A STUDY OF THE INFLUENCE OF COARSE AGGREGATE SHAPE CHARACTERISTICS ON PERMANENT DEFORMATION OF ASPHALT MIXES

M M MABUSE*, J K ANOCHIE-BOATENG*, J J KOMBA*, and J M NDAMBUKI**

*CSIR, PO Box 395 Pretoria, 0001, South Africa, Email: mmabuse@agrement.co.za,
Email: JAnochieBoateng@csir.co.za, Email: jkomba@csir.co.za
**Tshwane University of Technology, Department of Civil Engineering, Private Bag X680
Pretoria 0001, South Africa, E mail: NdambukiJM@tut.ac.za

ABSTRACT

The effect of aggregate shape properties such as angularity, texture, sphericity, roundness, flat and elongation on the performance of asphalt mixes have not been thoroughly investigated using direct measurement techniques. This is partly because aggregates do not have regular shapes, and it is a daunting task to accurately determine these properties. In this paper, three types of aggregates are used to produce asphalt mixes in order to study the effect of coarse aggregate shape properties on the permanent deformation. A modern three-dimensional (3-D) laser scanning device available at the Council for Scientific and Industrial Research (CSIR) in South Africa was used to directly obtained shape properties of the aggregates. Permanent deformation tests were conducted in the laboratory on three different mixes produced from the aggregates to compare performance. It was found that the three asphalt mixes have different resistance to permanent formation. The aggregates with high surface texture and angularity improve resistance to permanent deformation of the asphalt mix when compared with those with more rounded or spherical shapes.

1 INTRODUCTION

Aggregate shape properties play an important role in the performance of asphalt mixes. More cubical and rough textured aggregate particles are preferred in asphalt mixes due to their ability to provide better interlock, internal friction, mechanical stability and workability. On the other hand, flat and elongated aggregate particles are not preferred in asphalt mixes due there their tendency of breaking down during compaction, resulting to compaction related problems. Several research studies have shown that aggregate shape and surface properties including form, angularity, surface texture as well as the surface area and volume affects the performance of pavements (Kandhal and Parker, 1998; Saeed et al., 2001; Meininger, 1998; Huang, 2010).

One of the dominant failure modes of asphalt mixes is permanent deformation (rutting). Improving asphalt mixes design including better characterisation of aggregate shape properties could help to prevent rutting problems in asphalt mixes. Despite the current understanding of the influence of the aggregate shape properties on the permanent deformation behaviours of asphalt mixes, the characterisation of aggregate shape properties still remains a challenge. Recent research studies are employing advanced techniques such as aggregate imaging and laser scanning to characterise the aggregate shape properties (Illerstron, 1998; Lanaro et al, 1998, Tutumluer et al, 2000; Rao et al, 2001, Masad, 2003; Anochie-Boateng et al., 2010; Anochie-Boateng et al, 2011; Anochie-Boateng et al, 2012, Komba, et al, 2012).

The objective of this paper is to present the results of the laboratory study of the influence of coarse aggregate shape properties determined from 3-D laser scanning method on permanent deformation behaviour of three asphalt mixes manufactured from three types of aggregates. The scans data were analysed by using spherical harmonic analysis technique to compute form, angularity and surface texture indices of the aggregates. Permanent deformation behaviour of the three mixes were compared based on the shape indices of the coarse aggregates in the mixes.

2 COMPUTATION OF AGGREGATE SHAPE PROPERTIES

The fundamental aggregate shape and surface properties that influence the performance of pavements are illustrated in Figure 1.

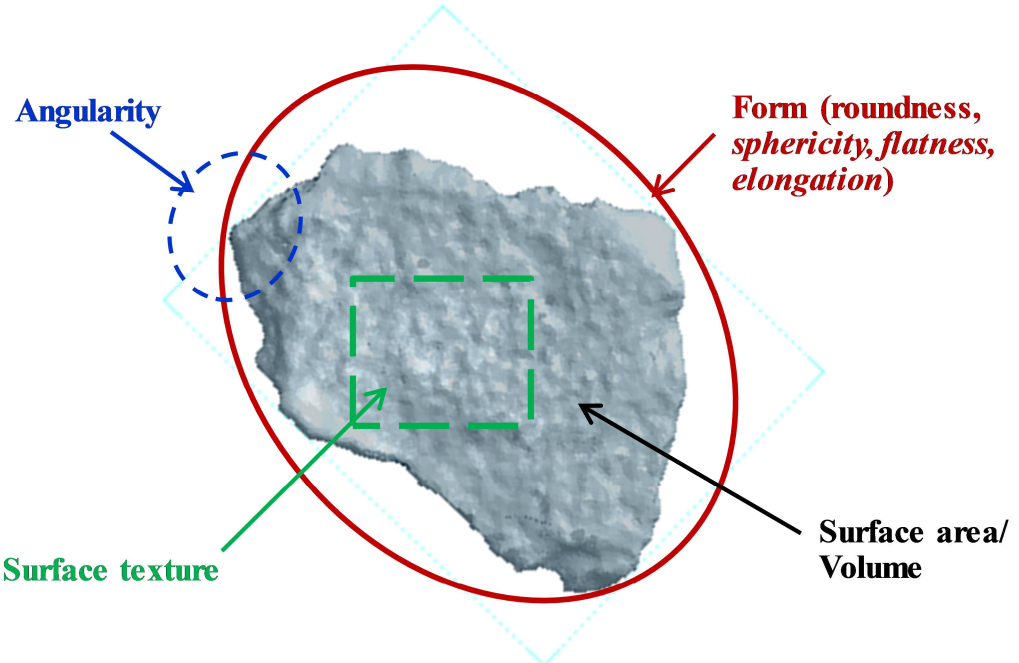


Figure 1: Fundamental aggregate shape properties (Anochie-Boateng et al., 2011).

Recently, there have been significant developments to improve the computation of aggregate form, angularity and surface texture characteristics. Masad (2003) has used the Aggregate Imaging Systems (AIMS) to measure the orthogonal dimensions of aggregate and compute sphericity to describe aggregate form (Equation 1).

$$Sphericity = \sqrt[3]{\frac{d_S d_I}{d_L^2}} \qquad (1)$$

Where:

d_L = longest dimension
d_I = intermediate dimension
d_S= shortest dimension

The sphericity of an aggregate particle can also be computed by using surface area and volume as presented in Equation 2 by Lin and Miller (2005).

$$Sphericity = \sqrt[3]{\frac{36\pi V^2}{A}} \qquad (2)$$

Where:

V =volume of aggregate particle, and
A =surface area of aggregate particle

The aggregate form has also been defined by using flat and elongated particle ratio. The flat and elongated particle ratio is computed by dividing the aggregate's longest dimension by the shortest dimension as shown in Equation 3 (Rao et al, 2001).

$$Flat\ \ and\ elongation\, ratio = \frac{d_L}{d_S} \qquad (3)$$

Mathematical techniques such as spherical harmonic, Fourier series, and wavelet analysis are also available to determine the form, angularity and surface textures of aggregates. Recently, Komba et al (2012) investigated the use of spherical harmonic technique to analyse data obtained from 3-D laser scanning method to compute form, angularity and surface texture indices of different types of aggregates. These researchers found that form indices computed by using aggregate physical dimensions (Equations 1 to 3) are comparable to aggregate form indices computed by using spherical harmonic analysis technique (Equation 6). The spherical harmonic equations were also used by Kutay et al, (2011) to determine form, angularity and surface texture indices of aggregates.

In the spherical harmonic method, the shape of an aggregate particle is defined as a function of a radius distance from the mass center to the surface points of the particle in three-dimensions using the below equation:

$$R(\beta,\alpha) = \sum_{1=m}^{1_{\max}} \sum_{m=-1}^{1} a_{1m} Y_1^m(\beta,\alpha) \qquad (4)$$

0≤ $\beta \leq \pi$, 0≤ $\alpha \leq 2\pi$

Where:

$R(\beta,\alpha)$	= radius from the aggregate mass center to the surface,
β	= angle measured from the positive z-axis
α	= angle measured from the positive x-axis
a_{1m}	= scalar coefficient, and
$Y_1^m(\beta,\alpha)$	= harmonic function of degree 1 and order

The computation of aggregate shape properties by using spherical harmonic analysis technique is based on solving the scalar coefficient (a_{lm}) in these equations.

$$a_{1m} = \int_0^{2\pi}\int_0^{\pi} d\alpha d\beta \sin(\beta) r(\beta,\alpha) Y_1^{m*} \qquad (5)$$

In order to eliminate the size effect of the aggregate particles the indices should be normalized by diving the equations by the first scalar coefficient, a_{00} (i.e. =0, m=0)

$$form = \sum_{l=0}^{5} \sum_{m=-l}^{l} |a_{lm}| \tag{6}$$

$$angularity = \sum_{l=6}^{25} \sum_{m=-l}^{l} |a_{lm}| \tag{7}$$

$$surface\, texture = \sum_{l=25}^{l_{max}} \sum_{m=-l}^{l} |a_{lm}| \tag{8}$$

Based on these findings, this paper employs the spherical harmonic equations defined in Equations 6 to 8 to determine form, angularity and surface texture of the aggregates used for this study.

3 MATERIALS AND LABORATORY TESTING

3.1 Materials

Three types of asphalt mixes were used in the study. The mixes were manufactured by using three different aggregate types, namely:

- Andesite obtained from Afrisam Eikenhof quarry in South Africa;
- Dolerite obtained from Afrisam Rooikraal quarry in South Africa, and
- Chrome slag aggregates obtained from Silverstone crushers in Bon Accord.

All three mixes were manufactured at the CSIR pavement materials laboratory by using same 35/50 penetration grade binder, dolomite limestone filler, and the three aggregates types.

Since the study focused on the influence of coarse aggregates on permanent deformation behaviour of asphalt mixes, the fine aggregate components (< 4.75 mm) of all the three mixes were made approximately the same aggregate type.

Table 1 presents the test results of physical properties of the aggregates used in the mixes.

Table 1: Aggregate test results for the three aggregate types.

Properties	Test method	Results		
		Andesite	Dolerite	Chrome Slag
Aggregate Crushing Value (ACV) (%)	TMH1 Method B1	5.9	12	19.2
Ten per cent Fine Aggregate Crushing Value(10 % FACT kN)	TMH 1 Method B2	504	344	262
Polishing Stone Value (PSV)	BS812	46	50	56.4
Flakiness Index (%)	TMH 1 Method B3	14.5	12.2	14.4
Bulk Relative Density	TMH 1 Method B14	2.899	2.96	3.033

(BRD) retained on 4.75 mm				
Bulk Relative Density (BRD) passing 4.75 mm	TMH 1 Method B15	2.739	2.883	3.147
Water Absorption retained on 4.75 mm	TMH 1 Method B14	0.41	0.39	0.7
Water Absorption passing 4.75 mm	TMH1 Method 15	0.73	0.75	1.2

3.2 Asphalt mix optimization and testing

In order to clearly differentiate the influence of the shape properties of the coarse aggregates on the respective asphalt mixes, the three gradings were engineered so that the fine aggregate portions are similar to each other. This was achieved by using optimization procedures, to combine different aggregate fractions using least square analysis method in *Microsoft Excel*^{TM}. Table 2 presents the aggregate grading results for the three types of asphalt mixes studied. The grading results are also plotted in Figure 2.

Table 2: Grading results of the asphalt mixes studied.

Sieve size (mm)	Mix 1[a]	Mix 2[b]	Mix 3[c]
26.5	100	100	100
19	93	94	92
13.2	82	83	83
9.5	71	72	70
6.7	58	66	59
4.75	51	51	51
2.36	35	36	38
1.18	25	28	29
0.6	18	24	20
0.3	13	19	12
0.15	8	8	8
0.075	5	5	5

[a]: Asphalt mix produced by using andesite aggregates
[b]: Asphalt mix produced by using dolerite aggregates
[c]: Asphalt mix produced by using chrome slag aggregates

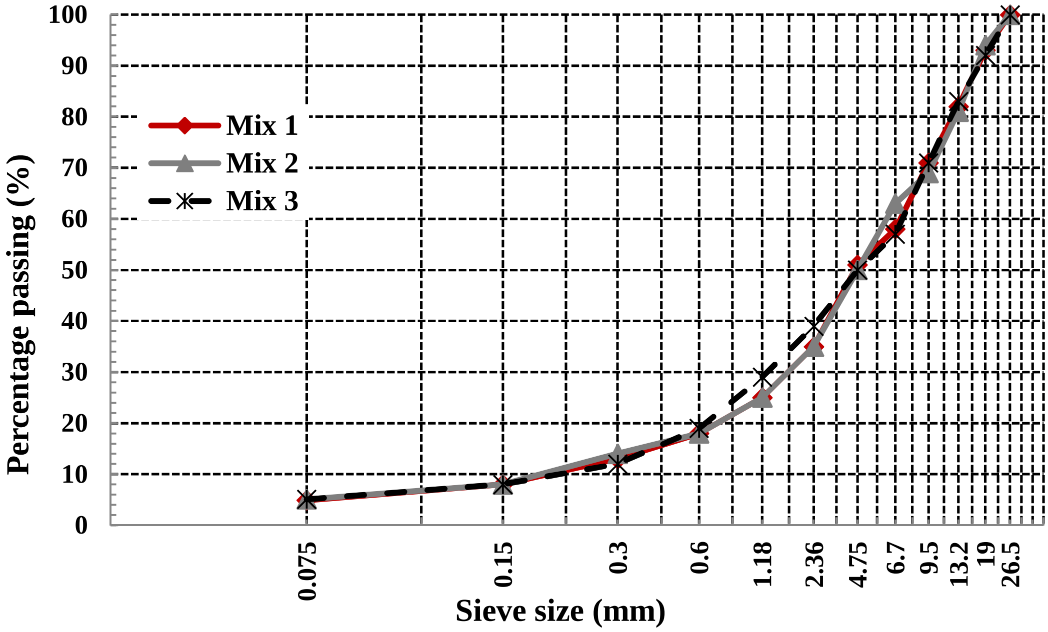


Figure 2: Plots of grading of the asphalt mixes studied.

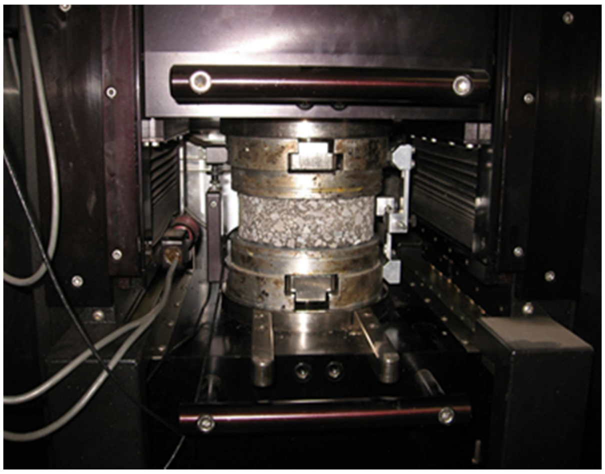
The Maximum Theoretical Relative Density (MTRD) of the three asphalt mixes where determined using the standard TMH 1 Method C3. The CSIR protocol was used to produce the three compacted asphalt slabs. The compacted slabs were then left overnight for drying and the moulds were removed in the morning, and the slabs where then cored. Bulk Relative Densities (BRDs) were determined on the cores using Corelok method. Table 3 presents the average results for the three asphalt mixes.

Table 3: Asphalt mixes void content.

Asphalt mixes	Specimen no	Binder content (%)	MTRD	BRD	Voids
Mix 1	Core 1	4.3	2.694	2.466	6.7
	Core 2			2.482	6.1
	Core 3			2.434	7.9
Mix 2	Core 1	4.3	2.694	2.516	6.6
	Core 2			2.512	6.7
	Core 3			2.522	6.4
Mix 3	Core 1	5.3	2.817	2.708	3.9
	Core 2			2.665	5.4
	Core 3			2.686	4.6

3.3 Permanent deformation testing

Repeated Simple Shear Test at Constant Height (RSST-CH) was used to evaluate permanent deformation behaviour of the asphalt mixes studied. The tests were conducted using the standard AASHTO test procedure documented as AASHTO T 320 protocol (AASHTO 320, 2007). The RSST-CH tests were conducted on specimens cored from laboratory compacted slabs. The specimen dimensions were 150 mm in diameter by 60 mm high. Testing at only one temperature was enough to achieve the objective of this study. Therefore, a relatively high test temperature of 55℃ was selected to properly study the shape characteristics on permanent deformation of the three mixes. For each mix three specimens were tested and the average of the two repeatable specimens was computed to represent the RSST-CH result of the mix. Figure 3a shows an instrumented RSST-CH test specimen whereas Figure 4b shows prepared specimen for testing.



(a) (b

Figure 3: (a) Instrumented RSST-CH specimen (b) RSST-CH specimens.

4 AGGREGATE LASER SCANNING

4.1 Laser scanning device

The 3-D laser scanning device at the CSIR was manufactured by Roland DGA Corporation USA. The laser scanner consists of laser beam moving vertically and horizontally, a rotary table and advance data processing software namely Rapidform. The maximum resolution of the 3-D laser scanner is 0.1 mm (100μm). The capability of the laser scanning device to measure aggregate shape properties has been previously evaluated by Anochie-Boateng et al (2010). Figure 4 shows a photograph of the CSIR laser scanning device.

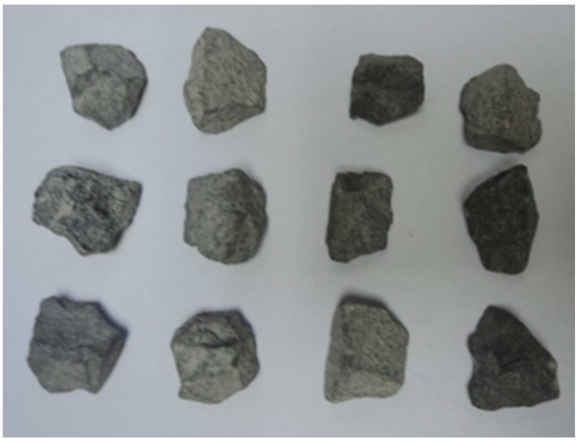
Figure 4: A photo of a laser scanning device at the CSIR.

4.2 Scanning of aggregates

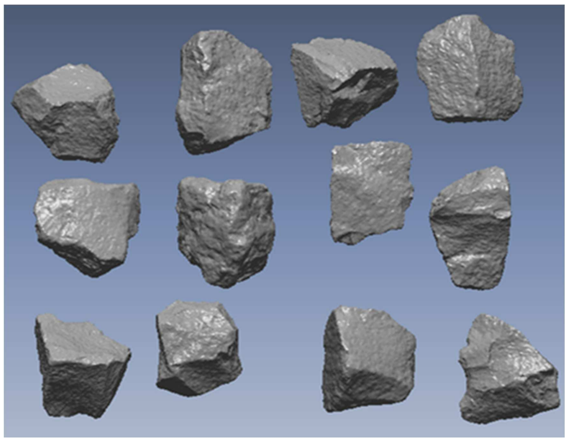
The aim was to scan 15 coarse aggregate particles retained on all coarse sieves 19, 13.2, 9.5, 6.7 and 4.75 mm sieve sizes for each mix in order to obtain a representation of each aggregate sample. Firstly, aggregate samples were scanned on a planar mode where four sides are scanned and followed by the top and bottom to complete the six faces of the aggregate. Once scanning is completed the Rapidform software was used to process the scanned results in order to obtain a complete aggregate particle in six face bounding box.

Different software's tools such as align, combine, triangulate/merge were also applied to bring the scanned surfaces together in order to obtain a complete aggregate and to remove any irregularities, fill holes and merge the scanned surfaces to obtain the representative scanned aggregate model. On average, 30 minutes was required to scan a 19.0 mm aggregate particle and 5 minutes was used to scan a 4.75 mm aggregate particle.

On completion of processing scans data volume and surface area and dimensions of bounding box were obtained directly by using the Rapidform software. Figure 5a to 5f shows samples of the actual and modelled aggregate particles for all the three mixes.

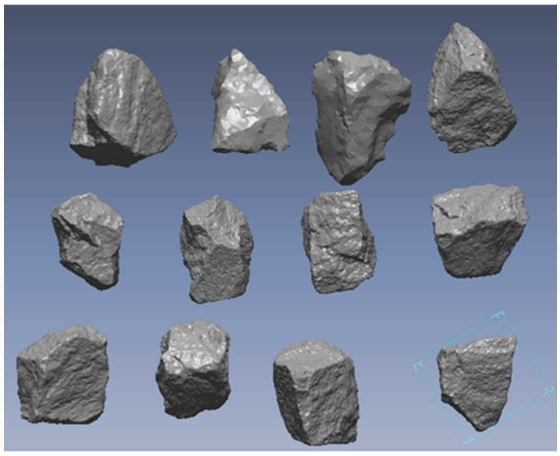


(a) Actual aggregate – Mix 1

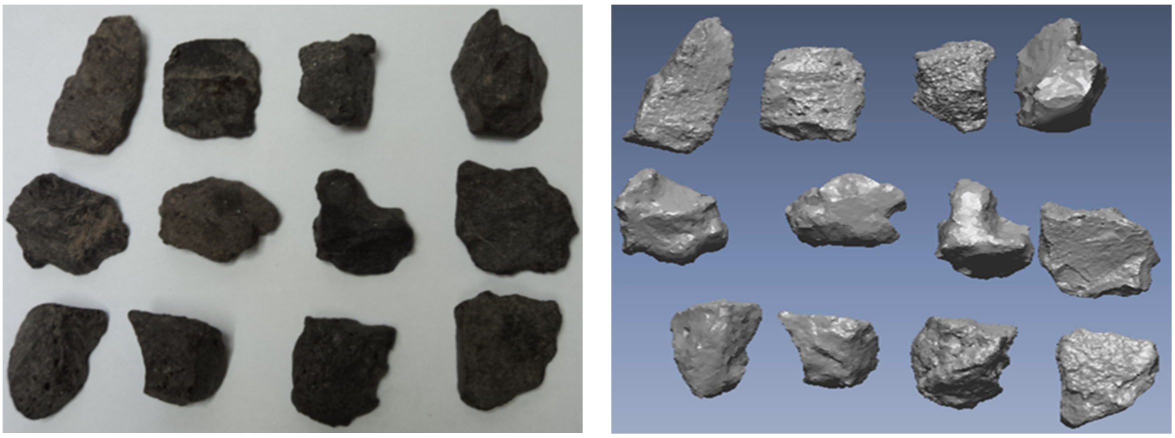


(b) Modelled aggregate –Mix1

(c) Actual aggregate – Mix 2



(d) Modelled aggregate – Mix 2



(e) Actual aggregate – Mix3 (f) Modelled aggregate – Mix 3

Figure 5: Actual and modelled aggregate particles.

5 RESULTS AND DISCUSSIONS

5.1 <u>Permanent deformation test results</u>

Figure 6 shows a plot of permanent plastic shear strain versus number of load applications for the three mixes tested at 55℃. It can be seen that Mix 3 generally showed lower permanent plastic strain when compared to the other two mixes. In comparison to Mix 1, Mix 2 showed high resistance to permanent deformation. This is supported by the fact that high number load application to failure obtained for Mix 3 in comparison with mixes 2 and 1. Therefore, of the three mixes studied Mix 3 has better resistance to permanent deformation followed by Mix 2, whereas Mix 3 has the poorest resistance to permanent deformation. These results are compared with the shape properties of the coarse aggregate used to manufacture the mixes later in Section 5.3.

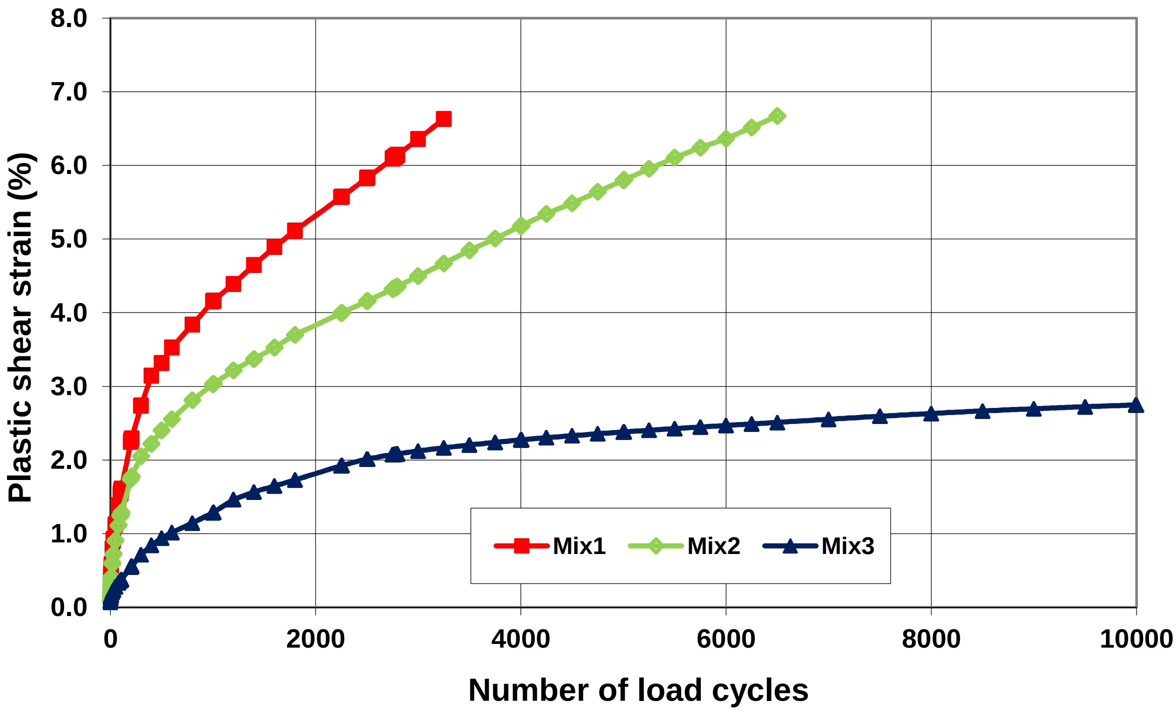


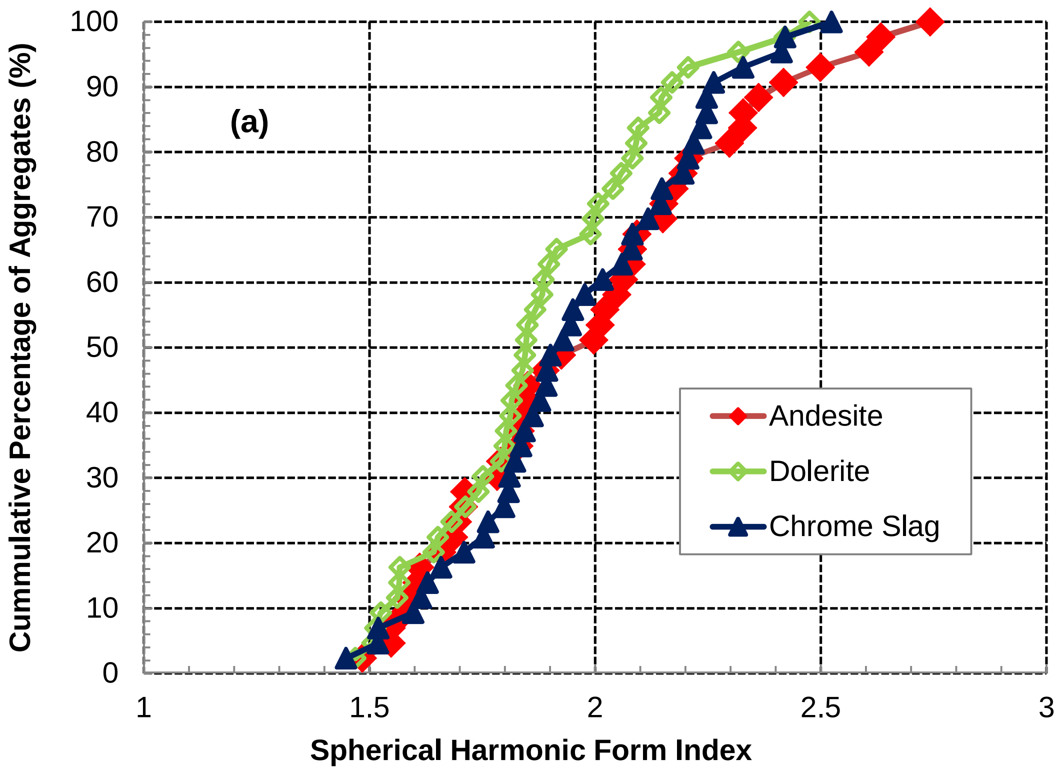
Figure 6: RSST-CH results

5.2 Aggregate laser scanning results

The results of the aggregate shape indices (form, angularity and surface texture) computed by using spherical harmonic analysis technique are shown in Figure 7. Figure 7a show plots of the distribution of the spherical harmonic form indices. Higher form indices were computed from andesite, followed by chrome, whereas the dolerite had the smallest form indices. This implies that dolerite aggregates has larger proportion of particles which tend towards becoming round-shaped as compared to chrome slag and andesite aggregates. On the other hand, andesite has larger proportion of aggregates tending towards becoming flat and elongated. The chrome slag is in between the two extreme cases (ie. not too round-shaped, and not too flat and elongated).

Figure 7b show plots of the distribution of angularity indices. Almost 80 per cent of Chrome slag and andesite appear to have similar angularity indices. Overall, the smallest angularity indices were computed for dolerite.

Figure 7c show plots of the distribution of the surface texture indices. Overall, the highest texture indices were computed for chrome slag, followed by andesite, whereas the dolerite had the smallest surface texture indices. These results are compared with that of permanent deformation (RSST-CH) in Section 5.3.



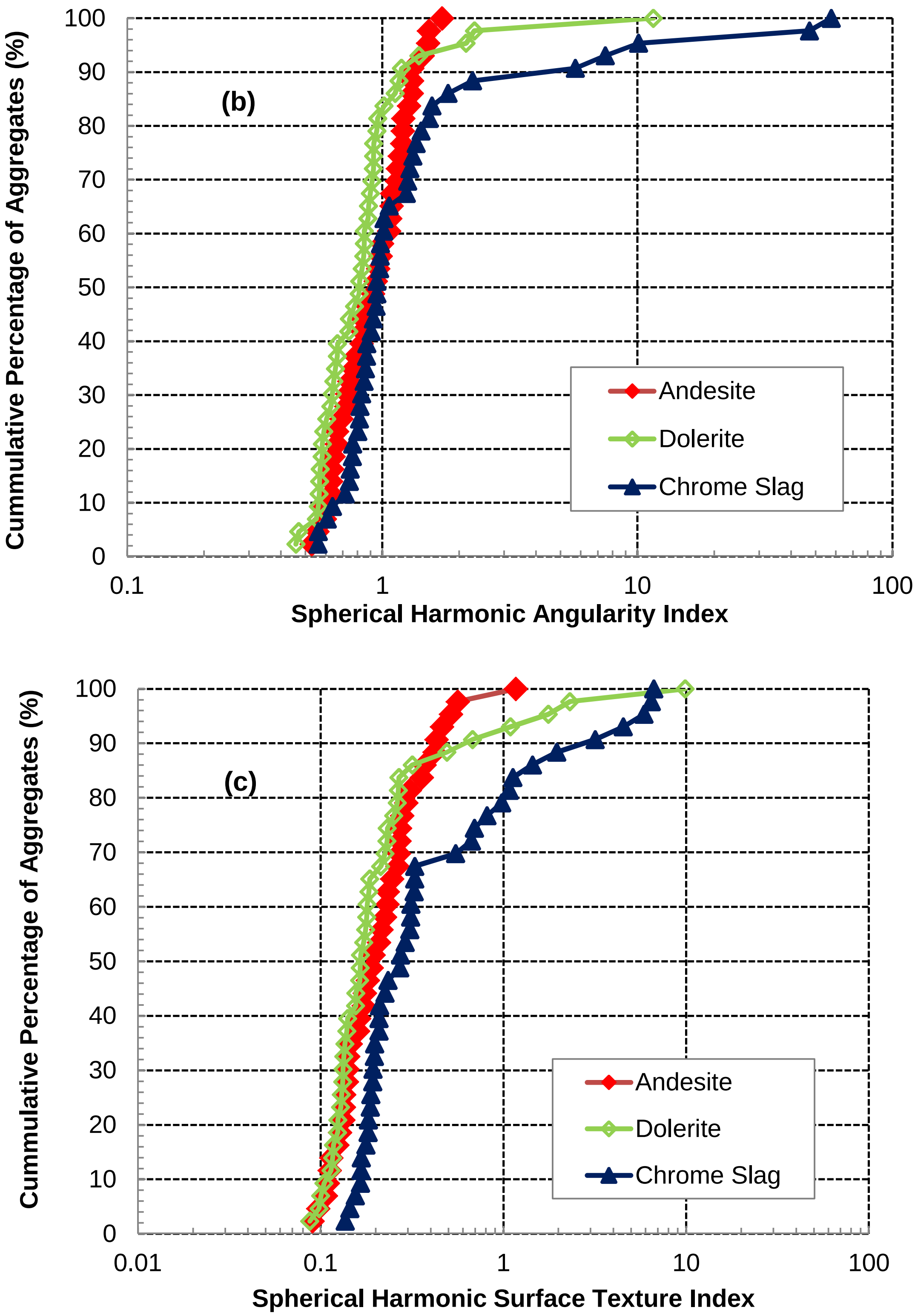


Figure 7: Aggregate form, angularity and surface texture indices.

5.3 <u>Effect of shape of properties on permanent deformation</u>

The permanent deformation test results indicated that an asphalt mix manufactured by using chrome slag aggregates (Mix 3) has better resistance to permanent deformation, followed by the asphalt mix manufactured using dolerite (Mix 2). The asphalt mix manufactured by using andesite aggregates (Mix 1) showed the poorest resistance to permanent deformation.

It can be seen from Figure 7 that dolerite has larger proportion of rounded (spherical) aggregates particles when compared to andesite and chrome (although chrome appears to be more rounded than andesite). In terms of angularity, the results show that chrome slag had more angular aggregate particles, followed by dolerite and andesite. Similar trend is observed for surface texture of the three aggregate types. Therefore, it is generally expected that the chrome slag with high angularity and surface texture would provide better resistance to permanent deformation.

This is shown in Figure 7 as the laboratory permanent deformation tests on the three asphalt mixes indicate that the chrome mix has lower plastic shear strain than the andesite and dolerite mixes. Also, the dolerite mix appears to have better resistance to permanent deformation than andesite mix.

It should be mentioned that this study was based on limited number of scanned aggregates particles. Therefore this results are preliminary. More aggregate particles are required to be scanned in order to make a valid conclusion on the effect of shape properties on performance.

6 CONCLUSIONS AND RECOMMENDATIONS

The paper presented a laboratory study of the influence of coarse aggregate shape properties on permanent deformation behaviour of three asphalt mixes. Based on the results presented in the paper, the following conclusions and recommendations can be made.

- Asphalt mixes manufactured by using coarse aggregates with different shape properties showed different resistance to permanent formation.
- The aggregates with high surface texture and angularity could improve resistance to permanent deformation of the asphalt mix.
- Limited aggregates and asphalt mix types were investigated in this study. Future research studies should increase the sample, and include other aggregate types and asphalt mixes. Some of such studies have already been initiated at the CSIR.
.

ACKNOWLEDGEMENT

The study presented in this paper was conducted as part of CSIR Strategic Research Panel (SRP) research project TA-2011-001. Funding for the project and the acquisition of the 3-D laser scanning device was provided by CSIR R&D office. Agrément South Africa in particular Dr Wekesa BW and Tshwane University of Technology in Pretoria also supported the study.

REFERENCES

AASHTO T 320. 2007. Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures using the Superpave Shear Tester (SST). American Association of State Highway and Transportation Officials, Washington D.C.

Anochie-Boateng, J.K., Komba, J., Makulenga, N. and Maharaj, A. 2010. Evaluation Of 3D Laser Device for Characterizing Shape and Surface Properties of Aggregates used in Pavements. *29th Annual Southern African Transport Conference, "Walk Together"*, CSIR International Convention Centre, Pretoria, South Africa, August 2010, pp 9. 16 – 19.

Anochie-Boateng, J.K., Komba, J.J. and Mvelase, G. 2011. Advanced and Automated Laser-Based Technique to Evaluate Aggregates. *The International Road Federation (IRF) Congress*, Moscow, Russia.

Anochie-Boateng, J.K., Komba, J. and Tutumluer, E. 2012. Aggregate Surface Areas Quantified Through Laser Measurements for South African Asphalt Mixtures. *ASCE Journal of Transportation Engineering*, 2012.

Garboczi, E.J. 2002. Three-dimensional mathematical analysis of particle shape using X-ray tomography and spherical harmonics: Application to aggregates used in concrete. Concrete and Cement Research, Vol. 32, No. 10, pp. 1621-1638.

Huang, H. 2010. Discrete element modelling of railroad ballast using imaging based aggregate morphology characterization, PhD Dissertation, University of Illinois at Urbana-Champaign, Urbana, USA.

Illerstrom, A. 1998. A 3-D Laser Technique for Size, Shape and Texture Analysis of Ballast. Msc Thesis, Royal Institute of Technology, Stockholm, Sweden.

Kandhal, P. S. and Parker, F. Jr. 1998. Aggregate Tests Related to Asphalt Concrete Performancein Pavements. NCHRP Report 405, TRB, National Research Council, Washington, D.C., 1998.

Komba, J., Anochie-Boateng J.K. and Steyn, W.JvdM. 2013 Analytical and Laser Scanning Techniques to Determine Shape Properties of Mineral Aggregates. In Proceedings, *92nd Transportation Research Board Meeting, Washington*, D.C., USA, 2013.

Lenarno, F., Jing, L. and Stephansson, O. 1998. 3-D Laser Measurements and Representation of Roughness of Rock Fractures. Int. Conference on Mech. of Jointed and Faulted Rocks, Vienna.

Lin, C.L. and Miller, J.D. 2005. 3D Characterization and Analysis of Particle Shape Using X-Ray Microtomography (XMT). Powder Technology 154, pp. 61-69.

Masad, E. 2003. The Development of a Computer Controlled Image Analysis System for Measuring Aggregate Shape Properties. National Cooperative Highway Research Program NCHRP-IDEA Project 77 Final Report. Transportation Research Board, National Research Council, Washington, D.C.

Meininger, R. C. 1998. Aggregate Test Related to Performance of Portland Cement Concrete Pavement." NCHRP Report 4-207 20A. *TRB, National Research Council*, Washington, D.C.

Rao, C., Tutumluer, E. and Stefanski, J.A. 2001. Flat and Elongated Ratios and Gradation of Coarse Aggregates Using a New Image Analyzer. *ASTM Journal of Testing and Standard*, Vol. 29, No. 5, pp. 79-89.

Saeed, A., Hall, J., and Barker, W. 2001. Performance-related tests of aggregates for use in unbound pavement layers. NCHRP Report 453, TRB, National Research Council, Washington, D.C.

Tutumluer, E., Rao, C. and Stefanski, J.A. 2000. Video Image Analysis of Aggregates. Final Project Report, FHWA-IL-UI-278. Civil Engineering Studies UILU-ENG-2000-2015, University of Illinois Urbana-Champaign, Urbana.