Task 409: Collaborative Research into the Next Generation of Asphalt Surfacings

Project Report

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The methodology adopted and the sources of information used by AECOM in providing its services are outlined in this Report. The work described in this Report was undertaken between March 2015 and November 2016 with the final report issued in February 2017. The report is based on the conditions encountered and the information available during the said period of time. The scope of this Report and the services are accordingly factually limited by these circumstances.

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Where field investigations are carried out, these have been restricted to a level of detail required to meet the stated objectives of the services. The results of any measurements taken may vary spatially or with time and further confirmatory measurements should be made after any significant delay in issuing this Report.

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EXECUTIVE SUMMARY

The primary objective of this project is “to ensure that asphalt surfacings continue to deliver value for money on the UK Strategic Road Network and to maximise the benefit from innovation”. This project was a collaborative effort between Highways England (HE), Mineral Products Association (MPA) and Eurobitume UK.

This project reviewed surfacing materials worldwide with the view to understanding and developing requirements for materials which offer significantly enhanced durability, reduced noise characteristics and improved skid resistance.

An idea gathering workshop attended by academics, contractors, consultants and clients from the UK, Germany and France was then convened. The key question put forward to participants was “What are your ideas for the next generation of asphalt surfacing for use on Highways England’s Strategic Road Network that will increase durability without compromising the current performance of Specification for Highway Works (SHW) Clause 942?” The agreed options for further investigation attained from this workshop comprised of SHW Clause 943 Hot Rolled Asphalt (Performance Related Design Mixture) using 6/10 mm chippings and the Premium Asphalt Surfacing System (PASS). The aim of the SHW Clause 943 Hot Rolled Asphalt (Performance Related Design Mixture) using 6/10 mm chippings was to minimise noise through embedment of smaller size chippings. The PASS was the top idea amongst a range of other options. The PASS concept is based on a low void, dense body of asphalt material with improved surface characteristics (low noise characteristics and good macrotexture properties).

The HRA and PASS mixtures were further developed in the specialist laboratories of AECOM’s Centre of Excellence for Asset Consultancy in Nottingham to establish proof of concept for the asphalt materials. The mix designs and the associated performance related assessments showed optimised properties which led to pilot scale demonstration trials at Alrewas Quarry, Staffordshire in June 2016. Further tests and analysis following this demonstration trial showed the potential to consider both the PASS and HRA asphalt mixtures.

The results from this project provide a significant advance in our understanding and present candidates (PASS and SHW Clause 943 HRA using 6/10 mm chippings) for the next generation asphalt surfacing materials with significantly enhanced durability, low noise characteristics and potential for good skid resistance.

The next phase of the project involves the review and optimisation of the PASS and HRA asphalt surfacing materials. This will be followed by pre-road trials and a large-scale trial on a section of the Highways England network. These works are planned for 2017.

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1 INTRODUCTION

Thin Surface Course Systems (TSCS) have been used in the UK since the late 1990s and regarded as the preferred surfacing for the Strategic Road Network. TSCS are "proprietary bituminous products with suitable properties to provide a surface course that is laid at a nominal depth of ≤ 50 mm" (Highways Agency, 2012). EAPA (2007) presented three families of asphalt surfacing with nominal layer thickness ≤ 50 mm. These asphalt surfacing materials are generally gap graded in order to provide stone to stone contact and an open surface texture.

- Ultra-Thin Asphalt Concrete (UTLAC) surfacing developed in France with a nominal (average design) thickness of 10 mm to 20 mm. Several varieties of this asphalt type are often used to provide a noise reducing layer.
- Very Thin Asphalt Concrete surfacings (VTAC) generally utilise polymer modified bituminous binder and are laid to a nominal thickness of 18 mm to 25 mm.
- Stone Mastic Asphalt (SMA) could make use of either paving grade bitumen with fibres or polymer modified bitumen and laid to a nominal thickness ranging between 25 mm to 50 mm.

Table 1-1 presents the durability of thin surfacing in years of service life for major roads, motorways and heavily trafficked roads in Europe. As can be seen, the life depends on the type of thin surfacing and increases with the nominal thickness. It was observed that SMA with a greater thickness had a longer life.

Table 1-1: Durability of Thin Surfacing on Major Roads (EAPA, 2007)

Type	Thickness	15% Lower Level Years	European Average Years	85% Higher Level Years
UTLAC	10 – 20 mm	8	10	12
VTAC	18 – 25 mm	8	10	12
SMA	25 – 50 mm	14	20	25

The European average life of thin asphalt surfacing is about 10 years for nominal thickness less than 25 mm and ranging on average 20 years for nominal thicknesses between 25 mm to 50 mm as detailed in Table 1-1. This experience is not dissimilar from that found in the UK although it should be stated that there were few cases where TSCS in the UK have failed prematurely (< 8 years) due to loss of aggregates, fretting and moisture induced damage. Previous research on UK thin surfacings has shown that these materials can be very durable and remain in service performing for at least 12 years, even on roads with high traffic levels (Nicholls, 2010; 2012).

Hot Rolled Asphalt (HRA) was widely used on the Strategic Road Network prior to the introduction of thin surface course systems. It was estimated that HRA surfaces last on average 20 years. Examples exist where the HRA material has been in service for more than 25 years, even in areas with very high traffic levels. However, hot rolled asphalt materials generate higher traffic noise levels than thin surfacings which can be disadvantageous in areas where residential dwellings are near the Strategic Road Network (SRN).

Subsequently, it has been considered that enhancements are needed in order to prolong the service life of thin surfacings to that of HRA whilst retaining good noise reduction and safety characteristics.

This report presents a detailed literature review of surfacing materials worldwide with a view to understanding and developing requirements for materials which offers significantly enhanced durability and offer optimised noise and skid resistance characteristics. This is followed by a report on the laboratory design process for Hot Rolled Asphalt at different chipping rates and a bespoke Premium Asphalt Surfacing System (PASS) developed at AECOM Laboratory in Nottingham. The findings and report following the demonstration trial of the new asphalt materials developed are presented in this report. This is followed by conclusions and recommendations for the project.

2 DURABILITY OF ASPHALT SURFACING

Asphalt properties change with time and under different conditions such as traffic loading and climatic conditions. The term durability has a relatively broad meaning which can be interpreted in different ways. In this study, the durability of asphalt surfacing has been defined as the ability of the surfacing material to resist degradation in service due to changes in chemical and mechanical properties of the material. These changes are not only caused by traffic loading but also compounded by one or a combination of these factors:

- Seasonal temperature variations (heat and cold);
- Loss of volatile bitumen components;
- Moisture Ingress;
- Winter maintenance (salt deposit and de-icing fluid may affect the adhesion and cohesion properties of the asphalt);
- Self-healing capacity.

As surfacing materials; durable asphalts must encompass mechanical properties (such as strength and stability parameters), interlayer strength (adhesion) and functional properties (such as skid resistance, noise and spray characteristics). As with any other engineering material, designing an asphalt mixture is about striking a balance between these properties as well as ensuring that the material is workable; taking into account the production and installation plant, also taking into account site specifics. An example is given in Figure 2-1 which illustrates a trade-off between stability and durability when deciding the target binder content during a mix design process (Note: Asphalt content in Figure 2-1 denotes binder content in European terminology). It must be stated that selecting target binder content is only one of the key parameters during mix design optimisation. Other parameters must be considered in optimising the mix design; these include composition, volumetrics, compaction and performance related requirements.

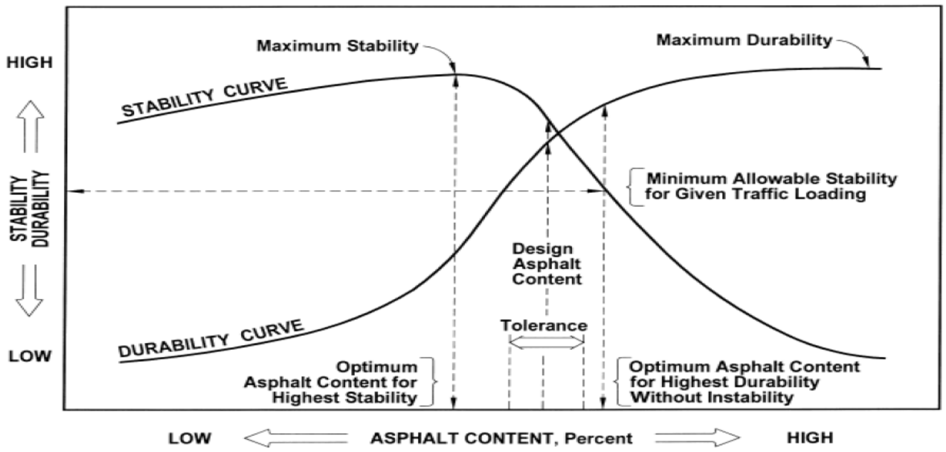


Figure 2-1: Schematic of Stability - Durability Relationship of Hot Mix Asphalt (FAA, 2000)

2.1 MIXTURE COMPOSITION

There are a number of factors in the mix composition which may contribute to asphalt durability. They include:

a) Aggregate packing;
b) Fines quality;
c) Filler type;
d) Binder type;
e) Binder content;
f) Bituminous Mastic

2.1.1 *Aggregate Packing Characteristics*

Aggregate plays a major role in the performance of asphalt mixtures. It typically forms around 93-95% of the asphalt mixture components. Aggregate packing can be gap or continuously graded. For gap-graded mixtures, components such as mortar-binder (mastic) have a substantial contribution to the stability of the mix. For continuously graded mixtures the aggregate skeleton acts as the backbone of the mix and has a substantial contribution to the mix stability. The degree and level of aggregate packing is a factor of the shape, surface texture, strength, particle size distribution as well as the type and amount of compaction energy applied to the aggregate particles. Most thin asphalt surfacings used in the UK are gap graded, be it gap graded asphalt concrete or stone mastic asphalt; therefore, their strengths are highly dependent on the performance of the bituminous mastic within a well-designed aggregate skeleton.

2.1.2 *Fines Quality*

The shape and surface texture values are two important parameters for selection of fines. Well shaped and angular fine aggregates increase stability, reduce rutting, improve water resistance and reduce bitumen sensitivity. Flat and elongated particles tend to resist packing in a dense configuration whilst cubical particles arrange better in dense configurations thereby increasing the strength of the asphalt mixtures as detailed in EN 13043. In the US, the fineness modulus is used to ascertain how coarse or fine the aggregate is. It is the percent weight of material passing the 75, 150 and 300µm termed as the FM_{300} in NCHRP Report 567 (Christensen and Bonaquist, 2006). The fineness modulus can be used to better control aggregate specific surface properties. This is vital in ensuring adequate mixture performance and good workability as very coarse aggregates are prone to bleeding and segregation while very fine aggregates are prone to segregation.

2.1.3 *Filler Type and Quality*

Table 2-1 details different filler types and their characteristics. Fillers are essential to produce asphalt mixtures that are dense, durable, cohesive and able to reduce/resist the ingress of water. Ahlrich (1996) noted that filler greater than 6% can produce unsatisfactory results by stiffening the mix thereby making it too difficult to compact. If there is too little filler, this could result in low cohesion and the mix will have low stability and durability.

In selecting filler types and ensuring adequate quality, the filler must be able to act as a void filling material which can be used to adjust grading and volumetric properties. Some filler improves the apparent bond between aggregate and binder. If required, the active filler is used to stiffen the mastic thereby improving the stability of the asphalt mixture (Vavrik et al., 2002). Fillers such as fly ash are used to improve mix compactability while hydrated lime through physiochemical interactions with the bitumen substantially reduces oxidation and ageing rate.

Table 2-1: Filler Types and Characteristics

Type Of Filler/Origin	Characteristics
Bag House (Reclaimed) Fines	• Low-cost option. • Variable characteristics which require control. • Some source types may affect mix durability. • Some types may render mixes sensitive to variations in binder content.
Limestone Filler	• Manufactured under controlled conditions and complies with set grading requirements. • More cost-effective than active filler. • Viewed as inert but the high pH value reduces moisture susceptibility.
Hydrated Lime (Active Filler)	• Relatively high cost. • Improves adhesion between binder and aggregate (dependent on aggregate type). • Improves mix durability by retarding oxidative hardening of the binder. • Low bulk density and high surface area. • Monitor effect on stiffness to ensure compactability.
Portland Cement (Active Filler)	• Relatively high cost. • Monitor effect on stiffness to ensure compactability.
Fly Ash (Non-Active Filler)	• Relatively high cost. • Low bulk density. • Variable characteristics which require greater control.

Figure 2-2 illustrates the effectiveness of adhesion promoting additives (such as hydrated lime) to slow down binder hardening (viscosity increase).

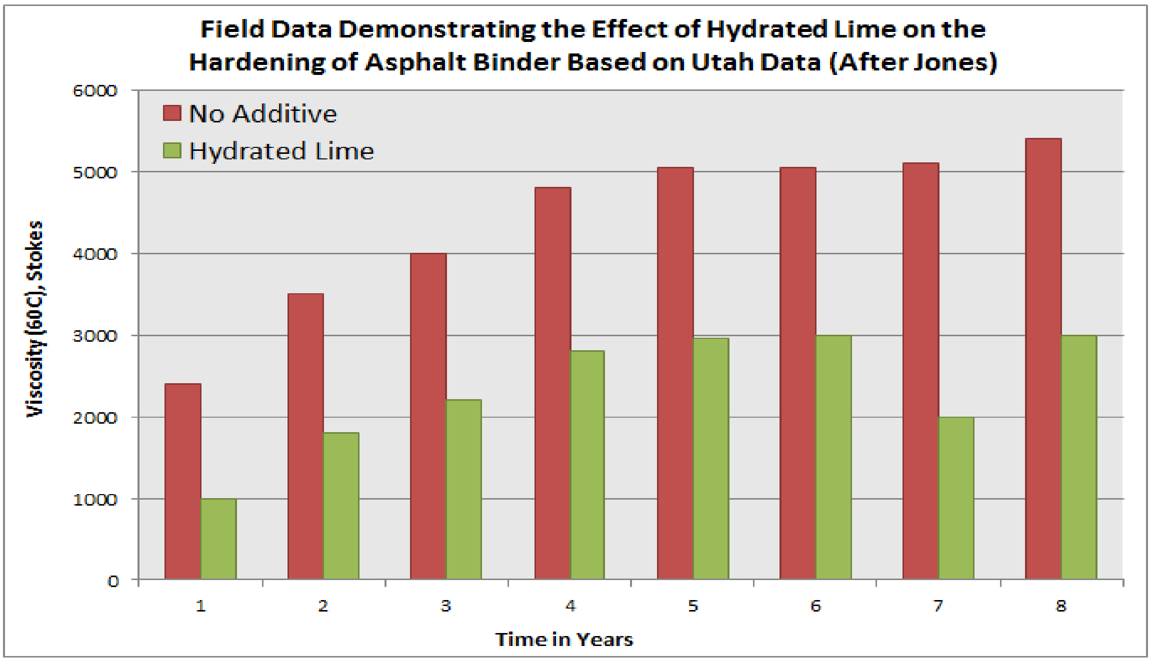
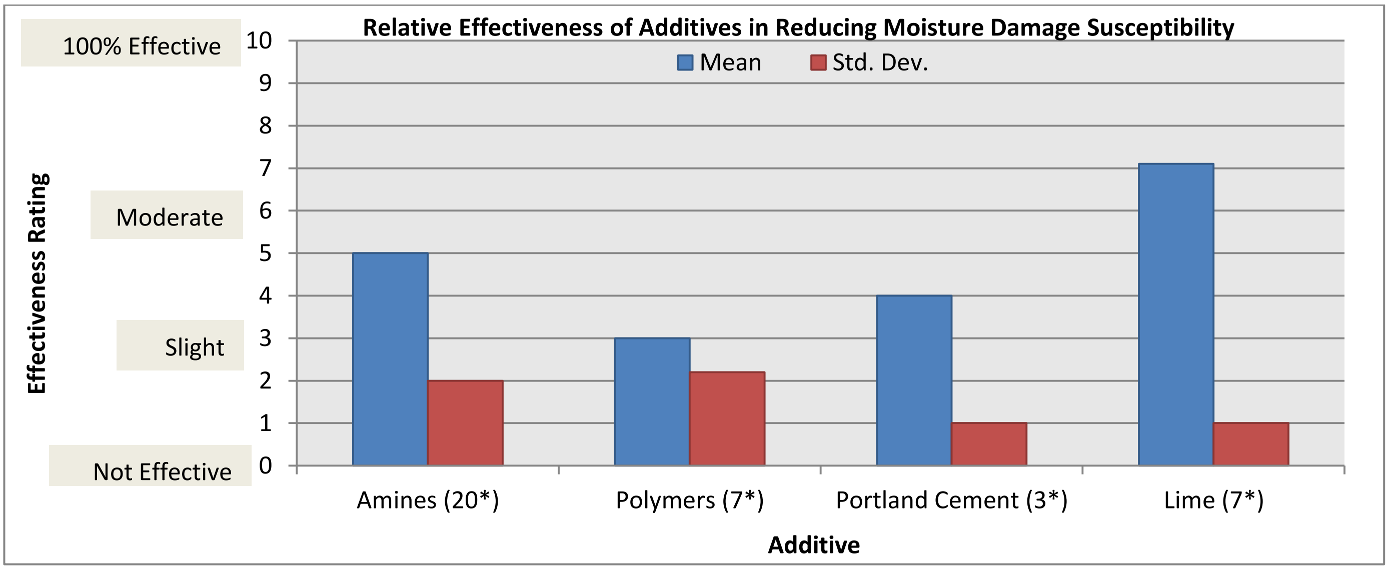


Figure 2-2: Influence of Hydrated Lime on Oxidative Hardening of Bitumen

Furthermore, anti-stripping additives can reduce the risk of moisture damage and, in this context, active fillers such as hydrated lime seems to be the most effective, as illustrated in Figure 2-3.



*** Number of Responses Rating Effectiveness**

Figure 2-3: Effect of Hydrated Lime as an Anti-Stripping Agent (After Hicks, 1991)

2.1.4 *Binder Type*

The binder used may either be paving grade or modified bitumens. Binder type selection should be based on factors including expected traffic loadings, climatic conditions, workability, failure modes (rutting, fatigue and ravelling), pavement structure and availability of binder and aggregate types.

Paving grade bitumen

This category comprises the range of standard paving grade bitumen according to EN 12591 and those special bitumens distinguished by “hard” paving grade in accordance with EN 13924.

Modified Bitumen

Modified bitumen materials consist of bituminous binders whose properties have been modified through the use of polymer modifiers or additives, which when introduced into the base bitumen modifies the chemical structure including the physical and mechanical properties. This category of material has been codified in EN 14023, which presents a classification of polymer modified bitumen into different grades but not necessarily performance related requirements. These bitumens are prepared prior to the application within a specialised unit. The additives employed include natural rubber, synthetic polymers, sulphur and other organic-metallic compounds. The use of polymer modified binders has been considered to offer an enhancement to the service life of asphalt pavement. A report by Asphalt Institute (Report Number IS-215) suggested improvements in the service life of flexible pavements by up to 10 years, depending upon the site feature and condition; these are illustrated in Table 2-2. In addition to this, Norfolk County Council (NCC) has used Dense SMA for more than 8 years incorporating PMB especially at roundabouts and high stress areas where they were showing improved mechanical and performance properties in comparison to SMA with paving grade bitumen.

2.1.5 *Bituminous Mastic*

Bituminous mastics are defined as dispersions of mineral fillers within a medium of the bituminous binder. The effect of mineral fillers is more prominent in gap-graded asphalt mixtures such as Stone Mastic Asphalt (SMA) that contain a lot of fines. Conducting tests on bituminous mastics can provide an insight into the interaction between the binder and mineral filler which in most cases cannot be captured by testing asphalt binders.

Recent research efforts have been directed towards relating the mastic behaviour to pavement performance such as rutting, fatigue and low temperature cracking (Abbas et al., 2005). This demonstrates the importance of controlling the filler portion in the mix design to achieve the required performance.

Table 2-2: Effect of Polymer Modified Bitumen in Asphalt to Service Life of Flexible Pavements (Glanzmann, 2005)

<table>
<tr><th>Site Feature</th><th colspan="2">Condition Description</th><th>Potential Increase In-Service Life attributed to the use of a PMB in Years[1]</th></tr>
<tr><td rowspan="2">Water Table Depth/Drainage</td><td colspan="2">Shallow; adequate drainage</td><td>5-8</td></tr>
<tr><td colspan="2">Shallow; inadequate drainage</td><td>0-2</td></tr>
<tr><td rowspan="5">Traffic</td><td rowspan="3">Low</td><td>Stop and Go/Intersections</td><td>5-10</td></tr>
<tr><td>Thoroughfares</td><td>3-6</td></tr>
<tr><td>Heavy loads/Special containers</td><td>5-10</td></tr>
<tr><td colspan="2">Moderate Volumes</td><td>5-10</td></tr>
<tr><td colspan="2">High Volumes</td><td>5-10</td></tr>
<tr><td rowspan="3">Climate</td><td colspan="2">Hot</td><td>5-10</td></tr>
<tr><td colspan="2">Mild</td><td>2-5</td></tr>
<tr><td colspan="2">Cold</td><td>3-6</td></tr>
<tr><td rowspan="2">Existing Pavement Condition</td><td rowspan="2">HMA</td><td>Good condition</td><td>5-10</td></tr>
<tr><td>Poor condition; extensive cracking[2]
Good condition[2]</td><td>1-3
3-6</td></tr>
<tr><td colspan="4">Notes:
1. The range of the increase in service life is based on the mechanistic-empirical damage-based analyses, comments from the experts and engineering judgment.
2. Without the use of any reflection cracking mitigation techniques.</td></tr>
</table>

2.2 MIXTURE VOLUMETRICS AND COMPACTION

The volumetric properties of a compacted asphalt mixture provide indications of the potential performance of the mixture on a pavement. The durability of asphalt mixtures is ensured when proper design volumetrics such as total air voids, voids in the mineral aggregate (VMA), voids filled with bitumen (VFB) and effective binder content as illustrated below in Figure 2-4 are measured and controlled.

The VMA are the void spaces between the aggregate particles of the asphalt mixture while the VFB is the portion of the voids in the mineral aggregate that contains binder which represents the volume of the effective binder content. VFB is inversely related to air voids; as air voids decrease, the VFB increases. The effective binder content is the total binder content not absorbed by the mineral aggregates which influence the binder film index. Thicker binder films produce mixes that are flexible providing adhesion, mixture cohesion and durability while thin films can produce brittle mixtures which tend to crack and ravel.

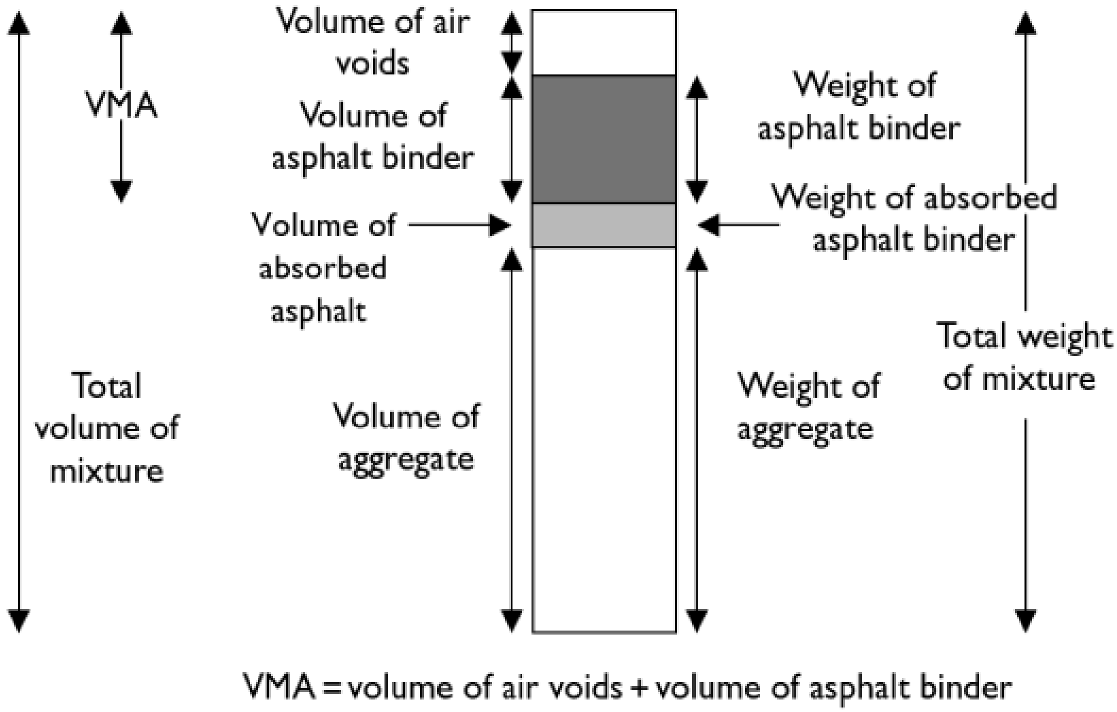


Figure 2-4: Asphalt Mixture Volumetric Compositions

Dependent on asphalt type, field performance has shown that air voids below 3% are susceptible to instability, rutting and shoving while air voids over 5% are susceptible to ravelling, oxidation and increased permeability of the hot mix asphalt mixtures. Typically an air void of 4% is ideal for dense asphalt concrete (Asphalt Institute, 2014). Factors that influence the volumetrics of asphalt mixtures include viscosity, mix temperature and time held at elevated temperatures.

In NCHRP Report 567, Christensen and Bonaquist (2006) presented some interesting discussions on the effect of mixture volumetrics, both as design and as laid, to the in-service performance of Superpave (Superior Performing Asphalt Pavements) mixtures. These discussions, summarised in Figure 2-5 to Figure 2-9, highlighted the importance of controlling variations in mixture volumetrics both at the design stage and during the construction.

Figure 2-5 depicts the effects of design air voids and in-place air voids to the in-situ fatigue life. Figure 2-5 shows that a 1% increase in in-place air voids results in a decrease of approximately 22% in the relative fatigue life (N_f) of the mixture.

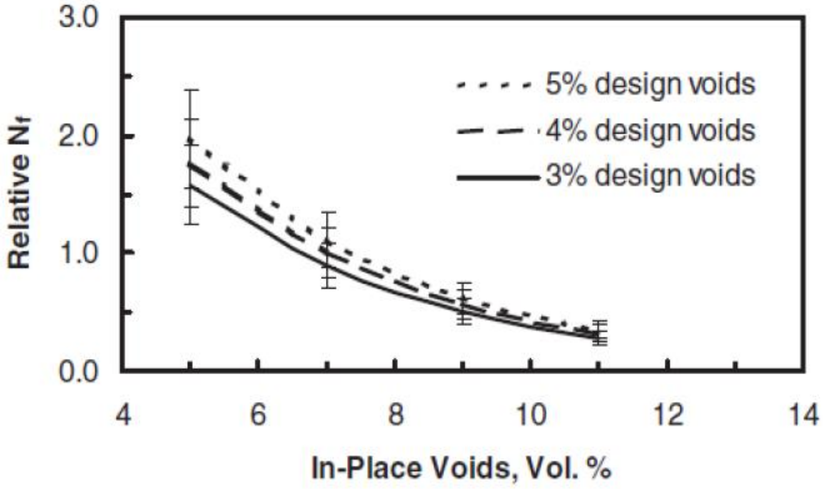


Figure 2-5: Effect of In-place and Design Air Voids on In-Situ Fatigue Life (NCHRP Report 567)

To summarise, fatigue resistance increases with an increase in the effective binder content. The fatigue life will increase with decreasing in-place air void content.

Figure 2-6 shows the purported effects of in-place air voids on the rutting rate at a constant design air void content of 4%. A reduction by 1% of the in-place air void content resulted in about 18% decrease in the rutting rate (mm/m/ESALs$^{1/3}$).

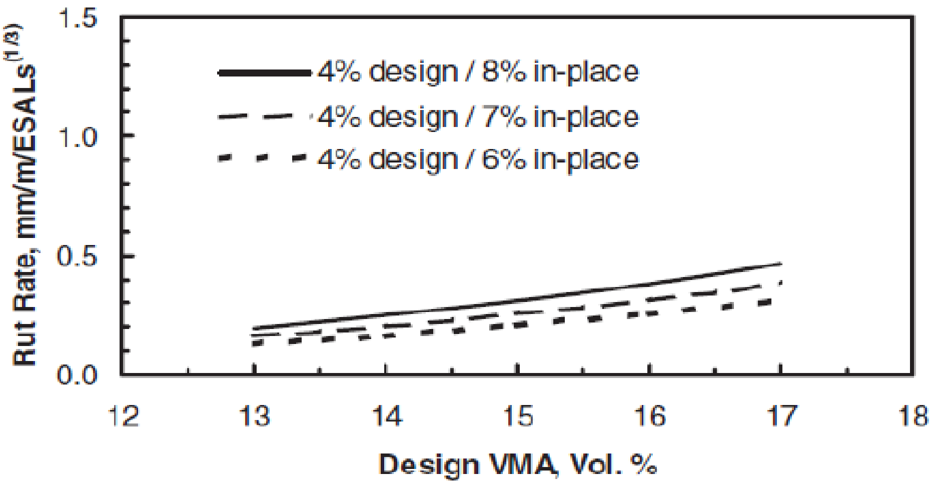


Figure 2-6: Effect of Mixture Volumetric on Rut Resistance (NCHRP Report 567)

Figure 2-7 shows the effect of VMA and aggregate fineness on rut resistance. As seen in Figure 2-7, the aggregate fineness has a significant effect on rut resistance which leads to the fact that this parameter should be carefully controlled in order to limit rutting in the pavement.

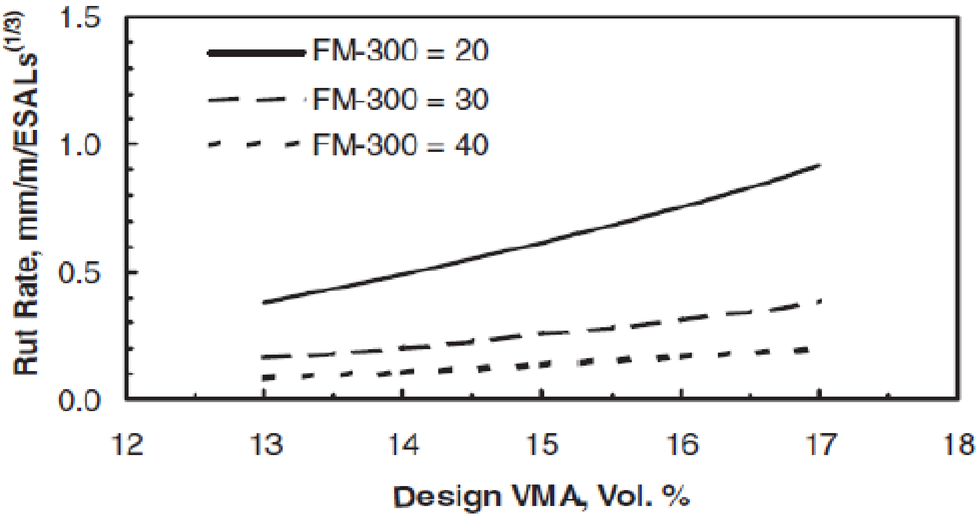


Figure 2-7: Effect of Mixture Volumetrics and FM-300 on Rut Resistance (NCHRP Report 567)

Figure 2-8 shows the effect of Fineness Modulus (FM-300) and in-place air voids on in-situ ageing. Figure 2-8 shows that an increase in FM results in a reduction in the ageing ratio. Increased in-place voids result in increased ageing ratio. The amount of age hardening that occurs is dependent upon the air voids and the FM.

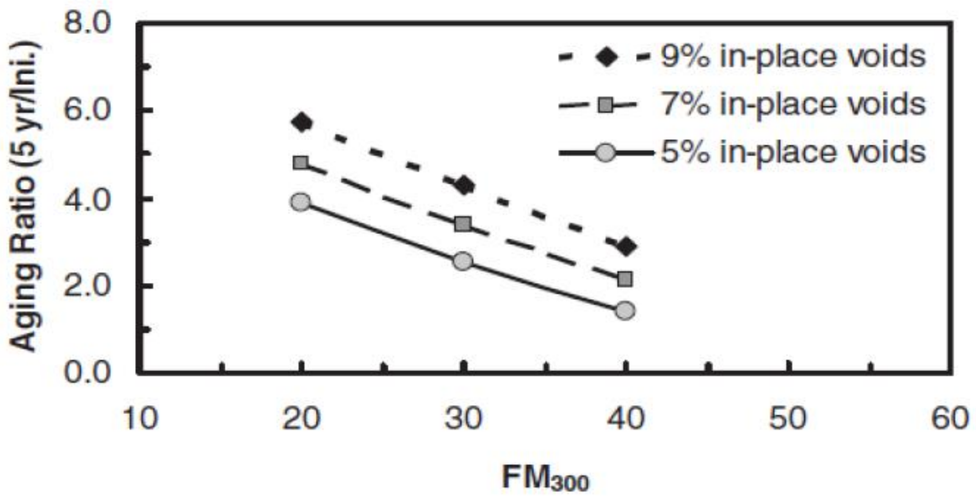


Figure 2-8: Effect of FM-300 and In-place Air Voids on In-Situ Ageing (NCHRP Report 567)

Figure 2-9 shows rutting rate as a function of binder film thickness. The figure suggests that rutting rate increases with increasing apparent film thickness (AFT). The plot suggests that HMA mixes with AFT values greater than 9 µm may be prone to excessive rutting.

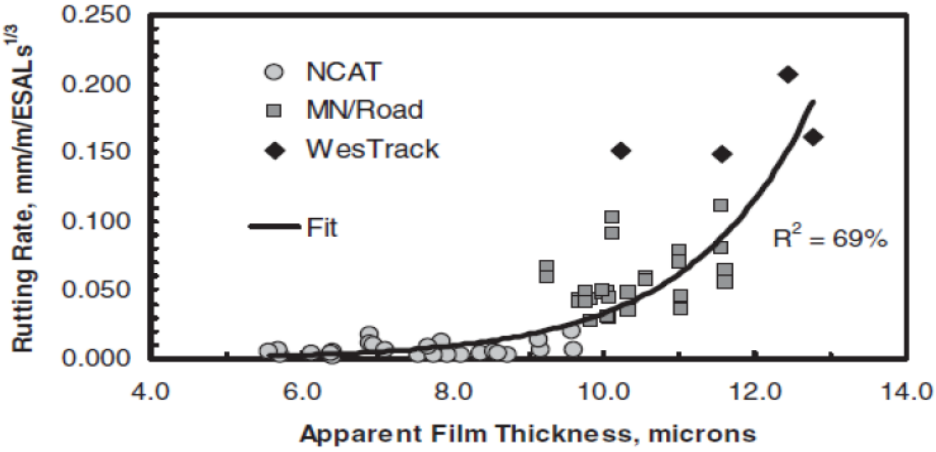


Figure 2-9: Effect of Binder Film Thickness on Rut Resistance (NCHRP Report 567)

Figure 2-5 to Figure 2-9 identifies the conflicting demands of materials used in pavement design and the need for optimisation in order to achieve required performance.

2.3 CONSIDERING DURABILITY IN THE DESIGN

Moisture diffusion and pore pressure development from entrapped water in the air voids (i.e. pumping action) were identified as the main physical and/or mechanical processes that ultimately can lead to pavement distresses such as fretting and cracking (Solaimanian et al, 2003). Binder ageing such as that caused by prolonged exposure to UV light can increase the rate of moisture diffusion (Varveri et al., 2015). Moisture diffusion through asphaltic materials is a long-term process that affects the durability of asphalt pavements. As moisture infiltrates into the asphalt mixture, the physicochemical properties of the binder can change hence reducing its cohesive strength. Additionally, in the presence of moisture, the adhesive bond between aggregate and asphalt binder deteriorates and can eventually result to stripping.

In asphalt mixtures, pores can be interconnected. When pores are interconnected, they allow the water to move through the pavement. Dynamic traffic loads can cause high water pressure fields within the pores that are filled with water. These high pore pressures can lead to cracking of the binder film thus facilitating the ingress of moisture to the binder/aggregate interface (Figure 2-10), and resulting in the increase of tensile stress within the material (Figure 2-11). The latter implies that higher traffic speed can increase the tensile stress (possibly due to increasing pumping action) and lower tensile stresses can be expected on denser asphalt mixtures with less than 5% air voids) or porous asphalts with more than 20% air voids (Thom, 2014). These findings suggest specific consideration must be given to asphalt mixtures with air voids ranging between 5% and 20% to minimise susceptibility to moisture damage.

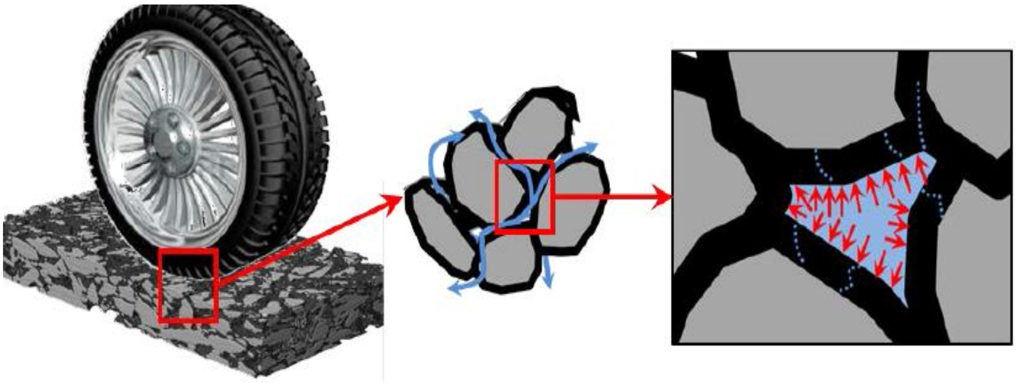


Figure 2-10: Pore Pressure Development Due to Pumping Action (after Solaimanian et al., 2003)

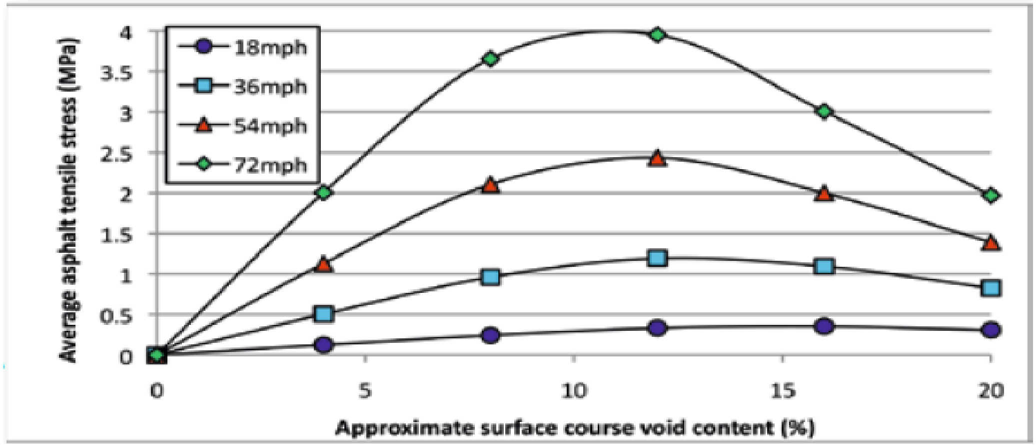


Figure 2-11: Tensile Stress as a Function of Surface Air Voids (Thom, 2014)

In addition to considering the risk from moisture damage, winter maintenance practices should also be considered. The effect of de-icing fluids on asphalt pavements have been reported as causing degradation and disintegration of asphalt pavements, softening of asphalt binders and stripping of asphalt mixes (Shi, 2008; Pan et al, 2008). In this context, damage related to the use of de-icing/anti-icing fluids can be treated as a type of moisture induced damage. Improving the properties of binders and/or aggregate may reduce or even eliminate the problem. Using stiffer bitumen and/or polymer modified binders could reduce the extent of de-icing/anti-icing related damage (AAT, 2009; Christensen et al, 2010; Santagata et al, 2013; Dehdezi et al, 2015). Furthermore, the addition of hydrated lime may decrease the severity of de-icing/anti-icing-related damage in susceptible mixes (Christensen et al, 2010). It was reported that damage related to the use of de-icing/anti-icing fluids increases in severity with increasing in-place air void content of asphalt mixtures (AAT, 2009; Christensen et al, 2010). Therefore, when an asphalt pavement is suspected of being susceptible to de-icing/anti-icing related damage special care should be taken to ensure that pavements constructed with the mixture are compacted to the target volumetric design.

2.4 PERFORMANCE RELATED TESTING

Most mix designs rely on recipe based design or the use of empirical testing. These approaches have limitations and cannot accommodate changes in design variables such as environment and loading conditions or new material technologies. In this context, performance related testing can provide a good approximation of the potential durability by application of accelerated loading under more simulative test conditions on new design asphalt mixtures. Performance related testing can also be supported by acceptance criteria for different loading and environmental variations. The following section presents two short-listed tests which can be considered to support the performance related mix design process.

2.4.1 *Hamburg Wheel Tracker*

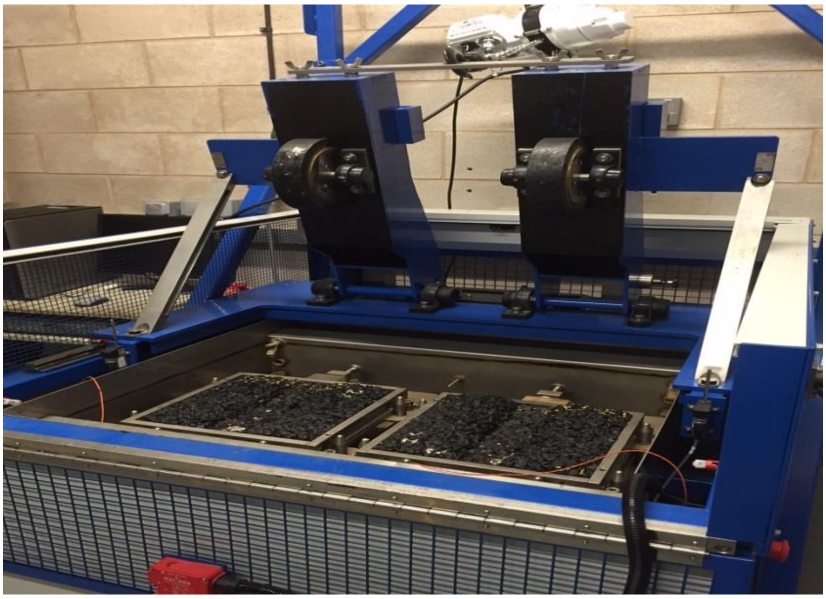


Figure 2-12: Hamburg Wheel Tracking Device

The Hamburg Wheel Tracker (HWT) developed in Germany is used to measure the rutting and moisture damage of asphalt mixtures by rolling a steel or rubber wheel across the surface of the specimen. The specimens are immersed in water under regulated load, speed and temperature conditions whilst development of rut is constantly monitored and recorded throughout the test.

Figure 2-12 shows a HWT at the University of Nottingham in which cored or laboratory prepared specimens can be used. Results from the HWT include rut depth, post-compaction, creep slope, stripping inflection point and stripping slope. The HWT is widely used in identifying mixtures that are susceptible to premature moisture failure in accordance with EN 12697-22 small size device, conditioned in water.

Aschenbrener (1995) evaluated factors that influence the results from the HWT in comparison to field conditions. He found that there was a good correlation between stripping observed in laboratory tests and the moisture damage of pavements with known field performance. There was also a good correlation between stripping inflection point and known stripping performance. The stripping inflection point is the point at which the creep slope and stripping slope intercept. This is used to evaluate permanent deformation due to moisture damage. It was found that for good pavements, the stripping inflection point was higher than 10,000 passes and for pavements that lasted for less than 1 year, the stripping inflection point was less than 3,000 passes.

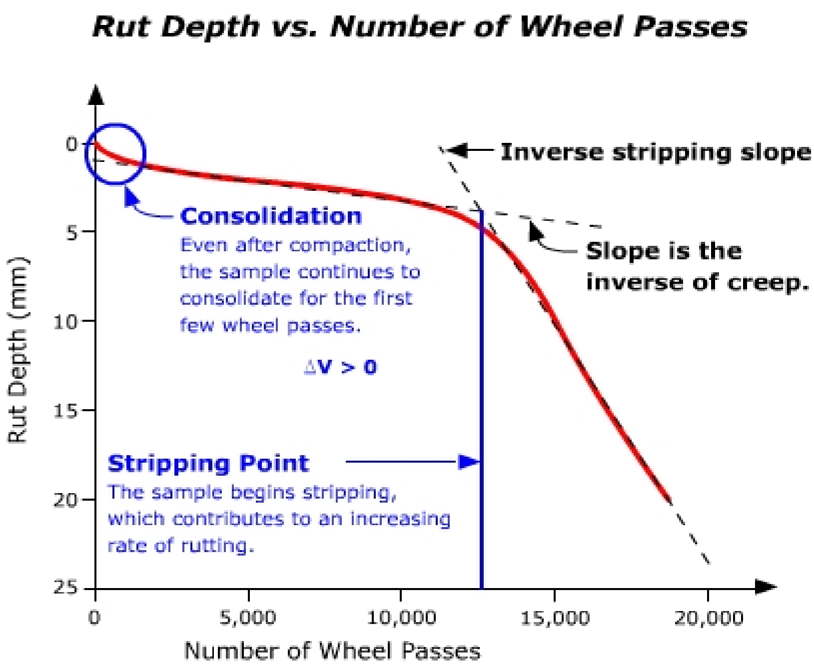


Figure 2-13: Typical Plot from a HWT including Key Parameters (Pavement Interactive, 2011)

The HWT can simulate the stripping mechanism that takes place when rainfall occurs during the hot time of the year; hence Aschenbrener (1995) recommended that test temperatures should be selected from the hottest time of the year. This recommendation may not be applicable to locations where water primarily enters the asphalt concrete during the cooler times of the year (Solaimanian et al., 2003).

Certain limitations with respect to HWT test results indicates sensitivity to aggregate properties such as dust coating on the aggregates, clay content, and high dust-to-asphalt ratios. It was also noted that as the short-term ageing increases, samples become more resistant to moisture damage, the HWT does not provide a fundamental property that can be used for modelling purposes. Recommended values for specific climates and traffic levels are also not available.

To conclude, The HWT has shown good repeatability with consistent test results (Asphalt Institute, 2004) although it must be stated that the HWT sometimes have difficulties in accurately evaluating the rutting susceptibility of Asphalt Concrete (AC) as detailed in Zhou et al., (2003).

2.4.2 *Model Mobile Load Simulator (MMLS3)*

The MMLS3 is a 1/3rd scale accelerated pavement test equipment which has been developed to evaluate the moisture susceptibility, damage and relative performance of asphalt mixes under repetitive wheel loads taking into account variances in loading and environmental conditions. MMLS3 test and its variants have been trialled and used in a number of countries in Europe, South Africa, USA and Australia; details can be found on this website: (http://www.pavetesting.com/). Current MMLS3 standard is in accordance with South African National Standard SANS 3001 - PD1: 2014 as a best practice protocol for use by practitioners in the asphalt industry.

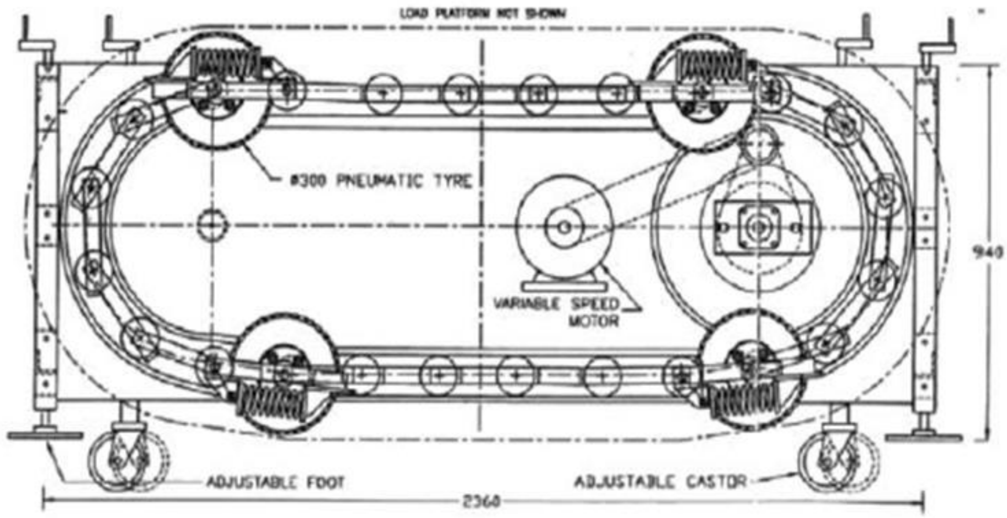


Figure 2-14: MMLS3 Equipment Layout

MMLS3 consists of four recirculating axles each with a single 300 mm diameter wheel as seen in Figure 2-14. The wheels can be laterally displaced across 150 mm in a normal distribution about the centre line to simulate traffic wandering. Tyres may be inflated up to a pressure of 800 kPa. Wheel loads for the MMLS3 range between 2.1 kN and 2.7 kN and are kept constant at a predetermined value by the special suspension system. Nominal wheel speed is 2.5 m/s applying about 7200 loads per hour. A single 1.5 kW variable speed motor drives the chain of four wheels. The MMLS3 test equipment can be used in the laboratory and directly on site for accelerated pavement testing in dry or wet conditions.

Figure 2-15: Laboratory Test Bed for MMLS3 (Left: Untrafficked and Right: Trafficked)

Figure 2-15 shows a laboratory test bed for MMLS3 and Figure 2-16 shows pavement testing in the field utilising an environmental chamber.

Figure 2-16: MMLS3 inside an Environmental Chamber

Points to understand and take into account when using the MMLS3 include temperature, rainfall, ageing, traffic volume, traffic speed, pavement structure and materials. Jenkins et al (2008) reported the effect of moisture damage during MMLS3 wet trafficking which resulted in the loss of aggregates. They reported that no side heaving occurred in the wheel path; instead, moisture ingress into the mixes destroyed the cohesive properties of the mixes and resulting in aggregate particles becoming loose. The fretting of coarse and fine aggregates occurs due to traffic loading coupled with moisture ingress. A similar trend was also reported by Partl (2008) as illustrated in Figure 2-17.

Figure 2-17: Moisture Sensitivity Testing under MMLS3

In summary, the MMLS3 seems to be capable of providing a means to simulate damage due to moisture under repetitive wheel tracking of the thin asphalt layer.

2.5 OVERALL SUMMARY

This section has presented complex interactions between parameters which may ultimately impact the durability of an asphalt surfacing. This includes interactions between mechanical properties of the material and interlayer strength against variations in environment and loading conditions. These complex interactions are schematically illustrated in Figure 2-18.

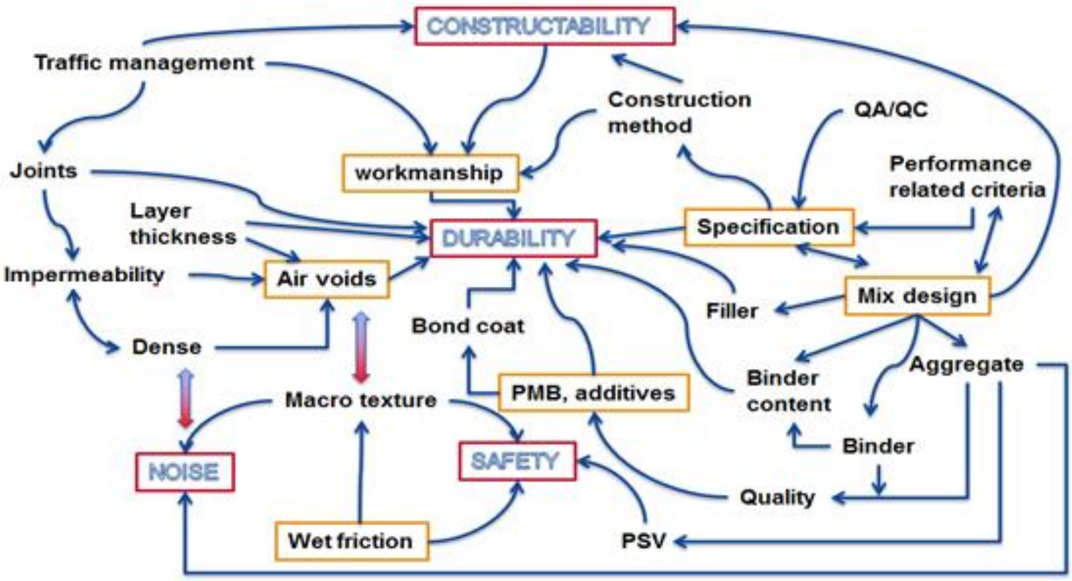


Figure 2-18: Interactions between Parameters Affecting Durability of Asphalt Surfacing

3 USE OF ASPHALT SURFACING MATERIALS WORLDWIDE

Under Harmonised European Standards (EN), asphalt materials for use in Europe shall fall under one of the following categories:

- EN 13108-1: Asphalt concrete
- EN 13108-2: Asphalt concrete for very thin layers
- EN 13108-3: Soft asphalt
- EN 13108-4: Hot rolled asphalt
- EN 13108-5: Stone mastic asphalt
- EN 13108-6: Mastic asphalt
- EN 13108-7: Porous asphalt
- EN 13108-9: Ultra-thin layer asphalt concrete

In the UK, soft asphalts and porous asphalts are not used on the Strategic Road Network (SRN). At the time of writing, hot rolled asphalts are permitted pavement surface course materials for new and maintenance construction. The following notes must be adhered to: No noise ‘sensitive receptors’ are located within an envelope 600 m from the roadside and 600 m from the ends of the sections, the scheme is not considered noise sensitive and does not have noise barriers or noise mitigation earth bunds, the location has not been identified as an Important Area, either with or without First Priority Locations as detailed in IAN 156/16. Alternative or proprietary materials which do not conform to the above or with non- harmonised properties must be certified by third-party accreditation bodies such as Highway Authorities Product Approval Scheme (HAPAS) Certificate. This should be applicable to the required product performance under the combination(s) of traffic level and site classification. This review presents some practices and experience on asphalt surfacing used in Europe, United States of America, New Zealand and South Africa.

3.1 UNITED KINGDOM

In the last 15 years, any resurfacing and new construction work on UK Strategic Road Network must use thin asphalt surface course systems (TSCS), as specified in MCHW 1 Clause 942. The surfacing has preferable performance especially with respect to reduced noise, spray and the speed of laying. The performance of TSCS resulted in the permitted use of thin asphalts as a pavement surfacing material for resurfacing and new construction without restriction in England (Highways Agency, 2006). Currently, it is estimated that about 60% of the UK Strategic Road Network has thin asphalt surfacing covered pavements. Furthermore, only TSCS that are hot mixed asphalts laid at above a nominal thickness depending on the aggregate size is currently permitted, see Table 3-1 and Table 3-2 from MCHW 1 Clause 942 TSCS.

Table 3-1: Design Target Thickness (excluding Site Categories H1, H2, L and J)

Nominal Aggregate Size (mm)	Design Target Thickness (mm)
6	20-30
10	25-40
14	35-50

Only thin surface course systems with an upper (*D*) aggregate size of 10 mm or less are permitted on Site Categories H1, H2, L and J and these sites need to be identified in the contract specific Appendix 7/1. The categories are denoted in Table 3-3.

Table 3-2: Design Target Layer Thickness for Site Categories H1, H2, L and J

Nominal Aggregate Size (mm)	Design Target Thickness (mm)
6	20-40
10	25-50

Table 3-3: Site Stress Level Classification

Site Category	Site Definition	Stress Level
H1	Bend (not subject to 40 mph or lower speed limit) radius 100-250 m	2
H2	Bend (not subject to 40 mph or lower speed limit) radius < 100 m	3
L	Roundabout	3
J	Approach to roundabout	4

In Clause 942, there is a mandatory requirement to carry out water sensitivity tests (BS EN 12697-12) but only for reporting purposes; there is no acceptance criterion at the mix design stage. The expected durability of TSCS has been based on the specification of the asphalt and best practice. TSCS are expected to be laid on properly designed, well compacted and bonded pavement layers where the durability of the surface layer is not determined by bottom-up fatigue cracking.

In addition, the durability of TSCS also depends on local conditions, climate, mix formula, bitumen and aggregate characteristics and traffic. In this context, minimum binder content is specified in MCHW1 Clause 942 TSCS in order to improve durability, as illustrated in Table 3-4. BBTM is the French term for Asphaltic Concrete (AC) laid as a very thin asphalt surfacing.

Table 3-4: Minimum Design Binder Content

Minimum Target Design Binder Content*		
Maximum Aggregate Size (D)	Mixture Types: EN 13108, Parts 1 and 2 (AC & BBTM with PMB to BS EN 14023)	Mixture Types: EN 13108, Part 5 (SMA – Paving Grade Bitumen to BS EN 12591 and Fibres SMA)
14	5.0	6.0
10	5.2	6.2
6	5.4	6.8 **

**This is the B_{min} value declared in CE marking and is uncorrected for aggregate density. Guidance on binder corrections for aggregate density is given in PD6691. Some aggregate types e.g. steel slag do not follow this correction process and the target binder content should be considered in light of the experience of satisfactory use.*

*** These mixtures are not considered appropriate for application on the Motorway and Trunk Road Network so should only be called up with very careful consideration.*

Nicholls et al., (2010) predicted that thin asphalt concrete has large variability in service from 7 years to at least 16 years. A more extreme case was reported from experience in Lincolnshire which suggests that majority of thin asphalt surfacing may require preventative treatment within 5 - 9 years of service. Figure 3-1 shows the age of the TSCS when they have been treated in Lincolnshire - the majority of sites were treated between 5 – 9 years in service as detailed in Figure 3-1(Neal, 2015).

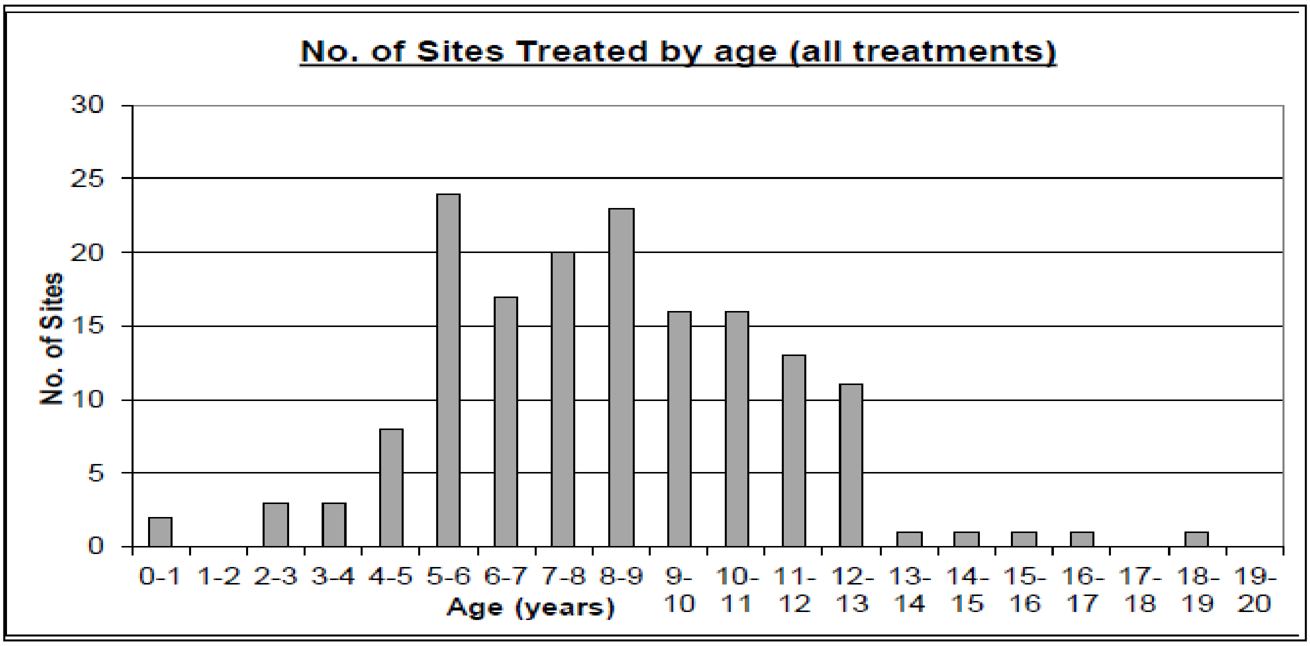


Figure 3-1: Number of Sites Treated at Different Age

Other thin surfacing types (outside Clause 942) have been used and adopted by local authorities such as Norfolk and Staffordshire. This is prevalent in Scotland also. In addition to this, innovative materials have been trialled on busy sections of local authority roads. These materials are summarised below.

3.1.1 *Scotland*

Transport Scotland commissioned a desk study that identified German asphalt thin surfacing materials as promising alternative to Clause 942 TSCS due to potential benefits that include superior durability, reduced noise levels, improved skid resistance, high resistance to deformation, decreased lifetime costs, excellent ride quality, reduced use of high friction surfaces and reduced use of expensive imported aggregates (TS 2010, 2015). Transport Scotland decided to develop the TS 2010 Surface Course Specification and Guidance (2015) based on German specifications and experience. The German SMA Mixture is a gap-graded aggregate mix utilising polymer modified bitumen and additives including fibres. Grit is applied to the newly laid SMA surfacing material to increase the early life skid resistance.

In recent times, Transport Scotland has started transitioning from Clause 942 TSCS to the TS 2010 SMA surface course on their road networks. Some key parameters which distinguish TS 2010 from TSCS are the specified higher binder contents, added fibres and the use of PMB. Furthermore, there are also stringent requirements on mixture volumetrics and Type Approval Installation Trials (TAIT). The TS 2010 specification is very prescriptive to gain initial confidence. In this context, grading of the mixed aggregates is strictly controlled. In addition to this, Transport Scotland conducts annual inspections every September to assess the road conditions of the TS 2010 surfacing materials.

<u>Binder</u>

The binder content has a tolerance of ±0.2% (by mass) which closely controls the amount of binder in the mix. In addition, the target values given are higher than those used in current UK mixtures. Empirical evidence from Germany highlights that high binder contents, with a close degree of control, are a fundamental requirement in ensuring the durability of an SMA mixture. However, it should be noted that, because certain mix designs may be sensitive to binder content above a certain level, the supplier is recommended to use the lower limit of the tolerance as the start point for design purposes (TS 2010, 2015). TS 2010 specification requires the inclusion of fibres to act as a binder carrier to reduce binder drain off from the aggregate during production, storage and transportation.

Nominal aggregate size

Three nominal aggregate sizes are commonly used (0/6 mm, 0/10 mm and 0/14 mm). The use of 0/8 mm is restricted owing to a lack of industry experience in producing mixtures to such a grading. 0/6 mm has been used on highly stressed areas and where high skid resistance is required. However, contractors have noted difficulties in working with this material with specific challenges relating to layer thickness and achieving bond between surfacing and binder layers. 0/10 mm is widely used with proven performance. 0/14 mm is available but used less since 0/10 mm has proven to perform well.

Applied grit

The grit used shall be free-flowing and free from agglomerations or bunching. For early life skid resistance, 2.8 mm lightly coated (1-1.5% bitumen content) angular grit is applied and rolled in during the second roller pass. The grit fills texture and remains on the surface with excess grit removed when the SMA has reached ambient temperature.

Surface characteristics

Assessments on a number of TAIT sites have shown relatively consistent texture depth between 1.0 – 1.1 mm. The grip tester is used to measure the skid resistance using the braked-wheel fixed slip device in accordance with BS 7941-2. This has been introduced as a performance requirement for the newly laid and early life condition of the material. This has created an opportunity to adopt a more flexible approach as opposed to the specification of only PSV and other techniques used for the measurement of skid resistance. An observation with the use of the TS 2010 SMA suggests that there is more spray in comparison to Clause 942 TSCS and this has slowed down traffic although the surface dries quickly when the rain stops.

3.1.2 *Norfolk*

Mix design

Norfolk County Council (NCC) has used Dense SMA for more than 8 years. NCC makes use of PMB with uncoated grit. The PSV of coarse aggregate is typically around 50-55. The air voids are specified to be ≤5%.

Surface characteristics

The target macro-texture is typically 0.8 to 1.3 mm. The material laid by NCC is considered quiet surfacing but experience shows that the SMA laid by NCC produces more spray in comparison to traditional TSCS which often leads to a slowing down of traffic under wet conditions.

3.1.3 *Innovative Materials*

Epoxy porous asphalt was trialled on A38 in Staffordshire in 1984 and 1987. It was reported that whilst the material on the mat area was performing well "with probable benefit to durability" (Daines, 1986; 1992). Anecdotal feedback from Staffordshire suggested that the material was highly stable but prone to mechanical damage. Following this trial, there was no follow-up of using this material on motorways until 2001 when Highways Agency was involved in a joint research project on Economic Evaluation of Long-Life Pavements in collaboration with a number of national institutions under the umbrella of the Organisation for Economic Co-operation and Development/European Conference of Ministers of Transport (OECD/ECMT).

Phase I of the OECD/ECMT project carried out between 2001-2003 identified that there were likely to be economic benefits from the development of road surfacing materials with a service life in excess of 30 years (Long Life Surfacing) (OECD, 2005). Phase II of the project (later called: Long Life Surfaces for Busy Roads and prepared under the aegis of the Joint OECD/ITF (International Transport Forum) Transport Research Centre), carried out between 2004 and 2007, comprised laboratory and accelerated load testing of two materials identified as having the potential to fulfil the requirement of Phase I; one of them was epoxy SMA (OECD, 2008). Benefits of epoxy asphalts include higher stiffness modulus at service temperatures as depicted in Figure 3-2.

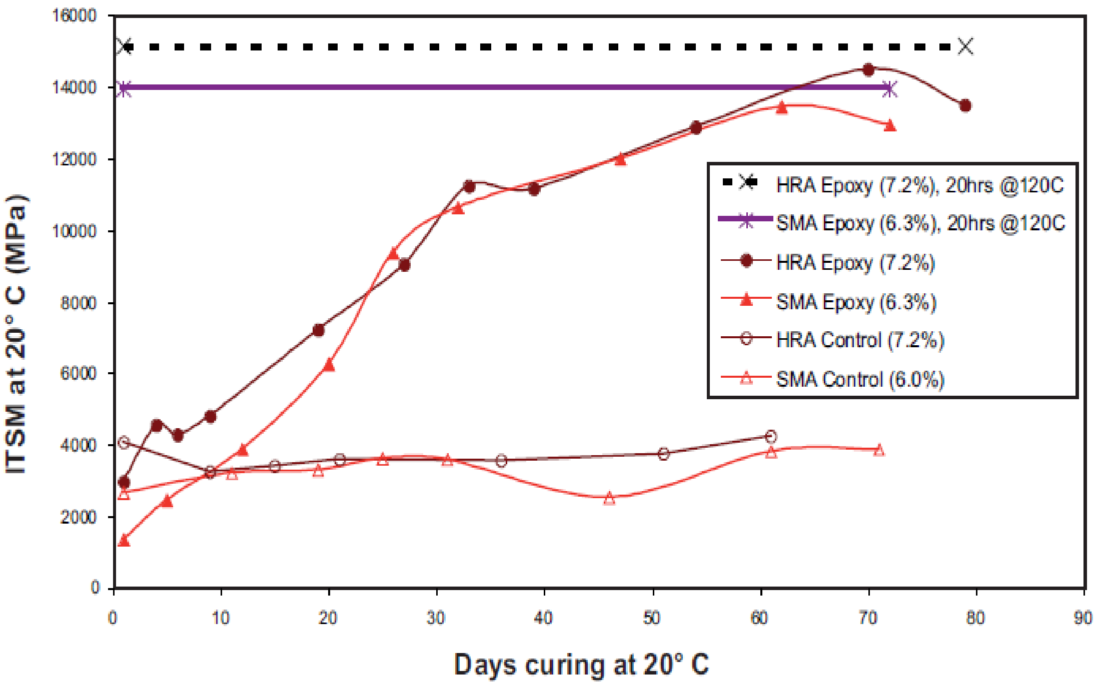


Figure 3-2: Stiffness Results for Hot Rolled Asphalts and Epoxy Asphalts

A field trial on epoxy SMA was completed in January 2012 on a heavily trafficked section of the A390 Trunk Road in the South West of England as part of Phase III of the project. The trial has a long way to go before a life of 30 years can be demonstrated, but early signs monitored over 12 months in service were reported as encouraging and considered as durable and potentially long-lasting (Elliott et al, 2008; 2013). Epoxy asphalts are thermosetting which could be challenging for motorway construction. If there was a delay during delivery of the material from the mixing plant to site beyond 2 hours after production; this could result in thermosetting of the asphalt. This was a concern raised during the trial on the A390 Trunk Road. At the time of writing this report, the epoxy SMA section has been reported to be in good condition, without any sign of defect.

3.2 GERMANY

Historically, Germany has been using SMA surface course with 0/8mm nominal aggregate size frequently used on heavily trafficked roads.

Mix design

PSV of coarse aggregate is typically above 51. Fines must satisfy requirements on flow coefficient. There are rigorous requirements on mastic components. Bituminous binders for heavy duty traffic normally incorporate PMB with performance related requirements such as DSR, BBR, elastic recovery and ductility testing; otherwise paving grade bitumen 50/70 is mostly used. Limestone filler must be used for the German SMA. The use of fibre is mandatory with bitumen coated cellulose fibre pellets being the preferred drainage inhibitor. Other additives are encouraged to promote workability and early opening of the road to traffic.

Surface characteristics

There is no target macro-texture but continuous friction measurement equipment (SCRIM type) is used to monitor wet skid resistance in service.

Construction

The works are normally carried out under full road closure arrangement, paving in echelon and grits applied at 0.5-1.0 kg/m^2. Paving quality is monitored in real-time by infra-red temperature readings and pavement density gauges. In situ air voids must not exceed 5%.

In recent times, designers are shifting to a hybrid between AC and SMA termed ‘AC-SMA’. This mix is a denser mixture whilst retaining the strong aggregate skeleton. This change was understood to address issues related to moisture induced damage. It is understood that currently there is also a study being carried out in Germany looking into accelerated durability testing for inclusion in the mix design process.

3.3 FRANCE

France has similar classifications as the UK on asphalt surfacings specifically: thin AC, VTLAC and UTAC. These materials are typically gap graded with 0/10 mm or 0/6 mm nominal size aggregate with options to adapt continuously graded mixtures. The shift in recent times is to “optimise” the mix design towards denser gap-graded mixtures with aggregate gradation between continuously graded Grave Bitumè (GB2) and gap-graded SMA as shown by the High-Performance Asphalts (HPA) materials in Figure 3-3 (Olard, 2012). This concept seems to be similar to that being developed in Germany i.e. the AC-SMA hybrid material.

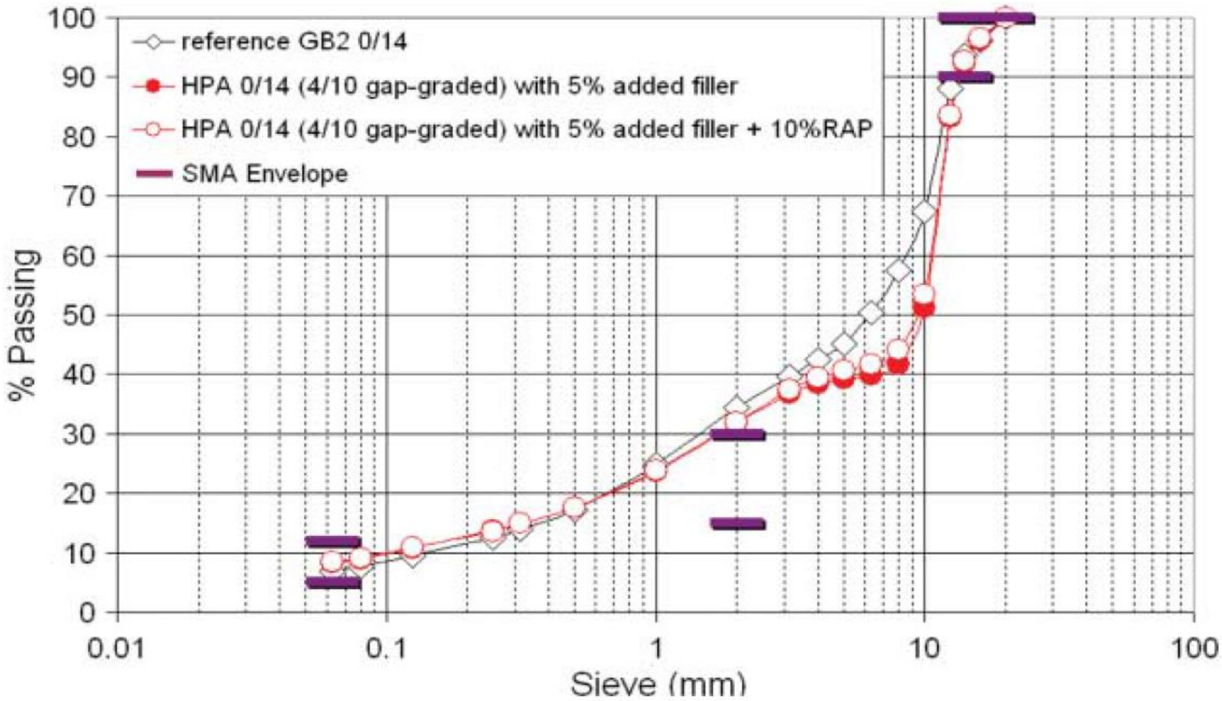


Figure 3-3: Grading of the Optimised Mix Design HPA Relative to GB2 and SMA

Mix design

Overall the mix design methodology is based on component characteristics, water-sensitivity testing, void content assessments using gyratory compaction, resistance to permanent deformation, stiffness and fatigue resistance. In practice this methodology has adopted two approaches: "empirical" and "fundamental":

- The empirical approach contains a recipe part (to a rather considerable extent), a volumetric part and an empirical testing part. Where applicable, performance related tests are used.
- The fundamental approach encompasses a much reduced prescriptive part, a volumetric part and performance-related tests.

Surface characteristics

For surface characteristics, the emphasis is placed on durable mixtures with high resistance to water action and resistance to permanent deformation. Other factors sought include spherical, angular shaped aggregates for adequate skid resistance and reduced rolling noise. Minimum PSV value specified is 50. Paving grade bitumen 50/70 or 35/50 or polymer modified bitumen 45/80-60 or 40/100-65 is typically specified at a minimum binder content of 5%. There is no target macro-texture but continuous friction measurement equipment (SCRIM type) is used to monitor wet skid resistance in service.

Construction and Experience

In-situ void measurements are usually measured using the gamma densitometer in order to check compliance with standard based specifications. The use of 6 mm aggregate had better skid resistance than 34500pavements with 10 mm aggregates although the use of 10 mm aggregates resulted in improved surface draining and reduced spray in comparison to the use of 6 mm aggregates. This was attributed to the increased number of contact points between the pavement and the tyre. Sand grit is usually applied during compaction to help improve skid resistance.

3.4 UNITED STATES

The Strategic Highway Research Program (SHRP) developed the Superpave (Superior Performing Asphalt Pavements) design which is based on performance specifications. The Superpave system combines asphalt binder and aggregate selection into the mix design process and takes into account traffic and climatic conditions. The compaction devices from the Hveem and Marshall procedures have been replaced by the gyratory compactor that takes into account climatic and traffic conditions.

The Superpave mix design procedure comprises of steps that include aggregate selection, binder selection, sample preparation including compaction, performance testing, density and voids calculations. Other steps include optimum binder content selection and evaluation of moisture susceptibility.

Aggregate Selection

The aggregate structure acts as the skeleton of the mixture and has an influence on skid resistance, stability and workability. The Superpave design method restricts control points for the gradation placing restrictions on angularity of the coarse, fine aggregates and the clay content as seen in Figure 3-4. The major point here is to promote optimum interlocking properties in the aggregate structure and also accommodate appropriate binder and void contents.

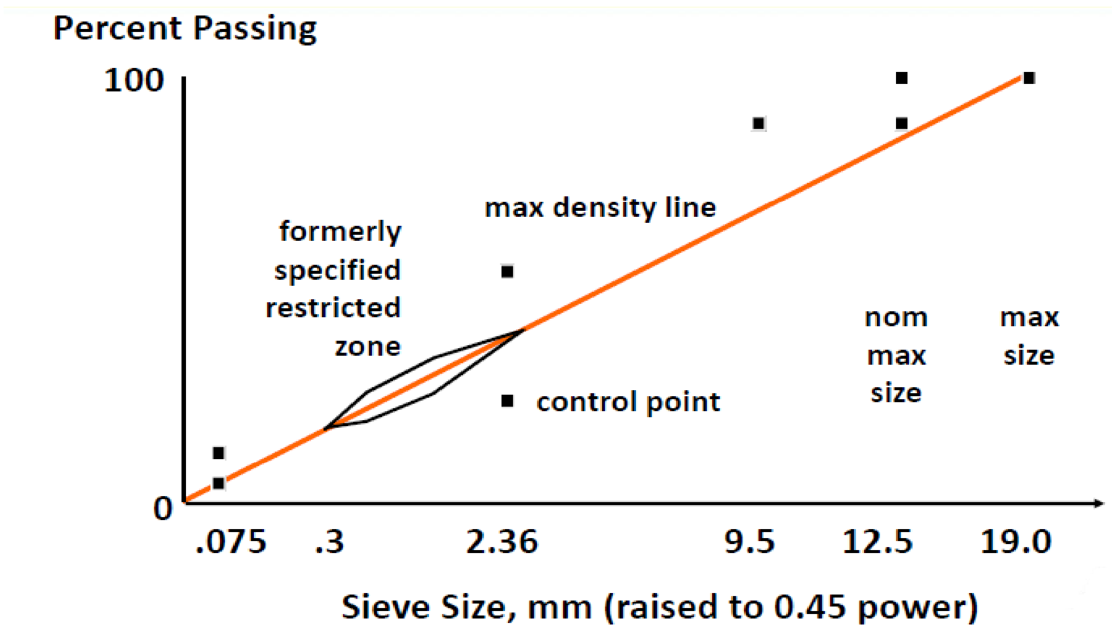


Figure 3-4: Aggregate Gradation Factors

Coarse aggregate angularity is ascertained using any number of test procedures that are designed to determine the percentage of fractured faces such as the flakiness and elongation tests. The fine aggregate angularity and the sand equivalent tests to determine clay content are shown in Figure 3-5. Table 3-5 shows the Superpave coarse aggregate angularity requirements. The fine aggregate and sand equivalent requirements are detailed in the Superpave asphalt mix design procedure.

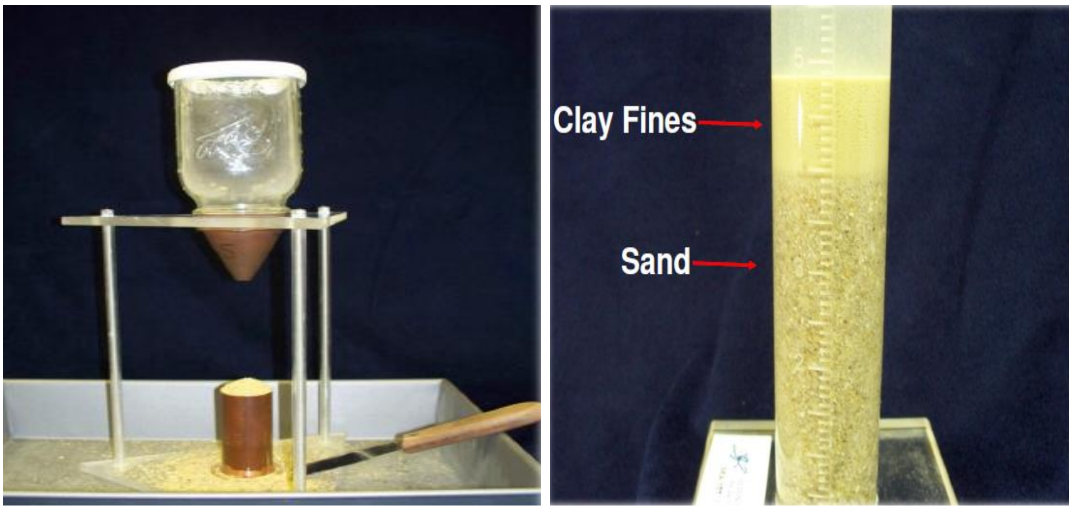


Figure 3-5: Fine Aggregate Angularity and Sand Equivalent Tests

Table 3-5: Fine Aggregate Angularity and Sand Equivalent Tests

Design Traffic Level	ESAL's	% Crushed 1-FF/2-FF ≤ 100 mm	% Crushed 1-FF/2-FF > 100 mm
F	< 300,000	55/-	-/-
E	300,000 to < 3,000,000	75/-	50/-
D	3,000,000 to < 10,000,000	85/80	60/-
C	10,000,000 to < 30,000,000	95/90	80/75
B	≥ 30,000,000	100/100	100/100

Binder Selection

Superpave introduced the performance grading (PG) system which is based on the expected pavement temperature extremes in the area of intended use. The Superpave mix design method determines both a high temperature which is based on the 7-day maximum pavement temperature and a low design temperature based on the minimum pavement temperature. A typical Superpave binder specification is shown below in Figure 3-6. The Multiple Stress Creep Recovery (MSCR) test is the latest improvement to the Superpave binder specification. This provides a new high-temperature binder specification that more accurately shows the rutting performance of the binder.

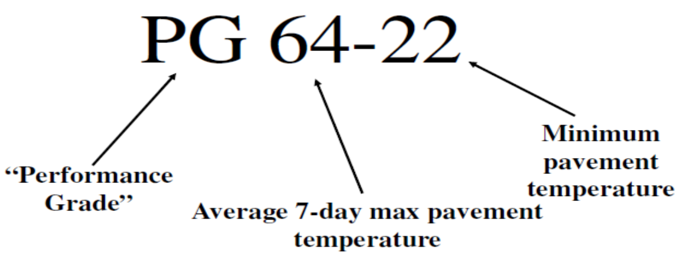


Figure 3-6: Example of Superpave Binder Specification

Mix Design

Trial blends are established and the best blend that meets all compaction and mixture requirement is selected. 4% design air voids and dust/effective binder ratio is between 0.6 and 1.6.

Construction and Experience

May (1996) summarised the major difficulties during construction of Superpave to include obtaining the specified density, meeting VMA requirements, segregation of coarse graded mixes, shoving under the intermediate roller and sticking of mix to truck beds. With Superpave, the most often heard remark and concerns from experience are the difficulties with obtaining the specified density.

This is been controlled by ensuring that the mix is mixed, compacted and placed at the correct temperatures. The use of material transfer vehicles such as the shuttle buggy and temperature sensors assist in ensuring the asphalt material is laid correctly and to the right temperature. Much of the observed cracking on Superpave especially load cracking appears to be more related to problems during construction other than mix design or material properties (Watson, 2003).

3.5 SOUTH AFRICA

South Africa's (SA) road network comprises national, provincial and local systems. A significant portion of the surfaced roads has asphalt as part of their pavement structure used in a variety of traffic loading and environmental conditions. Typical SA pavements comprise of thin asphalt surfacing course systems (<40 mm thick) overlaying a granular base layer.

Binder Selection

The type of binder is selected based on the following factors that include; traffic, climate, failure modes, pavement structure and availability of binder and aggregate types. Current developments mean SA is transitioning towards performance related specifications.

Mix Design

Key materials for thin asphalt surface comprise of high quality single sized road stone, a fine crusher dust, unmodified paving grade bitumen (40/50 or 60/70 depending on the environment) and a low lime content to act as a filler and adhesive agent. In some instances, an anti-stripping agent is used in the mixture to enhance the adhesion of the binder to potentially problematic aggregate. Experience has shown that it has not yet been necessary to modify the bitumen used in the asphalt.

Failure Mechanisms

Typical failure mechanisms experienced on SA roads usually occur as a combination of the following factors; ravelling, permanent deformation, cracking, loss of surface texture, stripping, the disintegration of the layer and bleeding of the asphalt surface. Ravelling of the pavement has been identified as the most probable failure mode to be expected with disintegration progressing from the surface downwards. In addition to this, a developing trend observed is permanent deformation experienced especially at slow moving or stationary traffic loading conditions. This has been attributed to the rise in high tonnage trucks and increasing traffic volume. High pavement temperatures, especially in summer which could easily exceed 40°C is another factor that could result in binder flow.

With respect to tackling the failure mechanisms, the influence of void content on the permeability of thin asphalt surfacing layers is significant and it is advised that a density study is undertaken on projects where the permeability of the asphalt layer is critical. With respect to moisture susceptibility, Table 3-6 shows typical mix additives added to help with tackling moisture susceptibility on SA roads based on the tensile strength ratio. The addition of 1% lime as an active filler had the best results and even better when the lime was injected in the drum with the bitumen.

Table 3-6: Moisture Susceptibility on South African Roads (Liebenberg et al., 2004)

Mix additives or active filler	Moisture susceptibility result (Laboratory prepared mixes)
No additives, no active filler	58,7 % 48,2 %
Polyamine added, no active filler	46,4 % 48,2 %
No additives, no active fillers, High P0,075 (P0,075 mm > 10)	3,2%
1% cement as active filler	41,9 %
1% lime as active filler	75,0 %
2% lime as active filler	50,5 %
	Moisture susceptibility result (Plant mixes)
No additives, no active filler	47,0 %
1% lime added – mixed with sand	52,9 %
1% lime added – injected in drum with bitumen	77,1 %

Construction

The Marshall method is widely used in designing asphalt layers in SA. However, there are two different approaches in producing the mixtures (Marshall or Gyratory) depending on the region. SA makes use of rolled in chips but this has been found to have a negative effect on the permeability of the thin asphalt layer. The expected life is between 8-12 years depending on traffic.

Model Mobile Load Simulator (MMLS3)

The use of the Model Mobile Load Simulator (MMLS3) as an accelerated pavement tester continues to garner worldwide attention. A protocol guideline method for evaluation of permanent deformation and susceptibility to moisture damage using the MMLS3 has been drafted by SANRAL (South African National Roads Agency SOC Limited). Key challenges and areas for more detailed focus include vehicle-pavement interaction and environment-pavement interaction. Further work is needed to improve Mechanistic-Empirical Pavement Design Guide (MEPDG) validation and improved reliability in pavement design while using the MMLS3.

Challenges

In recent correspondence with Herman Wolff (AECOM Executive for South Africa Office), a major challenge is the ability to manufacture asphalts with a high modulus of elasticity and a high strain at break. This requirement is to facilitate good load distribution and rutting resistance characteristics due to the high modulus of elasticity, while the high strain break will improve the fatigue properties on pavements with relatively high elastic deflections under load applications.

3.6 NEW ZEALAND

In recent times, New Zealand has installed trials of Epoxy-Modified Open Graded Porous Asphalts (EMOGPA) on the Christchurch Southern Motorway for use as a thin surface layer. Epoxy Asphalt is a premium material widely used in bridge decking solutions as opposed to road pavement surfacing due to cost implications. Epoxies are thermosetting materials that are hard and rigid after curing. These materials are two-part systems that result from the reaction of a curing agent (Part A) and a bitumen/resin component (Part B) as seen in Figure 3-7.

Construction

Production experience to date for the relatively small quantities used has almost exclusively been with a batch plant that gives good control of mixing time. Mixing time is an important parameter due to the thermosetting nature of the material. Extra care is required in the timing of manufacturing and construction phases to ensure the product is not under or over cured at compaction.

In 2007, Transport New Zealand installed a number of trial sections on Main North Road in Christchurch comprising a standard Porous Asphalt and EMOGPA with 20% and 30% design air voids. Observations during construction included roller pickup and the EMOGPA surfacing being “lively” within 3 hours of compaction. However, satisfactory performance was recorded during the assessment of the EMOGPA sections in 2010.

Figure 3-7: The Two-Component System of Epoxy Asphalts (OECD/ITF 2008)

The use of a continuous mix drum plant is also feasible for the production of epoxy asphalts. This has been used in New Zealand with no issues although further research and investigation has been highlighted with respect to optimising the curing profile with the desired rate of reaction for local conditions. This includes time for curing, distance of transportation and laying characteristics.

Benefits

Epoxy asphalts are not considered to be susceptible to moisture damage. There was a higher resistance to oxidative degradation at ambient temperatures; improved resistance to rutting, improved resistance to fatigue cracking although the benefits were marginal at high strain levels. Epoxy asphalt was more resistant to surface abrasion and loss of materials from tyre action even after oxidation as seen in Figure 3-8. Some epoxy systems have shown the ability to cure rapidly at a lower temperature than might be expected. To summarise, test performance indicates that the use of epoxy asphalts outperforms conventional mixtures providing a surfacing material with a maintenance life of more than 30 years if all the aspects of the process are correctly handled.

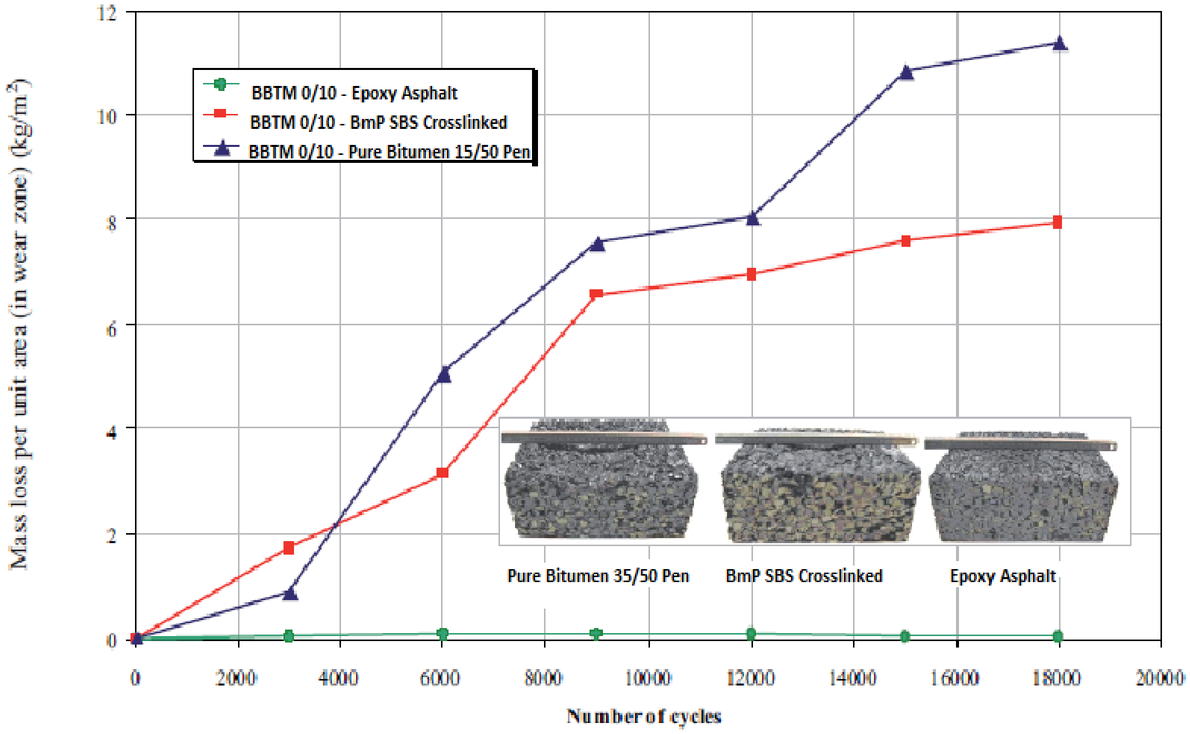


Figure 3-8: Evolution of Mass Loss

3.7 OVERALL SUMMARY

This section reviewed thin surface course systems used worldwide taking into account the mix designs, surface characteristics, construction issues and observed experience. The review conducted helps provide the base including factors to consider in developing the next generation of asphalt surfacing systems which offer significantly enhanced durability, reduced noise and improved skid resistance characteristics.

4 LABORATORY DEVELOPMENT OF NEW ASPHALT SURFACING MATERIALS

4.1 INTRODUCTION

The key objective of the project focused on developing new and innovative asphalt surfacing materials with significantly enhanced durability, whilst balancing other performance demands that include noise, skid resistance and safety. The major factors considered are stated below:

- Understanding issues and failure mechanisms.
- Performance requirements.
- Assessment criteria.
- Mix design and specification.
- Construction techniques.

A workshop was organised drawing upon leading experts and international experience. In this workshop, the participants were challenged with the following question: "*What are your ideas for the next generation of asphalt surfacing for use on Highways England Network that will increase durability without compromising the current performance of Specification for Highway Works (SHW) Clause 942?*"

Ideas presented in the workshop were collated into broad concept groups and an initial high-level evaluation of each concept was undertaken against durability, ease of implementation and likely relative cost. Figure 4-1 presents an overview of the initial evaluation, with ease of implementation increasing up the y-axis and durability increasing towards the right of the x-axis. The size of the circle represents an estimate of relative cost. Some concepts are shown as clouds due to a high degree of uncertainty on how they could be valued or ranked. The initial output was used to indicate the potentially most promising concept(s) in the project timescale. This is shown towards the top right of the chart as shown in Figure 4-1. Several ideas generated at the workshop related to the category of "good practice" (shown across the top of Figure 4-1). The key factors to be considered for potential options are stated below:

- The mix design process.
- A better understanding of aggregate packing.
- Constructability – Improving workmanship/operational upskilling/training.
- Substrate condition.
- The bond between layers.
- Improved safety and joint workmanship/enable echelon paving.
- Temperature control and prevention of mix segregation (potential use of shuttle buggies).

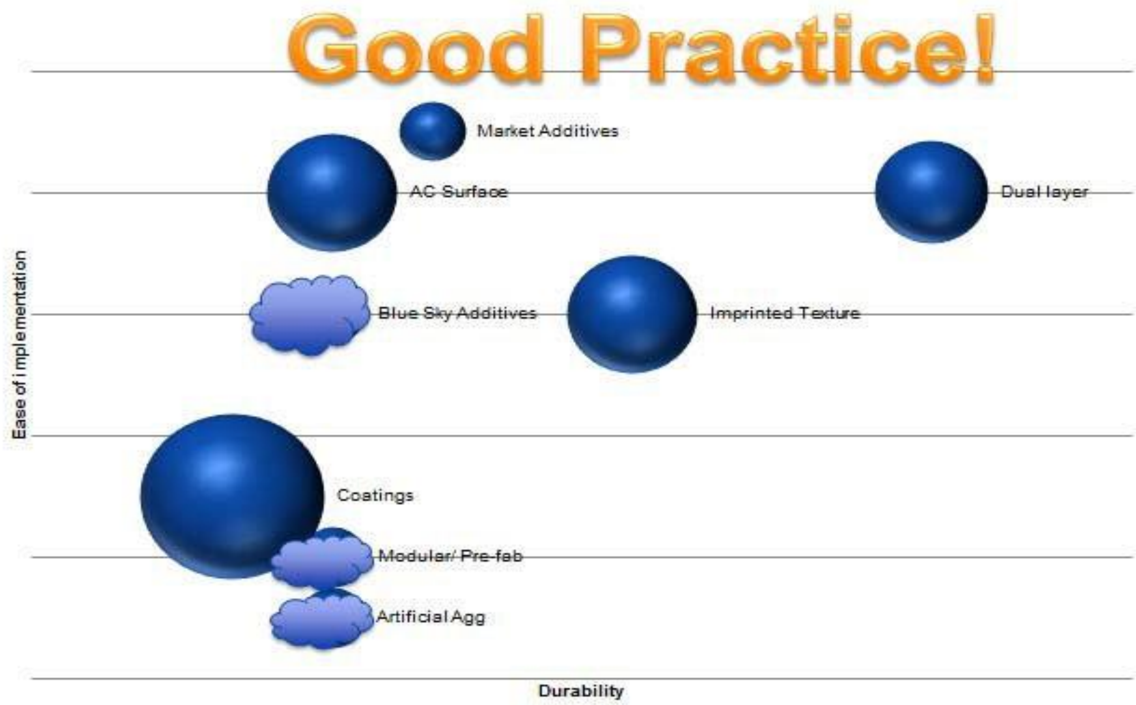


Figure 4-1: Summarised Concepts from Workshop

The dual layer was the top idea amongst a range of other options as shown in Figure 4-1. The Dual Density concept is based on a low voided, dense body of material with improved surface characteristics. In developing this concept further, the following methodologies were considered:

- Using a Polymer Modified Binder (PMB) over chipped Hot Rolled Asphalt (HRA) type material effectively creating a negative texture using 6, 10 or 14 mm embedded chippings.
- Dual layer with chippings applied.
- Dual layer surfacing with grit applied (on top or embedded).
- Dense body with surface dressing / bonded solution.
- Composite material, such as grouted macadam.

These ideas were explored further immediately after the workshop. The options detailed below were agreed by the project steering committee for development and trials in order to meet the objectives of the project:

1. Hot Rolled Asphalt (HRA) at different chipping rates.
2. Premium Asphalt Surfacing Systems (PASS).
   Note: The "Dual Layer" concept was renamed Premium Asphalt Surfacing Systems (PASS).
3. Thin Surface Course Stone Mastic Asphalt (SMA) – Control.

4.2 MATERIALS

The materials used for the project were supplied by the collaborative research partners. A summary of the materials received are detailed in Table 4-1.

Crushed basalt rock from Mancetter quarry was used in producing Mix 1 - 3 asphalt mixtures. The sand (0/2 mm) fraction was used for Mix 1 (HRA) and this was obtained from Bestwood quarry. Aggregate properties as obtained from the suppliers' data sheet are detailed in Figure 4-2 and Figure 4-4.

Table 4-1: Summary of Materials Received

Mix	Binder*	Nominal Maximum Aggregate Size
1 (HRA)	PMB Grade 40/100-65	0/14 mm
Chippings	Paving Grade 40/60	6/10 mm
2 (PASS)	PMB Grade 45/80-60	0/10 mm
3 (SMA)	Paving Grade 40/60	0/10 mm

***PMB denotes Polymer Modified Bitumen in accordance with (EN 14023); Paving Grade Bitumen is in accordance with (EN 12591)**

Table 4-2: Coarse Aggregate Properties*

Test	Standard	Test Result	Aggregate Size (mm)
Aggregate Abrasion Value	EN 1097-8	6.4	6/14
Los Angeles Abrasion	EN 1097-2	10	6/14
Magnesium Sulphate Soundness	EN 1367-2	3	6/14
Micro-Deval	EN 1097-1	17	6/14
Polished Stone Value (PSV)	EN 1097-8	62	4/10

***Information as obtained from supplier's material datasheet**

Table 4-3: Densities and Water Absorption Properties for the Coarse Aggregate Fractions*

TEST	STANDARD	0/4 mm	6 mm	10 mm	14 mm
Loose Bulk Density	EN 1097-3	1.60	1.31	1.33	1.37
Compacted Bulk Density	EN 1097-3	1.84	1.51	1.49	1.60
Apparent Particle Density	EN 1097-6	2.79	2.80	2.80	2.79
Saturated Surface Dry Density	EN 1097-6	2.75	2.72	2.72	2.74
Oven Dry Density	EN 1097-6	2.73	2.68	2.68	2.72

***Information as obtained from supplier's material datasheet**

Table 4-4: Densities and Water Absorption Properties for Sand used for Mix 1 Fine Aggregates*

Test	Standard	Sand (0/2 mm)
Loose Bulk Density	EN 1097-3	1.42
Compacted Bulk Density	EN 1097-3	1.61
Apparent Particle Density	EN 1097-6	2.65
Saturated Surface Dry Density	EN 1097-6	2.63
Oven Dry Density	EN 1097-6	2.62
Water Absorption	EN 1097-6	0.20

***Information as obtained from supplier's material datasheet**

The requirement for the flakiness index (FI) of the 6/10 mm chippings was set as 15_{max} in accordance with EN 933-3. The 6/10 mm chippings were obtained in 2 batches as detailed in Table 4-5. The aggregate gradations for the 6/10 mm chippings are shown in Figure 4-12.

Table 4-5: Flakiness Index for 6/10 mm Chippings

FLAKINESS INDEX FOR 6/10 mm CHIPPINGS	
Requirement = 15_{max}	
6/10 mm Chippings Batch 1	17
6/10 mm Chippings Batch 2	13

4.3 SHAPE ANALYSIS OF CHIPPINGS USING IMAGING TECHNIQUES

The aggregate shape is considered to be a key parameter for the design of asphalt mixtures and even more important for chippings. The aggregate shape is usually determined by calculating a ratio between the different dimensions of the particles and by comparing this ratio to either a flatness or elongation limit. The standardised methods used for this purpose vary in different countries. However, in order to increase the accuracy of aggregate shape determination, the following imaging techniques were investigated and they include:

1. VDG-40 Videograder.
2. Enhanced University of Illinois Aggregate Image Analyser (E-UIAIA).
3. Aggregate Imaging Systems (AIMS).

Table 4-6 summarises the advantages and disadvantages of the various imaging techniques (VDG-40, E-UIAIA and the AIMS).

Table 4-6: Shape Analysis Using Imaging Techniques

EQUIPMENT PARAMETERS	VDG-40 VIDEOGRADER	E-UIAIA	AIMS
Measured Aggregate Characteristics	Shape and Angularity.	Shape, Angularity and Texture.	Shape, Angularity and Texture.
Advantages	Widely used on highway control sites in France to Control grading of aggregate materials.	Measures the shape of a large quantity of aggregate materials.	Measures the three dimensions of aggregates.
	Can measure the shape of a large quantity of aggregate materials (75kg of materials in 10 minutes).	Makes use of three high-resolution cameras to capture three projections of a particle moving on a conveyor belt.	Uses a mechanism for capturing images at different resolutions based on particle size through the use of one camera and autofocus microscope.
	Previous research has reported a good correlation with manual measurements of flat-elongated particles.	Different types of mineral aggregates with a wide variety of colours can be scanned with the system.	Gives detailed analysis of texture.
Disadvantages	Uses one camera magnification to capture images of all sizes as they fall in front of a backlight.	Uses one camera magnification to capture images of all sizes as they fall in front of a backlight.	

Brief discussions about these techniques are presented in this section.

1. VDG-40 Videograder

Figure 4-2 shows the VDG-40 Videograder. The VDG-40 Videograder uses the shadowgraph principle as shown in Figure 4-3 (Caussignac and Leroy 1981) to capture images of aggregate particles. This principle consists of extracting the outline of an object that is located between a light source and a camera. The contrast between the background and object is sufficient to ensure a well-defined outline of the aggregate material resulting in the VDG-40 Videograder not being dependent on the colour of aggregate particles. In practice, images of particles are captured during their free fall through the measurement plane. Samples are scanned by a Charge Coupled Device (CCD) Line Camera with a resolution of 1024 dots and a 13 kHz scan frequency. In order to get a real-time determination of transition addresses, each line is analysed using a dedicated hardware located in a processing unit. The advantage of line CCD is to provide an exhaustive and unique image of the whole sample, which is not the case with devices using array CCD. A 50 mm focal lens is mounted on the camera, which provides a horizontal resolution of 0.2 mm for the VDG-40. The light source is a standard incandescent linear light tube. In order to prevent any disruption in the transition address determination stage, intensity variations of the light source due to alternative current are overcome using a specific circuit which adapts the line analysis features as detailed in (Descantes et al., 2006).

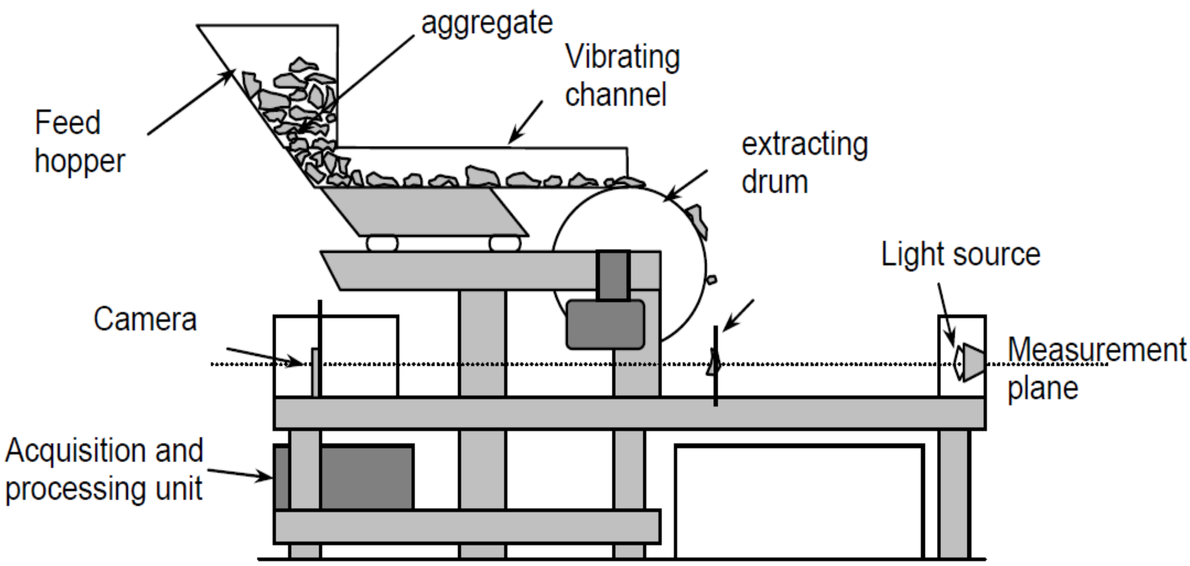


Figure 4-2: The VDG-40 Videograder

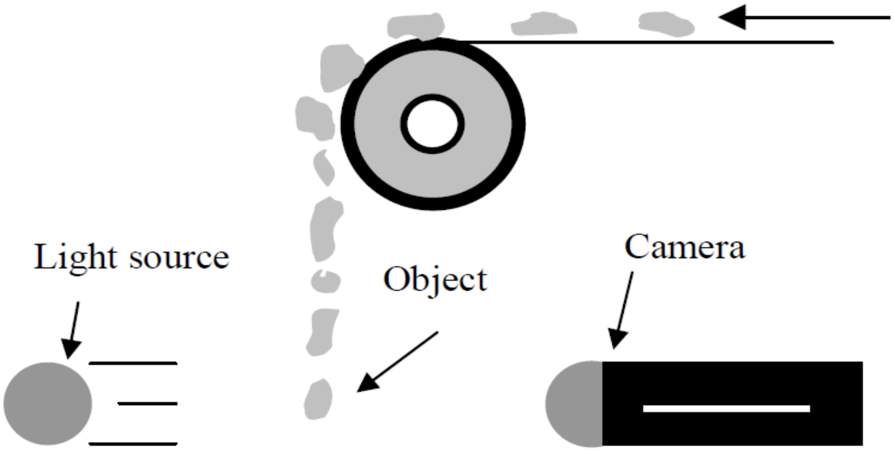


Figure 4-3: The Shadowgraph Principle for VDG-40

A feeding system, composed of a feed hopper, a vibrating channel and an extracting drum, separates the particles in a single curtain layer making them fall through the analysis area with their larger surface facing the camera. The velocity at the extracting drum perimeter being about 0.36 km/h, the particle fall speed is roughly 2.6 km/h during scan stage, which confers to the VDG-40 a vertical resolution of 0.2 mm according to the scan frequency. The use of the VDG-40 Videograder is covered by French standard XP P 18-566 (AFNOR 2002).

The following samples obtained from Table 4-1 were sent to IFSTTAR, France for further analysis using the VDG-40 Videograder:

- Sample 1: 6/10 mm Chippings Batch 1 (FI_{17})
- Sample 2: 6/10 mm Chippings Batch 2 (FI_{13})
- Sample 3: 0/10 mm (Mix 2) (FI_{22})

The samples were wet sieved on a 2 mm sieve and dried in an oven at 105°C prior to testing. The dry mass of the samples are detailed below, with the minimum mass calculated according to French standard XP P 18566 reported in parentheses:

- Sample 1: 787.6 g (600 g)
- Sample 2: 1064.6 g (600 g)
- Sample 3: 779.2 g (600 g)

The aggregate gradations using the VDG-40 Videograder for the samples are shown below in Figure 4-4.

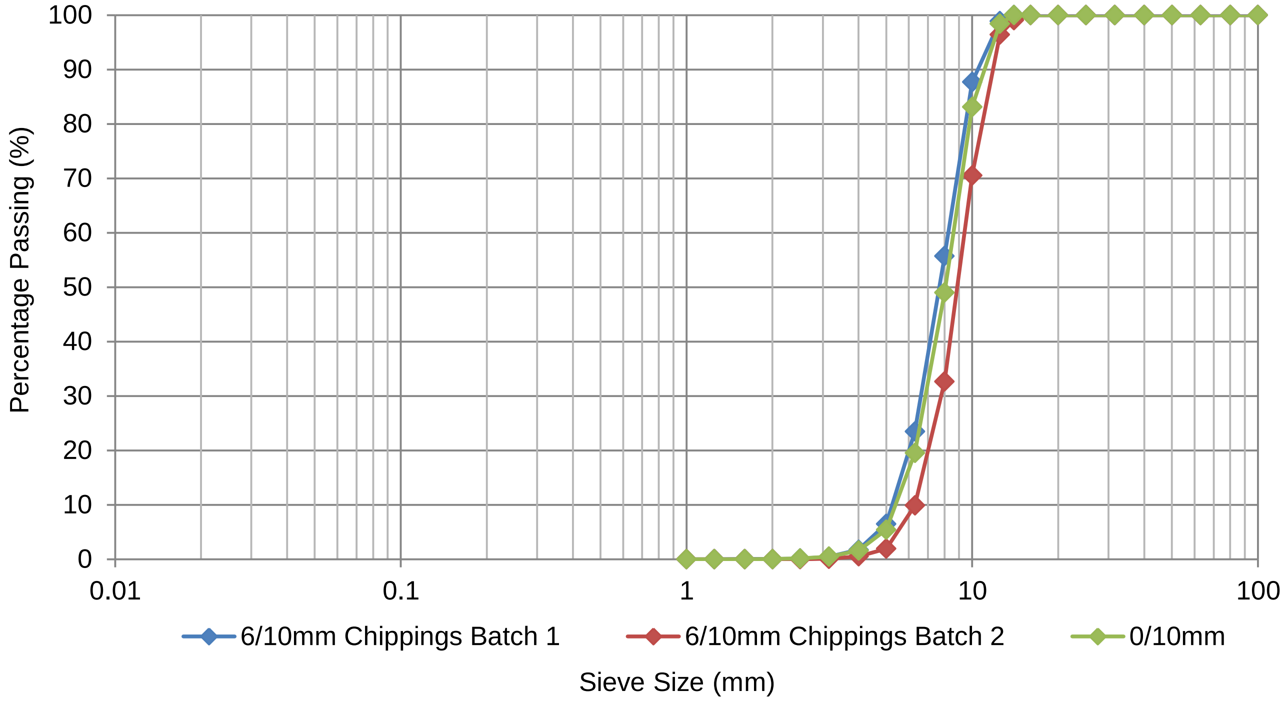


Figure 4-4: Aggregate Gradation Obtained Using the VDG-40 Videograder

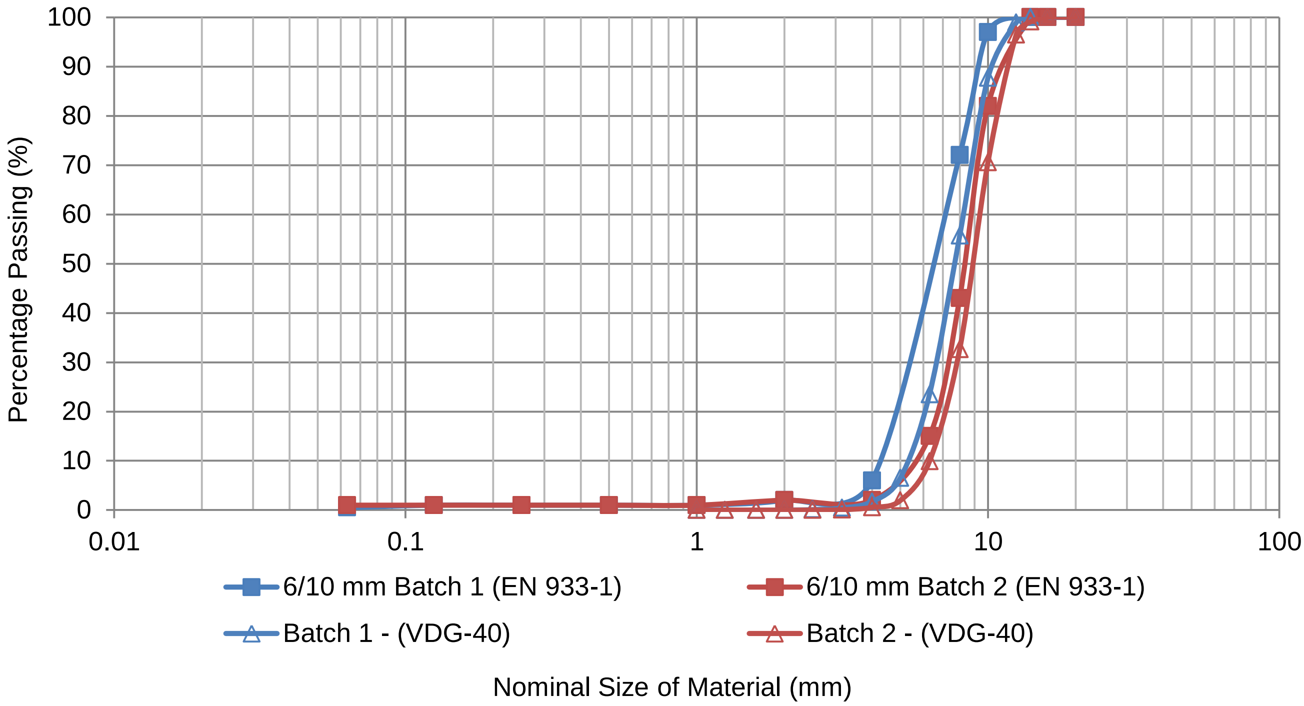


Figure 4-5: Comparison of Gradations of 6/10mm Chippings using EN 933-1 and VDG-40

Figure 4-4 shows 6/10 mm Batch 1, 6/10 mm Batch 2 and 0/10 mm aggregate gradations using the VDG-40. Figure 4-5 shows the aggregate gradations of the 6/10 mm chippings obtained using the VDG-40 in comparison to the aggregate gradations obtained in accordance with EN 933-1.

The result shows that the VDG-40 aggregate particles tend to be coarser in comparison to the aggregate particles tested using the sieve analysis method in accordance with EN 933-1. There was a greater deviation for the 6/10 mm Chippings Batch 1 that had flakier stones (FI_{17}) in comparison to 6/10 mm Chippings Batch 2 (FI_{13}). This could be as a result of the orientation of the aggregate materials as they fall from the conveyor as it was noted that the stones tend to rest more on the flaky side.

The angularities of the samples tested using the VDG-40 is presented in Table 4-7. The higher the angularity value indicates that the aggregate samples are more angular. Descantes et al., (2006) in their research using the VDG-40 showed a very strong correlation between individual angularity values delivered by the VDG-40 and the various crushed or rounded percentages of particles assessed according to EN 933-5, with R^2 factors above 92%.

Table 4-7: Angularity using the VDG-40

ANGULARITY					
Sample	**Repetition 1**	**Repetition 2**	**Repetition 3**	**Mean Angularity**	**Standard Deviation**
6/10 mm Batch 1	0.226	0.225	0.223	0.225	0.002
6/10 mm Batch 2	0.221	0.220	0.221	0.220	0.001
0/10 mm	0.223	0.222	0.221	0.222	0.001

2. Enhanced University of Illinois Aggregate Image Analyser (E-UIAIA)

The Enhanced University of Illinois Aggregate Image Analyser (E-UIAIA) is presented below in Figure 4-6. The E-UIAIA makes use of three high-resolution cameras with LED lighting arrangements to capture digital colour images of aggregate particles as they move on a conveyor belt. These projections are used to reconstruct three-dimensional representations of particles. Different types of mineral aggregates with a wide variety of colours can be scanned with the system.

Figure 4-6: Enhanced University of Illinois Aggregate Image Analyser (E-UIAIA)

The E-UIAIA provides information on the gradation. The shape is measured by calculating the flat and elongated ratio (FER). The shortest dimension perpendicular to the longest dimension is ascertained. Figure 4-7 depicts the FER using the E-UIAIA. The angularity index (AI) is measured using the outline slope method which measures the change in slope of the aggregates. This is shown in Figure 4-8. The surface texture is measured using the erosion-dilation method of aggregate particles shown in Figure 4-9. This describes the surface irregularities of the aggregate particles.

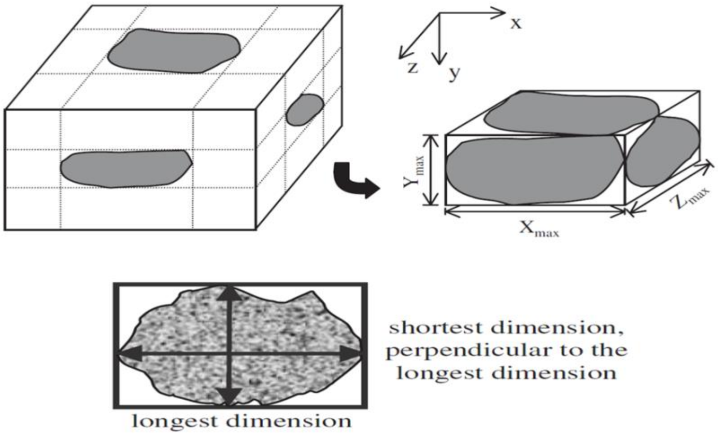


Figure 4-7: Flat and Elongation Ratio (FER)

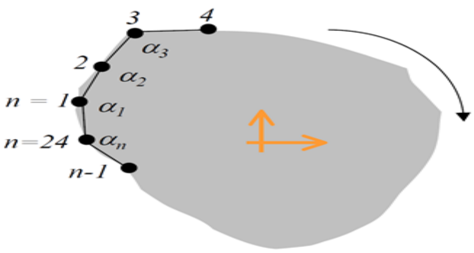


Figure 4-8: Angularity Index using the E-UIAIA

Figure 4-9: Surface Texture Index using E-UIAIA

The following samples obtained from Table 4-1 were sent to the University of Illinois at Urbana-Champaign for further analysis using the E-UIAIA to obtain the aggregate shape, texture and angularity properties:

- Sample 1: 6/10 mm Chippings Batch 1
- Sample 2: 6/10 mm Chippings Batch 2
- Sample 3: 0/10 mm (Mix 2)
- Sample 4: 0/4 mm (Dust for Mix 2)

Approximately 100 random aggregate particles were selected from each sample and scanned at the calibrated spatial resolution level of 430 pixels per inch using the three progressive scan colour CCD cameras installed on the imaging system of the E-UIAIA. Note that "Sample 4: Dust Mix 2" had only dust size fine particles (0/4mm) which were too small to scan using the E-UIAIA. Table 4-8 below summarises the calculated average and standard deviation values for the three main imaging based shape indices that includes the Angularity Index (AI), Surface Texture Index (STI) and Flat and Elongated Ratio (FER) for the aggregate samples.

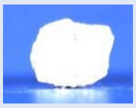
Table 4-8: E-UIAIA Test Results

SAMPLE	ANGULARITY INDEX (AI) (Degrees)		SURFACE TEXTURE INDEX (STI)		FLAT AND ELONGATED RATIO (FER)	
	AVERAGE	STD. DEV	AVERAGE	STD. DEV	AVERAGE	STD. DEV
6/10 mm Batch 1	463	84	2.72	1.18	2.28	0.78
6/10 mm Batch 2	431	77	1.87	0.49	1.91	0.40
0/10 mm	430	78	2.05	0.54	2.27	0.64

Table 4-8 shows that the 6/10 mm Batch 1 chippings had the highest AI and STI values. However, also note that both the 6/10 mm Batch 1 and 0/10 mm (Mix 2) had similar but slightly higher FER values. In general, high AI and STI are making these aggregates more angular and rougher in surface texture. The FER is simply the maximum dimension divided by the minimum. A higher value of FER is associated with increased slenderness which was consistent with the Flakiness Index (FI) values for the aggregate materials.

Table 4-9 shows example images of the aggregate materials tested using the E-UIAIA.

Table 4-9: Example Images of the Samples Tested using the E-UIAIA

SAMPLE	SAMPLE 1: 6/10 mm BATCH 1	SAMPLE 1: 6/10 mm BATCH 2	0/10 mm
Top View (RGB and Binary)	 	 	 
Side View (RGB and Binary)	 	 	 
Front View (RGB and Binary)	 	 	 

3. Aggregate Imaging Systems (AIMS)

The Aggregate Imaging Systems (AIMS) is shown in Figure 4-10. The AIMS operates based on two modules. The first module is for the analysis of fine aggregates; black and white images are captured using a video camera and a microscope. The second module is devoted to the analysis of coarse aggregates; grey images in addition to black and white images are captured by this module.

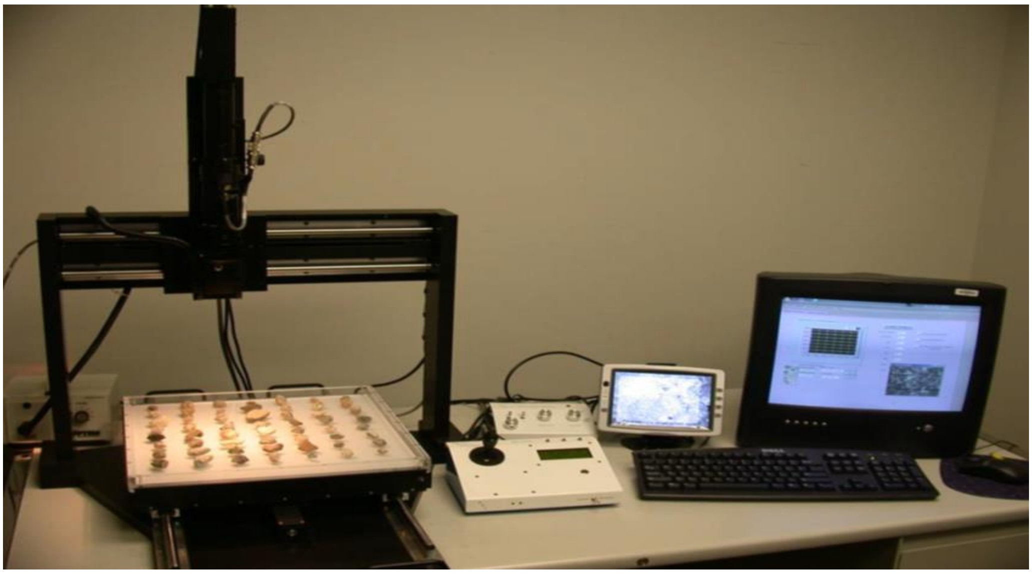


Figure 4-10: Aggregate Imaging Systems (AIMS)

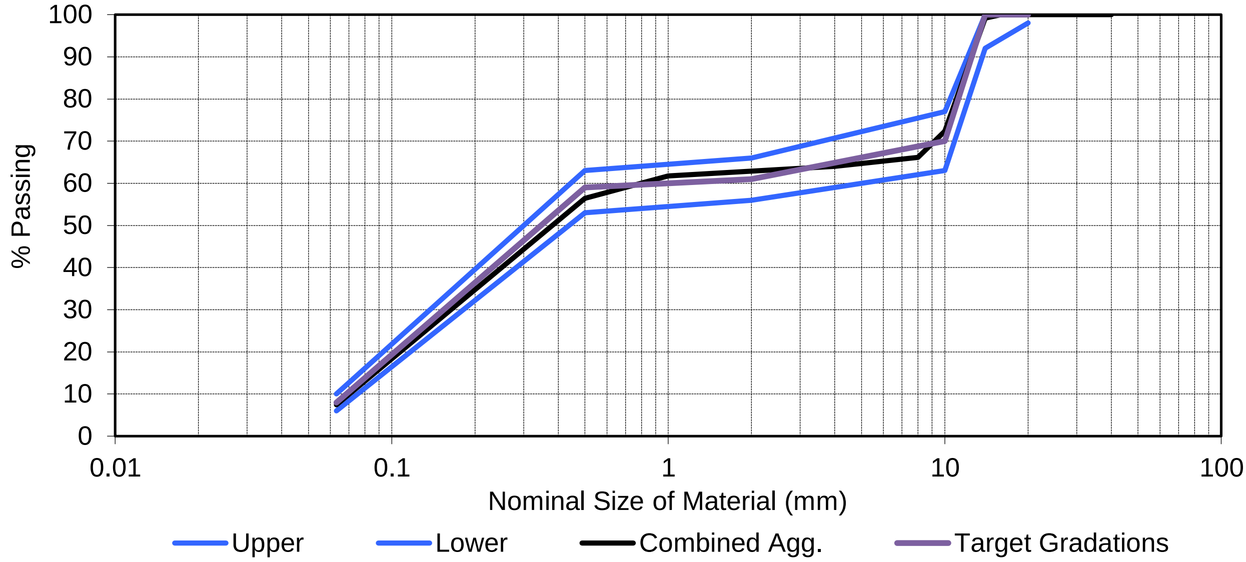
Fine aggregates are analysed for shape and angularity while coarse aggregates are analysed for shape, angularity and texture. The video microscope is used to determine the depth of particles, while the images of 2-D projections provide the other two dimensions. These three dimensions quantify shape. Angularity is determined by analysing the black and white images while the texture is determined by analysing the grey images as detailed in (Masad, 2003). This project did not make use of the AIMS. It was decided by the collaborative partners that only the VDG-40 and E-UIAIA would be used in assessing the imaging techniques for the aggregate materials.

4.4 LABORATORY MIX DESIGN

The following sections present details of the laboratory mix designs and methodologies used in producing HRA (Mix 1), PASS (Mix 2) and SMA (Mix 3).

4.4.1 *Hot Rolled Asphalt (HRA)*

The HRA used in the project conformed to SHW Clause 943 (Performance Related Design Mixture) designated as HRA 35/14 F surf 40/100-65 Class 2 with a target binder content of 7.7%. The design gradation for the HRA material is presented in Figure 4-11.



SIEVE (mm)	20	14	10	8	4	2	1	0.5	0.063
ENVELOPE (%)	98-100	92-100	63-77	-	-	56-66	-	53-63	6-10
COMBINED (%)	100	99	72	66	64	63	62	56	7.4

Figure 4-11: Aggregate Gradation for Mix 1 – HRA

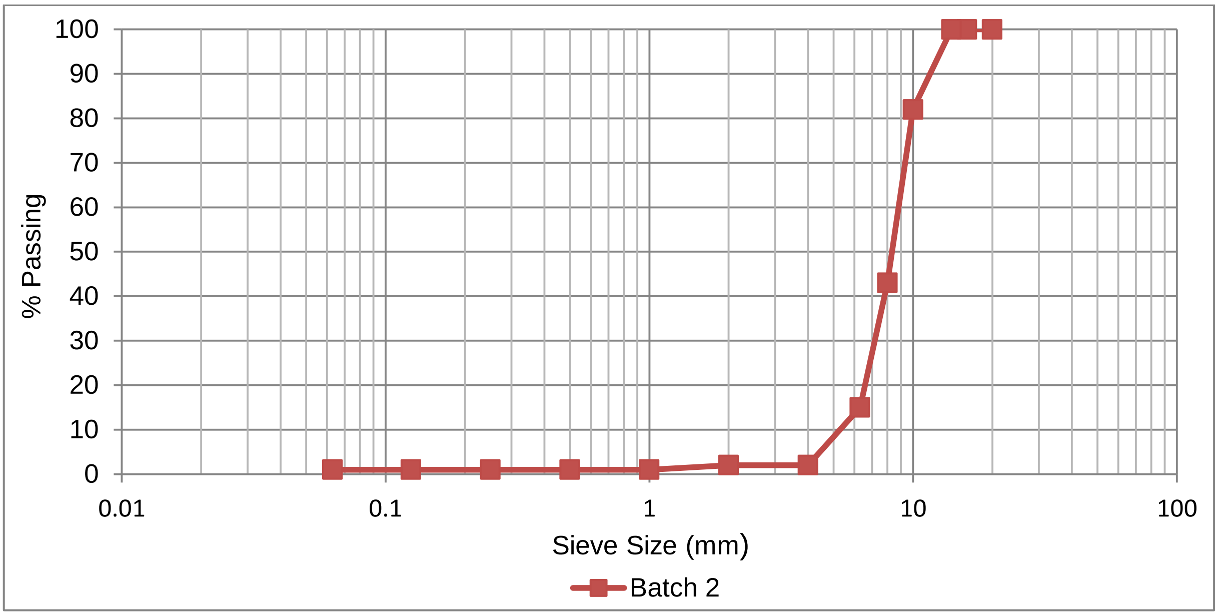
The desirable properties of the binder for use in the HRA for this project are detailed below:

- Polymer modified binder (PMB) which can promote good rutting resistance suitable for very heavily stressed sites requiring very high rut resistance.
- The binder must have sufficient flexibility and resilience against surface cracking.
- The binder must facilitate good workability for easy compaction under adverse weather application.
- The binder must allow sufficient time for embedment of the pre-coated chippings to the HRA and promote retention of the pre-coated chippings.

The PMB grade 40/100-65 (EN 14023) was considered to meet the properties as detailed above. The manufacturer's recommended mixing temperature ranges from 165°C to 190°C and the compaction temperature ranges from 120°C to 160°C.

4.4.2 *HRA with Pre-Coated Chippings (PCC)*

6/10 mm pre-coated chippings (PCC) with FI_{13} were applied at different spread rates to the designed HRA. The gradation of the chippings is presented in Figure 4-12.



SIEVE (mm)	20	14	10	8	6.3	4	2	1	0.5	0.25	0.125	0.063
% PASSING	100	100	82	43	15	2	2	1	1	1	1	1

Figure 4-12: Gradings for the 6/10mm Chippings

The chippings were pre-coated using 40/60 paving grade bitumen in accordance with SHW Clause 915. The desirable binder properties considered for pre-coating the chippings are detailed below:

- The binder must reduce the risk of clogging during chipping application.
- The binder should promote adhesion of chipping after being embedded to the HRA.
- The binder must not compromise the micro-texture properties of the chipping.

The pre-coated chippings were produced at 1.5% and 1.8% binder contents, and at variable spread rates from 10 to 16 kg/m^2. In preparing the pre-coated chippings, complete coating of the chippings was achieved in order to prevent binder run-off. The appearance of the pre-coated chippings produced at 1.5% and 1.8% binder contents are shown in Figure 4-13.

Figure 4-13: Pre-Coated Chippings (Binder Contents: 1.5% - Left and 1.8% Right)

4.4.3 *Premium Asphalt Surfacing Systems (PASS)*

The PASS concept is based on a low voided, dense body of material with improved surface characteristics. The mix design explored aggregate packing theories including Bailey's method (Vavrik et al., 2002) to produce the PASS. The Bailey's method provided a good starting point for the mix design of the PASS in order to obtain the required air voids and workability of the mix. The desired in-service performance properties for the PASS include resistance to rutting, long-term durability, improved skid resistance and reduced noise properties. The focus of the Bailey method is aggregate packing. The packing characteristics are determined by several factors that include the shape, strength and texture of the aggregates.

Other factors include the aggregate gradation and compaction effort applied. Cubical particles form a denser configuration in comparison to flat and elongated particles. Smooth particles slide together more easily than those with a rough surface texture. To better understand aggregate packing, it is important to establish what particles form the coarse aggregate structure and which ones fit into the voids created within the structure. Please note that in this section, the work of Vavrik et al., (2002) is used extensively in defining the aggregate packing structure for the PASS. Vavrik et al., (2002) identified four key principles to consider with the Bailey Method. These are stated below:

1. Establish coarse (CA Ratio) and fine aggregate (FA_c and FA_f) fractions.
2. It must be noted that packing of the coarse fraction influences packing of the fine fraction.
3. The fine aggregate coarse (FA_c) fraction relates to the packing of the overall fine fraction in the combined blend.
4. The fine aggregate fine (FA_f) fraction relates to the packing of the fine portion of the gradation in the blend.

In the Bailey Method, the sieve which defines coarse and fine aggregate is known as the Primary Control Sieve (PCS). The PCS is based on the Nominal Maximum Particle Size (NMPS) of the aggregate blend. The NMPS is defined as one sieve larger than the first sieve that retains more than 10% of the aggregate.
The PCS is obtained by:

$$PCS = NMPS\ x\ 0.22$$

The value of 0.22 used in the control sieve equation was determined through analysis of the packing of different shaped aggregate particles. The fine aggregate is broken down and evaluated as two portions. To determine where to split the fine aggregate, the same 0.22 factor used on the entire gradation is applied to the PCS to determine a Secondary Control Sieve (SCS). The SCS then becomes the break between coarse sand and fine sand. The fine sand is further evaluated by determining the Tertiary Control Sieve (TCS), which is determined by multiplying the SCS by the 0.22 factor. The fractions are shown in Figure 4-14.

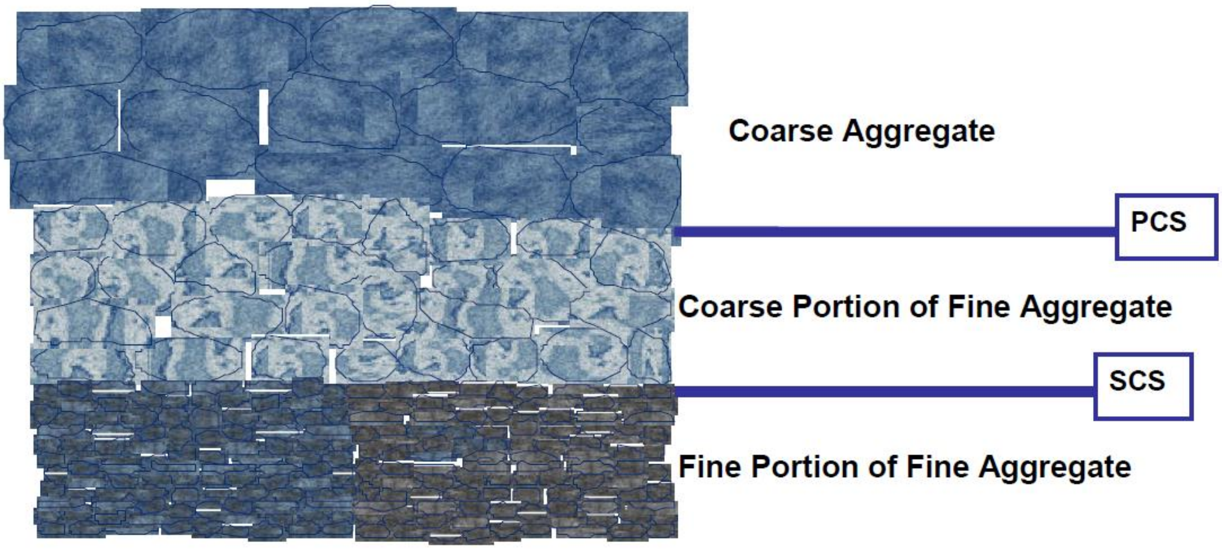


Figure 4-14: Overview of the Divisions for Analysis of the Aggregate Gradation (Vavrik et al., 2002)

The CA Ratio is used to evaluate packing of the coarse portion of the aggregate gradation and to analyse the resulting void structure. Understanding the packing of coarse aggregate requires the introduction of the half sieve. The half sieve is defined as half the NMPS. Particles smaller than the half sieve are called "interceptors." Interceptors are too large to fit in the voids created by the larger coarse aggregate particles spreading them apart. The balance of these particles can be used to adjust the mixture's volumetric properties. The equation for the calculation of the coarse aggregate ratio is detailed below:

$$CA\ Ratio = \frac{(\%\ Passing\ Half\ Sieve - \%\ Passing\ PCS)}{(100\% - \%\ Passing\ Half\ Sieve)}$$

The CA Ratio is a primary factor in the constructability of the mixture. A decrease in the CA Ratio (<1.0) results in an increase in the compactability of the fine aggregate fraction because there are fewer interceptors to limit compaction of the larger coarse aggregate particles. Mixtures with low CA Ratio typically require a stronger fine aggregate structure to meet the required volumetric properties. The FA_c creates voids that will be filled with FA_f. As the FA_c ratio increases, the fine aggregate fraction packs together tightly. It is recommended to have the FA_c ratio at < 0.50. Higher FA_c values indicate an excessive amount of FA_f in the mixture. The equation that describes FA_c is detailed below:

$$\mathrm{FAc} = \frac{\%\ Passing\ SCS}{\%\ Passing\ PCS}$$

The FA_f fills the voids created by the coarse portion of the fine aggregate. It is used to evaluate the packing characteristics of the smallest portion of the aggregate blend. This ratio shows how the FA_f packs together. The value of the FA_f ratio should be less than 0.50 for typical dense-graded mixtures. The equation that describes FA_f is detailed below:

$$FA_f = \frac{\%\ Passing\ TCS}{\%\ Passing\ SCS}$$

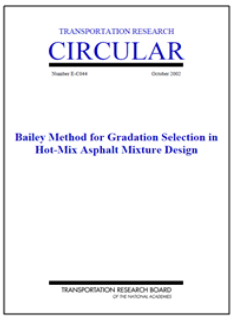
To summarise, the CA ratio describes how the coarse aggregate particles pack together and how these particles compact the fine aggregate portion of the aggregate blend that fills the voids created by the coarse aggregate. An increase in the CA ratio will result in an increase in the air voids and the Voids in the Mineral Aggregate (VMA). The FA_c ratio describes how the coarse portion of the fine aggregate packs together and how these particles compact the material that fills the voids it creates. Finally, the FA_f ratio describes how the fine portion of the fine aggregate packs together. The FA_f influences the voids that will remain in the overall fine aggregate portion of the blend as it represents the particles that fill the smallest voids created. An increase in the FA_c and FA_f can cause a decrease in the voids and VMA of the mixture. The recommended ranges of aggregate ratios are detailed in Figure 4-16. These ratios were used as a guide in the design and initial laboratory trials for the PASS. This method improves the gradation of the generic SMA providing a denser structure and texture on the surface of the PASS. Figure 4-16 presents the aggregate gradation for the PASS designed to meet as closely as possible the aggregate ratios defined as defined in this section. The actual ratios for the PASS using 14 mm NMPS are shown below in Figure 4-15.

For Dense Asphalt Mixtures

Recommended Ranges of Aggregate Ratios

	NMPS, mm					
	37.5	25.0	19.0	12.5	9.5	4.75
CA Ratio	0.80–0.95	0.70–0.85	0.60–0.75	0.50–0.65	0.40–0.55	0.30–0.45
FA_c Ratio	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50
FA_f Ratio	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50	0.35–0.50

NOTE: FA_c = fine aggregate coarse; FA_f = fine aggregate fine. These ranges provide a starting point where no prior experience exists for a given set of aggregates.



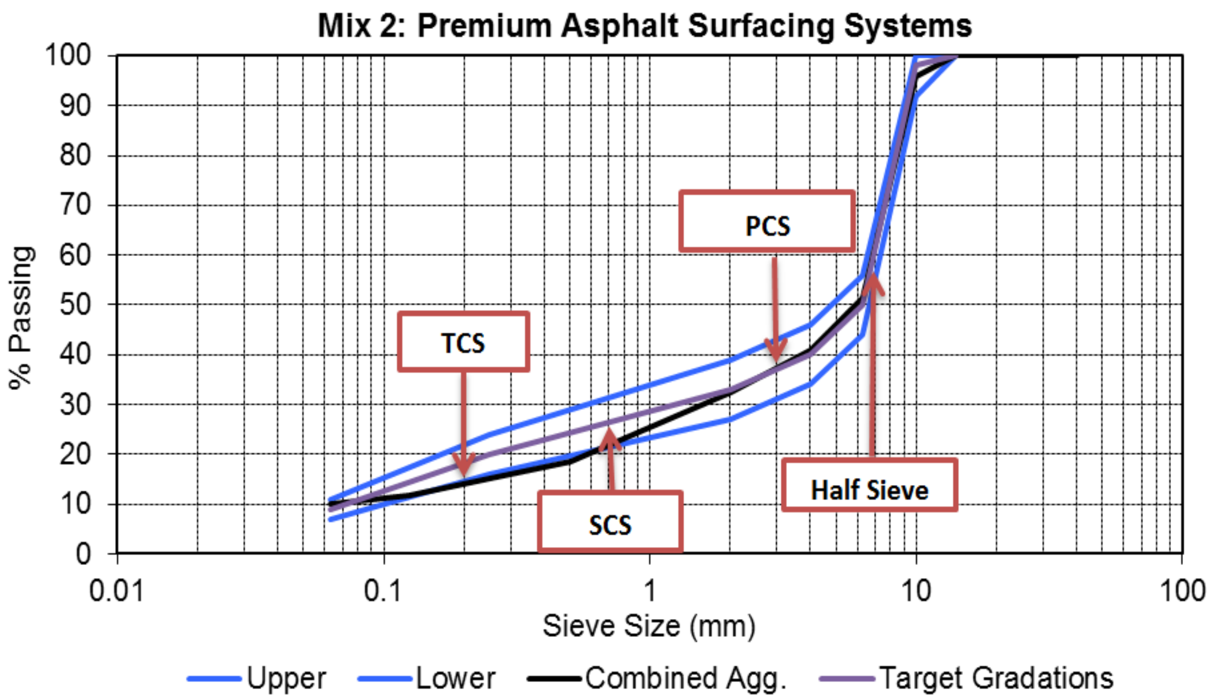
Recommended Ranges for Aggregate Ratios in SMA Mixtures

	NMPS		
	19.0 mm	**12.5 mm**	**9.5 mm**
CA Ratio	0.35–0.50	0.25–0.40	0.15–0.30
FA_c Ratio	0.60–0.85	0.60–0.85	0.60–0.85
FA_f Ratio	0.65–0.90	0.60–0.85	0.60–0.85

For PASS Layer with NMPS 12.5mm:
CA ratio = 0.45 – 0.50
FAc ratio = 0.55 – 0.70
FAf ratio = 0.55 – 0.70

Actual PASS Layer with NMPS 14mm:
CA ratio = 0.55
FAc ratio = 0.55
FAf ratio = 0.52

Figure 4-15: Recommended Ranges of Aggregate Ratios



SIEVE (mm)	14	10	6.3	4	2	0.5	0.25	0.125	0.063
ENVELOPE (%)	100	92-100	44-56	34-46	27-39	-	16-24	-	7-11
COMBINED (%)	100	96	51	41	32	19	15	12	10

Figure 4-16: Aggregate Gradation for Mix 2: PASS

The binder for the PASS must facilitate good workability particularly for easy compaction under adverse weather condition, promote good rut resistance and suitable for use in very heavily stressed sites. In addition to this, the binder must have sufficient flexibility against surface cracking promoting adhesion to the mix and not compromising the micro-texture of the surface course. The binder selected that meets the requirements and suitable for use in the project was PMB grade 45/80-60. The recommended mixing and compaction temperatures are 175°C and 155°C respectively. Delorme et al., (2007) detailed the method for ascertaining the binder content (TL_{int}) for the PASS mixtures taking into account the richness modulus, (K). This is detailed below:

$$K = \frac{\frac{100 \times TLint}{100 - TLint}}{\alpha \sqrt[5]{\Sigma}}$$

Where:

TL_{int} = Ratio of binder mass to the total mix mass

$$= \frac{Bitumen\ Mass}{Dry\ Aggregate\ Mass + Bitumen\ Mass}$$

$\Sigma = 0.25\ G + 2.3\ S + 12\ s + 150\ f$ with:

G: The proportion of aggregate particles greater than 6.3 mm.

S: The proportion of aggregate particles included between 6.3 mm and 0.250 mm.

s: The proportion of aggregate particles between 0.250 mm and 0.063 mm.

f: The proportion of aggregate particles less than 0.063 mm.

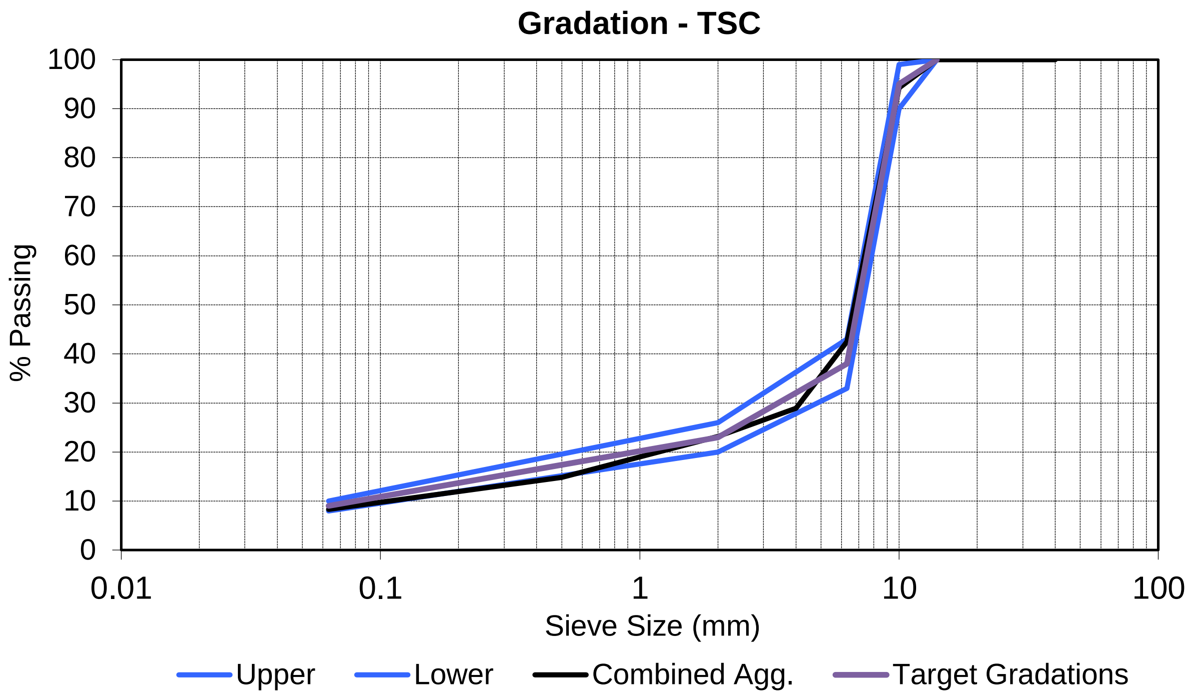
α: This is a correction factor relative to the density of the aggregates.

$\alpha = \frac{2.65}{\rho G}$; ρ_G is the mass density of aggregates = (2.8) detailed in Table 4-3.

The formulae, as shown above, were applied to obtain a target binder content of 5.4% at K, not less than 3.3.

4.4.4 *Stone Mastic Asphalt (SMA)*

A generic Stone Mastic Asphalt (SMA) produced in compliance with SHW Clause 942 designated as SMA 0/10 Surf 40/60 was used as a control mixture. The SMA gradation is presented in Figure 4-17. 6.5% binder content and 0.3% cellulose fibres were used for the mix.



SIEVE (mm)	14	10	6.3	4	2	0.5	0.063
ENVELOPE (%)	100	90-99	33-43	34-46	20-26	-	8-10
COMBINED (%)	100	94	43	29	23	15	8.3

Figure 4-17: Aggregate Gradation for Mix 3: Thin Surface Course Stone Mastic Asphalt (SMA)

4.5 MECHANICAL AND FUNCTIONAL PROPERTIES

This section presents the test results from mechanical and functional properties of the laboratory manufactured samples. Table 4-10 presents the matrix used for the laboratory testing.

Table 4-10: Laboratory Test Matrix

SECTION	TESTS
4.5.1	Workability of asphalt mixture.
4.5.2	Visual assessments and functional properties.
4.5.3	Resistance to deformation.
4.5.4	Determination of noise.

4.5.1 *Workability of Asphalt Mixtures*

The workability of the asphalt mixtures was monitored and assessed during the laboratory production. This was represented as the resistance of the asphalt mixture during high temperature mixing to the applied torque per unit weight. Figure 4-18 shows the high capacity asphalt mixer used in this study capable of mixing 50 kg of materials. A major advantage of this mixer was that it has temperature controlled mixing chamber and the capability to measure variations in mixing temperature and torque, and real-time data logger linked to a computer.

Figure 4-18: Asphalt Mixer

The workability test data and test results are presented in Table 4-10 and Figure 4-19.

Table 4-11: Workability Assessment for Asphalt Mixtures

WORKABILITY ASSESSMENTS							
Mix	Binder Content	Fibre	Target Mixing Temperature (ºC)	Measured Values (Average)			
				Actual Mixing Temperature (ºC)	Asphalt Weight (kg)	Torque (Nm)	T/W (Nm/kg)
Mix 1 – HRA	7.7%	-	175 +/- 5	175	40.413	24.6	0.608
Mix 2 - PASS	5.4%	-	175 +/- 5	175	36.376	20.0	0.550
Mix 3 – SMA	6.5%	0.3%	165 +/- 5	160	43.764	13.4	0.305

Note: T/W denotes normalised torque which is a ratio between the applied torque of mixing paddle and the weight of asphalt sample in the mixing chamber.

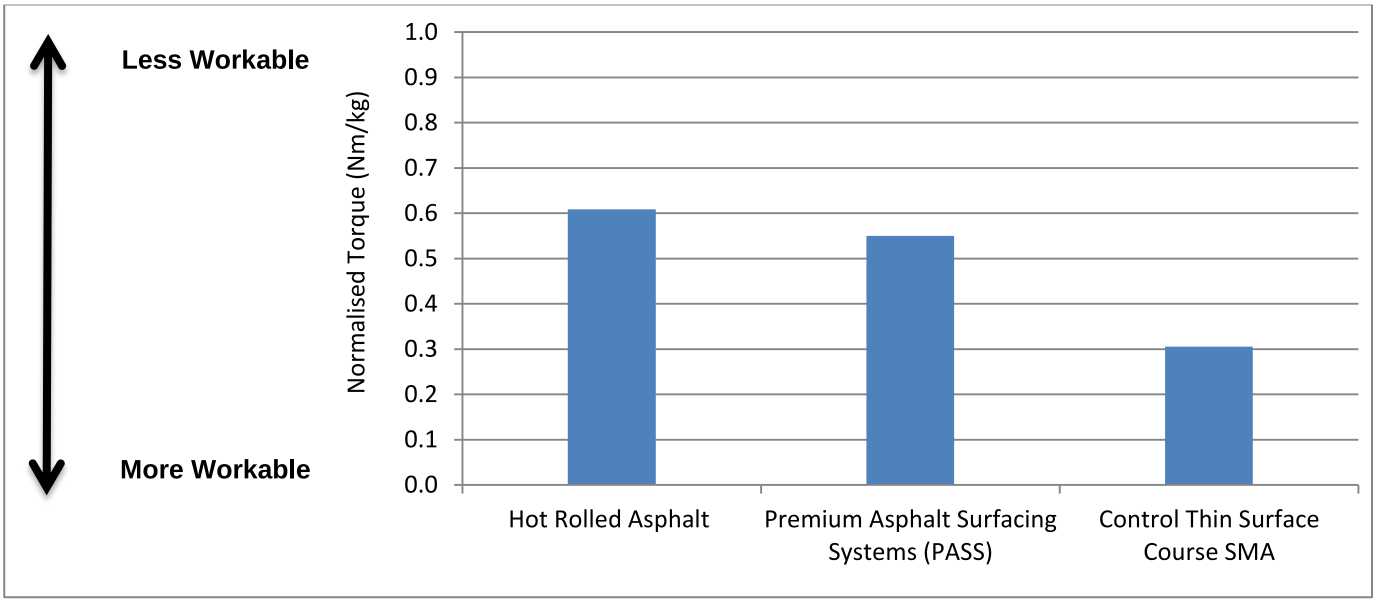


Figure 4-19: Workability Assessment of the Asphalt Mixtures

Lower resistance to normalised torque is considered to be an indication of better workability. Figure 4-19 shows that Mix 3 (SMA) with 40/60 pen binder required a lower mixing torque compared to both Mix 1 (HRA) and Mix 2 (PASS) with high-performance polymer modified bitumen (PMB). The lower workability of HRA and PASS samples could be attributed to the dense compositions of these mixtures in addition to the use of high viscosity PMB.

Nevertheless, the results show that PASS sample had slightly better workability than HRA samples. From a practical point of view, Clause 943 HRA has been installed successfully in many road projects and these results suggest that there is no foreseeable workability related issue with the installation of PASS on roads. The above results were reviewed during the demonstration trial, presented in Section 5 of this report.

4.5.2 *Visual Assessments and Functional Properties*

Asphalt slabs were manufactured to the target mixture volumetrics by using a laboratory roller compactor at AECOM laboratory in Nottingham. For the HRA slabs, PCC was applied manually following initial 2 passes using the roller compactor at the target spread rates. On completion of sample manufacturing, core samples were extracted from these slabs and they were subjected to further assessments. Surface finish of asphalt slabs and cut face of core samples were visually examined. Snapshot appearances of these samples are presented in Figure 4-20 to Figure 4-22.

Figure 4-20: HRA Sample (Unchipped)

Figure 4-21: PASS Sample

Figure 4-22: SMA Sample (post testing)

The HRA as depicted above in Figure 4-20 was dense had a high proportion of sand in the mix resulting in a low percentage of air voids after compaction. Figure 4-23 shows chipped HRA using 1.8% PCC at 10 kg/m^2. The PASS sample is shown in Figure 4-21 showing optimal packing of aggregates providing particle to particle contact and sufficient void space. The aggregate structure of the PASS is interconnected was well compacted and did not show voids in the mix. Figure 4-22 shows SMA sample showing a coarse stone skeleton; the appearance of the SMA showed that the samples were slightly voided in comparison to the HRA and the PASS.

Subsequently, tests were performed to assess functional properties of these samples, specifically:

- Mixture volumetrics to EN 12697 parts 5, 6, and 8
- Surface macrotexture to EN 13036-1
- Skid resistance pendulum value to EN 13036-4

The mean texture depth and skid pendulum test value (PTV) in accordance with EN 13036-1 and EN 13036-4 respectively for the HRA are detailed in Table 4-12. The results represent a mean at 4 test locations for the mean texture depth. Visual assessments of the HRA samples are shown in Figure 4-23. The HRA mixtures were dense and the PCC properly embedded with no visible signs of double chipping.

Table 4-12: HRA Test Results

HRA SLAB NUMBER	PCC BINDER CONTENT (%)	PCC SPREAD RATE (kg/m^2)	MEAN TEXTURE DEPTH (mm)	SKID PTV
1	1.5	16	2.2	55
2	1.8	16	1.8	56
3	1.5	10	1.7	51
4	1.8	10	1.6	53
5*	-	-	0.3	63

* PCC was not applied to the HRA Sample

Figure 4-23: Visual Inspection of the HRA Samples 1-3

Table 4-13 presents summarised test results for HRA (1.8% PCC, 10kg/m³), PASS and SMA.

Table 4-13: Summarised Test Results for the Asphalt Surfacing Materials

SAMPLE	BULK DENSITY (kg/m^3)	MAXIMUM DENSITY (kg/m^3)	AIR VOIDS (%)	MEAN TEXTURE DEPTH (mm)	PENDULUM TEST VALUE (PTV)
Mix 1 – HRA (1.8% PCC, 10kg/m³)	2214	2360	6.2*	1.4	53
Mix 2 – PASS	2380	2500	3.2	1.2	60
Mix 3 - SMA	2359	2506	5.9	1.1	72
Mix 1 – 40/100-65, 7.7% Binder Content Mix 2 – 45/80-60, 5.4% Binder Content Mix 3 – 40/60, 6.5% Binder Content *Volumetrics in accordance with BS EN 12697-6 on cores without PCC					

4.5.3 *Resistance to deformation*

Resistance to deformation of the asphalt cores was determined by using wheel track testing (WTT) (small device in air) to EN 12697-22. The test was run at 60ºC and:

- Up to 1000 and 10000 cycles for HRA samples;
- Up to 10000 cycles for PASS and SMA samples.

The test results for HRA samples are presented in Table 4-14 and Table 4-15. The results presented are the mean values of 2 HRA samples to obtain a representative test result.

Table 4-14: WTT Results (Procedure B)

HRA SLAB NUMBER	DESCRIPTION	WHEEL TRACKING SLOPE IN AIR ($mm/10^3$ cycles)	PROPORTIONAL RUT DEPTH AT 10,000 CYCLES (%)	MEAN RUT DEPTH AT 10,000 CYCLES (mm)
1	1.5% PCC, 16 kg/m^2	0.14	11.1	5.8
2	1.8% PCC, 16 kg/m^2	0.28	10.6	6.4
3	1.5% PCC, 10 kg/m^2	0.23	11.1	6.2
4	1.8% PCC, 10 kg/m^2	0.03	9.0	4.7
5	No PCC	0.06	12.4	6.1
PD 6691	-	1.00	-	-

Table 4-15: WTT Results (Procedure A)

HRA SLAB NUMBER	DESCRIPTION	WHEEL TRACKING RATE IN AIR (µm/cycles)	MEAN RUT DEPTH AT 1,000 CYCLES (mm)	MEAN RUT DEPTH AT 10,000 CYCLES (mm)
1	1.5% PCC, 16 kg/m^2	0.94	4.0	5.8
2	1.8% PCC, 16 kg/m^2	0.93	4.3	6.4
3	1.5% PCC, 10 kg/m^2	1.37	4.2	6.2
4	1.8% PCC, 10 kg/m^2	1.12	3.7	4.7
5	No PCC	0.71	2.7	6.1
PD 6691	-	15.00	7.0	-

Figure 4-24 and Figure 4-25 present the mean rut depth and rut profile of the HRA samples after 10,000 cycles with error bars shown.

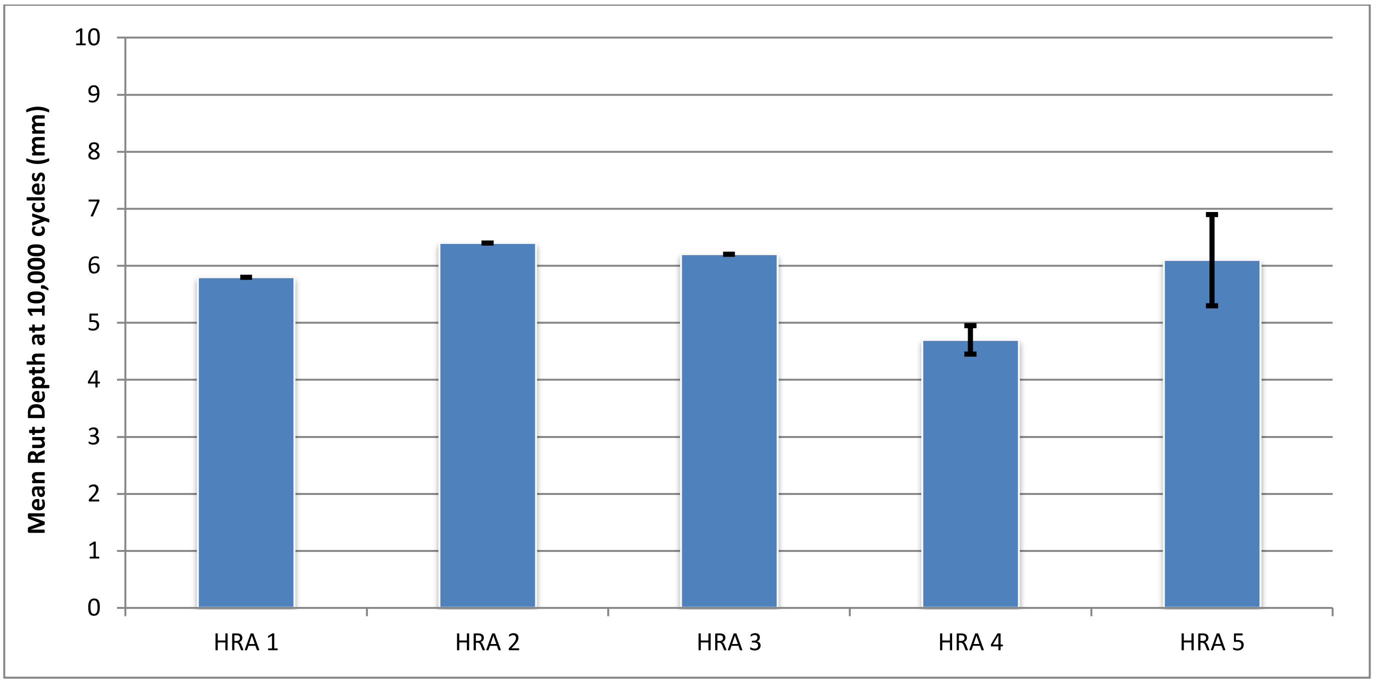


Figure 4-24: Mean Rut Depth of HRA Samples after 10,000 cycles (mm)

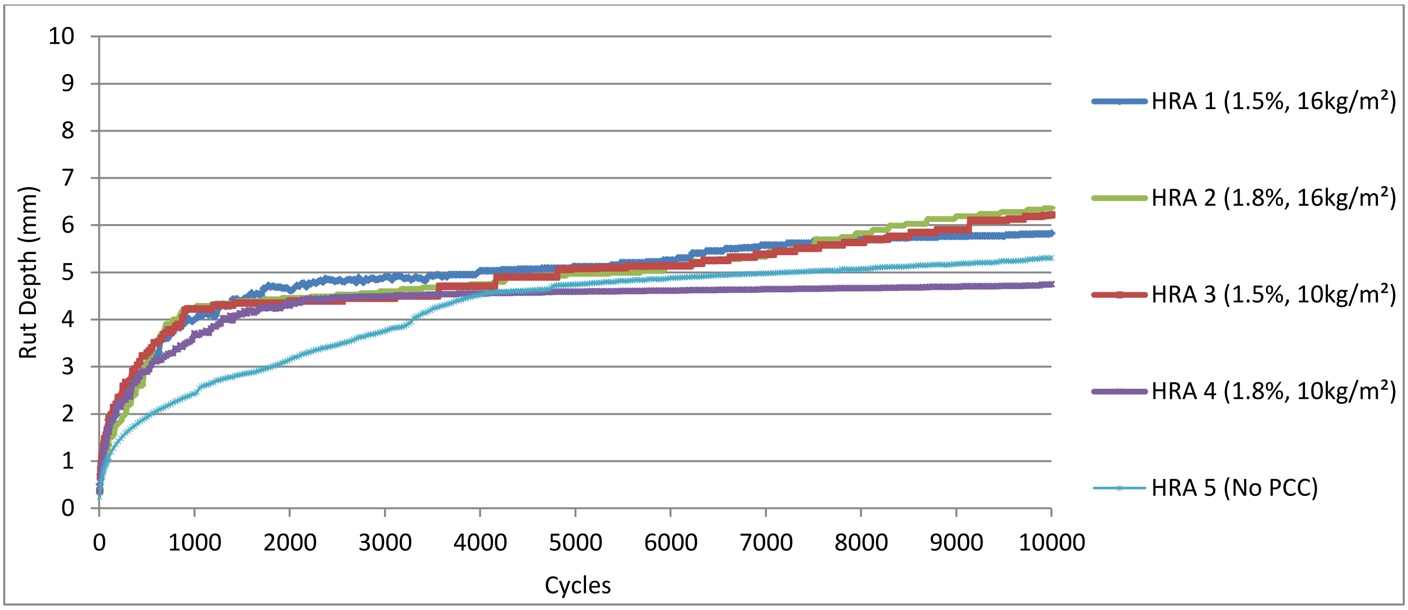


Figure 4-25: Rut Profile for the HRA Samples

Evaluating the test results, it was evident that HRA 4 with 1.8% PCC at 10 kg/m^2 spread rate had relatively good surface texture and skid resistance properties (Table 4-13) in addition to superior rutting characteristics in comparison to the other HRA samples. It was decided that HRA 4: 1.8% PCC, 10 kg/m^2 would be used as the HRA material for this project.

Table 4-16: WTT Results - Procedure B for the Asphalt Mixtures

SAMPLE	WHEEL TRACKING SLOPE IN AIR (mm/10^3 cycles)	PROPORTIONAL RUT DEPTH AT 10,000 CYCLES (%)	MEAN RUT DEPTH AT 10,000 CYCLES (mm)
Mix 1 – HRA (1.8% PCC, 10 kg/m^3)	0.03	9.0	4.7
Mix 2 – PASS	0.01	2.7	1.3
Mix 3 - SMA	0.06	6.1	3.2
PD 6691	1.00	-	-

The results presented are the mean values of 2 samples to obtain a representative test result. Figure 4-26 shows that Mix 2 - PASS had the lowest mean rut depth after 10,000 cycles in comparison to the HRA and SMA asphalt mixtures. The rut profile as shown in Figure 4-27 presents the rut depth as a function of number of cycles which also shows that the PASS has superior resistance to permanent deformation with a mean rut depth after 10,000 cycles of 1.3 mm in comparison to the HRA and SMA mixtures with mean rut depth after 10,000 cycles of 4.7 mm and 3.2 mm respectively.

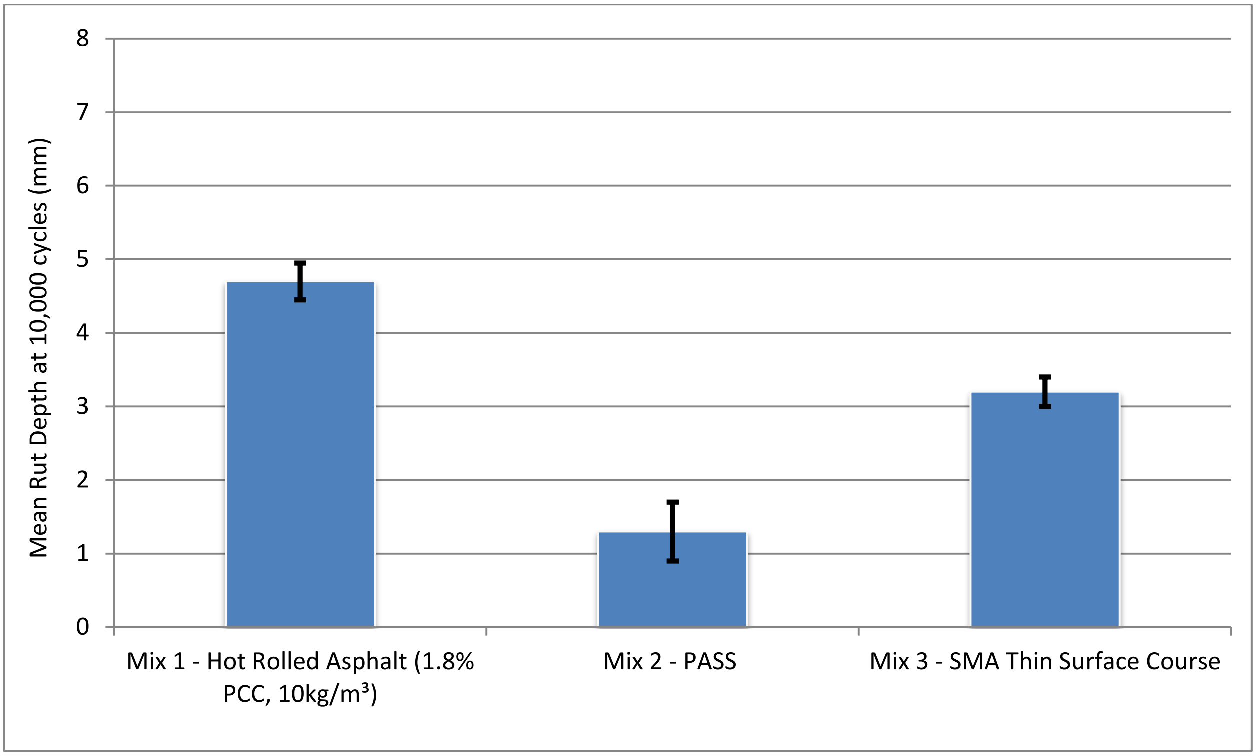


Figure 4-26: Mean Rut Depth after 10,000 cycles for the Asphalt Surfacing Materials

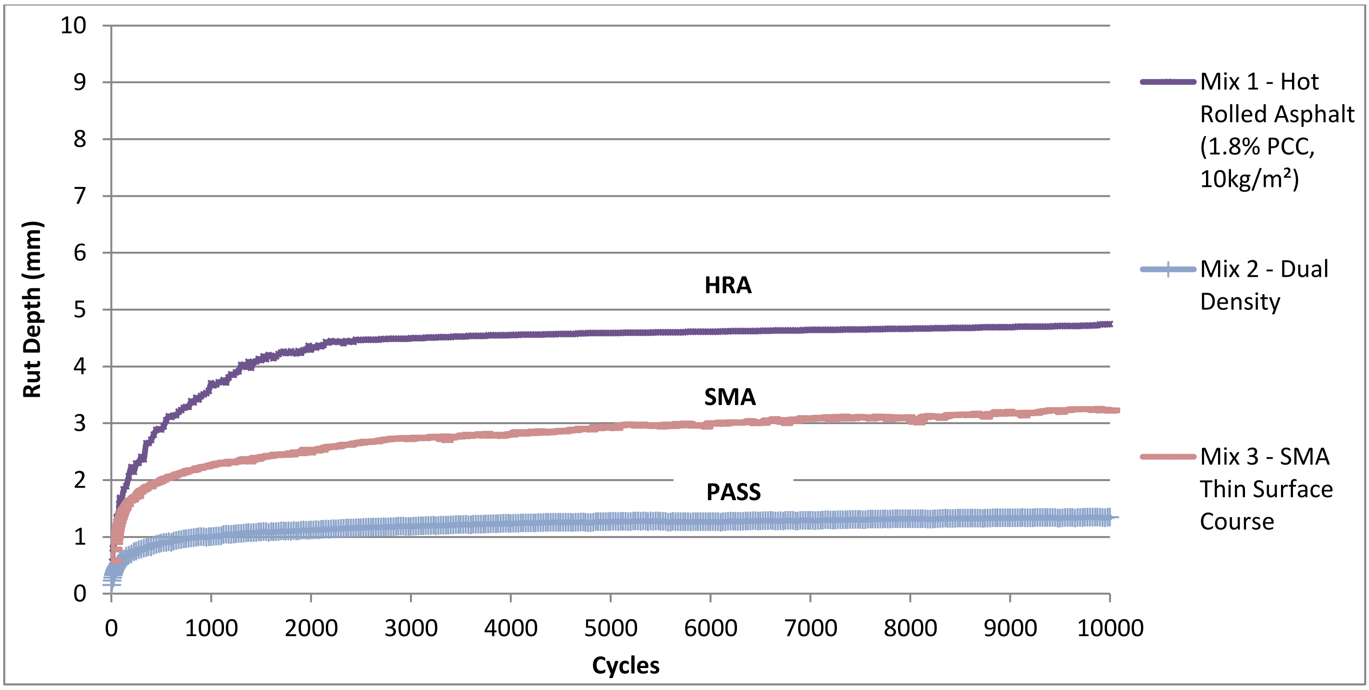
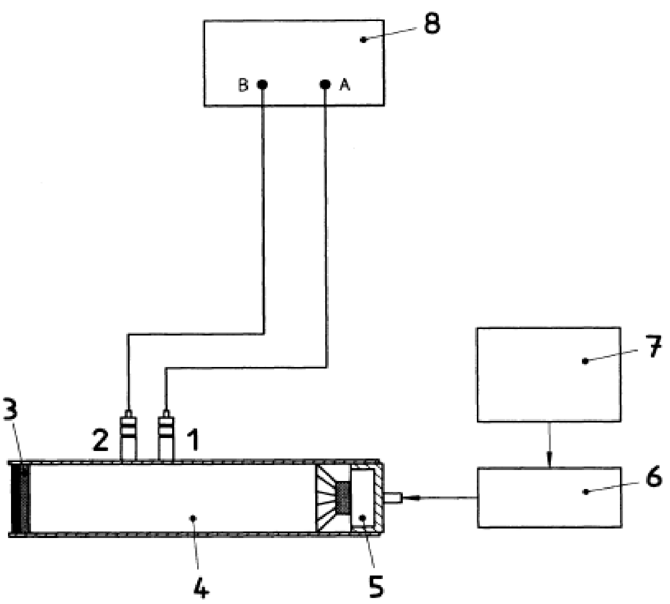


Figure 4-27: Rut Profile for the Asphalt Surfacing Materials

4.5.4 *Determination of Noise*

Sound absorption is an important road surface property when considering noise from vehicles. The test method proposed evaluated and qualified the sound absorption characteristics without damaging the surface of the asphalt mixtures. The test method for obtaining the sound absorption coefficient is detailed in EN ISO 13472-2 which is based on the propagation of test signal from the source to the asphalt surface and back to the receiver through an impedance tube. The test setup is shown below in Figure 4-28. The impedance tube covers an area of approximately 0.008 m^2 and a frequency range in one-third octave bands from 250 Hz to 1600 Hz under normal incidence conditions.



Key
1 Microphone A
2 Microphone B
3 Test specimen
4 Impedance tube
5 Sound source
6 Amplifier
7 Signal generator
8 Frequency analysis system

Figure 3 — Example of layout for test equipment

Figure 4-28: Impedance Tube Test Setup for obtaining Sound Absorption Properties

The test method is best suited for the determination of sound absorption coefficient of semi-dense to dense road surfaces and test tracks. It is also used to verify compliance of sound absorption coefficient on a road surface with design specifications. The test was conducted by Institute of Sound and Vibration (ISVR). ISO 13472-2 allows for the use of either two fixed microphones or a moving microphone as depicted in Figure 4-29. Seven different locations were used which improved the quality of the results.

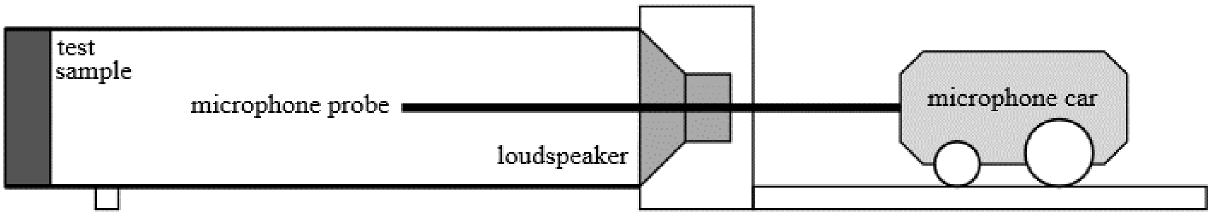


Figure 4-29: ISVR Impedance Tube Apparatus

Representative samples comprised of Hot Rolled Asphalt (HRA) at different chipping rates, Premium Asphalt Surfacing Systems (PASS) and the Thin Surface Course Stone Mastic Asphalt (SMA) were sent to ISVR for testing using the impedance tube to obtain their sound absorption coefficients. Representative samples sent to ISVR are shown in Figure 4-20 to Figure 4-22.

The measured absorption coefficients are plotted in 1/3rd Octave bands as shown in Figure 4-30 in accordance with ISO 13472-2.

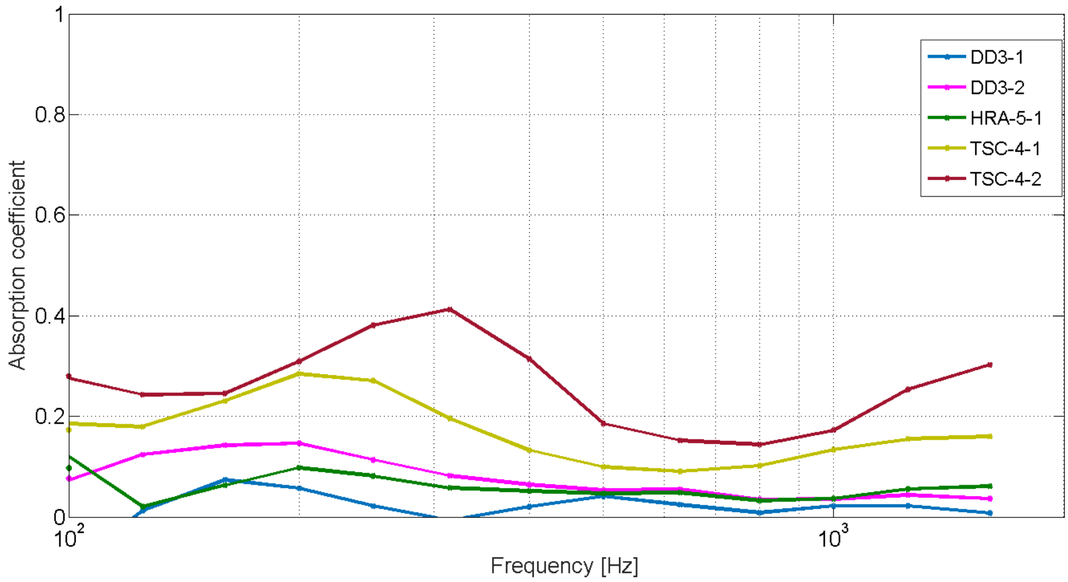


Figure 4-30: Absorption Coefficient - 1/3rd Octave Band Results

The SMA asphalt samples (TSC 4-1 and TSC 4-2) had the highest absorption coefficient which is most likely due to their higher void content in comparison to the HRA (HRA 5-1) and PASS (DD3-1 and DD3-2) samples. It should be noted however that the surface roughness of these samples will cause some scattering of the incident sound field which may result in an increase in the apparent absorption coefficient.

4.6 OVERALL SUMMARY

The agreed next generation asphalt mixtures for further development comprised of:

- **Polymer Modified Hot Rolled Asphalt at different Chipping Rates:** The use of 6/10 mm chippings at high application rates. The aim was to minimise noise through embedment of smaller size chippings. The HRA used in the project conformed to SHW Clause 943 (Performance Related Design Mixture) designated as HRA 35/14F surf PMB Class 2

- **Premium Asphalt Surfacing Systems (PASS):** PASS layer was the top idea amongst a range of other options. The PASS concept is based on a low voided, dense body of material with improved surface characteristics (low noise, good macrotexture).

In developing the next generation asphalt mixtures, it was established that the aggregate shape is a key parameter for the design of asphalt mixtures and even more importantly for the 6/10 mm chippings used in the HRA asphalt mixture. This project investigated aggregate shape characteristics using imaging techniques that included the VDG-40 Videograder and Enhanced University of Illinois Aggregate Image Analyser (E-UIAIA). The VDG-40 Videograder provided a practical means of ascertaining the aggregate shape, angularity and texture properties of the 6/10 mm chippings. The E-UIAIA provided an innovative and advanced tool that made use of three high-resolution cameras to capture three projections of the aggregate particle moving on a conveyor belt.

The mean texture depth and skid pendulum test value (PTV) in accordance with EN 13036-1 and EN 13036-4 respectively for the HRA and PASS had average values of 1.4 and 1.2 mm respectively while the skid resistance values of the HRA and PASS had average values of 53 and 60 respectively. The HRA mixtures were dense and the PCC properly embedded with no visible signs of double chipping. The PASS mixtures were dense with design voids in the 2-4% range. The PASS mixtures had the lowest mean rut depth after 10,000 cycles in comparison to the HRA. The rut profile showed that the PASS had superior resistance to permanent deformation with a mean rut depth after 10,000 cycles of 1.3 mm in comparison to the HRA with mean rut depth after 10,000 cycles of 4.7 mm.

The laboratory test results showed optimum performing mechanical and performance properties for the HRA and PASS asphalt mixtures. The proof of concept and laboratory bench scale research of these asphalt mixtures led to a pilot scale demonstration trial at an access road at Alrewas Quarry and Ready Mix Plant in Burton-on-Trent in Staffordshire. The demonstration trial is presented in detail in Chapter 5.

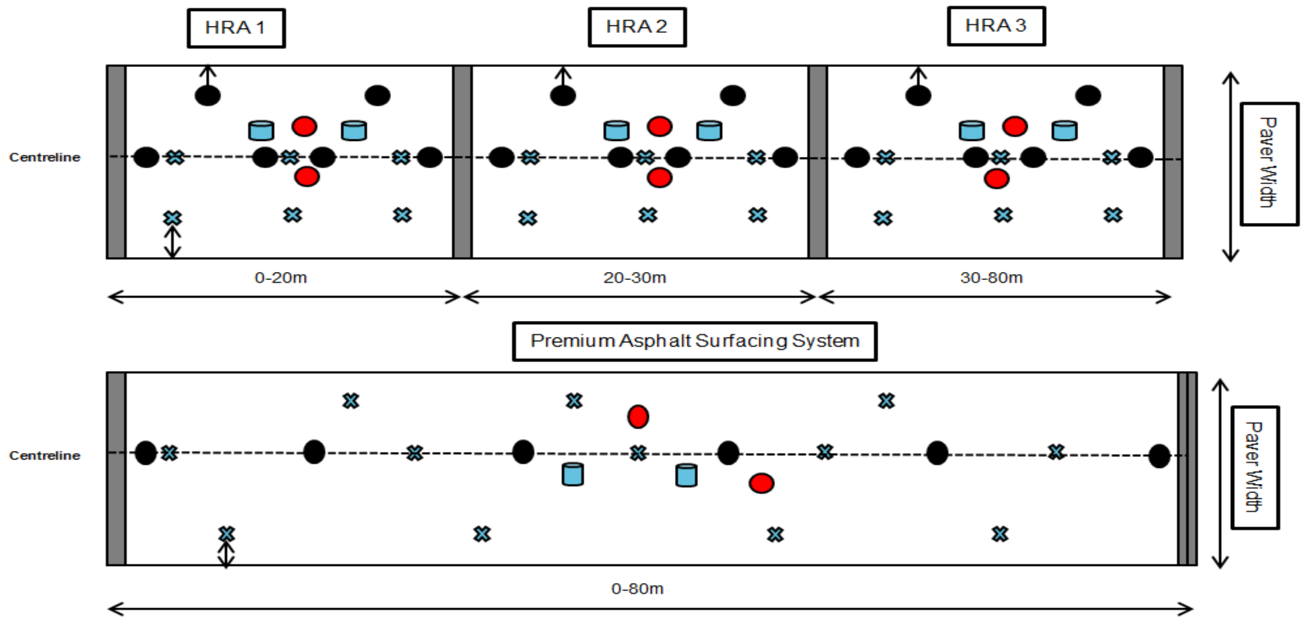
5 DEMONSTRATION TRIAL

5.1 INTRODUCTION

The major objectives of the trial was to validate the optimised laboratory mix designs as detailed in Section 4 and demonstrate constructability of the new asphalt surfacing materials that comprised:

- Mix 1: Polymer Modified HRA at different Chipping Rates.
- Mix 2: PASS.

The demonstration trial was conducted on 27th June 2016 at Tarmac's Alrewas Quarry, Croxall Road, Alrewas, Burton-on-Trent in Staffordshire, DE13 7LR with dry and sunny weather conditions with surface temperatures averaging 20°C. Figure 5-1 shows the test layout for the demonstration trial.



200mm dia. core – Wheel Tracking Tests (WTT)	150mm dia. core – Mixture Volumetrics (Air Voids)
100mm dia. core – Impedance Tube Tests	200mm dia. core – Pressure Mapping using XSensor Technology
Buffer/Transition Zone	Cores to be taken100mm from edges

Figure 5-1: Test Layout for the Demonstration Trial

Mix 1: HRA at different Chipping Rates

The HRA material complied with Clause 943. However, it must be noted that the objective of using this material involved making use of 6/10 mm chippings and to assess embedment of the chippings evaluating the resulting macrotexture. Table 5-1 presents the material composition and limits for Mix 1 designated as HRA 35/14 F surf 40/100-65 at 7.7% binder content.

Table 5-1: Aggregate Gradation for Mix 1 - HRA

SIEVE (mm)	SPECIFICATION (% PASSING)	OBTAINED RESULTS FROM TRIAL (% PASSING)
20	100	100
14	95-100	99
10	62-81	73
2	56-66	61
0.500	44-63	58
0.250	16-46	30
0.063	6-10	10

The 6/10 mm chippings were pre-coated using 40/60 paving grade bitumen at 1.8% binder content in accordance with SHW Clause 915. Figure 5-2 shows the appearance of PCC used in the trial which was well coated but remained relatively "loose".

Figure 5-2: 1.8% 6/10 mm PCC

The 6/10 mm chippings were applied to the HRA at 3 spread rates, specifically: 3 kg/m^2, 5.5 kg/m^2 and 6 kg/m^2 as detailed in the layout shown in Figure 5-1. Attempts to increase the chipping rate above 6 kg/m^2 were abandoned due to evident double chipping. The finished surface of the HRA is shown in Figure 5-5.

Mix 2: PASS

Table 5-2 presents the material composition and limits for Mix 2 used in the trial. The PMB used was classified as 45/80-60 at 4.9% binder content. The finished surface of the PASS is shown in Figure 5-5.

Table 5-2: Material Composition and Limits for Mix 2 - PASS

SIEVE (mm)	SPECIFICATION (% PASSING)	OBTAINED RESULTS FROM TRIAL (% PASSING)
14	100	100
10	92-100	94
6.3	44-56	49
4	34-46	42
2	27-39	33
1	-	24
0.5	-	18
0.250	16-24	15
0.125	-	13
0.063	7-11	10
Binder	**5.4**	**4.9**

Notes from Contractor

1. Both materials (HRA and PASS) were reported as being relatively easy to batch with no problems encountered at the asphalt plants. This observation confirmed the findings from asphalt workability assessments (Section 4.4.1) that both materials are expected to have comparable workability and that there is no foreseeable workability related issue with the installation of PASS in road construction. Note: Mix 1 and 2 were produced at different asphalt plants due to the 2 different polymer modified binders used for the asphalt mixtures.
2. The chipper used for applying PCC on the HRA sections was modified with a new 10 mm scroll to replace the existing 20 mm scroll with adjustments made to the flow gates to reduce the gap to the scroll. The modified chipper is shown in Figure 5-3.
3. A three-pin dead weight roller was used as a lead roller for the HRA as this is standard practice with HRA and chippings.

4. This was followed by the use of a BOMAG 130 equivalent roller, which was used as a polishing roller. The same rollers were used to compact the PASS. Figure 5-4 shows the paving operation in progress.
5. Three rates of spread were used for the PCC. HRA 1, 2 and 3 as shown in Figure 5-1 represented 3 kg/m^2, 5.5 kg/m^2 and 6 kg/m^2 respectively. The initial rate was chosen to give a 70% shoulder to shoulder spread rate and this was increased to give the maximum possible rate before double chipping occurred. A very short section at 6.5 kg/m^2 resulted in double chipping and loss of chips and was therefore omitted from subsequent assessment.
6. The chippings process achieved a reasonably uniform spread. Although, it may be possible to improve uniformity with further refinement of the chipper.
7. The PASS laying characteristics were very similar to those of a thin surface course. The relatively finer grading meant that a good dense joint to the adjoining mat was achieved on site.

Figure 5-3: Modified Chipper

Figure 5-4: Paving Operation for the Demonstration Trial

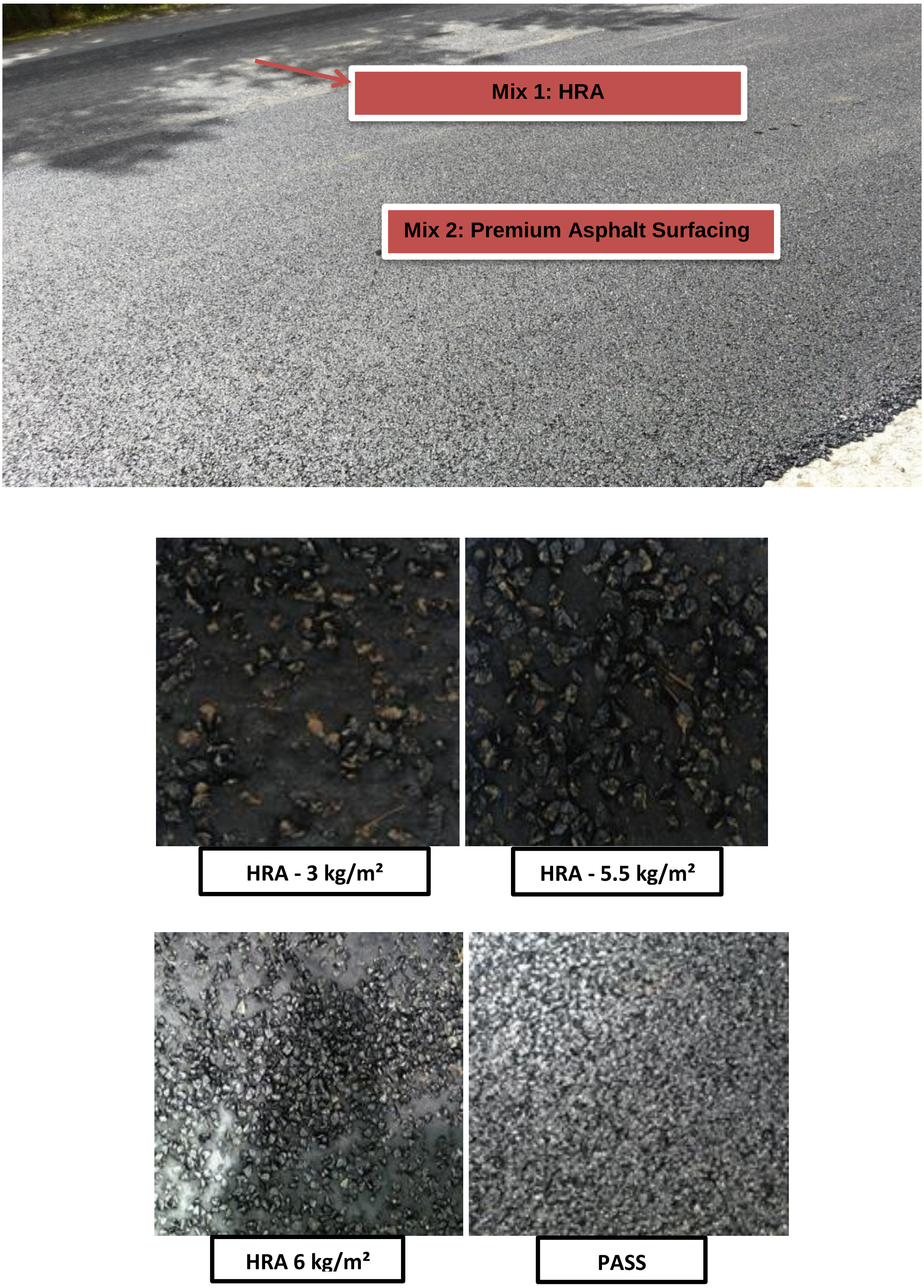


Figure 5-5: Finished Surfaces for the Asphalt Mixtures

5.2 TEST RESULTS

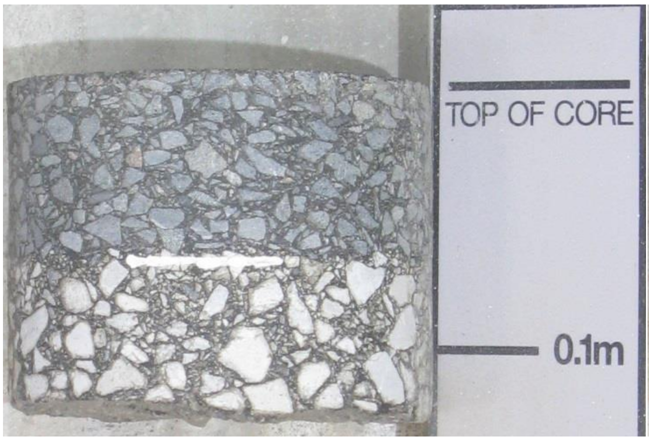
This section presents test results from the demonstration trial. Table 5-3 presents the test matrix for this stage of the project.

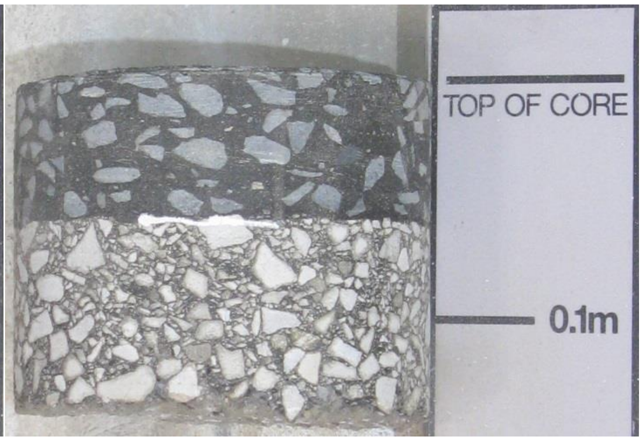
Table 5-3: Test Matrix - Demonstration Trial

SECTION	TESTS
5.2.1	Visual assessments.
5.2.2	Mixture volumetrics and functional properties.
5.2.3	Resistance to deformation.
5.2.4	Compositional Analysis.
5.2.5	Resistance to moisture damage.
5.2.6	Determination of noise.
5.2.7	Pressure Mapping.

5.2.1 *Visual Assessments of Samples*

Figure 5-6 shows the typical cross section of the PASS and HRA samples obtained from the demonstration trial. The PASS (layer 1) appeared to be dense with a high coarse aggregate content and had good interlocking properties. The HRA (layer 1) showed a high proportion of sand in the mix with the coarse stones floating in the asphalt providing a dense impervious layer. These visual conditions suggest that the materials were well compacted.





(A) **(B)**

Figure 5-6: Cross Section of (A) PASS and (B) HRA asphalt mixtures

5.2.2 *Mixture Volumetrics and Functional Properties*

The air void contents of the asphalt mixtures are detailed in Figure 5-7 with the mean results shown from an average of six samples per mixture type. The standard distribution is shown as a ± after the mean value in the chart. It should be noted that the HRA samples were tested on unchipped samples. The HRA mixtures had air void contents <2% while PASS mixtures had air voids within specified design limits of 2-4%.

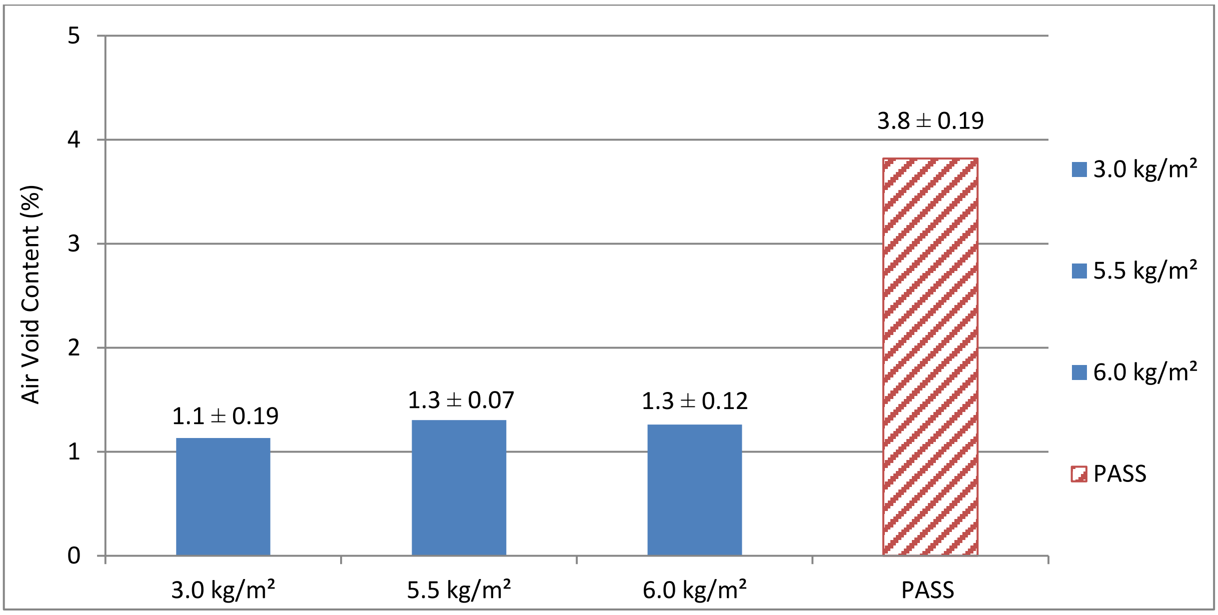


Figure 5-7: Air Void Content of Samples from Demonstration Trial

The pavement surface macrotexture in accordance with EN 13036-1 was obtained on site following installation of the asphalt surfacing materials (Figure 5-8) representing an average of ten macrotexture measurements on site and from cores extracted from site (Figure 5-9) representing an average of six measurements on 200 mm cores from the demonstration trial site. The macrotexture test results conducted on site and on core samples obtained from the site as shown in Figure 5-8 and Figure 5-9 are in agreement with very similar test results.

The macrotexture test results for the HRA samples could be considered as being outside (lower than) those specified in SHW Clause 921; specifically, this trial was aiming for macrotexture of not less than 1.2 mm. This factor could be attributed to the fact that smaller chippings (6/10 mm) were used in comparison to the conventional use of 14/20 mm chippings. This is being reviewed with the view to evaluating steps to optimising and improving the macrotexture for the HRA surfacing whilst realising that the smaller chipping size could be the limiting factor.

The surface macrotexture for the PASS was also low but it was agreed that there is still scope for improving the surface finish. This could be further optimised by adjusting the combined aggregate gradation for the PASS mixtures.

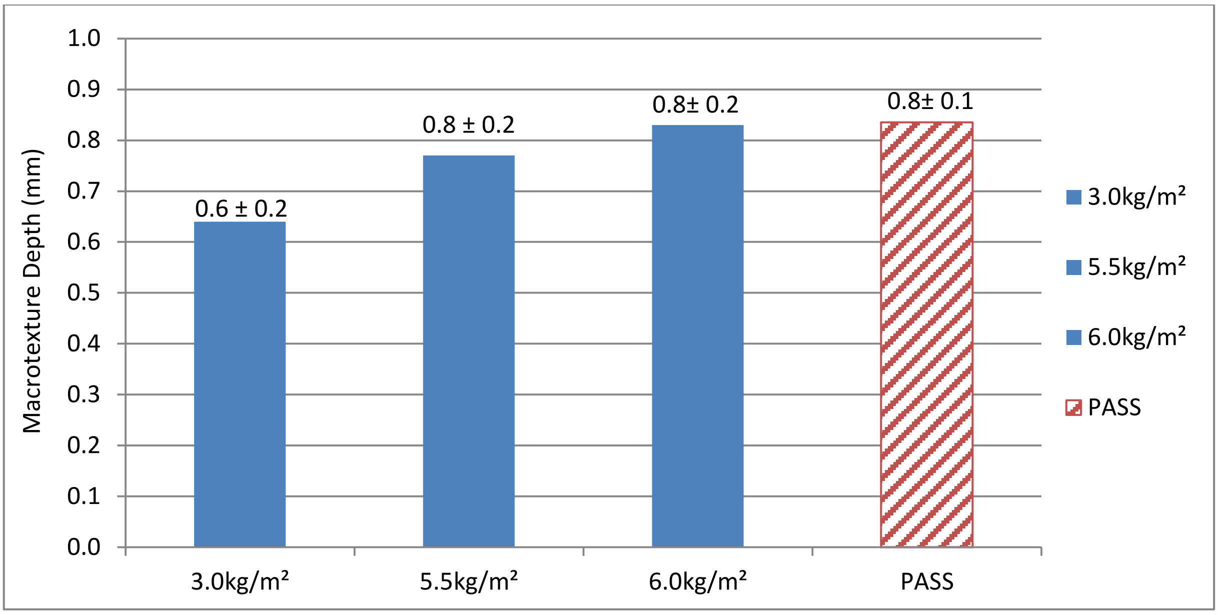


Figure 5-8: Pavement Surface Macrotexture Depth – On Site

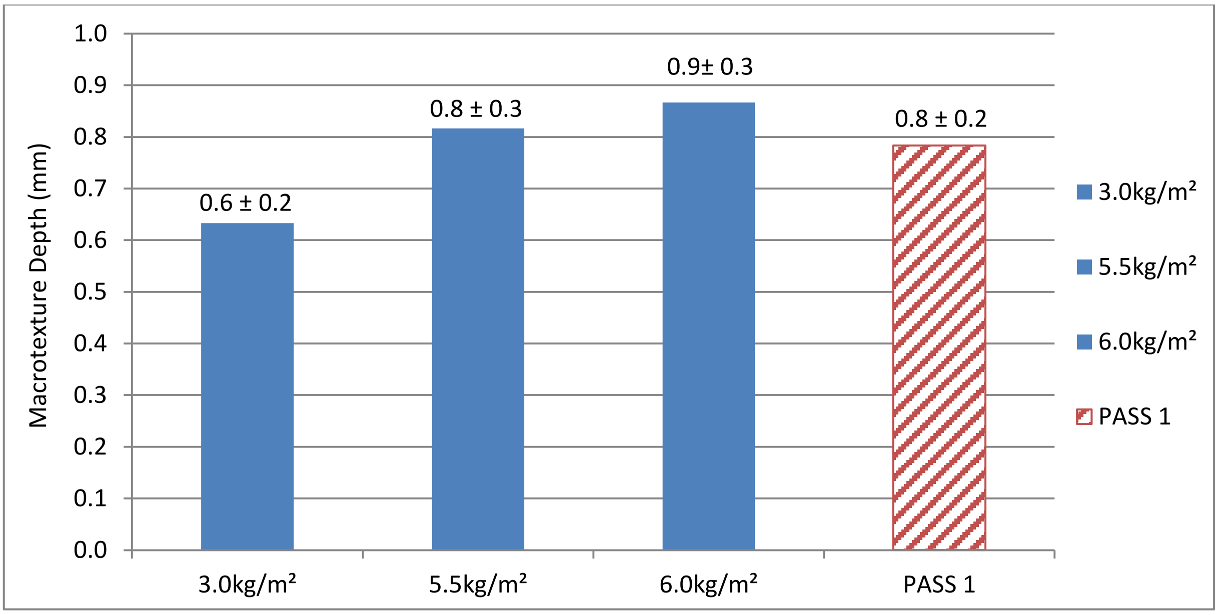


Figure 5-9: Pavement Surface Macrotexture Depth – On Cores from Site

The skid pendulum test value (PTV) was obtained in accordance with EN 13036-4. The results are detailed in Figure 5-10. The results represent a mean of six measurements on 200 mm cores from the demonstration trial site. The results show encouraging PTV values (exceeding 70) for the asphalt mixtures which are higher than those obtained from the laboratory manufactured samples.

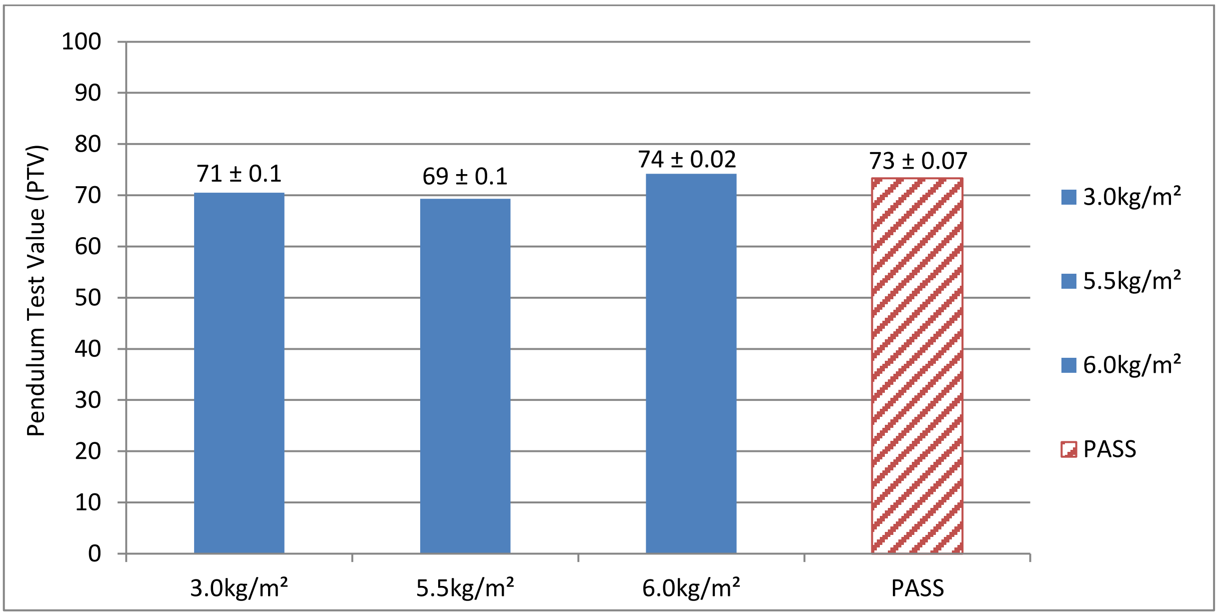


Figure 5-10: Skid Pendulum Test Value – On Cores from Site

5.2.3 *Resistance to Deformation Measured by using Wheel Track Testing*

Resistance to deformation was measured by using the Wheel Tracking Tests (WTT) in accordance with EN 12697-22 using the small device to 10,000 cycles. The WTT was conducted in two independent UKAS accredited laboratories for comparison. The test results are presented in this section. The results presented are the mean values of 3 samples per laboratory in order to obtain representative test results. Table 5-4 presents the WTT results and Figure 5-11 shows the typical rut profile for the PASS core samples obtained from the demonstration trial site. PD 6691 states that the wheel tracking slope in air should be less than 1 mm/1000 cycles. As seen in Table 5-4, the PASS asphalt mixture performance passed this satisfactorily. This trend is reflected in Figure 5-11 with rut depth after 10,000 cycles less than 5 mm for the PASS core samples reported by both laboratories (A and B) which were comparable to those designed and tested in AECOM laboratories designated as ALDT. A typical appearance of a PASS sample after WTT is shown in Figure 5-12.

Table 5-4: WTT Results – PASS (Procedure B)

Sample		Wheel Tracking Slope in Air (mm/10³ cycles)	Proportional Rut Depth at 10,000 cycles (%)	Mean Rut Depth at 10,000 cycles (mm)
LAB A	PASS 1	0.14	5.28	3.50
	PASS 2	0.08	5.84	3.05
	PASS 3	0.09	3.57	2.14
LAB B	PASS 1	0.03	4.60	2.10
	PASS 2	0.04	3.70	1.90
	PASS 3	0.04	4.80	2.30
PD 6691		1.00	-	-

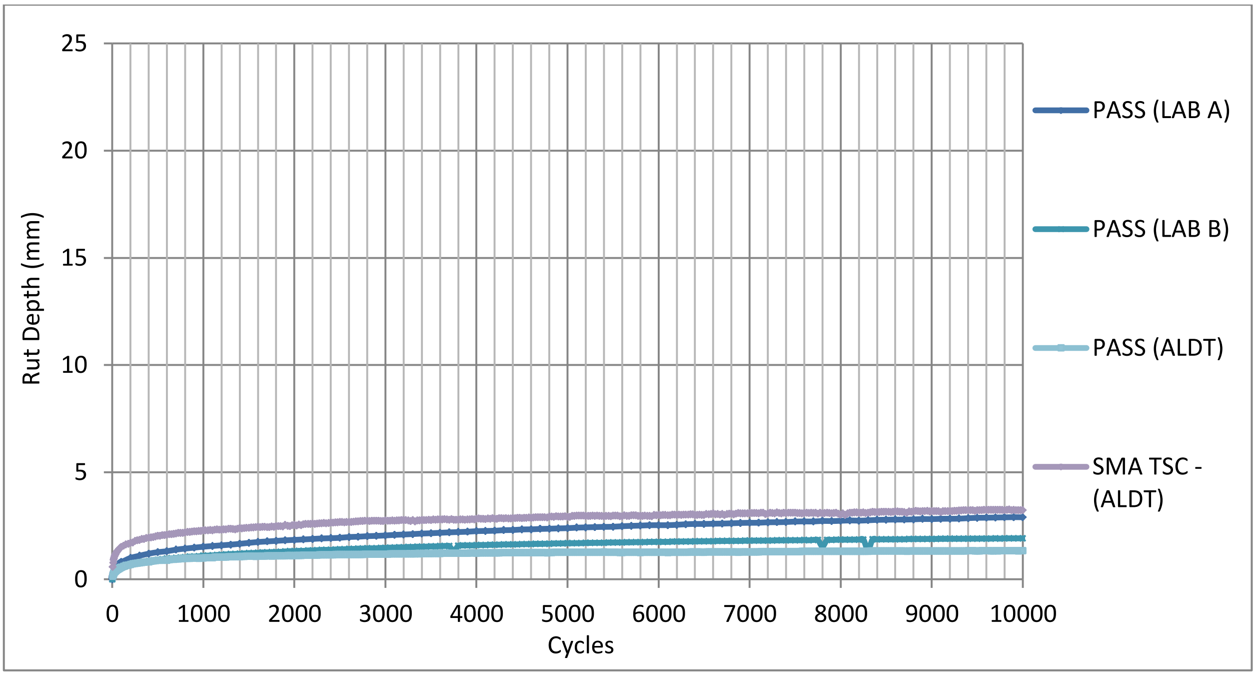


Figure 5-11: Rut Profile for PASS Mixtures

Figure 5-12: PASS Sample after WTT

Table 5-5 presents the WTT results and Figure 5-13 shows the rut profile for the HRA core samples at different chipping rates obtained from the demonstration trial site. PD 6691 states that the mean rut depth at 1,000 cycles should not exceed 7 mm for HRA samples to be applied on very heavily stressed sites requiring very high rut resistance.

Table 5-5: WTT Results – HRA Samples (Procedure A)

AECOM Sample Identifier			Wheel Tracking Rate in Air (µm/cycles)	Mean Rut Depth at 1,000 cycles (mm)	Mean Rut Depth at 10,000 cycles (mm)
LAB A	HRA DTB - 1 (3 kg/m²)	Sample 1	8.48	16.16	Samples reached 20 mm rut depth < 2,100 Cycles
		Sample 2	9.17	17.31	
		Sample 3	8.53	15.56	
	HRA DTB - 2 (5.5 kg/m²)	Sample 1	8.77	14.71	
		Sample 2	8.13	15.73	
		Sample 3	7.53	19.99	
	HRA DTB - 3 (6.0 kg/m²)	Sample 1	5.76	11.65	
		Sample 2	7.92	14.53	
		Sample 3	7.90	15.93	
LAB B	HRA DTB - 1 (3 kg/m²)	Sample 1	6.69	7.16	Samples reached 20 mm rut depth < 7,500 Cycles
		Sample 2	5.70	6.39	
		Sample 3	4.73	5.95	
	HRA DTB - 2 (5.5 kg/m²)	Sample 1	8.33	8.52	
		Sample 2	8.86	8.99	
		Sample 3	7.83	8.78	
	HRA DTB - 3 (6.0 kg/m²)	Sample 1	7.60	7.45	
		Sample 2	7.06	7.57	
		Sample 3	5.36	6.68	
PD 6691			15	7	-

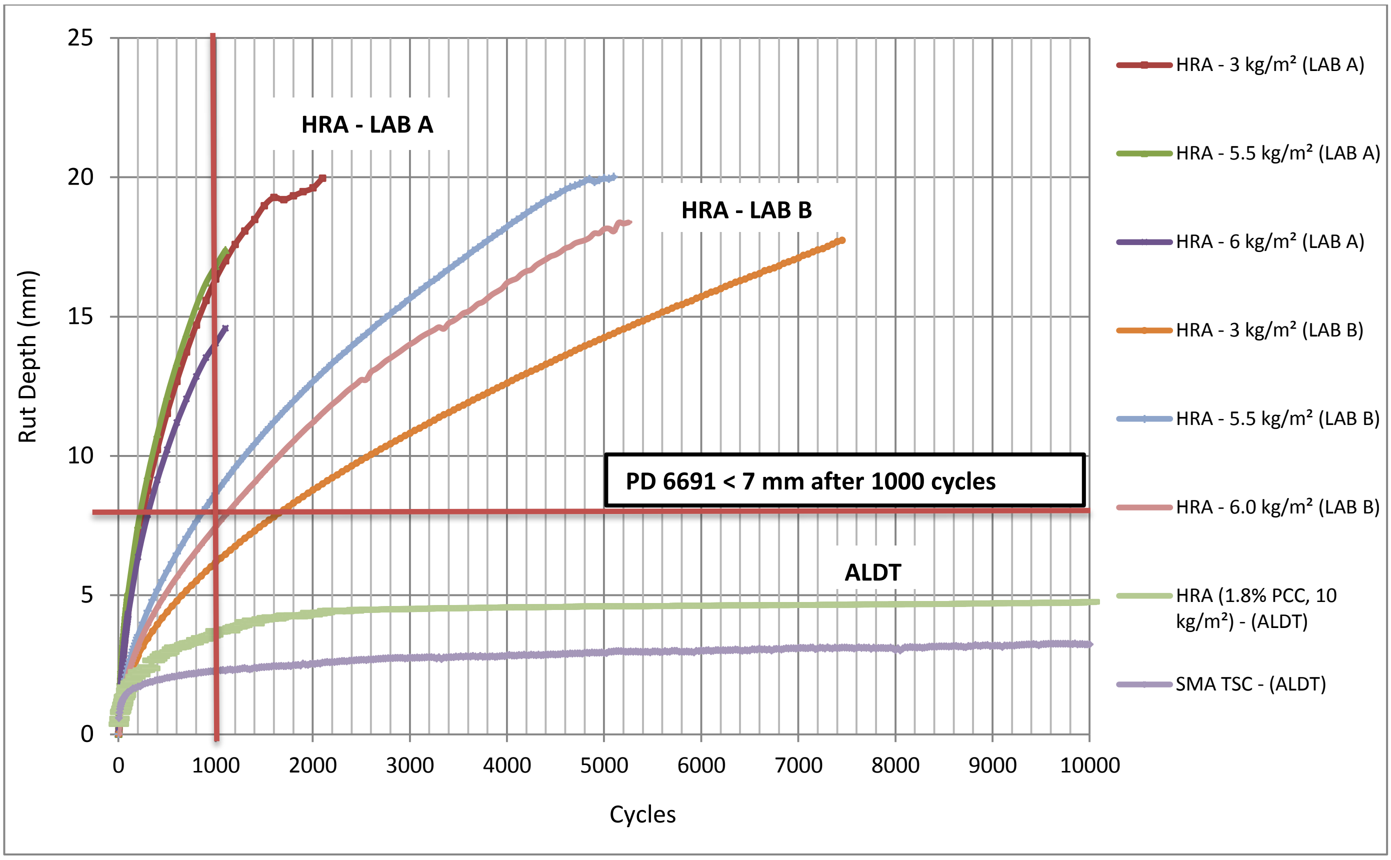


Figure 5-13: Rut Profile for HRA Mixtures

As detailed in Table 5-5, the HRA asphalt mixtures at different chipping rates did not meet this performance requirement with the HRA samples tested in LAB A on average having rut depths exceeding 15 mm after 1,000 cycles. This trend is reflected in Figure 5-13 with HRA samples from LAB A reaching a rut depth of 20 mm or completely failing after less than 2,100 cycles and LAB B samples reaching a rut depth of 20 mm before 10,000 cycles. This was in stark contrast to the HRA samples designed and tested in AECOM laboratory (ALDT). Figure 5-14 typically shows the HRA materials following WTT.

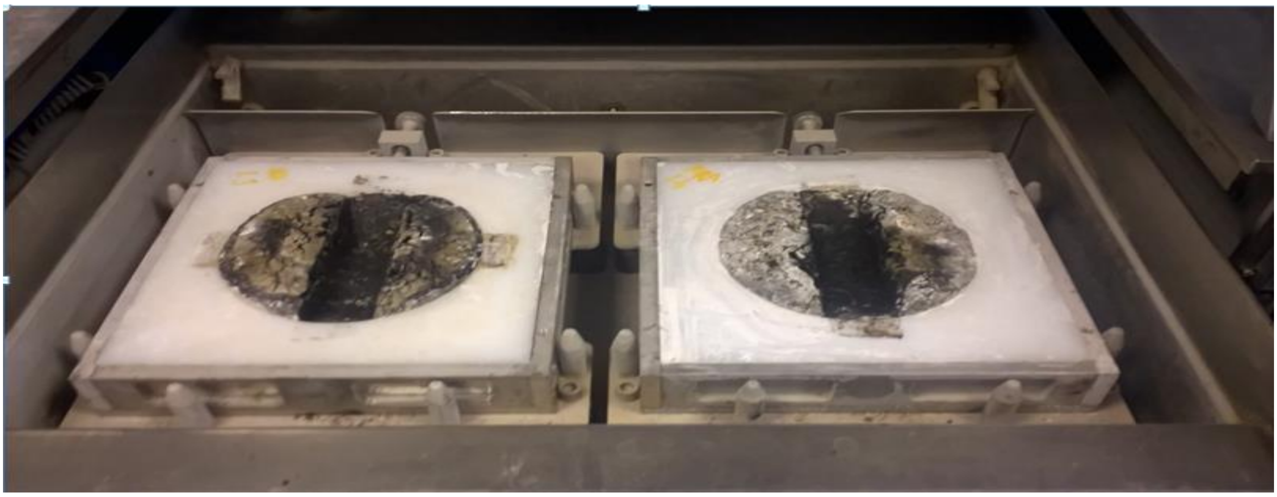


Figure 5-14: HRA Samples after WTT

It should be noted that the Clause 943 HRA material did not perform as expected on the demonstration trial. Whilst it is beneficial to identify the cause of the poor WTT results, it must be noted that the Clause 943 HRA material has a track record of performing well in previous laboratory testing and on site. As part of this project, the main objective was to evaluate the use of 6/10 mm chippings and how the resulting embedment of the chippings may affect the macrotexture, skid resistance and noise characteristics. These properties are respectively presented and discussed in sections 5.2.2 and 5.2.6 of this report.

5.2.4 *Composition Analysis*

Composition analysis was conducted in accordance with EN 12697-1 Annex D and EN 12697-39. The test results are presented in Table 5-6.

Table 5-6: Binder Compositional Analysis

Sample Type	Binder	Binder by Difference BS EN 12697-1 Annex D (%)	Binder by Ignition Method BS EN 12697-39 (%)	Design Specification (%)
HRA Sample 1	**PMB 40/100-65 (SP = 60.4°C)***	7.7	7.5	7.1 – 8.3
HRA Sample 2		7.7	7.7	7.1 – 8.3
PASS Sample 1	**PMB 45/80-60 (SP = 58.2°C)***	4.5	4.9	4.9 – 5.4
PASS Sample 2		4.9	5.0	4.9 – 5.4
PASS Sample 3		5.5	4.6	4.9 – 5.4
***Tested on Site Recovered Samples**				

Figure 5-15 and Figure 5-16 shows typical aggregate gradations of loose bulk samples obtained from the asphalt plants for the HRA materials. Composition analysis of the PASS samples was conducted only in accordance with EN 12697-1 Annex D.

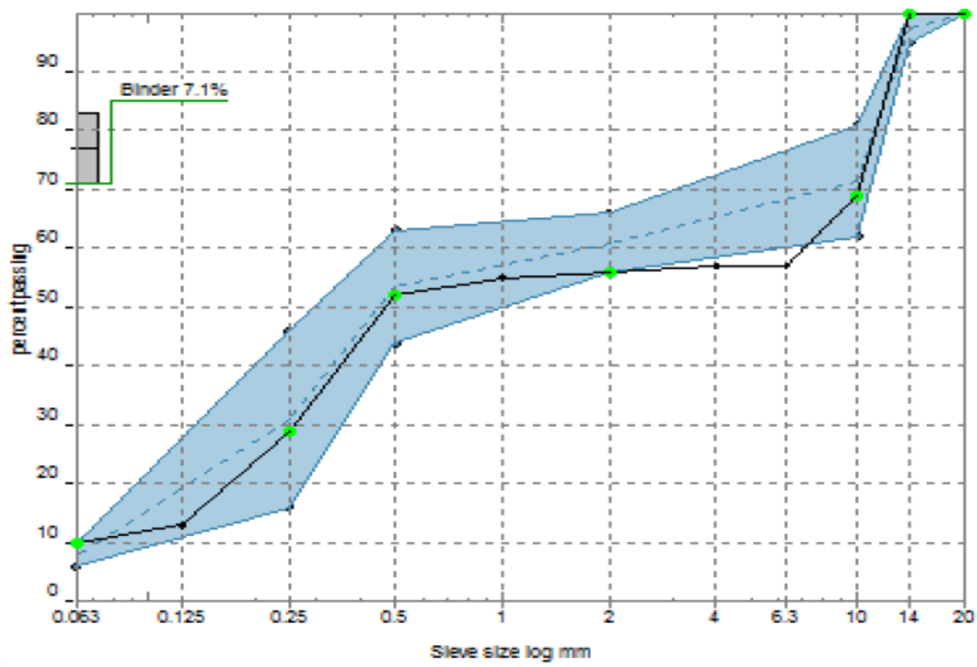


Figure 5-15: Typical Aggregate Gradation (HRA) – EN 12697-1: Annex D

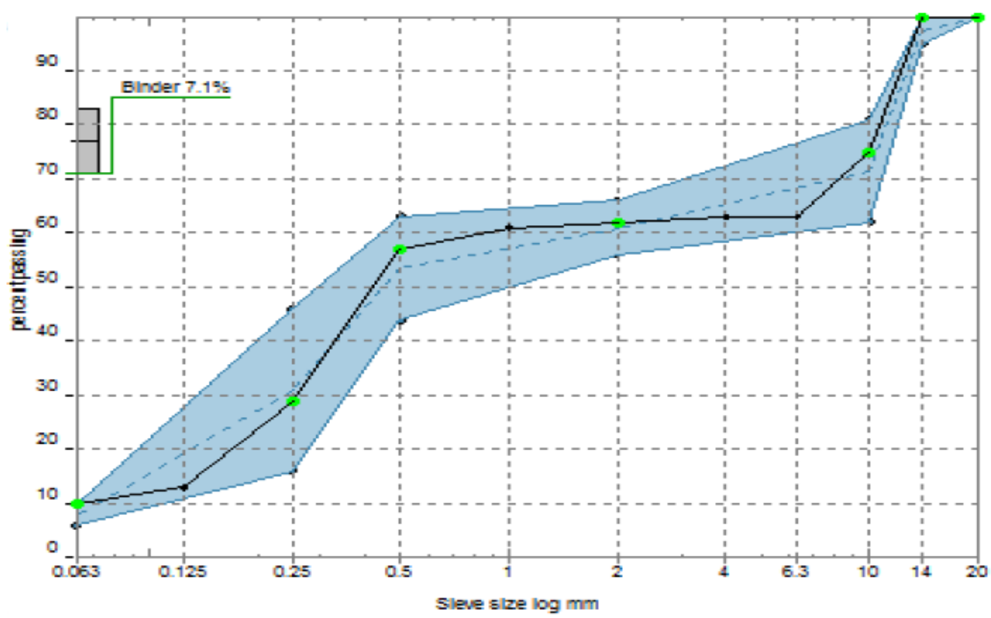


Figure 5-16: Typical Aggregate Gradation (HRA) – EN 12697-39: Ignition Method

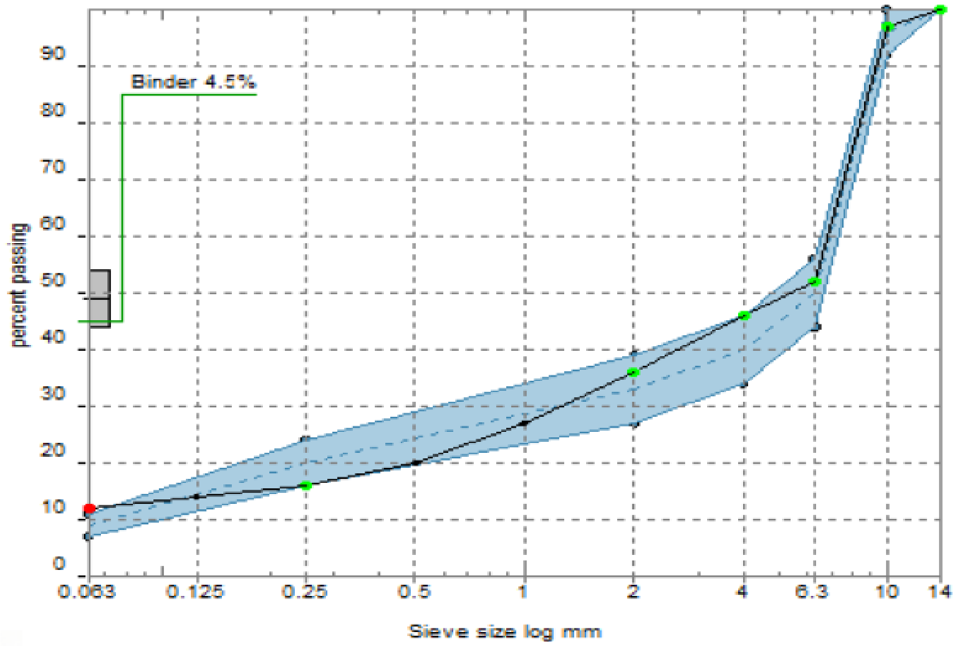


Figure 5-17: Typical Aggregate Gradation (PASS) -– EN 12697-1: Annex D

5.2.5 *Resistance to Moisture Damage*

Resistance to moisture damage was obtained by ascertaining the water sensitivity of the next generation asphalt mixtures in accordance with EN 12697-12. The test results are shown in Figure 5-18.

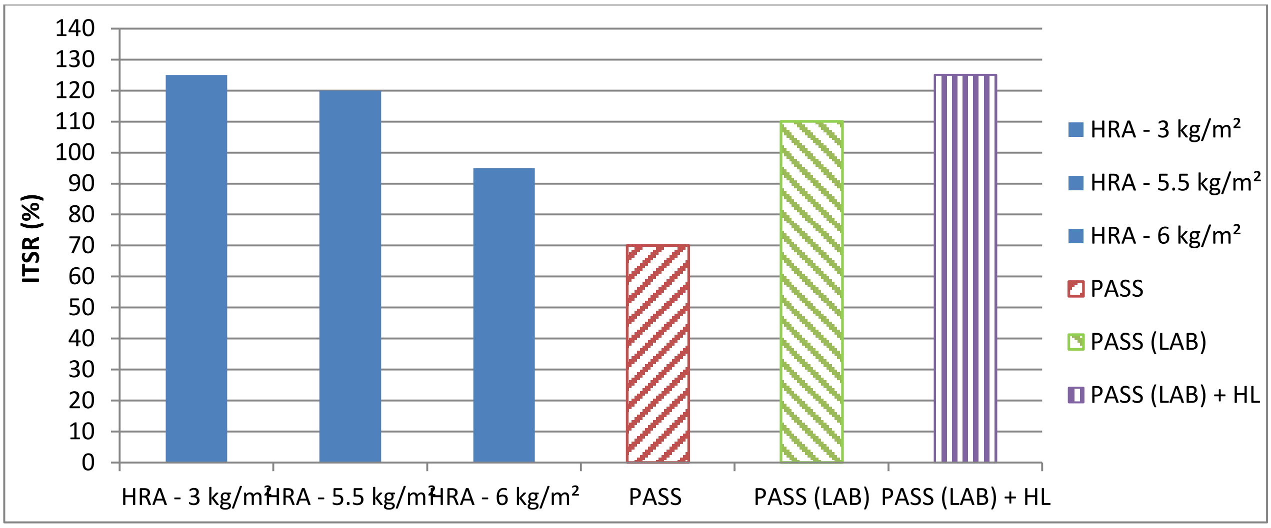


Figure 5-18: Determination of Water Sensitivity - ITSR

5.2.6 *Determination of Noise*

Measurements of the absorption coefficient on 100 mm diameter core samples from the demonstration trial were carried out in accordance with EN ISO 10534-1: 2001. The test set-up is shown in Figure 4-29 which involves installing the 100 mm diameter core samples in the impedance tube where a broadband normal incident sound field is generated using a white noise signal to the loudspeaker.

Figure 5-19 presents absorption coefficients for the samples obtained from the demonstration trial. Two sets of measurements were carried out for each mixture type. The absorption coefficient of a surface is by definition the ratio between the amplitude of the reflected and incident waves. A high absorption coefficient will be helpful in reducing vehicle noise by absorbing both tyre noise and engine noise. The results show small variations between the various samples at frequencies above 250 Hz. At frequencies below 250 Hz, the difference between samples is visible but not significant. Therefore, it is possible that the values at low frequencies may be partly a function of the fit of the samples in the tube. It is recommended that for the road trials, the Statistical Pass-By method in accordance with ISO 11819-1 or the Close Proximity Method in accordance with ISO 11819-2 should be carried out to ascertain the noise characteristics of the next generation asphalt surfacing materials.

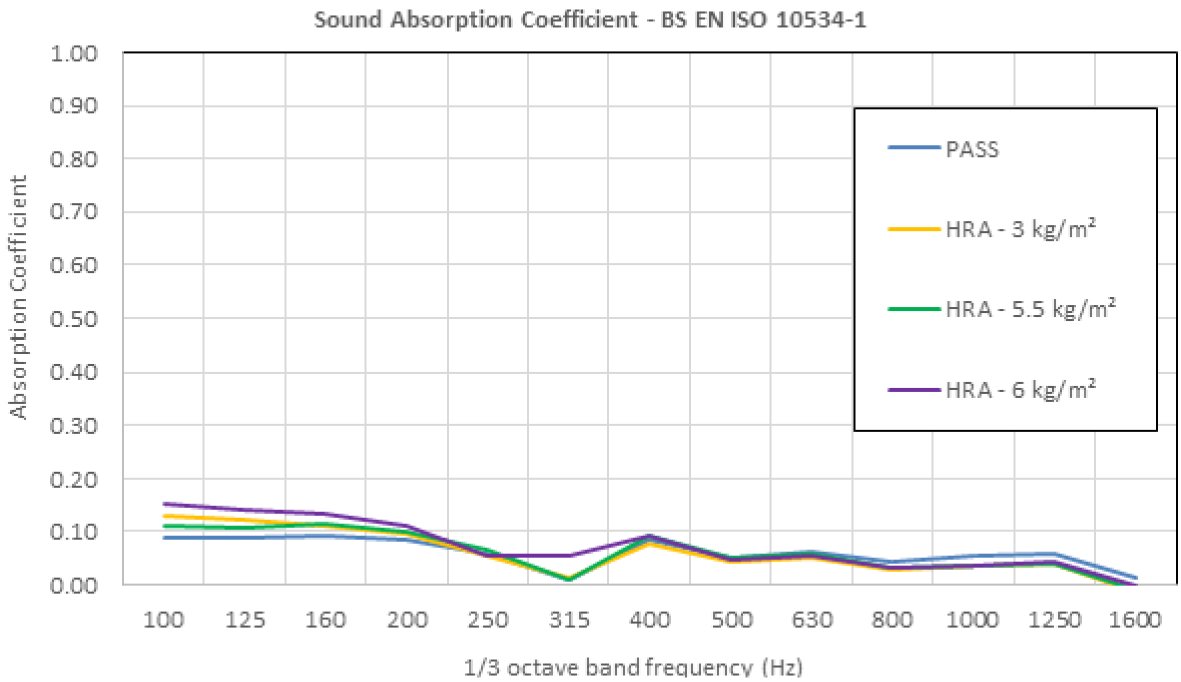


Figure 5-19: Sound Absorption Coefficient

Figure 5-20 shows a selection of samples used for the impedance tube test. In summary, the impedance tube test could not adequately differentiate between the different asphalt mixture types.

PASS

HRA – 3 kg/m^2

HRA – 5.5 kg/m^2

HRA – 6 kg/m^2

Figure 5-20: Photos of the Test Samples for the Impedance Tube Test

5.2.7 *Comparison of Surface Macrotexture using the XSENSOR Pressure Mapping System*

Knowledge of the contact patch between a tyre and the road surface is essential to improve understanding of surfacing properties. This section investigates the relationship between contact area of the asphalt surfacing materials and tyre inflation pressure. The methods used were developed at Ulster University which comprised of the Contact Patch test methods. The contact patch method involved tracking the surface of each core with an ASTM friction tyre as used in the GripTester. Contact pressures were measured using a pressure pad. 200 mm diameter cores were sent to Ulster University for the tests to be conducted. The results using both methods are summarised in this section. A comparative analysis is conducted with hot rolled asphalt with 20 mm pre-coated chippings.

Table 5-7 details the core references and description of samples sent for testing.

Table 5-7: Core Description for Pressure Mapping Samples

Core Reference	Description	Chipping Distribution (Visual)
CR 0961 1-7	HRA – 3 kg/m^2	Light to medium chipping with patchy distribution
CR 0961 1-8L1		Light to medium chipping patchy distribution
CR 0961 2-7L1	HRA – 5.5 kg/m^2	Heavy chipping with good distribution
CR 0961 2-8L1		Heavy chipping with good distribution
CR 0961 3-7	HRA – 6 kg/m^2	Heavy chipping with good distribution
CR 0961 3-8		Light to medium chipping with patchy distribution
CR 0961 DD7 1-1	PASS	Good texture distribution
CR 0961 DD8 L1		Good texture distribution, some fatting up of surface was visible

<u>Contact Patch Test Method</u>

The contact patch test method comprises of three main elements that include:

I. An ASTM friction tyre as used in the GripTester.
II. Z-axis pressure mapping system.
III. Device that measures static or dynamic interface properties.

I. The ASTM Friction Tyre

The tyre used is an ASTM E 1844 smooth surfaced pneumatic friction tyre. This tyre is fitted to the GripTester (BS 7941-2). A longitudinal friction device in the form of 3 wheel towed trailer that measures skid resistance by simulating the interaction of a fixed slip tyre with the road/runway surface in a longitudinal direction. This friction device is widely used to measure skid resistance of highway and runway surface materials around the world.

II. Z-axis Pressure Mapping System

The interface conditions between the ASTM friction tyre and the core surface is measured using a z-axis pressure mapping system manufactured by XSensor. This consists of a flexible mat with 2.54 x 2.54 mm resolution and 16,384 sensing elements. The pressure mapping system comprises two grids with parallel conductive strips separated by a thin compressible elastomer. A capacitive node is formed where two conductive strips intersect. If pressure is applied to a node the elastomer will compress and the conductive strips will be forced closer together causing capacitance at the node to increase. The change in capacitance relates to pressure distribution through a process of calibration. The system is sequenced through each line on the input and output sides of the sensor matrix with the use of multiplexing circuitry which allows for the measurement of the capacitance and thus the pressure distribution of the whole sensor matrix. Proprietary XSensor software developed at Ulster University records and displays real-time data from the pressure mapping system. Data is recorded in frames, whereby one cycle of the sensor reading is carried out for every capacitive node in the sensor matrix. The frame rate of the sensor system depends on the sensor pad resolution and size. When data recording is complete it can be displayed in 2D or 3D format as a continuous model or as individual frames. The data may be exported in CSV format for further analysis purposes or as modelling inputs. The pressure mapping system has a calibrated pressure range of 10 psi to 200 psi (68.9 to 1378 kPa) with a data acquisition rate of up to 16 frames per second during dynamic testing.

III. Device that measures static or dynamic interface properties

A Wessex small wheel tracking device was modified to allow static or dynamic measurement of ASTM friction tyre/test specimen interface properties. The small wheel tracking device is based on the principle of a test specimen moving in a controlled dynamic mode under a loaded tyre. This device was modified to allow the pressure mapping system to be placed under the loaded tyre. The ASTM friction tyre replaces the solid tyre of the small wheel tracking device. The lever arm of the small wheel tracking device was modified to accommodate the extra width of the ASTM friction tyre. Load on the tyre can be varied using weights applied to the end of the lever arm.

The flexible pressure mapping system is placed on top of the test specimen for tyre/test specimen interface measurements. This allows static interface measurements to be taken. Dynamic interface measurements are obtained by pushing the test specimen slowly under the loaded friction tyre whilst continuously recording interface data.

Testing of Cores using the Contact Patch Test Method

The cores were washed to remove dirt associated with coring. The surface of each core was visually assessed and a representative orientation selected for contact testing with the ASTM friction tyre. The total vertical static load under the ASTM friction measuring tyre was 22.5 kg. This is similar to the static loading conditions of the ASTM friction tyre when mounted to a GripTester.

The testing orientation was marked on each core surface as shown by the white dots in the photographs of each core in this report. Each core was mounted on the modified tracker. Approximately 70 individual frames were recorded as each core was pushed slowly under the ASTM friction tyre. The individual frames were merged to create a continuous footprint showing variation in contact area and pressure distributions in relation to the underlying macrotexture of the core surface.

Appendix 1 shows a representative photograph of each core surface and a series of merged contact patches at different minimum threshold values. The pressure pad software can illustrate how contact pressure and its distribution can change as a result. This helps to better understand the relationships between factors such as macrotexture, asphalt type, particle size, contact area and contact pressure. The first image shows all the pressure contact data recorded for the range of 10 to >75psi. The lower threshold is then increased to 20psi in the second image. This shows how the amount of contact for pressures >20psi has reduced.

Successive images for a given core show how contact area continues to decrease as the threshold value is increased. The most noticeable reduction is shown in the last of the series of images showing contact >50psi. Table 5-8 shows the total area of merged contact patch at different threshold contact pressures. The actual contact patch for each core was different and so the actual contact area has been expressed as a percentage of the total area of the contact patch. The data is plotted in Figure 5-21. The data shows the cores to behave differently under the ASTM friction tyre with respect to % contact area although the general trend observed was that an increase in contact pressure resulted in a decrease in the contact area for the asphalt surfacing materials. The pressure pad is a grid of 128 x 128 sensing elements with a 2.54 x 2.54 mm resolution. Each cell within this grid has a pressure value. The pressure data for the merged contact patch from the pressure pad was exported into Excel for further analysis. This involved analysing the individual pressure data from each cell to give a frequency distribution based on measured contact pressure.

Table 5-8: Contact Patch Data

Core Reference	Description	Total Area of Contact Patch (mm^2)	Contact at Different Contact Pressure Thresholds (%)				
			>10 psi	>20 psi	>30 psi	> 40psi	>50 psi
CR 0961 1-7	HRA 3 kg/m^2	7487	100	86	67	38	20
CR 0961 1-8L1		7294	100	87	70	41	12
CR 0961 2-7L1	HRA 5.5 kg/m^2	7394	100	76	60	42	22
CR 0961 2-8L1		7425	100	72	54	36	24
CR 0961 3-7	HRA 6 kg/m^2	6542	100	77	56	39	24
CR 0961 3-8		7009	100	90	69	44	21
CR 0961 DD7 1-1	PASS	7027	100	90	69	43	21
CR 0961 DD8 L1		7033	100	89	67	44	25

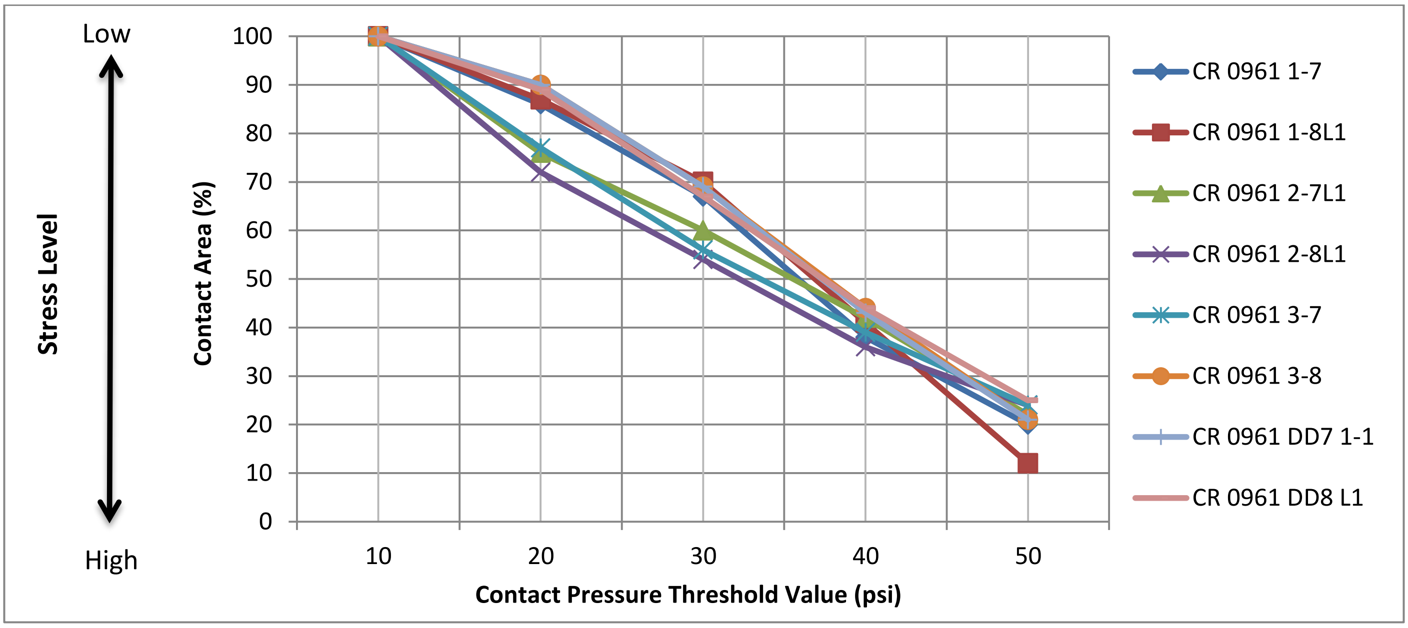


Figure 5-21: Relationship between Contact Area and Contact Pressure Threshold

Table 5-9 summarised the cumulative frequency distributions for each merged contact patch grouping the individual readings based on an upper limit value. The data is plotted in Figure 5-22 to Figure 5-24. Figure 5-21 to Figure 5-24 show 2 main groupings in the data related to contact area and contact pressure. Core references CR0961: 2.7, 2-8 and 3-7 vary in behaviour in comparison to the remaining cores in relation to how they interface with an ASTM friction measuring tyre. It should be noted that the ASTM friction measuring tyre is influenced by the number of contact points. More points of contact imply lower stresses. The points of contact for the HRA cores are reflected in the rate of chip application and their distribution. Reduced chipping rate for the HRA cores will result in an increase in the area of contact during contact patch measurement resulting in lower stresses.

Table 5-9: Frequency Distributions for Each Merged Contact Patch

Upper Limit (psi)	CR0961 1-7	CR0961 1-8L1	CR0961 2-7L1	CR0961 2-8L1	CR0961 3-7	CR0961 3-8	CR0961 DD7 1-1	CR0961 DD8
9	244	201	312	350	296	244	257	225
19	161	127	180	227	182	133	132	124
29	225	174	195	207	193	201	219	229
39	324	314	194	206	184	335	272	252
49	220	346	218	144	149	262	244	212
59	139	104	148	92	116	111	145	165
69	72	27	57	61	66	43	84	76
79	12	11	26	48	31	15	17	25
89	16	5	22	24	16	10	6	11
99	4	1	12	12	10	4	2	8
109	2	0	1	18	9	2	2	1
119	1	1	5	12	1	0	0	0
129	0	0	3	5	1	0	0	2
139	0	0	1	2	1	0	0	0
149	0	0	2	5	1	0	0	0
159	0	0	1	3	1	0	0	0
169	0	0	2	3	1	0	0	0
179	0	0	1	0	2	0	0	0
189	0	0	0	1	0	0	0	0
199	0	0	0	0	0	0	0	0

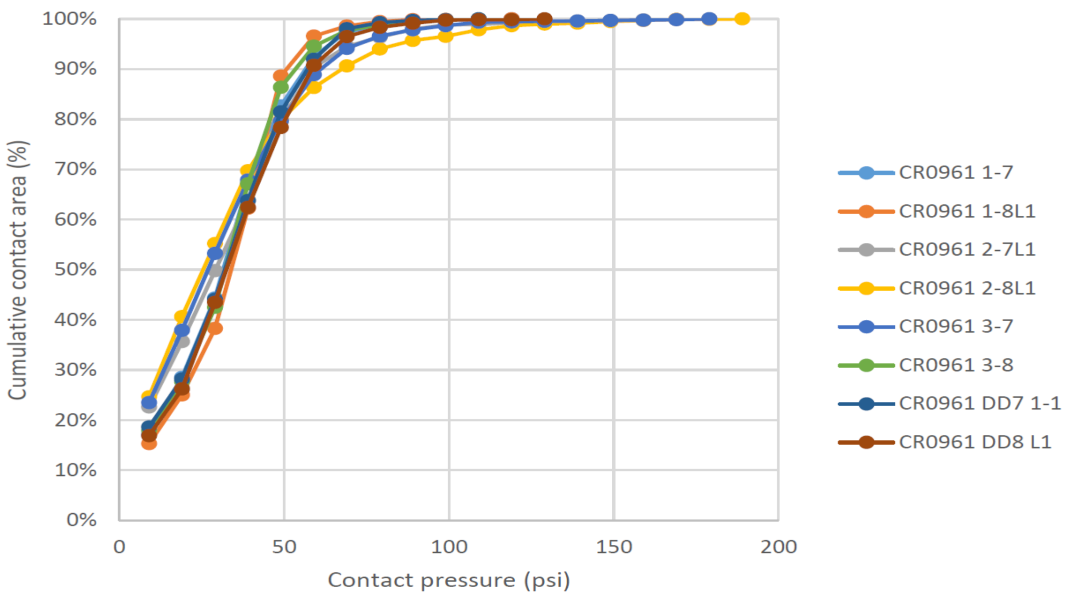


Figure 5-22: Frequency distributions – all data

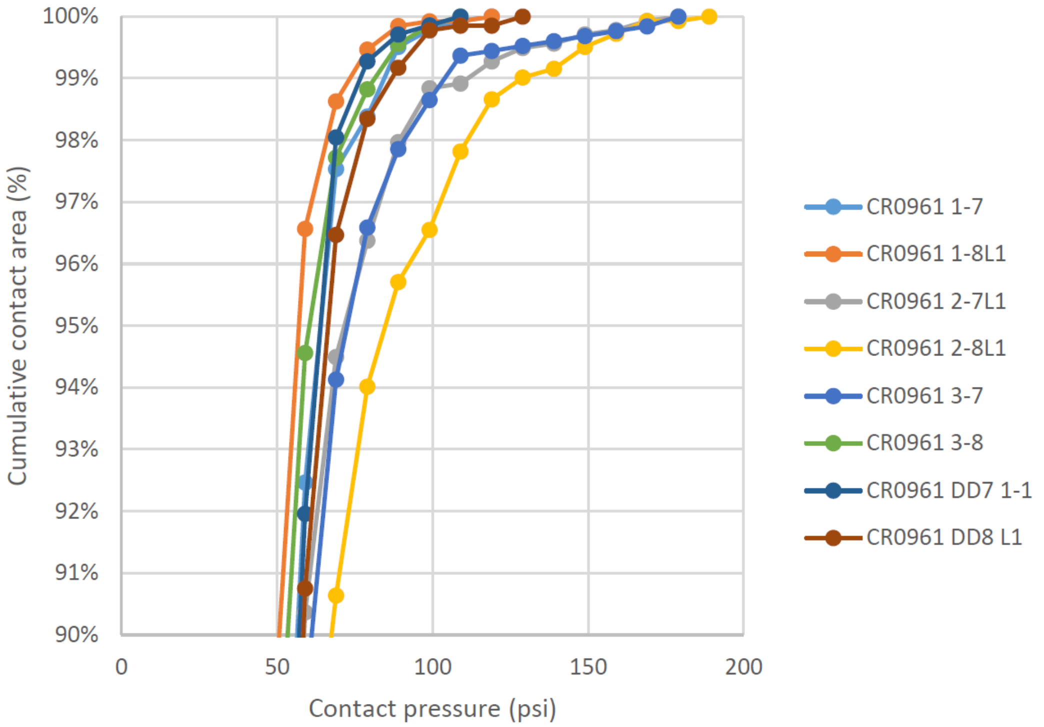


Figure 5-23: Frequency distributions – all data > 50 psi

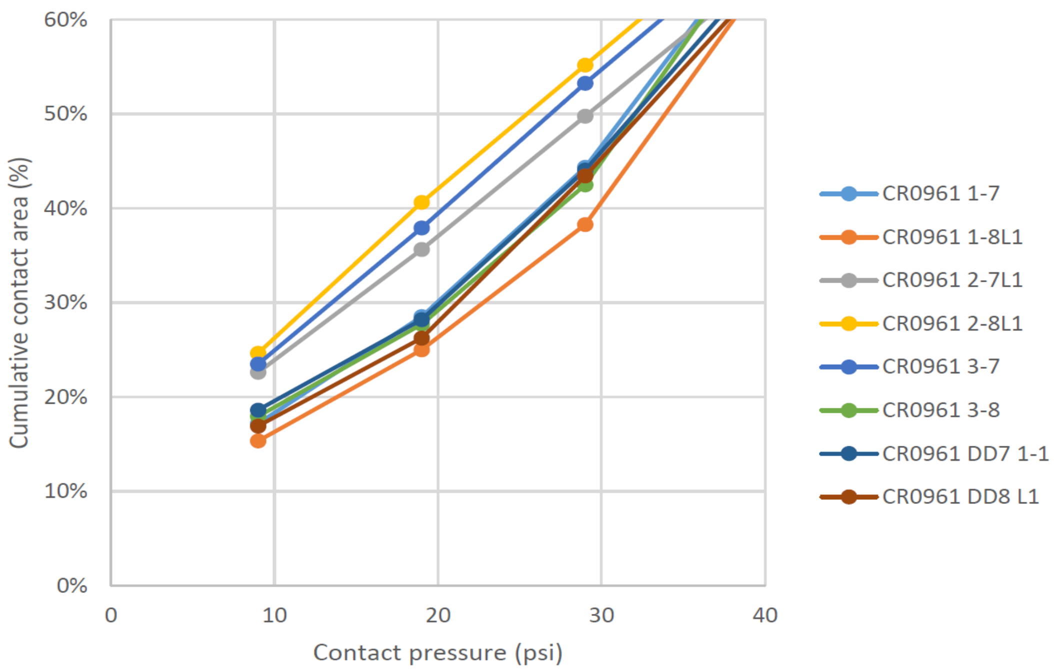


Figure 5-24: Frequency distributions – all data 9 to 40 psi

Comparative Analysis of HRA with 6/10 mm and 14/20 mm Pre-Coated Chippings

A comparative analysis of contact patch pressure distribution was carried out. This compared the HRA test samples obtained from the demonstration trial as detailed in Table 5-8 with 3 HRA samples produced using laboratory roller compacted slabs 305 x 305 x 50 mm in size with 20 mm pre-coated chippings at 0 kg/m^2, 10 kg/m^2 and 16 kg/m^2. The slabs were assessed using the contact patch method.

The results are shown in Figure 5-25 and Figure 5-26. Figure 5-25 shows three distinct groupings in the data with respect to pressure threshold i.e. HRA with no pre-coated chippings, HRA with 20 mm pre-coated chippings and HRA with 6/10 mm pre-coated chippings. The HRA mixtures with 20 mm pre-coated chippings had higher stress levels with increasing contact pressures in comparison to the HRA with 6/10 mm pre-coated chippings as seen in Figure 5-25. Figure 5-26 shows a similar grouping with respect to cumulative percentage contact area.

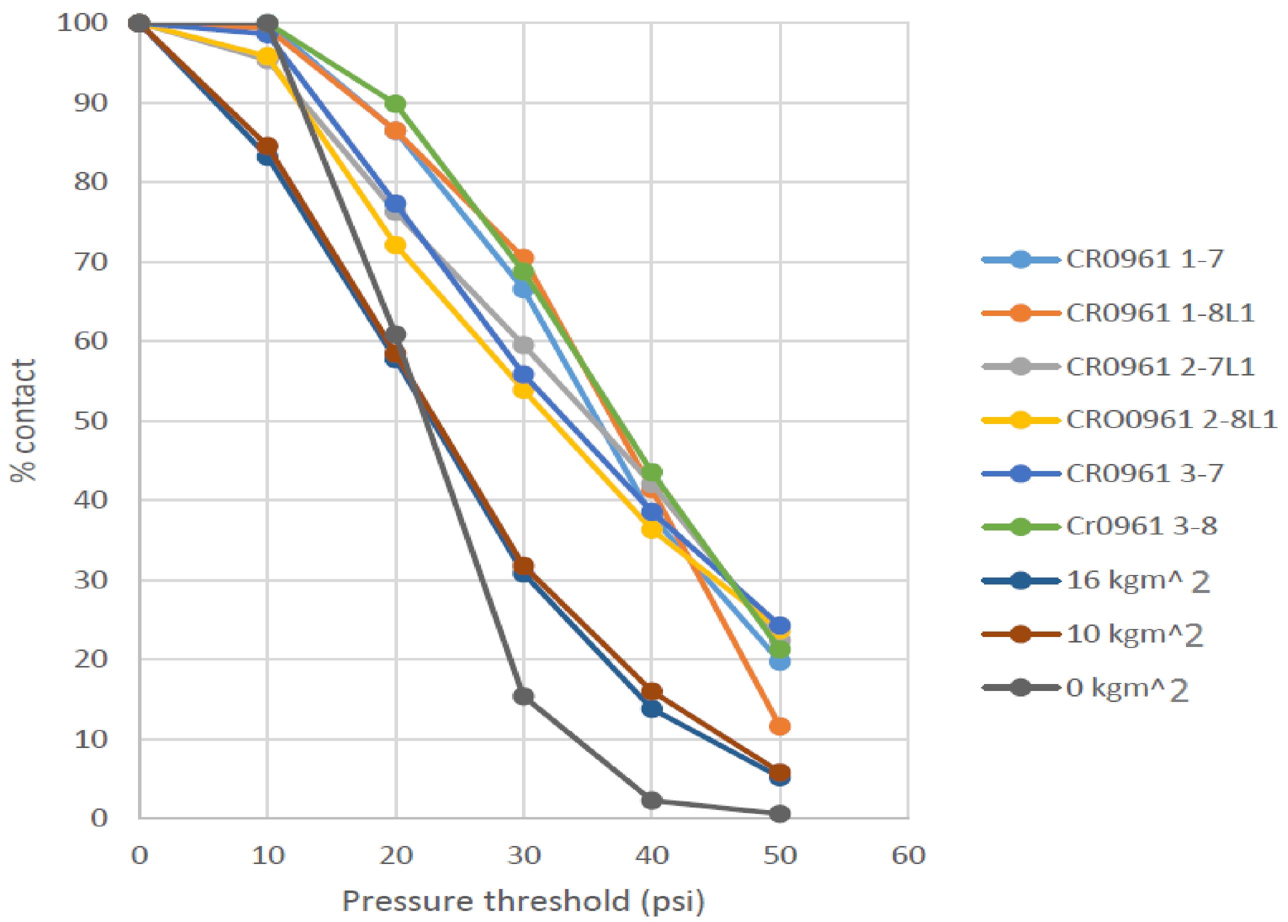


Figure 5-25: Contact Area vs Contact Pressure Threshold

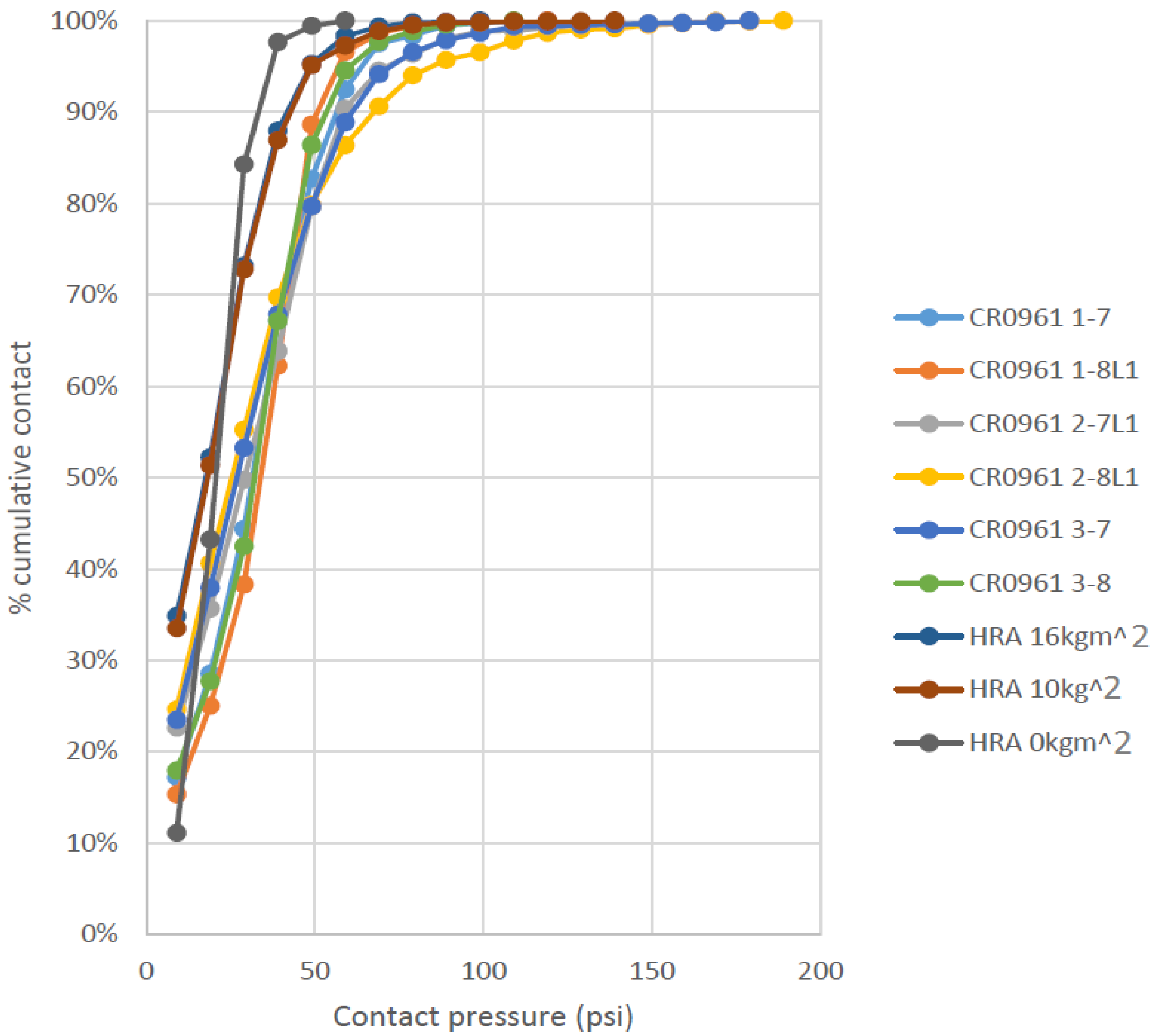


Figure 5-26: Frequency distributions – all data

<u>Conclusions</u>

Eight cores as detailed in Table 5-8 were submitted for contact patch analysis. HRA samples from the demonstration trial were compared with 14/20 mm pre-coated chippings. The HRA mixtures with 20 mm pre-coated chippings had higher stress levels with increasing contact pressures in comparison to the HRA with 6/10 mm pre-coated chippings.

5.3 OVERALL SUMMARY

The demonstration trial validated the laboratory mix designs and confirms constructability of the PASS and Polymer Modified HRA at different chipping rates.

Feedback from the contractor indicated that the HRA and PASS mixtures were relatively easy to batch with no problems encountered at the asphalt plants. Further adjustments to the modified chipper are required to ensure spread rate evenness and uniformity.

The typical cross sections of the PASS and HRA samples obtained from the demonstration trial showed that the PASS was dense with a high coarse aggregate content and good interlocking properties. The HRA had a high proportion of sand in the mix with the coarse stones floating in the asphalt providing a dense impervious layer.

The macrotexture test results for the HRA samples could be considered as being outside (lower than) those specified in SHW Clause 921 which could be attributed to the fact that smaller 6/10 mm chippings were used in comparison to the conventional use of 14/20 mm chippings. This is being reviewed with the view to evaluating steps to optimising and improving the macrotexture. The skid pendulum test value (PTV) results show encouraging PTV values (exceeding 70) which indicates improved skid resistance properties.

The PASS showed superior resistance to deformation with rut depths after 10,000 cycles less than 5 mm. The Clause 943 HRA material did not perform as expected on the demonstration trial. However, the result was considered independent of the objective of the project with respect to using 6/10 mm chippings to assess embedment of chipping and the resulting macrotexture. Nevertheless, the high rut was considered not typical for Clause 943 material. It should be noted that the PASS and HRA material developed in the laboratory showed optimal performing properties as detailed in Chapter 4.

The HRA mixtures with 20 mm pre-coated chippings had higher stress levels with increasing contact pressures in comparison to the HRA with 6/10 mm pre-coated chippings as ascertained using the XSENSOR Pressure Mapping System.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The results from this project provide a significant advance in the understanding and development of requirements for materials which offer significantly enhanced durability, reduced noise characteristics and improved skid resistance that includes HRA using 6/10 mm chippings and the Premium Asphalt Surfacing System (PASS). The major factors considered and addressed by this project are stated below:

- Understanding issues and failure mechanisms.
- Performance requirements.
- Assessment criteria.
- Mix design and specification.
- Construction techniques.

The project identified aggregate shape to be a key parameter for the design of asphalt mixtures, especially for the 6/10 mm chippings. In order to increase the rapidity and accuracy of aggregate shape determination, the VDG-40 Videograder and Enhanced University of Illinois Aggregate Image Analyser (E-UIAIA) were used to ascertain aggregate shape properties. The VDG-40 Videograder provided a practical means of ascertaining the aggregate shape, angularity and texture properties of the 6/10 mm chippings. The E-UIAIA provided an innovative and advanced tool that made use of three high-resolution cameras to capture three projections of the aggregate particle moving on a conveyor belt.

The HRA and PASS mixtures were further developed to establish proof of concept for the asphalt materials. The mix designs and the associated performance related assessments showed optimised mechanical and performance properties which led to pilot scale demonstration trials at Alrewas Quarry, Staffordshire in June 2016.

The PASS samples showed optimal packing of aggregates providing particle to particle contact. The PASS laying characteristics were very similar to those of a thin surface course with voids in the ideal 2 – 4% range. The relatively finer grading meant that a good dense construction joint to the adjoining mat was achieved on site. The test results from the demonstration trial showed satisfactory performance for the PASS asphalt mixtures.

The HRA was dense and had a high proportion of sand in the mix resulting in a low percentage of air voids after compaction.

The HRA laid on the demonstration trial did not meet the expected performance requirements for SHW Clause 943 Hot Rolled Asphalt (Performance Related Design Mixture). The supplied material was not reflective of a typical Hot Rolled Asphalt and an investigation undertaken to understand the variance. In terms of the project objectives, this issue was taken into account when considering the project learnings with respect to using 6/10 mm chippings; including assessment of the embedment of chippings in the HRA, the resulting macrotexture and noise characteristics.

The demonstration trial showed that both materials (HRA and PASS) were reported as being relatively easy to batch with no problems encountered at the asphalt plants confirming the findings from asphalt workability assessments. The demonstration trial also demonstrated the practicality of using the chipper modified to accommodate 6/10 mm chippings which achieved a reasonably uniform spread although it may be possible to improve uniformity with further refinement of the chipper.

6.2 RECOMMENDATIONS

A robust detailed technical review of the next generation low noise surfacing materials that comprises polymer modified hot rolled asphalt with different rates of pre-coated 6/10 mm chipping and the bespoke performance based polymer modified premium asphalt surfacing system developed in this collaborative research project should be conducted.

It has been established that aggregate shape is a key parameter for the design of asphalt mixtures and even more importantly for the 6/10 mm chippings used in the HRA asphalt mixture. The use of advanced imaging techniques could provide a suitable means of assessing and characterising the shape properties of aggregate materials. Suitable methodologies were identified and investigated within the project; however, standardisation would be required prior to their direct adoption into a specification.

In summary, the VDG-40 Videograder provided a practical means of ascertaining the aggregate shape, angularity and texture properties of the 6/10 mm chippings. The E-UIAIA provided an innovative and advanced tool that made use of three high-resolution cameras to capture three projections of the aggregate particles moving on a conveyor belt. Further tests using imaging techniques should be conducted to improve and ascertain the repeatability and reproducibility of test results using a representative range of aggregate sources.

It is recommended that the mix designs for these next generation asphalt mixtures should be optimised further to ensure that the mechanical and performance properties including the macrotexture values specified can be consistently obtained.

The demonstration trial validated the laboratory mix designs and confirms constructability of the PASS and Polymer Modified HRA at different Chipping Rates asphalt mixtures. Improvements to the modified chipper are required to ensure uniformity and an even spread rate during application in future projects using 6/10 mm chippings.

The macrotexture test results for both asphalt mixtures measured during the demonstration trials are considered as being lower (0.6 – 0.8 mm) than those specified in SHW Clause 921. For the HRA, this could be attributed to the fact that smaller 6/10 mm chippings were used in comparison to the conventional use of 14/20 mm chippings. Suggestions with respect to improving the macrotexture for the HRA could mean increasing the chipping size to 10/14 mm.

The aggregate grading could be adjusted to improve macrotexture properties of the PASS. A paradigm shift in approach could mean a relaxation in the macrotexture specification for these asphalt mixtures with a preference for friction tests although this would require further research studies and tests to ascertain safety implications.

The PASS has shown relatively superior laboratory based mechanical and performance properties, with rut depths after 10,000 cycles less than 5 mm. It is required that the PASS and HRA with 6/10 mm chippings are to be further optimised with adequate quality control measures to ensure design specifications and compliance to best practice are adhered to in construction as the materials are at an advanced stage ready for implementation on a large scale trial.

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Appendix 1

Photographic Image of Cores

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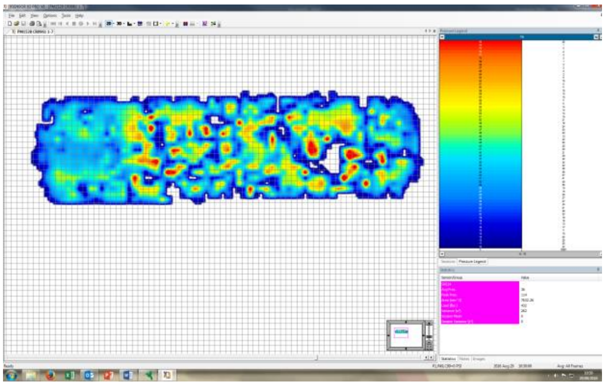

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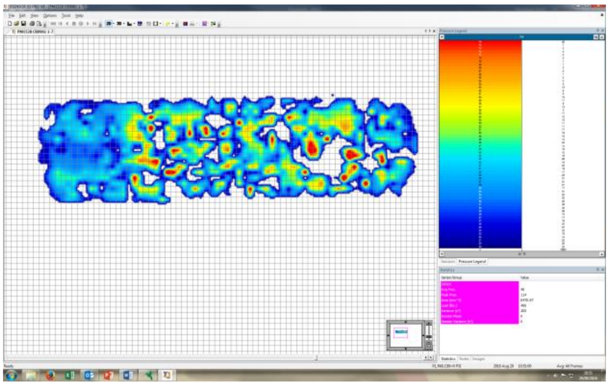

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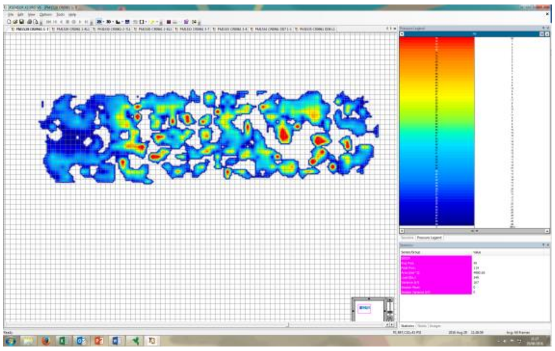

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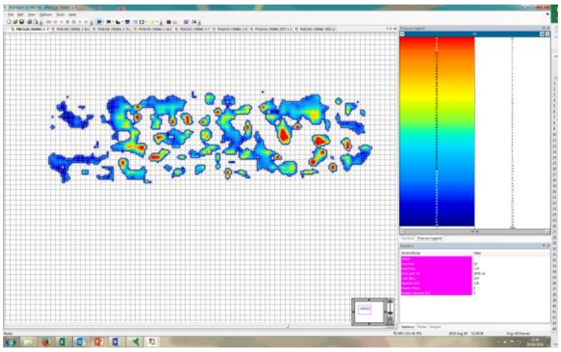

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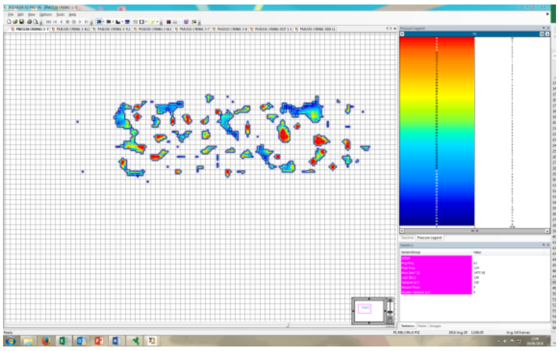

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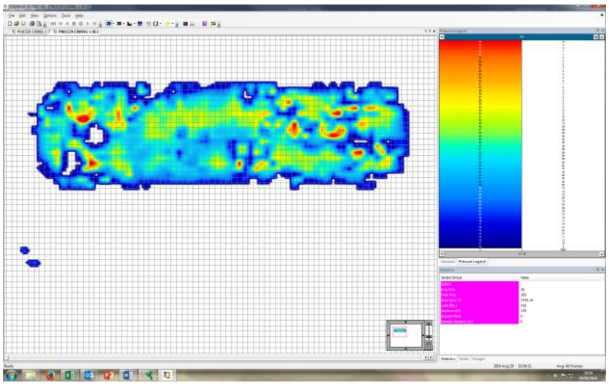

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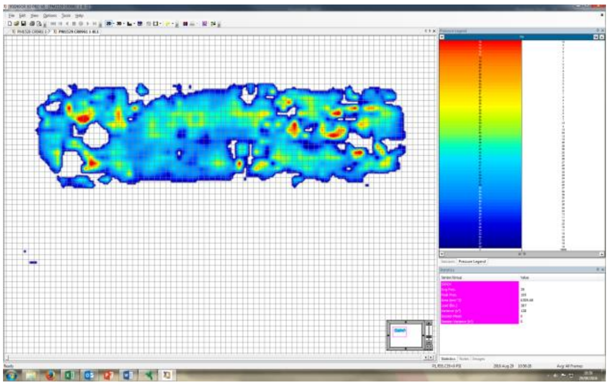

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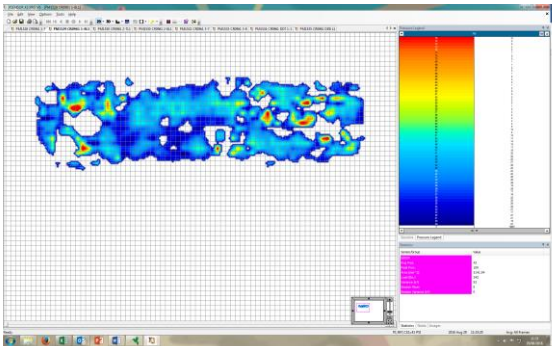

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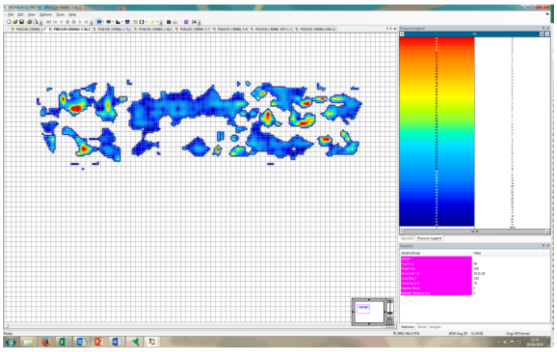

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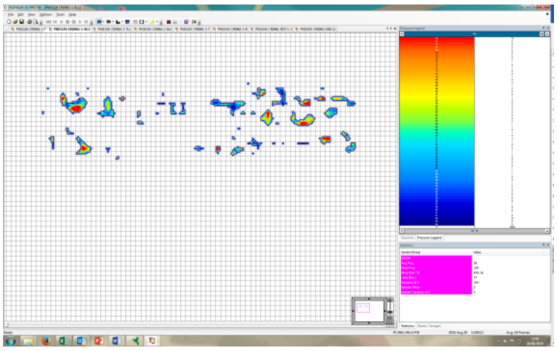

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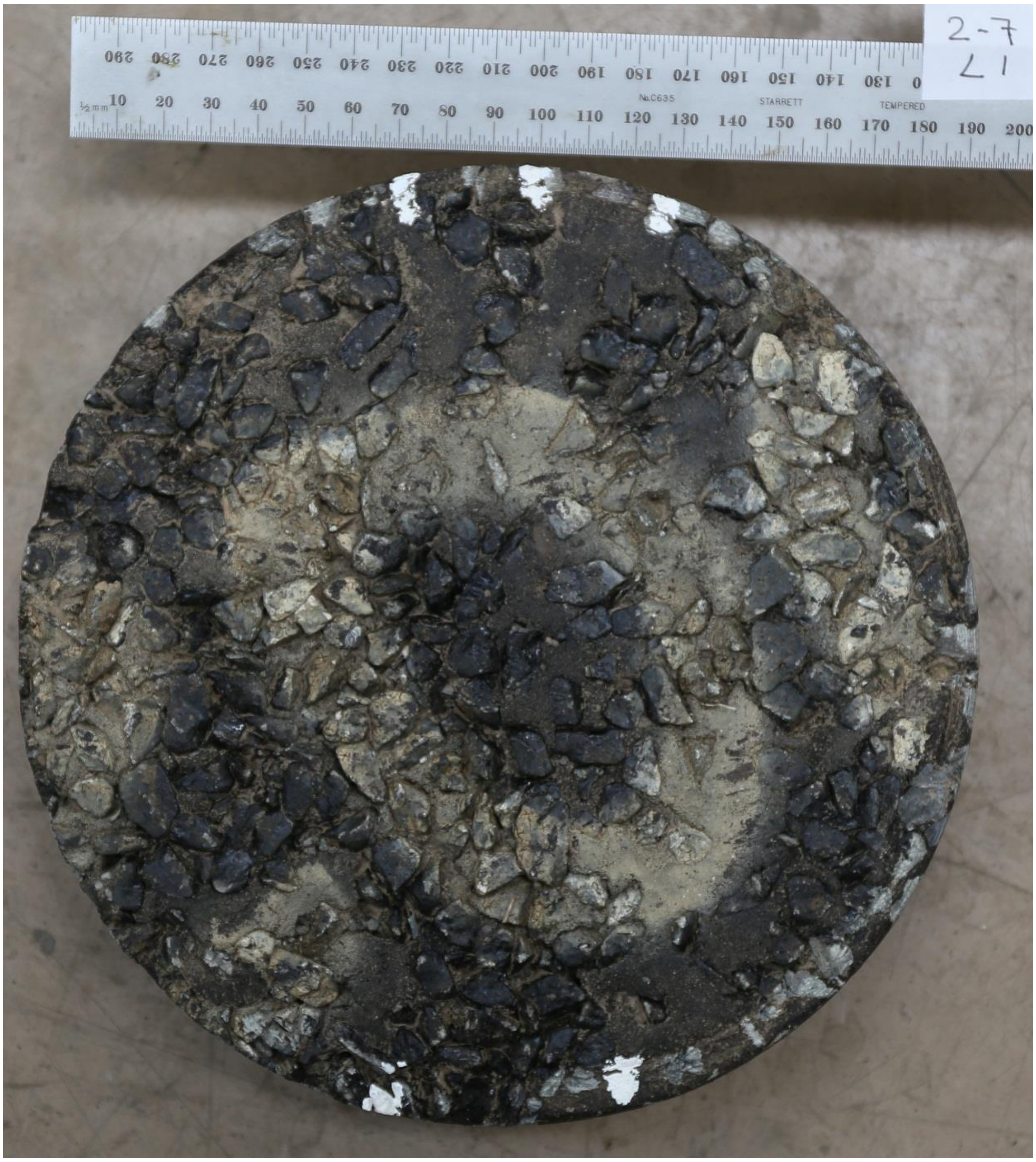

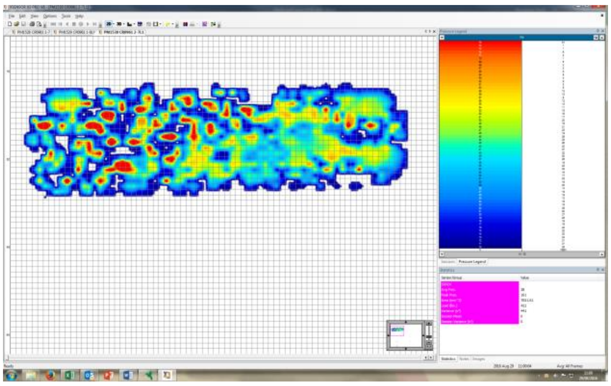

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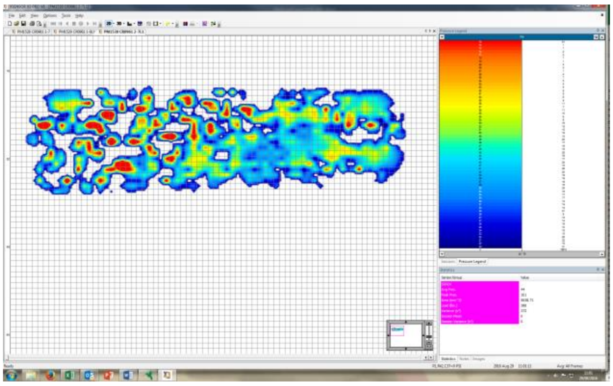

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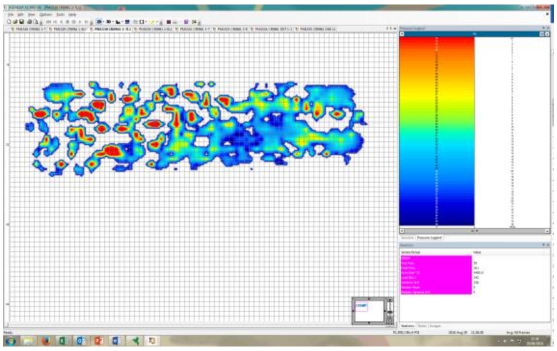

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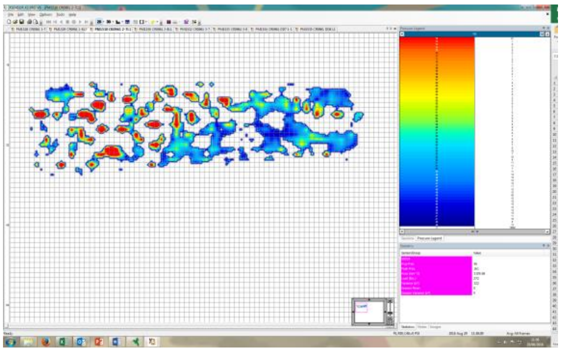

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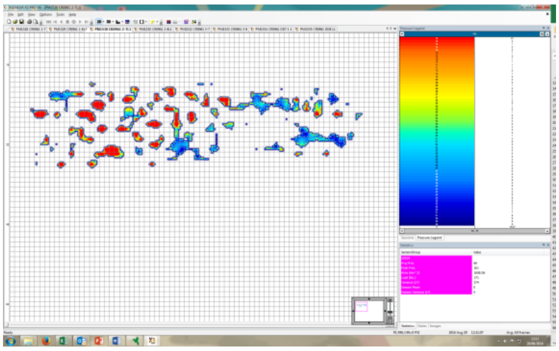

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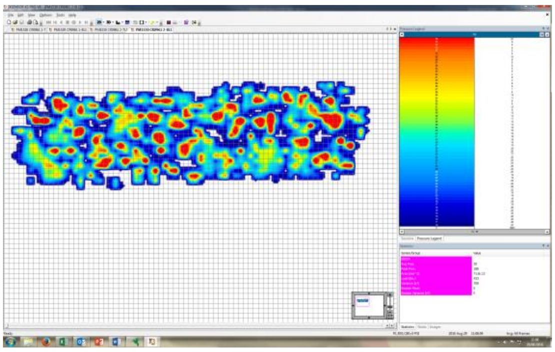

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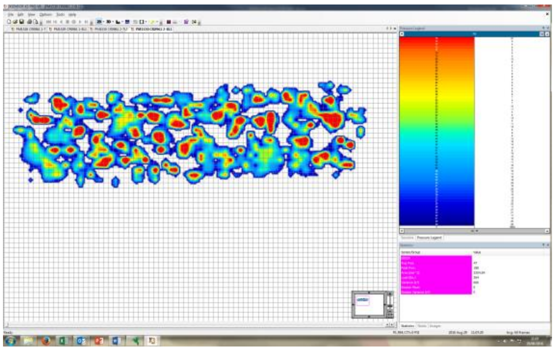

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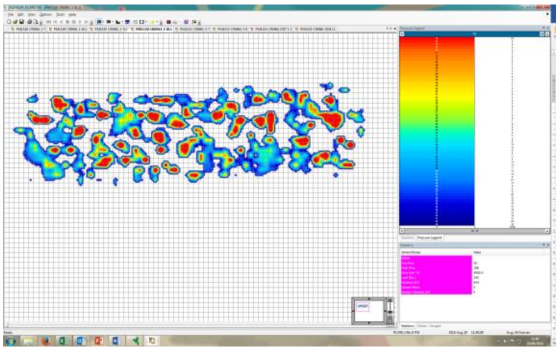

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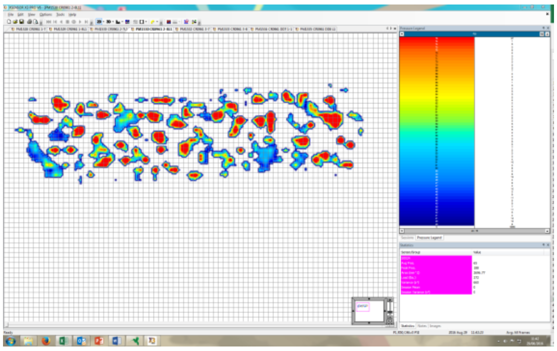

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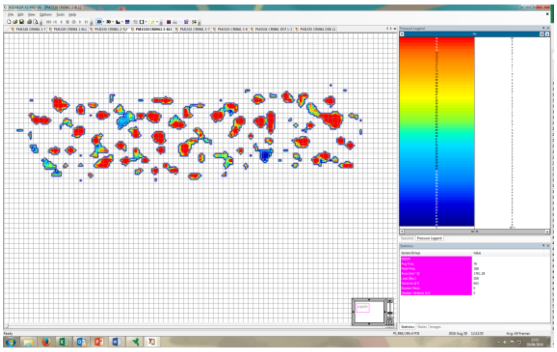
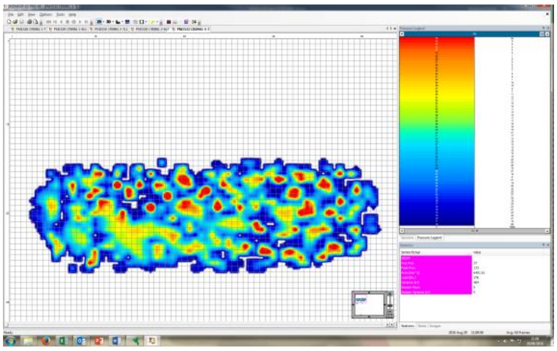
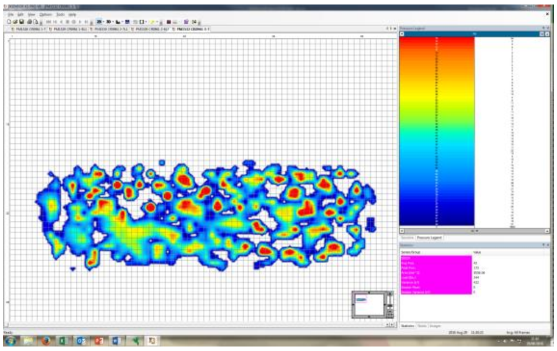


Legend 50 to >75 psi

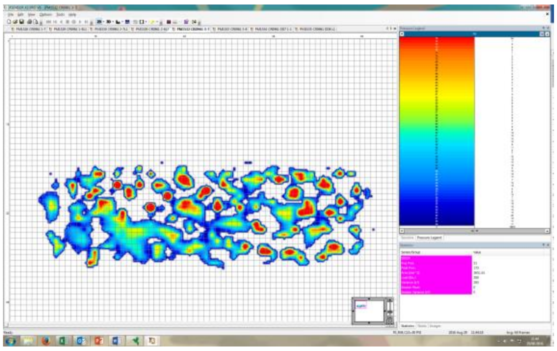
CR0961 3-7



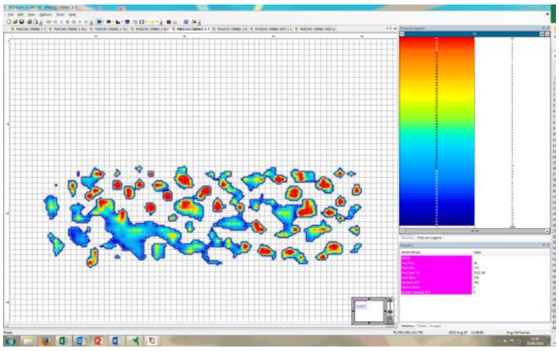
Legend 10 to >75 psi



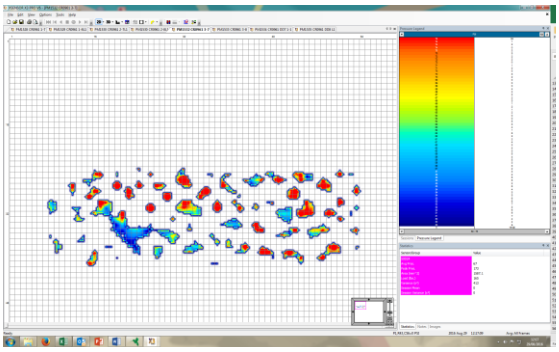
Legend 20 to >75 psi



Legend 30 to >75 psi

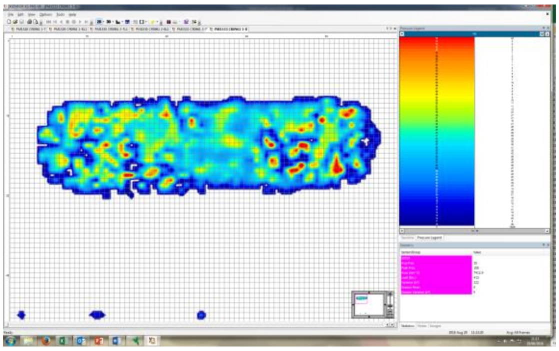


Legend 40 to >75 psi

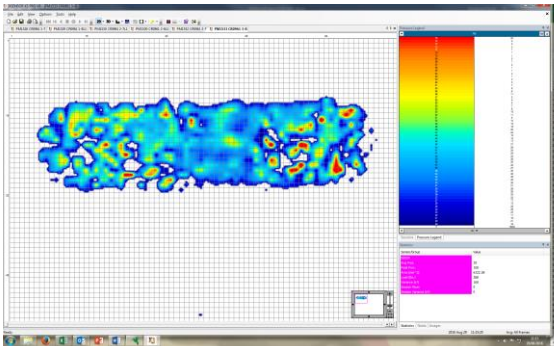


Legend 50 to >75 psi

CR0961 3-8



Legend 10 to >75 psi



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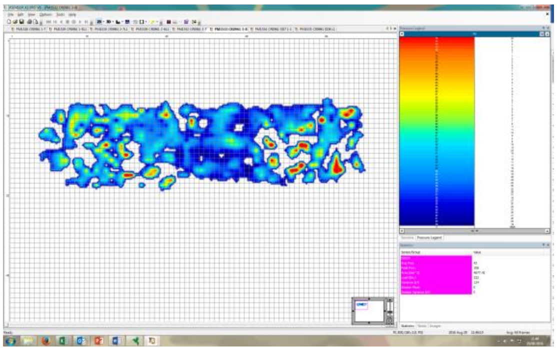
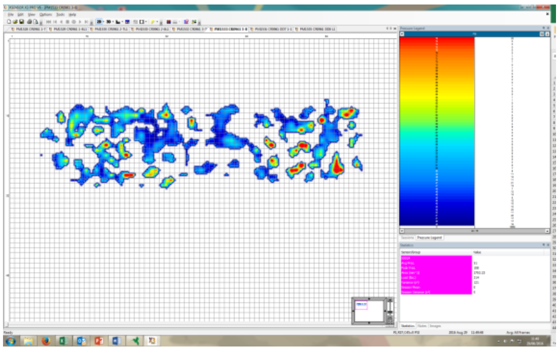
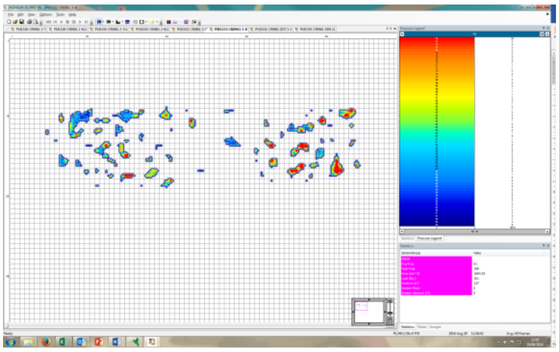


Legend 30 to >75 psi

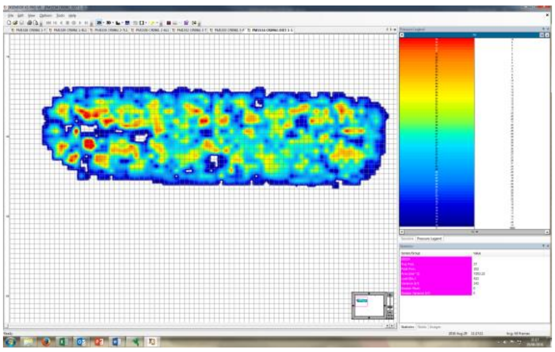


Legend 40 to >75 psi

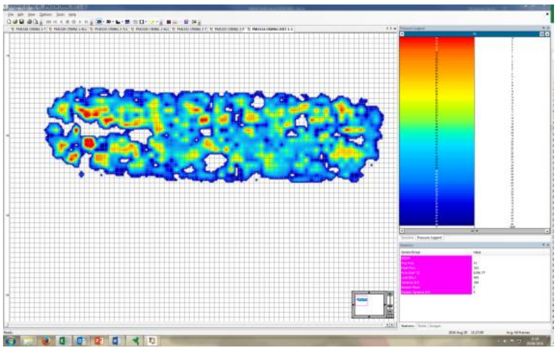


Legend 50 to >75 psi

CR0961 DD7 1-1



Legend 10 to >75 psi



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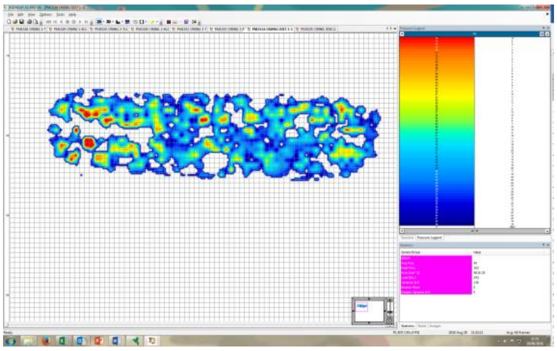
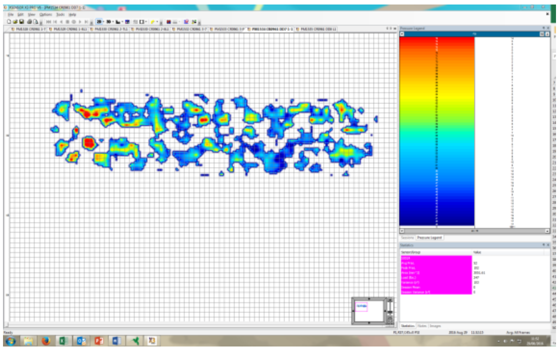
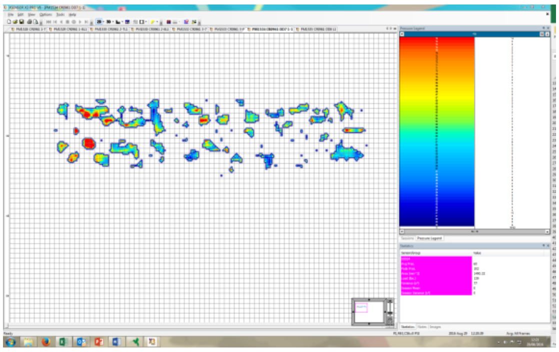


Legend 30 to >75 psi

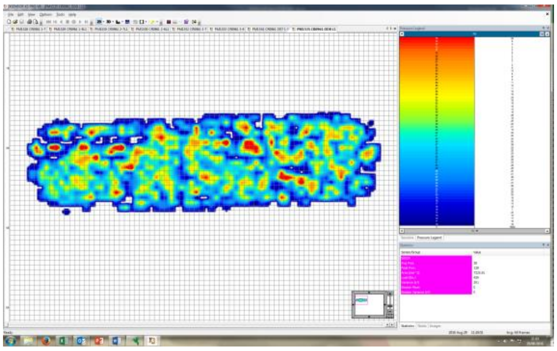


Legend 40 to >75 psi

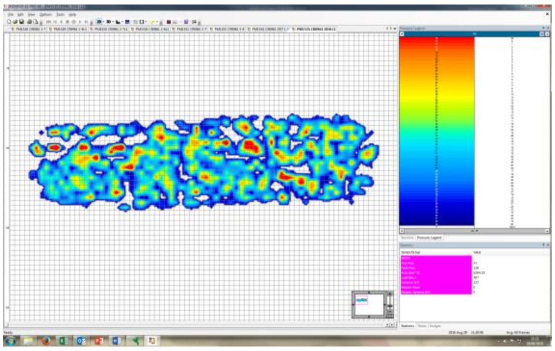


Legend 50 to >75 psi

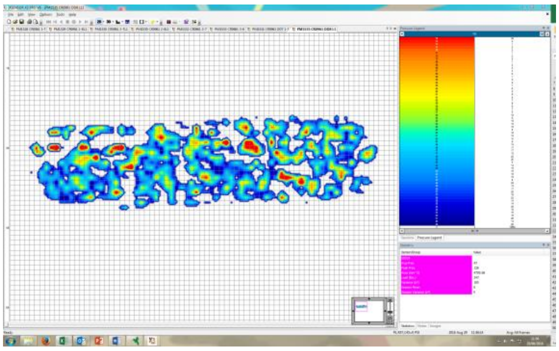
CR0961 DD8 L1



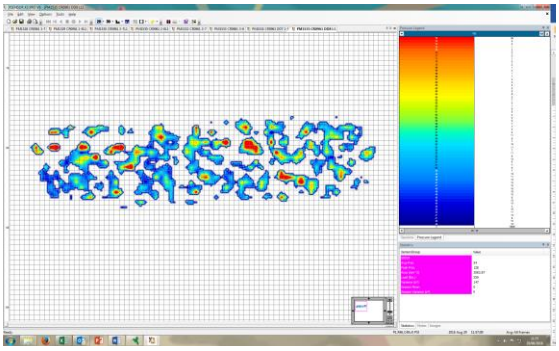
Legend 10 to >75 psi



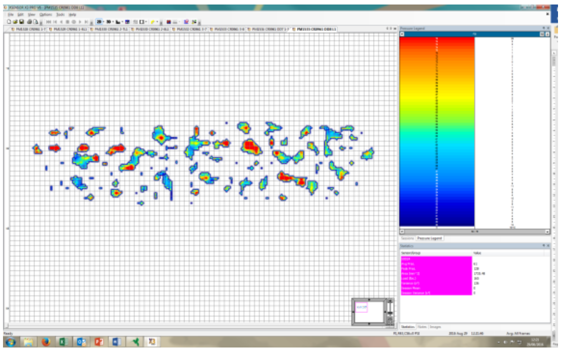
Legend 20 to >75 psi



Legend 30 to >75 psi



Legend 40 to >75 psi



Legend 50 to >75 psi