EVALUATION OF 3D LASER DEVICE FOR CHARACTERIZING SHAPE AND SURFACE PROPERTIES OF AGGREGATES USED IN PAVEMENTS

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ABSTRACT

A new three-dimensional (3D) laser scanning device has been acquired by CSIR Built Environment to determine rock aggregates shape and surface properties. The overall objective is to employ laser-based techniques to accurately determine characteristics of shape, volume, angularity, surface texture, surface area, and grading of rock aggregates that influence performance of road and airfield pavements in South Africa. This paper presents results obtained from a comprehensive scanning evaluation program for the 3D laser device using fifteen different spherical and twelve cubic shaped objects. The laser device was evaluated for accuracy and repeatability to compute aggregate surface area and volume properties. The results showed that the laser device measurements were in very good agreement with the computed theoretical values of the spherical and cubical objects. Thus, there is potential that the laser device will provide accurate and reliable shape and surface properties of rock aggregates to efficiently rank and utilize the sources of aggregate stockpiles used for pavement construction.

1 INTRODUCTION

The performance of asphalt and Portland cement road and airfield pavement materials depend largely on the rock aggregate shape and surface characteristics. These characteristics also affect the aggregates used in unbound base and subbase layers in the pavement structure. Rock aggregates constitute approximately 80 to 90% by mass of the materials used in road and airfield pavement structures. Aggregate shape factors including flatness and elongation, angularity, surface texture and surface area, i.e., rugosity, influence the pavement behaviour and performance. Aggregate characteristics such as equi-dimensional, angular, rough surface and large specific surface area are preferred to flat and elongated, rounded and smooth aggregates for road and airport pavement construction. Aggregate shape has been directly related to rutting and fatigue characteristics of pavements, and affects density and stiffness of road materials (Barksdale et al. 1992; Alrich 1996; SHRP-A-407). Figure 1 shows the three independent morphological properties used to define aggregate properties.

The American Association of Testing and Methods (ASTM) D 5821 is the standard method for determining coarse aggregate properties for pavements. In this standard, coarse aggregate angularity is determined manually by counting the number of fractured faces to determine the percentage of fractured particles in the bulk aggregate. ASTM D 4791 is another standard method which is used to determine flat and elongated particles in coarse aggregates. For this procedure a proportional caliper is used to manually obtain aggregate dimensions to evaluate the flatness and elongation ratio, which is defined as the ratio of the maximum dimension to the minimum. In South Africa, a standard method for road construction materials (Technical method for highways (TMH) 1:1986) has been used for

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determining the dimensions and shapes of individual aggregate particles. Grading analysis with the use of sieves is carried out while manual measurements by gauging are used to determine the dimensions and shape of individual particles. TMH 1 follows similar procedures employed in ASTM, and American Association of State Highway and Transportation Officials (AASHTO). Although, these procedures have been successful and continue to be used worldwide, subjectivity involved in the test results may vary from person to person. Moreover, it is time consuming and labour intensive to use the standard methods, and repeatability of test results is very low.

A new three dimensional (3D) laser scanning device has been acquired by CSIR Built Environment (CSIR BE) to determine shape and surface properties of crushed and natural rock aggregates as well as non-conventional aggregates commonly used in pavements. In this paper, fifteen spherical and twelve cubic shaped objects of different materials including steel, aluminium and ceramic with known theoretical dimensions were used to evaluate the laser scanning device. In addition, a limited number of rock aggregates used for road construction in South Africa were scanned to determine their surface area and volume properties. The objective of this study was to evaluate the capabilities of the laser device system for precise and accurate measurements of aggregate characteristics such as shape, volume, angularity, surface texture, specific surface area, and volumetric gradation. The evaluation will provide practical indication of potential use of the laser device by researchers and the industry to provide reliable shape and surface properties of rock aggregates for road and airfield design and construction.

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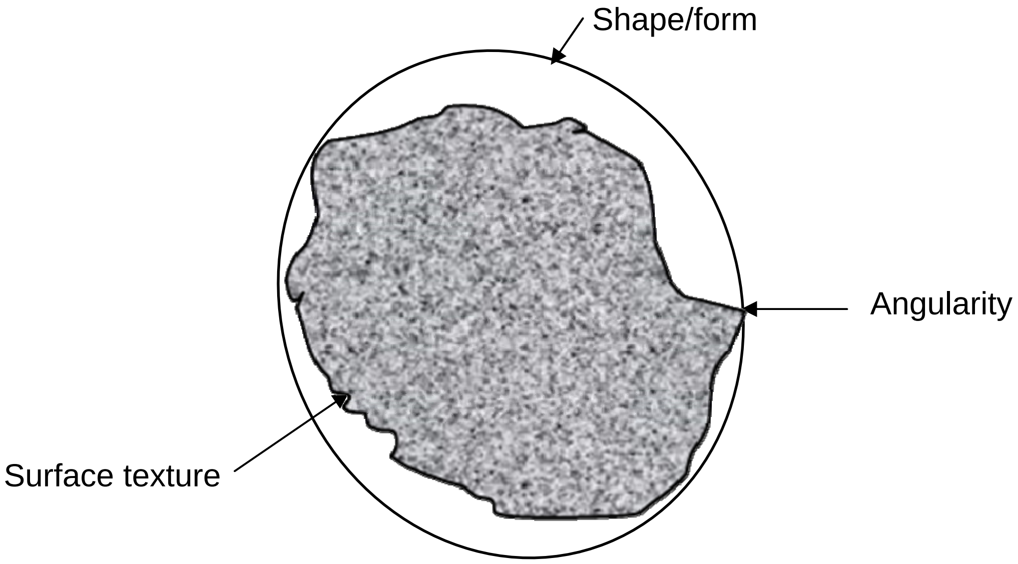


Figure 1 Key shape and surface properties of an aggregate particle

2 IMAGE AND LASER BASED ANALYSIS OF AGGREGATES

With the advent of digital image processing techniques, pavement engineers and researchers are trying to employ automated approaches such as X-ray tomography, laser profiling and photogrammetry for aggregate shape characterization. Most of the current image processing techniques used for aggregates shape analysis capture a two-dimensional (2D) image of aggregates. Although some researchers and the industry have successfully measured the volume of aggregates by taking three orthogonal views of aggregates using image processing techniques, the shape parameters are obtained as area fraction and not as volume fraction (Rao & Tutumluer 2000). Thus, the use of imaging techniques for aggregates analysis provides only 2D information about the geometry of the aggregate particles, which makes it difficult to measure the shape parameters in terms of mass or volume.

A more sophisticated way of evaluating 3D shape of an aggregate particle is through the use of X-ray computed tomography (CT) techniques, which can estimate the surface area of the bituminous binder in hot-mix asphalt mixes in addition to the surface properties of the aggregates. However, the X-ray CT technique is extremely expensive for this purpose, and has a high maintenance cost. The cost for such X-ray CT equipment is approximately US $ 1.32 million. The X-ray CT technique is also complex and the time associated with its operation could be very long. Furthermore, X-ray equipment has stringent safety and radiation monitoring requirements.

The use of the 3D laser scanning technique for quantifying aggregate morphological characteristics has received much attention lately as a more viable and cost effective alternative to both imaging and X-ray CT techniques. Three dimensional laser scanning technique has been used for characterizing the roughness of rock fracture surfaces and railroad ballast materials (Illerstron 1998; Lanaro et al. 1998). Recently, Tutumluer & Pan (2006) used 3D laser scanner to determine aggregate surface characteristics for hot-mix asphalt materials. Aggregate surface area obtained from the 3D laser scanner was also used to compute bitumen film thickness of asphalt mixes to demonstrate its potential application in hot- mix asphalt design. In the following sections, a 3D laser device to study aggregate shape and surface characteristics at CSIR BE is presented.

3 SCANNING PROGRAM FOR THE 3D LASER DEVICE

3.1 Materials scanned and the laser scanning device

Fifteen spherical shaped objects made of different materials including steel, ceramic, rubber and plastics as well as twelve cubic shaped steel, aluminium and brass objects were acquired to evaluate and verify the capability and accuracy of the 3D laser scanning device. The spherical objects were of diameters ranging from 5 mm to 63.5 mm (Table 1), and sizes of the cubic objects ranged from 8mm to 50 mm (Table 2). All the materials were prepared to fit in the 3D laser chamber for scanning. In addition, samples of sixteen rock aggregates used for road construction in South Africa were evaluated for surface area and volume characteristics. The aggregates were sampled from the materials retained on the 9.5mm sieve after routine sieve analysis.

3.2 The laser scanning device

The 3D laser scanning device at CSIR BE was designed and manufactured by the Advanced Solutions Division of Roland Company in the United States. The device uses an advanced non-contact laser sensor to scan objects in three dimensions and up to a 0.1mm scanning resolution. A combination of precision optics and motion control with a rigid cast aluminium frame produces high quality scans of objects. The scanner requires no complicated settings or advanced technical expertise, and offers high flexibility as it can operate in both rotary and plane scanning modes to make it suitable for aggregates of different types and sizes used for roads and airport pavement construction. In the rotary mode, spherical and smooth-surfaces are scanned on a fully integrated rotating table using a laser beam, which travels vertically up the rotating object to generate a digital scan file. The plane scanning mode captures flat areas, hollow objects, oblique angles and fine details of objects with the laser beam, and can scan up to six surfaces at right angles. Figure 2 shows photos of the CSIR BE acquired 3D laser scanning device.

(a) 3D Laser scanning device at CSIR BE (b) Sample aggregate on rotating table

Figure 2 Photo of laser scanning device at CSIR BE pavement materials laboratory

An integral part of the 3D laser scanner is advanced data processing software, namely Rapidform software. While the object is being scanned, the software captures and streamlines the data editing process to provide high quality scans. The Rapidform software allows users to merge scans for increased quality, change the shape around curved surfaces, sharpen edges, extend shapes, add thickness and perform Boolean operations on polygon surfaces. These features are essential for obtaining accurate morphological properties of aggregates used in road and airport pavements. A different version of the 3D laser scanner is currently used for research in aggregate shape analysis at the Federal Aviation Administration (FAA) Center of Excellence for Airport Technology, and Illinois Center for Transportation, all located at University of Illinois in the United States.

3.3 Procedure for scanning

Samples selected for the study were scanned individually in the laser device. The objects were initially measured to get a rough idea about the size to indicate in the software. Once the sample was placed in the scanning device, the parameters such as type of scanning (rotational or planar), dimensions of the object, and number of surfaces to be scanned and resolution of scanning were entered into the software program. The laser device scanned objects on a fully integrated rotating table using a laser beam, which travels vertically up the rotating object to generate a digital scan file.

All the spheres were scanned in the rotational mode, whereas the cubes and the rock aggregates were scanned in the planar mode. During scanning in planar mode, four surfaces were firstly scanned, followed by the top and bottom surfaces. Once the scanning process was completed, the Rapidform software was used to integrate and merge the surfaces so as to obtain the complete object. Different functions of the software were applied to firstly bring the surfaces together to obtain a complete object and secondly to remove any irregularities, fill holes and merge the scanned surfaces so as to get the best representative of the original object. The surface areas and volume could then be calculated using the post processing software.

As mentioned earlier the laser device software scan objects with a 0.1mm scanning resolution. The time taken for scanning process depends on both the resolution and size of the object. The higher the resolution (in this case > 0.1mm is low resolution) the longer the scanning time. On the other hand, larger object size implies longer scanning time. Generally, a scanning time of about 25 minutes is needed to scan about 35 mm cubic object. Although a resolution of say 1mm reduces the scanning time and provides a general shape of the aggregate, there is loss of finer details of the object’s surface texture. It should be mentioned that objects with very dark and reflective (shinny) surfaces cannot be properly scanned by the laser device. Such objects must be coated with flat white or light grey paint prior to obtain good scanned objects. The steel balls used in this evaluation were painted with a grey paint to study the amount of error introduced when scanning with coated surfaces.

4 RESULTS AND ANALYSES OF EVALUATION

The evaluation of the laser device involved using perfect shaped objects such as spheres and cubes of known theoretical surface areas and volumes. The goal was to use these objects to verify the capability of the 3D laser as the reference device for accurately measuring the surface properties of irregular shaped objects such as rock aggregates. At the same time these objects were used to calibrate the laser device.

Equations 1 and 2 were used to compute the theoretical surface area and volume of the spherical objects, whereas Equations 3 and 4 were used to compute the surface area and volume of the cubic objects.

$$\text{Surface area of a sphere} = 4\pi r^2 \tag{1}$$

$$\text{Volume of a sphere} = \frac{4}{3}\pi r^3 \tag{2}$$

$$\text{Surface area of a cube} = 6L^2 \tag{3}$$

$$\text{Volume of a cube} = L^3 \tag{4}$$

where r = the radius of the sphere and L = the length of a side of the cube.

Tables 1 show the scanned results of the measured surface area and volume for the 15 spherical objects and the theoretical values computed using Equations 1 and 2. Figure 3 compares the theoretical and measured surface areas of the spherical objects. The results show that the 3D laser scanner provided essentially the same surface areas as theoretical or computed values. The high coefficient of correlation values (R^2 = 1) indicate that the laser device exhibits high accuracy in terms of surface area and volume computations of the objects scanned.

Similarly, Table 2 shows the scanned results of the measured surface area and volume for the 12 cubic objects and the theoretical values computed using Equations 3 and 4. It is clear that there is very good correlation between the 3D laser measurement and the theoretical values obtained for the cubic objects. The high coefficient of correlation values (R^2 = 1) also indicate that the laser device exhibits high accuracy for the surface area and volume characteristics of the objects scanned (Figure 4). Thus, there is no significant difference between the theoretical and the measured values obtained by the laser scanner as indicated by the percentage difference vales. A high percentage difference in volume was obtained for the 5mm diameter object, but the inconsistency can be considered as insignificant errors attributed to the light grey paints applied on the surfaces of the objects to ensure optimum scan.

Table 1 Evaluation results for spherical objects

Spherical objects	Diameter (mm)	Surface area (cm^2)			Volume (cm^3)		
		Theoretical	Measured	% difference	Theoretical	Measured	% difference
1	5.0	0.79	0.78	-1.282	0.07	0.06	-16.667
2	12.7	5.08	5.08	0.000	1.08	1.07	-0.935
3	15.9	7.90	7.89	-0.127	2.09	2.08	-0.481
4	19.1	11.43	11.44	0.087	3.63	3.63	0.000
5	20.0	12.57	12.64	0.554	4.19	4.19	0.000
6	22.0	15.22	15.27	0.327	5.58	5.61	0.535
7	25.0	19.62	19.56	-0.307	8.17	8.13	-0.492
8	25.4	20.19	20.14	-0.248	8.53	8.49	-0.471
9	32.0	32.21	32.25	0.124	17.19	17.21	0.116
10	36.5	41.82	41.96	0.334	25.43	25.54	0.431
11	38.1	45.50	45.76	0.568	28.86	29.09	0.791
12	44.5	62.13	62.32	0.305	46.05	46.24	0.411
13	50.0	78.66	78.82	0.203	65.59	65.77	0.274
14	50.9	81.29	81.34	0.061	68.91	68.95	0.058
15	63.5	126.60	127.10	0.393	133.94	134.70	0.564

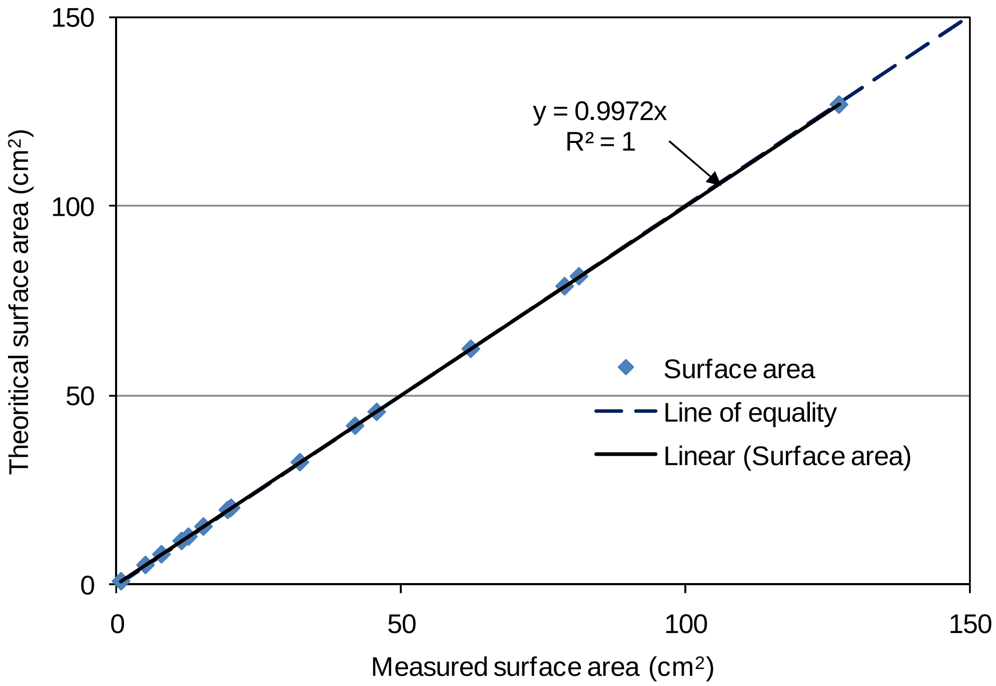


Figure 3 Comparison of theoretical and measured surface area for the spheres

Table 2 Evaluation results for cubic objects

Cubic objects	Size (mm)	Surface area (cm^2)			Volume (cm^3)		
		Theoretical	Measured	% difference	Theoretical	Measured	% difference
1	8	3.84	3.73	-2.949	0.51	0.50	-2.811
2	12	8.64	8.60	-0.465	1.73	1.73	0.173
3	15	13.50	13.60	0.735	3.38	3.43	1.689
4	20	24.00	23.86	-0.570	8.00	8.01	0.091
5	21	26.46	26.46	0.000	9.26	9.25	-0.108
6	25	37.50	37.28	-0.590	15.63	15.55	-0.508
7	28	47.04	46.99	-0.106	21.95	21.97	0.077
8	30	54.00	53.87	-0.233	27.00	27.10	0.364
9	35	73.50	73.25	-0.341	42.88	42.76	-0.267
10	40	96.00	95.65	-0.366	64.00	63.72	-0.438
11	45	121.50	122.03	0.434	91.13	91.89	0.833
12	50	150.00	149.95	-0.034	125.00	125.49	0.393

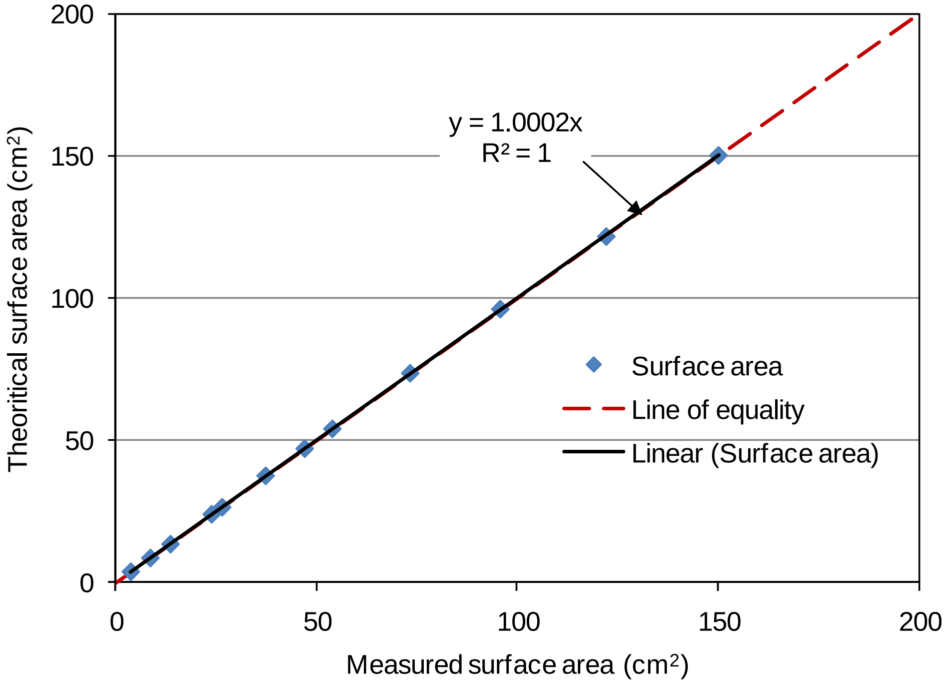
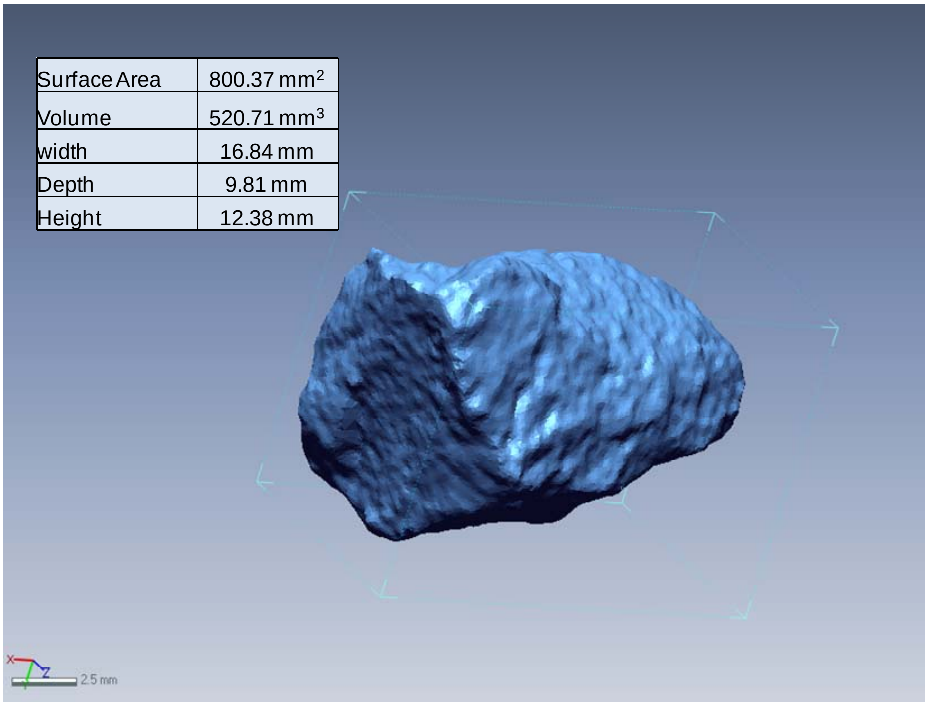


Figure 4 Comparison of theoretical and measured surface area for the cubes

As mentioned earlier, sixteen rock aggregates retained on sieve size 9.5mm were also scanned with the 3D laser device to determine surface area and volume characteristics. The particles were scanned as described in Section 3.3. Figure 5 shows a scanned aggregate namely particle number 1, and the 3D geometrical properties of the aggregate. Figure 6 shows a plot of aggregate parameter (surface area and volume) against various particle numbers for all the 16 rock aggregates scanned. It can be seen that the surface areas and volumes are not necessarily the same for aggregates retained on the same sieve size (in this case 9.5mm). The assumption to use the same surface area for asphalt binder computations may need to be re-examined based on these results.



Surface Area	800.37 mm^2
Volume	520.71 mm^3
width	16.84 mm
Depth	9.81 mm
Height	12.38 mm

Figure 5 Scanned topography of aggregate number 1 in 3D axonometric view

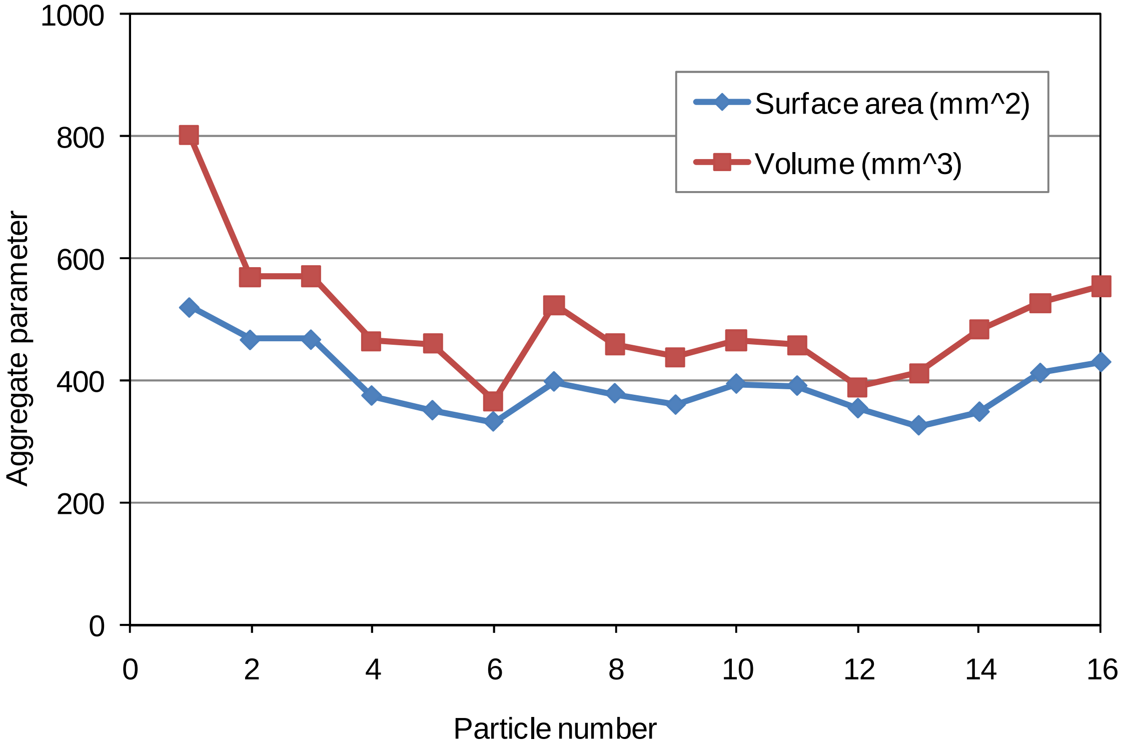


Figure 6 Surface parameters of 16 rock aggregate particles

5 SUMMARY AND CONCLUSIONS

A new 3D laser scanning device has been evaluated to conduct scanning of rock aggregates used for road and airfield construction. The scanned results indicated that the laser device system will be applicable to natural, crushed and marginal aggregates commonly used for construction of road and airfields pavements. This study shows that laser scanning device has potential use in the following areas:

- Reference device for accurate measurement of the shape, angularity and surface texture properties of rock aggregates used in pavements.
- Verification/validation tool for the current conventional test methods of aggregates including flakiness index, grading, angularity and other physical tests related to rock aggregates.
- Analysis tool for establishing rock aggregate database to efficiently rank and utilize the sources/quarries of aggregate stockpiles in South Africa and rank different aggregates crushers.
- Appropriate device to overcome and improve the limitations associated with the conventional test methods provided in AASHTO, ASTM and TMH1 specifications.
- Tool for providing test data that can be numerically analysed and modelled to characterize the properties of common aggregates used in pavement construction.
- Tool for forensic or investigative studies by evaluating performances of aggregates used in in-service pavements.

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