Effect of round particles on shear strength properties of railway ballast

G.M. Mvelase[1], J.K. Anochie-Boateng[2] and L.L. Msibi[3]
[1,3]Transnet Freight Rail, Technical Rail Network, South Africa.
[2]CSIR Built Environment / Tshwane University of Technology, South Africa.

Abstract

The railway industry in South Africa is facing a problem where passage of trains on the heavy coal haul lines are causing degradation by means of wear (roundness) of ballast materials, and consequently, leading to differential track settlement and unevenness of the surface. Railway ballast remains an important component material in a rail track structure system. However, their fundamental attributes of shape have not been determined accurately, and quantitatively related to the performance of the tracks in a more rigorous and scientific way. This paper presents a case study of five ballast materials used by Transnet Freight Rail heavy coal line in South Africa. The objective is to investigate the effect of ballast particle roundness determined from a modern three-dimensional (3-D) laser scanning technique on the internal frictional angle of the ballast materials. The results indicated the effect of ballast shape on shear strength, as fresh ballast from the quarry provided higher internal frictional angle when compared with ballast that have been degraded and rounded. It was established that there is a strong relationship between frictional angle and roundness (i.e. shape) of the ballast materials and a pebble sample that was used as a control material for extremely rounded ballast.

Keywords: Railway ballast, grinding and wearing, geometry deterioration, advanced laser, roundness index, friction angle, track structure.

1 Introduction

Railway ballast has several functions in the track structure, including the transfer of the applied load from the wheel to the subgrade. Ballasted track has remained virtually unchanged for centuries and still the most cost-effective and maintainable design. The railway industry in South Africa is facing a problem where heavy trains subject ballast to repeated loading. The grinding and wearing of sharp corners of ballast under sleeper leads to round particle shapes, causing differential track settlement and increasing geometry deterioration. The major challenge is how to accurately measure the shape properties in a direct manner and used them to evaluate performance. Overtime, due to traffic and maintenance procedures, the ballast material is subjected to degradation by means of wear (roundness) and breakage phenomena. It is the main reason why problems associated with this essential component of the railway track structure system need to be addressed more rationally and by using available modern and scientific approaches or techniques.

The increasing demands of higher axle loads means that understanding railway ballast behaviour and its interactions with track components still remains a critical element to design and successful operation of ballasted railway tracks. Therefore, characterisation and modelling of ballast properties and their behaviour have to be researched and discussed in a more systematic and scientific way. In the geotechnical field, mathematical descriptors are common and useful due the reproducibility of the measurements, and these can be used to measure ballast shape properties with confidence. Flakiness, roundness and sphericity are important shape parameters, which have been used to quantify ballast shape properties. However, the irregular shape of ballast stones presents a modelling challenge.

The Council for Scientific and Industrial Research (CSIR) in South Africa recently embarked on an extensive research and development in the use of a modern three-dimensional (3-D) laser scanning and numerical modelling techniques to improve measurements of the shape properties of aggregates and ballast materials, [1, 2, 3]. The overall goal was to link the shape parameters of aggregates and ballast obtained from the laser system to engineering properties and performance. The laser device has been evaluated for accuracy and precision, and calibrated to determine basic shape properties of aggregates and ballast materials used in roads and railways, [4, 5, 6]. This paper focuses on the effect of round particles on shear strength properties of railway ballast. The main objective is to present the relationship between roundness determined from 3-D laser scanning technique and the internal frictional angle of ballast materials tested in a static triaxial testing system.

2 Materials used for the study

One fresh ballast sample from a quarry, and four recycled ballast from a heavy haul coal line on the Vryheid region was selected for this paper. A typical pebble material was also included to act as a reference material for determining the roundness of the ballast materials. The parent rock of recycled ballast remains mostly the same as that of fresh crushed ballast. Because dolerite is the most commonly used ballast type in the heavy haul line, preliminary testing for the reproducibility of tests was conducted using a dolerite obtained from a quarry near Vryheid East, South Africa. The same dolerite was used in the main testing programme. The field materials were selected from the Vryheid depot of Transnet Freight Rail (TFR), which noted repetitive ballast tamping, track geometry (*cant* loss on curves) and ballast roundness.

Sieve analysis (grading) tests were conducted on all samples to determine particle size distribution in accordance to the specification [7]. Fig. 1 presents the particle size distribution of the six materials and compares the four recycled ballast, fresh crushed ballast and river pebbles to TFR recommended specification for heavy haul tracks. All recycled ballast material failed to meet specifications limit. The five ballast materials composed of particles ranging from 19 mm to 63 mm. The aim of the grading was to obtain samples for laser scanning.

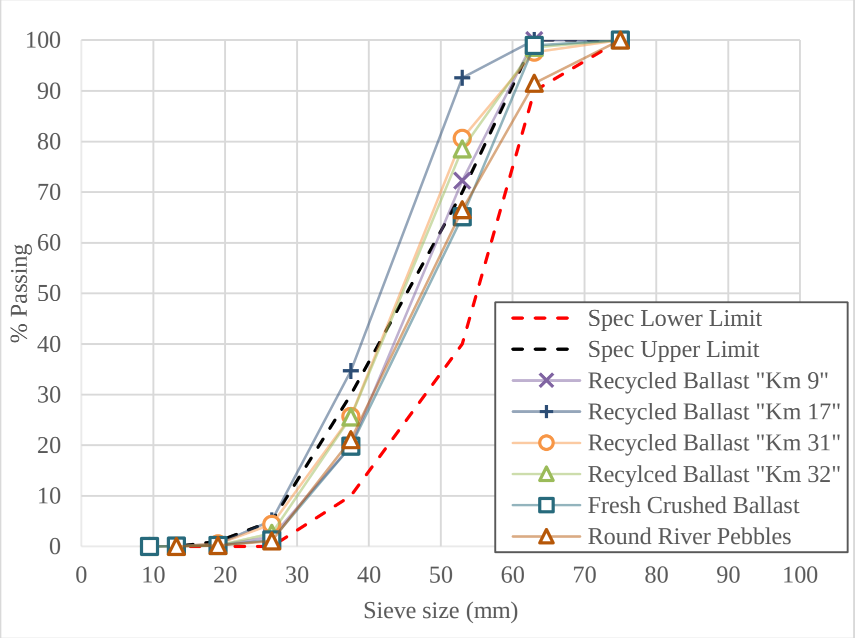
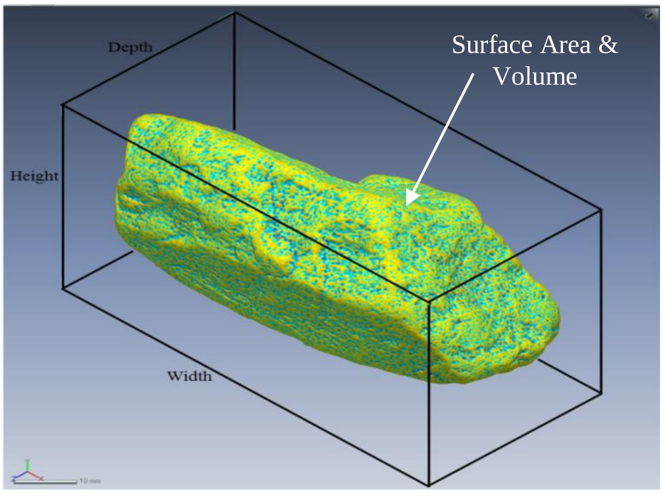


Figure 1 : Grading analysis result of the six materials compared to TFR specs.

3 Ballast scanning and results

3.1 Scanning of ballast particles

All the ballast particles used for this study were scanned in accordance with the CSIR guideline for scanning of aggregates and ballast particles [8]. In order to obtain a statistical representative scanned sample, a quartering approach was used to scale-down the samples for laser scanning. A total of 358 particles from six material sources were scanned in the laser scanning system available at the CSIR to evaluate roundness index. After the scanning was completed, software which is an integral part of the laser device system was used to model the ballast particles in three-dimensions to directly obtain the depth height and width dimensions of ballast particle as illustrated in Fig. 2. The surface area and volume of ballast particle were also obtained directly from the software after post-processing.



Surface Area & Volume

Figure 2: A 3-D modelled ballast particle from laser.

3.2 Scanning results

Table 1 presents results of dimensions, surface area and volume of 37.5 mm particles of the six samples. The dimensions, surface area and volume of particles were used to compute the ballast roundness index.

Table 1 : Scan results of 37.5 mm size ballast particles.

Material Description	Dimensions (mm)			Volume (mm^3)	Surface area (mm^2)
	Width	Height	Depth		
Recycled Ballast "Km 9"	62.52	60.41	47.65	92824.88	12317.86
	82.15	54.07	38.47	82853.46	12334.36
	74.22	51.21	44.50	74449.93	10295.27
	64.99	57.67	30.45	44478.04	7947.43
Recycled Ballast "Km 17"	58.70	54.26	42.91	48352.48	8136.48
	74.89	63.56	36.41	78103.63	11119.24
	78.57	52.06	50.03	71916.01	10869.70
	83.79	57.96	40.73	62345.31	9943.85
Recycled Ballast "Km 31"	58.84	71.38	38.10	52962.87	9115.14
	61.72	60.95	47.77	61760.83	9820.92
	74.72	59.83	31.74	50027.79	9018.83
	56.92	64.07	44.49	69163.66	10211.00
Recycled Ballast "Km 32"	63.63	14.79	25.19	43962.13	8066.60
	56.36	15.66	35.67	95652.23	9524.35

	51.47	47.31	30.94	34898.85	6409.80
	67.23	43.93	37.96	34801.40	6335.68
Fresh Crushed Ballast	93.06	53.17	39.50	72116.30	11352.66
	80.99	51.19	21.12	46993.56	9450.28
	87.83	55.35	23.15	39073.41	8794.51
	76.90	65.12	42.06	75147.22	12231.15
River Pebbles	102.19	58.70	39.46	126345.86	14314.31
	90.17	52.26	46.00	101164.83	12202.71
	102.95	61.82	33.43	108125.91	13352.61
	86.24	59.01	39.22	104678.42	12708.93

4 Discussion of ballast roundness

Roundness, or its inverse, angularity, represents the curvature of particle’s corners. According to Wadell, roundness is the ratio of the average radius of curvature of the corners to the radius of the largest inscribed circle. The definition, which is presented in eqn (1) has been universally adopted as an ideal one.

$$Roundness = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{r_i}{R}\right) \qquad (1)$$

Where, r_i = individual corner radius, R = radius of circle inscribed about the particle, and N = number of corners on particle. A projected two-dimensional (2-D) image of the particle is used to obtain roundness in eqn (1). Particles in a sample are grouped according to their angularity, with group categories ranging from angular to well-rounded (Fig. 3). The average roundness for the sample is defined by eqn (2).

$$Roundness_a = \frac{1}{N_t}\sum_{i=1}^{N_t} n_i m_i \qquad (2)$$

Where, n_i = number of particles in group i, m_i = mid-point roundness of group i, and N_t = total number of particles. Fig. 3 provides comparable charts for a visual assessment of particle roundness developed by [9]. This assessment only gives an idea about the particle shape in two dimensions. It is important to highlight that charts like this one have high degree of subjectivity. Folk [10] concluded that when charts are used for classification, the risk of getting errors is negligible for sphericity but large for roundness. The roundness is between 0 and 1, where the value of 1 is an indication of a more rounded particle. Eqn (3) shows how roundness index was determined by [11].

$$Roundness = \frac{4\pi A}{P^2} \qquad (3)$$

where, A= area of the particle image; P= perimeter of the particle image.

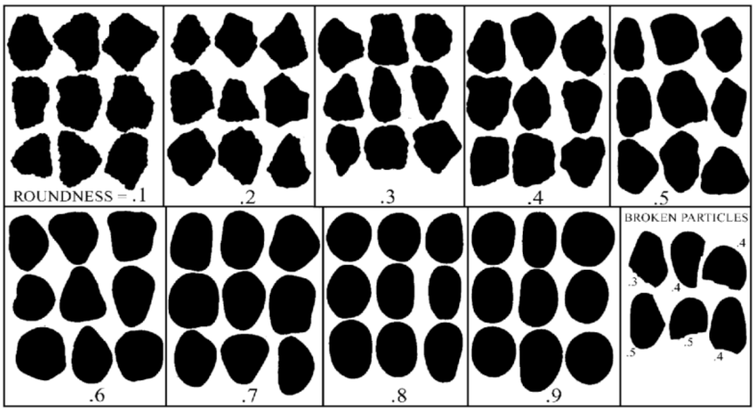


Figure 2 : Chart for visual evaluation of roundness of aggregate (Krumbein,1941).

The methods discussed above are called traditional methods of characterising the physical properties of ballast. The results of such methods are affected by human errors and are very subjective [12]. It is believed that the introduction, of automation such as imaging and laser techniques in ballast shape measurements will be an improvement in these traditional methods [13].

4.1 Roundness index results

In this study, roundness of the ballast and pebble materials was determined based on direct measurements from a 3-D laser scanning system. The definition of roundness proposed by [14] as presented in eqn (4) was used to evaluate the roundness of the six ballast materials. Ballast roundness was defined as an approximation ratio of surface area of an ellipsoid (SA_e) to the surface area of the particle (SA_p).This equation allows for the use of 3-D measurements of the particle as the actual shape of ballast is in three-dimensions.

$$Roundness = \frac{SA_e}{SA_p} \qquad (4)$$

The surface areas of individual ballast particles obtained from the laser scanned particles were used to compute roundness index that is defined by Eq. 4. The results show that a roundness value of 1 or less is typical for excessive rounded particle, while angular particles roundness values are greater than 1. Consequently, the river pebbles sample is expected to have lower roundness values than fresh crushed ballast. Table 2 provides comparable charts for visual assessment of the roundness of six selected particle of the materials investigated.

Table 2 : Ballast roundness chart developed from 3-D laser results.

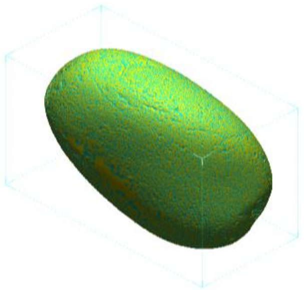
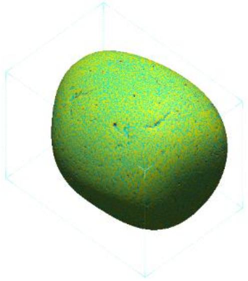
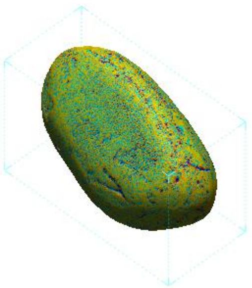
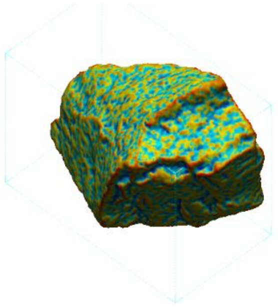
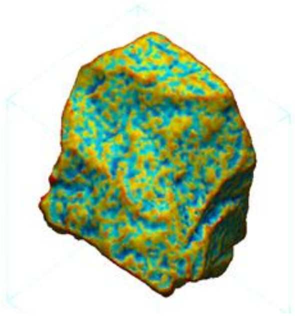
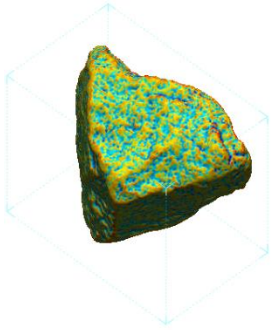
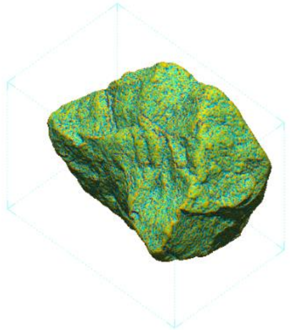
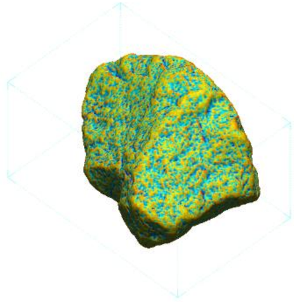
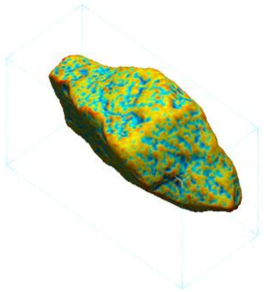
 **0.88**	 **0.92**	 **1.00**
 **0.97**	 **0.98**	 **0.99**
 **1.02**	 **1.05**	 **1.08**

Fig. 4 shows roundness results where 50% of highly angular crushed ballast particles have roundness greater than 1.0 while natural rounded pebbles particle have 5% particles with roundness less than 1.0. River pebbles have excessive roundness to be set as the lower limit and fresh crushed ballast to be the higher limit, which was expected. It can be seen that most of the recycled ballast samples scanned is approaching the shape of pebbles. The current problem experienced by

TFR coal line is crushed ballast becoming rounded. Recycled ballast from Km 9 is a sample with highly rounded particles compare to other recycled samples.

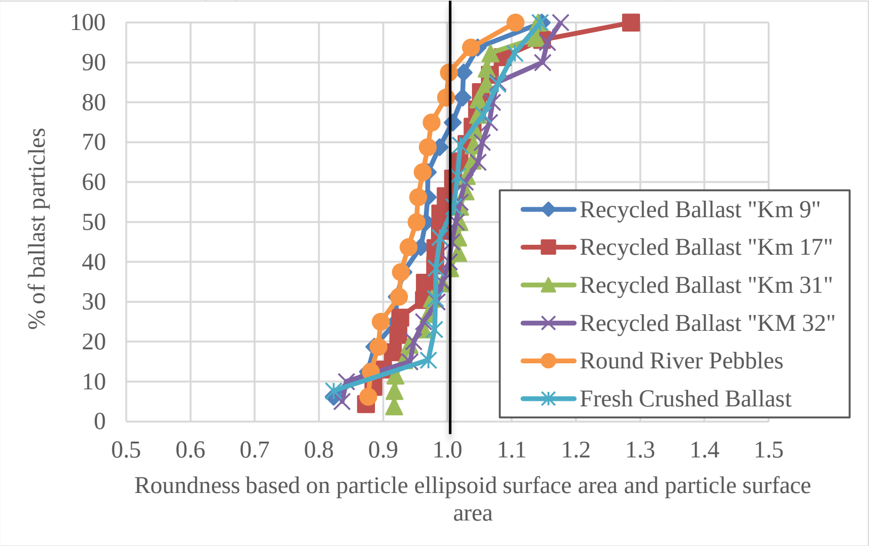


Figure 4: Distributions of roundness index.

5 Triaxial testing of ballast samples

Static triaxial tests are used solely for the determination of the strength parameters c (apparent cohesion) and ϕ (angle of internal friction). All materials used for this study were tested in accordance with the triaxial testing guideline developed for granular material [14]. The specimen dimensions were a height (H) of 385 mm and a diameter (D) of 210 mm, corresponding to an acceptable H/D ratio of 1.85 was used for the triaxial tests. The largest particle size (d) of the ballast materials was 53 mm, yielding a specimen diameter to particle size ratio (D/d) of 4.

During testing, three different confining stresses of 70 kPa, 90 kPa and 120 kPa were applied on the samples. A universal testing machine with loading capacity of 100 kN was used for the testing. The loading frame was operated using the 10% of full load capacity setting yielding a full capacity of the system, allowing satisfactory control at the relatively small loads needed on the samples. After the sample was placed on the loading plate, a confining vacuum was maintained at all times to prevent sample collapse. Fig. 5 shows ballast particles and triaxial specimen before testing. All tests performed in this study are consolidated-drained triaxial tests.

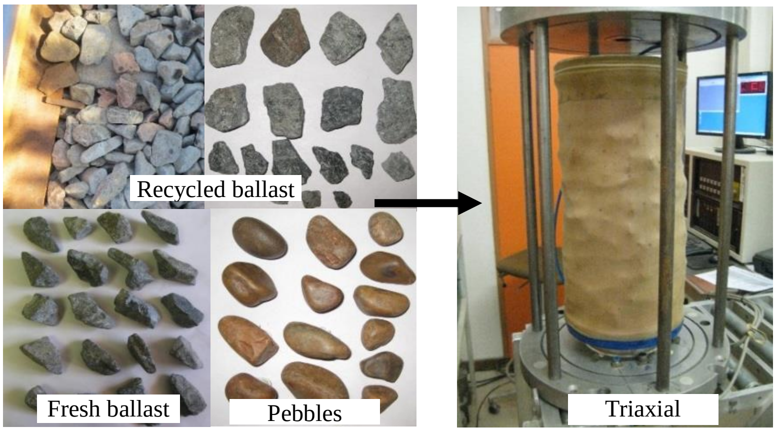


Figure 5: Ballast particles of samples and triaxial specimen.

5.1 Discussion of triaxial test results

The well-known Mohr-Coulomb model is a perfect elastic-plastic model commonly used for geotechnical calculations. The results from such characterisation provide parameters, which are employed in analysing the stability of the tested materials. In this study, Mohr-Coulomb strength properties were used to develop shear strength models for individual samples at different confining pressure. The Mohr-Coulomb failure envelop is defined by eqn (5).

$$\tau = c + \sigma \tan\phi \qquad (5)$$

where c is a cohesion and ϕ is the angle of internal friction of the material. The maximum shear stresses were used to construct Mohr’s circles to represent the six samples. The peak strength was defined as the peak value of deviator stress.

The results of the triaxial shear strength tests of the six samples are presented in Fig. 6, and the effect of ballast shape characteristics on strength property. Generally, higher shear strength was obtained for fresh crushed angular ballast. As expected, increasing confining pressure resulted in increased deviator stress at failure as shown in Fig.6. In comparison, the fresh crushed ballast exhibits higher internal friction angle, followed by the recycled ballast, and the river pebble shows lower internal friction angle. It is believed that relatively higher angularity of new crushed ballast contributes to better particle interlock.

Based on extensive study on bituminous sand materials, [15] reiterated that higher inter-particle contacts should usually result in higher friction angle within the sample. Thus, in this study, lower inter-particle contacts or lower friction angle can be directly associated with a more rounded sample. Also aggregate interlock under static loading conditions makes the material stiffer when confining stress increases [15]. Round ballast is usually smooth and because they do not have sharp corners, they cannot interlock and are therefore resulting in relatively lower internal friction angle.

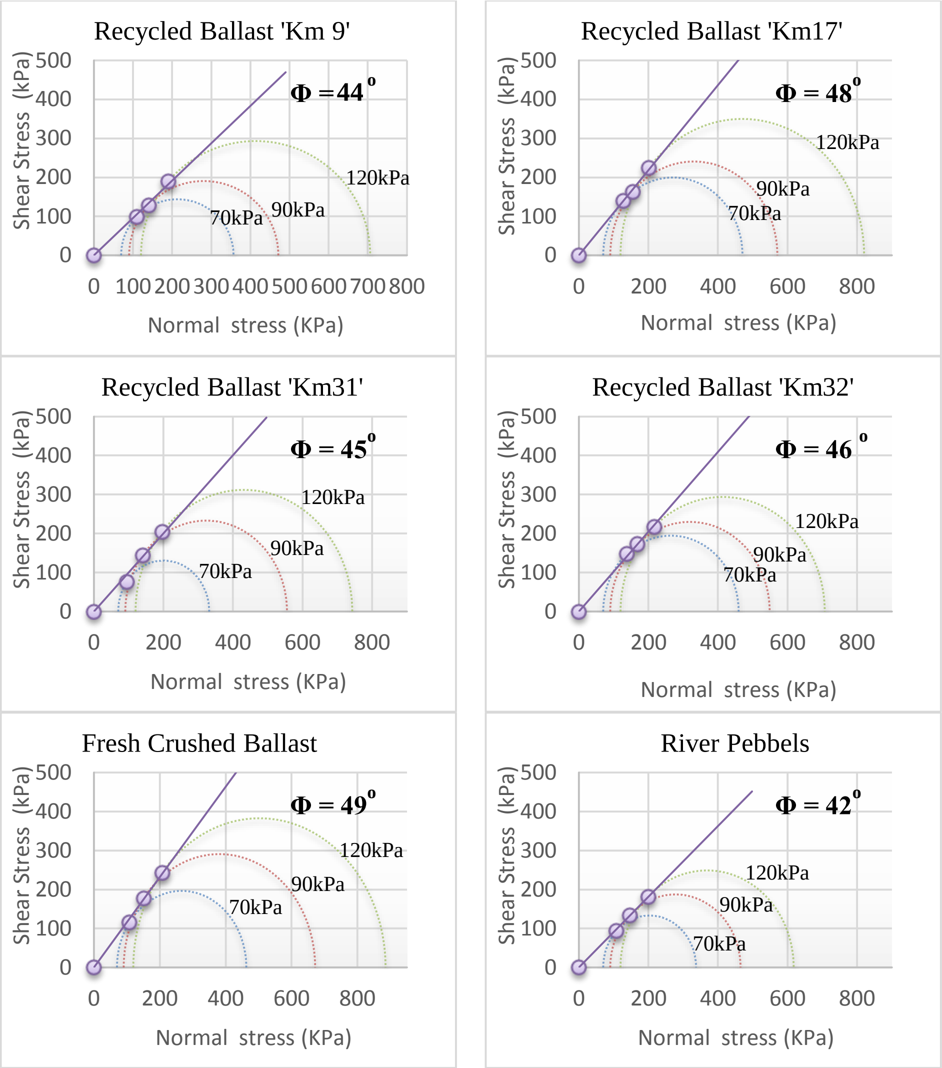


Figure 3 : Mohr circles and failure envelope for the six samples

5.2 Roundness effects on shear strength

The effect of ballast roundness on the shear strength properties of railway ballast is presented in Figure 7. A pebble sample was used as a control for ballast material in the worse condition. Generally the internal frictional angle increases when the roundness of the particles is increasing. One would expected that recycled ballast ‘Km 32 and Km 31” will have the same friction angle because of their roundness value. However, the difference in frictional angle could be due to ballast breakdown creating fines. In general, angularity increases frictional interlock between grains which increases shear strength. The grinding of sharp edges of recycled ballast, during repeated loading, is considered to be the key reason for its reduced friction and decreasing roundness leading a possible settlement from the coal line.

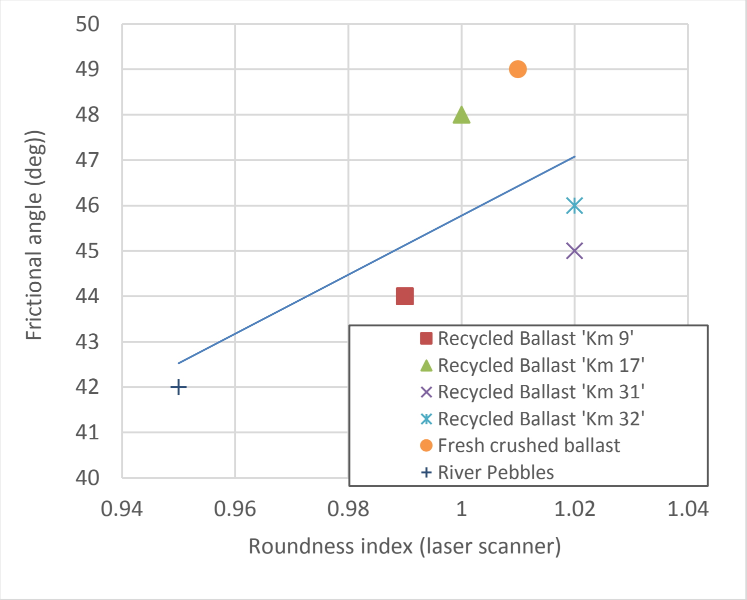


Figure 4 : Effect of roundness index on frictional angle

6 Summary and Conclusions

A modern 3-D laser scanning technique was used to determine the roundness parameter and link it with the internal frictional angle of the ballast materials. Based on the results presented in this paper, it can be concluded that there is a strong correlation between the internal friction angle and roundness parameter of the ballast materials investigated. Thus, the performance of the rail track structure can be linked to ballast shape properties. The use of automation and advanced techniques such as laser scanning of ballast materials is however, required to accurately determine the ballast shape attributes in order to confidently determine roundness of the ballast particles.

Acknowledgements

The work presented in this paper was funded through CSIR R&D Office thematic project TA-2011-001. The authors are grateful to the CSIR for the financial support.

References

[1] Anochie-Boateng, J.K., Komba, J.J. & Mvelase, G.M., Three-dimensional laser scanning technique to quantify aggregate and ballast shape properties. *Construction and Building Materials*, **43**, pp. 389-398, 2013.

[2] Mvelase, G.M., Anochie-Boateng, J.K. & Grabe, P.J., Application of laser based technology to Quantify shape properties of railway ballast. *Proc. of the 31st Southern African transportation Conference,* Pretoria, pp. 12, 2012.

[3] Anochie-Boateng, J.K., Komba, J.J. & Tutumluer, E., Aggregate surface areas quantified through laser measurements for South African asphalt mixtures. *Transportation Engineering,* **138 (8)**, pp. 1-11, 2012.

[4] Anochie-Boateng, J.K., Komba, J.J. & Mvelase, G.M., Advanced and automated laser-based technique to evaluate aggregates. *Proc. of the International road Federation Congress*, Russia, pp. 22-24, 2011.

[5] Anochie-Boateng, J., Komba, J. & O'Connell, J., Laser-based approach for determining flakiness index of aggregates used in pavements. *Proc. of the 30th Southern African transportation conference.* Pretoria, 2011.

[6] Anochie-Boateng, J., Komba, J., Mukalega, N. & Maharaj, A., Evaluation of 3D laser device for characterizing shape and surface properties of aggregates used in pavements. *Proc. Of the 29th Annual Southern African Transportation Conference,* Pretoria, 2010.

[7] Arangie, P.B.D, Specification for the supply of stone. *Transnet Freight Rail technical document*, 2011 [S406].

[8] Anochie-Boateng, J.K., Test protocol for determining particle shape and surface properties of aggregate and ballast using laser scanning technique. *CSIR technical document*, 2014.

[9] Wadell, H., Sphericity and roundness of rock particles. *Geology*, **41**, pp. 310-331, 1933.

[10] Krumbein, W.C., Measurement and geological significance of shape and roundness of sedimentary particles. *Sedimentary Petrology*, **11**, pp. 64-72, 1941.

[11] Folk, R.L., Student operator error in determining of roundness, sphericity and grain size. *Sedimentary Petrology,* **25**, pp. 297-301, 1955.

[12] Janoo, V.C., Quantification of shape, angularity, and surface texture of base course materials. *US Army Corps of Engineers*. Cold Region Research and Engineering Laboratory. Special report 98-1, 1998.

[13] Tolppanen, P., Illerstrom, A. & Stephansson, O. 3-D Laser analysis of size, shape and roughness of railway ballast. Research in progress. *Proc. of the 7th Annual symposium, ICAR*. Austin; 1999.

[14] Hayakawa, Y. & Oguchi, T., Evaluation of gravel sphericity and roundness based on surface-area measurement with a laser scanner. *Computer and Geosciences,* **3**: pp. 735–741, 2005.

[15] Anochie-Boateng, J.K., Advanced testing and characterization of transportation soils and bituminous sands. *PhD Thesis,* University of Illinois at Urbana-Champaign USA, 2007.