

APPLICATION OF LASER BASED TECHNOLOGY TO QUANTIFY SHAPE PROPERTIES OF RAILWAY BALLAST

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ABSTRACT

The fundamental measurements of railway ballast shape characteristics are essential for good quality control and, ultimately, for understanding their influence on performance of the track structure. Flakiness, roundness and sphericity are important shape parameters to quantify ballast shape properties. It is well known that the current test methods for determining the shape properties of railway ballast have some limitations; they are laborious and subjective, which could lead to poor repeatability of test results. This paper presents the use of laser scanning technique to quantify the shape properties of railway ballast. The objective is to establish the concept of using three-dimensional laser scanning technique to directly obtain the shape properties of ballast particles. The study demonstrated that an advanced automated technique such as laser scanning method could be explored to accurately quantify the shape properties of railway ballast.

1 INTRODUCTION

The performance of the railway track structure can be significantly influenced by the ballast shape properties; roundness, flatness, elongation, sphericity, angularity and surface texture. Railway ballast materials must fulfil several quality requirements including shape properties. The source of ballast (parent rock) varies from country to country depending on the quality and availability of the rock, regulations and economic considerations. An accurate measurement of the shape properties is important for developing and revising specifications for quality control and quality assurance of ballast. The railway industry in South Africa is facing a peculiar problem of rounded ballast due to excessive number of repeated loading. The breakage of sharp corners of aggregates, repeated grinding and wearing, as well as crushing of weaker particles under heavy repeated loading cause differential track settlement and unevenness of the surface. Current track ballast specifications do not address in a direct manner the measurement of shape properties, thus leading to inconsistent interpretation of test results. If rounded ballast is to be avoided then an even more restrictive specification of ballast shape properties would be required.

The problems associated with the use of the traditional methods of quantify ballast properties are reported by some researchers (Krumbein, 1941, Tutumluer et al., 2011 and Bowman et al., 2001). Anochie-Boateng et al. (2011a, 2012) emphasised the efforts made by researchers in pavements to develop accurate procedures to measure important shape parameters of rock aggregates. The major problem is that aggregate or ballast particles

have irregular and non-ideal shapes with variable surface textures. Hayakawa et al. (2005), Tolppanen et al. (2008) reported that digital modelling of gravel particles based on three-dimensional (3-D) laser scanning could be useful, reliable, repeatable and relatively fast to evaluate the properties of ballast material. Recently, the Council for Scientific and Industrial Research (CSIR) acquired a 3-D laser scanning device to accurately quantify aggregates and ballast shape and surface properties.

The objective of this paper is to establish the concept of the use of 3-D laser scanning technique to accurately quantify the roundness, flakiness, elongation and sphericity shape properties of selected ballast materials. The properties of the ballast for this study are currently being investigated by Transnet Freight Rail (TFR), Track Technology Centre in South Africa.

2 SHAPE CHARACTERISTICS OF RAILWAY BALLAST

2.1 Current test methods

On South African railways, TFR uses only flakiness index to quantify ballast shape properties. The standard test method used for the determination of flakiness index of ballast aggregates is contained in TFR ballast specification (1998). In this method, a metal gauge with rectangular slots representing various aggregate sieve sizes are used to obtain the masses of aggregate particles passing the slots.

In general, ballast that satisfies the durability test is subjected to further test that evaluates shape, surface characteristics, grading and unit mass. A new technique introduced at the CSIR to quantify shape properties of railway ballast particles. Figure 1 shows the shape and surface properties defined by CSIR researchers for typical aggregate/ballast particle.

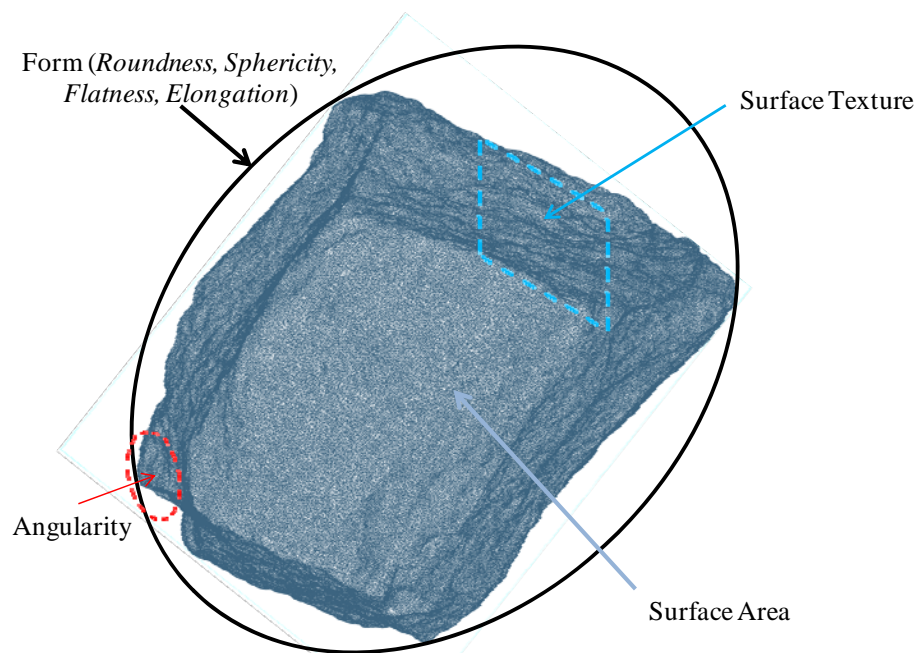


Figure 1: Shape and surface properties defined for railway ballast particle

2.2 Flat and elongation parameters

The physical dimensions (length, width and height), surface area and volume have been used to compute index parameters commonly used to describe the shape properties of aggregate/ballast. The physical dimensions of a railway particle are demonstrated in Figure 2.

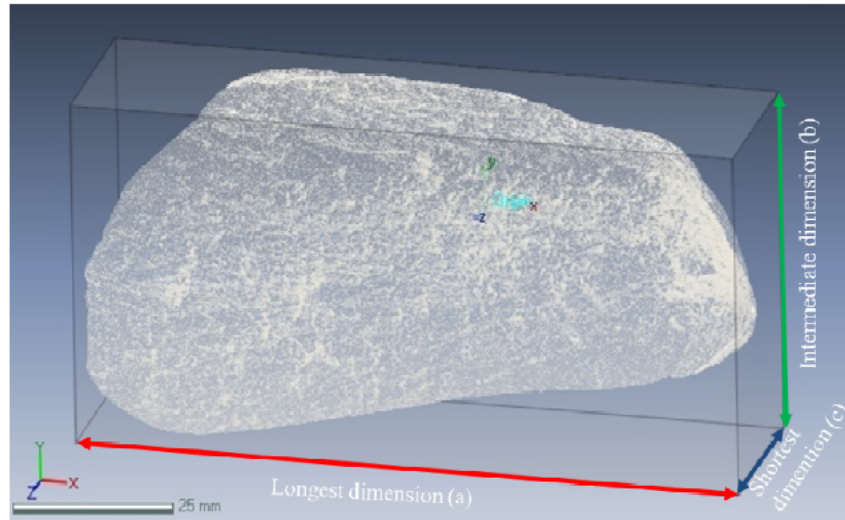


Figure 2: Principal dimensions of ballast particle scanned at CSIR

Kuo et al. (1998) defined two fundamental parameters to describe the shape of a rock aggregate as elongation and flatness ratios (Equations 1 and 2). Elongation ratio is defined as the ratio of the particle longest dimension in the plane perpendicular to the intermediate dimension. Flatness ratio is defined as the ratio of the particle intermediate to the longest dimension perpendicular to long and short dimension. Shape factor of an aggregate particle can be related to flatness and elongation characteristics (Equation 3).

$$\text{Flatness } (F) = \frac{S}{I} \quad (1)$$

$$\text{Elongation } (E) = \frac{I}{L} \quad (2)$$

$$\text{Shape factor } (SF) = \frac{SL}{I^2} \quad (3)$$

where,

- L = longest dimension of a particle;
- I = intermediate dimension of a particle;
- S = shortest dimension of a particle;

2.3 Sphericity

Sphericity is a measure of how much the shape of a particle deviates from a sphere. A perfect sphere has a sphericity of one. The sphericity of an aggregate particle is quantified based on the surface area and volume properties of the aggregate (Lin et al., 2005 and Hayakawa et al., 2005). Thus, an accurate measurement of the surface area and volume has direct influence on the sphericity of the aggregate particle. Ballast aggregates have irregular and non-ideal shapes. It is therefore, difficult to obtain a direct measurement of the surface area and volume properties using the traditional methods for quantifying the shape properties of aggregates. Advanced techniques such as laser scanning method allows for accurate measurements of surface area and volume.

$$\psi = \frac{\sqrt[3]{36\pi V^2}}{A} \quad (4)$$

where,

ψ =sphericity
A =surface area
V =volume

2.4 Flakiness index

The flakiness index parameter gives an indication of the flatness of the particle. The standard test method for the determination of flakiness index of railway ballast in South Africa is contained in the TFR specification 1998, which is based on Technical Methods of Highway (TMH) Method B3 (TMH 1, 1986). In the TFR specification, flakiness index is defined as the ratio of the total mass passing *bar sieve* slots, which are 0.5 of the sieve size, to the total mass of aggregate retained on three specific sieve sizes.

Mathematically, the flakiness index (FI) of a ballast material can be represented as follows:

$$FI = \left(\frac{M_p}{M_T} \right) \times 100 \quad (5)$$

where,

M_p = total mass of aggregate passing a bar sieve slots;
 M_T = total mass of aggregate retained on a specific sieve size (grading analysis).

2.5 Roundness index

Roundness refers to the sharpness of the corners and edges of a particle. Waddell (1932) defined roundness of a particle as the average radius of curvature of the corners to the largest inscribed circle radius.

Ballast deformation could be related to the roundness, which is influenced by several factors including the number of load cycles (Indraratna et al., 2006). Well rounded ballast could approach the shape of a river pebble. Thus, an ellipsoid instead of a sphere could be

used to represent the shape of a typical rounded railway ballast particle. Ballast roundness was defined as an approximation ratio of surface area of an ellipsoid to the surface area of the particle (Hayakawa et al., 2005) as presented in Equation 6.

$$\rho = \frac{SA_e}{SA_p} \quad (6)$$

where,

- ρ = individual particle roundness;
- SA_e = surface area of an ellipsoid;
- SA_p = surface area of ballast particle.

3 BALLAST TESTING AND SCANNING

3.1 3-D laser scanning device

The 3-D laser scanning device used for this study is available at CSIR. The device is currently being used in an R&D project that employs laser scanning and novel numerical techniques to effectively address a number of difficulties associated with characterisation of aggregate and ballast shape and surface properties, and their influence on the performance of transport infrastructure in South Africa. The laser device has been evaluated for accuracy and precision, and calibrated to determine basic shape properties of conventional and non-conventional aggregates used in pavements and railways (Anochie-Boateng et al., 2010; Anochie-Boateng et al., 2011b, 2011c, 2011d). In addition, the laser device has been validated for direct measurements of shape and surface properties of aggregates (Anochie-Boateng, et al., 2010).

The device uses an advanced non-contact sensor to capture flat areas, hollow objects, oblique angles and fine details of scanned objects in three dimensions with scanning resolution that ranges from 1mm (1000 μ m) to 0.1-mm (100- μ m). Figure 3 shows a photograph of the 3-D laser device at the CSIR. An integral part of the laser device is advanced data processing software that is used for obtaining accurate shape properties of the ballast particles.

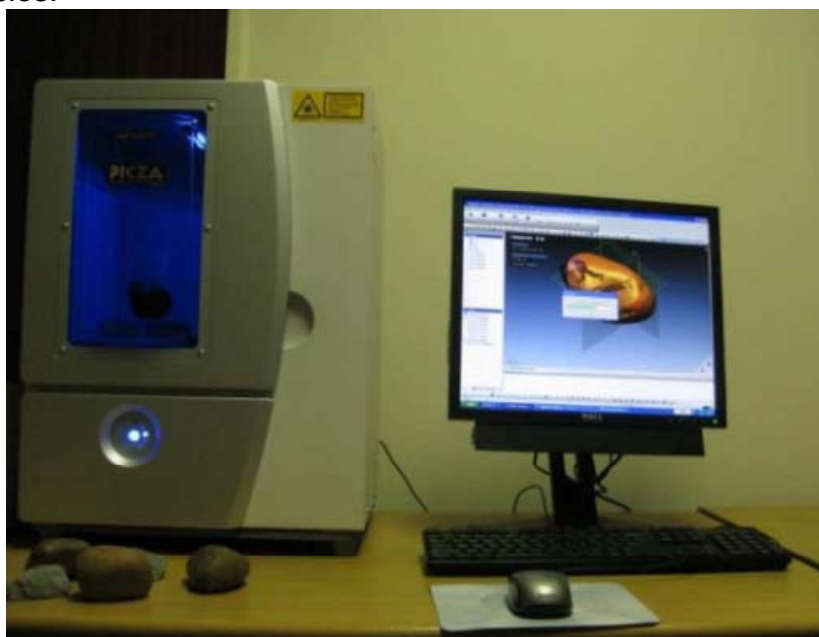


Figure 3: 3-D Laser scanning set-up at CSIR

3.2 South African freight rail specification

The 1998 South African Freight Railway Specification (S406) for supply of ballast stone calls for specific shape descriptors to ensure stability of the ballast layer. The particle size distribution (PSD) range for freshly quarried ballast rock is presented in Figure 4. More than 95% of the ballast material should be between the sizes 19 mm and 63 mm diameter. Less than 30% of the material should be 'flat' with height (or length) dimensions greater than 1:2.

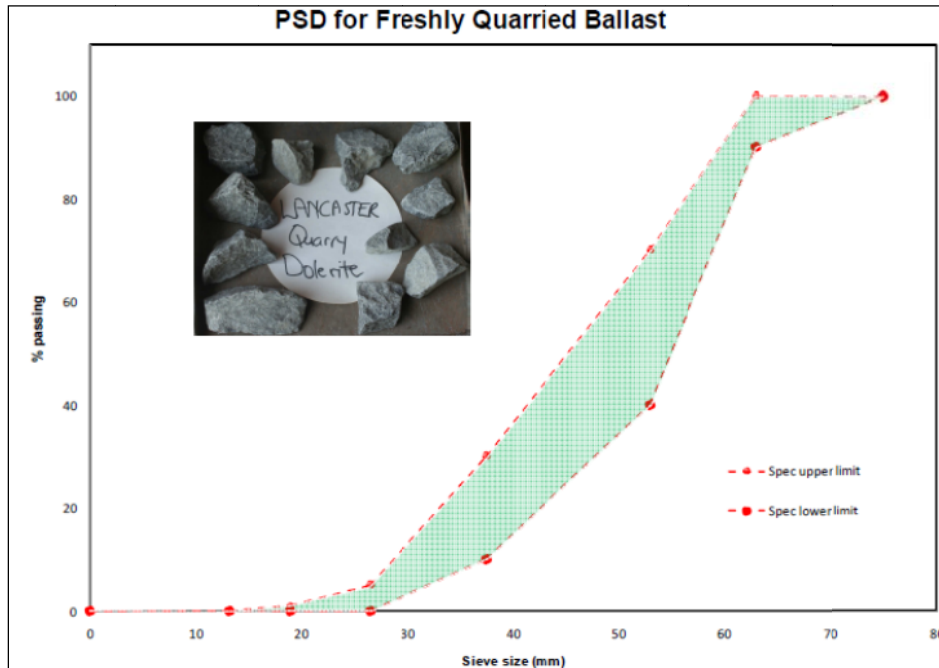
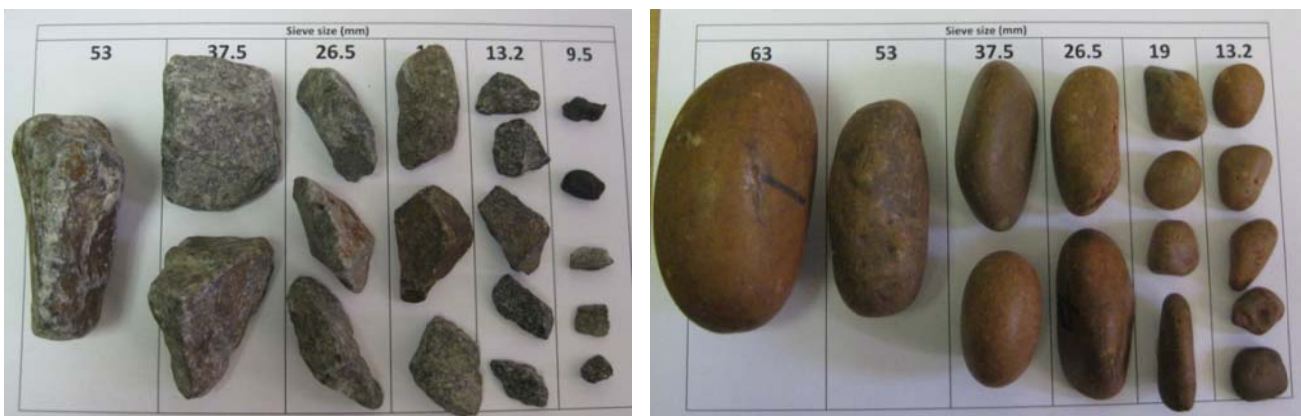


Figure 4: Heavy haul coal export line specification for railway ballast (1998)

3.3 Ballast sample selection

The Kwa-Zulu Natal (KZN) coal line was chosen for this study because of the repetitive ballast tamping, track geometry and ballast roundness reported by the Vryheid depot. The materials selected for the study are presented in Figure 5. The study area is located approximately 10 km from Vryheid, between Vryheid East and Tintasdrift station (see Figure 6).



(a) Crushed dolerite from coal line

(b) River pebbles from Kimberley

Figure 5: Types of selected material for this study

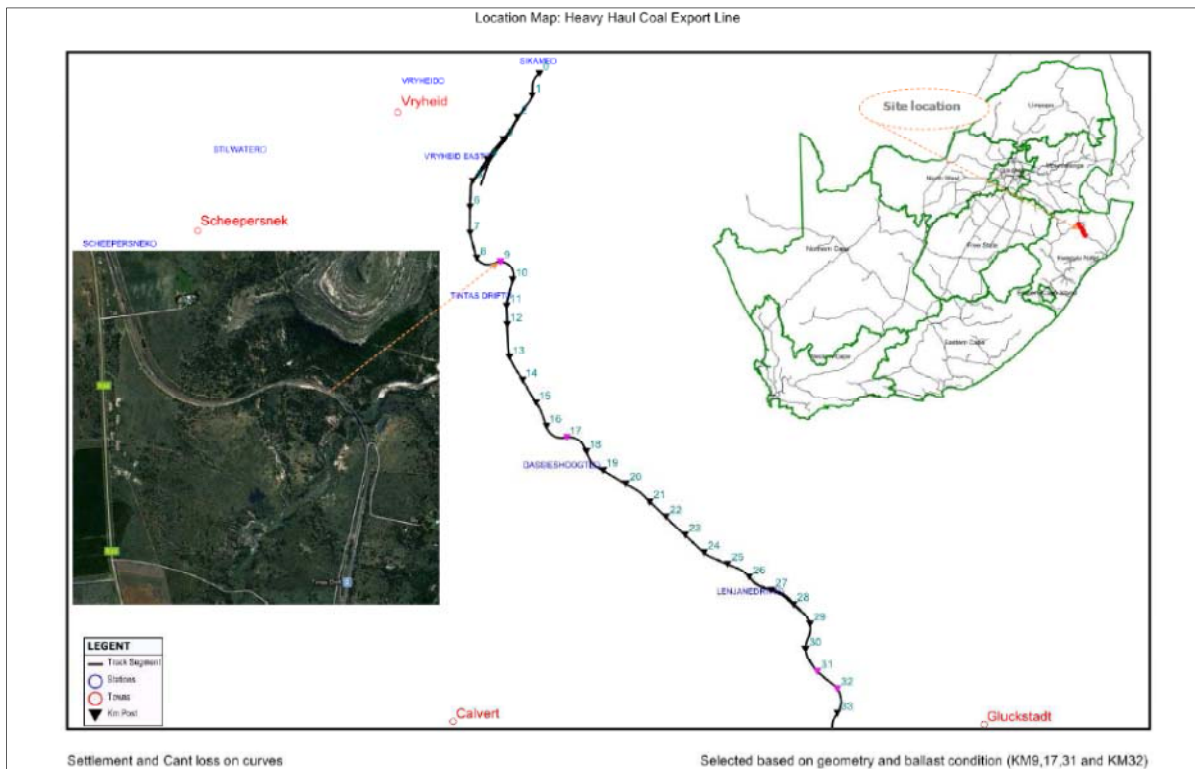


Figure 6: Field test locations on the heavy haul Coal export line near Vryheid, KZN

3.4 Sample testing

Table 1 presents the grading analysis of each sample type for the study. A total of 50 particles were scanned for the crushed dolerite sample, whereas 27 particles were scanned for the pebbles in this study. Usually a random sample of 30 particles retained on each sieve would be a more representative for a study like this one. However, fewer than 30 particles are normally retained on the bigger sieves especially 63 and 53 mm sieve sizes. Following the grading analyses, ballast samples were riffled until the reduced number of particles needed for scanning was achieved (see Table 2).

Table 1: Sieve analysis results of aggregates used in the study

Nominal aperture size of sieve mm	Limits of percent passing each sieve (recommendation ballast grading)	% by mass passing	
		Crushed dolerite	Uncrushed river pebbles
75.0	100	100	100
63.0	90-100	98	93
53.0	40-70	67	75
37.5	10-30	13	47
26.5	0-5	0	16
19.0	0-1	0	1
13.2	0	0	0

Table 2: Ballast particles reduced for scanning

Nominal aperture size of sieve mm	Crushed Dolerite particles	Uncrushed river pebbles particles
63.0	-	3
53.0	3	3
37.5	3	3
26.5	21	10
19.0	12	5
13.2	6	3
9.5	5	-
Total	50	27

3.5 Scanning and data acquisition

All the ballast particles used for this study were scanned in accordance with the CSIR guideline for scanning of aggregates and ballast particles (Anochie-Boateng et al., 2011c). Firstly, four surfaces are scanned and then followed by two surfaces to complete the scanning of an aggregate/ballast particle.

After the scanning was completed, the laser scanning software was used to integrate and merge the scanned surfaces to obtain the complete in a six-face bounding box to directly obtain the longest, intermediate and shortest dimensions of ballast particle. The surface area and volume of ballast particle were also obtained directly from the software after post-processing.

4 DISCUSSION OF RESULTS

4.1 Ballast shape parameters

The ballast was classified by visual assessment as sub-rounded ballast with particles of nearly plane sides but have well-rounded corners and edges according to American Society for Testing and Materials (ASTM), ASTM 2488-00 (2000). The plot of flatness against elongation ratio using all ballast particles scanned for this study is shown in Figure 7. It can be seen that the dolerite sample have more equi-dimensional particles when compared to the river pebbles. The average shape factor for the angular dolerite sample is 1.01, whereas that of river pebbles is 1.3. The flat and elongated particles tend to break under repeated loading and cause differential track settlement and unevenness of the surface.

Figure 8 shows a plot of sphericity against roundness of the dolerite and pebble samples scanned. As expected all the pebbles scanned are more rounded and spherical than the dolerite particles, as it can also be seen in the actual photos presented in Figure 5. The dolerite particles have low sphericity and roundness, which validates the fact that crushed stones generally, should be less rounded than pebbles. The current problem experienced by TFR coal line is crushed ballast becoming rounded. This study demonstrates that most of the crushed stones scanned are approaching the shape of pebbles. This could only be shown by the laser scanning method.

Based on the 3-D laser results a general roundness index can be developed for ballast materials used in the coal line, which could be extended to railway ballast materials.

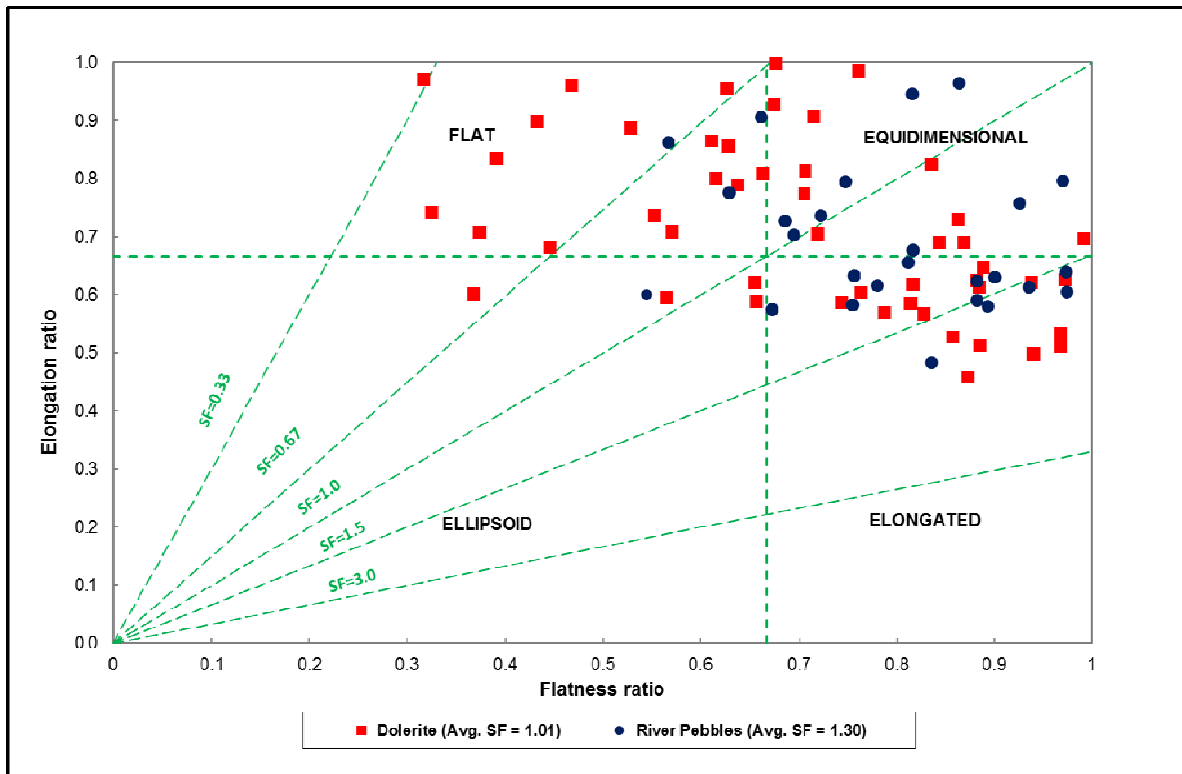


Figure 7: Chart of ballast particle shape properties

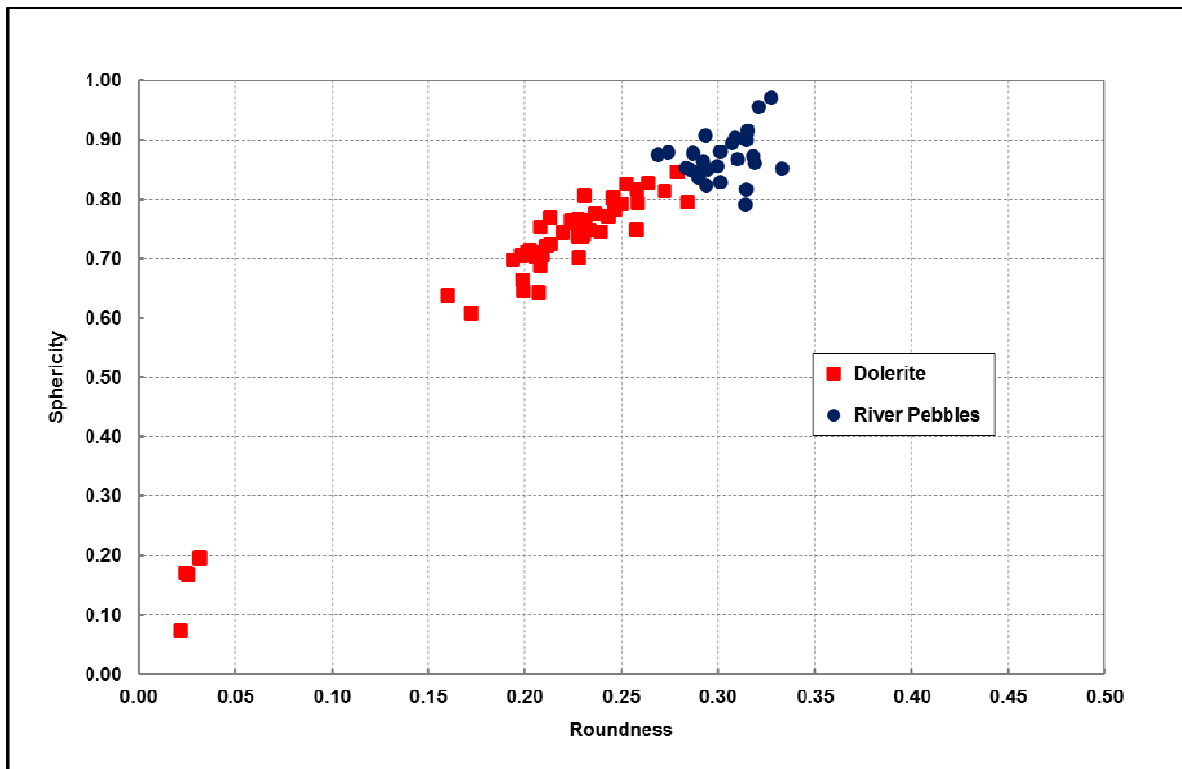


Figure 8: Relationship between roundness and sphericity

4.2 Ballast flakiness index

A new flakiness index equation that is based on 3-D laser scanning technique was proposed to determine the flakiness of aggregate particles used in road construction (Anochie-Boateng et al., 2011b). The equation uses volume ratio instead of mass ratio

presented in TMH 1 to compute the flakiness index of the aggregate particle (see Equation 7). The 3-D laser scanning device is used to directly obtain the volume parameters of the aggregate particle to compute flakiness index.

$$FI_v = \left(\frac{V_p}{V_T} \right) \times 100 \quad (7)$$

where,

- FI_v = flakiness index based on volume;
- V_p = total volume of flaky aggregates scanned;
- V_T = total volume of the aggregate sample.

The flakiness index obtained for the dolerite sample using the standard test method based on Equation 5 is 8.3%, whereas the flakiness index based on volume approach (i.e. laser scanning method, Equation 7) is 3.3%. Thus, an error of 60.2% could be introduced in flakiness index when using the current method. This is attributed to the fact that the technicians performing the flakiness index test could force an equi-dimensional aggregate particle for instance, to pass through the flat gauge slots by pushing it harder, thereby introducing significant error in the flakiness index. That is, human errors could significantly affect the determination of flakiness index of ballast particles using the current TFR specification. Therefore, the use of automation approach to quantify ballast properties is essential and must be considered. A review of the railway specifications/standards with the new technology may then be required.

5 CONCLUSIONS

This paper introduced a new approach for the determination of shape properties of railway ballast. The approach is based on the use of 3-D laser scanning technique to directly obtain the flakiness index, roundness and sphericity of ballast particles of a heavy haul coal line in South Africa.

Based on the results presented in this paper, the following conclusions can be made:

- It is established that a 3-D laser scanning technique can be used to determine the physical dimensions, surface area and volume properties of railway ballast to further determine shape indices.
- There is a need for automated techniques that is based on accurate measurements to quantify shape properties of railway ballast in order to mitigate human errors associated with the ballast shape properties.
- The CSIR has capability to demonstrate application of laser scanning technology to quantify the shape properties of ballast. It is therefore, important for the railway industry in South Africa to take this opportunity to improve and develop new guidelines and test methods for ballast in order to improve the performance of railway track structures.

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