MAPPING INTERFACIAL STRESS DISTRIBUTIONS TO DIGITAL SURFACE MICROTOPOGRAPHY

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ABSTRACT

The ability to characterise highway surfacing textures is essential to better understanding their performance. Traditional volumetric methods such as sand patch produce data based on estimation of a single geometry and offer little insight to early life deformations of bitumen coatings, changes in aggregate shape or longer term performance of the asphalt. Durability of an asphalt surfacing is a function of its ability to withstand static and dynamic contact stresses applied during its life. This paper reports the initial findings of a study into the use of stress mapping based on digital models of real surfaces. These are manipulated using ArcGIS to form a spatial framework for analysing surface textures. Initial results suggest that this methodology offers improved understanding of tyre / surface interaction. This approach has potentially wide ranging application in understanding the mechanics of in-situ wear and the design of more durable asphalt surfacing materials.

INTRODUCTION

This paper reports the initial findings of a new area of research being developed at the University of Ulster into understanding the different levels of asphalt surfacing textures i.e. at micro and macro levels and how this interacts with a tyre. The asphalt surface / tyre interaction governs properties such as grip, noise generation, rolling resistance and durability. These properties cannot be viewed or studied on their own. This requires a holistic approach. Unfortunately this holistic relationship between many different variables is extremely difficult to predict [1]. The costs and practicality of monitoring an asphalt surface, particularly new types of mix that may contain local instead of more expensive imported aggregates, throughout its serviceable life are prohibitive and unsustainable. It therefore follows that there is the need for predictive laboratory testing that assesses not only the aggregate, or the bitumen, but subjects the asphalt mix to accelerated simulated trafficking conditions. Obviously, these need to be related to observable and measurable performance in-situ. Most standard test methods offer little insight in this regard as they do not fully address how material performance and properties vary with time and space. This paper reports the initial findings of an investigation into how interfacial texture and stress mapping can be readily achieved in the laboratory and so contribute to better understanding of material performance at the tyre/surface interface.

Development of a Test Methodology

Texture mapping

The complex nature of asphalt surfacing materials has led to development of numerous methodologies and systems for characterising their surface texture. They range in complexity from the sand patch test to high speed laser systems. Researchers such as Ivanov et al [2] have explored the use of fuzzy logic to evaluate tyre-surface interaction parameters. The majority of these offer little insight into surface performance. However, a number of studies considered surface performance based on three dimensional models. Analysis of three dimensional models of real materials can greatly improve on the limited knowledge of single geometry methods such as sand patch. Millar et al [3] showed that mean texture depths estimated from volumetric analysis of 3d digital models correlated well with mean texture depth

(MTD) and mean profile depth (MPD). The three dimensional models were generated from stereo images captured using a simple 10 mega-pixel SLR camera. However, Millar et al [4] established that depth analysis of these digitally captured 3d models may be used to predict the vulnerability of an asphalt material to the potentially damaging effects of water. For example, an asphalt surface may have localised pockets of trapped water that are subject to extreme hydraulic pressures under dynamic wheel loading or lead to high concentrations of de-icing salt/water solutions. Both scenarios potentially cause premature failure mechanisms and effect durability of the asphalt. This ability to identify and rank asphalt surface vulnerability is therefore an area of importance with regard to predicting durability and in highway asset management.

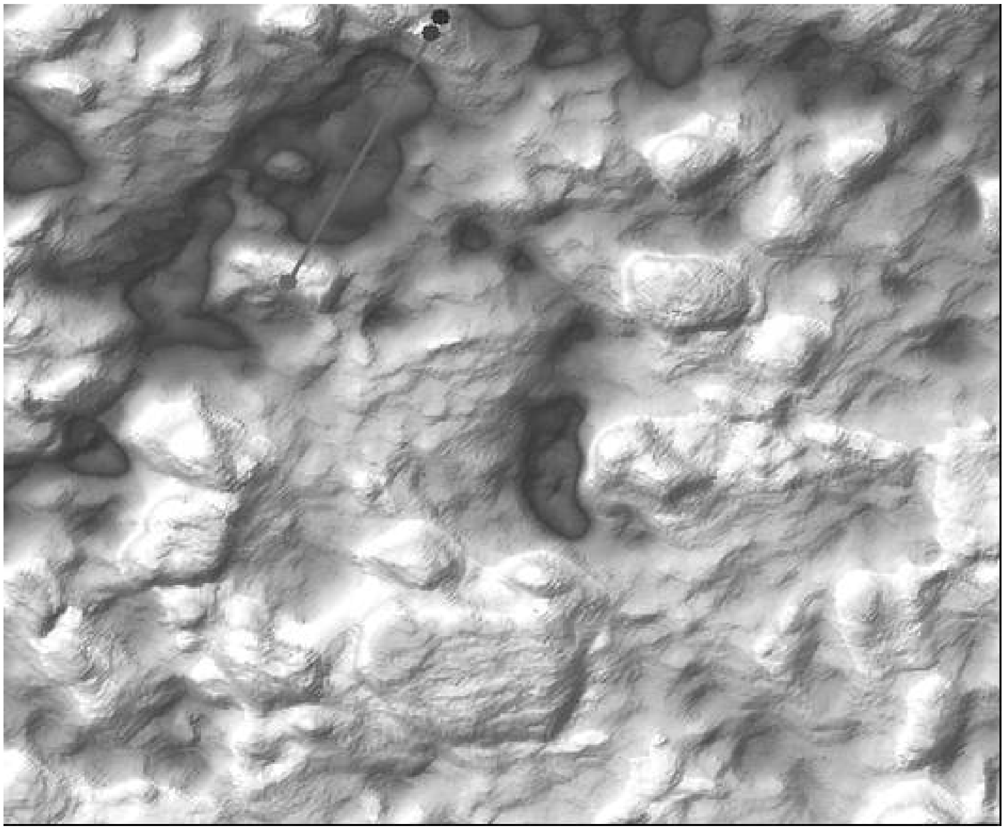

Figure 1: Surface depth classified in ArcGIS showing potential areas of water entrapment (dark areas)

Figure 1 shows an example of a three dimensional model of an asphalt surface that has been depth classified using ArcGIS. Potential areas of water entrapment are represented by the darker areas. In the initial study reported by Millar et al [4] all of the 23 asphalt surfaces were found to entrap water. Some low textured surfaces were found to be at high risk whilst other highly textured surfaces showed relatively low risk of water entrapment. Figure 2 plots Risk Index (a higher value denotes a surface with greater amounts of entrapped water) against mean texture depth for a range of asphalt concrete mixes. The random distribution of points indicates that a relationship between Risk Index and Mean texture depth has not been established. Simple estimation of texture depth by sand patch would appear not to be a significant indicator of a surface's capacity to entrap water in localised areas.

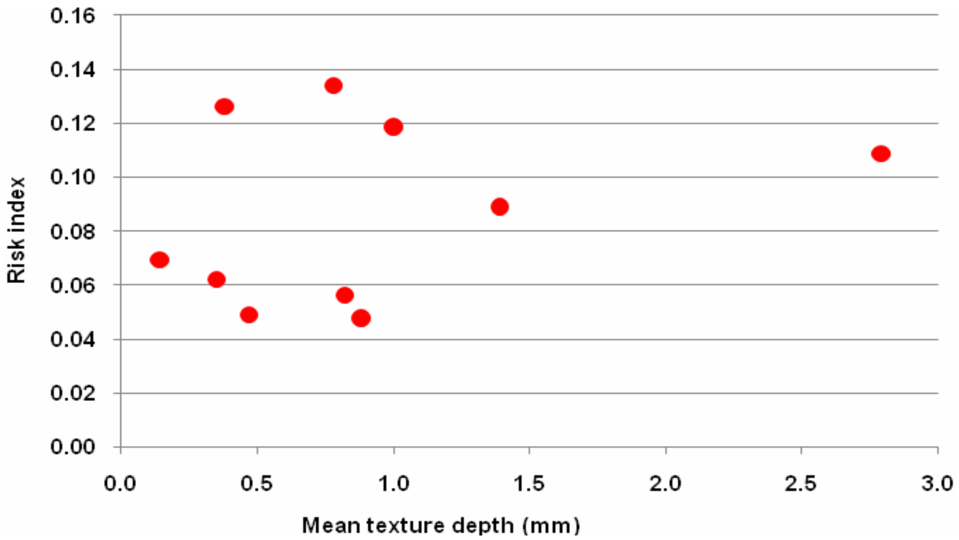

Figure 2: Plot of Risk Index against mean texture depth for AC mixes

This 3d methodology is exceptionally versatile allowing rapid data capture at source and the ability to generate a theoretically unlimited number of profiles in any plane. This facilitates assessment of surface textures' change e.g. deformation; wear and polishing over time and space. The 3d surface models may be used to estimate volume of material loss and displacement with time. For example, Figure 3 shows the plan view of a 3d model for an asphalt concrete test slab containing what may be termed an embryonic pothole i.e. the missing aggregate particle in the centre of the image.

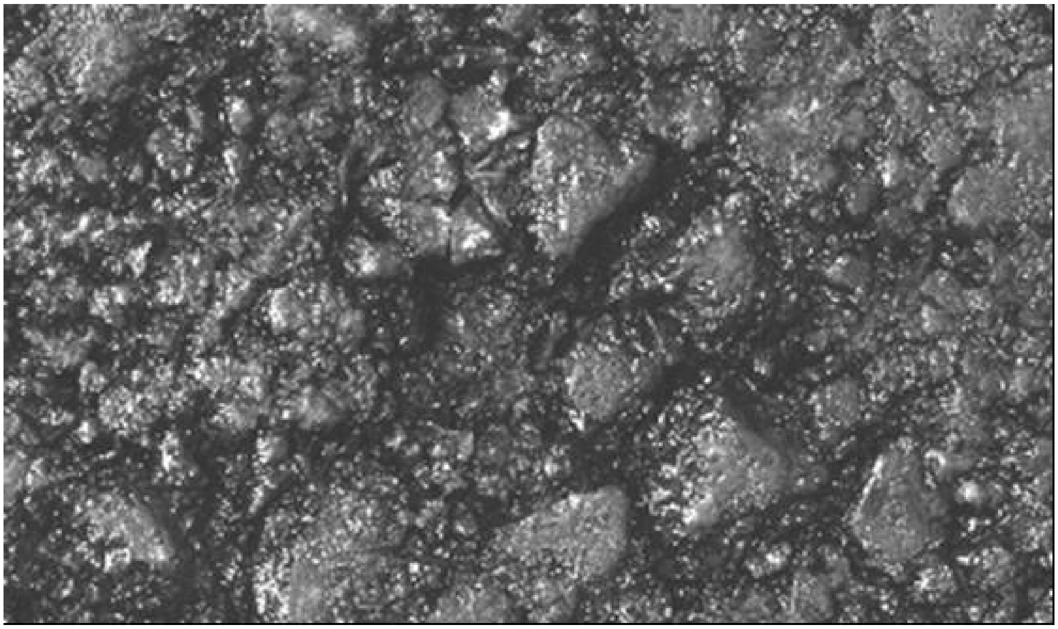

Figure 3: Three dimensional model of small area of asphalt concrete slab

The detailed features of this asphalt surface are not easily discernible directly from the visual image. Surface relief is more easily discerned from the triangular irregular network (TIN) data set upon which the 3d model is based. Figure 4 shows the TIN mesh for the AC test slab. The embryonic pothole is circled. This hole is the result of removal of just a single coarse aggregate particle and yet as this study will show its modelling and associated stress distribution may offer significant insight into pothole propagation and enlargement. Although the TIN mesh appears as a grey rendered solid this is in fact due to the choice of a mesh spacing of 0.3mm and without the application of any filters that would tend to smooth the surface. This spacing offers a clear rendition of the surface relief.

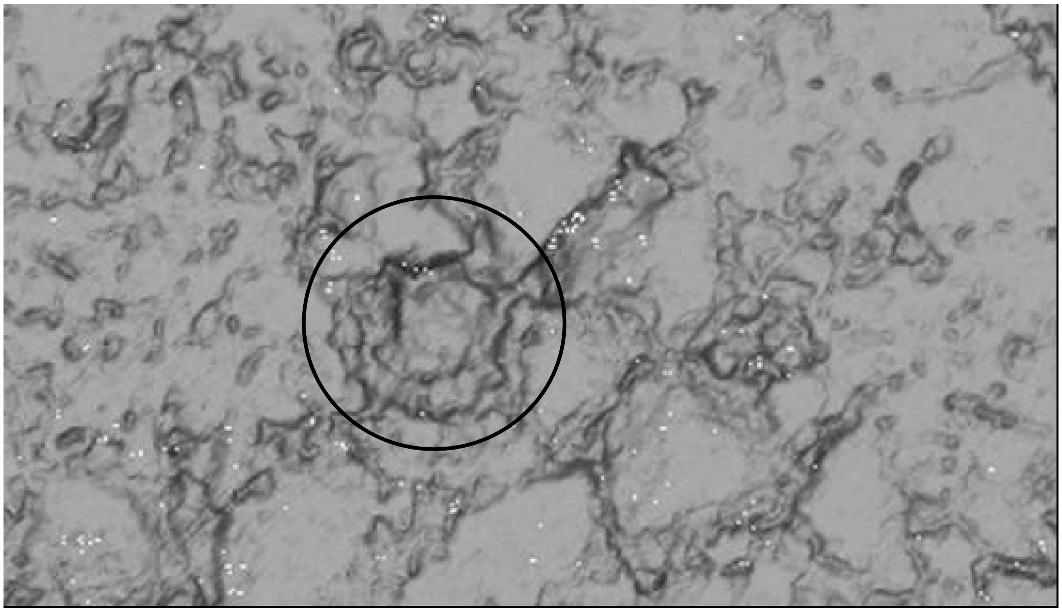

Figure 4: TIN mesh of the AC slab shown in Figure3

Figure 5 shows the same TIN mesh shown in orthographic perspective. This better resolves both the 10mm deep embryonic pothole and general surface configuration of the AC test slab.

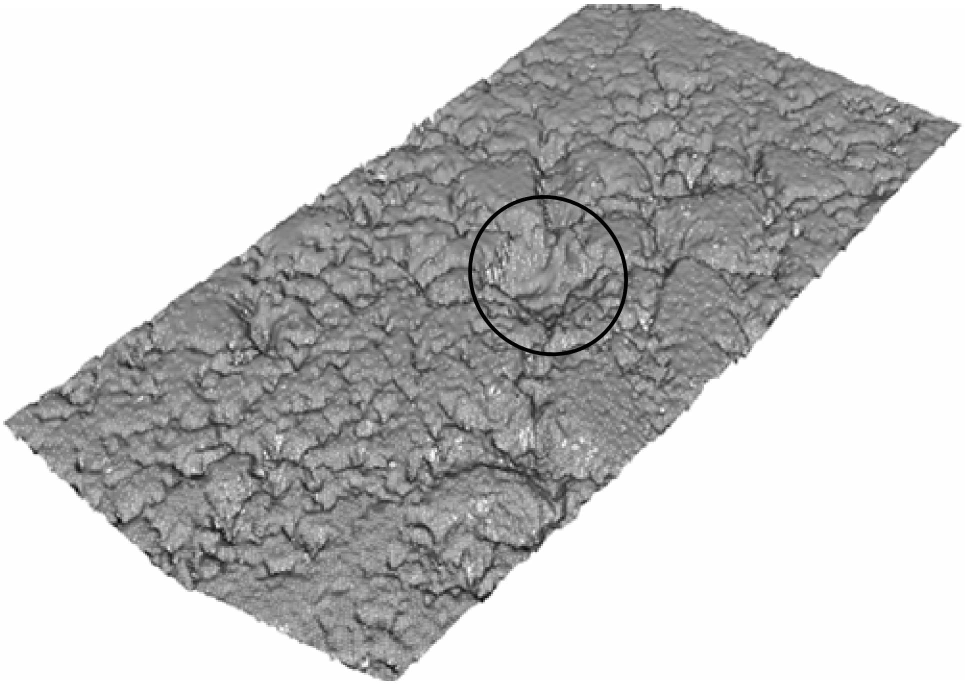

Figure 5: Orthographic perspective of TIN mesh shown in Figure 4

The stereo images from which the mesh was derived were processed using ImageMaster proprietary photogrammetric software. Control points were cross matched and scale provided using two graduated steel rules. A full three dimensional coordinate reference framework would have offered more control over the orientation but this is not strictly necessary for investigative purposes. The ability to rotate the surface of the 3d model about any of the three axes by small increments allows effects due to gradient, cross-fall or deformation of the asphalt to be easily assessed.

Interfacial stress mapping

The tread pattern of a tyre can be less than 20% of the contact patch between a tyre and asphalt surface [5]. The available contact area of an asphalt surface is only a proportion of the plan area. A method of estimating this amount of contact would help explain issues such as the relationship between textures and a surfacing's ability to expel surface water to minimise aquaplaning. Mapping of real full scale interfacial stress distributions within a three dimensional reference system is challenging. A review of relevant existing literature is presented by Douglas [6] who developed an instrumented pin type technology. Although this significantly extended knowledge in this area it highlighted the challenges of this type of measurement methodology.

Conville [7] developed a new approach that is subsequently being developed to show how tyre/ surface interaction develops with time. The method tries to accommodate some of the holistic ideals in predictive laboratory testing. It allows either static or dynamic measurement of contact pressure. A Wessex dry wheel tracker was modified to allow 305 x 305 x 50mm asphalt samples to move under a loaded tyre in a controllable manner. The test methodology allows the change in contact patch phenomena to be easily assessed as the test slabs can be subjected to simulated trafficking using the Road Test Machine located at University of Ulster.

Figure 6: Modified Wessex wheeltracker test rig with slab and pressure mat

The test apparatus is shown in Figure 6. This shows a GripTester tyre fitted allowing correlation between measurement of in-situ grip and laboratory measured phenomena within the contact patch. Contact area and pressure distribution over the tracked test sample surface is measured using a flexible XSENSOR® pressure mat interfaced with XSENSOR® 3 Pro Version 6 software. The flexibility of the mat makes it ideal for assessment of rough surfaces. The ability to measure stresses in this way over real surfaces is considered essential as Siegfreid [8] and Douglas [9, 10] found that stresses due to a tyre rolling over a highway surface are highly concentrated and exploit any surface weakness such as microtexture and aggregate characteristics.

The XSENSOR® mat is capable of capturing up to sixteen frames per second (individual contact images) and merging them into a single composite trace showing the passage of the tyre across the test slab. The contact patch data includes contact area and pressure variation. The test sample can be assessed in a static condition with tyre variables such as load and pressure measured. Large numbers of individual contact images can be recorded and assessed statistically.

Further development of the test methodology considered the optimum number of single frames to form a composite image of the tyre moving dynamically across the test slab. It was found that the quality and completeness of the composite image did not improve beyond approximately one hundred frames. Figure 7 shows an example of number of frames plotted against measured contact area of the merged images. This is for a 305mm x 305mm AC slab prior to accelerated trafficking on the University of Ulster's Road Test Machine (RTM). This approximate number of 100 frames was found to apply to a wide range of materials and loading conditions.

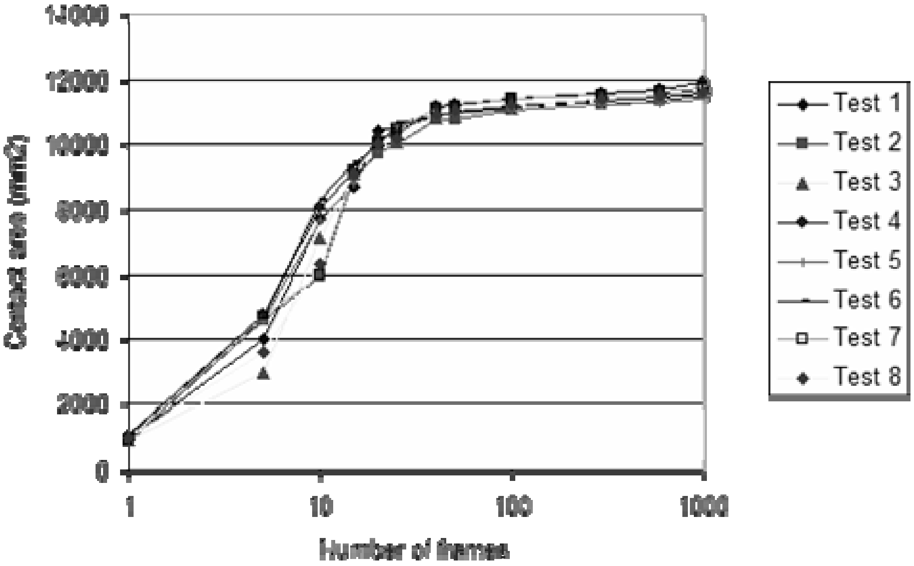

Figure 7: Relationship between measured contact area and number of frames

Figure 8 shows example contact area plots based on merging 100 individual frames collected during dynamic testing [1]. From left to right the images are for chipped HRA, unchipped HRA, 6mm SMA and 14mm SMA. Tracking with the GripTester tyre has caused the flexible pressure pad to highlight the areas of contact between the smooth GripTester tyre and the asphalt surface. These simple examples show the variation in pressure and clearly show how this is concentrated on the protruding chippings especially for the chipped HRA and the larger sized SMA.

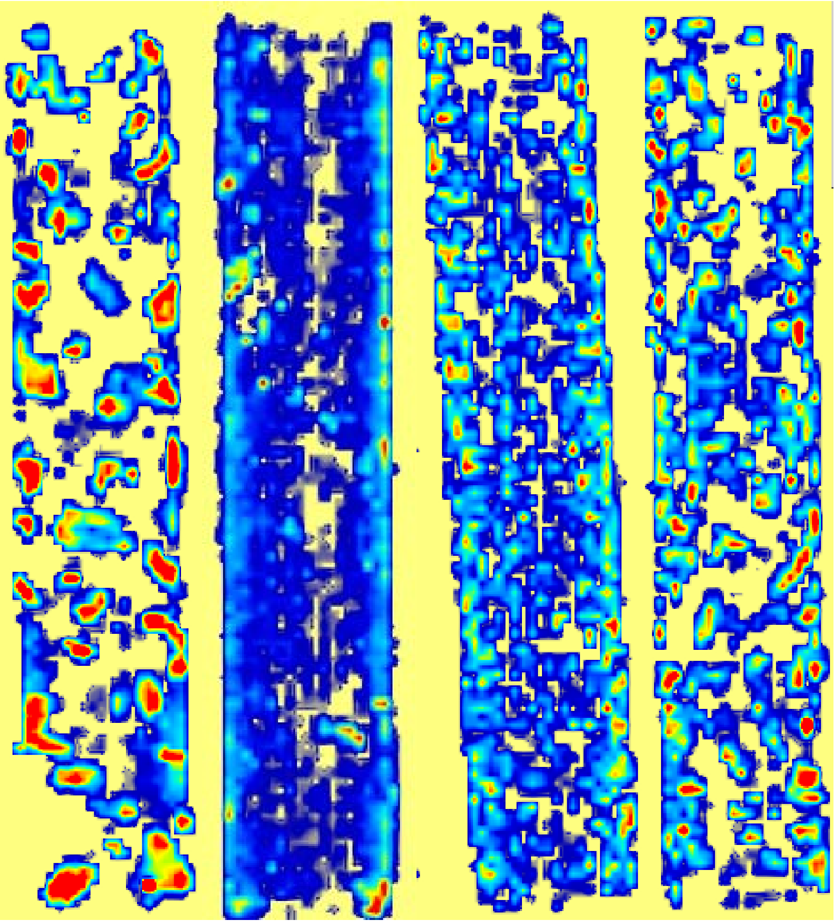

Figure 8. Example composite contact pressure maps for (left to right) chipped HRA, unchipped HRA, 6mm SMA and 14mm SMA [1]

Figure 9 plots the contact area for the merged composite images of 6 different asphalt mixes as a percentage of the value measured for a glass plate / smooth GripTester tyre combination [1]. In the example shown, the 6 asphalt materials had been made with the same greywacke aggregate and subjected to the same period of simulated trafficking [11]. The contact area measured for the glass plate is taken as 100%. The six asphalt materials were 14mm SMA, 10mm SMA, 6mm SMA, unchipped hot rolled asphalt, lightly chipped hot rolled asphalt and chipped hot rolled asphalt.

This example shows their contact area after a 100,000 wheel pass Road Test Machine test (equivalent to 4 days of continuous accelerated trafficking). A ranking of materials in relation to material type and nominal aggregate size is evident. The contact area for the low texture unchipped HRA is almost as great as the glass plate. The application of chips decreases the contact area with the smallest contact area for the examples shown recorded for the chipped HRA. The 14mm and 10mm SMA materials had comparable contact area with the 6mm SMA having a higher contact area.

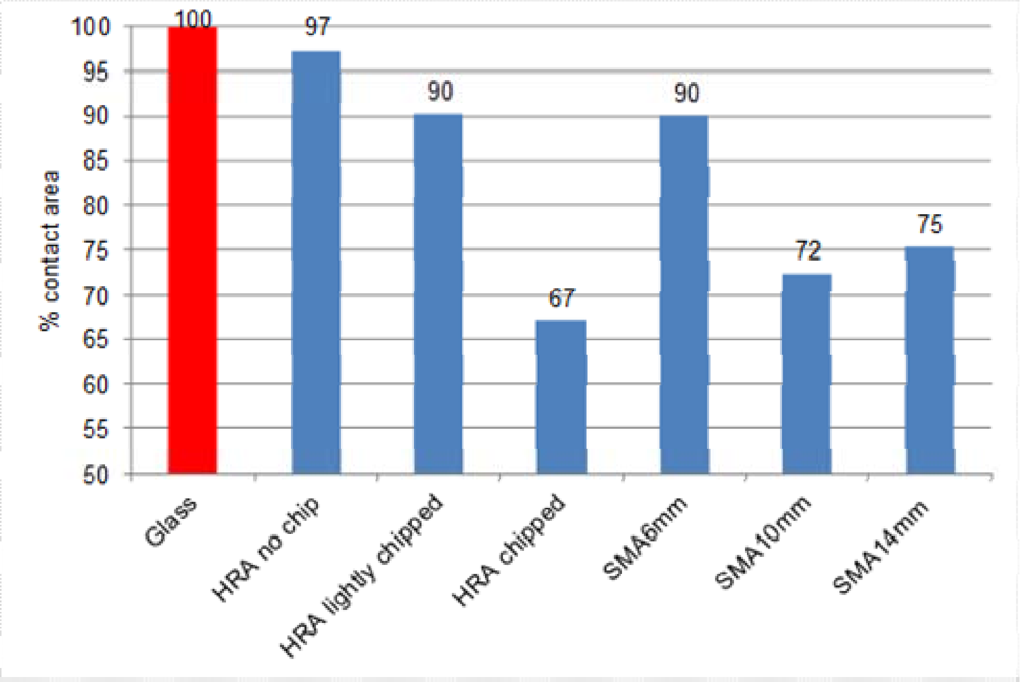

Figure 9. Percentage contact area related to a glass surface of 100% for 6 asphalt surfaces [1]

Figure 10 shows a composite pressure distribution of the tracked AC slab test specimen shown in Figures 2, 4 and 5. This example clearly shows a zone of increased contact stressing around the hole in the centre of the image reflecting how a tyre would interact with the surface in such circumstances. Subsequent trafficking weakened the surrounding aggregate / bitumen bond leading to growth of an embryonic pot-hole.

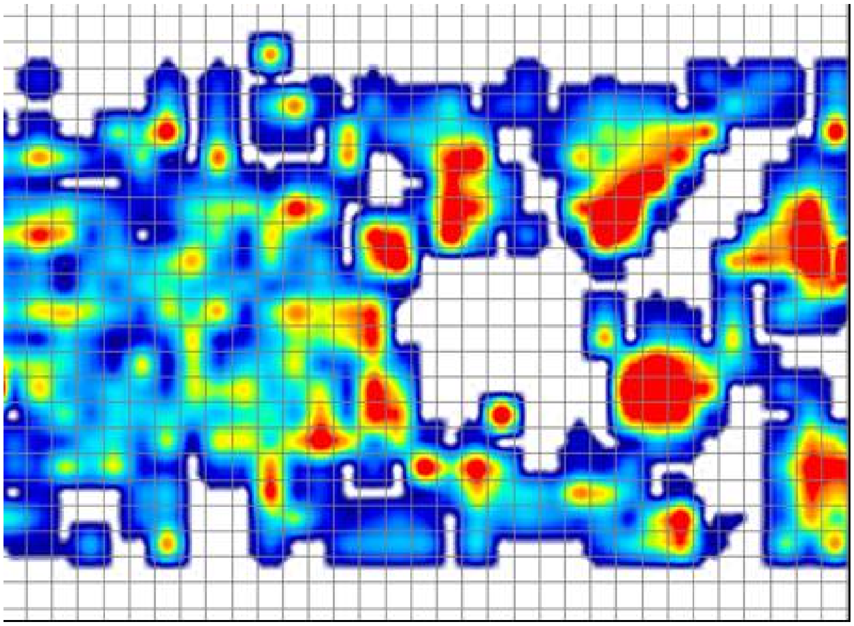

Figure 10. Pressure map showing concentrated contact around a missing piece of coarse aggregate in the centre of the image i.e. an embryonic pot-hole [1]

Such differential pressures accelerate pothole development and other asphalt surface textural changes at the macro and micro scale. The stress distribution shown in Figure 10 indicates that modest variation in texture configuration can result in significant variation in stress. It also indicates that there is a rapid fall in stress at and around the margins of the surface aggregate in contact with the tyre. Should the void be sealed by the tyre and full of water for example, the resulting hydraulic pressure will accelerate breakup of the surface.

Discussion

Methods have been developed to improve the measurement of surface textures and surface / tyre interaction. Variation in surface textures results in considerable peaking or rapid fall-off in contact stress. Combination of topographical and interfacial stress datasets allow improved understanding. Figure 11 is a further depth banded reconstruction to show surface relief. Figure 12 shows a 3d stress plot of the same area. The correspondence of key features in each image is obvious.

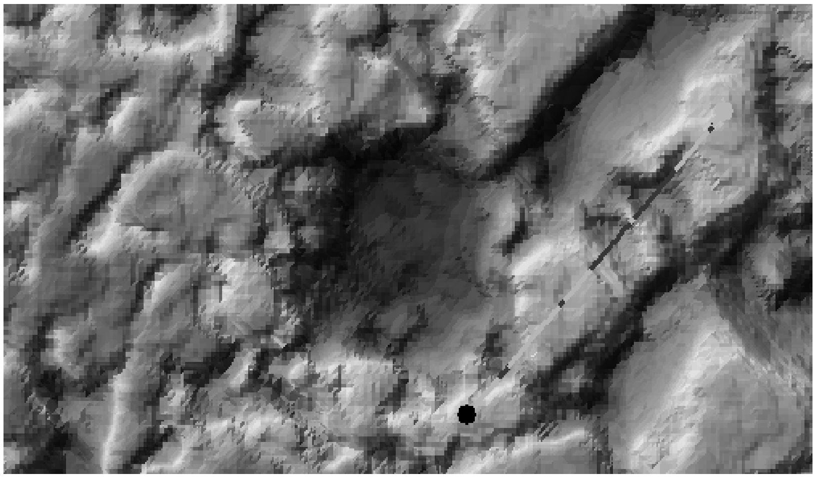

Figure11: Depth banded surface relief reconstruction

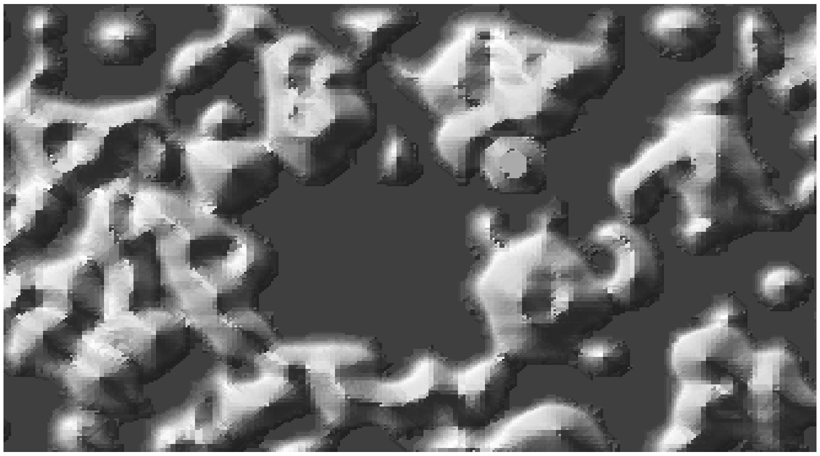

Figure 12: Three dimensional stress plot

Figure 13 shows comparative stress and topographic profiles across a section of this image. The highest stresses are associated with the highest elevations. Although there is good agreement between the plots there are also anomalies. For example, the flat bottoms of the stress plot suggests the depth to which the tyre may drape into the surface texture indicating the potential for water entrapment.

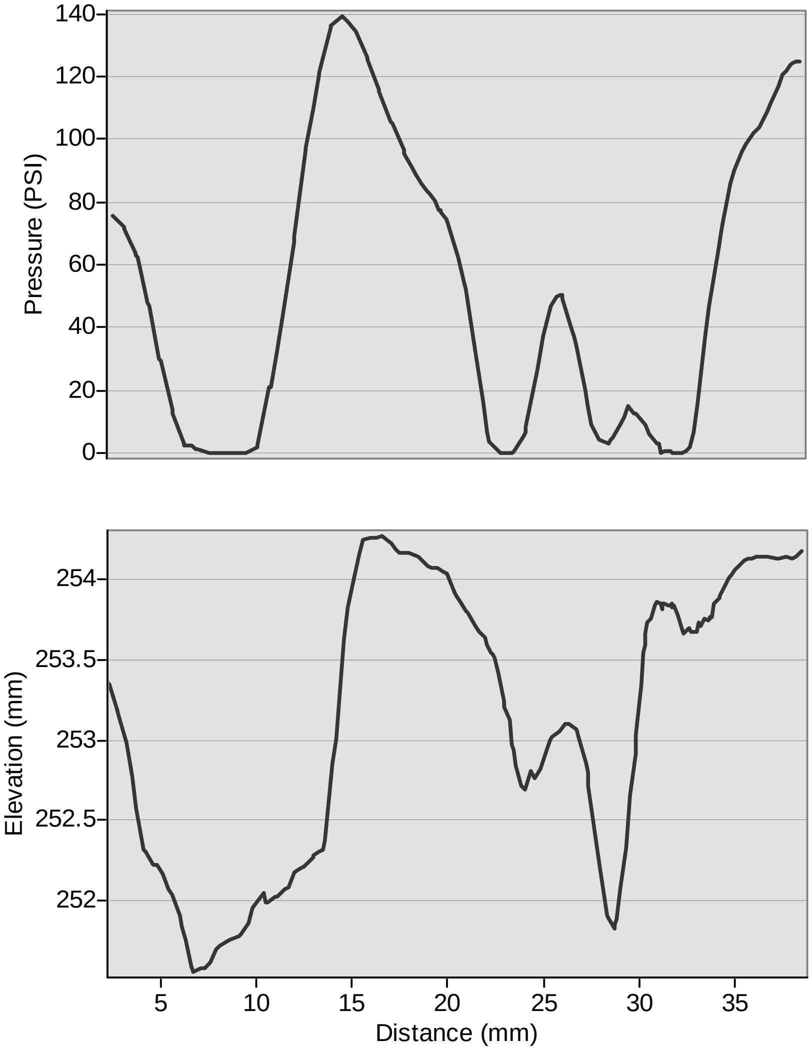

Figure 13: Comparative plots of peak pressure (top) and topography (bottom)

Although the XSENSOR® mat is highly flexible at only 1.1mm overall thickness it seems likely that insertion of any rubber sheet between tyre and surface will potentially reduce draping and smooth contact stresses. Preliminary research at Ulster indicates that this is likely to be modest and a function of the elasticity of the sheet as well as its thickness. For example insertion of an additional 1.2mm ethylene propylene diene monomer (EPDM) rubber reduces contact area by approximately 0.4% whereas EPDM cloth, a thinner and more elastic material increases contact area by approximately 10.9%. More extensive research is required in order more precisely evaluate the extent to which interfacial membranes affect contact area and stresses.

CONCLUSIONS

This paper presents a methodology for mapping interfacial stress to surface micro and macro-topography. A new method of measuring both static and dynamic contact patch phenomena such as contact area and stress variation has been summarised. 3d images based on stereo images captured using a standard SLR camera was used to build TIN surface meshes. Stress distribution traces were imported as raster data sets and transformed to the same reference system. Mapping interfacial stress to surface topography clearly indicates how contact pressure may vary significantly across the surface of an asphalt material. Even modest variation in the different scales of surface texture can have significant impact on stress. There are significant areas of the contact patch where there is no contact between the tyre and asphalt surface.

Depth banding suggests that below a certain depth there is rapid drop in stress indicating the draping effect of a tyre on a textured surface. The example of an embryonic pothole shows how interfacial stress values are significantly elevated locally around its perimeter. This developing research area is showing how the combination of tyre draping effects, localised stressing, entrapped water, hydraulic pressures lead to selective weakening of asphalt surfacings and better understanding of its longer term durability.

REFERENCES

Woodward D, Millar P and Friel S, From Vehicle /Surface Interaction to Quiet Surface Dressings. Presented at 10th International Conference on Sustainable construction Materials and Pavement Engineering, 16-17th February 2010, Liverpool, UK.

Ivanov V, Shyrokau B, Augsburg K, and Algin V. Fuzzy evaluation of tyre-surface interaction parameters. Journal of Terramechanics. Volume 47, Issue 2, April 2010, pages 113-130.

Millar P, Woodward D and Woodside A. Use of Close Range Terrestrial Photogrammetry to assess Accelerated Wear of asphalt concrete surfacings. *The Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control, July 8-10, 2009, POLITECHNICO DI TORINO, Italy. Torino,* pp. 734-740.

Millar P and Woodward D, Application of Digital Elevation Models to Delineate Areas of Residual Water in Highway Surfaces, *Proceedings of ITRN 2010, 31st August to 1st September 2010*, University College Dublin, Ireland.

Liu GX. The area and stresses of contact between tyres and road surface and their effects on road surface. DPhil thesis, School of the Built Environment, University of Ulster, 1992.

Douglas R A. Tyre / road contact stresses measured and modelled in three coordinate directions. NZ Transport Agency research report 384. ISSN 1173-3764, 2009.

Conville S. The measurement of contact phenomena under a GripTester tyre. MSc Thesis, School of Built Environment, University of Ulster, 2010.

Siegfried. The study of contact characteristics between tyre and road surface. DPhil thesis, School of the Built Environment, University of Ulster, 1998.

Douglas RA, Woodward WDH and Woodside AR. Road contact stresses and forces under tires with low inflation pressure. Canadian Journal of Civil Engineering, 27, pp 1248-1258, 2000.

Douglas RA, Woodward WDH and Rogers RJ. Contact pressures and energies beneath soft tires: modelling effects of central tire inflation-equipped heavy-truck traffic on road surfaces. TRB Record 1764, Washington, pp 59-69, 2003.

Friel S, Woodward D, Woodside A and Fitzpatrick S. Laboratory prediction of early life asphalt surfacing properties. *Proceedings of ITRN 2010, 31st August to 1st September 2010*, University College Dublin, Ireland

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