean profile line;
- ***peak to valley height (Rt),*** that is the maximum vertical distance between the highest peak value and the lowest profile valley;
- ***levelling depth (Ru)***, that is the depth resulting from the distance between average line and a straight line tangential to the profile peak;
- ***mean depth (Rm)***, that is the distance between average line and a parallel line tangential to the most accentuated cavity, that is the lowest point.

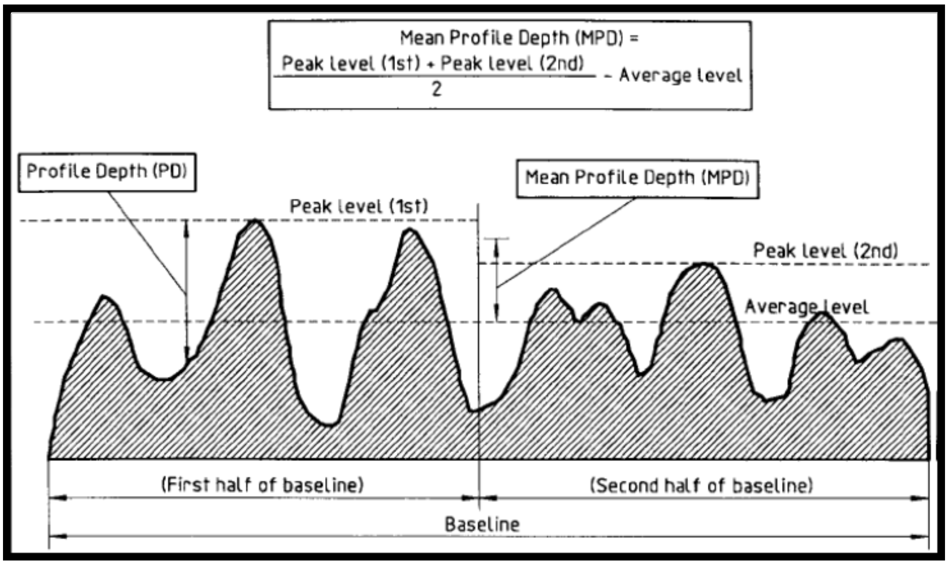


Figure 3.9: Mean Profile Depth Evaluation

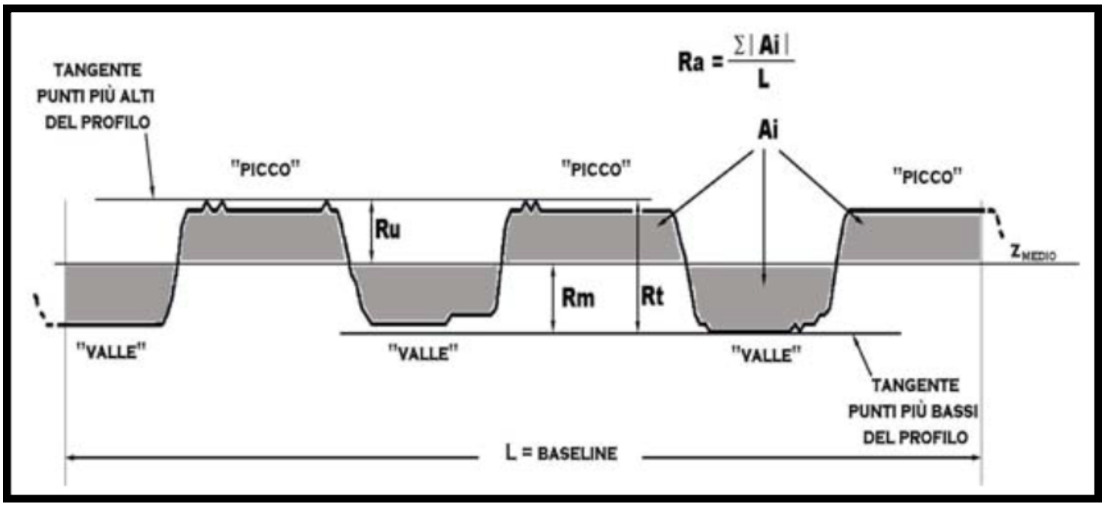


Figure 3.10: Indicators detected by means of profilometers

It can be seen that:

- in calculating roughness with ***Ra'*** (volume-surface ratio) and with average ***Ra*** (surface-length ratio) does not show any particular deviation, when calculated along all samples points;

MPD value generally shows max-min deviations of 20-35% among samples. The draining sample shows more significant deviations, indicating a more accentuated availability of peaks and valleys. When considering the same sample, MPD and HS values are very similar. This trend finds an evidence in test operating modes: sand shaving on sample tends to conform at higher peaks, getting closer to mean profile depth represented by MPD.

Examined materials can be also assessed in terms of water drainage on road surface, assuming that water layer is an even plan intersecting roughness and by recreating the emerged bitumen surface according to water volume increase on sample.

For instance, analyzing a draining sample, it's possible to notice that it has a bigger capacity, as it includes almost a double water volume. At equal water volume values, it keeps a higher emerged surface value, thus increasing the tyre-pavement surface and adherence accordingly. Individual draining features should also be taken into account, as they allow for different degrees of down flow.

Obtained results confirm 3D laser scanner potentials in detecting road surface texture patterns.

In fact, this technique offers a 3D datum on surface course and thus implies several benefits both in monitoring mixture laying, and in case of on-site checks such as:

- volumetric and surface studies involving adherence and tyre-pavement grip;
- on-site or log monitoring of pavement status in order to keep wear under control during surface life cycle;
- surface compressing level, through monitoring of macro-texture after treatment with tamping rollers. [3]

3.4 CHARACTERIZATION OF SURFACE TEXTURE USING PHOTOGRAMMETRY

Another important method, widely used for characterizing the surface texture is photogrammetry. it was first used by a French military officer in 1851, and in few years, there was a development of photogrammetric techniques to document building surveys predating aerial applications for which the method is now best known. Development of terrestrial photogrammetry from plane table techniques through analog to contemporary digital processing has greatly enhanced its usefulness and potential across many aspects of civil engineering and aligned disciplines. In fact is possible to use photogrammetric techniques to quantify texture depth change for highway surface course mixes under accelerated laboratory trafficking conditions.

The photogrammetric method was chosen as it offers a number of benefits to alternative techniques and because of the simplicity of the method; post processing and stereo matching are carried out using proprietary software.

Close range sub-pixel accuracy is achievable with modest camera technology which has significant implications for rapid capture surface monitoring. This made it ideally suited for exploratory investigation under the accelerated laboratory conditions.

The initial investigation had several objectives related to real world scenarios i.e. to quantify aggregate wear and to explore additional uses of the data e.g.

the application of triangular irregular network (TIN) meshes to model changes in the characteristics of surfaces subject to increasing trafficking under simulated conditions. [9]

The fundamental principle used by photogrammetry is triangulation. By taking photographs from at least two different locations, so-called "lines of sight" can be developed from each camera to points on the object. Taking photographs is, of course, essential for making a photogrammetric measurement. To obtain the high accuracy, reliability and automation the system is capable of, photographs must be of the highest quality. The three main considerations for good photography are:

- *Field of View*
- *Focusing*
- *Exposure*

The camera's field of view defines how much it sees and is a function of the focal length of the lens and the size of the digital sensor. For a given lens, a larger format sensor has a larger field of view. Similarly, for a given size sensor, a shorter focal length lens has a wider field of view. The relationship between format size, lens focal length and field of view is shown in the two pictures below:

Figure 3.11 – Field of view 1

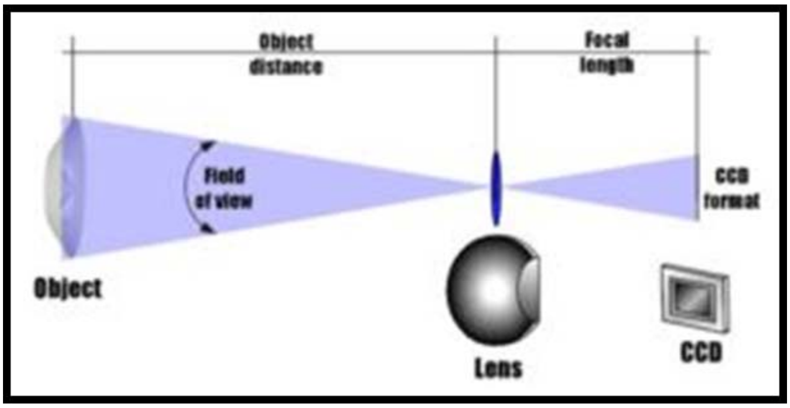


Figure 3.12 – Field of view 2

The wider the field of view, the more you see from a given location. For a medium angle lens, a convenient rule of thumb is that you will generally need to get back as far from the object as the size of the object. For example, you will get about three meters back to see a three-meter object. In general, there is a tradeoff between the field of view of a lens and accuracy. Although wider-angle lenses need less room around the object, they also tend to be less accurate. Thus, you generally want to use the longest focal length lens you can. One consideration for normal photography is, of course, focusing the lens so the image is sharp. The range of acceptable sharpness is called the depth of focus. The depth of focus of a lens is a function of many factors, including: the focal length of the lens, the format size, the distance from the camera to the object, the size of the object, and the f-number of the lens. As you can appreciate from all the factors listed above, the depth of focus can be a complex function. For photogrammetry purposes, it is desirable to set the targets bright and the background dimension. When retro-reflective targeting is used, the target and background exposures are almost completely independent of each other. The target exposure is completely determined by the flash power while the background exposure is determined by the ambient illumination. The amount of background exposure is controlled by the shutter time. Eliminating the background exposure makes the targets easier to find and measure. However, if there is no background image whatsoever, trying to figure out which target is which can be difficult. Usually, a compromise is reached and the background exposure is set so the object is dim enough to not interfere with target measurement, but still bright enough that it can be seen when enhanced. The shutter time is used to control the background exposure. The flash power setting for the target exposure depends on the distance from the camera to the targets, and the target size. If the targets are smaller than this, you may want to increase the flash power setting one step to help compensate.

Photography in its broadest sense is a process that converts the real three dimensional world into flat two dimensional images. The camera is the device that makes this transformation or mapping from three dimensions to two dimensions. Unfortunately, we cannot map the three dimensional world onto two dimensions completely so some information is lost, primarily the depth. Photogrammetry instead reverses the photographic process described above. It converts or maps the flat two dimensional images back into the real three dimensional world. However, since information is lost in the photographic process, we cannot reconstruct the three dimensional world completely with just one photograph. As a minimum, we require two different photographs to reconstruct the three dimensional world. If this process was perfect, the two photographs are more than enough information to perfectly reconstruct the three dimensional world they represent. Unfortunately, the photography and measuring process is not perfect so the reconstruction of the three dimensional world is also imperfect. However, we can take more photographs and use the extra information in them to improve the process. The three dimensional coordinates we produce from the measurements of multiple photographs are the end result of photogrammetry. Photogrammetry uses the basic principle of Triangulation, whereby intersecting lines in space are used to compute the location of a point in all three dimensions. However, in order to triangulate a set of points one must also know the camera position and aiming angles, together called the orientation, for all the pictures in the set. A process called Resection does this. Finally, because the camera is a precision measuring instrument, it must be calibrated so its errors can be defined and removed.

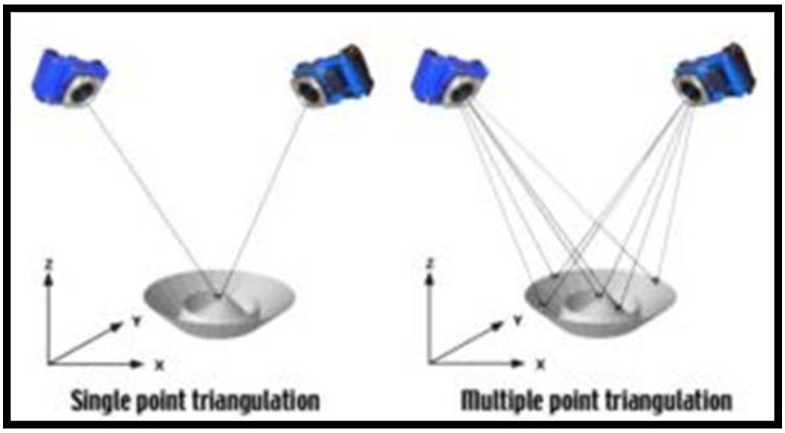


Figure 3.13 – Triangulation

Triangulation is the principle used by both photogrammetry and theodolites to produce three dimensional point measurements. By mathematically intersecting converging lines in space, the precise location of the point can be determined. However, unlike theodolites, photogrammetry can measure multiple points at a time with virtually no limit on the number of simultaneously triangulated points. In the case of theodolites, two angles are measured to generate a line from each theodolite. In the case of photogrammetry, it is the two-dimensional (x, y) location of the target on the image that is measured to produce this line. By taking pictures from at least two different locations and measuring the same target in each picture a "line of sight" is developed from each camera location to the target. If the camera location and aiming direction are known, the lines can be mathematically intersected to produce the XYZ coordinates of each targeted point. However, the accuracy of a photogrammetric measurement can vary significantly since accuracy depends on several inter-related factors. The most important are:

1. The resolution and quality of the camera you are using.
2. The size of the object you're measuring.
3. The number of photographs you're taking.
4. The geometric layout of the pictures relative to the object and to each other.

To scale a photogrammetric measurement, we must have at least one known distance. If we know the actual coordinates beforehand of some targeted points, we can compute the distances between these points and use these to scale the measurement. Another possibility is to use a fixture with targets on it and measure this along with the object. The distance between the targets on the bar is known and can be used to scale the measurement. Whenever possible, you should use more than one distance to scale the measurement. This is important because when a single scale distance is used and it is in error, the entire measurement will be incorrectly scaled. On the other hand, if you have multiple scale distances, scale errors can be detected and removed. With two known distances, if one is in error you will be able to detect a scale error but usually you cannot tell which one is in error. With three known scale distances, you can usually detect if one of them is in error and remove it. In some cases, a measurement may not need to be precisely scaled. For example, some surface or shape measurements do not require accurate scale. [11]

3.4.1 LABORATORY EXPERIENCE

Lots of tests developed at the University of Ulster, are based on the evaluation of texture depth, using photogrammetric techniques. The slabs are usually subjected to simulated trafficking using the Road Test Machine (RTM) located at the University of Ulster, stopping tests after different number of wheel passes and recording digital image pairs.

The stereo image pairs of each sample are then post processed using proprietary digital photogrammetric software, transformed within a prescribed reference framework and projected onto a two dimensional plane.

A stainless steel mesh overlay is used to provide control for post processing and to indicate possible differential distortion of the slab due to trafficking.

Following transformation slab surfaces are modelled using TIN meshes to generate 3D images to assess a range of parameters and variables. For example, it is possible to determine how the negative texture of the sample develops with time. The software can show how the perimeter of either an individual aggregate particle or a given area of the slab changes with increasing number of wheel passes. It is possible to quantify texture in relation to a reference plane that can be specified at 0.5mm intervals vertically down through the TIN mesh. The images may also be projected as contour and photo realistic texture maps.

The lighter areas are the trafficked slab/tyre interface whilst the darker areas are the negative texture of the asphalt concrete. Figure 3.15 shows the same image with a superimposed 0.1mm vertical contour interval.

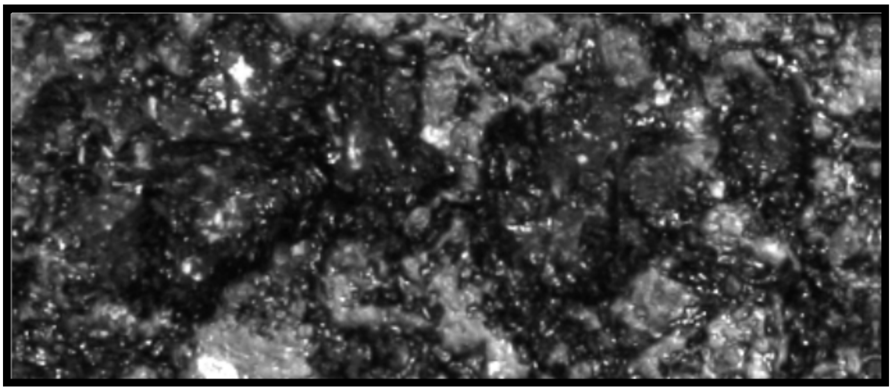


Figure 3.14 - Simple orthorectified digital image of trafficked asphalt concrete slab surface

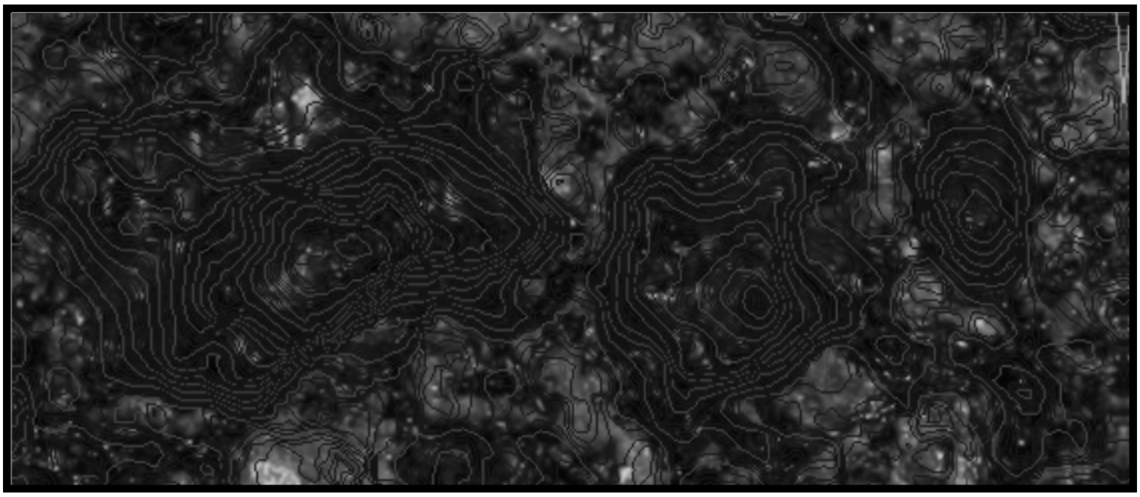


Figure 3.15 - Superimposed contours plotted at a 0.1mm vertical interval.

It's also possible to highlight the perimeter of three distinct areas of negative texture depth. The volume of each negative textured area enclosed by the polylines may be determined from the TIN mesh.

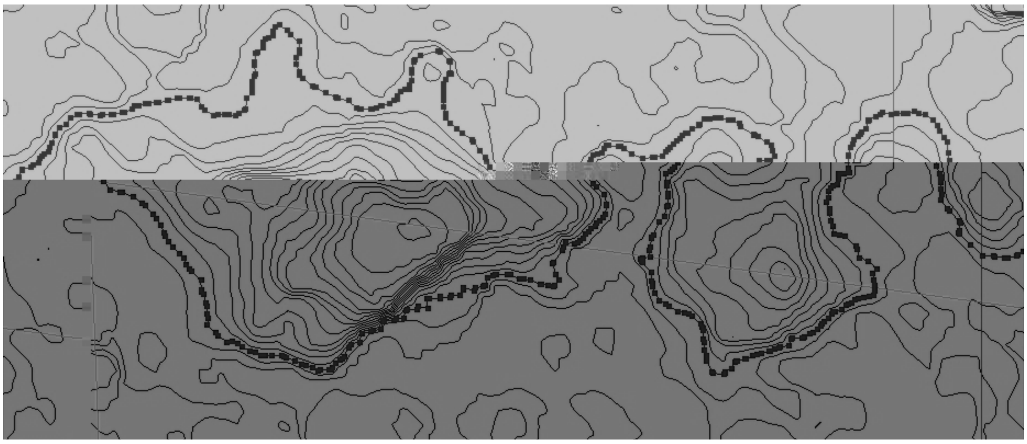


Figure 3.16 - Contoured surface showing 3 areas of negative texture

This allows to plot the change in area of the selected negative texture areas, or depressions, throughout the experimental cycle from different numbers of wheel passes. The general trend shows a reduction in area with increasing number of wheel passes indicating surface wear. Continued trafficking then continues to wear the asphalt surface causing a gradual reduction of texture depth. [9]

3.5 STEREO-VISION APPLICATIONS TO RECONSTRUCT THE 3D TEXTURE OF PAVEMENT SURFACE

Macrotexture measuring devices that map the pavement surface with a high degree of precision provide additional information and may allow a better understanding and modelling of the tyre–pavement interaction.

With the progress in image-processing technology, different techniques can be used for extracting pavement information from images. First, Schonfeld, in 1970, used stereophotography for documenting pavement conditions.

The procedure required the capture of 5–10 photographs of a surface viewed through two different micro-stereoscopes and interpreted to determine various surface texture parameters.

The edge-detection technique was used for studying aggregate size, angularity and texture. For a grey-scale image of an aggregate sample, a predetermined intensity for the background was used (white background), and threshold grey intensity was applied to distinguish between soil particle colours and their background. The image was converted to a binary image in which a black colour region represents the surface of a particle.

The edge-detecting technique can be extended to reconstruct the 3D shape of an aggregate by using two or three orthogonal camera positions.

Since aggregate is one of the components used to construct the pavement surface, studying aggregate properties only is not sufficient to represent the pavement surface texture. Also, the orthogonal camera technique is not applicable to measuring surface heights of a pavement sample.

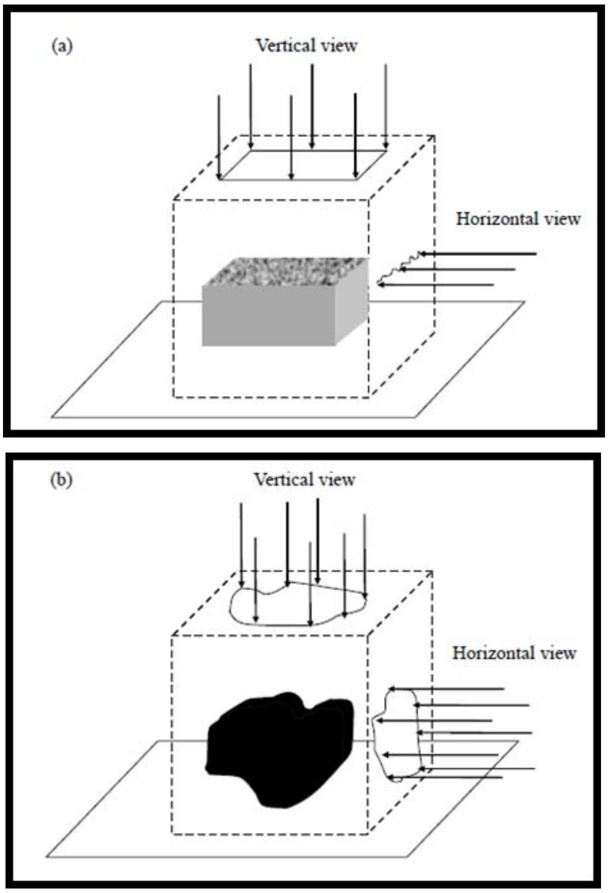


Figure 3.17 - Setup of orthogonal camera position:
(a) pavement sample and (b) aggregate sample.

The maximum value of the 2D Fourier transform of a filtered image was found to be correlated with the qualitative performance rating of the chip-sealed pavement surface. Also, one-image analysis can successfully provide 1D texture indicator such as the root mean square roughness (RMSR) by analysing the variation in the pixel grey intensity values. One-image analysis cannot be used to recover the 3D heights of pavement surface, even when analysing an image to extract a 1D texture indicator, the limitations of this analysis should be taken into consideration.

For the recovery of the 3D heights, multiple images are required. An analysis of multiple images, usually called photometric stereo, can be successfully used for recovering surface heights of an object. The surface of an object reflects a fraction of the incident illumination in a given direction on the basis of the optical properties of the surface material.

The fraction of light reflected in a given direction is characterised by the surface orientation On the basis of the reflectance model, several techniques are available to recover the 3D shapes of objects. The photometric stereo technique is one of these techniques, where multiple images are captured of the same scene under different lightand view angle conditions. Although photometric stereo techniques have been successfully used for recovering surface texture applying such techniques for recovering pavement surface required adding extra features to overcome the problems raised from the properties of the pavement surface, which include specularity and shadow effects.

The stereovision system (SVS) recovers surface height by capturing two images of the same scene using two cameras separated by a small baseline distance. As a result, they get slightly different views of a 3D scene. Then the two images are compared by making relative shifts, effectively placing one image on top of the other and translating them to find the parts that match. The shifted amounts are called the disparity values. The disparities, at which objects in the images have best match, are used by the processing software to calculate their distances from the camera.

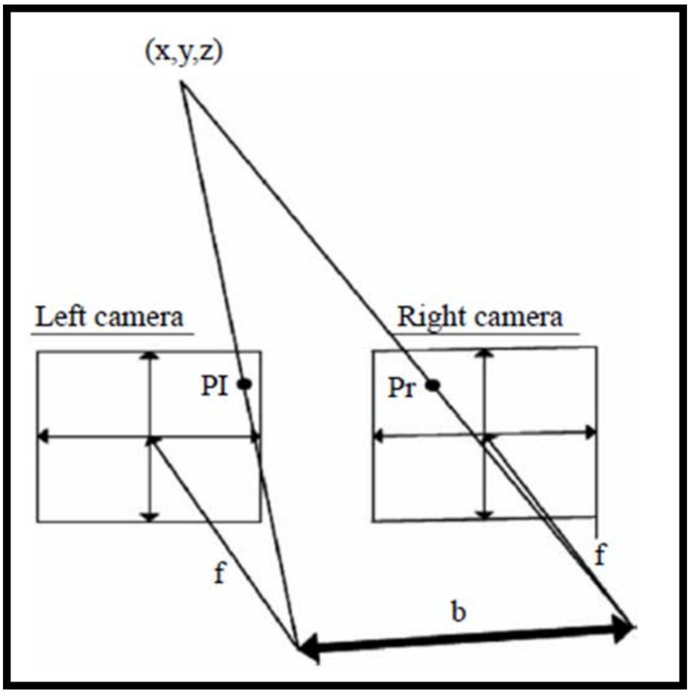


Figure 3.18 - Stereo-vision principle

The figure 3.18 shows the location of the points (x, y and z coordinates) in the pavement surface can be determined using triangulation in stereo imaging, considering cameras located at a distance from the surface. By knowing the distance between the cameras and finding the corresponding pixel match from images taken by both cameras, we obtained the depth information, where pixel Pl taken from the left image is matching with pixel Pr taken from the right image. The surface-measuring process begins by setting the appropriate properties of the camera (aperture, focus, gain, etc.), pointing the cameras downward facing the pavement surface at a distance of 0.39m from the ground, and taking a pair of stereo images.

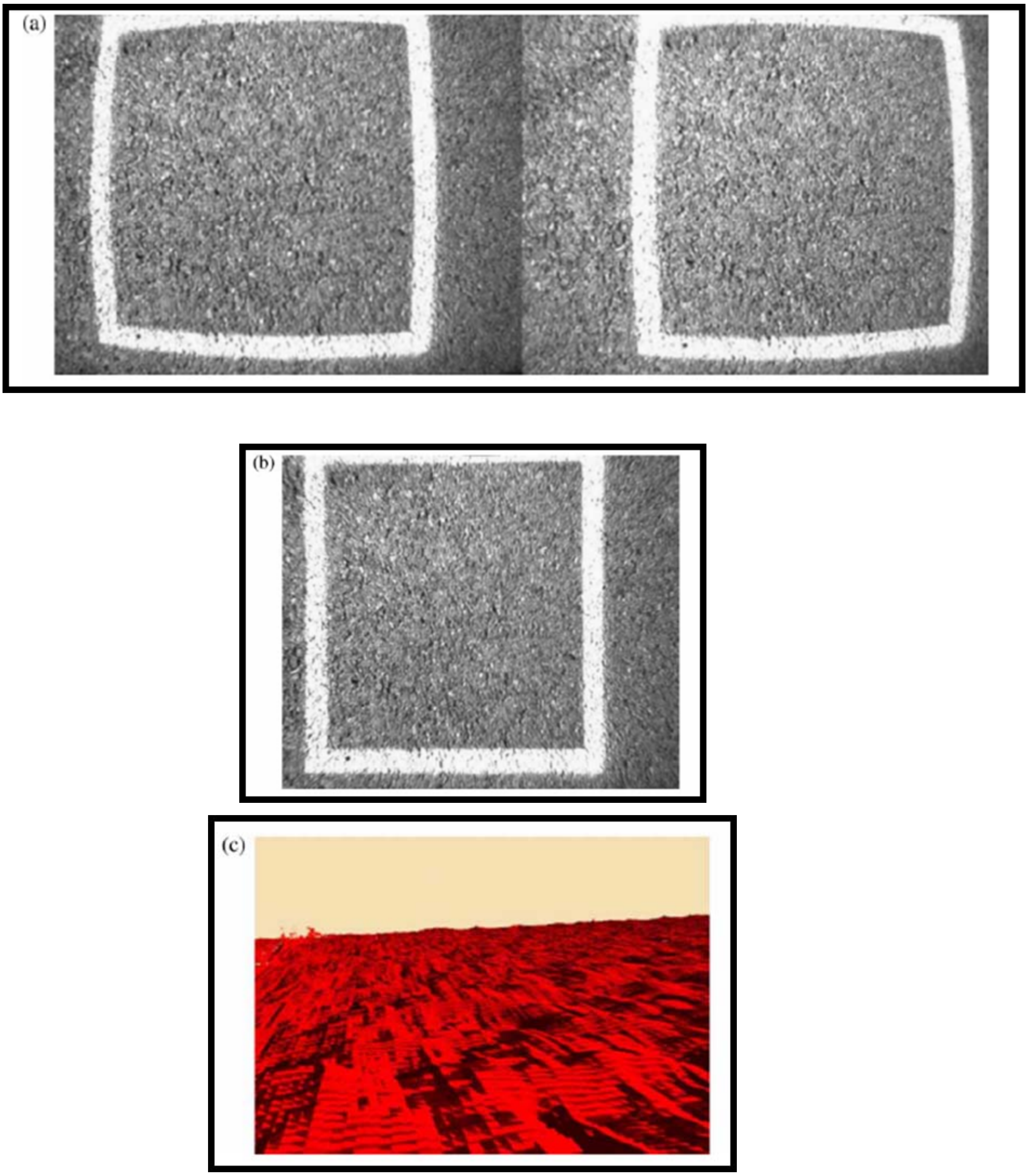


Figure 3.19 - Stereo-vision digital images and reconstructed surface: (a) raw digital images, (b) rectified stereoscopic image and (c) 3D map.

The captured images were then processed to remove lens distortions, and rectified to align the epipolar lines Additional constraints for texture validation, surface size validation and disparity range reduce false matches and improve accuracy of the resulting disparity image. The disparity values can be converted to a grid with x, y and z coordinates, which represent the 3D heights of the pavement surface. Statistics such as average depth can then be calculated to quantify the surface texture.

Mean texture depth (MTD) equivalents are computed as the overall maximum average depth difference of the 12 sectors in which an image is divided after matching all the pixels and obtaining individual z-coordinates for each one. Non-valid points are not considered in the computations.

3.5.1 PHOTO TEXTURE TECHNIQUE

The three-image photometric stereo technique was proposed by Woodham (1980), where three images are captured under three different directions of incident illuminations, whereas the viewing direction (camera location) being held constant. Assuming a constant light intensity and since the image geometry is not changed, any three incident directions which do not lie in a plane were sufficient to reconstruct the 3D surface heights. But because of the properties of the material of the pavement surface, specularity and shadow effects are some of the problems encountered when photometric techniques are used. When a point on the surface is oriented such that its specular spike is in the same direction as one of the three light sources, a spike is produced in the reflected intensity. A fourth source is added to detect the existence of specularity by computing four surface normal vectors; one normal for each combination of the three images. Similarly, shadow appears when an object blocks the incident rays from reaching a certain area In the same manner, the fourth source can be used for detecting shadow contribution, where image with shadowing contribution can be excluded from the surface recovery procedure. The four different light sources were replaced with one source, which was manually repositioned in the required four light directions. Because the dark monotone of the pavement surface requires a high-illumination intensity to produce a reasonable variation in surface reflectance, a fibre optic light source with adjustable illumination intensity was used. The light intensity was adjusted so that the digital still camera had an optimum scene exposure. A practical application of the systems reviewed in this paper is the determination of commonly used parameters to measure texture depth. Pavement texture is defined as the deviation of a pavement surface from a true surface within a specified wavelength range. The most common texture indicator, the MPD, is the standard method for computing the average depth of pavement surface macrotexture from surface profile

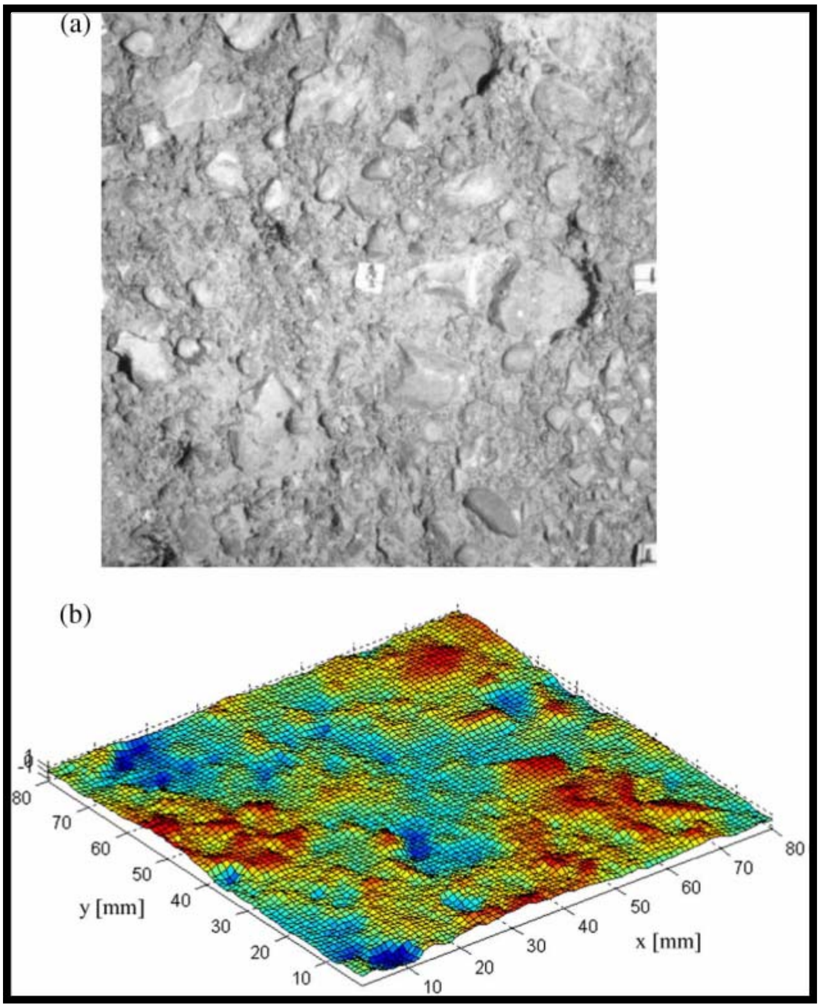


Figure 3.20 - 3D recovery of surface heights: (a) pavement sample and (b) the 3D recovery.

Generally, the MPDs computed from PhotoTexture were smaller than those computed from manual measurements because of the method of integrability used to recover the 3D heights of the surface.

The Root mean square roughness (RMSR) for a typical profile of pavement is the standard deviation of the height of the surface profile. As an advantage, the area-based measurement technique allows computing the power spectrum energy (PSE).

The quality control of measuring the uniformity of pavement texture is another innovative application that cannot be achieved with conventional technologies.

The University of Manitoba tested a new paved section in Illinois to study the effect of texturing type on tyre– pavement noise and fiction, and Photo Texture 2.0 was used for the testing performed immediately before the road was opened for traffic.

The comparison of the tested samples with their corresponding map of heights demonstrates the ability of Photo Texture to detect texturing successfully.

Different systems for recovering pavement surface texture from digital images, have been shown. Laboratory and field experiments conducted with these new tools supported that photometric stereo can be used successfully for measuring pavement surface heights in the range of macrotexture.

Since current texture indicators, such as the MPD, are based on unidirectional profiles, a new indicator was proposed and assessed. The PSE based on a 2D Fourier transform of an area-based grid of surface heights is proposed as a texture indicator. The results suggest that area-based macrotexture indicators and measurement techniques will provide a better understanding of pavement surface properties, and more accurate simulation of tyre–surface interaction and pavement surface maintenance and rehabilitation needs. [7]

CHAPTER 4

EXPERIMENTAL PHASE

4.1 INTRODUCTION

The aim of this project was to analyze a range of asphalt surfacing materials used in the UK, in order to improve current understanding of their surface texture. Each surface has been first assessed using standard methods, such as Sand Patch and after that using 3D photogrammetry and 3D laser techniques. Properties such as tyre-pavement contact areas, water storage and horizontal water drainage have been determined. The analysis has involved the use of different software applications; the additional classification properties carried out from these, enabled a better understanding of the role of surface textures in analyzing features such as grip, wear, durability, spray generation and noise. The purpose was to appreciate how the Skid Resistance and the Texture Depth varied through the process of wear, subjecting the samples to the effect of trafficking. The experimental phase followed different stages as showed in the flow chart in Figure 4.1. After an initial study about the mix design, the preparation of the samples and the analysis of some properties such as voids content, laboratory tests were effectuated. It has been determined the Texture depth, the Skid Resistance and the Contact Area of the samples before and after trafficking them with the RTM. Successively the use of 3D techniques were required to reconstruct the texture of the specimens and to analyze some properties of the surface.

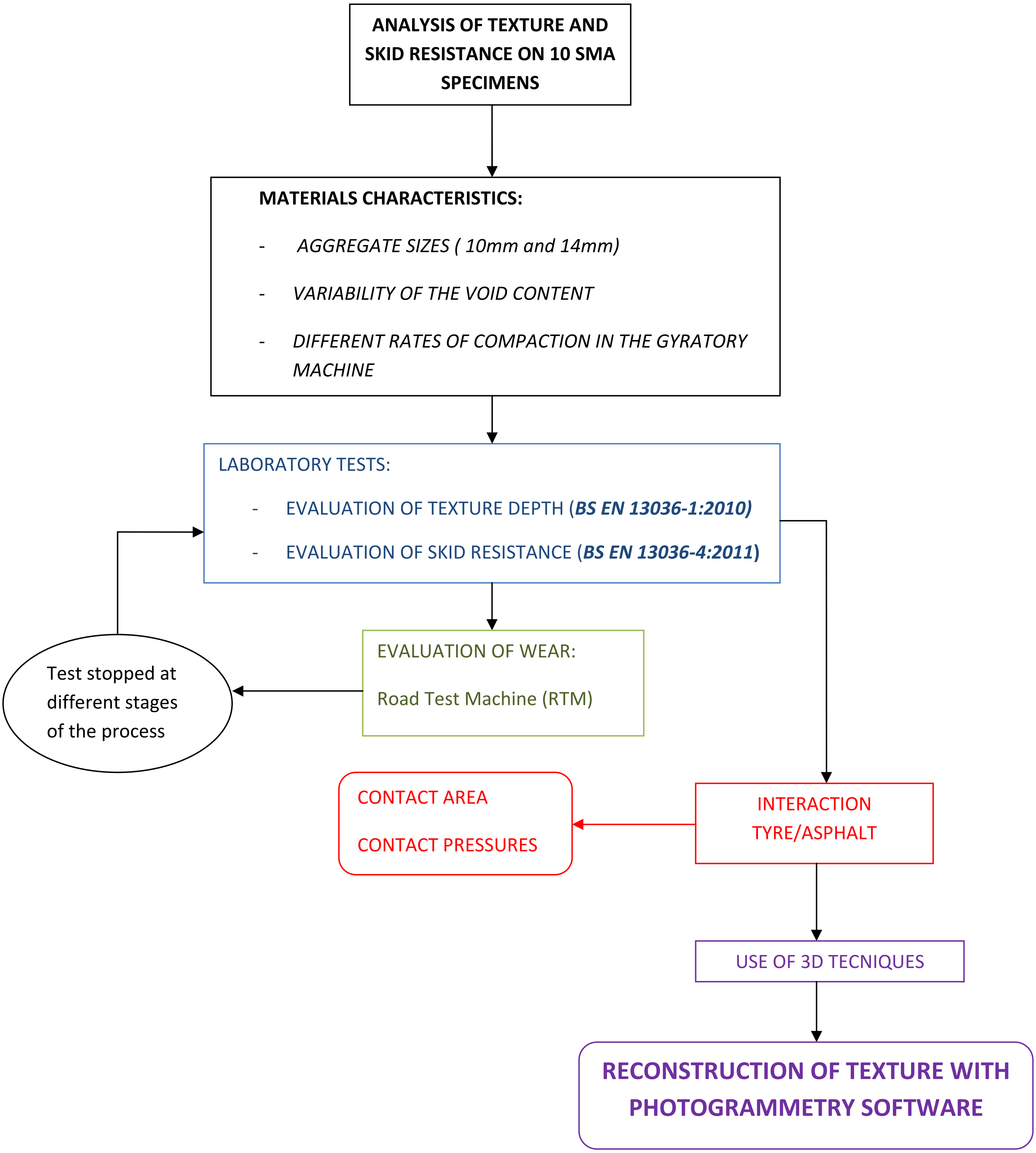


Figure 4.1 – Flow chart

4.2 PREPARATION OF THE SAMPLES

The first stage of the project comprises the creation of SMA (Stone Mastic Asphalt) samples, with aggregates sizes of 10mm and 14mm, using the ELE-SERVOPAC Gyratory compactor. The main characteristics of the materials have been summarized in tables 4.1 and 4.2 below and graphically represented in Figure 4.2 and 4.3:

BS SIEVE SIZE (mm)	PERCENTAGE PASSING (%)	CONFORMITY SPECIFICATION (%)
20,0	100	98-100
16,0	100	
14,0	97	89-100
10,0	51	44-58
8,0	39	
6,3	34	23-37
4,0	31	
2,0	22	16-28
1,0	17	
0,500	15	
0,250	12	
0,125	10	
0,063	7,6	5,7-9,7

Table 4.1 - SMA 14 SURF (FIBRES)

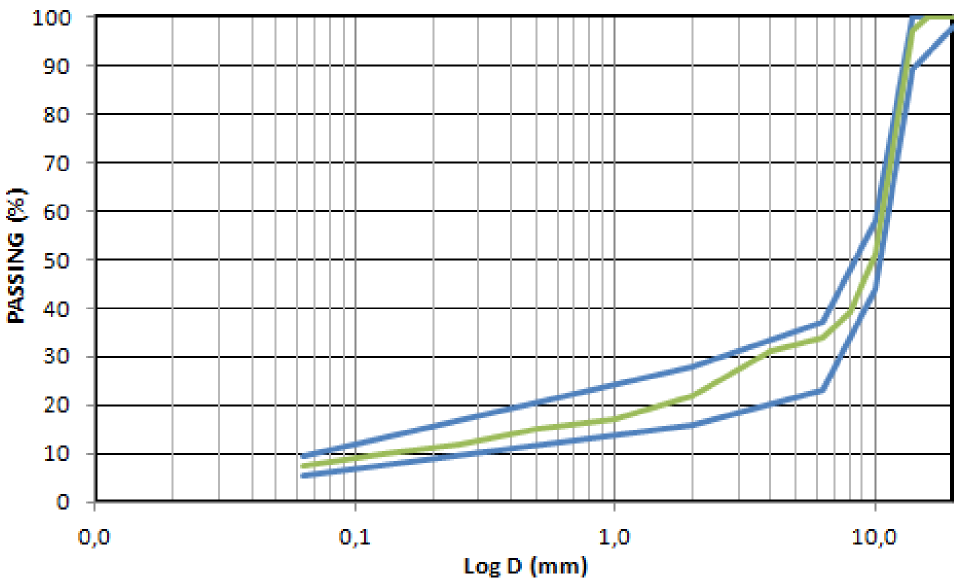


Figure 4.2 – Percentage of passing (14mm)

BS SIEVE SIZE (mm)	PERCENTAGE PASSING (%)	CONFORMITY SPECIFICATION (%)
14,0	100	98-100
10,0	99	90-100
8,0	74	
6,3	44	40-54
4,0	35	
2,0	26	19-31
1,0	18	
0,500	15	
0,250	12	
0,125	10	
0,063	7,7	6,0-10,0

Table 4.2 - SMA 10 SURF (FIBRES)

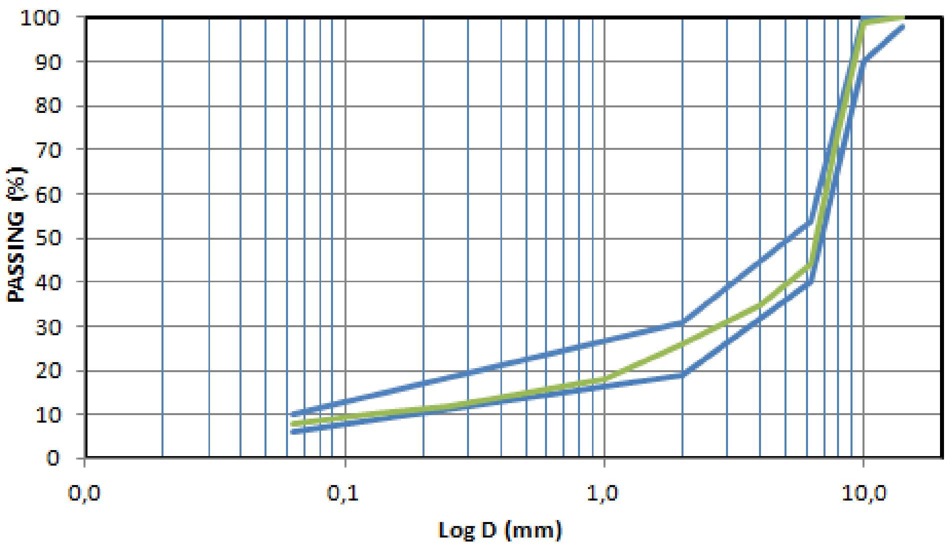


Figure 4.3 - Percentage of passing (10mm)

The first mix contains the 6% of binder, while the second one a percentage of 6.2%.

The materials have first been heated in an oven set to 160 °C (Figure 4.4), successively weighed and put in the gyratory compactor mould with filter paper at the bottom and on the top (Figure 4.5). The different weights used, vary from 1600g to 2400g for 14mm samples and from 1750g to 2400g for 10mm ones.

Figure 4.4 – Some stages in the samples' preparation

After this, using the gyratory compactor, it was possible to create some samples for each kind of SMA with a different rate of compaction and different kind of surface texture, ranging from a smooth to a open textured one.

Figure 4.5 – Successive stages of the Gyratory compaction process

At the end, 5 samples from each aggregate size were chosen to begin testing. The main features of these samples are shown in the tables below:

SAMPLE	***HEIGHT (m)***	***WEIGHT (kg)***	***GYRATIONS***
12 *(1A)*	0.052	2.150	500
11 *(2A)*	0.049	1.940	300
14 *(3A)*	0.050	1.800	23
15 *(4A)*	0.050	1.700	9
16 *(5A)*	0.050	1.600	3

Table 4.3 – 14 mm samples

SAMPLE	***HEIGHT (m)***	***WEIGHT (kg)***	***GYRATIONS***
X *(1B)*	0.050	2.100	950
V *(2B)*	0.052	2.100	300
I *(3B)*	0.050	2.000	300
IX *(4B)*	0.050	1.900	90
XIII *(5B)*	0.050	1.750	16

Table 4.4 – 10 mm samples

4.2.1 THE GYRATORY COMPACTOR MACHINE

The gyratory compactor simulates the kneading action of rollers used to compact asphalt pavements by applying a vertical load to an asphalt mixture while gyrating a mold tilted at a specified angle. The Superpave Gyratory Compactor (SGC) is used in the Superpave mixture design system to prepare asphalt specimens for determining volumetric and mechanical properties. It produces specimens that are similar to pavements in aggregate orientation and mechanical properties, and it can be used for quality control at hot-mix plants. To compact a specimen, an asphalt mixture is placed in a steel mold that has an inner diameter of 150 mm and a steel base plate that serves as a lower platen. The assembly is placed inside the SGC where a load is applied through an upper ram and platen. The bottom of the mold is shifted horizontally along one diameter to provide the required angle of

1.25 degrees. The angle is then applied to the mold in a circular manner at a constant speed of 60 gyrations per minute. The platens remain parallel to each other during compaction, but are free to move with respect to the mold as the mixture densifies. Compaction occurs due to the pressure from the ram and the kneading action provided by the revolving angle. The standard ram pressure is 600 kPa. As the specimen densifies and becomes shorter in height, a pressure gauge signals the loading system to adjust the position of the loading ram so that the 600 kPa pressure is maintained throughout the compaction process. The SGC uses a linear variable differential transformer to record the position of the upper loading ram. The vertical change in ram position provides a measurement of the specimen height during compaction. The SGC methodology uses the change in height to determine the change in density with gyrations. Density is the mass of the specimen by its volume. Thus, the SGC provides a compaction curve, which is the relationship between density and the number of gyrations. In the Superpave volumetric mixture design, the optimum binder content is chosen so that it provides a 4% air void content at the design number of gyrations, called N_{design}. N_{design} for dense-graded mixtures ranges from 68 to 172. It depends on the traffic level and the climate where the mixture will be placed. N_{design} for stone mastic asphalt is 100. Two other gyration levels are also used to evaluate a mixture: the initial number of gyrations, called $N_{initial}$, and the maximum number of gyrations, called $N_{maximum}$. $N_{initial}$ is used to eliminate tender mixtures. $N_{maximum}$ is used to eliminate rutting if the air-void level in the pavement falls below the design level of 4 % because of uncertainties such as increased traffic. [12]

4.2.2 ELE-SERVOPAC GYRATORY COMPACTOR

The Servopac is a fully automated, servo-controlled, gyratory compactor designed to compact asphalt mixes by gyratory compaction. Compaction is achieved by the simultaneous actions of static compression and the shearing action resulting from the mould being gyrated through an angle about its longitudinal axis. A number of ergonomic features have been designed into the Servopac to ensure operator safety and minimise manual handling of the hot and heavy asphalt-filled moulds. The mould slides from a bench directly into the compaction chamber, and following compaction, to the pneumatically operated specimen extraction device, thus eliminating any lifting. The compaction chamber is completely enclosed, and the access door is fitted with safety glass to allow the operator to view the compaction process. The door closes and opens automatically and a safety interlock prevents the machine from operating while it is open. The Servopac has a four column frame for increased rigidity. Vertical stress is measured by a load cell and is accurately controlled during compaction. The gyratory motion is also servo-controlled, enabling the gyratory angle to be accurately controlled during compaction, irrespective of load and minor flexing of the machine's components. The servo-control operation of the machine allows the vertical stress, gyratory angle and speed to be quickly modified from a hand-held control pendant or PC. The optional PC 'Windows' interface provides a screen to input test parameters and display and plot either height, density or angle against gyratory cycles in real time. Test data may be stored and retrieved or transferred to other software analysis packages. The Servopac is designed to comply with SHRP Superpave asphalt mix design requirements and the recommendations of the draft CEN European standard on gyratory compaction. [13]

4.3 MAIN PROPERTIES OF THE SAMPLES

It was interesting to analyze some of the relationships between different features of the samples during the compaction process. For instance, the change in the heights of the samples has been evaluated after an established number of gyrations. This analysis was stopped after 200 gyrations and the results show that the sample’s height reduces with the increase of the gyrations. The experiment was carried out using 5 specimens of 10mm SMA and 5 of 14mm SMA, all with varied weights, as we can see in these two graphs:

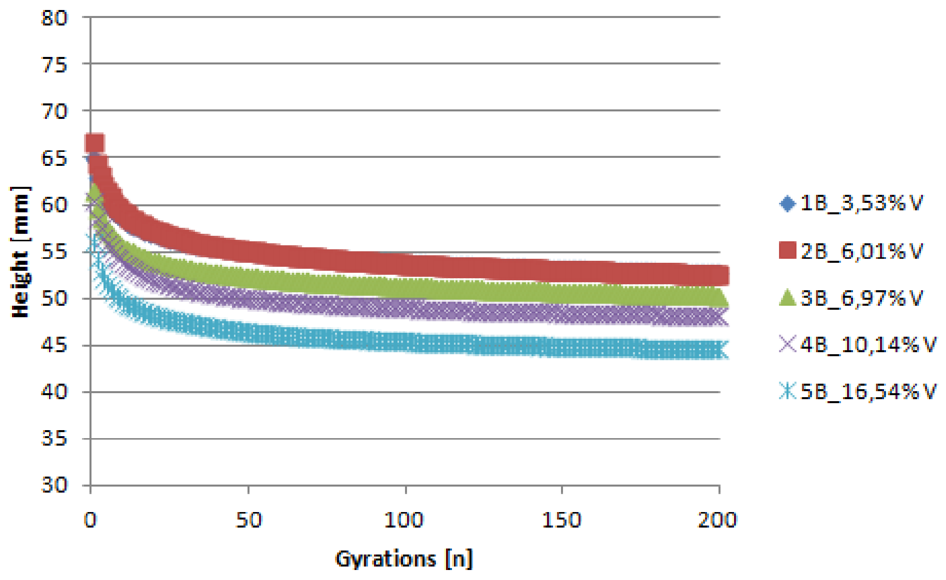


Figure 4.6 – Relationship between heights and gyrations for 10 mm samples

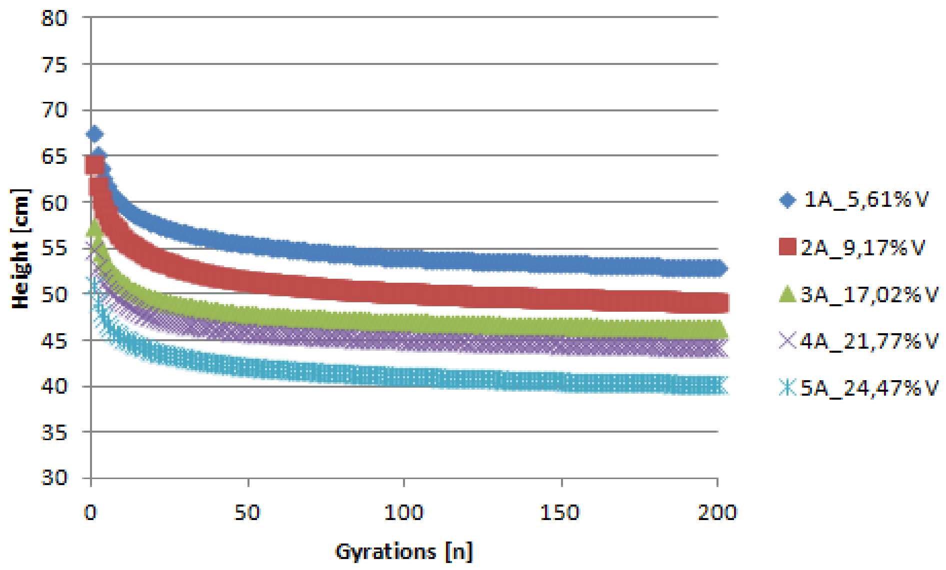


Figure 4.7 – Relationship between heights and gyrations for 14 mm samples

It is important to realise that in both of these two diagrams, the trend is the same. The heights of the specimens decrease with the increasing void content, but for the 14 mm aggregate, it's possible to notice a wider range of values, that reflect in an higher variability of texture.

The relationship between density and number of gyrations was another interesting aspect of this experiment. This analysis has been completed after 200 gyrations. Firstly, it was necessary calculate the volume of each sample, considering a radius of 150mm and a variable height, changing with the evolution of the compacting process:

$$V = \pi * r^2 * H \quad [m^3]$$

and so the density is the ratio between mass and volume:

$$\rho = W/V \ [kg/m^3]$$

The results are summarized in the tables below, and represented in Figure 4.8 and 4.9.

SAMPLE	***WEIGHT [kg]***	***DENSITY AFTER 200 GYRATIONS [kg/m³]***	***VOLUME AFTER 200 GYRATIONS [m³]***
1B	2,100	2,2553	0,9311
2B	2,100	2,2631	0,9279
3B	2,000	2,2486	0,8894
4B	1,900	2,2329	0,8508
5B	1,750	2,2219	0,7876

Table 4.5 – Density - Volume for 10 mm samples

SAMPLE	***WEIGHT [kg]***	***DENSITY AFTER 200 GYRATIONS [kg/m³]***	***VOLUME AFTER 200 GYRATION [m³]***
1A	2,150	2,3027	0,9341
2A	1,940	2,2379	0,8682
3A	1,800	2,2023	0,8173
4A	1,700	2,1769	0,7809
5A	1,600	2,2522	0,7103

Table 4.6 – Density – Volume for 14 mm samples

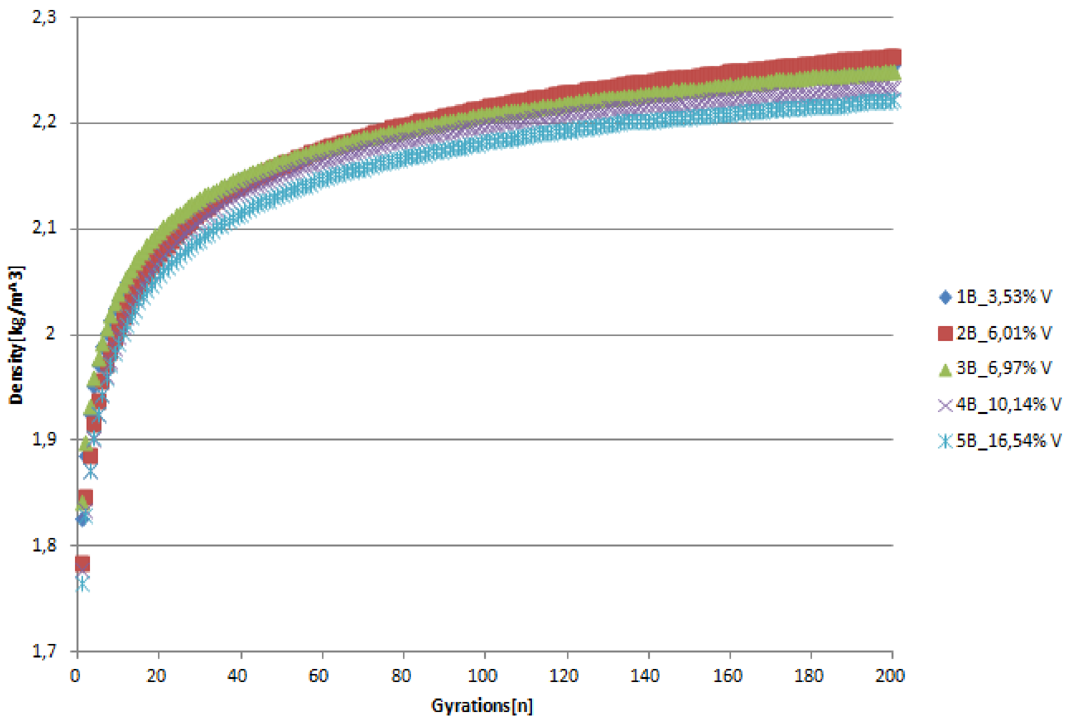


Figure 4.8 – Evaluation of density after 200 gyrations (10 mm samples)

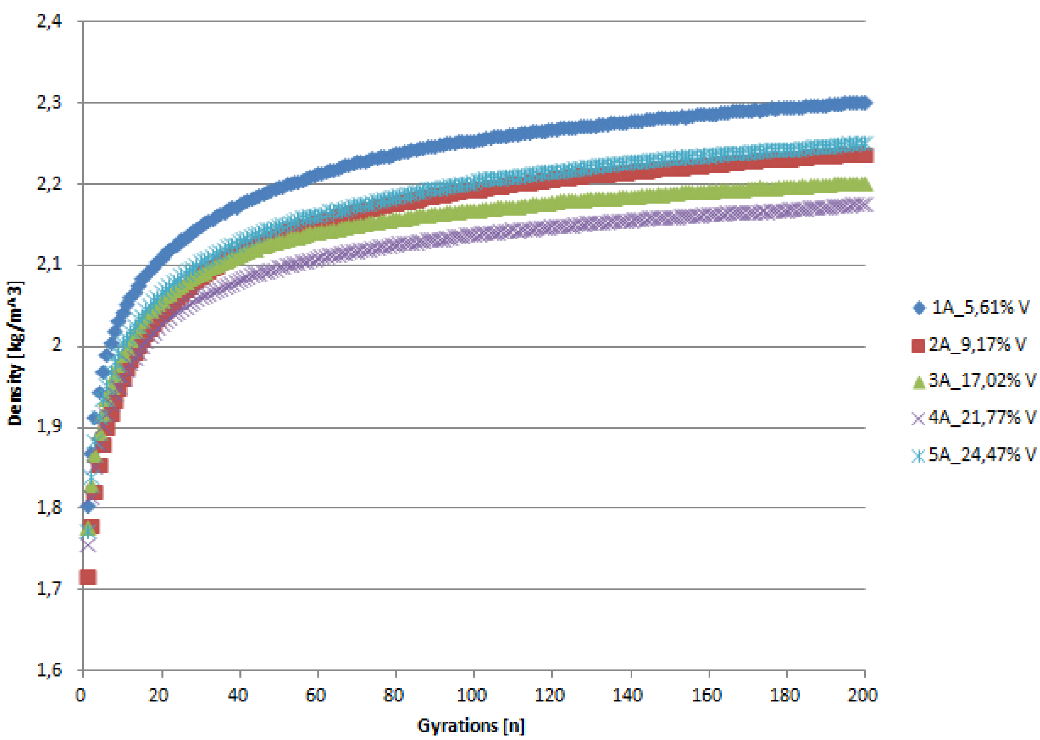


Figure 4.9 – Evaluation of density after 200 gyrations (14mm samples)

In these two graphs, the density increase with the number of gyrations, and there's a variability of values between the samples.

In the last step of this stage, the interest was focused on the voids content. Two different percentages of voids content have been calculated. The first one, was obtained using the maximum density written in the normative (ρ_1), and the maximum density calculated for each sample (ρ_i), according to the formula:

$$\textit{Air Voids 1} = [1 - (\rho_1 / \rho_i)] * 100 \quad [\%]$$

The second one was calculated considering the maximum density for each sample (ρ_i), and the density obtained after 200 gyrations in the gyratory compactor (ρ_k), as follows:

$$\textit{Air Voids 2} = [1 - (\rho_i / \rho_k)] * 100 \quad [\%]$$

The two different graphs for 10 mm and 14 mm SMA, are plotted in Figures 4.10 and 4.11:

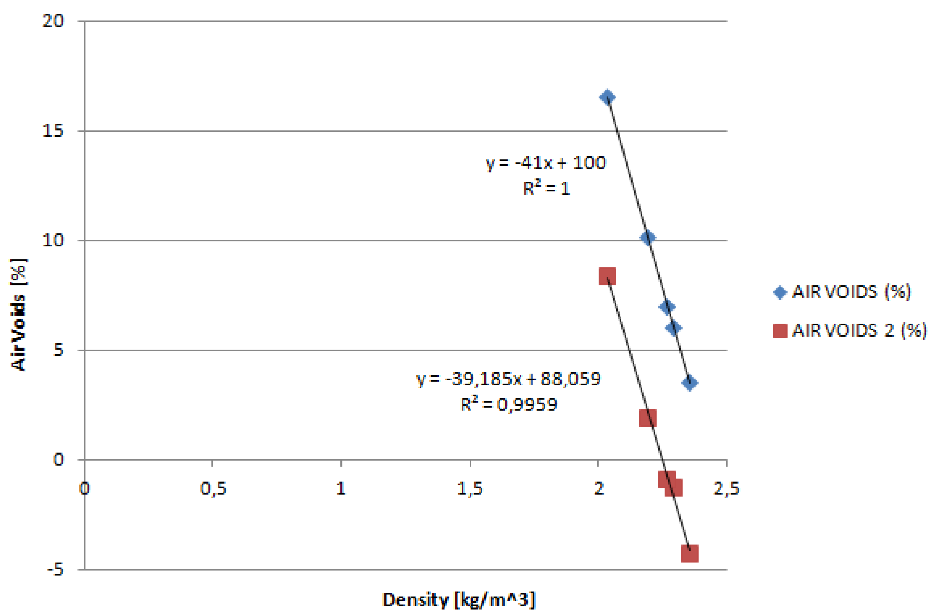


Figure 4.10 Air Voids percentage for 10 mm SMA

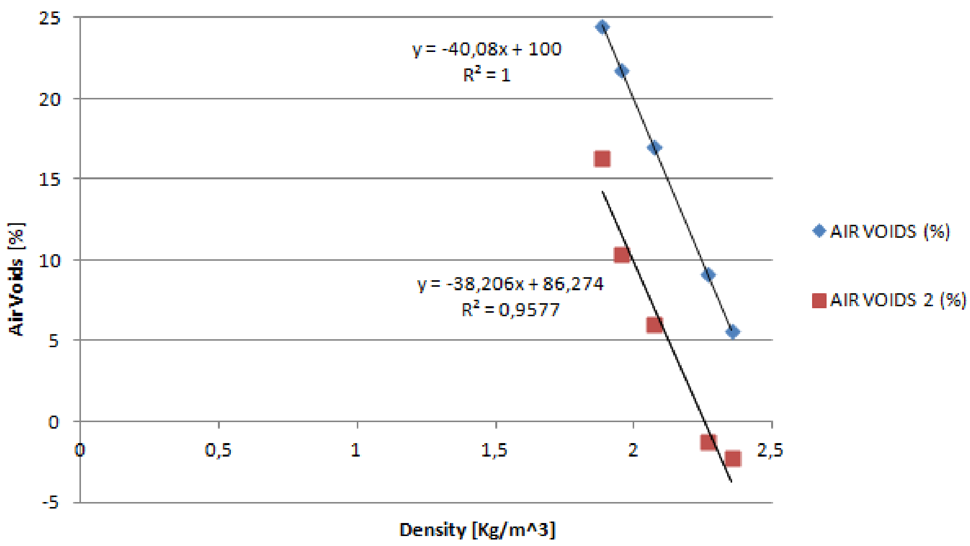


Figure 4.11 Air Voids percentage for 14 mm SMA

In these two graphs, the relationship for the two different kind of air voids are perfectly linear, both for 10 mm (B) samples and for 14 mm (A) ones. The straight line representing the trend of *Air void content 2*, shows negative values. This is due to the fact that this percentage of void has been calculated considering the maximum density for each sample, and the density after 200 gyrations. As some of the sample have been prepared after an higher number of gyrations, as illustrated in tables 4.3 and 4.4, there are negative values. For this reason, the straight of *Air voids 1*, is more reliable in representing the real trend of air voids content. The data are shown in table 4.7:

Sample	*1A*	*2A*	*3A*	*4A*	*5A*	*1B*	*2B*	*3B*	*4B*	*5B*
Air Voids content 1 (%)	5,61	9,17	17,02	21,77	24,47	3,53	6,01	6,97	10,14	16,54
Air voids content 2 (%)	-2,26	-1,25	5,99	10,34	16,33	-4,31	-1,29	-0,90	1,85	8,38

Table 4.7 – Air Voids content

4.4 SAND PATCH METHOD

Road surface texture is usually measured by the Sand Patch Method (*BS EN 13036-1:2010)* on small areas of sand, and for practical purposes this method gives a fairly accurate assessment of road surface texture. The principle is simple: the greater the texture, the more the sand will be taken up by it and the smaller the circle that can be achieved from the standard quantity of sand. In this case the method was a bit different from the standard one, but, all the same, it carried out an evaluation of average texture depth. The followed stages are:

- A small measure containing 50mm of sand was weighted three times, and an average weight of the sand was considered.
- Each sample was weighed at the beginning, then covered by sand in order to fill all the asperities on the surface texture, and weighted again.
- After that, the difference in weight between the two steps, was determined.

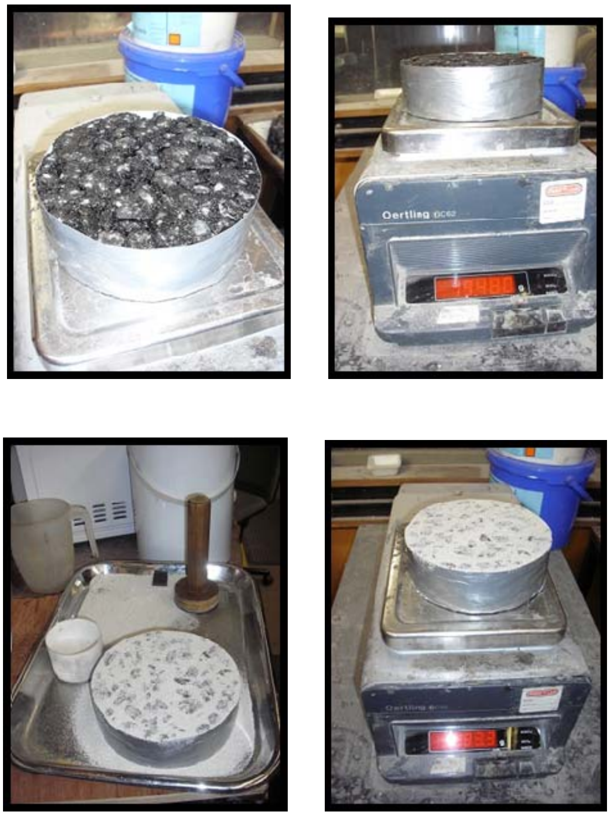


Figure 4.12 – Laboratory Sand patch method on compacted specimens

- The volume of sand was calculated considering the volume of the measure (V_m = 50ml), the weight of the sand contained in it (W_s = 61,5g) and the weight of each sample (V_i), according to this formula:

$$V_s = V_m / W_s * V_i$$

- The area of the sample with a radius of 75mm was calculated, and so it was finally possible to determine the texture depth, obtained by the ratio between the volume of sand (V_s) and the area of sample (A):

$$T_{depth} = V_s / A$$

The results for both 10 mm and 14 mm SMA are shown below:

Sample	***Weight (g)***	***Weight with Sand (g)***	***Difference in Weight (g)***	***Volume of sand (mm^3)***	***Area of Sample (mm^2)***	***Texture Depth (mm)***
1A	2144	2175,5	31,5	25609,756	17671,45	***1,4492***
2A	1948	1983,3	35,3	28699,187	17671,45	***1,6240***
3A	1804,8	1862,8	58,0	47154,471	17671,45	***2,6683***
4A	1702,5	1783,4	80,9	65772,357	17671,45	***3,7219***
5A	1604,4	1702,5	98,1	79756,097	17671,45	***4,5132***

Table 4.8 – Texture depth for 14 mm SMA

Sample	***Weight (g)***	***Weight with Sand (g)***	***Difference in Weight (g)***	***Volume of sand (mm^3)***	***Area of Sample (mm^2)***	***Texture Depth (mm)***
1B	2091,8	2109,4	17,6	14308,943	17671,45	***0,8097***
2B	2103,1	2128,3	25,2	20487,805	17671,45	***1,1593***
3B	1985,3	2020,7	35,4	28780,487	17671,45	***1,6286***
4B	1896,7	1930	33,3	27073,171	17671,45	***1,5320***
5B	1742,2	1815,7	73,5	59756,097	17671,45	***3,3815***

Table 4.9 – Texture depth for 10 mm SMA

These results show that the values of texture depth are higher in 14 mm SMA than in 10 mm ones, as would be expected. It is possible to notice these differences in texture also simply via visual inspection, because 14 mm SMA are more open textured, than 10 mm ones.

4.5 SKID PENDULUM TEST

Next stage of this project, concerned the evaluation of the skid resistance for each sample, with the Skid Pendulum Test *(BS EN 13036-4:2011).* This test equipment is used for measuring PTV's and SRV's, following the instructions contained in ROAD NOTE 27 from the Transport and Research Laboratory. The test's name originates from the pendulum action of the rubber slider that contacts the surface to be tested. The process is quite simple, the pendulum is released from the horizontal position by a quick release button, it swings down with uniform force each time, and the rubber slider at the bottom of the pendulum contacts the road surface for a fixed length that has been previously set by highering or lowering the height of the pivot of the pendulum. The degree to which the pendulum will rise up the calibration on the left-hand side of the image will be dependent on the friction/resistance the rubber slider meets on the road surface. The more friction resistance, the less the pendulum will rise and the higher the Skid Resistance Value (SRV) of the road surface. Swinging with the pendulum is a pointer that cannot be seen on the photograph, and as the pendulum falls back the pointer will be left in place indicating the SRV. The test has been developed carrying out the values of PTV after 0 wheel passes in the Road Test Machine, and thus the samples haven't been subjected to trafficking. The results are summarized in the table below:

SAMPLE	*1A*	*2A*	*3A*	*4A*	*5A*	*1B*	*2B*	*3B*	*4B*	*5B*
PTV	62	56	56	67	65	65	64	59	51	65

Table 4.10 – PTV value after 0 wheel passes in the RTM Machine

4.6 CONTACT AREA

The attention is now focused on the role of contact area on wet skid resistance and texture depth.

An asphalt surfacing is subjected to direct contact with the tyre and all of the imposed stressing associated with a moving vehicle: weight, axle, suspension, acceleration, braking, cornering and speed. Both road surface and tyre require minimum levels of grip and texture to remove water and minimize aquaplaning. The measurement of actual, rather than assumed, full-scale tyre surface contact stress distributions in all three of the co-ordinate directions is difficult.

Researchers at the University of Ulster have been involved in the development of static and dynamic testing technologies since the 1990’s. As highlighted before, the contact envelope between tyre and surface is elliptical in shape and directly proportional to wheel load and inversely proportional to tyre pressure. Whereas wheel load is important to pavement design, tyre inflation pressure is more important for the conditions experienced at the road/tyre interface. The tread pattern of a tyre is generally only 14 to 18% of the contact envelope, and the stresses involved due to a tyre rolling over a road surface are highly concentrated and will exploit any weakness present such as micro-texture on the aggregate surface, the chipping edges or inferior quality constituents. This helps into explaining how factors such as grip, noise and rolling resistance are closely inter-related to not only one another, but also to the amount and type of texture.

For these reasons a new approach was developed at the University of Ulster to measure static and dynamic tyre-asphalt surface contact properties. It complements existing test methods such as the Noise and Rolling Resistance Indices and uses roller compactor slabs subjected to accelerated trafficking using the Road Test Machine (RTM) to show development of surface properties with time. The dynamic aspect of testing is achieved by modification of a Wessex dry wheel tracker to cause the asphalt test specimen to move under a loaded tyre in a controllable manner. It’s possible to modify the wheel tracker lever arm to accommodate a range of wheel sizes ranging from the solid tyre as used in the rutting test, a smooth Findlay Irvine GripTester test wheel to a smooth SCRIM tyre.

In the case of the Grip/Tester tyre, *BS 7941 (2000)* states that the static load on the GripTester test wheel under normal operating conditions should be between 22kN and 28kN. An additional 3.343kg load to the end of the wheel-tracker arm gives an idealised equivalent static load of 25kN. This allows for potential direct correlation of laboratory measured contact area with grip measured using GripTester. The test apparatus in shown in Figure 4.13:

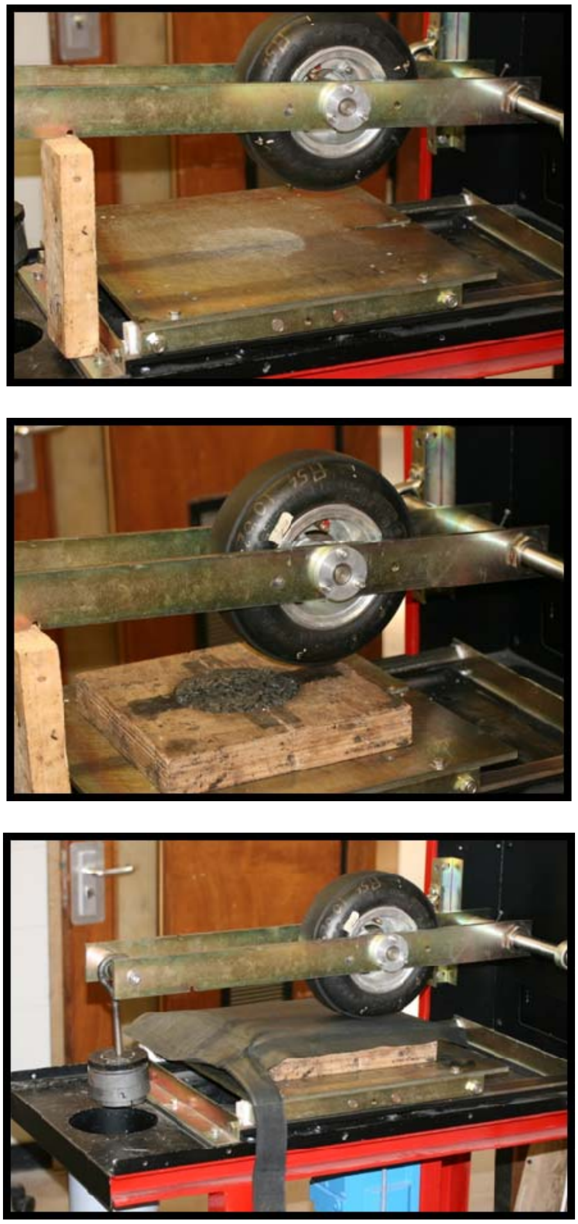
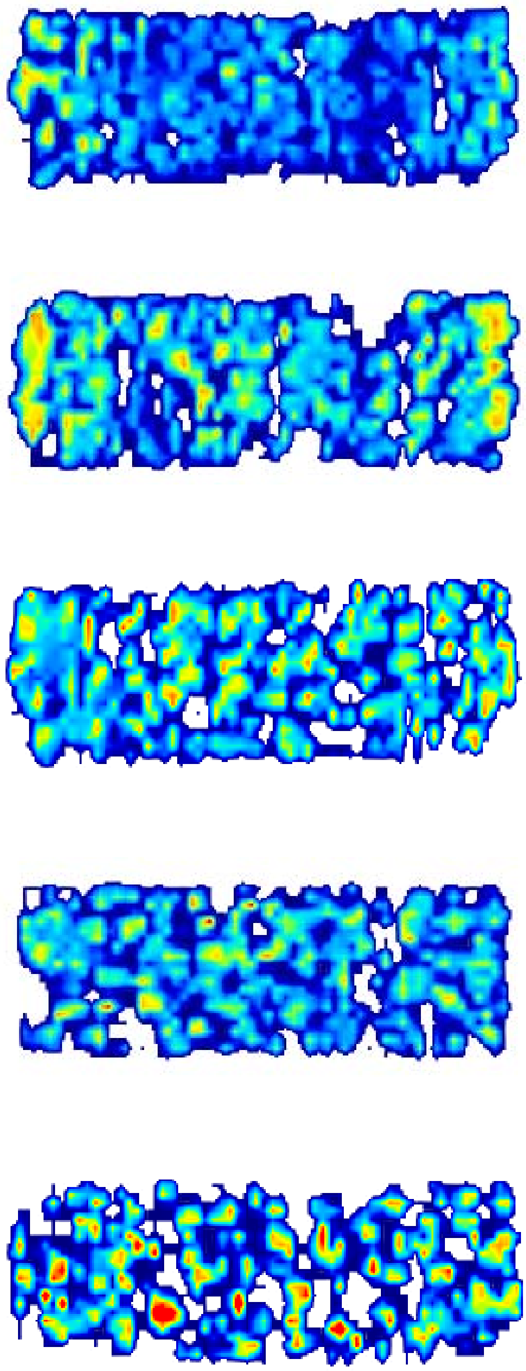


Figure 4.13 – Modified Wessex test equipment ltd

Two XSensor pressure mapping systems can be used to quantify pressure distributions under the test tyre. This type of measuring system was developed for dynamic pressure measurement at the interface between two surfaces i.e. in this case the tyre and asphalt surface. An X500:256.256.22 high resolution sensor is used to obtain images of the tyre. This system is designed for high-quality pressure images and is used for tyre-tread analysis and tyre design. It is mounted on a Plexiglass backing and is capable of measuring 6 frames per second. With 65,536 sensing points this system has a 1.15mm resolution. The second sensor used is an IX500:128.128.10. This resembles a flexible mat and has been designed for uneven surfaces. Although it has a 2.54mm resolution its high data-acquisition rates, make it suitable for dynamic testing. XSensor 3 Pro Version 6 software has been used for initial analyse of pressure data. An export facility allows the data to be used in other software packages. This setup allows the asphalt samples to move dynamically under the test tyre with contact phenomena measured either under static or dynamic conditions. The lower resolution pressure pad is located upside down on the test specimen and pressure distributions recorded as it moves under the loaded wheel. Although each frame can be assessed individually, the XSensor software allows individual frames to be merged together representing the track of the test wheel across the pressure pad. [15]

In this case, the pressure mat interfaces with XSensor 3 Pro Version 6 software and is capable of capturing up to sixteen frames per second, with individual contact images, and merging them into a single composite trace showing the passage of the tyre across the pressure map. Figure 4.14 and 4.15 show examples of 2D contact area plots based on merging 200 individual pressure maps collected during dynamic testing for 10 mm SMA and 14 mm SMA: [8]



Sample 1B

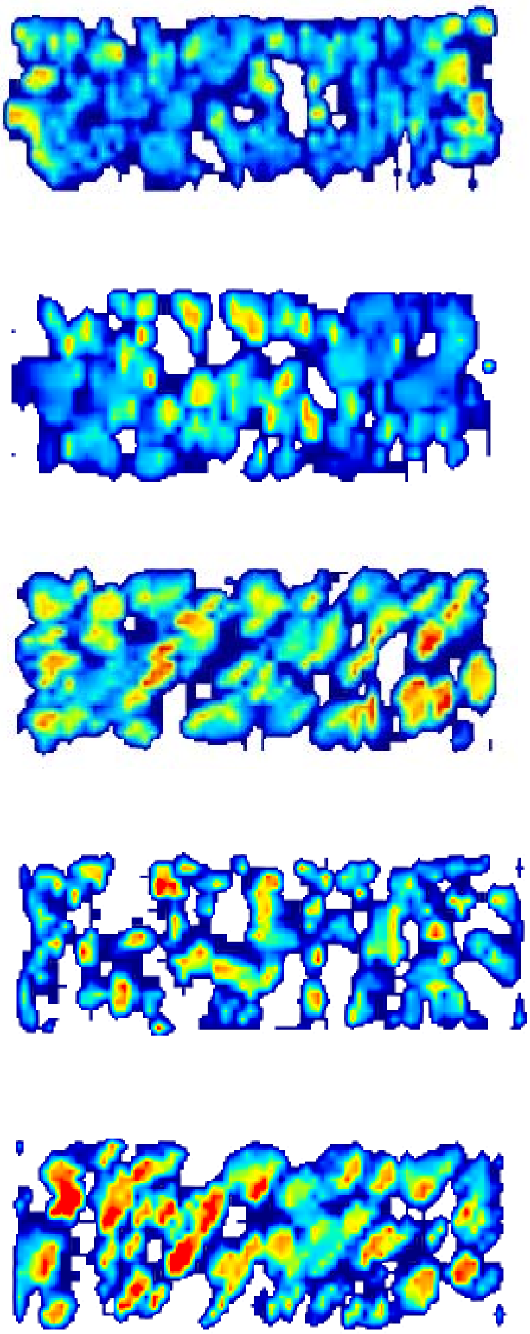
Sample 2B

Sample 3B

Sample 4B

Sample 5B

Figure 4.14 – Contact area pressure distribution plots for 10 mm samples after 0 wheel passes



Sample 1A

Sample 2A

Sample 3A

Sample 4A

Sample 5A

Figure 4.15 – Contact area pressure distribution plots for 14 mm samples after 0 wheel passes

These two figures show how the pressure are distributed on the surface of specimens and highlight the differences in texture between the samples.
It's possible to notice that there are concentrated pressures around missing pieces of coarse aggregate in the centre of SMA samples, as shown in the figure below:

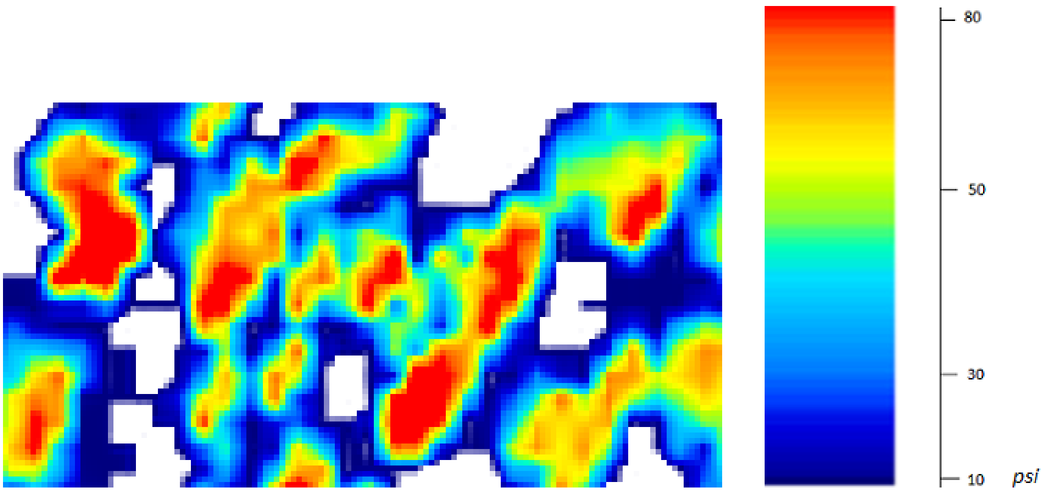


Figure 4.16 – Pressure Map in a SMA sample

For each sample, the software carried out a 3D image, that allows a better understanding of the distribution of pressures on the contact areas, as shown in Figure 4.17 and Figure 4.18.

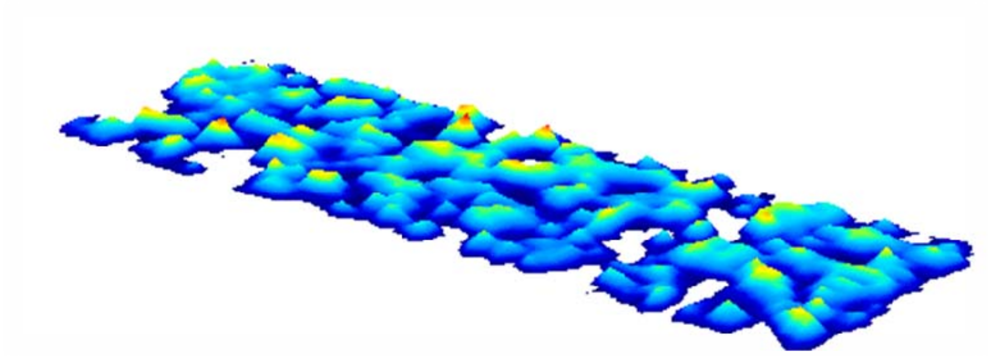


Figure 4.17 – 3D image of contact pressure for a 10 mm sample

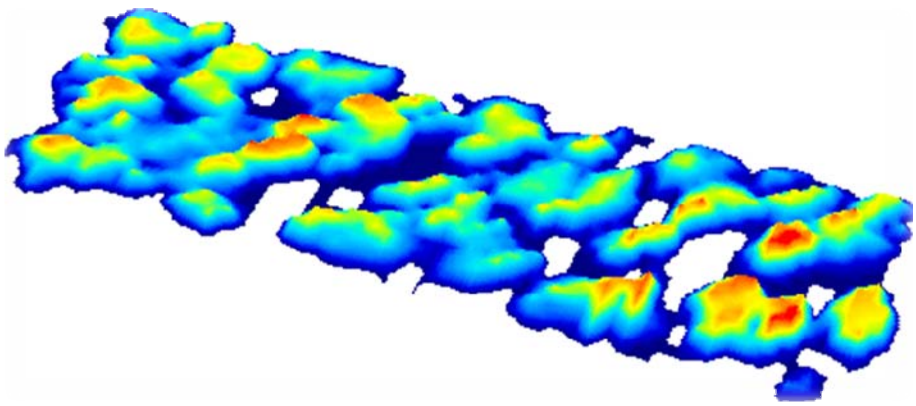


Figure 4.18 – 3D image of contact pressure for a 14 mm sample

4.7 THE EFFECTS OF TRAFFICKING – ROAD TEST MACHINE

After years of testing at the University of Ulster into sustainable highway construction, to improve the prediction of asphalt surfacing material performance, it was discovered that the simplistic assumption that use of texture or use of hard aggregate equals safer longer lasting roads is not a sustainable option if the aggregate or mix only lasts for a limited number of years failing prematurely.

For this reason, it's now essential to understand and quantify what happens to these materials with time.

Improved sustainable highway construction implies the use of materials that will perform at adequate levels for longer period of time.

However, it is difficult to test the durability of asphalt materials in conditions similar to those experienced in-situ. The use of simple methods such as wet/dry testing of asphalt using Marshall stability or Indirect Tensile Stiffness Modulus does not consider the effect of traffic stressing. This has prompted considerable research into assessment of the wear characteristics rather than simple moisture sensitivity.

The Road Test Machine (RTM) consists of a rotating table on which 10 slabs or cores are subjected to accelerated trafficking using 2 full-size tyres. The equipment is housed in an environmental chamber that controls test temperature and subjects the test slabs to accelerated wear. The development of properties such as skid resistance is measured using the British Pendulum Tester with texture depth measured using the Sand Patch method.

The RTM is currently accredited by the British Board of Agreement to assess the wear characteristics of High Friction Surfacings (HFS) for Highways Authorities Product Approval Scheme (HAPAS) accreditation. HAPAS was set up in the 1990's with the objective of developing national approval arrangements for innovative products, materials and systems for use in highways and related areas. The effect of accelerated trafficking is assessed by measuring change in texture depth and skid resistance generally after 100,000 wheel passes.

The RTM can used to study the wear characteristics of a wide range of asphalt materials including hot rolled asphalt, porous asphalt, bitumen macadam, asphalt concrete, micro-asphalt, or SMA, like in this project. These asphalt investigations typically involve making 305 x 305 x 50mm slabs from materials sampled on-site or mixed in the laboratory, but it's possible to make it suitable for cores with 150mm of diameter and height of 50mm, utilizing a wooden mould.

This allows combinations of aggregate and bitumen to be easily and quickly assessed without the need for full-scale road trials under controlled repeatable conditions. [16]

In this study testing was periodically stopped, particularly during the early stages, after 500, 2000, 5000, 10000, 20000, 50000 and 100000 wheel passes. This allows different periods in the life of an asphalt surfacing material to be determined and ranked against other types. Generally, the presence of water can substantially reduce friction between dry and wet test conditions. The presence of water can also change the ranking of asphalt mixes in dry and wet conditions. In this case all testing were carried out in dry conditions.

All the samples were removed and tested for skid resistance using the Pendulum tester (PTV) and Texture Depth using the Sand Patch method. Each test specimen was photographed at each stage of testing to record changes in their visual appearance and subsequently analysed for Contact Area between test sample and test tyre using the new dynamic pressure mapping system developed at the University of Ulster, as already described.

CHAPTER 5
ANALYSIS OF DATA

5.1 INTRODUCTION

The main objectives of this investigation were to determine how each asphalt material, made with two different sizes of aggregate, 10mm and 14mm, responded to simulated trafficking under controlled laboratory conditions, analyzing the effect of nominal aggregate size on wet skid resistance and texture depth. It was determined how these properties developed with time and assessed the importance of contact area on wet skid resistance and texture depth. These objectives were achieved using the data collected with increasing number of wheel passes in each test method.

5.2 SKID RESISTANCE

The wet skid resistance (PTV) has been evaluated for increasing number of wheel passes, and the evolution of the values are shown in Table 5.1:

SAMPLE	0	500	2000	5000	10000	20000	50000	100000
1A	62	49	50	57	62	57	56	54
2A	56	45	50	57	61	60	54	55
3A	56	53	55	60	67	63	64	60
4A	67	51	55	61	63	59	62	57
5A	65	46	60	61	63	62	65	63
1B	65	51	55	65	64	61	61	60
2B	64	48	55	64	60	59	58	56
3B	59	54	58	65	60	57	59	53
4B	51	49	55	60	64	62	59	57
5B	65	51	59	62	63	59	60	59

Table 5.1 – Values of wet skid resistance (PTV)

Figure 5.1 plots all of the data for all of the samples. This shows a general trend: there's an initial loss of skid resistance in early life, followed by an increase and thereafter a reduction to equilibrium conditions. If the bulk of the aggregate is moisture sensitive or contains particles that are moisture sensitive, they will quickly lose their bitumen coatings and so facilitate the development of early or very early life skid resistance.

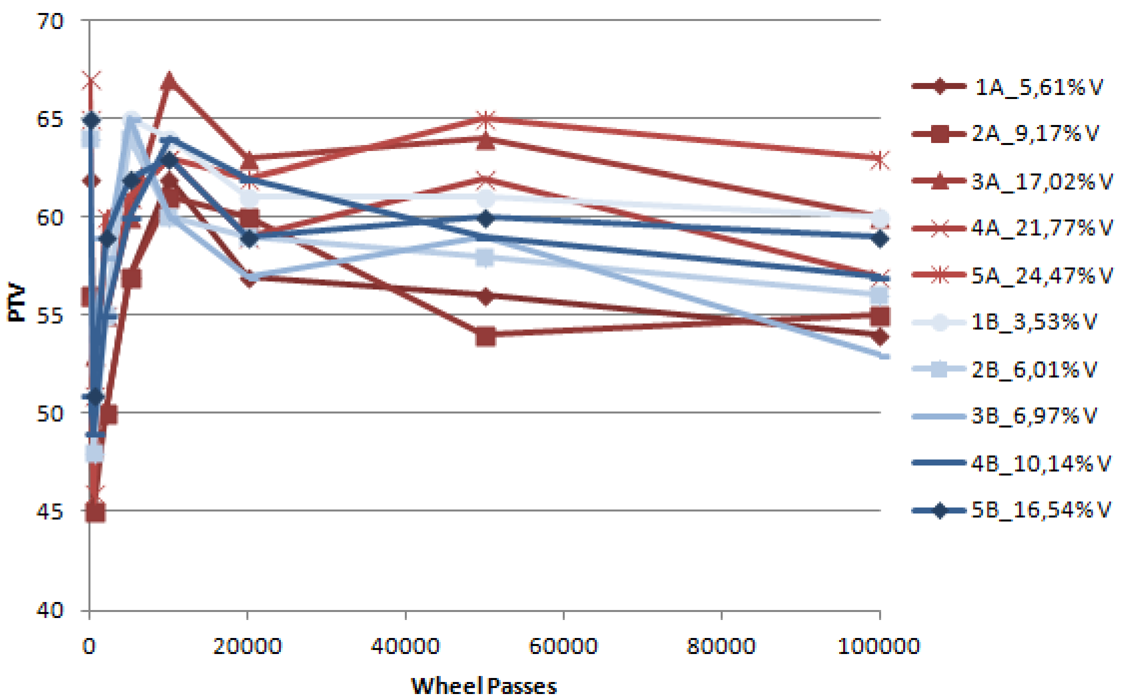


Figure 5.1 – Change in wet skid resistance for increasing number of wheel passes

The main exceptions are the 14mm samples number 3A, 4A and 5A that gained skid resistance in the later stages of testing due to severe surface reveling.

This premature loss of particle edges or loss of individual particles may affect mix durability and tyre-surface contact patch phenomena, both in early and more importantly in mid life.

These data are in agreement to what has been found during these last years of researches at the University of Ulster.

In fact, it was discovered that an asphalt surface, during his service life, reaches a level of performance equilibrium after a period of 1 or 2 years. There's a period before this equilibrium stage, during which it was claimed that certain types of road surface material may become slippery with problems of aquaplaning and bituplaning. It was found that there are reductions in wet skid resistance over the first few days, weeks or months. This time period is referred to as very early life and varies depending on asphalt mix, aggregate / bitumen combination and in-service conditions.

This general trend during the early life is confirmed also in this project as we can see in Figure 5.1 and in Figure 5.2. The last one, plots the data for the first 5000 wheel passes and shows in more detail this early life development of skid resistance.

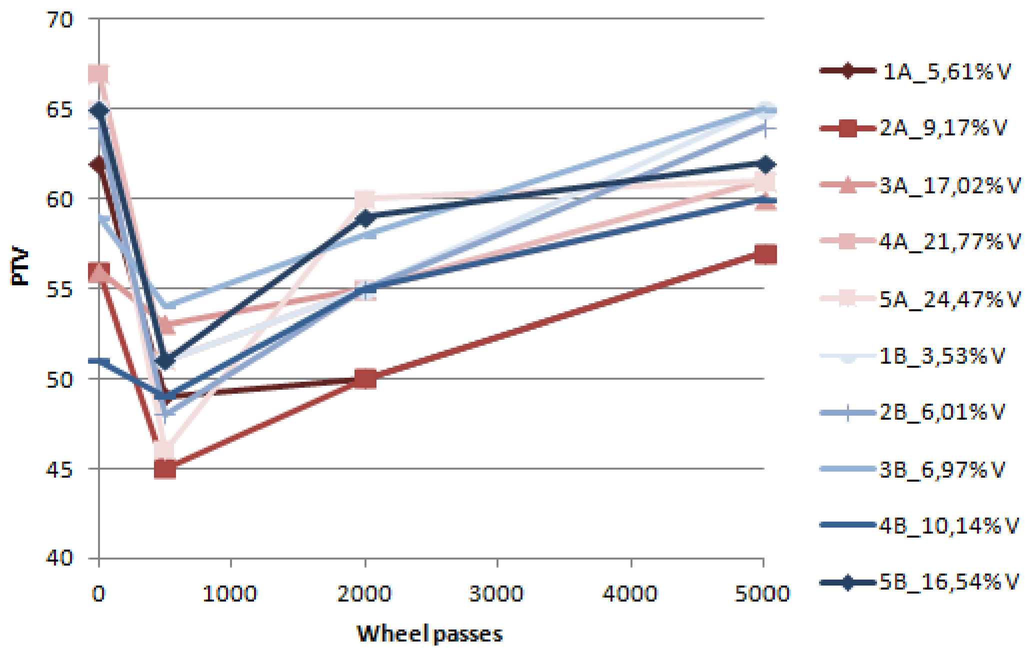


Figure 5.2 - Change in wet skid resistance for first 5000 wheel passes

This figure also shows a wide range in PTV values during the early stages of testing. This is despite all of the mixes being made with the same aggregate and reflects the complex interactions of aggregate nominal size, grading, bitumen content, texture depth and contact area.

Generally, as it's possible to observe in Figure 5.1, reducing the nominal aggregate results in an increase in wet skid resistance as measured using the pendulum tester. This is confirmed in all of the specimens, except for the samples 3A, 4A and 5A, for the reasons previously explained.

5.3 TEXTURE DEPTH

The values of texture depth calculated for increasing number of wheel passes are summarized in Table 5.2:

SAMPLE	**0**	**500**	**2000**	**5000**	**10000**	**20000**	**50000**	**100000**
1A	1,44	1,13	1,24	1,08	1,05	1,09	1,18	1,00
2A	1,61	1,36	1,43	1,45	1,52	1,60	1,55	1,47
3A	2,67	2,48	2,59	2,46	2,74	2,77	3,00	2,72
4A	3,70	3,00	3,11	2,93	3,17	2,91	2,88	2,99
5A	4,46	3,94	3,99	3,82	3,89	4,08	4,47	4,56
1B	0,65	0,72	0,65	0,68	0,63	0,73	0,73	0,69
2B	1,05	1,07	1,05	1,03	1,02	1,14	1,13	1,18
3B	1,36	1,39	1,36	1,38	1,36	1,35	1,33	1,26
4B	1,30	1,31	1,30	1,34	1,35	1,36	1,28	1,34
5B	2,53	2,59	2,53	2,41	2,36	2,22	2,88	2,94

Table 5.2 - Values of texture depth (mm)

Figure 5.3 plots all of the texture depth data and similar to the skid resistance data shows a general trend in terms of texture depth development during testing. It’s clearly highlighted an early life decrease followed by increase and then either gradual decrease or increase. In terms of texture, this increase in the later stages of testing relates to surface raveling and stone loss, because the surface of the test specimen is starting to disintegrate due to simulated trafficking.

This suggests that the testing method is a simple means of putting a time-scale against the relative performance of an asphalt surfacing material, not only in skidding resistance and texture but also in its structural integrity.

It should also be pointed out that all of the RTM testing reported in this project is carried out in dry conditions. It would be expected that should the test samples be preconditioned by soaking in water that more rapid failures may happen.

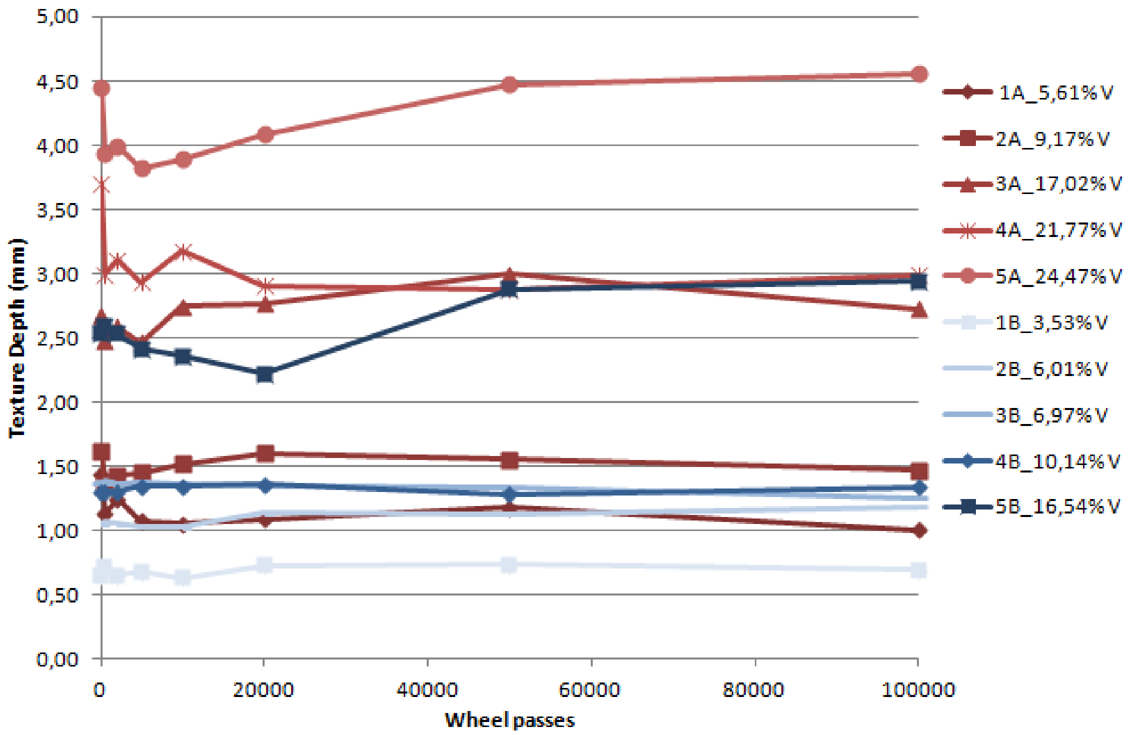


Figure 5.3 - Change in texture depth for increasing number of wheel passes

The reduction of texture depth in the very early life of the material, is clearly shown in Figure 5.4, in which it is represented the evolution for the first 5000 wheel passes.

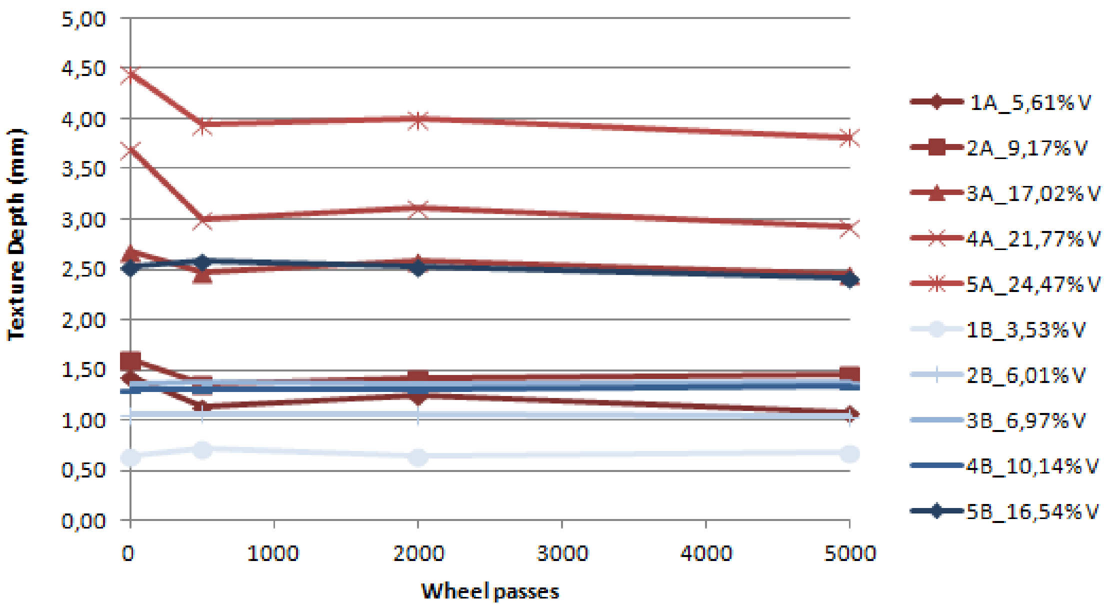


Figure 5.4 - Change in texture depth for first 5000 wheel passes

It has been noticed during the first 500 wheel passes a decreasing of texture depth. This may be explained by smearing and migration of the binder on the trafficked aggregate surfaces. After this point, all the samples show an overall trend: a small increase in texture depth as this migrated bitumen was removed by trafficking. This increment is more evident in samples 5A and 5B, that are the samples with the most open textured surface.

Moreover the two previous figures, clearly show the influence of nominal aggregate size. In fact a smaller nominal aggregate size results in lower texture, and this would be expected.

There’s a wide range of values between the samples and it’s possible to recognize two different zones: the first on the top of the graph represents the range of texture depth for 14 mm samples; the second shows the trend for 10 mm ones. Moreover, all of the samples have a similar parallel plot and achieve equilibrium approximately after 2000 wheel passes.

This laboratory ranking of texture change is more or less in agreement with expected in-service performance and suggests that the RTM testing protocol may be a suitable method to rapidly predict how asphalt materials will perform.

5.4 RELATIONSHIP BETWEEN SKID RESISTANCE AND TEXTURE DEPTH

Analysis of data has been concentrated on single properties of materials, such as wet PTV and texture depth. The data was further analysed to consider the relationship between these properties with time, after an increasing number of wheel passes.

Figures 5.5 and 5.6 plot the relationship between wet skid resistance and texture depth for all data measured after 0 and after 100000 wheel passes.

Figure 5.5 shows that the values are very scattered. This may be due to the differences in the rate of compaction. In fact these values range from 3 to 900 gyrations in the gyratory compactor and this well relates with having a wide range in texture depth and skid resistance.

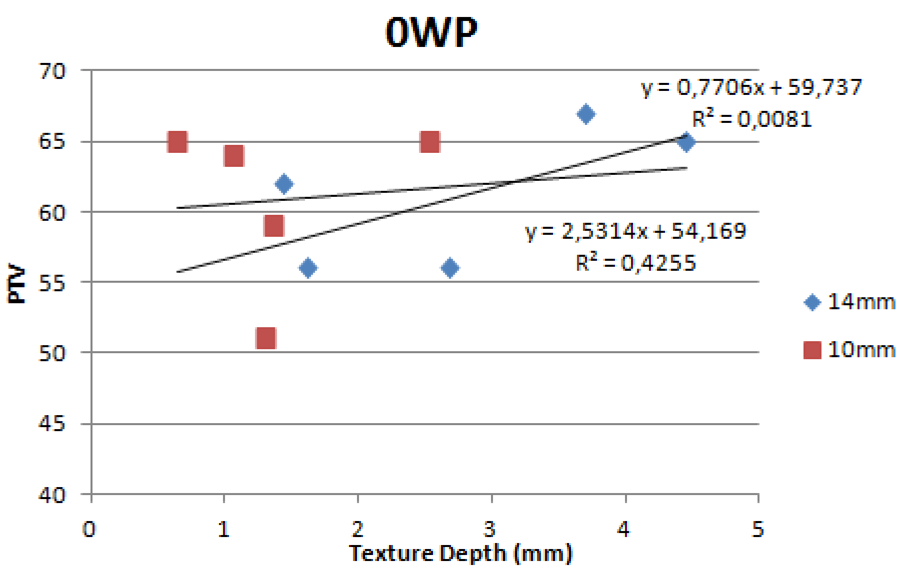


Figure 5.5 – Relationship between PTV and TD after 0 wheel passes

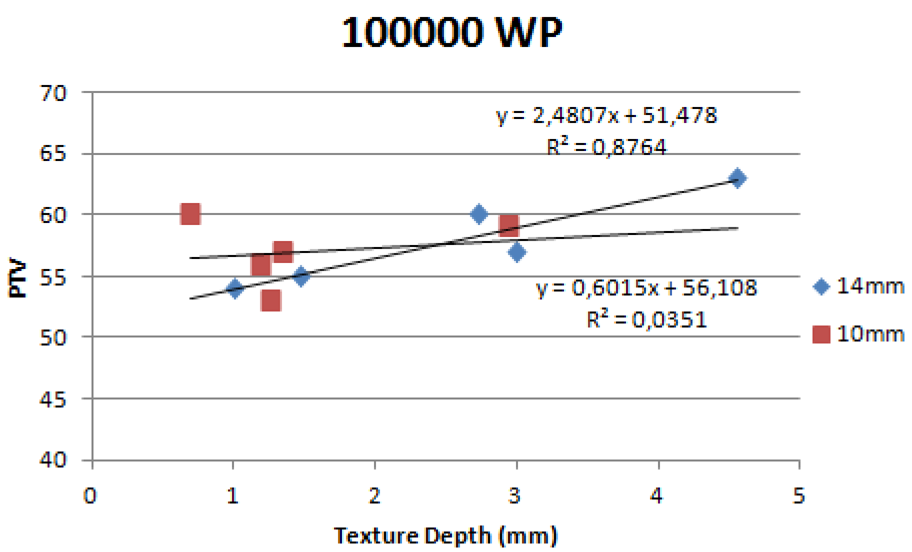


Figure 5.6 – Relationship between PTV and TD after 100000 wheel passes

After 100000 wheel passes the situation changes radically. As shown in Figure 5.6, we can see three distinct sets of data related to nominal aggregate size. This shows how these properties are susceptible to change during their early life. This is probably due to the smearing of bitumen coatings and temporary in-filling of surface textures, exposure of the aggregate and subsequent on-set of aggregate polishing. This last figure shows that an equilibrium state has been achieved for the SMA samples, after prolonged simulated trafficking. This is true except for sample 1B, that doesn't totally agree with this trend.

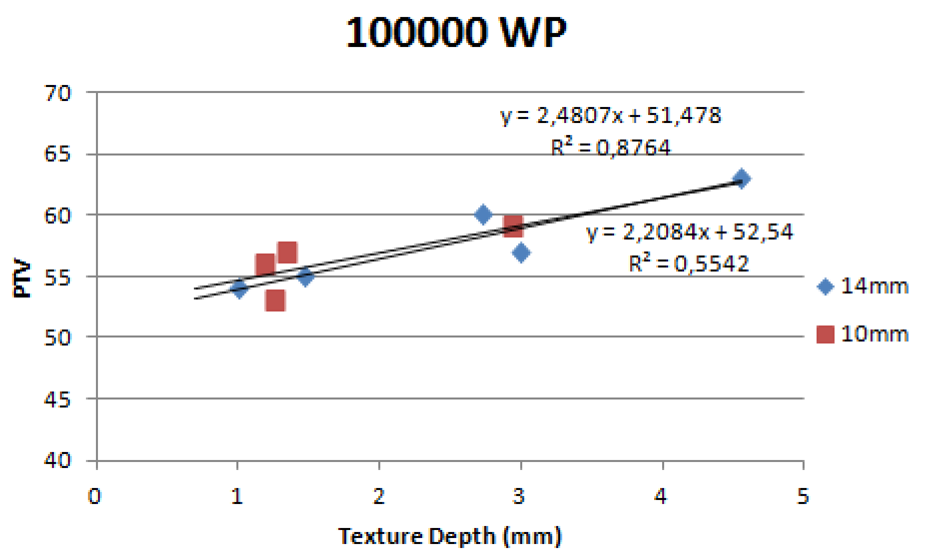


Figure 5.7 – Relationship between PTV and TD after 100000 wheel passes, not including sample X

For this reason the values of sample 1B were removed from the graph and this allow to have a linear trend for both of the two aggregate sizes, as shown in Figure 5.7. This equilibrium state represents a stable and durable material and this is typical of how SMA would be expected to perform in situ.

5.5 CONTACT AREA

Upon considering the role of contact area on wet skid resistance and texture depth. As explained in the previous chapter, this new methodology developed at the University of Ulster allows a test specimen to move under a loaded tyre in a controllable manner.

Tracking with the tyre has caused the flexible X Sensor pressure pad to highlight the areas of contact between the smooth GripTester tyre and the asphalt surface.

The aim of this stage of the project, was to analyze the changes in contact area after different number of wheel passes, and to relate these changes with the main parameters worked out from the XSensor 3 Pro Version software.

The evolution in contact area for all the samples are summarized in the table 5.3.

	CONTACT AREA ***(mm^2)***				
SAMPLE	***0 WP***	***500 WP***	***5000 WP***	***20000 WP***	***100000 WP***
1A	6961,29	6103,23	5683,87	5645,16	5458,06
2A	6070,97	4464,52	3774,19	4141,94	5670,96
3A	6974,19	4658,06	4864,52	3587,1	3974,19
4A	5980,65	3845,16	3832,26	3219,35	3535,48
5A	6735,43	3303,23	3393,55	2812,9	2464,52
1B	7477,42	5335,48	5729,03	6438,71	6580,65
2B	7212,9	5341,94	5896,77	5303,23	5232,26
3B	7251,61	5167,74	5135,48	4425,81	4554,84
4B	7064,52	4548,39	4387,1	4000	4341,94
5B	6812,9	3541,94	3374,19	4129,03	2877,42

Table 5.3 – Contact area data

The plot of these data is represented in Figure 5.8. The overall trend shows a rapid decrease of the values of contact area especially after the first few hundred wheel passes. The situation remains the same for all the samples until 5000 wheel passes; after this point most of the cores continue in decreasing the contact area, as it would be expected.

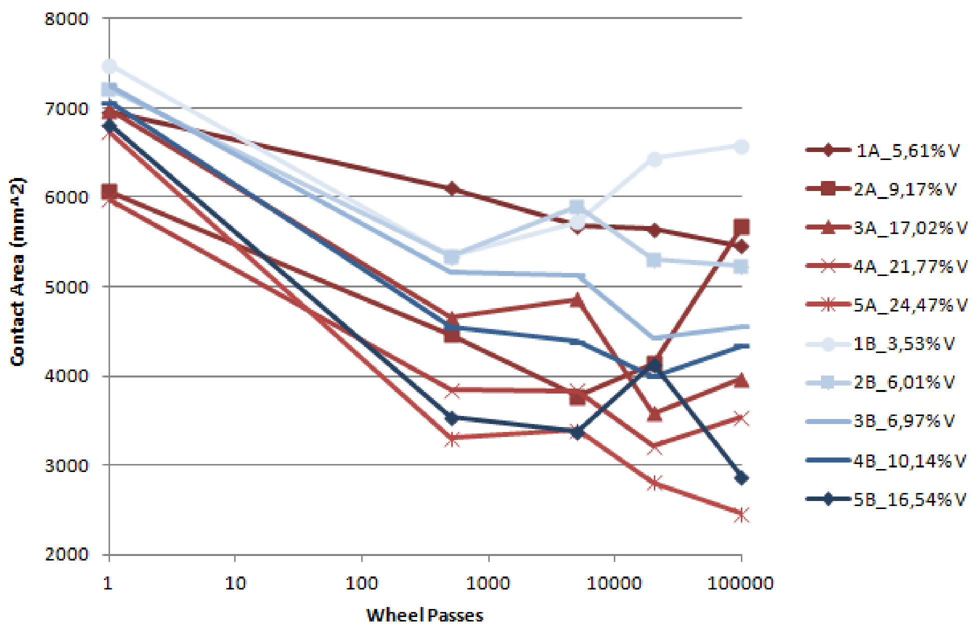
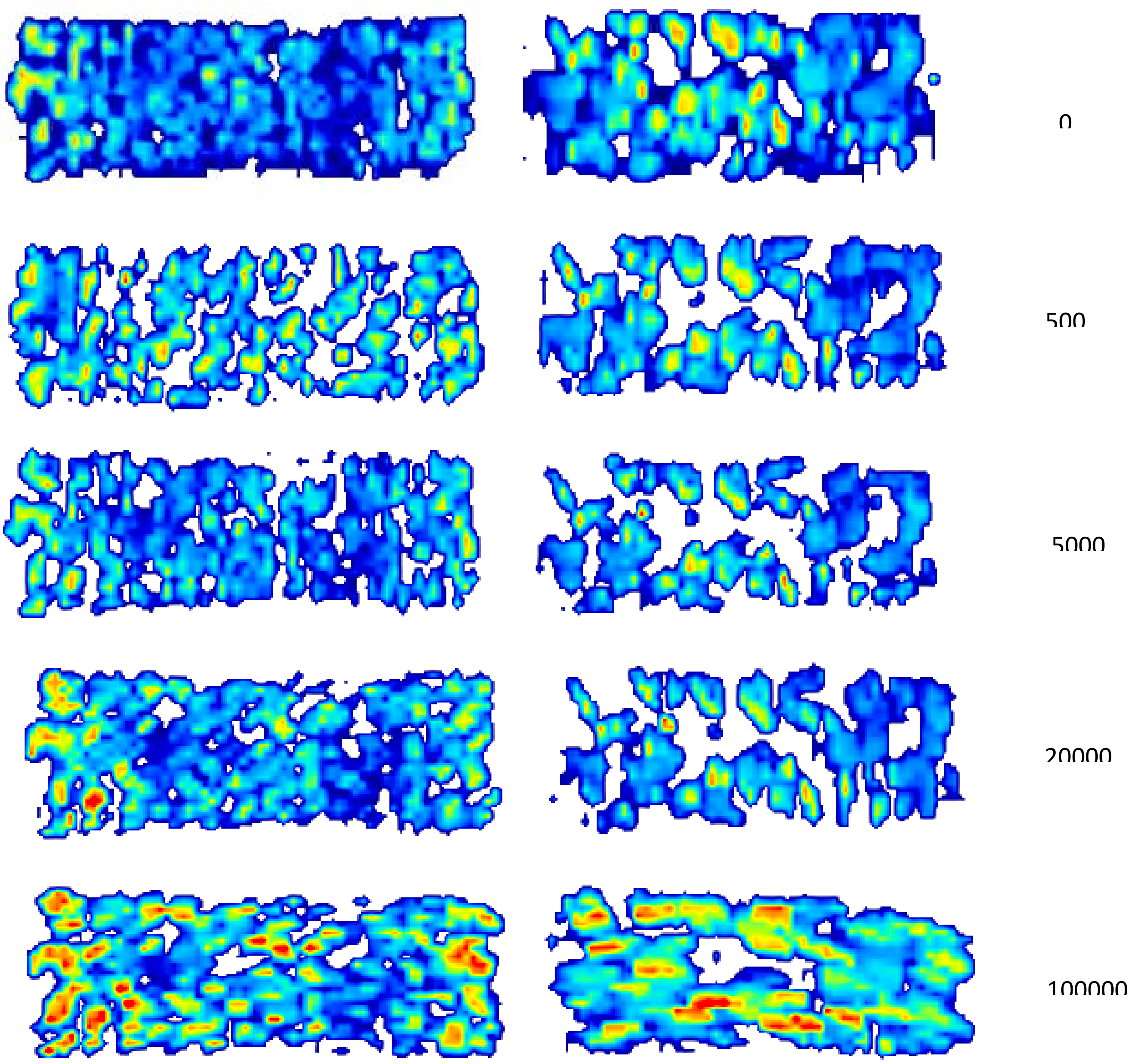


Figure 5.8 – Relationship between contact area and number of wheel passes

However test have carried out particular results for the sample 1B and especially for sample 2A. This may be due to trafficking that in this two samples has attenuated the roughness in texture.

Other interesting parameters have been analyzed: the peak pressure due to the contact between tyre and asphalt, and the average pressure.

A visual evolution in the peak pressure and in the contact area, is shown both for a 10 mm aggregate sample and for a 14 mm, in the figures below:



Sample *1B (10 mm)* *Sample 2A (14 mm)*

Figure 5.9 - Evolution in contact area and change in the distribution of pressure for an increasing number of wheel passes (0, 500, 5000, 20000, 100000)

In these images is easily recognizable an increase with trafficking in the values of pressure for both the two samples, but also an increase of contact patch after 5000 wheel passes for specimen 1B and after 20000 wheel passes for specimen 2A, and this is not in agreement with what it would be expected.
In order to explain what should be the actual evolution of contact patch and pressure's distribution, an example is shown in the Figure 5.10.

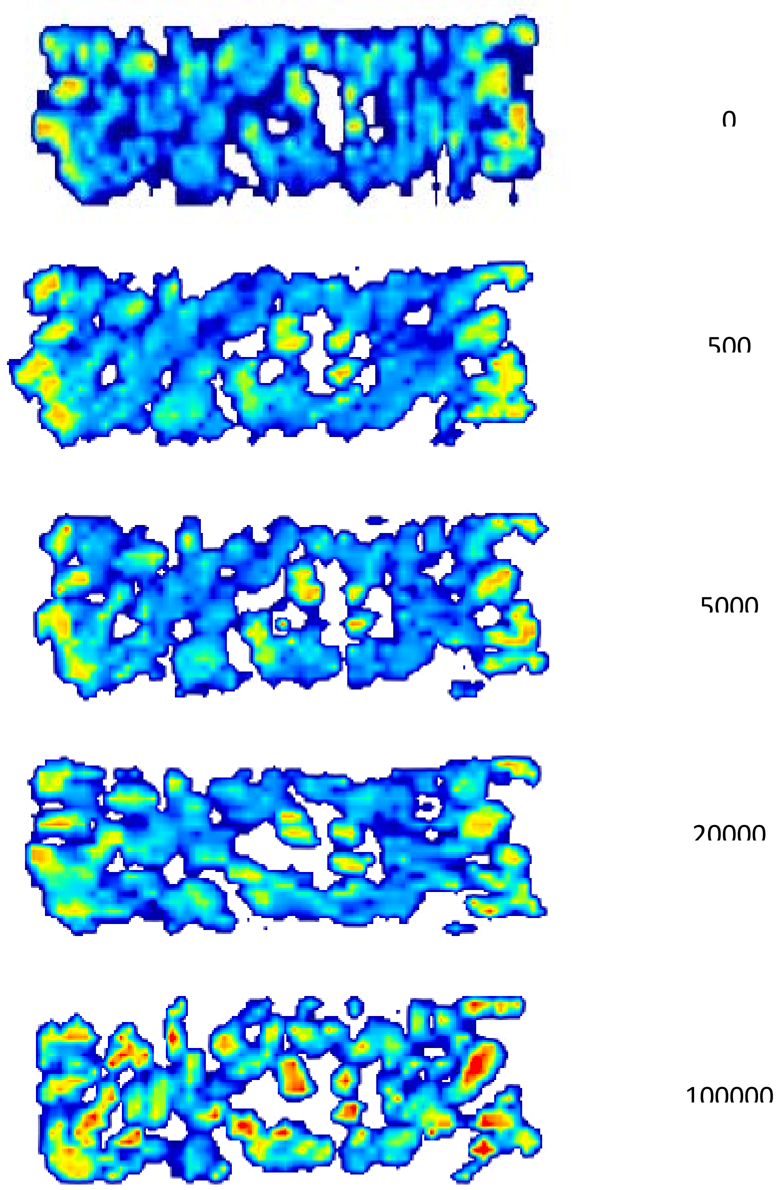
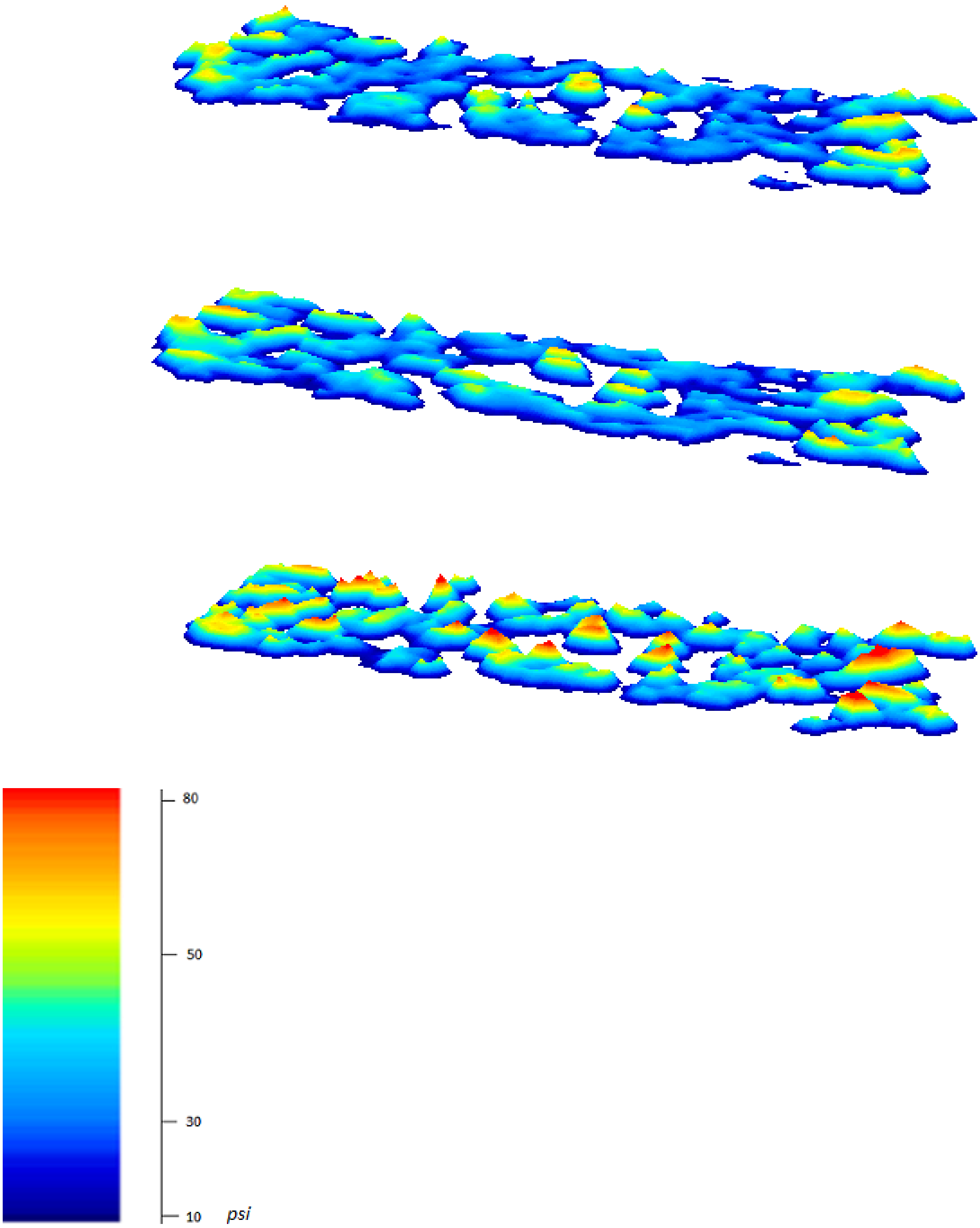


Figure 5.10 - Evolution in contact area and change in the distribution of pressure for core 1A (14 mm)

In this figure it's easy to see the reduction of the contact area with increasing number of wheel passes. In order to understand better also the evolution of the pressure, the 3D models of some of these contact patches are shown in Figure 5.11.



5.11 – Distribution of pressure after 5000, 20000 and 100000 wheel passes for sample 1A (14 mm)

These simple examples clearly show how the high values of pressure are concentrated on the protruding chipping and this happens especially for the larger sized samples of SMA.

The peak pressure and the average pressure have been evaluated for all the samples. The data are summarized in Table 5.4 and Table 5.5 and plotted in Figure 5.12 and in Figure 5.13.

	PEAK PRESSURE (psi)				
CORES	***0 WP***	***500 WP***	***5000 WP***	***20000 WP***	***100000 WP***
1A	70,81	71,02	75,87	78,27	102,13
2A	72,92	73,19	83,06	81,79	107,81
3A	91,75	96,07	100,77	106,57	172,00
4A	94,41	99,93	102,6	130,29	256,00
5A	110,9	114,35	116,51	152,25	256,00
1B	65,75	66,24	68,27	94,99	119,32
2B	74,04	74,93	75,59	100,30	155,06
3B	78,21	79,59	81,18	101,71	163,30
4B	79,25	81,18	88,23	99,27	189,67
5B	84,94	85,89	89,26	200,11	256,00

Table 5.4 – Peak pressure data

	AVERAGE PRESSURE (psi)				
CORES	***0 WP***	***500 WP***	***5000 WP***	***20000 WP***	***100000 WP***
1A	26,50	31,94	31,03	32,00	36,71
2A	26,77	29,50	27,83	27,93	38,91
3A	33,08	37,30	38,41	35,13	44,72
4A	25,63	39,00	40,87	42,53	53,70
5A	34,52	40,80	43,77	43,02	55,81
1B	24,32	25,75	28,40	31,12	37,49
2B	30,21	33,03	35,67	36,85	40,03
3B	29,74	33,56	34,68	33,42	37,84
4B	26,28	29,44	32,75	35,23	38,81
5B	26,69	35,90	35,28	42,02	48,42

Table 5.5 – Average pressure data

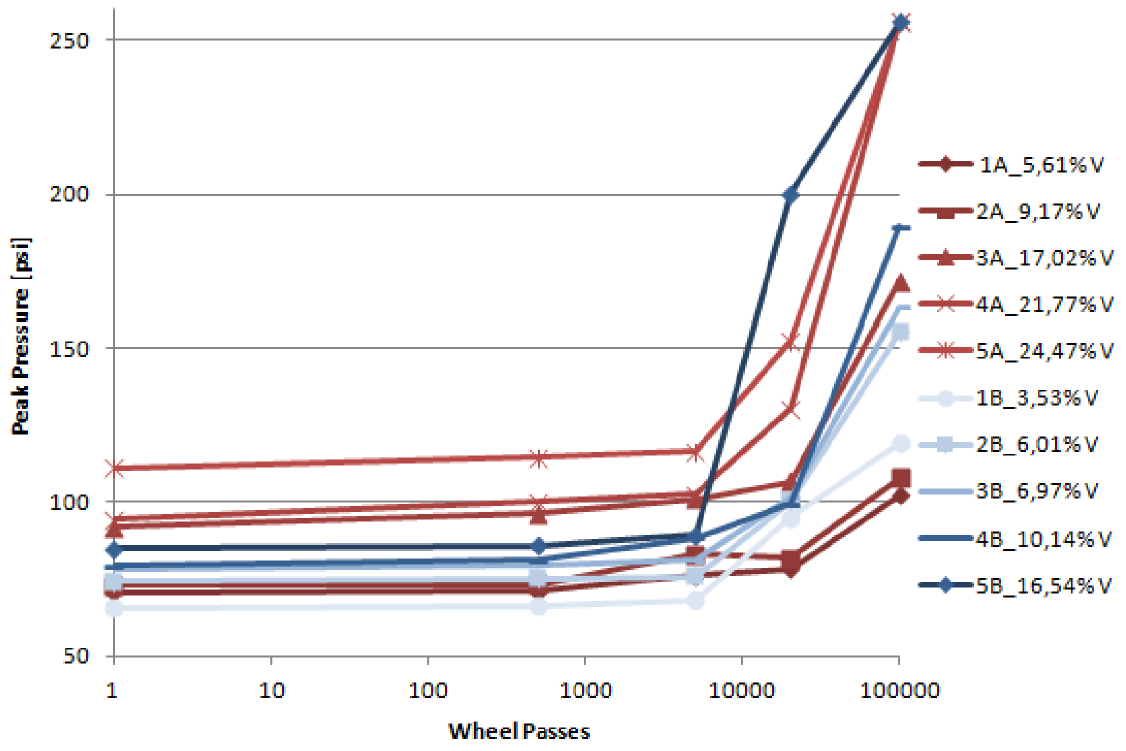


Figure 5.12 – Relationship between peak pressure and wheel passes

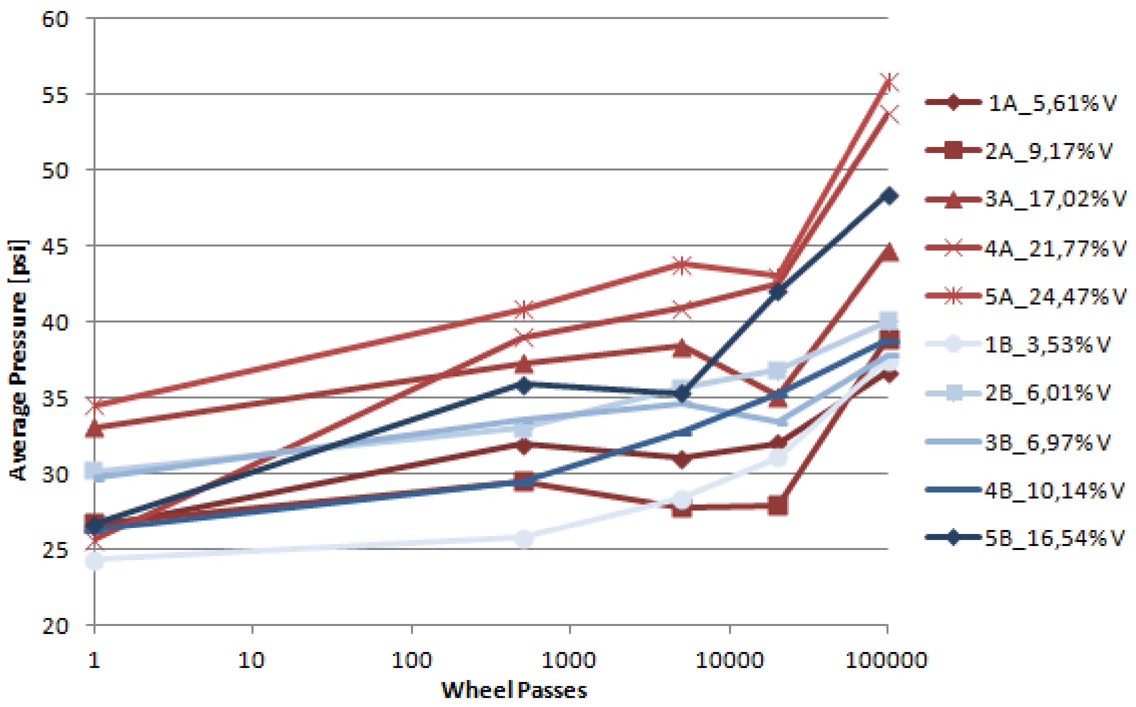


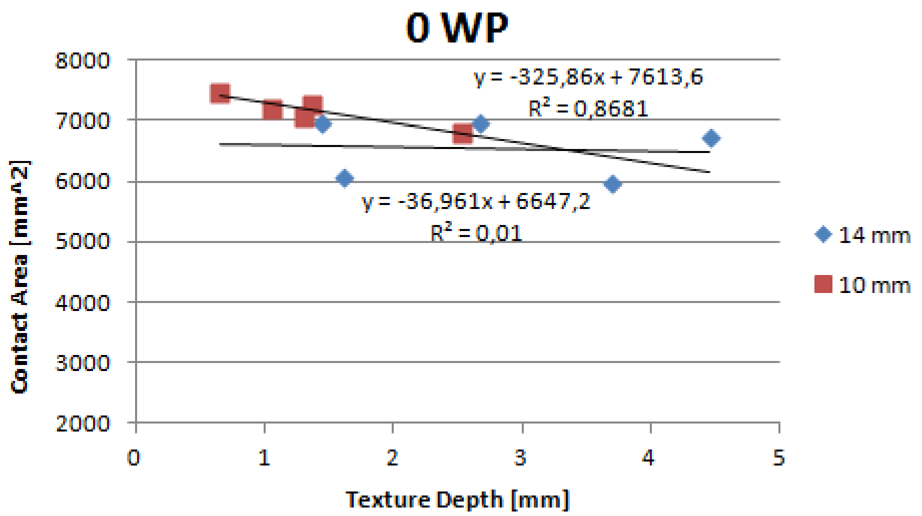
Figure 5.13 – Relationship between average pressure and wheel passes

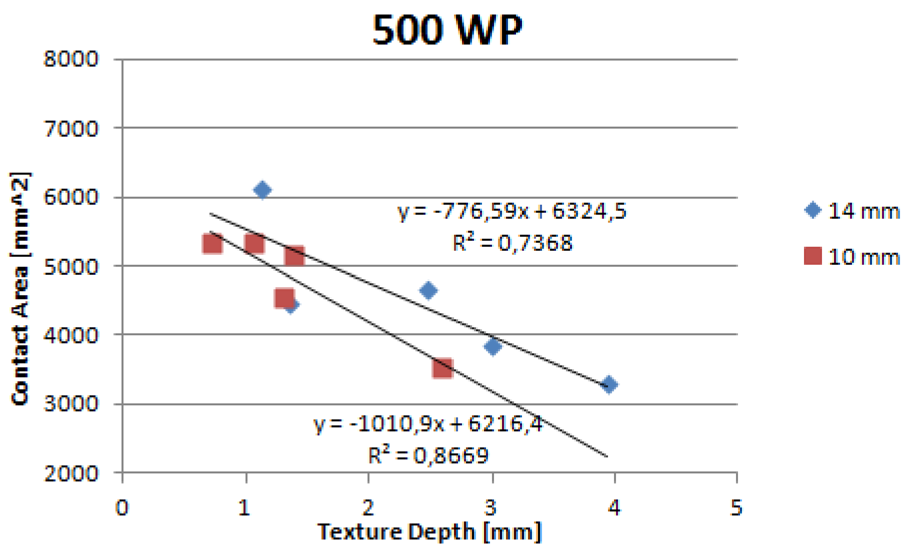
From these two graphs the trend appears well defined. In both of these and for all the samples, there are an increase of peak pressure and average pressure with the increasing number of wheel passes. This well relates to the effect of trafficking.

5.6 RELATIONSHIP BETWEEN CONTACT AREA, TEXTURE DEPTH AND SKID RESISTANCE

In order to have a better understanding of the behaviour, some relationships between the main indicators have been evaluated.

Figure 5.14 plot the change in contact area and in texture depth after 0, 500, 5000, 20000 and 100000 wheel passes.





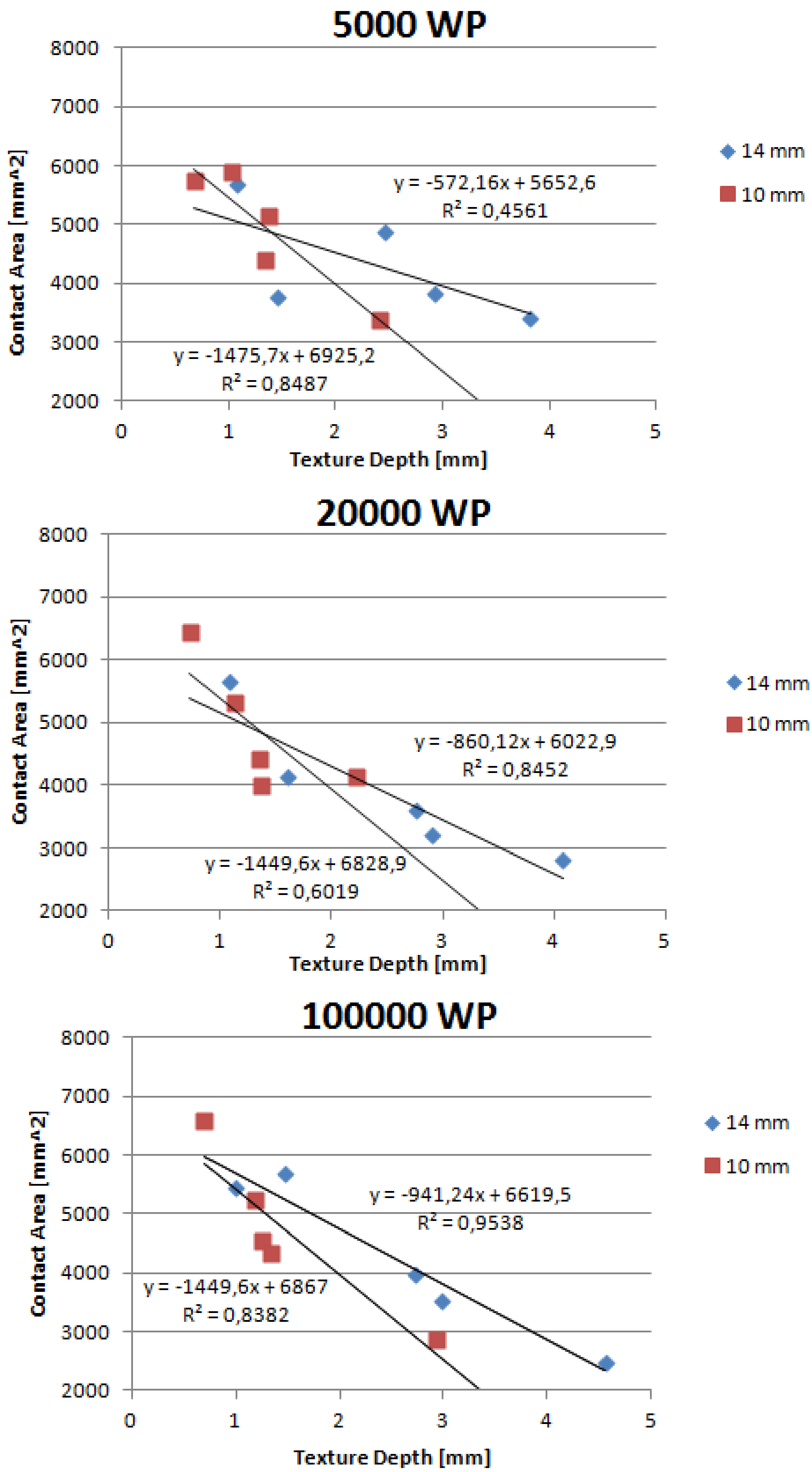


Figure 5.14 – Contact area against Texture depth

The first graph shows similar values of contact area for all of the 5 sample of 10 mm aggregate and this reflects in a linear trend. The situation is different for the 14 mm sample; in fact the values are very scattered because of the wide range of texture in the 5 samples.

The situation starts to change after the use of RTM machine to simulate trafficking. In fact the values of contact area and texture depth are decreased with the increasing number of wheel passes, and this has caused an alignment of points. For this reason now the relationship between contact area and texture depth is linear for both of the two groups of specimens.

These changes in texture depth and in contact area have caused an increase in the angles of the two straight lines.

Analyzing the two equations for the trendilines found in the last graph, it's possible to find the two point of intersection between these two straight lines and the y-axis; the two equations are listed below:

$$y = -1449{,}6x + 6867 \quad \textit{(10 mm)}$$

$$y = -941{,}24x + 6619{,}5 \quad \textit{(14 mm)}$$

This allow to calculate the maximum value of contact area, in which there is 0 mm of texture depth. That points represent a completely smooth surface.

These two values are 6867 mm^2 for the 10 mm samples and 6619,5 mm^2 for the 14 mm ones.

Subsequently the values of contact area and texture depth have been gathered in two groups, depending on the aggregate size, as it's possible to see in Figure 5.15 and Figure 5.16.

These two graphs clearly highlight a linear trend for all the stages of trafficking and for both of the groups and confirm the reduction in the values of contact area with the increasing number of wheel passes.

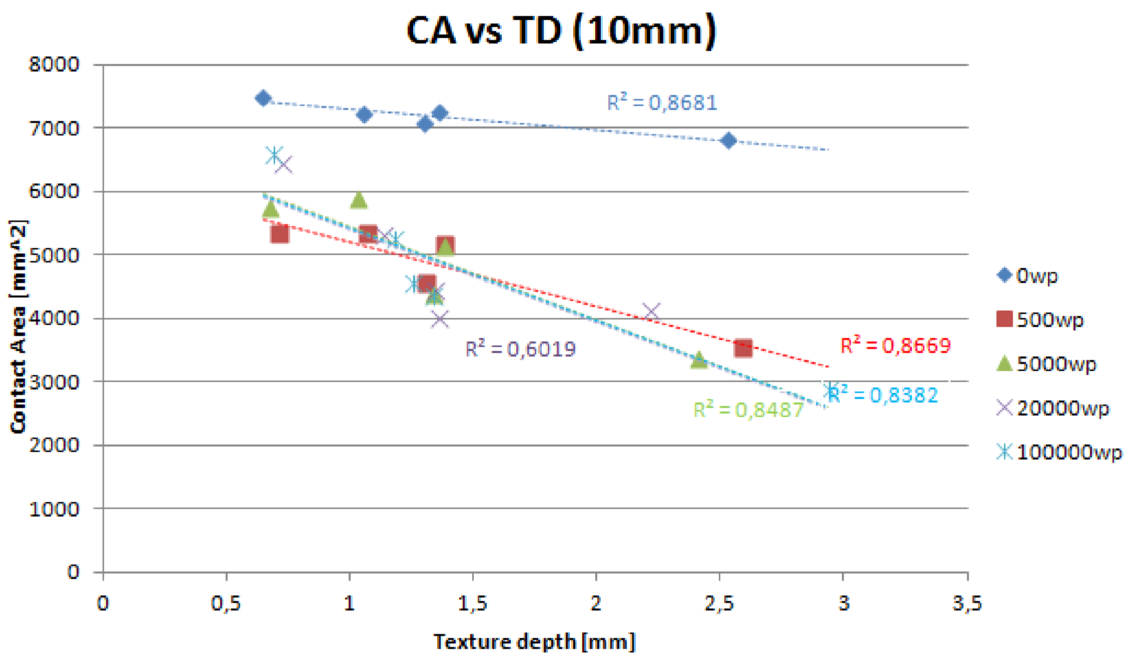


Figure 5.15 – Contact area against texture depth (10 mm)

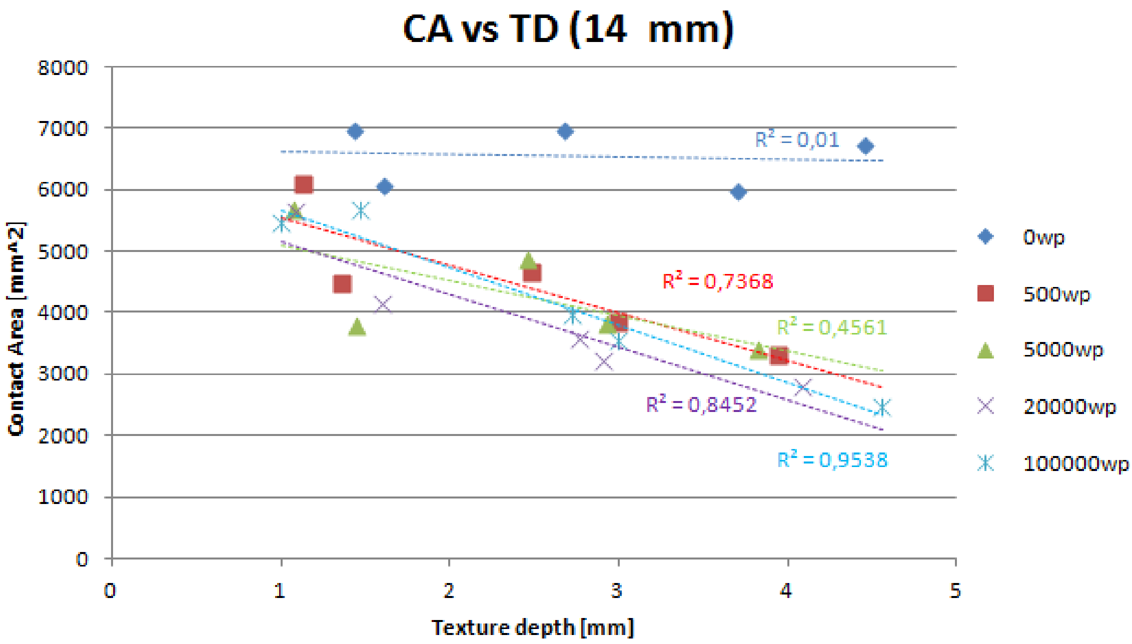


Figure 5.16 – Contact area against texture depth (14 mm)

Another important relationship has been evaluated. It concerns the evolution in contact area and in skid resistance, by means of PTV index, obtained from the pendulum skid test.

Figure 5.17 plot the data for this relationship in 2 graphs, for the two different aggregate size, reflecting the changes of the values after different levels of trafficking (0, 500, 5000, 20000, 100000 wheel passes).

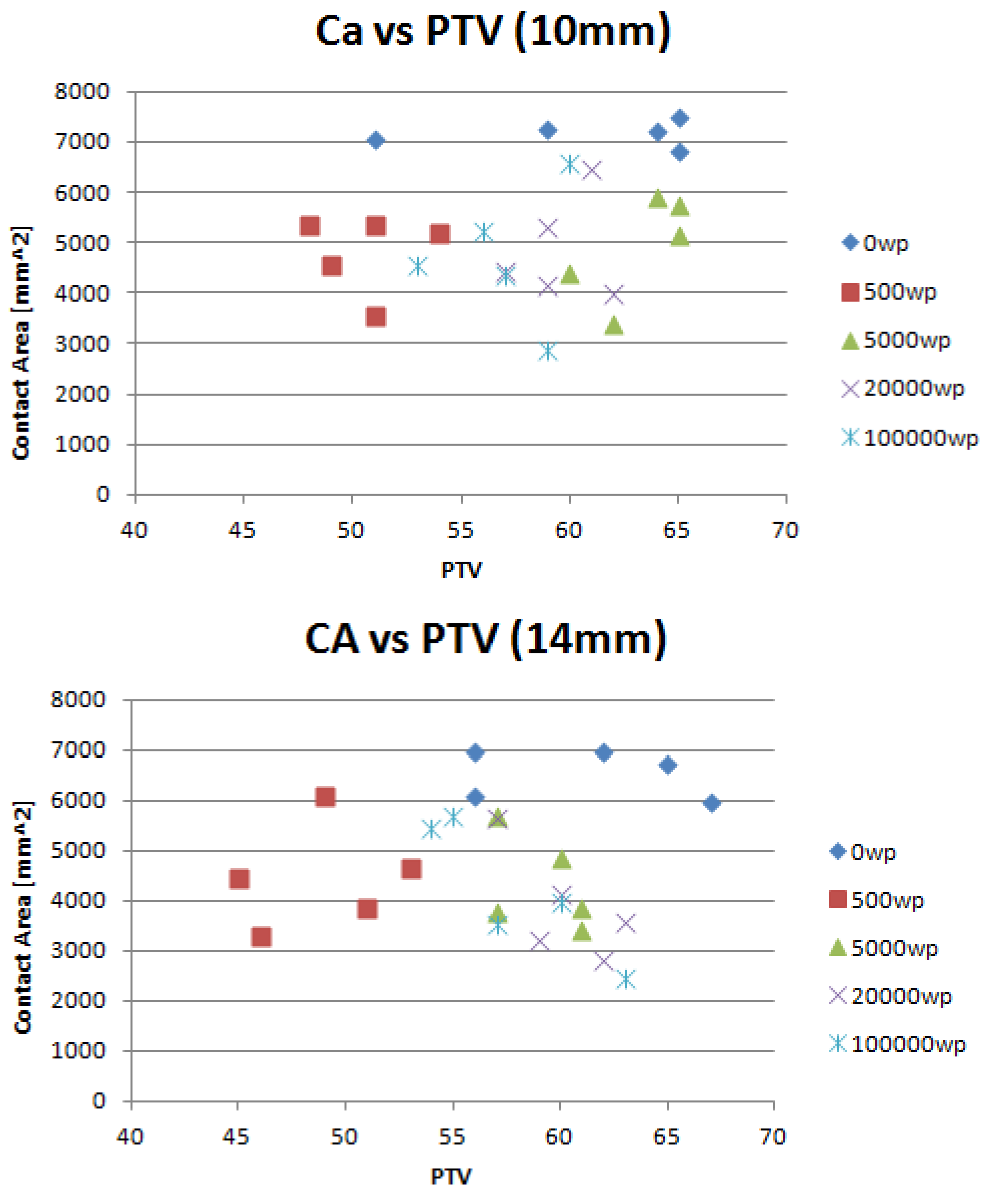


Figure 5.17 – Contact area against PTV

At the beginning (0WP), it's possible to notice a wide range of PTV values, due to the differences in texture and in the rate of compaction.

Subsequently under the effect of trafficking, the range of PTV values has started to decrease while the contact area decreases as well.

After 500 wheel passes in the RTM, the points in the graphs have moved through lower values of skid resistance, and after that through higher ones, remaining almost constant until the end of testing.

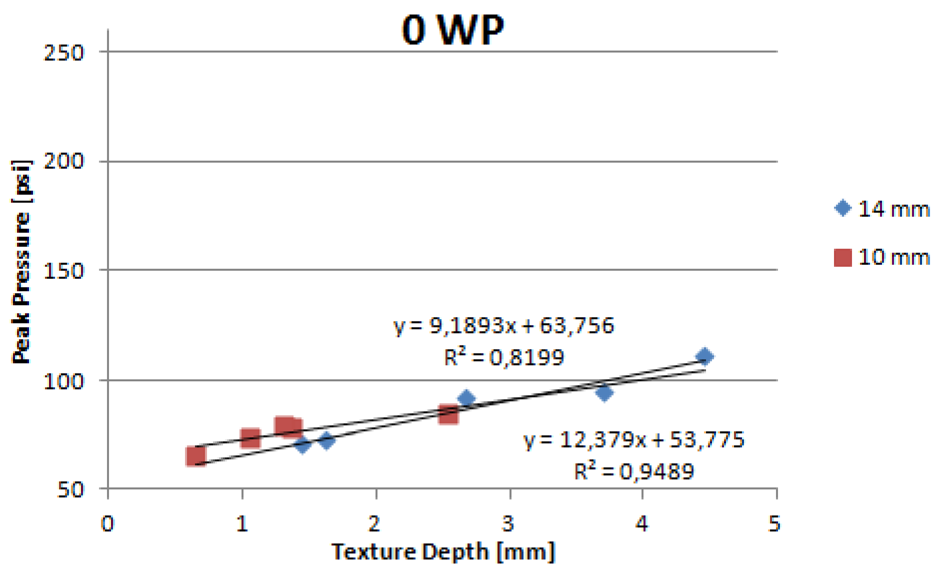
This fact is perfectly in agreement with the behavior of SMA during his early life, with a decrease of skid resistance and texture depth, due to the loss of its bitumen coating, followed by a rapid increase of values proceeding with trafficking, and finally reaching a state of equilibrium.

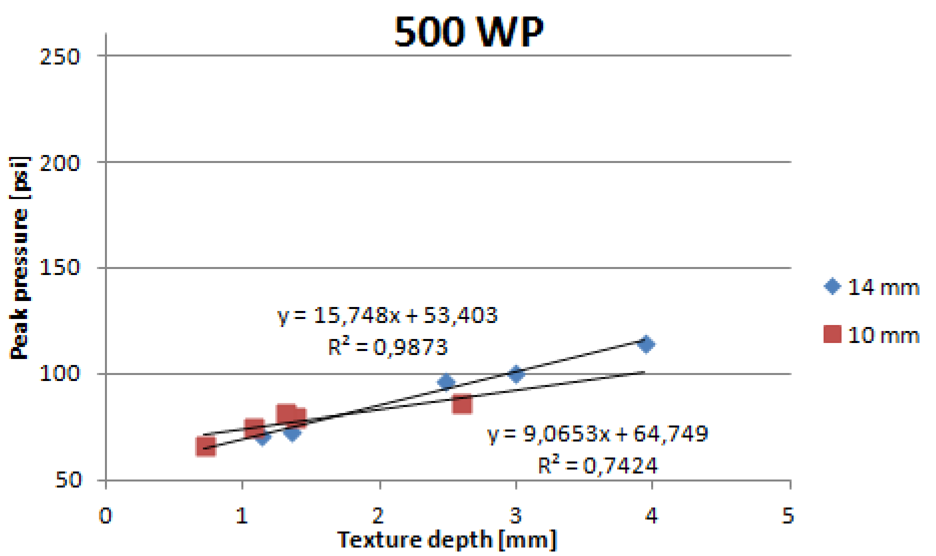
5.7 THE INFLUENCE OF PRESSURE ON TEXTURE DEPTH AND SKID RESISTANCE

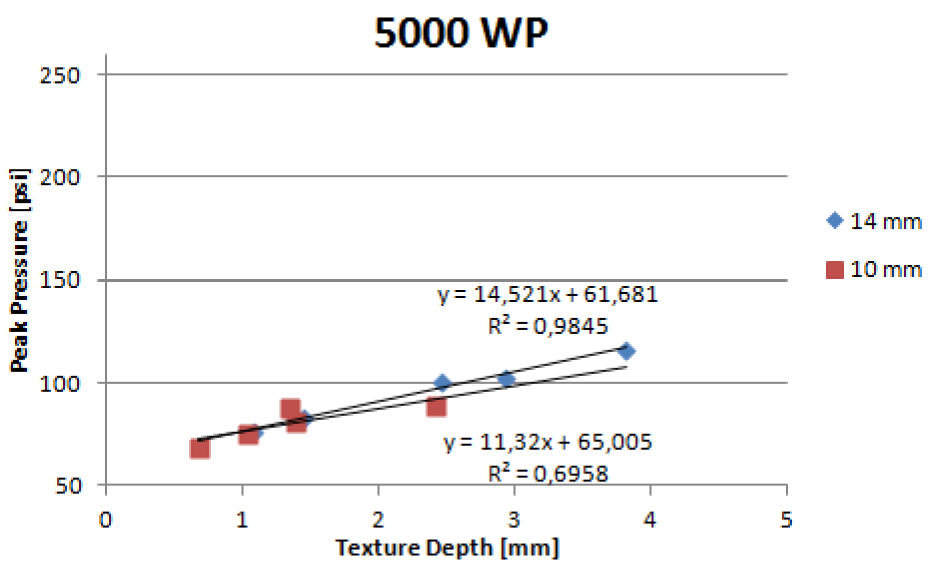
Another important parameter considered in this analysis concerns the role of pressure in influencing properties of the sample, such as texture depth and skid resistance.

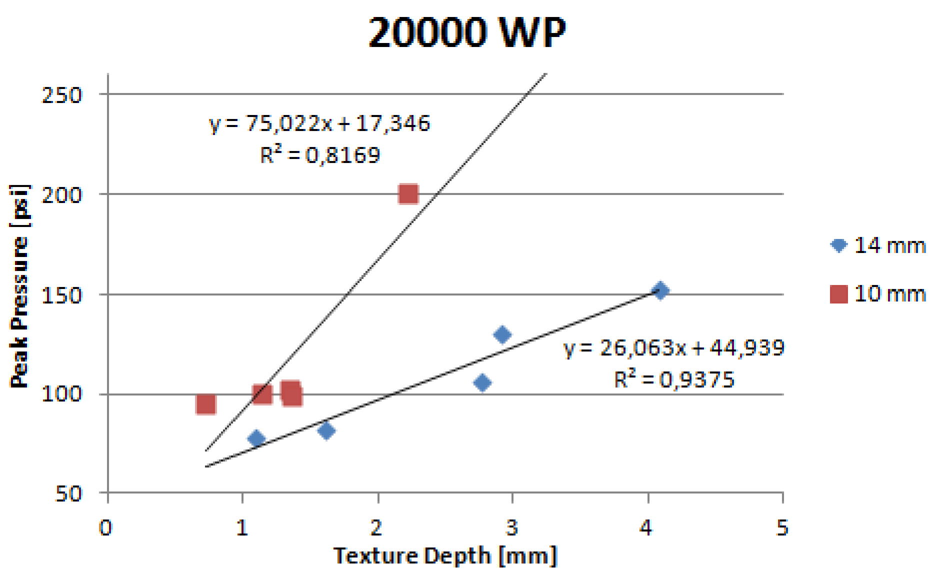
For all the samples, the values of average pressure and peak pressure after different number of wheel passes in the RTM machine, have been evaluated.

It has been found a very significant relationship between Peak pressure and texture depth, as shown in Figure 5.18.




500 WP
Peak pressure [psi]
250
200
150
100
50
0
1
2
3
4
5
Texture depth [mm]
y = 15,748x + 53,403
R² = 0,9873
y = 9,0653x + 64,749
R² = 0,7424
14 mm
10 mm


5000 WP
Peak Pressure [psi]
250
200
150
100
50
0
1
2
3
4
5
Texture Depth [mm]
y = 14,521x + 61,681
R² = 0,9845
y = 11,32x + 65,005
R² = 0,6958
14 mm
10 mm


20000 WP
Peak Pressure [psi]
250
200
150
100
50
0
1
2
3
4
5
Texture Depth [mm]
y = 75,022x + 17,346
R² = 0,8169
y = 26,063x + 44,939
R² = 0,9375
14 mm
10 mm

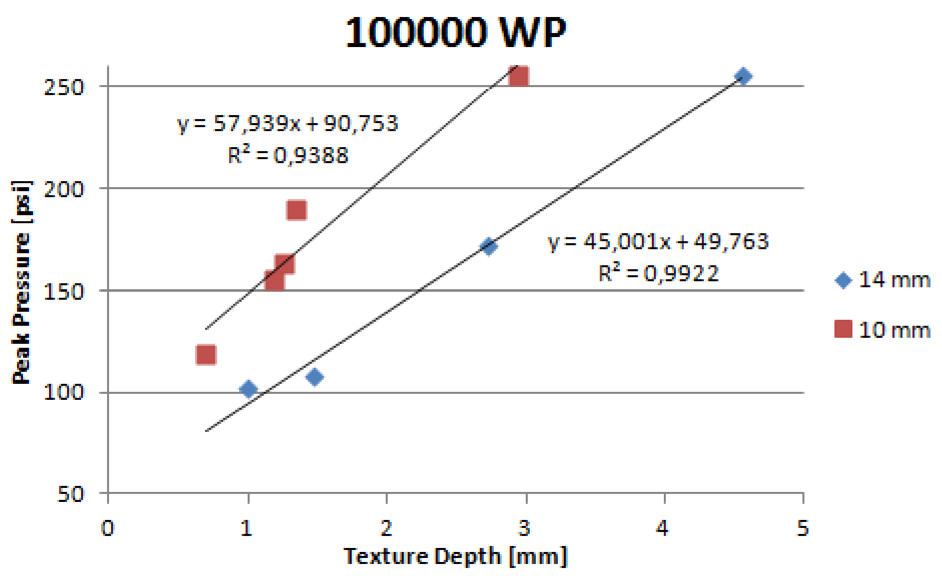


Figure 5.18 – Peak pressure against Texture depth

The relationships shown in these graphs are perfectly linear, for all the stages of testing. This is testified by the high values of the correlation.

This linear trend suggests that an increase in texture depth, causes an increase of Peak pressure between tyre and material, as well.

These two trendlines found for the two groups of aggregate size, give us a way to find one of these two parameters, just knowing the other one.

Moreover this well relates with what would have been expected; in fact generally an increase in texture depth is due to the reveling aggregates and to the widening of the surface's holes, and this cause a growth in the values of pressure around these particular characteristics of the surface.

The linear relationship between Peak pressure and texture depth represented in Figure 5.19 shows an increase in the angle of the trendlines for each stage of trafficking till 45°, the bisector of the axis.

This is due to the fact that with the increasing number of wheel passes, the surface texture is generally worn, with missing pieces of cores that reflects in an increase of texture depth and Peak pressure.

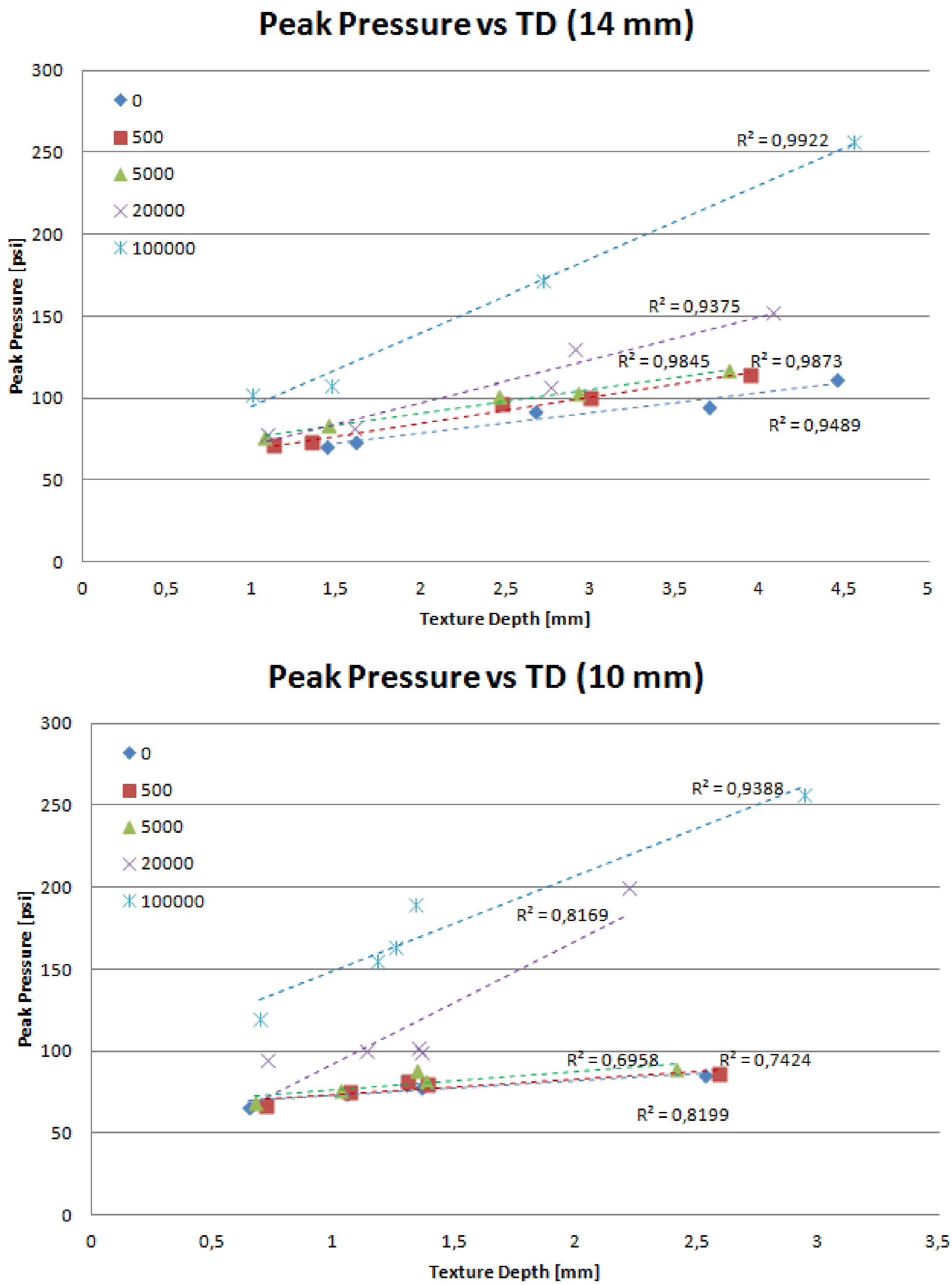


Figure 5.19 – Peak pressure against Texture depth

After this the connection between Peak pressure and PTV was also considered, as presented in Figure 5.20.

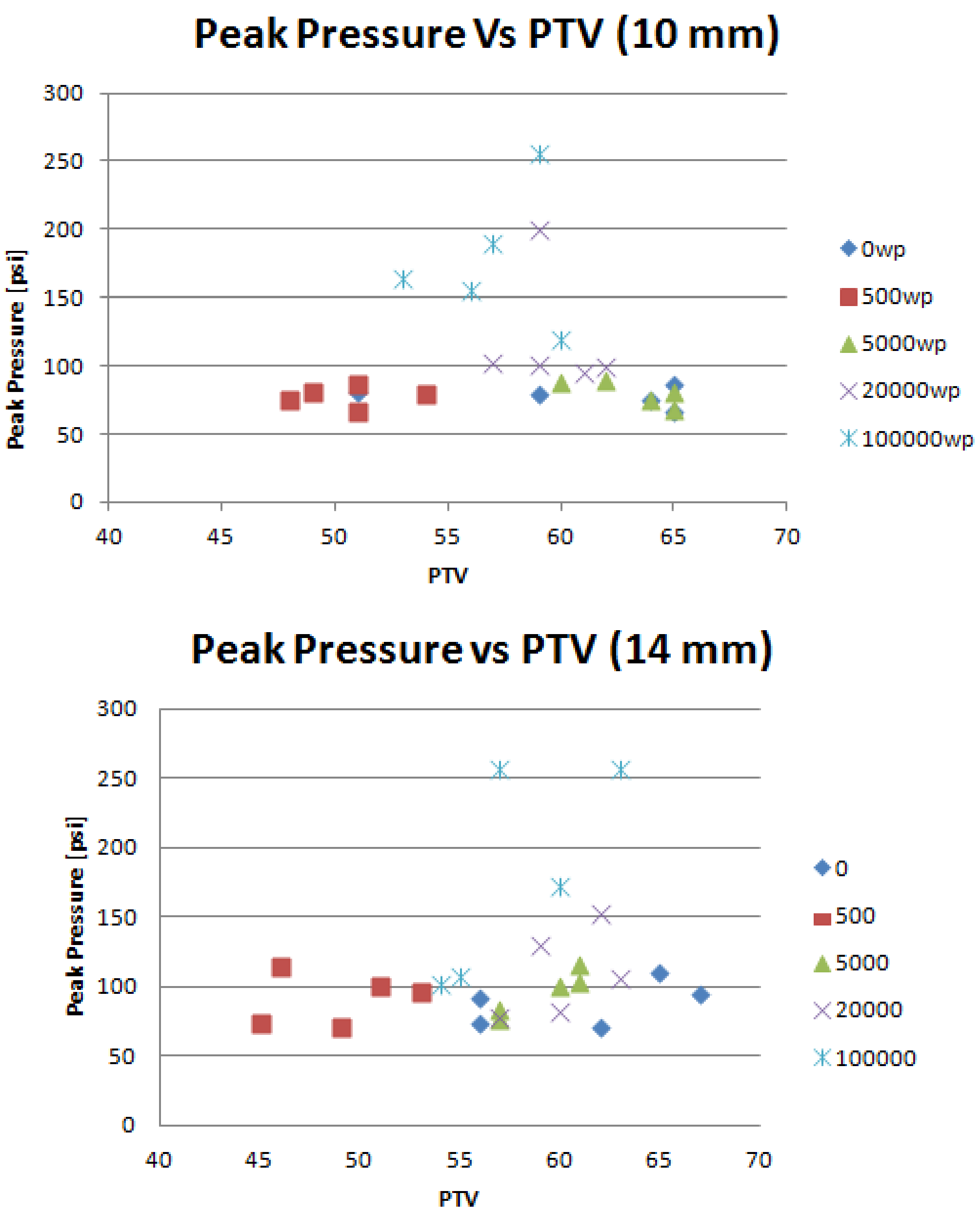
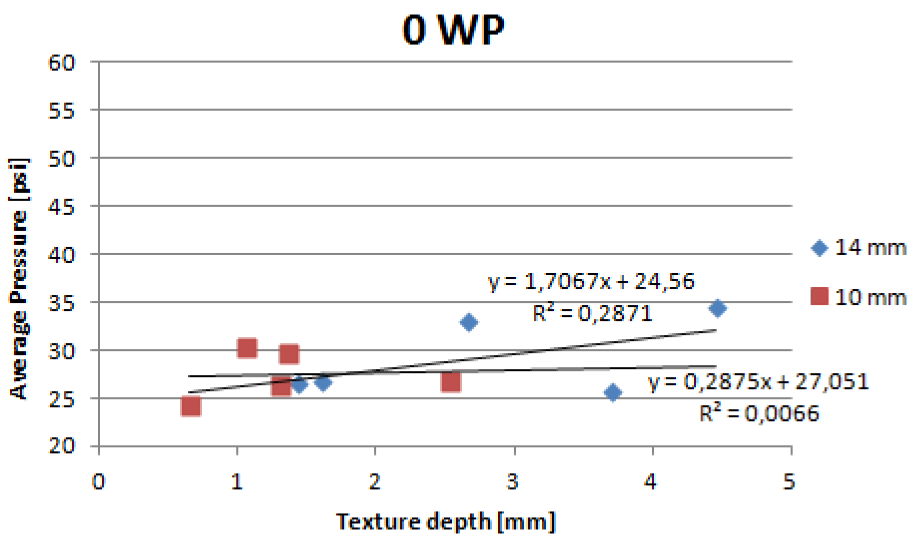


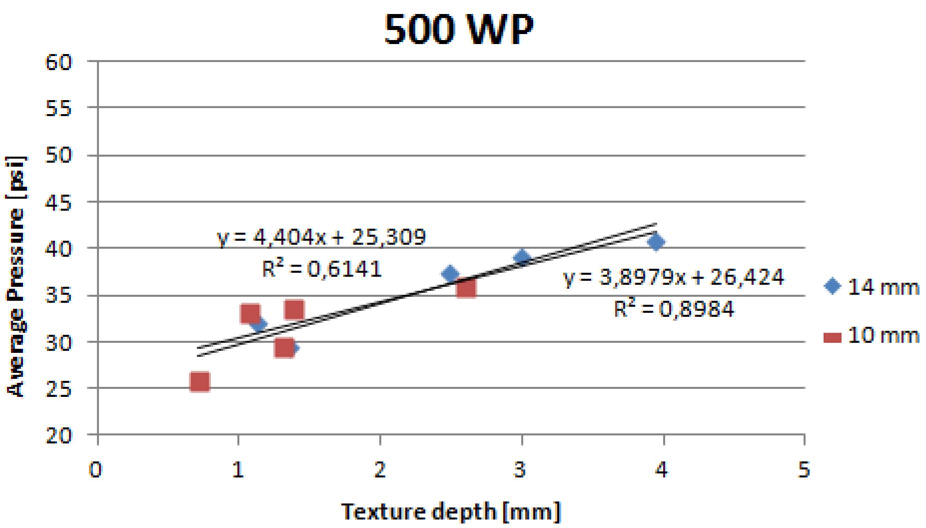
Figure 5.20 – Peak pressure against PTV

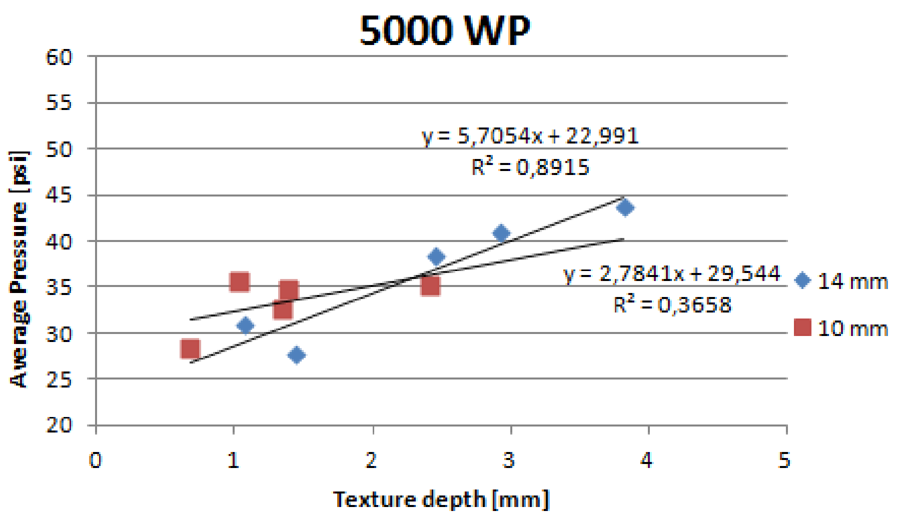
The values are very grouped for all the stages of trafficking, for what concerns both the Peak pressure and the PTV values. The only exception is for some samples after 100000 wheel passes in which the effect of the wear on the specimens, have caused an increase of the values of Peak pressure. In fact in this last stage of trafficking there's more variability in the values of PTV. The reveling of aggregates causes a gain in PTV and a concentration of pressure around missing pieces of coarse.

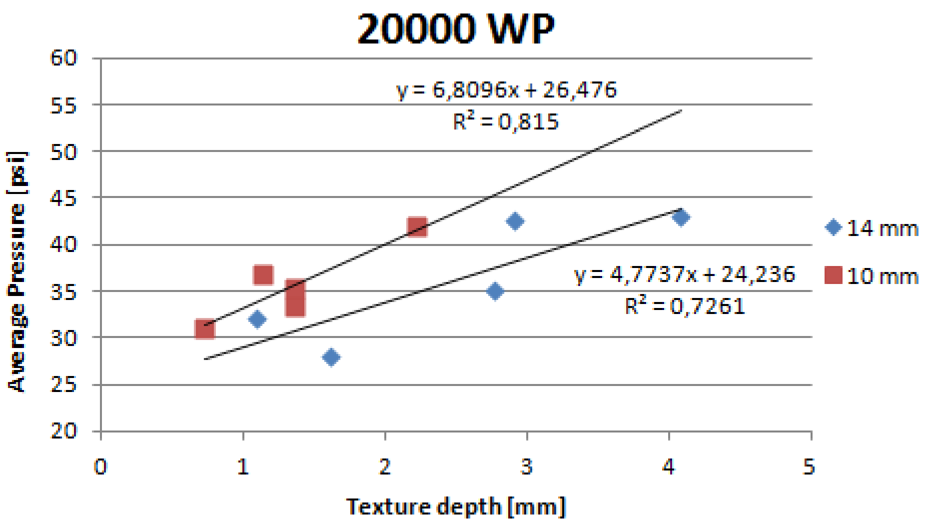
Considering the same relationships for the average pressure it's possible to notice that the trend is very similar to the previous one. This is because an increase in the values of peaks causes also an increase in the values of the average.

In fact the relationship between average pressure and texture depth is linear especially in the last two graphs of Figure 5.21 as already seen in Figure 5.18 and Figure 5.19.









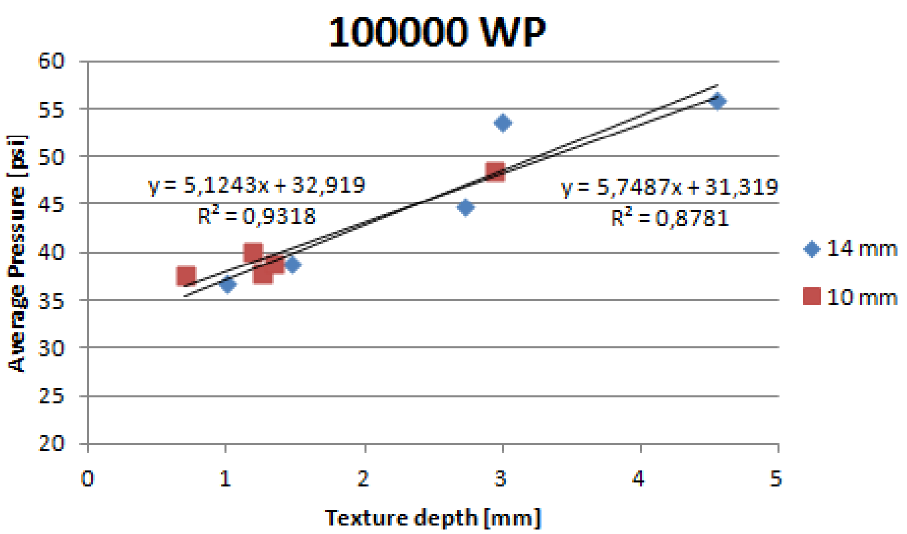
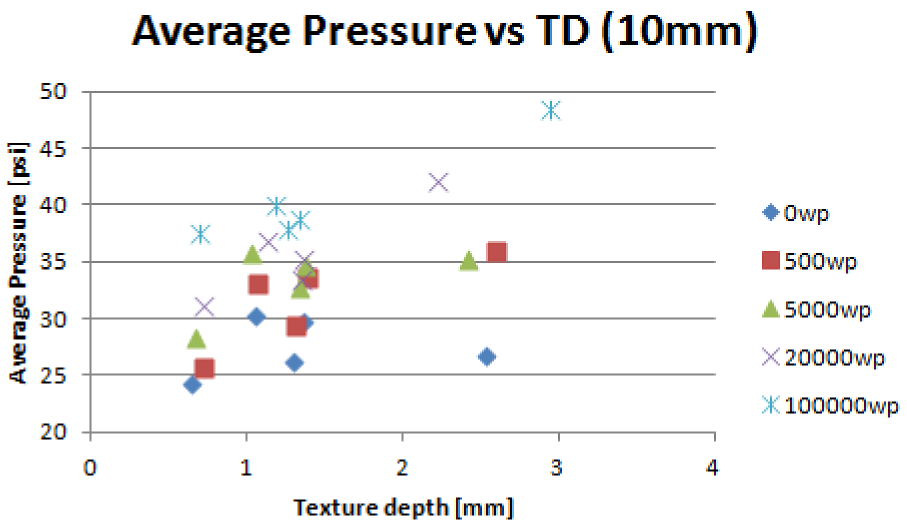


Figure 5.21 – Average pressure against texture depth (0, 500, 5000, 20000, 100000 wheel passes)

The same trend is also identifiable in Figure 5.22, in which are represented two graphs for the two different aggregate sizes.



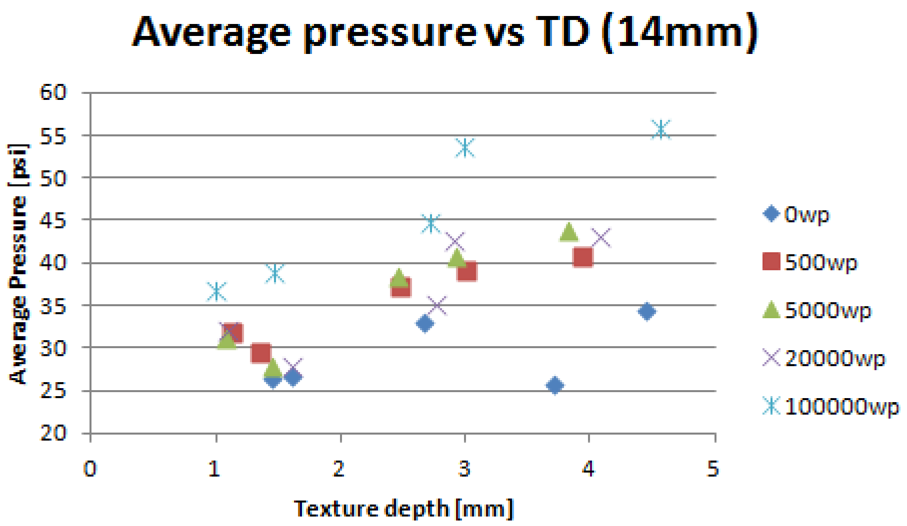
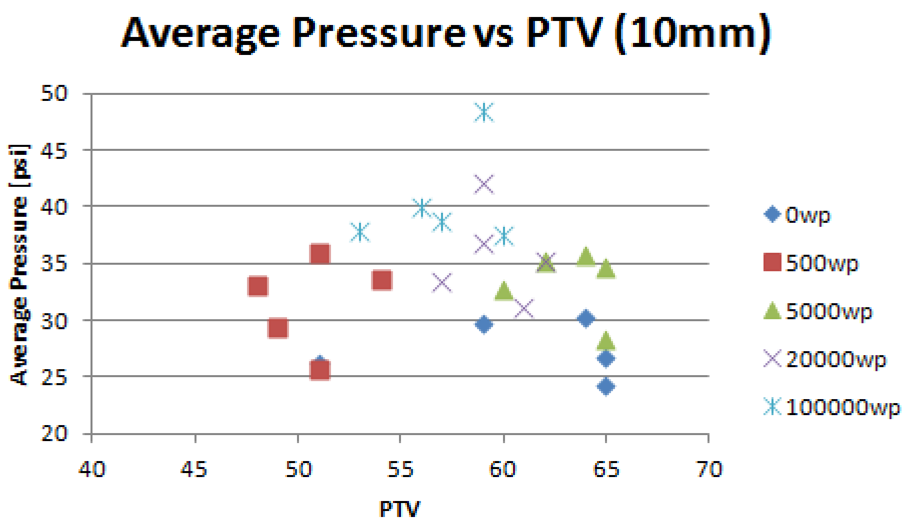


Figure 5.22 – Average pressure against texture depth

The same behavior is recognizable also in the link between average pressure and PTV.



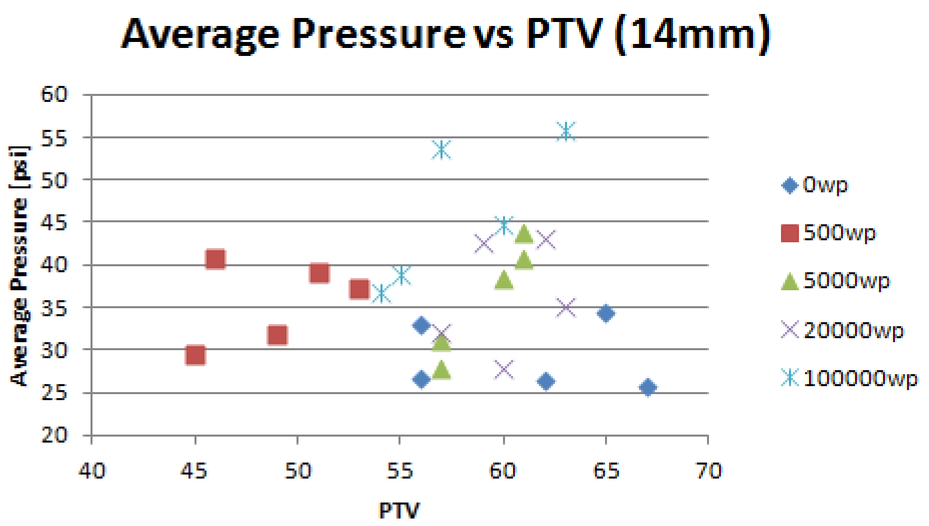


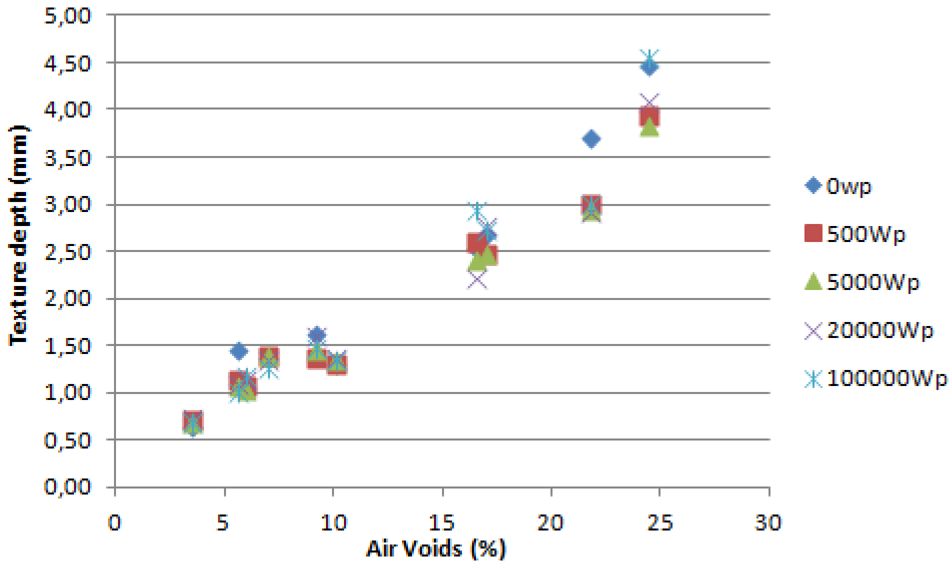
Figure 5.23 – Average pressure against PTV

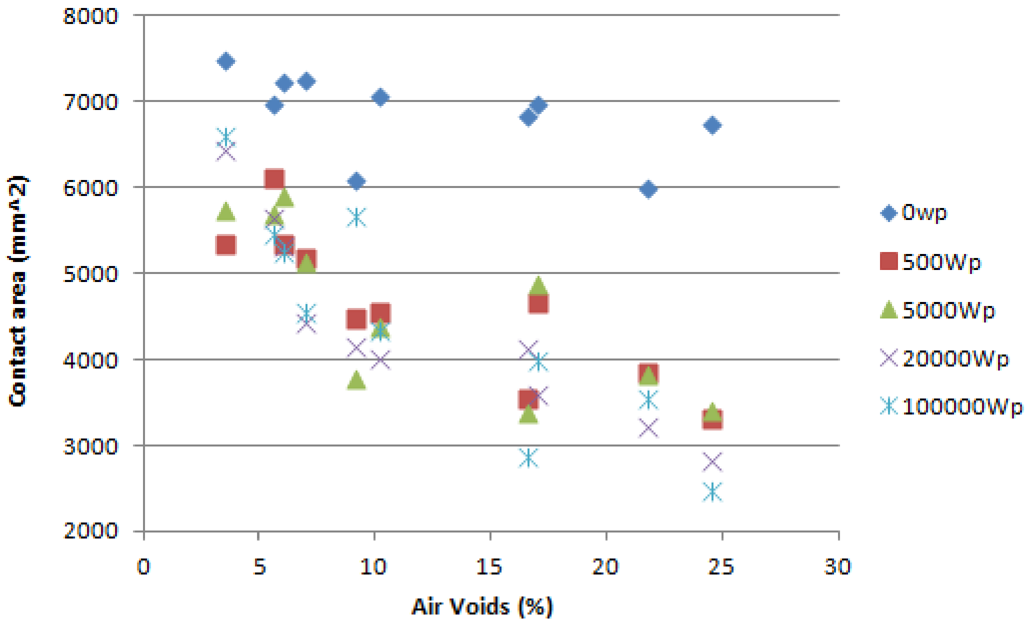
5.8 THE INFLUENCE OF AIR VOIDS CONTENT

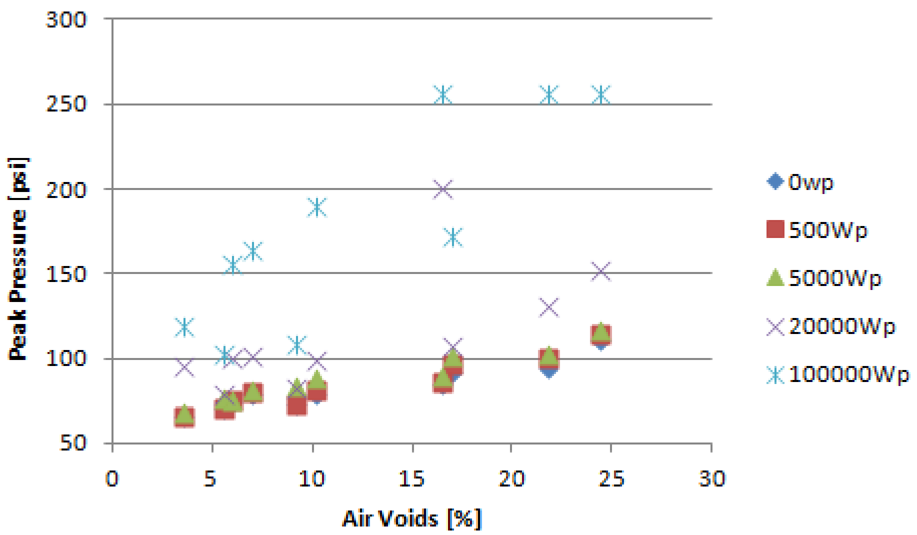
As it has been previously explained, the samples have a very different range of texture due to the difference in rates of compaction in the gyratory machine.

This is reflected also in a wide range of Air void content (%). For these reasons it has been necessary to analyze how the percentage of voids influences the different parameters considered in this project.

It has been considered the relationship between Air voids content and texture depth, PTV, Peak pressure and Average pressure, as illustrated in Figure 5.24.


5,00
4,50
4,00
3,50
3,00
2,50
2,00
1,50
1,00
0,50
0,00
Texture depth (mm)
0
5
10
15
20
25
30
Air Voids (%)
0wp
500Wp
5000Wp
20000Wp
100000Wp


8000
7000
6000
5000
4000
3000
2000
Contact area (mm^2)
0
5
10
15
20
25
30
Air Voids (%)
0wp
500Wp
5000Wp
20000Wp
100000Wp


300
250
200
150
100
50
Peak Pressure [psi]
0
5
10
15
20
25
30
Air Voids [%]
0wp
500Wp
5000Wp
20000Wp
100000Wp

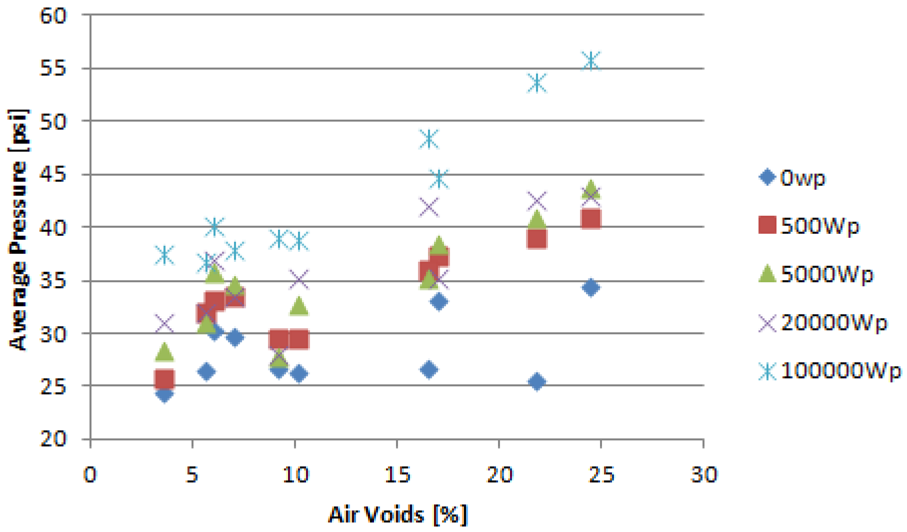


Figure 5.24 – relationship between Air voids and TD, PTV, Peak pressure and Average pressure

The evolution of each sample in the process of trafficking, is characterized by a group of points on the vertical lines, each of them representing the different percentage of voids in the specimens. For all the parameters analyzed in these graphs is possible to see the same trend. In fact the values are very gathered in the first stages of trafficking and they become very scattered after 20000 and 100000 wheel passes. This behavior is clear in the first and in the last of the graphs in Figure 5.24, in which the values of Texture Depth and Average Pressure have a wider range in the samples with an open texture and higher percentage of voids.

The main exception is in the second graph, in which it's possible to recognize high variability of the values, in the first stages of trafficking, especially analyzing the differences in Contact Area before the RTM's effect and after 500 wheel passes. This great changes in Contact Area with the effect of RTM, influence the behavior of all the parameters considered.

The analysis of data has carried out a general trend for all the samples. As shown in Figure 5.8 the Contact Area decreases with the process of trafficking in all of the samples with the exception of specimen 2A. In order to understand this strange behavior, a 3D analysis was required; the methodology and the results are illustrated in the next chapter.

CHAPTER 6

ANALYSIS OF TEXTURE USING 3D PHOTOGRAMMETRY SOFTWARE

6.1 INTRODUCTION

The ability to characterise highway surfacing textures is essential to better understanding their performance. Traditional volumetric methods such as sand patch produce data based on estimation of a single geometry and offer little insight to early life deformations of bitumen coatings, changes in aggregate shape or longer term performance of the asphalt. Durability of an asphalt surfacing is a function of its ability to withstand static and dynamic contact stresses applied during its life. For these reasons, in the last years, 3D techniques have been used to create digital models of real surfaces. [10] Previous studies developed at University of Ulster, suggest that these methodologies offer improved understanding of tyre/surface interaction, and they have been used in this thesis, to appreciate why sample 2A has a different behavior compared to the others. For this purpose, the use of photogrammetry was required. The images have been manipulated using ArcGIS to form a spatial framework for analysing surface textures. ArcGis is a geographic information system that integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information. GIS allows to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. It helps to answer questions and solve problems by looking at data in a way that is quickly understood and easily shared.

6.2 THE USE OF PHOTOGRAMMETRY

Photogrammetry is a versatile, powerful, and flexible measuring technology broadly used in many fields, for a wide variety of measurement tasks. The fundamental principle used by photogrammetry is triangulation, therefore it is necessary to take photographs from at least two different camera angles. For this reason, two pictures were taken for each sample, from both right and left sides.

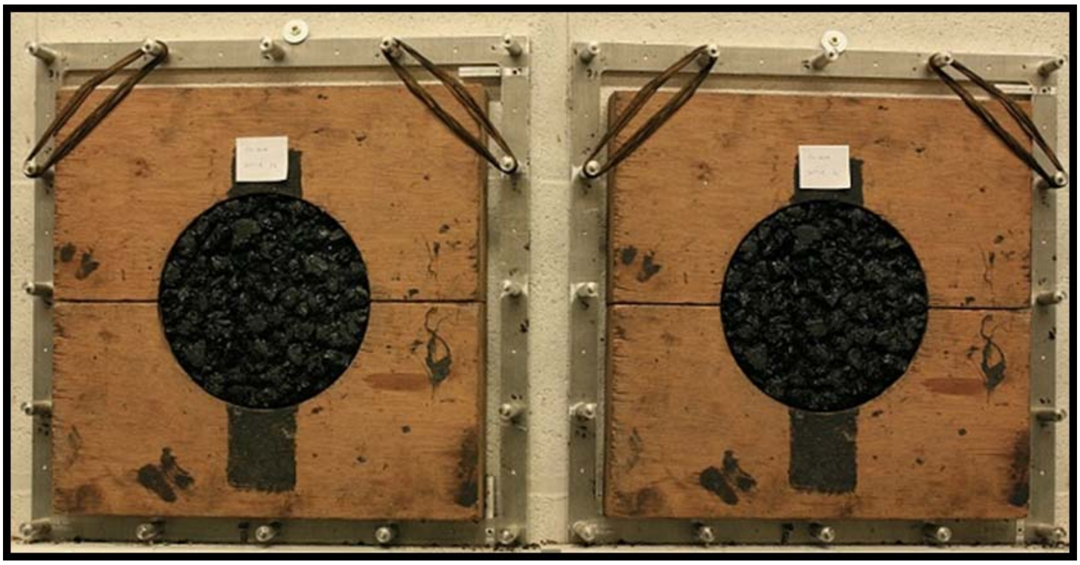


Figure 6.1 – Photographs of the same sample taken from the right and left side

These two pictures taken from each sample, were then loaded in a photogrammetry software, called Topcon Image Master, in order to create the 3D model. Image Master is photogrammetric software recently released by Topcon. This program allows the use of digital photos for various surveying purposes, such as photogrammetric measurements or preparing orthophotos. Originally designed to be used with an imaging total station, it can also be used with a digital camera. It uses photogrammetric methods that allow the parallax in a pair of stereo photos to be measured and converted into XYZ coordinates. The process involves several steps:

1. *Calibrate the camera*. the camera can be calibrated by taking five photos of a test pattern from specific angles and processing them with the calibration software. The test pattern is provided with the software, which consists of a grid of dots and diamonds. This calibration only needs to be done once for a fixed-length lens.
2. *Take a stereo pair of photos of the subjec*t. Each of the photos need to be taken a similar distance from the target, with the camera oriented in the same direction and the entire subject included in each photo. Each pair of photos creates one stereo model. If the subject is large, multiple stereo models can be stitched together later.
3. *Measure the coordinates of at least four control points that are visible on both photos and are distinctive.*

4. *Load the control coordinates, the stereo photos, and the lens parameters* into ImageMaster and designate the location of each control point in both photos. The software will then calculate the parallax of the photos and return the error residual of each point.
5. *Coordinates of any point identifiable on both photos can now be measured.* ImageMaster also has the ability to create a TIN and contours from the points, and the photos can be draped over the TIN to make orthophotographs. [14]

All these models were generated with a TIN mesh of 0.5 mm. Some also utilized the 0.3 mm mesh, to have a better understanding of the texture and to show more details. The two figures below show how it's possible to have a more detailed reconstruction of texture by moving from a 0.5 mesh to a 0.3 mm one, for the same sample.

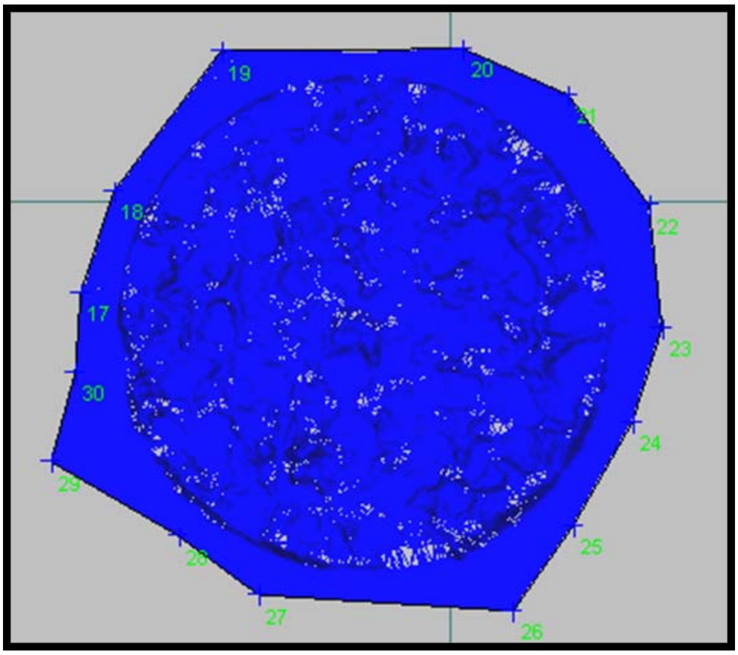


Figure 6.2 – 3D model for a 14mm SMA with 0.5 TIN mesh

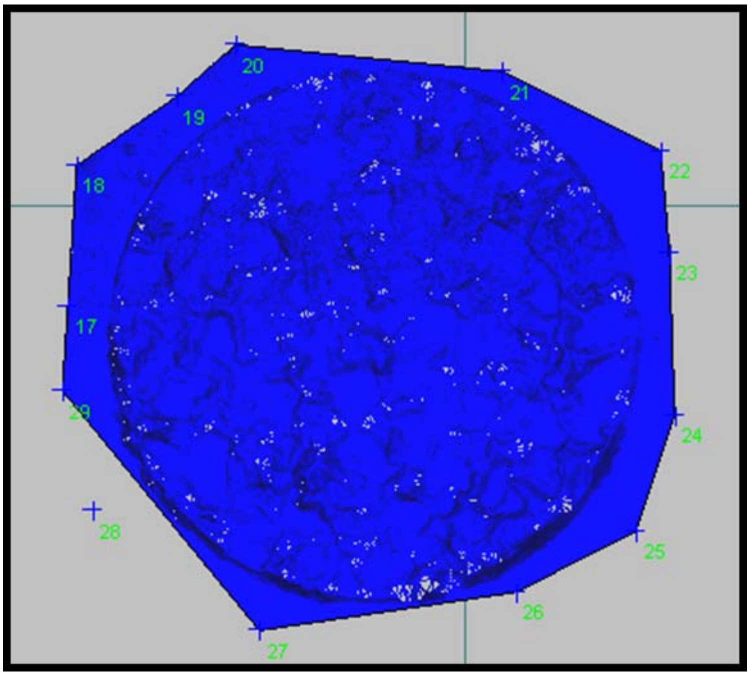


Figure 6.3 – 3D model for a 14mm SMA with 0.3 TIN mesh

In particular for sample 11 was analyzed the difference in texture considering the situation before testing and the one after 100000 RTM wheel passes. In order to do this, a 3D model for each sample was created, with a 0,3 TIN mesh.

Figure 6.4 – Reconstruction of texture pre and after trafficking using Topcon Image Master

Its behavior in fact is considered strange considering the relationship between wheel passes and contact area. As it has been previously shown, sample 2A and also sample 1B have an increase in contact area after the effect of trafficking.

Focusing the attention on figure 6.4, it clearly shows how the effect of RTM has reduced the deeply of the asperities and so the surface appears now flatter; this explains that an increase in the contact area is possible. With the intention of understanding why, the use of ArcGis software was successively required.

In this case, the software has been used to highlight the differences in the height on the sample's surface, before and after trafficking. An example of this is shown in Figure 6.5 for sample 11 before testing, and in Figure 6.6 after 100.000 wheel passes.

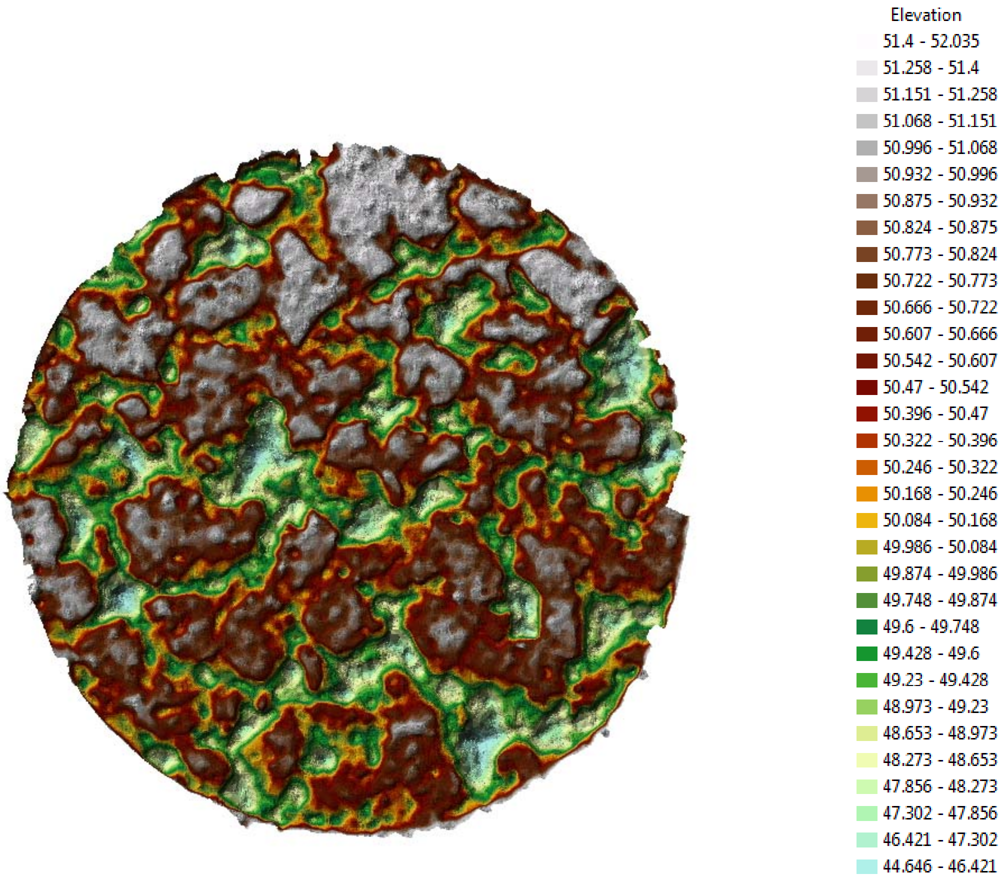


Figure 6.5 - Topographic map processed in ArcGis (0 wheel passes)

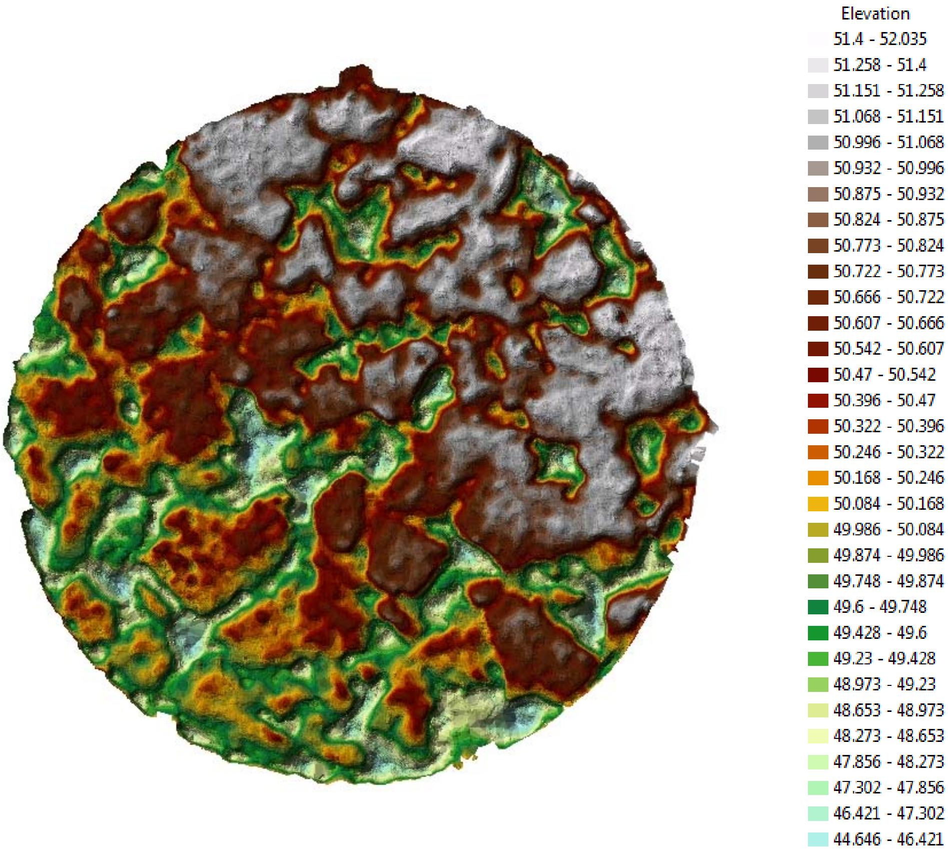


Figure 6.6 - Topographic map processed in ArcGis (100.000 wheel passes)

This software permits to better understand texture depth change; a reference plane at 0mm texture depth was chosen to calculate the loss in volume after 100000 wheel passes. This was possible overlapping the two models, as shown in Figure 6.7, and it was found a reduction in volume with the effect of wear.

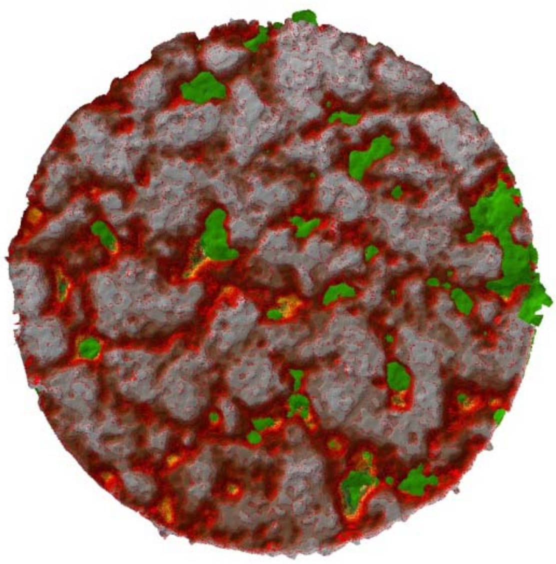


Figure 6.7 – Superimposition of the images to appreciate the differences in texture

This figure illustrates the variations in texture between the two samples and confirms the existence of potential areas of water entrapment.

This is water entrapped in small pockets having a definable perimeter within the area of a tread-block or as an area of surface water with no clear drainage path. All surfaces were found to entrap water.

This suggests that simple estimation of texture depth alone gives a limited indication of a surface's capacity for surface water retention. This is an area that offers potential for predicting the effect of water on durability of asphalt surfacing materials and it suggests a very interesting topic for futures development and studies.

CONCLUSION

This thesis has summarised the findings of a laboratory investigation to assess whether it is possible to rank the relative performance of 10 samples of SMA, with different air voids content and rates of compaction.

The ten specimens were made with two different sizes of aggregate, 10 mm and 14 mm, to investigates how asphalt type relates to texture and wet skid resistance.

The Road Test Machine was used to simulate controlled trafficking conditions. The change in wet skid resistance and texture depth was determined at regular intervals during testing.

By stopping periodically the complex interrelationships between asphalt mix properties such as asphalt type, nominal aggregate size, wet skid resistance and texture depth can be better understood and how they develop with time.

The data shows a general trend: there's an initial loss of skid resistance in early life, followed by an increase and thereafter a reduction to equilibrium conditions; with the exceptions of some 14mm samples that gained skid resistance in the later stages of testing due to severe surface reveling. The texture depth was found to increase as the nominal stone size increased.

It is concluded that the RTM can be used as a tool to quickly assess the relative performance of an asphalt material under controlled laboratory test conditions allowing material use to be optimized and reducing reliance on lengthy and costly road trials.

After this was considered the role of contact area on wet skid resistance and texture depth. It was found that the contact patch of the tyre had a significant role in rolling resistance being affected by tyre loading, inflation pressure and type of tyre. As the inflation pressure increased, the contact area decreases and there is an improvement in rolling resistance.

The data carried out with this test show a general decrease in contact area for all the sample with the effect of trafficking and this is true for the most of the samples, and an increase of Peak pressure and average pressure with the increasing number of wheel passes.

The evolution of each sample in the process of trafficking was analyzed in relationship with all the parameters considered in this project. The analysis of this factors in correlation with the air voids content was very significant. All the values are characterized by a group of points on vertical lines, each of them representing the different percentage of voids in the specimens. For all the parameters it's possible to recognize the same trend. In fact the values are very gathered in the first stages of trafficking and they become very scattered after 20000 and 100000 wheel passes. This behavior is clear in the graphs of Texture Depth and Average Pressure in which there's a wider range of values in the samples with an open texture and higher percentage of voids.

The main exception is in the analysis of Contact Area in which significant changes are shown also after 500 wheel passes. This great changes in Contact Area with the effect of RTM, influence the behavior of all the parameters considered.

The data of a smooth GripTester tyre interacting dynamically with a surface can be combined with 3D photogrammetric and spatial analysis.

This was required to better understanding the behavior of some samples, that not well relate with the general trend found for the others.

This 3D methodology is exceptionally versatile allowing rapid data capture at source and the ability to generate a theoretically unlimited number of profiles in any plane. This facilitates assessment of surface textures change, such as deformation, wear polishing, over time and space. The 3D surface models may be used to estimate volume of material loss and displacement with time. For this reason, in this thesis has been used the photogrammetry to model and monitor surface macro-texture change of asphalt cores subjected to laboratory accelerated trafficking. Stereo image pairs were taken during testing and processed using a photogrammetric software and subsequently exported in ArcGig to show change in macro-texture profiles, depression perimeters and volumes and analyze the different behavior of sample 2A. This changes suggests an early re-deposition of material in voids and infilling of surface texture during early life trafficking due to smearing of the bitumen coating off the trafficked asphalt concrete surface. In contrast the conventional sand patch method offered much less insight of the processes taking place during the trafficking period. It is concluded that stereo photo analysis, and the use of 3D techniques in general, offer a potentially viable method of correlating mechanical processes at the tyre/surface interface with surface characteristics and give us a better understanding of the texture. This is very important for road security and also from an economic point of view. In fact some studies have proved that reducing the texture depth of positive textured surface dressing resulted in significant reductions in road/ tyre noise and that surface texture appeared to be the main surfacing property that needed to be considered when developing more fuel-efficient surfacing materials. Moreover the relationship between road surface is the main factor in the safety; in fact both road surface and tyre require minimum levels of grip and texture to remove water and minimize aquaplaning.

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