Three-dimensional laser scanning technique to quantify aggregate and ballast shape properties

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ABSTRACT

There is a need to improve the measurements of shape characteristics of aggregates and ballast materials used in the construction of road, airfield, and railway track infrastructures. The fundamental shape properties of aggregate and ballast, including form (roundness, flatness, elongation, sphericity), angularity, and surface texture (roughness) have not been accurately quantified because of their irregular and non-ideal shapes. Current developments are shifting from manual and subjective methods towards a more accurate and automated techniques to quantify aggregate shape properties. This paper validates a new flakiness index equation using three-dimensional (3-D) laser scanning data of aggregate and ballast materials obtained from different sources (quarries) in South Africa. The new equation uses volume ratio instead of the traditional mass ratio to determine flakiness index of aggregates and ballast materials. It is concluded that the validated equation can be used with confidence to determine flakiness index of aggregate and ballast materials.

Keywords: Flakiness index; Aggregates; Ballast; Shape properties; Laser scanning; Pavements; Railways track structure.

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1. Introduction

The use of imaging and scanning techniques for quantifying the shape and surface properties of aggregates in pavement layers and ballast in railway track structures has recently emerged as an attractive and viable option over the current standard (*manual*) test procedures. The major advantages of these techniques include their ability to evaluate the shape and surface properties of the aggregates/ballast in a quick and accurate manner, and allowing automation of the measurements. This is in contrast with the existing standard test procedures, which are subjective in nature, time consuming and laborious.

Shape and surface characteristics of rock aggregate and ballast are well known to influence the performance of asphalt and concrete pavements, and railway track structures. The pavement and railway track structures are influenced by roundness, flatness, elongation, sphericity, angularity and surface texture of the aggregate/ballast. At the same time, these properties must meet specifications. The bond between bituminous binder and aggregates in asphalt and spray seals, the cement/aggregate bond in concrete and the interlocking ability to resist shearing and deformation in unbound materials are also affected by angularity and surface texture. A peculiar problem of ballast is linked to excessive number of repeated loading under the train. The breakage of sharp corners of ballast, repeated grinding and wearing, as well as crushing of weaker particles under heavy repeated loading cause differential track settlement and unevenness of the surface.

Although researchers have made frantic efforts to develop methods/procedures for measurement of aggregate shape properties, the process has been hampered by the fact that aggregate/ballast particles have irregular and non-ideal shapes and variable surface textures. A major problem is that the current standard test methods for quantifying the shape properties of aggregates and ballast are tedious and involves a process in which the results are mainly based on the judgment of a technician. Thus, there is lack of confidence in the inter-laboratory results to be used on a daily bases for quality control and quality assurance. The problems associated with the use of the traditional methods are widely reported by some researchers [1–3].

The Council for Scientific and Industrial Research (CSIR) in South Africa is currently undertaking a research project to automate the quantification of shape and surface properties of aggregate and ballast materials used for construction of roads, airfields and railway track structures. The project employs modern three-dimensional (3-D) laser scanning technique to effectively address a number of difficulties associated with characterization of aggregate/ballast surface and shape properties, as well as the influence of these properties on the performance of pavements and railway track structures. This paper validates a new equation proposed for the computation of flakiness index of aggregate/ballast particles. Aggregate materials from seven sources, and ballast materials from two sources were scanned in a 3-D laser system to determine their flakiness properties. These materials are mainly used for construction of roads, airfields and railway track structures in South Africa.

2. Review of automated methods to quantify aggregates shapes

The shape properties of aggregates used in asphalt and concrete pavements, as well as ballast in railways track structures have a significant influence on their engineering properties [4–7]. As mentioned earlier, the form, angularity, surface texture, surface area and volume of aggregate particles influence their mutual interactions and interactions with any binding or stabilising agents, and are related to performance of the pavement [8,9].

The recent state-of-the-art has attempted to analyse aggregate shape properties using imaging techniques/video imaging systems [10–12]. These techniques are generally fast, efficient and provide additional benefits of automation that eliminates the subjectivity associated with the traditional manual methods. However, most of these methods capture a two-dimensional (2-D) image of the aggregates and provide only 2-D information about the geometry of the aggregate particles, which makes it difficult to measure the shape properties in terms of mass or volume.

An accurate way of evaluating 3-D shape properties of an aggregate particle is through the use of X-ray computed tomography (CT) technique. The sophisticated X-ray CT technique is expensive for routine use in this study. Moreover, X-ray equipment has stringent safety and radiation monitoring requirements.

Recently, 3-D laser scanning technique for quantifying aggregate shape characteristics has received much attention as a more viable and cost effective alternative to both imaging and X-ray CT [13,14]. The 3-D laser scanning technique has been used for characterizing the roughness of rock fracture surfaces and railway ballast materials [15,16]. Hayakawa et al. [17] and Tolppanen et al. [18] reported that digital modelling of gravel particles based on laser scanning could be useful, reliable, repeatable and relatively fast to evaluate the properties of ballast material. Pan and Tutumluer [19] used 3-D laser scanning to validate surface area factors of crushed and uncrushed natural aggregates for asphalt mix designs. The use of 2-D tomographic images to reconstruct 3-D surface area of an irregular shaped aggregate particle has also been proposed [20–23].

Advanced technologies to quantify the shape and surface properties of aggregates and ballast in pavements and railway track structures is relatively new. In the United States for instance, efforts to use imaging techniques to characterize aggregate shape properties have been made through collaborative research by state departments of transportation, research institutions, the industry and the academia. For example, a national pooled fund imaging project was pursued by National Center for Asphalt Technology (NCAT), and eight state highway agencies in collaboration with University of Illinois [24]. Recently, CSIR researchers have demonstrated that modern three-dimensional (3-D) laser scanning technique could be adapted and used to accurately determine aggregate and ballast shape and surface properties [25–28]. Fig. 1 presents shape and surface properties defined for a typical scanned aggregate particle by the CSIR researchers [27].

3. Flakiness index of aggregates

3.1. Flakiness index and performance

The flakiness index parameter gives an indication of the flatness of a sample of aggregate particles, and computed from their dimensions (length, width and thickness). Low flakiness index value is an indication that the aggregate is close to cubical shape, which is a preferred shape for aggregates used in pavements and railway track structures.

Flaky aggregate particles have a tendency to lie flat in pavements, creating slippage planes and reducing interlock and overall performance. Flaky and elongated particles tend to lower the workability of concrete mix, which may impair the long-term durability. Aggregates particles that break during production and construction will reduce the durability of the asphalt mixes in the asphalt layer leading to raveling, pop-outs, and potholes. In addition to the influence on workability, Siswosoebrotho et al. [29] found that flaky aggregates affect stiffness, as well as the volumetric properties (voids in mineral aggregate, air voids content) of asphalt mixes. In seal (surface dressing) pavements, good embedment properties are generally, the desirable characteristics for the aggregates. The flakiness index value indicates how well the aggregates will be embed in the bitumen sprayed surface of the seal.

Similarly, flaky particles are not desired in railway track structure since they break easily under repeated train loading. Traditionally, angular, crushed hard rocks, which are uniformly graded and free from dust aggregates enhance performance in the track structure.

3.2. Flakiness index test procedure

The current test methods are performed on coarse aggregates (size > 4.75 mm). In South Africa, the flakiness index of aggregates is determined using procedures described in the South Africa Department of Transport technical methods for highways [30], and the specifications are presented in the Committee of Land Transport Officials (COLTO) manual [31]. The COLTO manual recommends a maximum value of 35% for aggregate particles used as base and surfacing materials in roads, and 20% for aggregates that are used as roll-in-chip. The same test method and specifications are used for ballast particles.

To conduct flakiness index test, a representative sample of aggregates is sieved, and separated into the different size fractions using a standard sieve analysis methods. Aggregates retained on the 75 mm and passing the 4.75 mm sieves are discarded. Aggregates retained on the sieves between 75 mm and 4.75 mm are tested particle by particle for ability to pass through an appropriate gauge using the slot for that fraction. The flakiness index of the sample is then calculated as the ratio of the sum of the mass of particles passing through the gauges to the total mass of all the particles tested. Mathematically, the flakiness index of an aggregate particle is expressed as follows:

$$FI = \left(\frac{M_p}{M_T} \right) \times 100 \tag{1}$$

where FI is flakiness index of the sample; M_p is the total mass passing slot gauge on flakiness plate; M_T is the total mass of sieve fractions retained tested for flakiness.

The procedures used to compute flakiness index in South Africa is not dissimilar to methods used in Europe and Australia [32,33]. In the United States, the standardized method for the determination of aggregate particle shape and texture characteristics is given in the American Society of Testing and Materials (ASTM [34]). In this method, the volume of voids space between particles after compaction is used to determine a particle index parameter to quantify the shape and texture of the aggregate. In addition, flat and elongation ratio, which is not dissimilar to flakiness index, is commonly used to evaluate aggregates for hot-mix asphalt mix designs in the United States. The standard test method for flat and elongation ratio is ASTM [35].

4. Three-dimensional laser scanning at CSIR

The CSIR in South Africa recently acquired a portable 3-D laser device to conduct basic and applied research in quantifying aggregate shape and surface properties affecting the performance of pavement and railway track structures. The laser device has been calibrated to determine basic shape properties of conventional and non-conventional aggregates used in pavements. The laser device has been evaluated at CSIR for accuracy and repeatability [25]. In addition, the capacity and precision of the laser scanning device to accurately measure surface properties of irregular objects was also verified through measurement of volume of aggregates [28]. The results indicated that the 3-D laser scanning device would provide accurate surface area and volume measurements of individual aggregate particles for a reliable evaluation of shape characteristics of the aggregates. Based on direct measurements from a 3-D laser scanning approach, Anochie-Boateng et al. [28] found that the surface area factors for coarse aggregates used in five South African asphalt mixes range between 0.13–0.44 m^2/kg, compared to the Hveem estimated fixed value of 0.41 m^2/kg for all coarse aggregate particles combined [36]. Moreover, the results obtained from the 3-D scanning of coarse aggregate particles could be used to develop a mathematical relationship to compute the surface area of fine aggregate particles [28].

The 3-D laser scanning device at the CSIR was designed and manufactured by Roland DGA Corporation in the United States. The device uses an advanced non-contact sensor and a spot-beam triangulation scanning method to scan the particles in three dimensions. The wavelength of the scanner is about 660 nm, and the highest scanning resolution in this case is 0.1 mm (100 μm). The device operates in both rotation and plane scanning modes to make it suitable to scan different types and sizes of aggregates and ballast. In the rotary mode, objects 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.

An integral part of the 3-D laser scanning device is advanced data processing software, which allows automatic calculation of the surface area, volume, and dimensions (width, height and depth) of individual particles using the "*Properties Tree*" tool in the software. The software allows users to merge scans for increased quality, change the shape around curved surfaces, sharpen edges, extend shapes, add thicknesses and perform Boolean operations on polygon surfaces. Fig. 2 shows the photograph of the 3-D laser scanning device at CSIR.

4.1. Materials sampling

Aggregate materials from the three primary rocks (i.e., igneous, sedimentary and metamorphic) as well as a wide range of geological ages were sampled from seven different sources across South Africa for this study. In addition, fresh ballast materials were also sourced from one quarry together with recycled ballast from a heavily trafficked railway coal line. The selected aggregates are commonly used for road construction, whereas the ballast materials are used in railways. Crusher run (i.e., full grading as produced from the crushers) samples were obtained from each source for the scanning programme.

Representative fractions of each of the samples were screened out and five coarse aggregate components (i.e., 4.75, 9.5, 13.2, 19.5, and 26.5 mm) in each of the fractions were sampled for scanning. A random sampling approach was used to sample 30 pieces of particles from the bulk population of aggregates in each sieve fraction in order to obtain a statistical representation from each source. Usually, 30 particles retained on each sieve would be a more representative for a study like this one. Thus, a total of 1,050 aggregate particles from the seven sources were scanned. The ballast materials were mainly of three sizes (i.e., 26.5, 37.5 and 53 mm). Only few particles are normally retained on the large sieve size (i.e., 53 mm). A total of 123 particles of the fresh and recycled ballast materials were scanned.

For the purpose of this study, bulk relative density (bulk specific gravity) tests were performed on the aggregate and ballast samples using the South African standard method [30]. Table 1 shows the description of the aggregate materials, sources and rock types, as well as the results of the relative density tests. Fig. 3 shows the particle size distribution of all aggregates and ballast materials used for this study.

4.2. Laser scanning of materials

Individual aggregate or ballast particles were scanned in the laser device as a three-dimensional solid element (object) with six plane faces. Based on the shape of aggregate/ballast particles, the planer scanning mode option in the software was selected for scanning. Using this mode of scanning, four planes (representing four side surfaces) of the particles were first scanned, followed by two planes (representing top and bottom surfaces) to complete the total of six faces for each particle. The workflow of the plane scanning mode was used for processing the scanned data to obtain a modelled aggregate or ballast particle.

During the processing, different tools including the align, triangulate/merge tools available in the software were applied to firstly to bring the scanned surfaces together, and secondly to remove any irregularities, fill holes and merge the scanned surfaces to obtain a complete 3-D modelled aggregate and ballast particles. The software puts particles in a six-face bounding box directly in order to obtain the longest, intermediate and shortest dimensions of a particle. The surface area and volume values of each particle were also obtained directly from the software after post-processing.

The time taken for scanning process depended on the resolution and size of the aggregate particle. High resolution and large particle size implied long scanning time. On the average, the total time for scanning an aggregate particle was approximately 25 minutes for all aggregate particles scanned, whereas it took a longer time (average, 50 minutes) to scan a ballast particle. In this study, the highest resolution of 0.1 mm (100 μm), was used to scan all the particles. Fig. 4 presents the flowchart of the scanning process, and Fig. 5 shows the four side faces and two side faces of a typical aggregate scanned into the six-face bounding box. Fig. 6 shows 19 mm size modelled aggregate particles of different shapes to represent the various aggregate types used for this study. For each aggregate type, the figure shows representative particles ranging from a more cubical to flaky shapes in the left to right direction.

5. Surface area and volume validation/verification

The software integrated in the 3-D laser scanning device has been programmed to directly compute both the surface area and the volume of a modelled aggregate or ballast particle. Direct validation of the measured surface area of regular shaped particles with the 3-D laser scanning device was already accomplished in previous study [28]. During the validation process, 15 spherical objects of different materials including steel, ceramic, rubber and plastics, and 12 cubic objects of steel, aluminium and brass with known theoretical surface areas and volumes were scanned. The spheres had diameters in the range of 5 mm to 63.5 mm, and the cubes had sizes ranging from 8 mm to 50 mm. Volume of the irregular objects have also been verified through measurement of volume of aggregate [29].

In numerical analysis, 3-D shapes are commonly approximated by a polygonal mesh of irregular tetrahedral in the process of setting up equations for finite element analysis. Numerical computations were used to verify the surface area and volume data obtained from scanning. In three dimensions, the area of a triangle with vertices $A = (x_A, y_A, z_A)$; $B = (x_B, y_B, z_B)$; $C = (x_C, y_C, z_C)$ is the *Pythagorean sum* of the areas of the respective projections on three principal planes ($x = 0$, $y = 0$ and $z = 0$), and computed as follows:

$$Area = \frac{1}{2}\sqrt{\left|det\begin{pmatrix} x_A & y_A & 1 \\ x_B & y_B & 1 \\ x_C & y_C & 1 \end{pmatrix}\right|^2 + \left|det\begin{pmatrix} y_A & z_A & 1 \\ y_B & z_B & 1 \\ y_C & z_C & 1 \end{pmatrix}\right|^2 + det\begin{pmatrix} z_A & x_A & 1 \\ z_B & x_B & 1 \\ z_C & x_C & 1 \end{pmatrix}^2} \qquad (2)$$

where

$$\left|det\begin{pmatrix} x_A & y_A & 1 \\ x_B & y_B & 1 \\ x_C & y_C & 1 \end{pmatrix}\right| = \left|x_A y_B - x_A y_C + x_B y_C - x_B y_A + x_C y_A - x_C y_B\right|;$$

$$\left|det\begin{pmatrix} y_A & z_A & 1 \\ y_B & z_B & 1 \\ y_C & z_C & 1 \end{pmatrix}\right| = \left|y_A z_B - y_A z_C + y_B z_C - y_B z_A + y_C z_A - y_C z_B\right|;$$

$$\left|det\begin{pmatrix} z_A & x_A & 1 \\ z_B & x_B & 1 \\ z_C & x_C & 1 \end{pmatrix}\right| = \left|z_A x_B - z_A x_C + z_B x_C - z_B x_A + z_C x_A - z_C x_B\right|.$$

For N triangles, the total surface area (SA_T) of the scanned aggregate or ballast can be computed by summing up the surface areas of all poly-faces that make up the particle (Eq. 3).

$$SA_T = \sum_{i=1}^{N} A_i = A_1 + A_2 + A_3 + \ldots + A_N \qquad (3)$$

For a tetrahedron (triangular base) with vertices $\boldsymbol{a} = (a_1, a_2, a_3)$; $\boldsymbol{b} = (b_1, b_2, b_3)$;$\boldsymbol{c} = (c_1, c_2, c_3)$; $\boldsymbol{d} = (d_1, d_2, d_3)$, the volume V can be computed using a *dot product* and a *cross product* as presented in Eq. 4.

$$\boldsymbol{V} = \frac{\left|(\boldsymbol{a}-\boldsymbol{d})\cdot((\boldsymbol{b}-\boldsymbol{d})\times(\boldsymbol{c}-\boldsymbol{d}))\right|}{6} \tag{4}$$

Similarly, the total volume (V_T) for N tetrahedral can be expressed as follows:

$$V_T = \sum_{i=1}^{N} V_i = V_1 + V_2 + V_3 + \ldots + V_N \tag{5}$$

In the 3-D laser scanning system, the surface area of a particle is determined using triangulation method from the matrix of mesh points of triangular elements. The laser scanning software divides the surface mesh of modelled aggregate particle into triangular sub-surfaces called poly-faces that make up the particle. The total surface area is computed based on the sum of the surface areas of all poly-faces, and the total volume is equal to the sum of the sub-volume of all voxelised (tetrahedral) mesh. Fig. 7 illustrates two scanned aggregates showing details of poly-faces with the resulting surface area and volume parameters.

Table 2 presents the laser scanning results of 20 poly-faces (triangles) as an example of verification by the Pythagorean computation (theory). The results show that the surface areas obtained directly from the 3-D laser software agree with the theoretical Pythagorean computations Eq. 2). The absolute sum of the differences between the surface areas of the theoretical and the laser based methods is 6.55 $\times 10^{-6}$ mm².

6. Laser-based determination of flakiness index

The volume data of individual aggregate/ballast particle obtained directly from the 3-D laser scanning system were used for the computation of flakiness index of the aggregates and ballast samples. The following steps were followed for the development of the flakiness index equation based on the 3-D laser scanning technique:

- Obtain the three orthogonal physical dimensions (width, height and depth) of the individual aggregate/ballast particle from a 3-D bounding box generated by the laser scanning software;

- Determine flaky particles by comparing the dimensions of the 3-D bounding box of individual particles with that of the standard gauge slots (TMH 1 [30]);
- Obtain volume of flaky aggregate particles, also from the 3-D laser scanning results after comparing the aggregate dimensions from the bounding box with respective gauge sizes;
- Obtain total volume of all scanned aggregates/ballast directly from the laser scanning software;
- Compute flakiness index by dividing the total volume of flaky particles by the total volume of all particles scanned.

Eq. (6) is used to define flakiness index based on the 3-D laser scanning volume concept.

$$FI_v = \left(\frac{V_p}{V_T} \right) \times 100 \tag{6}$$

where FI_v is flakiness index based on volume; V_p is the total volume of flaky aggregates scanned; V_T is the total volume of aggregate/ballast sample scanned.

7. Validation of volume based flakiness index equation

Current developments in the pavement construction industry are shifting from gravimetric towards volumetric relationships, which can be easily established using 3-D laser-based scanning data. For instance, the standard method for the determination of aggregate shape and texture in the United States is based on volume [34]. Also, modern approaches to asphalt mix design for example, often rely on volumetric design principles to determine the correct the aggregate structure.

It is a common practice to use bulk relative density to convert mass (weight) measurements to volumes. For example, in hot-mix asphalt designs, the mass of aggregates are always converted to volume in order to determine important volumetric properties such as air voids content, voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA). In the asphalt mixes, the volume of permeable pores in the aggregate surface is usually represented by the volume of the bulk aggregate, the total volume of binder and the volume of absorbed binder.

The mass and volume of a material are related to density. Aggregate or ballast particles originating from the same parent rock are usually assumed to have the same specific gravity hence the ratio by mass is equivalent to the ratio by volume. Based on this knowledge, the mass of all aggregates/ballast scanned for this study was derived from the volume data obtained directly from the 3-D laser device to validate the volume-based flakiness index equation. The bulk relative densities (see Table 1) and the volume of scanned samples were used to obtain the mass derived from the 3-D laser device. Eq. (7) is the relationship between mass and volume.

$$M = RD_B \times V \tag{7}$$

where M is mass; RD_B is the bulk relative density; V is volume.

The volume-based flakiness index equation (Eq. 6) was first proposed by [26] based on limited aggregate materials used for asphalt mix designs. The proposed equation uses volume ratio instead of mass ratio presented in TMH 1 [30] to compute the flakiness index of the aggregate particle. The 3-D laser scanning device is used to directly obtain the volume parameters of the aggregate particle to compute flakiness index. Aggregates used in the production of asphalt mixes are blend of two or more aggregates, and usually have different bulk specific gravities. The volumetric calculations are done using the average values for the blend, which could introduce errors in the results. A more rational approach to validate this equation was to use aggregates and ballast from various rock formations and sources (quarries), and conduct tests to obtain individual bulk relative density for each aggregate source. In addition, the aggregates and ballast materials were selected based on usage in major transport infrastructures in South Africa, i.e., roads, airfields and railway track structures.

Fig. 8 presents a plot of the actual mass of the aggregates/ballast particles obtained by weighing, and the derived masses for all aggregates and ballast samples scanned. The total mass of all the particles weighed was 4.584 kg compared to the total derived mass from volume (3-D laser) of 4.555 kg. It can be seen that the mass of the aggregates estimated from the 3-D laser device agree quite well with the physically measured (weighed) values. An excellent correlation (R^2 = *0.9994*) exists between the computed and the actual mass although there is an insignificant error. This inherent inaccuracy can be reduced by scanning large samples of aggregate and ballast particles in order to improve confidence in the results.

8. Discussions of laser-based and standard flakiness test results

The standard laboratory test for flakiness index [30] was conducted on all aggregate/ballast particles scanned to compare results with those obtained from the 3-D laser scanning method. Recall, that flakiness index computed from the standard method is based on mass ratio whereas the laser scanning approach computes flakiness index based on volume ratio. Table 3 shows the flakiness index results of the two methods for all samples studied. As expected, there are differences in the results of the standard (*manual*) and the laser scanning (*automation*) methods.

There is obviously, subjectivity in the standard methods in the sense that the test results vary from person to person. The tendency of technicians, who are performing manual tests to force an equi-dimensional aggregate/ballast particle for instance, to pass through the flat gauge slots by pushing it harder, could introduce a significant error in the flakiness index since coarse aggregate particle weighs by far more than medium or small size aggregate particle. The standard methods cannot capture profiles of the irregularly shaped aggregate particles. The apertures of the slot gauge allow for considerable variation in the shape of different aggregates passing through, resulting in poor repeatability of flakiness index obtained from the same material. Similarly, two different aggregates having the same flakiness index may in reality differ significantly in terms of their shape and volume. That is, human errors could significantly affect the determination of flakiness index of aggregate/ballast particles using the current methods.

One the other hand, in the 3-D laser scanning approach, aggregate particles are conveniently placed in a 3-D bounding box by software to obtain the actual dimensions needed for the computation of flakiness index. This automated procedure would mitigate the human errors associated with the manual methods.

Tables 3 shows the flakiness index test results obtained from the 3-D laser scanning compared with the results obtained from the standard test method [30] used in South Africa for all aggregates and ballast materials tested, and Fig. 9 compares the results from these two methods graphically. With the exception of the alluvial gravel material (mainly rounded particles) it can be seen that the manual method could significantly underestimate the flakiness index of some aggregate and ballast materials. The large differences between the results for granite, dolerite, andesite and the fresh ballast materials cannot be explicitly explained at this stage although the enumerated shortcomings of the standard methods could be the major contributing factors. Additional samples may be required to verify these differences. The results of the tillite, hornfles, quartzite, and the recycled ballast materials, however shows that the automated laser based method (volume ratio) is applicable to the determination of shape properties of both aggregates and ballast materials.

9. Conclusions

The use of automated techniques to quantify the shape properties of aggregates and ballast materials has recently received much attention as they provide more accurate and reliable results than the existing standard test methods. Flakiness index is an important shape parameter for aggregate and ballast materials used the construction of road, airfield and railway track infrastructure. In this paper, a new flakiness index equation was validated using three-dimensional (3-D) laser scanning volume data of aggregates and ballast materials sourced from various quarries in South Africa. The following conclusions are drawn:

- The much needed improvements in the measurement of the shape properties of aggregates and ballast materials has been demonstrated in this study through the use of 3-D laser based scanning method. Results obtained from the laser scanning technique could be used for quality control in the quarries or aggregate production sources. Laser scanning technique provides a more accurate results when compared with the traditional methods for evaluating aggregate shape properties, and improve aggregate selection for construction purposes.

- A new 3-D volume-based flakiness index equation has been successfully validated for aggregate and ballast materials. Excellent correlation between the mass derived from the 3-D laser and the actual mass suggests that the new volume ratio equation can be used with confidence to accurately define flakiness index of aggregates/ballast with known relative density.
- The surface area and volume results obtained from the 3-D laser scanning system agree very well with numerical computations. This implies that the validation of the new flakiness index equation conforms to sound mathematical theories. Reliable flakiness data can now be obtained for aggregates and ballast materials used in the construction of pavements and railway track infrastructures. Currently, aggregates particles from 15 to 20 sources in South Africa are being scanned to develop laser-based aggregate properties for all sources.

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Table 1

Aggregate and ballast material sources

	Material description	Source/ quarry	Rock type	Bulk relative density
Rock aggregates	Granite	Jukskei	Igneous	2.634
	Tillite	Verulam	Sedimentary	2.670
	Hornfels	Peninsula	Metamorphic	2.709
	Quartzite	Ferro	Metamorphic	2.650
	Dolerite	Rooikraal	Igneous	2.939
	Andesite	Eikenhof	Igneous	2.815
	River gravel (quartzite)	Molopo river	Metamorphic	2.649
Rock ballast	Dolerite (Recycled ballast)	Railway track	Igneous	2.976
	Dolerite (Fresh ballast)	Lancaster	Igneous	2.989

Table 2
Area verification of the laser results.

Poly-face no.	Area of principal planes			Poly-face Area		Difference *Area* $\times 10^{-6}$ (mm^2)
	Area XY $\times 10^{-6}$ (mm^2)	*Area YZ* $\times 10^{-6}$ (mm^2)	*Area ZX* $\times 10^{-6}$ (mm^2)	Pythagorean *Area* $\times 10^{-6}$ (mm^2)	Laser *Area* $\times 10^{-6}$ (mm^2)	
1	169.2354	493.0536	230.9698	14943.72	14943.74	-0.02
2	191.9350	1395.7502	374.8352	22150.17	22145.81	4.36
3	391.7549	1013.1871	138.1201	19640.91	19642.67	-1.76
4	204.0647	370.0068	73.7443	12726.11	12727.96	-1.85
5	1133.7160	1088.4338	714.1107	27093.64	27089.92	3.72
6	603.9129	181.0513	147.8979	15271.40	15262.52	8.88
7	567.7698	21.2538	129.1519	13399.40	13401.56	-2.16
8	360.3649	2.2850	98.8513	10741.29	10759.03	-17.74
9	1388.2212	65.1046	228.1393	20502.84	20518.31	-15.47
10	266.9257	73.1962	140.8960	10966.06	10968.42	-2.36
11	227.1399	86.8512	122.0663	10440.99	10439.99	1.00
12	264.6833	267.7609	32.4540	11883.79	11873.54	10.25
13	184.5318	368.0654	181.8280	13550.14	13534.56	15.58
14	86.1277	666.0766	106.8333	14654.67	14647.39	7.28
15	43.1677	538.3982	130.3666	13341.03	13346.43	-5.40
16	383.0597	657.3378	563.1200	20021.97	20019.01	2.96
17	70.1470	46.1049	65.0071	6731.62	6733.24	-1.62
18	118.9461	34.3640	59.4207	7292.65	7290.19	2.46
19	54.0285	27.1375	53.3681	5799.44	5797.89	1.55
20	150.4999	200.2406	130.4612	10968.15	10971.26	-3.11

Table 3

Flakiness index (%) results from standard and laser methods

Material type	TMH 1[a] [30]	3-D Laser technique	Difference
Granite	28.1	24.1	4.0
Tillite	21.8	21.2	0.6
Hornfels	29.9	29.3	0.6
Quartzite	36.4	35.3	1.1
Dolerite	18.4	14.9	3.5
Andesite	29.6	23.4	6.2
Alluvial gravel	3.1	5.5	-2.4
Dolerite (Recycled ballast)	3.1	2.9	0.2
Dolerite (Fresh ballast)	20.2	13.8	6.4

[a]: TMH 1 results on scanned particles

Figure captions

Fig.1. Surface and shape properties of typical aggregate particle.

Fig. 2. 3-D Laser scanning setup at CSIR.

Fig. 3. Particle size distribution of the aggregates and ballast samples.

Fig. 4. Process of laser scanning and modelling of aggregate particles.

Fig. 5. Four-and two- side scanned faces and modelled aggregate in six-face bounding box.

Fig. 6. Modelled aggregate particles in 3-D bounding boxes for different samples.

Fig. 7. Mesh of triangular elements (poly-faces) to determine surface area and volume.

Fig. 8. Comparison of total masses for the aggregate/ballast samples studied.

Fig. 9. Comparison of flakiness index determined from the standard and 3-D laser methods.