QUANTIFICATION OF AGGREGATE GRAIN SHAPE CHARACTERISTICS USING 3-D LASER SCANNING TECHNOLOGY

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ABSTRACT

Aggregate shape and surface characteristics influence the performance of both bound and unbound pavement materials. This paper presents some results of an on-going study on the characterization of aggregates using a three-dimensional (3-D) laser scanner technology. A sample of coarse aggregate andesite particles passing 19.0 mm and retained on 13.2 mm sieve was used for the study. The 3-D images from the laser scanning device were fully utilized in quantifying the shape descriptors in order to identify the differences between individual aggregates. It was possible to quantify differences in particle shape characteristics at the small particle scale. The study has demonstrated the advantages of the innovative 3-D laser scanning technology to quantify the shape characteristics of aggregate particles.

1. INTRODUCTION

The paper presents preliminary work which forms part of an on-going investigation at the CSIR, in the quantification of the aggregate shape parameters using a 3-D laser scanning technology, and then linking them to the performance of pavement materials. The development of methods for the description of particle shape can be traced as far back as in the 1930s, with early work being attributed to sedimentary petrologists (Jaboo, 1998). There are several reasons why quantification of aggregate grain shape is important and the development of methods of aggregate shape characterization continues to date. The reasons include, for example, the fact that determinant factors for the overall macroscopic response of a granular material is affected by the shape, angularity and size distribution of the grains at the micro-scale (Das, 2006) and the particle shape has been shown to play a role on fabric formation and macro-scale soil properties (Santamarina and Cho, 2004). The increase in angularity and surface roughness of the soil particles resulted in an increase in angle of internal friction (Alshibi et al., 2004). Accordingly, aggregate shape and surface characteristics will influence the performance of pavement materials. Santamarina and Cho (2004) discuss aggregate shape characterization and its importance and cite a number of researchers who have shown that form and surface texture of aggregates have a significant effect on the mechanical properties of bituminous mixes. These mechanical properties include shear resistance, stiffness, fatigue resistance, rutting resistance, workability, and bitumen demand. Good adhesion between a binder and an aggregate is extremely important in surfacing materials such as seals or asphalt mixes. The adhesion of bitumen to aggregates is dependent on several factors including the physical characteristics of the aggregates. Aggregate characterization is therefore a key factor in understanding the performance of both bound and unbound materials in the pavement layers.

Test methods for the determination of descriptors in order to quantifiably describe aggregate shape are summarised in Santamarina and Cho (2004). The most commonly reported procedures for the quantification of aggregate shape characteristics, for example in Rao et al. (2002), involves use of the apparatus which comprises three cameras to collect aggregate images from three orthogonal directions. The particles that are analyzed are fed on to a conveyor belt system, which carries the particles – one by one – towards the orthogonally placed cameras. Each particle is detected by the cameras as they travel into the field of view of a sensor. The cameras are synchronized so the three pictures are taken at the exact same time. However, recent developments in technologies for image acquisition and image analysis such as the 3-D laser scanning make it possible to capture a complete 3-D image as presented by Anochie-Boateng et al. (2010). A projected 2-D image of the 3-D particle can be acquired and various size and shape parameters can be calculated from this 2-D image. Since a complete 3-D image is available from the 3-D laser scanner, the calculation and quantification of shape characteristics can be done on multiple particle views at the small scale and therefore identifying the differences between individual aggregates.

2. QUANTIFICATION OF AGGREGATE GRAIN SHAPE

Particle shape can be classified by the flatness and the elongation ratio; (Barksdale et. al.,1991, Janoo,1998, Masad and Burton, 2000, Al-Rousan et al.,2007). The flatness ratio is defined as the ratio of the shortest dimension (thickness), d_S, to the intermediate dimension (width), d_I. The elongation ratio is the ratio of the intermediate dimension to the longest length (length), d_L. .The combination of elongation and flatness is completely measureable using the 3-D laser technology. The definition of the referencing dimensions is based on the stable position of the particle as shown in Figure 1.

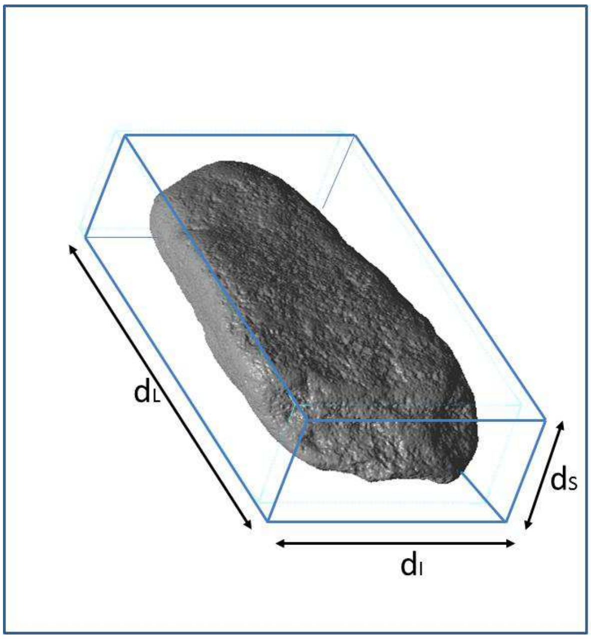

Figure 1: Particle referencing dimensions

Form, roundness and surface texture are the common shape descriptors used in quantifying particle morphology; Das (2006) and Janoo (1998) have presented definitions of some important shape descriptors. Form is quantified in terms of sphericity and is independent of angularity and surface roughness (Sukumaran and Ashmawy, 2001). Roundness, angularity reflect the variation in edges, corners, faces and are related to surface texture. Surface texture in turn reflects the roughness along the particle

(Sukumaran and Ashmawy, 2001). Three different scales for describing the particle shape are clearly identified (Mitchell and Soga, 2005 and Arasan et al., 2010). First order descriptors, such as sphericity and elongation are used to describe aggregate shape at the large particle scale. Second order descriptors, roundness and angularity are used at the intermediate particle scale and finally roughness and smoothness are used at the small particle scale. By combining the flatness- and the elongation ratio the shape of the aggregates can be described by a shape factor, and the sphericity (Uthus et al., 2005) based on the Krumbein definition. The shape factor is the ratio of the elongation ratio and the flatness ratio. There are however challenges in the definition of shape descriptors. Rodrigeuz et al (2013) show how the same shape description quantities are defined differently by different authors. The current work however focuses on flatness ratio, elongation ratio, sphericity, circularity, roundness and solidity of the examined aggregates. The definitions adopted in this paper are presented below and the results of the image analysis will be discussed in terms of these descriptors.

Sphericity is defined in terms of the three aggregate dimensions as shown in Figure 1, based on Krumbein definition (Al-Rousan et al., 2007).

$$\mathrm{Sphericity} = \sqrt[3]{\frac{\mathrm{d_S} + \mathrm{d_I}}{\mathrm{d_L}}} \qquad (1)$$

Roundness in ImageJ software is defined as follows:

$$\mathrm{Roundness} = 4 \text{ x } \frac{[\mathrm{Area}]}{\pi \text{ x } [\mathrm{Major\ axis}]^2} \qquad (2)$$

[Area] is the area of the 2-dimensional projection of the aggregate particle. The roundness varies between 0.1 and 0.9. A value greater than 0.6 indicates high roundness, between 0.4 and 0.6 indicates medium roundness, and less than 0.4, low roundness (Janoo 1998).

Circularity is a measure of the particle's shape relative to a perfect circle. A perfect circle has a circularity of 1, while an irregular object has a circularity value closer to 0.

$$\mathrm{Circularity} = 4\pi \frac{[\mathrm{Area}]}{[\mathrm{Perimeter}]^2} \qquad (3)$$

Solidity is the ratio of area of the 2-dimensional projection of the aggregate particle to the convex area. The convex area can be defined as the area enclosed by an imaginary "string" wrapped around the object (Janoo, 1998). Solidity has values in the range 0 to 1. A low solidity towards 0 indicates a rough particle edge. A high solidity of 1 indicates a smooth particle edge.

$$\mathrm{Solidity} = \frac{[\mathrm{Area}]}{[\mathrm{convex\ area}]} \qquad (4)$$

3. IMAGE ANALYSIS

ImageJ software was used to complement the 3-D laser scanning results for particle characterization. ImageJ is a public domain image processing software (http://rsb.info.nih.gov/ij/). Scanned images from the 3-D laser scanner were processed and analyzed using this software. For the current study, specific plugins were added to the library to perform desired analyses. A built-in option for analyzing particles is available, which produces the descriptors defined by the equations above as output. The particles in this study were fully characterized using the parameters represented by equations above.

4. RESULTS

Nine aggregate particles were studied in order to identify the subtle differences between the individual particles. The particles were randomly selected from a population of 30 particles, passing the 19.0 mm sieve and retained on the 13.2 mm sieve, which were individually scanned in a 3-D laser scanning device at the CSIR. Figure 2 shows the images of the studied particles from the 3-D laser scanning device.

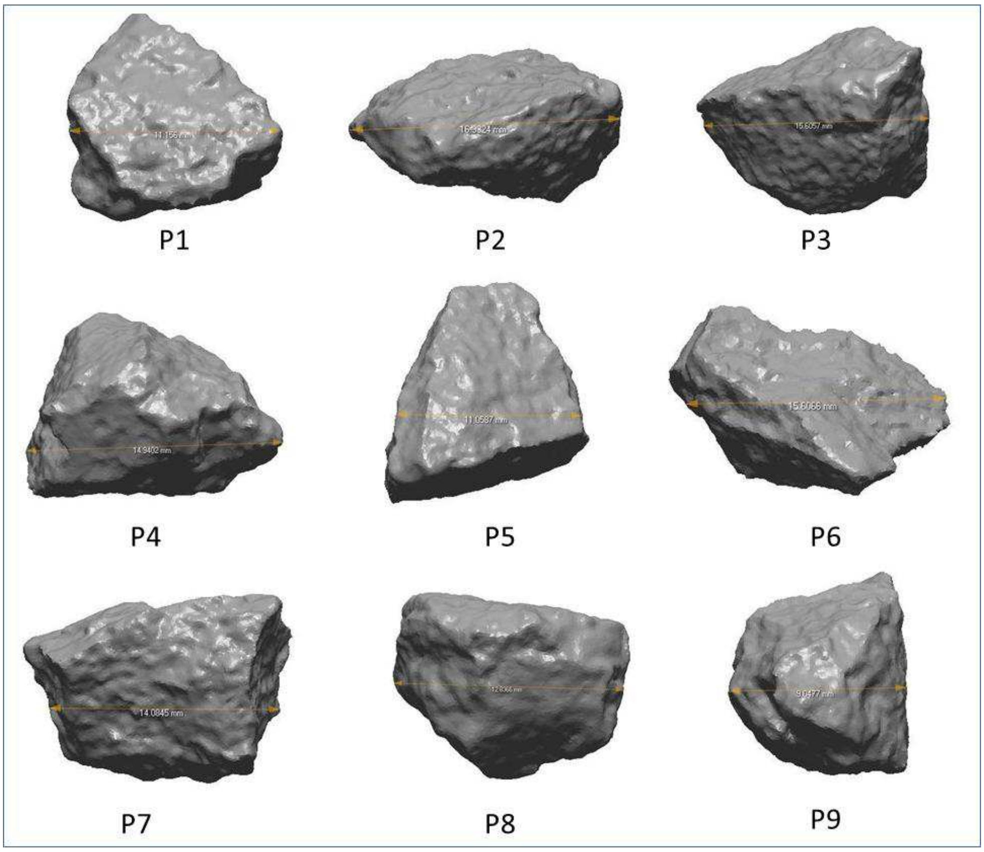

Figure 2: Sampled aggregate particles

Figure 3 shows that at the large particle scale, the particles are generally of similar form and can be described to be spherical or cubic rounded according to Lees (1964).

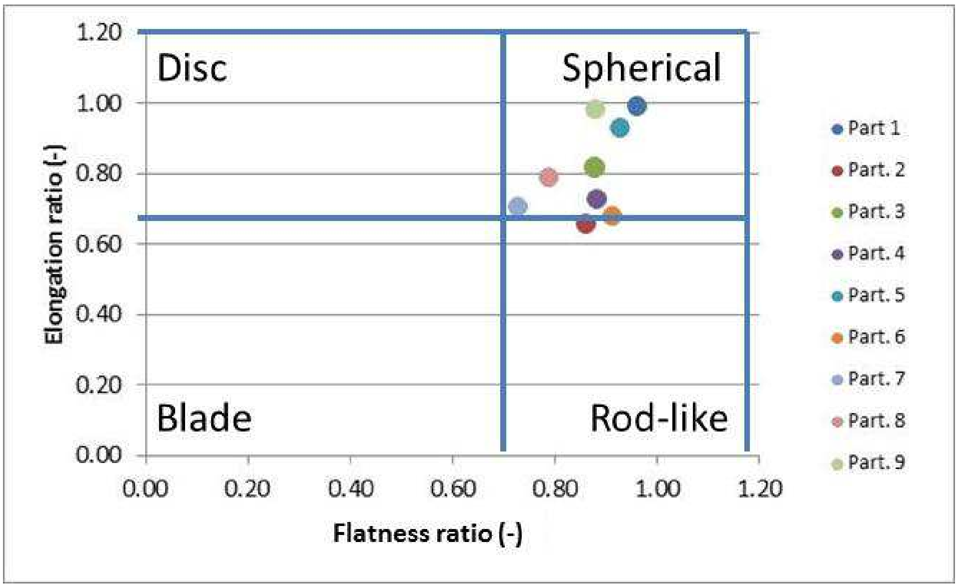

Figure 3: Characterization of grain shape after Lees (1964)

However, particles 2, 6 and 7 are on the lower boundary with rod-like grain shape.

The availability of the 3-D images from the laser scanning device, made it possible to acquire six views for each particle, for analysis. Figure 4 shows different side views of a particle and the corresponding images produced by the ImageJ software for analysis. For brevity, results for only one particle are presented. Each individual particle was processed the same way. The objective of using six views was to identify and quantify the scale of differences in the shape descriptors for an individual particle. The calculation of the shape descriptors is based on the 2-D projections of the particle views.

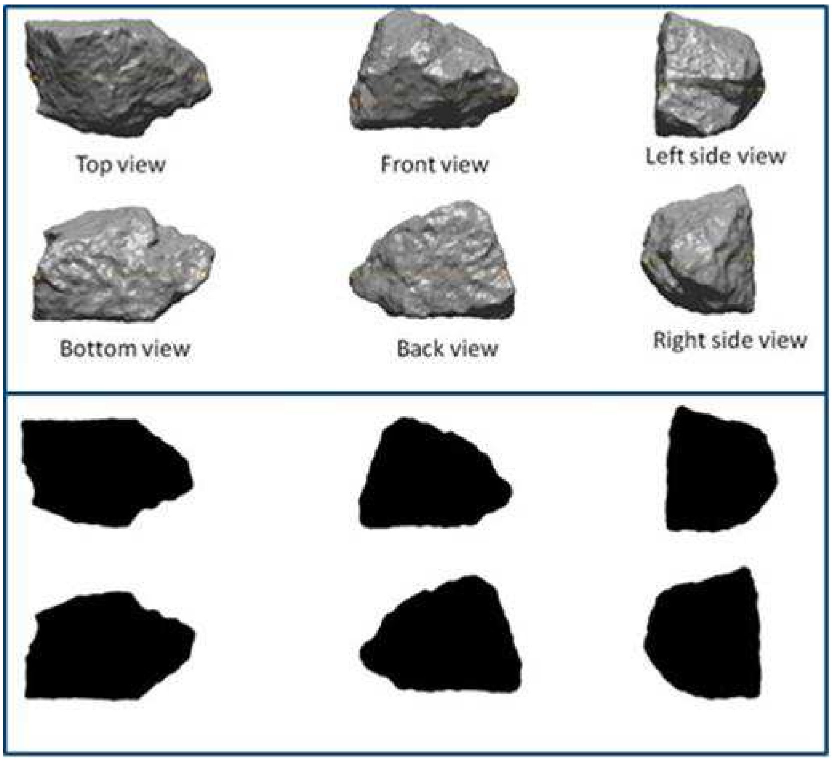

Figure 4: Particle views and corresponding processed images

The results of the image analysis for the shape descriptors, roundness, circularity and solidity, corresponding to each view are shown in Figures 5 to 7. The numbers 1 to 6 refer to the views; bottom, front, left side, right side, back and top, respectively

Based on the viewing referencing used in this paper, the shape descriptor values vary depending on the view being considered for a given particle. Roundness ranges from 0.45 to 0.92 with the left and right side views giving higher values for a given particle. Particle 1 had the lowest difference in the values of roundness Circularity varies between 0.61 and 0.78 and solidity varies between 0.92 and 0.98, showing generally smooth edged particles, but depends on the particle view. Particles 1, 5 and 9 plot the highest in the spherical grain shape category in Figure 3 and have the highest values with respect to roundness, circularity and solidity. Particles 2, 6 and 7 on the other hand generally show lower values for circularity and roundness, particularly with respect to the top and bottom view. These are the particles at the boundary between the spherical and the rod-like grain shape categories as shown in Figure 3. Implication of these observations is discussed later.

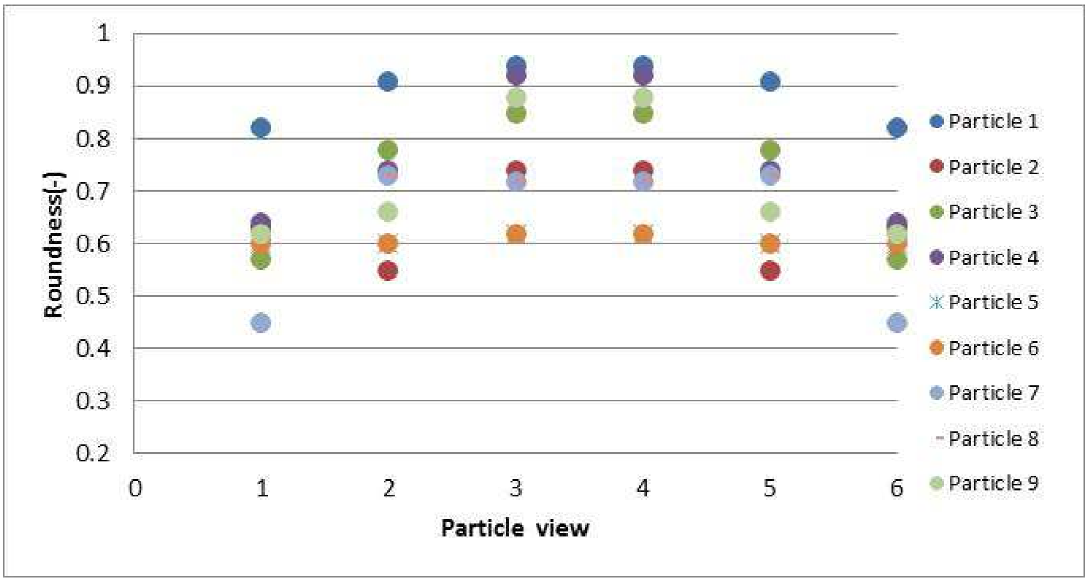

Figure 5: Roundness for the individual particle views

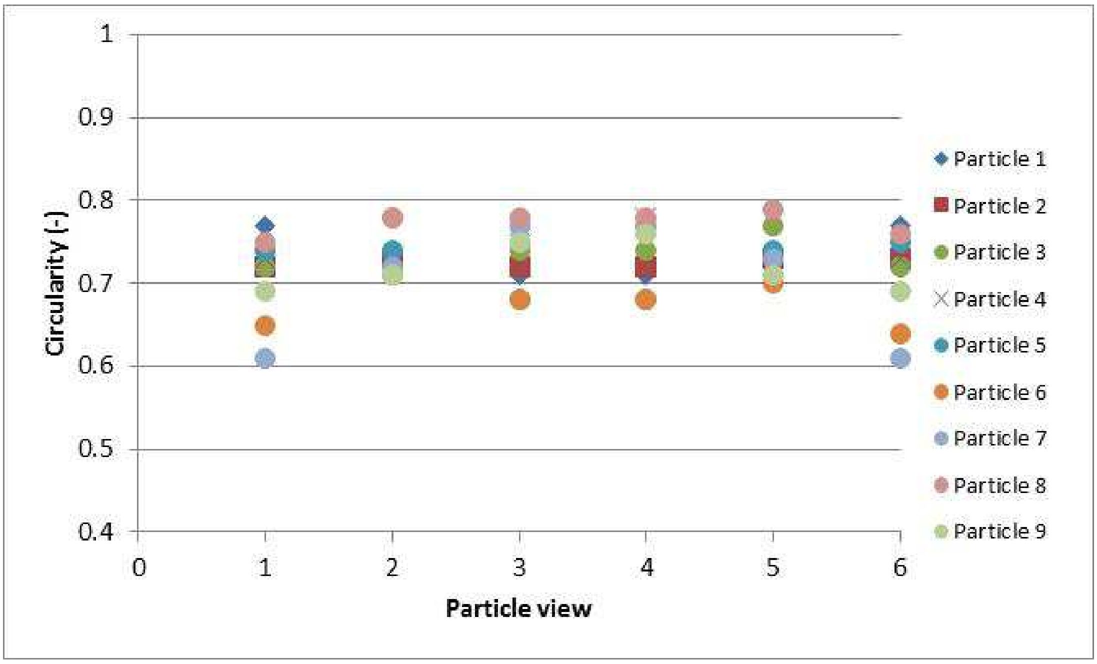

Figure 6: Circularity for the individual particle views

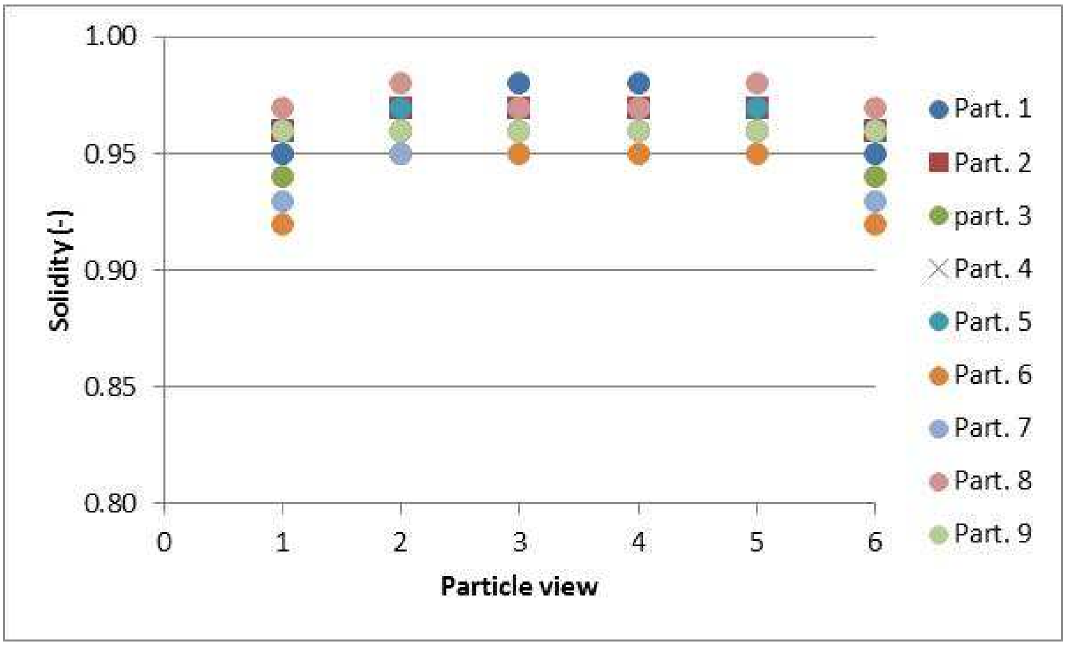

Figure 7: Solidity for the individual particle views

The above assessment of particle shape descriptors was done by considering two dimensional image projects of the particles. However, aggregates are three dimensional objects and therefore quantification of three dimensional description of particle geometry is more appropriate. The advantage of using the laser scanning device is that data for full 3-D quantification of the particle geometry (shape) is directly obtained from the acquired images, including volume and surface area of the particles. The basic particle form descriptor is sphericity, defined by equation 1 above. Sphericity and aspect ratio are very important shape factors in understanding the performance of materials in the pavement layers. The association between volume-to-surface-area factor (V/A_S) and aspect ratio was also examined.

Figure 8 shows the variation of sphericity with aspect ratio for 13 andesite aggregate particles of different sizes. Aspect ratio in this paper has been defined as the ratio of the largest dimension (dL) to smallest dimension (dS) as illustrated in Figure 1. Figure 9 shows the variation of 3-D Sphericity with aspect ratio for a tillite sample. This evaluation comprised of 30 particles from each of three particle size ranges; (i) passing the 37.5 mm sieve but retained on 26.5 mmm sieve, (ii) passing the 26.5 mm sieve but retained on 19 mm sieve and (ii) passing 19 mm sieve but retained on 13.2 mm.

The results in Figure 8 show that the association between the 3-D sphericity and aspect ratio as well between the volume-to-surface-area and aspect ratio are both statistically significant. The equation for the association between volume-to-surface area factor and aspect ratio describes 84.5% of the variability of volume-to-surface area factor. The equation for the relationship between 3-D sphericity and aspect ratio describes 91.2% of the variability of 3-D sphericity. The R^2 values for linear equations to describe the relationship between 3-D sphericity and aspect ratio and between the volume-to-surface area factor and aspect ratio were 75.9% and 73.5% respectively. The associations can better be described by non-linear equations.

Examination of the association between 3-D sphericity and aspect ratio for the tillite sample in Figure 9 shows the association to be statistically significant. A total of 90 particles were used in this analysis. A meaningful correlation exists between 3-D sphericity and aspect ratio.

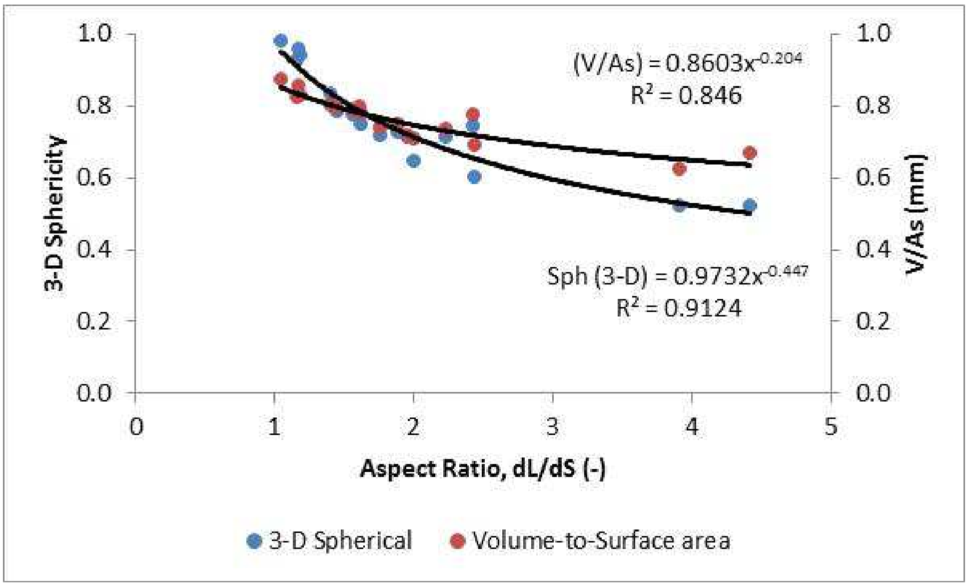

Figure 8: Relationship between sphericity, volume-to-surface area and aspect ratio

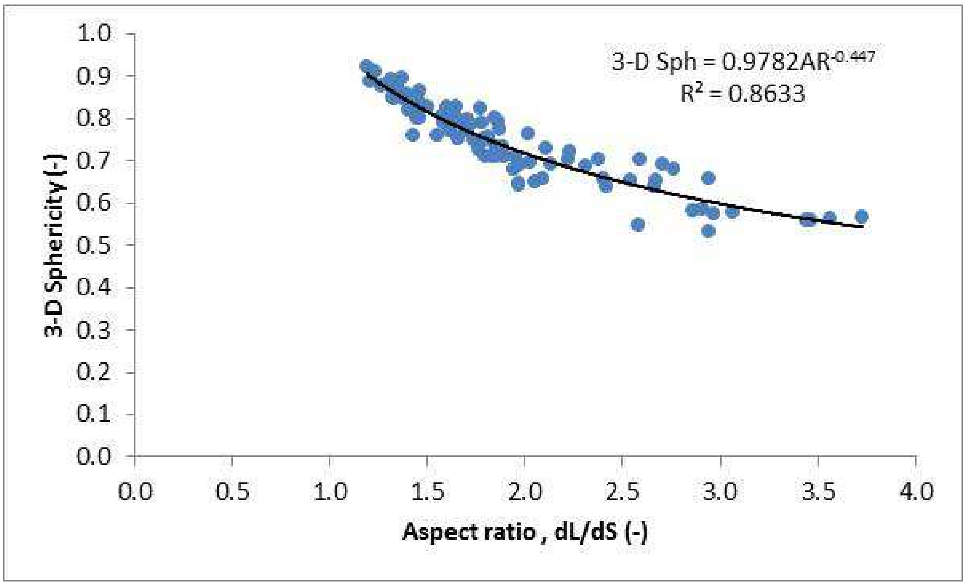

Figure 9: Variation of 3-D sphericity with aspect ratio

Based on the current preliminary results, the coefficients in the equations for describing the relationship between 3-D sphericity and aspect ratio for the andesite and the tillite are not significantly different. Work is continuing to examine different materials and quarry sources.

5. DISCUSSION AND WAY FORWARD

Most current methods in particle characterisation are in the 2-dimensional domain. However, aggregate particles are three-dimensional objects, and proper characterization is therefore essential. The application in this study of the innovative 3-D laser technology in aggregate characterization has made it possible to calculate aggregate particle descriptors for different particle views. The results reveal that the shape descriptors are different for each of the six particle faces, but mirror the values of the opposite view. The different particle faces give roundness values greater than 0.6 indicating high roundness. The particles in the first series of testing, andesite sample, have generally smooth edges as solidity values for the different faces are towards 1, but differences between particles are quantifiable. The values of the circularity, a measure of the particle's shape relative to a perfect circle, show the particles to be nearly equi-dimensional, confirming their location in Figure 3. The results of image analysis are therefore consistent with established methods of grain shape characterisation. The irregularities in the surface texture may then be quantified by solidity, but this requires further investigation. However, the lack of a characteristic scale of which surface texture can be analysed makes it difficult to do direct measurements (Santamarina and Cho, 2004).

The results of the image analysis show that it is possible to determine parameters that can adequately quantify aggregate shape characteristics to identify differences between individual aggregates, from the same sieve size range. The fact that results reveal that the shape descriptors mirror the values of the opposite view, means that three directional image acquisitions will generally be adequate for quantifying the first and second order grain shape descriptors, but this is because 2-D image projections are used. However, the multi-directional images from 3-D laser scanner technology have an added advantage in that a visual assessment will assist in characterising complete surface details which can be missed in three directional image acquisition methods. Such details may be contributing factors to the prediction of material performance that rely on aggregate texture. The 3-D laser scanning technique therefore provides more information about the particle shape.

Discrete Element Method (DEM) in the field of micromechanical modelling should benefit from results of three-dimensional particle characterisation. This is a numerical technique which allows modelling of a system of discontinuous material as an assembly of discrete elements interacting with each other (Das, 2007). The introduction of innovative 3-D laser scanning technologies ensures accurate characterization and quantification of particle shapes including irregular particle shapes. Thus the quantitative information from the 3-D image analysis should provide better input in numerical modelling. It is possible to identify the differences between the individual particles, which could be relevant to discrete element modelling.

The developments in the quantification of particle morphology and its influence on the mechanical response of granular assemblies continue to receive attention in the area of pavement material research. As the study is on-going, particles in a different grain size range as well as materials of other common aggregates will be investigated. A methodology is to be developed to determine an optimum sample size for each sample to be used in the image analysis. Work is also underway to directly link the aggregate shape characteristics determined from the image analysis, to the performance of pavement materials, this includes bitumen retention on the aggregate surface, shear strength and deformation response. This development will further advance the understanding of the effect of grain shape on mechanical behaviour of granular pavement material.

6. CONCLUSION

The paper has presented some results of an on-going study on the characterization of aggregates using the 3-D laser scanner technology. Samples of coarse aggregate andesite and tillite particles were used for the study. The work presented in this paper fully utilized the 3-D images from a 3-D laser scanner in quantifying the shape descriptors in order to identify the differences between individual aggregates The study has demonstrated the advantages of the innovative 3D laser scanner technology in studying the shape characteristics of aggregate particles. The results have shown that the 3-D laser scanning technique makes it possible to quantify shape descriptors from first to third order scale in identifying the subtle differences between aggregates. The results should contribute to a better understanding of inter-particle as well as particle binder physical interaction at different particle size scales. Image analysis should serve as a complimentary method in the quantification of particle shape characteristics for performance prediction of materials in transport infrastructure, rail road ballast and aggregates in road construction.

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