-Final Paper-

Advanced and Automated Laser-based Technique to Evaluate Aggregates

Theme: **Innovations in Road Planning and Design**
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Abstract:

The Council for Scientific and Industrial Research (CSIR) is undertaking a research project to investigate the use of laser-based scanning technology to quantify the morphological/shape properties (i.e., form - flatness, elongation and sphericity; angularity; surface texture) of aggregates used in pavements and railway ballast. To date, no automated method is available for direct measurements of shape properties of these materials in Africa. The objective of this paper is to present a three-dimensional laser scanning technique to determine flatness, elongation and sphericity of aggregates used in South African roads. A three-dimensional (3-D) laser scanning device was used to obtain the dimensions, surface area, volume, and subsequently, compute flat and elongated ratio of six different aggregate samples. The results were compared with the standard manual method that is currently used by the road industry to quantify aggregate shape properties. It is expected that, this study would influence decisions to improve aggregate material characterization and pavement design.

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1. Introduction

The use of imaging and scanning techniques for quantifying shape properties of aggregates in pavement (roads/airfields) layers and ballast in railways 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 properties of the aggregates/ballast in a quick and accurate manner, and allowing automation of the shape measurements. This is in contrast with the existing standard test procedures, which are subjective in nature, time consuming and laborious, making it tedious to be used in routine bases for quality control.

As part of the efforts by the road pavement engineers and researchers to address limitations of the current standard methods for quantifying aggregate shape properties, the Council for Scientific and Industrial Research (CSIR) has acquired a three-dimensional (3D) laser scanning device to conduct basic and applied research to improve aggregate material characterization and pavement design in South Africa. The laser-scanning device offers a direct measurement of aggregates and ballast shape/surface properties including form, angularity and surface texture, surface area and volume. These shape/surface properties are related to durability, workability, shear resistance, stiffness, cracking, permanent deformation, binder content and, ultimately, performance of the pavement (*1*, *2*). Figure 1 shows the shape properties of an aggregate particle.

This paper focuses on flatness, elongation and sphericity of six different types of aggregates commonly used in South Africa road pavements. Flat and elongation ratio is commonly used to evaluate aggregates used in pavements construction. The American Society of Testing and Materials (ASTM) standard procedure ASTM D 4791 (*3*) is the current standard test method for the determination of flat and elongated aggregate particles. South Africa and most African countries use flakiness method, which is similar to the ASTM D 4791 to describe the shape of aggregates and railway ballast. However, there is no standard test procedure to determine the sphericity of aggregate particles.

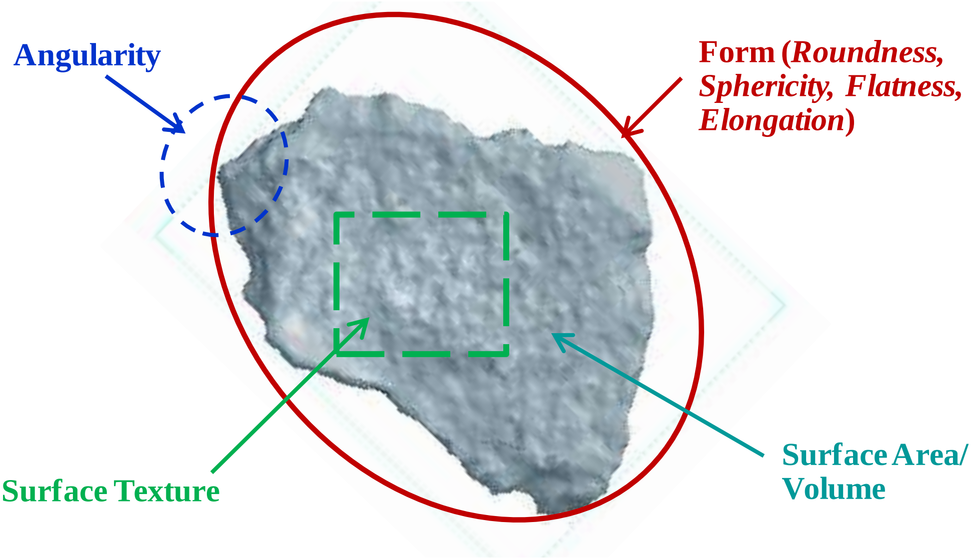

Figure 1 Aggregate shape/surface properties

2. Aggregate form properties

2.1 Flat and elongated ratio

The shape of an aggregate particle could be described in three dimensions, i.e., longest (L), intermediate (I), and the shortest (S) dimensions. The flat and elongated ratio of an aggregate particle is defined as the ratio of the longest dimension to the shortest dimension. Equations 1 to 3 show the definition of flat, elongated as well as flatness and elongation ratio of individual aggregate particle (*4*). Figure 2 demonstrates the three important dimensions used to define flat or elongated aggregate particles.

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

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

$$\text{Flat \& Elongated ratio (F \& E)} = \frac{L}{S} \tag{3}$$

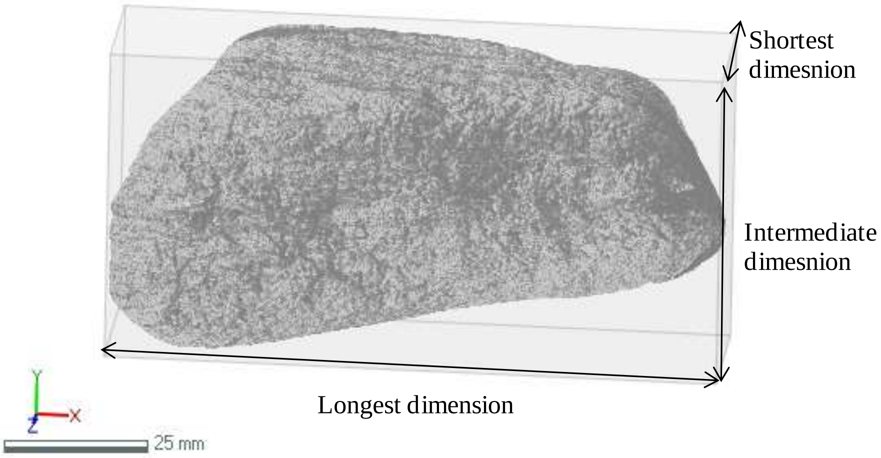

Figure 2 Three dimensions of an aggregate particle scanned as part of this study

2.2 Sphericity

The sphericity of an aggregate particle is a measure of the roundness of its shape, and it is defined based on the surface area and volume properties of the aggregate (*5*, *6*). Thus, an accurate measurement of the surface area and volume of has direct influence on the sphericity of the aggregate particle.

A completely spherical shaped aggregate would assume sphericity value of 1 (pebbles aggregate particles have values close to 1, whereas irregular shaped aggregates would have sphericity values close to zero).

$$\Psi = \frac{\sqrt[3]{36\pi V^2}}{A} \tag{4}$$

where,

Ψ = Sphericity
A = Surface area
V = Volume

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 allows for accurate measurements of surface area and volume, the CSIR laser scanning project, for example.

3. Aggregate testing and scanning

3.1 Aggregates and sample preparation

Six types of aggregates used in South African road pavements were selected for this study (see Table 1). All the aggregates are used as surfacing layers. The samples were obtained from six different sources (quarries) in South Africa, and delivered at the CSIR pavement materials laboratory for the study.

The aggregate samples were firstly rifled to obtained representative sample sizes. Then, the samples were washed and oven dried for flat and elongated test and scanning. Overall, 30 particles were randomly selected to represent each type of aggregate used in the study.

Table 1 Aggregate materials

Number	Material	Rock type	Specific gravity	Max. aggregate size (mm)
1	Quartzite	Metamorphic	2.738	19.0
2	Granite	Igneous	2.690	
3	Tillite	Sedimentary	2.710	
4	Hornfels	Metamorphic	2.770	
5	Andesite	Igneous	2.815	
6	Dolerite	Igneous	2.930	

3.2 Standard ASTM D 4791 approach

The standard ASTM D 4791 test method was used to determine the flat and elongated particles of the six aggregate types used for this study. Individual coarse aggregate particles were tested manually for the ratios of longest to the shortest dimensions by using a proportional calliper device. Using this procedure, the flat and elongated aggregate particles were determined, and their percentages by mass were used to calculate by Equation 5.

$$F\ \&\ E = \left(\frac{M_{FE}}{M_T} \right) \times 100 \tag{5}$$

where,

$F\&E$ = flat and elongated ratio

M_{FE} = mass of flat and elongated aggregate particles

M_T = total mass of sample

3.3 3D laser scanning approach

3.3.1 3D laser scanning device

The 3D laser scanning device used for this study was originally designed and manufactured by Roland DGA Corporation in the United States for solid shape modeling in medical and manufacturing applications. The laser device was recently evaluated for accuracy and precision, and calibrated to determine basic shape properties of conventional and non-conventional aggregates used in pavements and railways (*7*). The device uses an advanced non-contact sensor to capture flat areas, hollow objects, oblique angles and fine details of scanned objects with the laser beam in three dimensions, and up to a 0.1-mm (100-µm) scanning resolution.

An integral part of the laser device is advanced data processing software, which 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. These features are essential for obtaining accurate morphological properties of the aggregates and ballast. It should be emphasized that this device is mainly used to study coarse aggregates. However, the laser scanning device at CSIR has been successfully used to scan fine aggregates up to 2.36 mm. Anochie-Boateng et al. (*7*) have validated the capacity and precision of the laser scanning device with perfect spheres and cubes for scanning aggregate particles.

3.4 Scanning of aggregates

Aggregate particles from six different sources were scanned in this study. A total of 180 aggregate particles (i.e. 30 particles each, for the six types of aggregates) were scanned. The aggregates were scanned individually in the laser device. Each aggregate particle was scanned as a three-dimensional solid element (object) with six plane faces. Using the planar mode scanning option in the software, four surfaces of the aggregate particles were first scanned, followed by the top and bottom surfaces to complete the total of six faces for the solid aggregate particle. After the scanning was completed, the software was used to integrate and merge the scanned surfaces to obtain the complete aggregate particle in a six-face bounding box to directly obtain the longest, intermediate and shortest dimensions of an aggregate particle. The surface area and volume of an aggregate particle were also obtained directly from the software after post-processing. Figure 3 illustrates scanning and post-processing procedures for an aggregate particle.

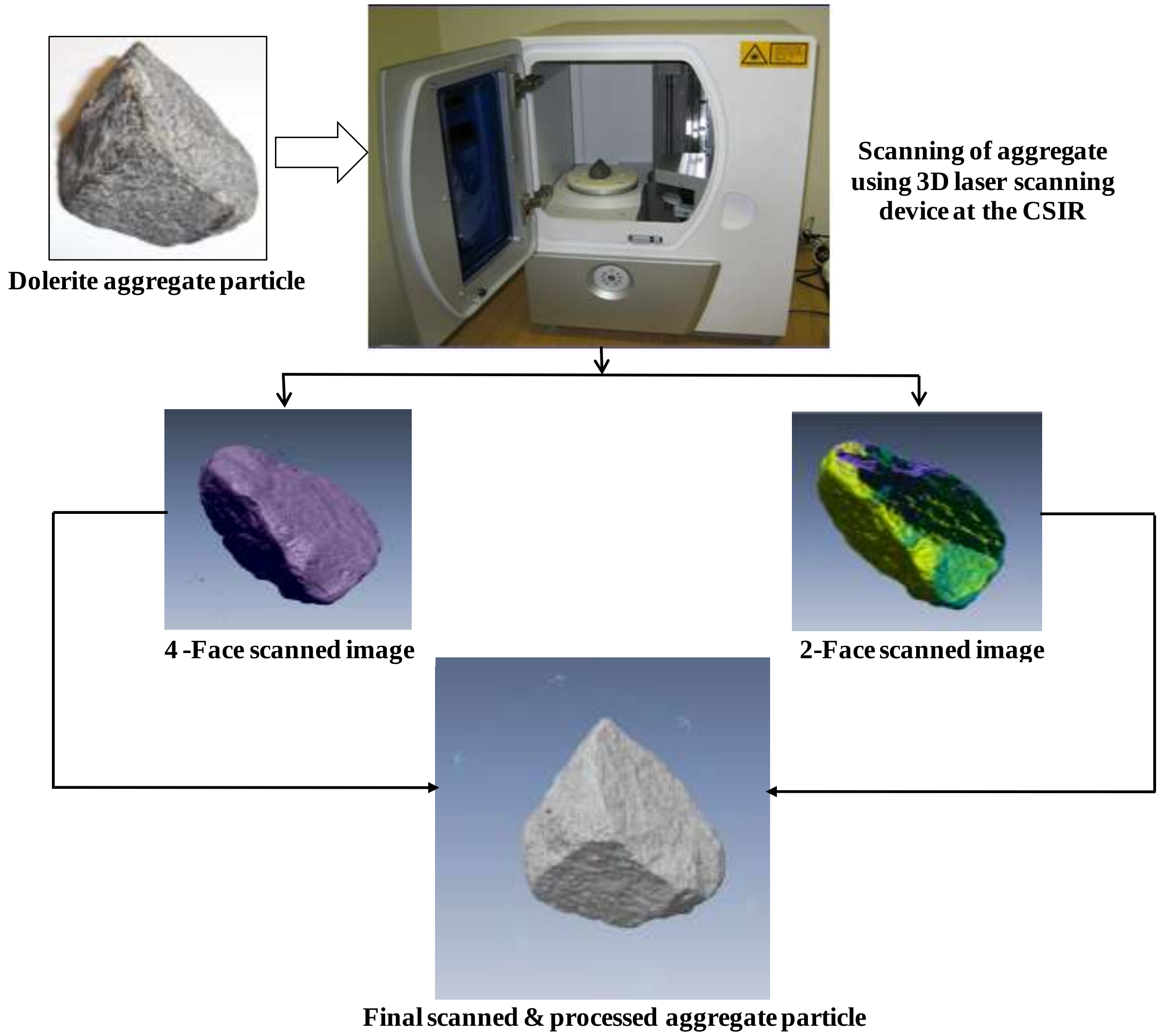

Figure 3 Illustration of aggregate scanning and processing

3.5 Surface area

The surface mesh of scanned aggregate particle can be divided into triangular sub-surfaces called poly-faces. A triangular poly-face consists of three vertices (a, b and c), with x, y and z coordinates as shown in Figure 4. For a given triangular poly-face T_i in 3D space with vertices $a = (a_x, a_y, a_z)$, $b = (b_x, b_y, b_z)$ and $c = (c_x, c_y, c_z)$, Equation 6 can be used to compute its surface area (A_i). The total surface area of an aggregate particle is then computed by summing up the surface areas of all poly-faces that make up the aggregate particle. The software integrated in the 3D laser scanning device has been programmed to compute surface area of processed aggregate particles.

$$A_i = \frac{1}{2}\begin{vmatrix} a_x & a_y & a_z \\ b_x & b_y & b_z \\ c_x & c_y & c_z \end{vmatrix} = \frac{1}{2}\left|\left[a_x(b_y c_z - b_z c_y) - b_x(a_y c_z - a_z c_y) + c_x(a_y b_z - a_z b_y)\right]\right| \qquad (6)$$

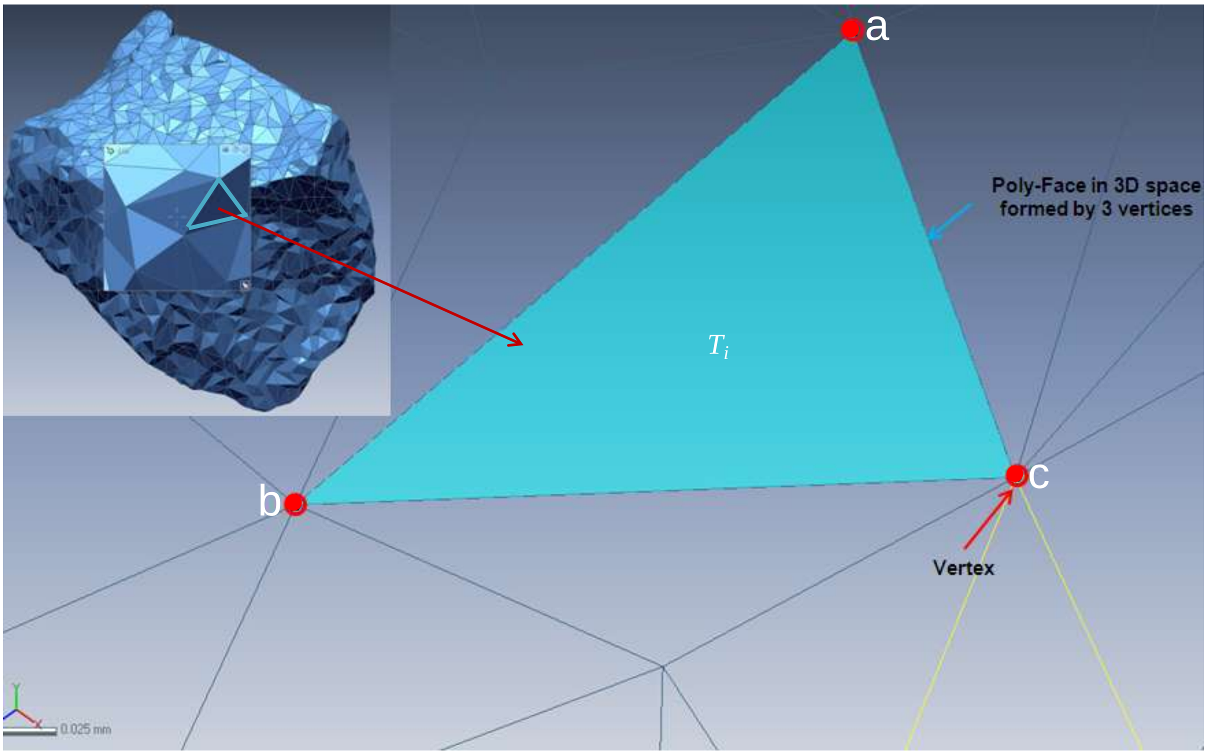

Figure 4 Surface mesh of the scanned aggregate particle

4. Discussion of results

4.1 Flat and elongated ratio

The following steps were followed to compute flat and elongated ratios from the laser scanning technique:

1. Dimensions (longest, intermediate, and shortest) of the individual aggregate particle were obtained directly from the 3D bounding box.
2. Flat and elongated ratio of individual aggregate particle was computed by dividing the longest, of aggregate particle to its shortest.
3. Total volume of scanned and volume of flat and elongated aggregate particles were obtained from the 3D laser results.
4. Finally, the percentage of flat and elongated aggregate particles was calculated by dividing the total volume of flat and elongated particles by the total volume of the sample.

Aggregate particles from the same parent rock are usually assumed to have the same specific gravity hence the mass is equivalent to the volume. Aggregates from five different parent rocks with various bulk densities were used for the evaluation (*8*). Equation 7 was used to derive the mass of the aggregate samples scanned. It was shown that an excellent correlation exists between the derived and the measured masses.

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

where,

M = mass of aggregate (kg)
D = density of aggregate (kg/m^3)
V = volume of aggregate (m^3)

The percentage of flat and elongated ratio based on 3D laser concept of volume can mathematically be represented as follows:

$$F \,\&\, E_v = \left(\frac{V_f}{V_T} \right) \times 100 \qquad (8)$$

where,

$F\&E_v$ = Flat and elongated ratios based on volume
V_f = Total volume of flat and elongated aggregates scanned
V_T = Total volume of the aggregate sample

Various specifications limit the amount of flat and elongated particles in hot-mix asphalt mixtures (*9*, *10*). The flat and elongated ratios vary between 2:1, 3:1 and 5:1. The American Superpave asphalt mix design specification characterizes aggregate particle to be flat and elongated aggregate if the ratio of longest to the shortest dimensions is greater that 5:1(*9*).

Figure 5 compares the flat and elongated ratios from the two test methods. For each aggregate type, the percentage of aggregates with F&E ratios less than 2:1; between 2:1 and 3:1; between 3:1 and 5:1; and greater 5:1 obtained from the ASTM D 4791 were plotted against the F&E ratios obtained from the laser scanning approach. It can be seen from the Figure 5 that excellent correlation exists between the ASTM D 4791 and the laser scanning approach. Thus, the 3D laser scanning approach can potentially be used for automation of flat and elongated ratio measurements. The observed variations in the graph, however, could be associated with manual approach when using a proportional calliper in the ASTM D 4791. In comparison, the automated procedure would mitigate human errors associated with the standard ASTM D 4791 method.

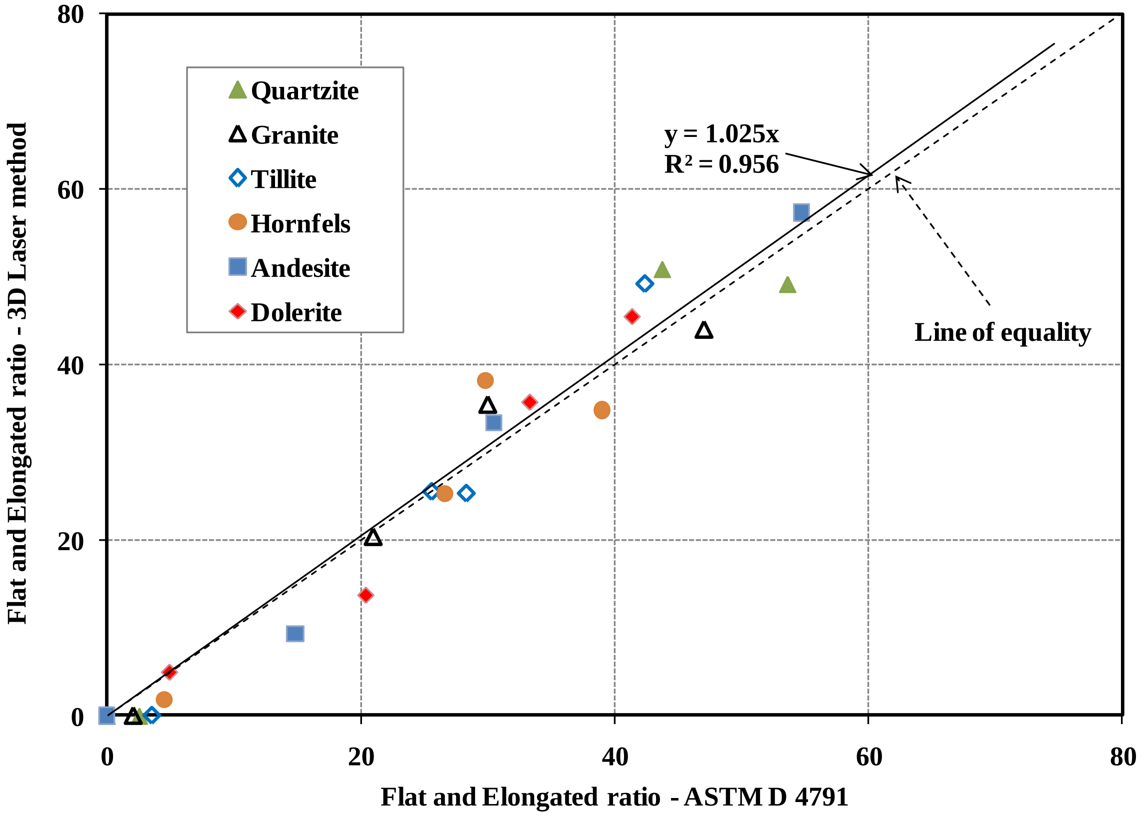

Figure 5 F&E ratios: ASTM D 4791 versus laser scanning methods

4.2 Sphericity

The sphericity of individual aggregate particle was computed based on surface area and volume (see Equation 5). Figure 6 shows the plot of sphericity against flat and elongated ratios for 180 aggregate particles studied. It can be seen that as the sphericity decreases, the flat and elongated ratio increases. Recall that for an aggregate particle with a shape close to a perfect sphere, the sphericity value approaches 1. On the other hand, flat and elongated aggregate particle is far from being a perfect sphere; hence its sphericity value will approach zero. The observed trend, clearly demonstrate the capability of the 3D laser scanning approach to objectively distinguish form of different aggregate particles.

It can be seen from Figure 6 that dolerite and tillite samples tested have more flat and elongated particles when compared to the other four types of aggregates.

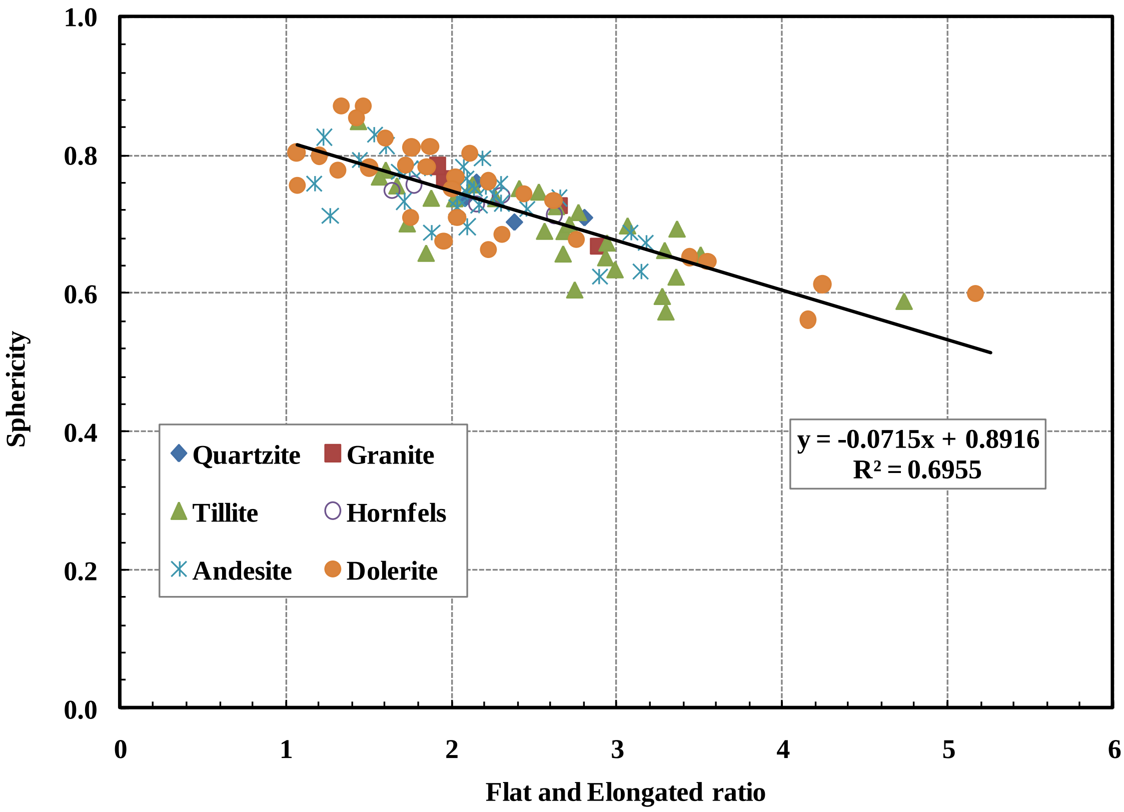

Figure 6 Sphericity versus F&E ratio

5. Conclusions

This paper introduced a new approach for the determination of flat and elongated ratios and sphericity of aggregates used in road construction in South Africa. The following conclusions are drawn based on the results presented in this study:

- The use of three-dimensional laser scanning techniques to quantify flat, elongation and sphericity of aggregates is advancement towards automating the evaluation of aggregates properties, and for accurate quantification of the irregular shape aggregate particles. This technique is fast, accurate and provides a more repeatable/reliable data for pavement (roads and airfields) and rail track design and construction.
- There was an excellent agreement between the flat and elongated ratios obtained from the laser scanning techniques and the standard ASTM D 4791 method. Furthermore, it was established that there exist a relationship between flat and elongated ratios, and the sphericity of the aggregate particles studied. Thus, human errors associated with current standard methods for evaluating shape properties of aggregates can be mitigated by using more accurate and advanced techniques such as 3D laser scanning.

Acknowledgement

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