APPLICATION OF DIGITAL ELEVATION MODELS TO DELINEATE AREAS OF RESIDUAL WATER IN HIGHWAY SURFACES

P.A. Millar[1] and W.D.H. Woodward[2]

1. School of the Built Environment, University of Ulster, Northern Ireland; email: p.millar@ulster.ac.uk
2. School of the Built Environment, University of Ulster, Northern Ireland; email: wdh.woodward@ulster.ac.uk

ABSTRACT

In spring 2010 Ireland emerged from one of the most protracted periods of cold weather in decades. Time will tell the full extent to which highway pavement surfaces and transport infrastructure have been affected by the extreme freeze/thaw conditions and the impact of traffic on standing melt water. The effectiveness and efficiency of a pavement surface to clear water is largely a function of its macrotexture through a network of continuous water channels. These may be 2-dimensional and restricted to surface flow, or 3-dimensional and allow additional drainage within the surface layer. If water is not removed there is significant potential for damage to the surface due to freeze/thaw and/or hydraulic processes applied to pockets of trapped water. This paper reports the findings of a study which demonstrates the potential of digital elevation models to identify and delineate areas of water entrapment. In this study, digital elevation models (DEM) were generated for a range of surface textures measured during a road trip in Western Europe. They were combined with raster overlays within a proprietary GIS platform and used to highlight potential areas of water lock-in by applying depth banded thresholds. Critical entrapment depths are specified for the full range and diversity of textures. A simplified methodology for capturing discrete surface areas using close range photogrammetry is included. The DEM data may be used to gauge the susceptibility of a pavement to surface breakdown and trigger appropriate remedial measures.

Keywords: Digital Elevation Models, Macrotexure

1 INTRODUCTION

Protracted periods of cold weather have the potential to expose highway surfaces to prolonged effects of water. Texture at the tyre surface interface is vulnerable to cyclic freeze thaw mechanisms but standing melt water and reduced rates of evaporation exacerbate the stresses within the material due to hydraulic pressures due to dynamic traffic loading. It seems reasonable therefore that a methodology which aids in identification of vulnerable surfaces would be very welcome.

The benefits of such are potentially significant. Knowledge of vulnerable areas would allow costly maintenance resources to be concentrated where they are most needed based on a ranking system. Avoidance schedules could be designed and implemented so that access to high risk areas could be curtailed. De-icing regimes could be applied in a targeted manner.

It may be argued that attempting in any way to control vehicular access to already overloaded highway networks is impracticable. But, given that vast areas of the highway network are barely negotiable during sever weather conditions this is not considered a valid argument. Any regime that has the potential to optimise use of the network in a sustainable manner by targeting limited resources during financial constraint is to be welcomed. A contribution to the development of such is presented in this paper.

The propensity for water to accumulate on and within highway pavement surfaces leads inevitably to a consideration of surface textures and in particular the macrotexture. There are numerous definitions of surface texture such as that by Flinstch et al, (2003) in which it is described as '*The feature of the road surface that ultimately determines most tire-road interactions such as wet friction, noise, splash and spray, rolling resistance and tyre wear*. It may reasonably be concluded therefore that a methodology that can aid in the accurate in-situ characterisation of the tyre-surface interface has much to contribute to the prediction of risk and performance.

There is little doubt that the tyre-surface interface is complex. The range of techniques and technologies developed to evaluate it is evidence enough in itself and highlights the challenges facing researchers in this respect.

Bushan, (1997) notes for example that modelling of the contact of rough surfaces is difficult especially with a view to the development of a theoretical model because rough surfaces exhibit a random structure. That this remains a challenge is not in doubt as newer systems and methodologies such as that by Erdogan et al (2006) frequently combine sophisticated technologies.

This paper advocates a spatial approach which goes beyond simple geometric estimation. The well known and researched sand patch for example has stood the test of time but offers little direct insight to process occurring at the tyre surface interface.

In this study digital elevation models (DEM) of discrete areas of highway surface textures are imported into a proprietary GIS. The meshes are thresholded to highlight areas of texture liable susceptible to protracted water entrapment. Such areas are by definition vulnerable to freeze thaw and dynamic hydraulic mechanisms with resultant surface breakdown with obvious implications for maintenance requirements.

There are few studies addressing a three dimensional approach to characterising highway surface textures. Erdogan et al (2006) describes new techniques for characterising the shape of aggregates. The study combines X-ray computed tomography, two and three dimensional image analysis and three dimensional particle reconstructions from two dimensional slices.

However as Erdogan acknowledges, acquiring true, full three dimensional imaging using this method is challenging noting that the scanning process can require hours. Against this background the benefits of a methodology based on rapid capture of surface images at source.

This paper advocates a simplified approach to surface characterisation in which images are captured directly using consumer grade technology. In addition it is intended to present potential area of water entrapment as a predictor of risk in the form of a simple. Indices are expressed as the fraction of the area of water entrapment relative to the overall two dimensional area of the sample overall two dimensional sample area index. A 10,000mm^2 pothole for example would have an index of 1.

As stated by Woodward et al (Date?) predicting for risk is *essentially testing for failure and applies to both on-site measurement and laboratory prediction.* It has been shown by Millar et al, 2009 that DEMs are a viable analytical aid in the mechanical performance of asphalt samples in the laboratory. The opportunity to explore their potential in-situ is therefore welcome.

2 AIM AND OBJECTIVES

The overarching aim of this study is to assess and establish the application of banded DEMs to assessment of the risk of highway surfaces to freestanding water. For the purpose of the study this is to be understood in two ways. In the first instance it may be resident in small pockets having a definable perimeter likely to fall within the area of a tread block. Secondly it may be understood as an area of water extending beyond a tread block perimeter but with no clear drainage path. Whilst each has its own implications in respect of risk to the pavement it is the first definition which is the main focus of this paper. This water may be in the form of small pockets of melt water having a definable perimeter.

It is proposed to realise this aim through a number of objectives. In the first instance it will be confirmed that surfaces modelled from image captured at source present a fair reflection of the surface relief. This will be demonstrated by superimposing original raster images over contoured models to indicate clear correspondence. Secondly the suitability of the sample size and its geometric integrity will be confirmed by comparison with data derived from sand patch tests. Finally the potential correlation of DEM properties and areas of water entrapment with statistical measures will be explored.

3 METHODOLOGY

A study by Slimane et al, (2008) notes that '*Road Surfaces can be considered as 3D textured images in which micro-asperities existing on aggregate surfaces are the microtexture, and aggregate contours are the macrotexture'* The study further notes the difficulties associated with extracting surface relief information from images.

For this reason the authors advocate a direct controlled approach in which stereo photo pairs are captured or real surfaces (referred to in this paper as samples) in-situ. This has the benefits of contextualising the study to the actual highway network and reduces significantly any dependency on controlled lighting conditions or sophisticated technological enhancements.

Stereo photo pairs were captured under non controlled ambient but dry conditions of highway surface textures at twenty three locations in Italy, France and the United Kingdom. The surfaces varied significantly in material type, age, and wear. Immediately following image capture the mean texture depth was estimated using the sand patch method. A typical configuration is illustrated in Figure 1

Figure 1: Typical Image Capture Configuration

A simple arrangement of stainless steel rules was used to provide scale for the processed images. This avoided the requirement for referencing the images using a template of three dimensional control coordinates. Whilst this rendered the orientation of the images arbitrary it allowed the DEMs to be transformed by incremental rotations to simulate camber or crossfall. The areas of models ranged form approximately 7,088mm^2 to approximately 28,307mm^2.

The mean texture depth as determined by the sand patch test and subsequently by the triangulated model showed an R^2 correlation coefficient of better than 0.93

In order to characterise the surface the transformed images were meshed at an interval of 200 microns. A typical surface model is shown in Figure 2.

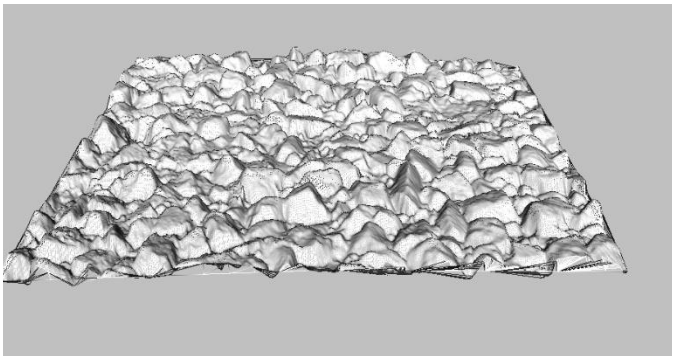

Figure 2: Three Dimensional Model

The solid appearance of the texture shown in Figure 2 is due not to greyscale rendering but to the density of the mesh. The three dimensional coordinates of each of the triangle vertices was exported as a straightforward comma separated values (CSV) file and then imported to a proprietary GIS. Having reformed the surfaces they were depth banded at 0.1mm intervals from the base coordinate elevation value.

A typical depth banded surface is shown in Figure 2. This includes contours at a vertical interval of 0.5mm in order to enhance the surface relief. To avoid unnecessary occlusion the 0.1mm contours are not displayed. A number of the enclosed vulnerable areas are circled for clarity.

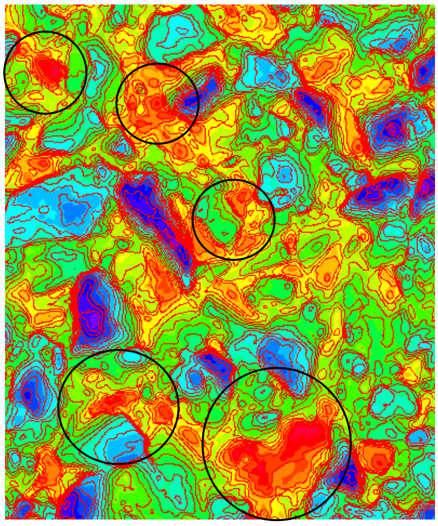

Figure 3: Depth Banded Surface

A raster overlay of each of the original images was superimposed over or, where necessary transformed to the surface of each model. This was in order to associate the enclosed areas with the configuration of the surface. A typical model/raster overlay is shown in Figure 4

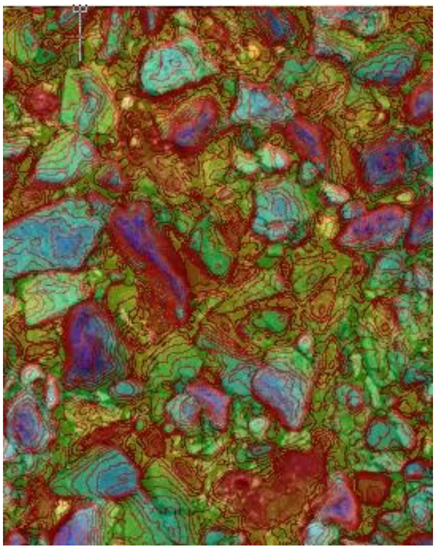

Figure 4: Model with Superimposed Raster

A statistical analysis was carried out on each of the coordinate data sets. This included descriptive statistics and frequencies. The objective was to ascertain to what extent highway surface textures were truly random by investigating their conformity to a normal distribution. In doing so it is acknowledged by the authors that there is much useful additional information which may be gleaned from the DEMs that is not available from older surface profiling methods,

This has been recognised but perhaps seldom exploited. For example Jim Zhu J and Zhu W, (1996) noted even then that the tendency was to characterise surface by a one figure statistic of pavement profile data whilst discarding '*a rich body of useful pavement information'* and went on in the study to propound a Stochastic Roughness Index.

It is not the objective of this paper to add anything in detail at this stage to a consideration of roughness indices so much as explore the extent to which water lock in may be correlated to some aspect of the frequency distribution of the modelled surface.

4 RESULTS

Each of the twenty three images was processed successfully and areas of confined water retention clearly delineated across the full range of textures.

Figure 5 for example shows a banded model of a fine textured 10mm asphalt concrete with limestone aggregate.

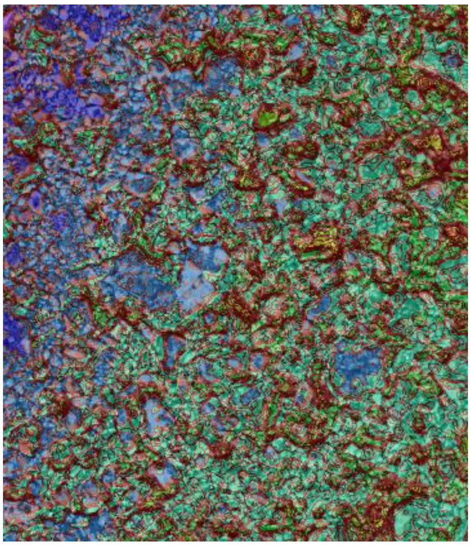

Figure 5: Depth banded model of 10mm asphalt concrete

By contrast Figure 6 shows a depth banded model of a 14mm crushed gravel asphalt concrete. The model of a 6mm/14mm surface dressing is already shown in Figure 4 earlier in the paper. It was found that all the sampled surfaces exhibited areas of risk of water confinement not exceeding 3.5mm above the base coordinates for each model.

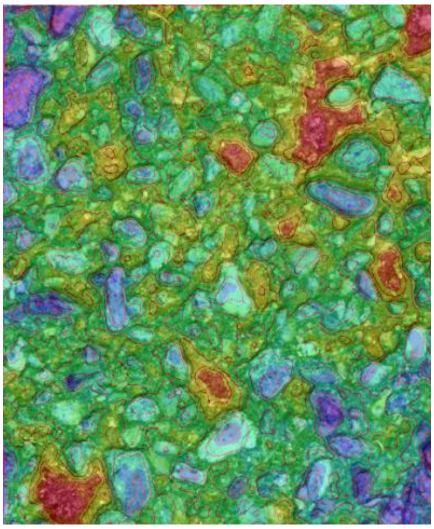

Figure 6: Depth banded model of 14mm/6mm surface dressing

A risk index based was determined based on the fraction of the overall area of each sample vulnerable to water confinement. This ranged from 0.007 to 0.165 with a median value of 0.087.

The mean texture depth as determined by the sand patch test and volume calculations of the models displayed a correlation coefficient better than 0.93 as shown in Figure 7

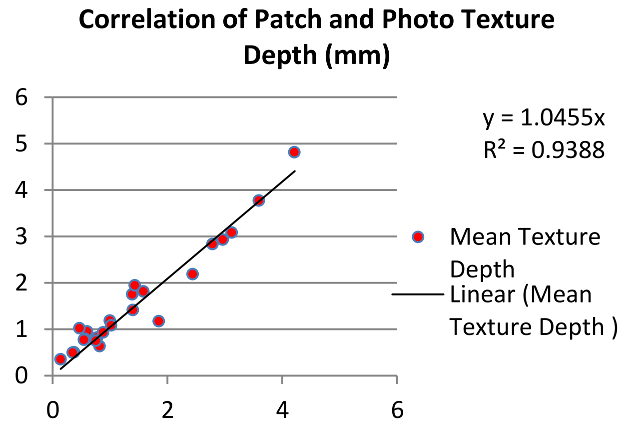

Figure 7: Correlation of MTD estimated by sand patch and DEM

Frequency analysis of the data sets indicated that most surfaces coordinates are characterised by a normal distribution. Figure 8 for example shows the distribution for a 14mm/6mm surface dressing. Other distributions displayed significant skew and kurtosis. Figure 9 for example shows the distribution for a heavily trafficked 14mm single size surface dressing characterised by pronounced areas of discrete surface relief.

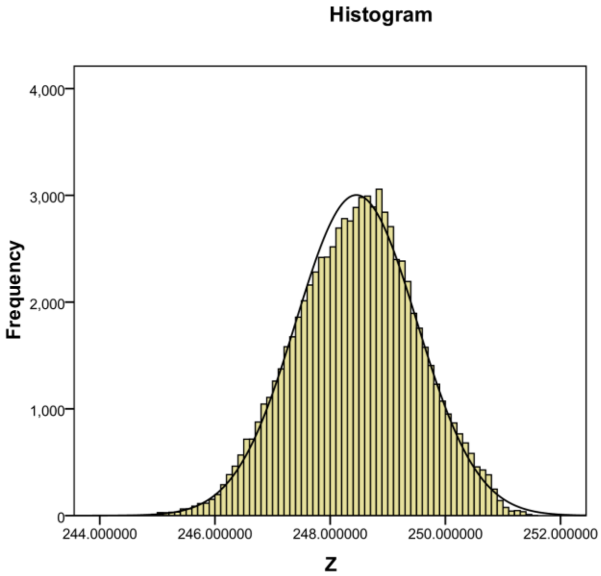

Figure 8: Frequency distribution for 14mm/6mm surface dressing

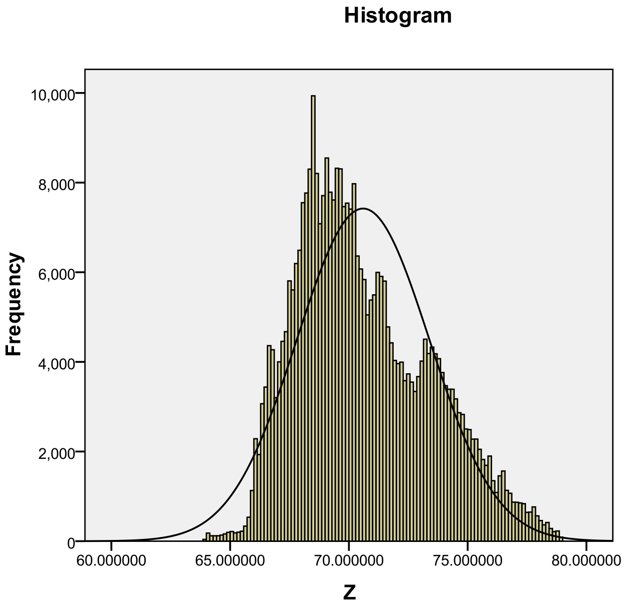

Figure 9: Frequency distribution for heavily trafficked 14mm single size surface dressing

The original image and corresponding model of the 14mm surface dressing and overlay are shown side by side in Figure 10. This shows clear agreement of the model and the raster overlay

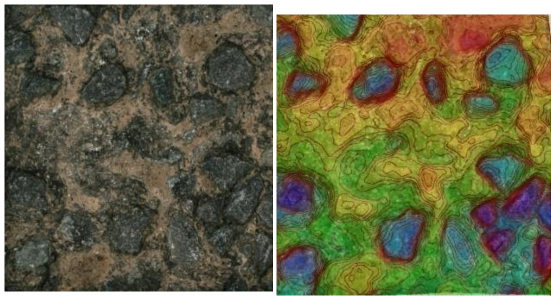

Figure 10: Image and corresponding model of 14mm single sized surface dressing

A possible correlation between mean texture depth and the standard deviation of the frequencies for all the samples was investigated and found to be unconvincing displaying an R^2 coefficient of only 0.407. However, removal of one obvious outlier, corresponding with a particularly poor transformation improves the correlation to 0.709 as shown in Figure 11.

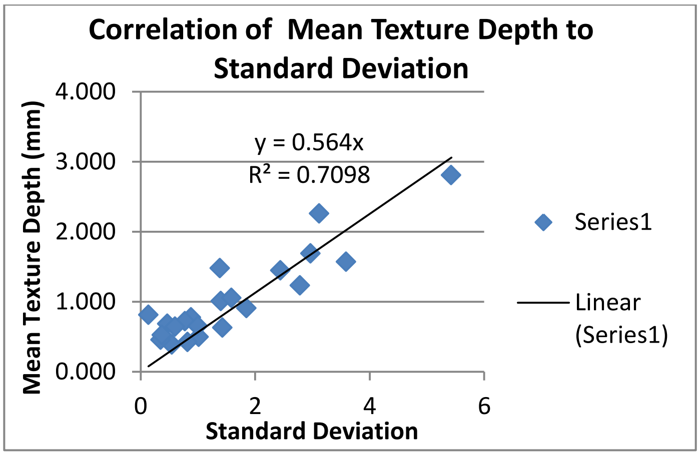

Figure 11: Correlation of MTD and standard deviation

A possible correlation of various measures of water confinement in this paper (2D area, index) with statistical descriptives was investigated but found to be initially disappointing. Apart form an area of poorly define cluster near the area axis the point plot was found to be quite random as shown in Figure 12

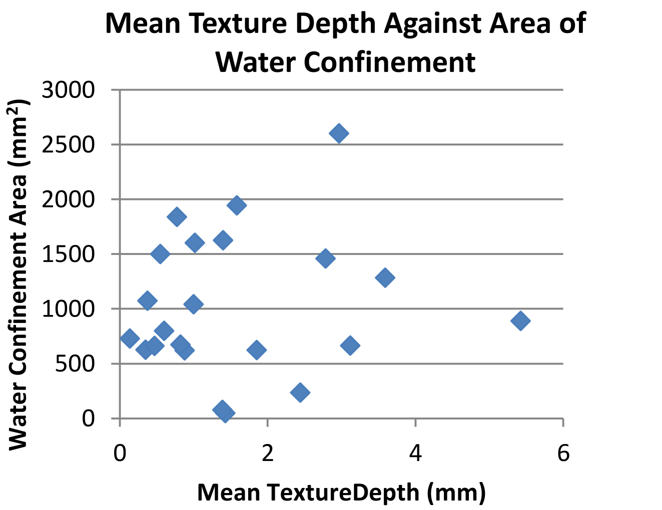

Figure 12: Plot of Mean Texture Depth Against Area of Water Confinement

Correlations were then investigated for groups of samples. Three groups were compiled based on the proximity of notionally straight line clusters near the area axis in Figure 12 and highlighted in Figure 13. R^2 correlations for groups 1 to 3 were promising ranging from 0.74 to 0.94. Two additional groups were complied from points to the right of the plot but correlations were unimpressive at 0.54 and 0.45 respectively. The correlation plot for Group 2 comprising five samples is shown in Figure 14

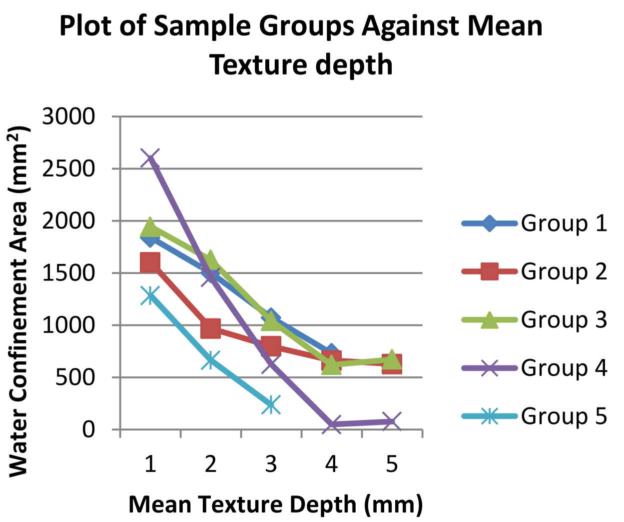

Figure 13: Plot of sample groups against mean texture depth

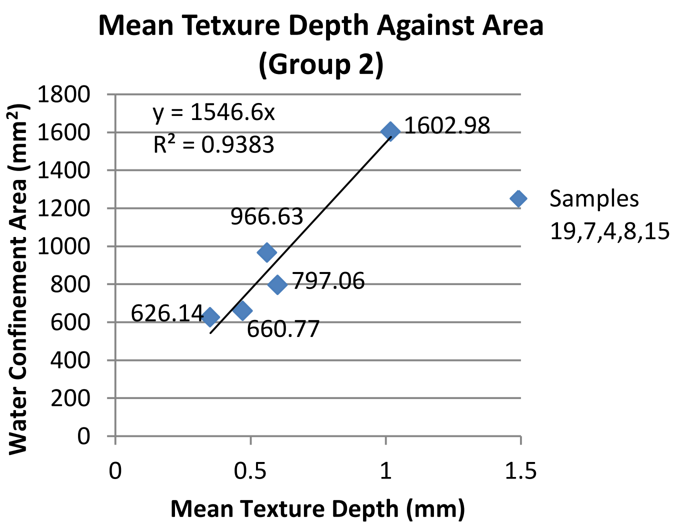

Figure 14: Correlation plot for sample group 2

5 DISCUSSION

The facility for banded DEMs to indicate areas of water confinement is not in doubt as is clearly shown in Figures 3,4,5,6 and 10 in which the contoured surface relief and raster overlays clearly match within the same coordinate system. Nevertheless the usefulness of the methodology to rank surfaces in terms of risk is only as sound as the quality of the DEM. The mean texture depth determined from the DEM correlates strongly with that determined using the well researched and extensively applied sand patch method. It is therefore reasonable to conclude that the integrity of the DEM is sound. It also goes some way to confirming that the photo analysis sample sizes are representative and appropriate.

No sample exhibited a water confinement cut-off level higher than 3.5mm above the base coordinate level. However as this applied to one sample only it is more reasonable to conclude that maximum cut off levels are likely to be somewhere between 3 and 3.5mm. The majority of samples fall within the 1.5 to 2.5 classification. It is likely that setting a closer banding increment of say 0.1mm would offer a more definitive range and more accurate area estimates.

Frequency analysis on the surface datasets suggests that the surfaces tend to be randomly rough. This may be why direct correlations between variables are somewhat difficult. There are however distributions such as that shown in Figure 9 which display a pronounced skew. It is clear from Figure 10 that the distribution is reflected in the protrusion of aggregate on a heavily trafficked road. It cannot therefore reasonably be concluded that such surfaces are randomly rough but it seems reasonable to suggest that the distribution could be a quality indicator.

Figure 15 shows a heavily skewed distribution of the surface of a 10mm asphalt concrete. It is noted by Kerr et al (2003) that a few extreme values can significantly skew the distributions. This can indicate a level of error or bias in some types of research study. It is not so in this instance. The surface is what it is and it is not surprising therefore that this sample has cavities in the underlying matrix.

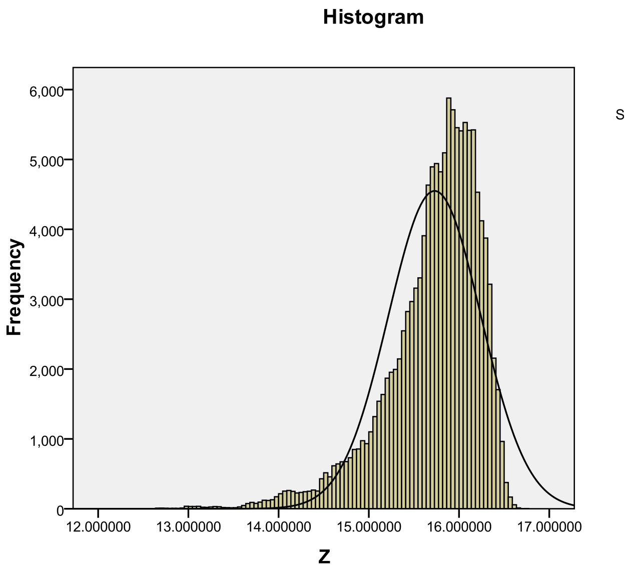

Figure 15 Frequency distribution showing significant skew and kurtosis

As may be observed from Figure 12 there is no clear correlation of area of water confinement to mean texture depth for the samples in this study. This is unsurprising given the range of samples and their characteristics. Grouping samples according to the line clusters located near the area axis produces better correlations (R^2 up to 0.94) where the group sample points are closely spaced. This would suggest that rather than an analysis of a range of indiscriminate samples it may be better to carry out focused analyses of surfaces exhibiting similar characteristics.

6 CONCLUSIONS

A range of datasets comprising the coordinates of DEM vertices were successfully imported and the DEM rebuilt in a proprietary GIS. The resultant models were depth banded at 0.5mm vertical intervals commencing at the base coordinate value in each case. Areas of water containment are clearly delineated and measurable to give a simplified risk index for each of the samples as a fraction of the overall two dimensional area in each case.

The containment indices range from 0.007 to 0.166 indicating that every sample is vulnerable to the effects of entrapped water however slight that risk might be. Although critical containment cut off depths extended to 3.5mm above the base level it is concluded that the majority of surfaces will fall within the 1.5 to 2.5 cut-off limit. This accounts for 16 or 70% of the surfaces sampled in this study.

There does not appear to be a direct correlation of mean texture depth to areas of water confinement when considered across the whole sample. However sub groups of samples displaying similar characteristics show R^2 correlation coefficients ranging from 0.74 to 0.94. The correlation degrades with increasing spacing between points on the plot.

There is an R^2 correlation between the mean texture depth and the standard deviation of the coordinate values across all samples of 0.71. The correlation is sensitive and liable to significant variation from addition or removal of mean texture depth values.

REFERENCES

BS 598-105:2000 - Sampling and examination of bituminous mixtures for roads and other paved areas. Part 105: Methods of test for the determination of texture depth

Erdogan, S., Quiroga, P., Fowler, D., Saleh, H., Livingstone, R., Garboczi, E., Ketcham, P., Hagedorn, T., and Satterfield, S., 2006. Three Dimensional shape analysis of coarse aggregates: new techniques for and preliminary results on several different coarse aggregates and reference rocks. *Cement and Concrete Research*, Vol 36 (2006), pp1619 - 1627.

Flintsch, G.W., de Leon, E., McGhee, K., and Al-Quadi, I. L., 2003.Pavement Surface Macrotexture Measurement and Application. *Journal of the Transportation Research Board*, Vol 1860, pp 201-209.

Jim Zhu J., and Zhu W., 1996, STOCHASTIC MODELLINGOF PAVEMENT ROUGHNESS, *Journal of IEEE (more details required)*

Kerr A. W., Hall H, K., and Kozub S.A., 2003, *Doing Statistics With SPSS.* London, Sage Publications Ltd.

Luhman, T., Robson, S., and Kyle, S., 2006. *Close Range Photogrammetry: Principles, Techniques And Applications.* Oxford, Wiley

Millar P., Woodward. D. and Woodside. A., 2009. 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

Slimane A., Khoudeir M., Brochard J. and Do M, 2007. Characterization of Road Microtexture by Means of Image Analysis. *Wear (2008),* Vol 264, pp464-468.

Transport and Road Assessment Centre, (Date?), Early and mid life SMA skid resistance. University of Ulster: Woodward, W.D.H., Woodside, A.R. and Jellie., (Date)., SKIDGRIP project.