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Analytical and Laser Scanning Techniques to Determine Shape Properties of Aggregates

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ABSTRACT

The fundamental shape attributes of aggregates used in pavements i.e., form, angularity, and surface texture have not been accurately quantified historically, because of their irregular and non-ideal shapes. This paper presents selected results using a laser-based scanning technique to determine the form of aggregates used in construction of pavements in South Africa. A three-dimensional (3-D) laser scanning system was used to scan aggregate materials from different sources, and the data were processed to reconstruct 3-D models of the aggregate particles. The models were further analyzed to determine the form properties. Two analysis approaches, based on the aggregate physical properties and spherical harmonic analysis were employed to determine the form indices, and the results were compared. The indices based on the physical properties include; (a) sphericity computed from the surface area and volume, (b) sphericity computed from three orthogonal dimensions, and (c) flat and elongated ratio computed from the longest and shortest dimensions of an aggregate particle. Good correlations were observed between the form indices obtained from the aggregate physical properties, and the spherical harmonic form index. It is concluded that laser scanning technique could be employed to better quantify the form properties of aggregate materials used in pavements.

INTRODUCTION

Shape or morphological characteristics of aggregates used in construction of pavements have significant influence on the overall performance of the pavements. The key aggregate shape properties that influence to the performance of pavements are form (i.e., sphericity, roundness, flatness and elongation), angularity and surface texture (*1*). Pavement performance indicators affected by aggregate shape properties include permanent deformation, shear resistance, skid resistance, stiffness, fatigue resistance, stability and workability of hot-mix asphalt mixes (*2–7*). Therefore, accurate predictions of future performance of pavement require better characterization of aggregate shape properties.

In South Africa, coarse aggregate form is currently evaluated manually using the Flakiness Index. The test procedure is contained in Technical Methods for Highways (TMH 1) Method B3 (*8*). The aggregate form can also be evaluated using flat and elongated ratio of the particles. The American Society of Testing and Materials (ASTM) standard procedure ASTM D 4791 is the current standard test method for determination of flat and elongated aggregate particles (*9*). For evaluation of aggregate angularity, counting the number of fractured aggregate faces in accordance with ASTM D 5821 (*10*) test method is used. The aggregate surface texture is measured indirectly using the particle index as per ASTM D 3398 (*11*) test method. Although these standard methods support the current understanding of the influence of aggregate shape properties on pavement performance, they have several limitations including the use of manual and visual approaches (subjective in nature), to evaluate shape properties, as well as they are time consuming and laborious (*9, 10*). Also, the current standard methods quantify aggregate shape properties indirectly, resulting in a lack of a direct relationship with fundamental aggregate properties governing pavement performance.

Recent advances in imaging and laser scanning techniques resulted in the development of effective and reliable techniques for direct measurement of aggregate shape characteristics (*12–15*). These techniques have been successfully used to evaluate surface and shape properties of aggregates (*16–20).* A more accurate method to evaluate aggregate shape properties could be the use of X-ray computed tomography (CT). However, X-ray CT technique could be too expensive for routine use in the industry. The Council for Scientific and Industrial Research (CSIR) in South Africa is currently undertaking a research that is aimed at improving pavement performance through better aggregate material characterization using automated three-dimensional (3-D) laser scanning and advanced numerical modeling techniques.

The objective of this paper is to present the results obtained from the 3-D laser scanning that were used to determine aggregate form properties. These aggregates are mostly used in pavement construction in South Africa. The paper provided data on the shape properties of aggregates, which is otherwise non-existent at all in South Africa. The database will lead to future developments such as aggregate usage in pavements, selection criteria for aggregates used in pavements, and the development of aggregate manuals for the aggregate industry. Six aggregate sources were selected for the study in order to determine sphericity, flat and elongated ratio of the scanned aggregate particles. The results obtained are compared with the spherical harmonic numerical analysis of aggregate shape properties.

COARSE AGGREGATE SHAPE PROPERTIES

Fundamental Aggregate Shape Properties

The shape or morphology of aggregate particles is distinguished by using three independent fundamental properties (i.e., form, angularity and surface texture). These properties are defined based on their scales with respect to an aggregate particle size. Aggregate form describes the overall three dimensional physical dimensions (i.e., length, width and height) which defines the sphericity, roundness, flatness and elongation. Angularity of an aggregate particle describes the sharpness of corners. Crushed aggregate particles in particular, have sharp corners compared to uncrushed aggregate particles such as river gravels. Aggregate surface texture describes the smoothness or roughness of an aggregate particle. For instance, a typical pebble is smoother than a crushed aggregate particle. Figure 1 illustrates the three fundamental aggregate shape properties (*20*).

Determination of Aggregate Form

Aggregate Form Indices

Several 3-D indices have been proposed to describe the aggregate form indices. These indices are computed using the physical orthogonal dimensions of aggregate particles (i.e., length, width and height), as well as the surface area and volume. The orthogonal dimensions are sometimes referred to as longest, intermediate and shortest, respectively (*14, 21*).

Recently, an Aggregate Imaging System (AIMS) was developed to measure aggregate shape properties (*14*). AIMS use the three orthogonal dimensions to compute the sphericity of an aggregate particle (Equation 1). For equal dimensional aggregate particles such as round aggregates, the sphericity value approaches 1.

$$\text{sphericity} = \sqrt[3]{\frac{d_S \times d_I}{d_L^2}} \tag{1}$$

where

d_L = longest dimension of aggregate particle,

d_I = intermediate dimension of aggregate particle, and

d_s = shortest dimension of aggregate particle.

Aggregate form can also be described by flatness ratio and elongation ratio. These ratios are also defined based on the three orthogonal dimensions, and computed using Equations 2 and 3 (*21, 22*). The ASTM provides additional parameter in terms of the longest and shortest dimension of an aggregates particle as flat and elongated ratio, which is expressed mathematically by Equation 4. The standard test method for the determination of flat and elongated particles is described in ASTM D4791 (*9*).

$$\text{flatness ratio} = \frac{d_S}{d_I} \tag{2}$$

$$\text{elongation ratio} = \frac{d_I}{d_L} \tag{3}$$

$$\text{flat and elongated ratio} = \frac{d_L}{d_S} \tag{4}$$

From Equations 2 and 3, it can be deduced that for equal dimensional particles such as round aggregates, the flatness and elongation ratios would approach a value of 1. As an aggregate particle becomes flatter or more elongated, the flat and elongated ratio increase.

Aggregate sphericity can also be described or defined based on the volume and surface area of an aggregate particle, as presented in Equation 5 (*23*). Similarly, the sphericity for round particles will approach 1 in Equation 5.

$$\text{sphericity} = \frac{\sqrt[3]{36\pi V^2}}{A} \tag{5}$$

where
V = volume of aggregate particle, and
A = surface area of aggregate particle.

A more realistic approach to describe the aggregate particle form should ideally be based on 3-D measurement techniques. The main challenge is the ability to accurately quantify the three orthogonal dimensions, volume and surface area of the 3-D shapes of aggregate particles. The irregularity of aggregate particles makes it difficult to measure these physical properties using the standard test methods. New techniques, such as imaging and laser scanning techniques allows for direct and a more reliable measurement of these physical properties. A 3-D laser scanning technique was used in this study.

Spherical Harmonic Analysis

Mathematical analysis techniques such as spherical harmonic, Fourier series, and wavelets analysis have been used to quantify the shape properties of aggregates (*24*). A technique was proposed for 3-D analysis of aggregate shape using X-ray tomography measurement and spherical harmonic analysis (*24*). Using this technique, the shape of aggregate particle is described as a function of a radial distance from the mass center to the surface points of an aggregate particle in 3-D using Equation 6.

$$R\,(\beta,\alpha) = \sum_{l=0}^{l_{max}} \sum_{m=-l}^{l} a_{lm} Y_l^m(\beta,\alpha) \tag{6}$$

$$0 \le \beta \le \pi, 0 \le \alpha \le 2\pi$$

where
$R(\beta, \alpha)$ = radius from the aggregate mass center to the surface,
β = angle measured from the positive z-axis,
α = angle measured from the positive x-axis,
a_{lm} = scalar coefficient, and
$Y_l^m(\beta,\alpha)$ = harmonic function of degree *l* and order *m*.

The use of the integral shown in Equation 7 was proposed to evaluate the scalar coefficient a_{lm} in Equation 6 (*25*).

$$a_{lm} = \int_0^{2\pi}\int_0^{\pi} d\alpha d\beta \, sin(\beta) r(\beta,\alpha) Y_l^{m*} \tag{7}$$

By using the scalar coefficients a_{lm}, three descriptors were computed to describe form, angularity and surface texture of an aggregate particle (*25*). The form, angularity and surface texture indices are computed by using Equations 8–10. These indices should be normalized by dividing the equations by the first scalar coefficient, a_{00} (i.e., $l = 0$, $m = 0$) in order to eliminate the size effect of the aggregates particles (*26*).

$$\text{form} = \sum_{l=0}^{5} \sum_{m=-l}^{l} |a_{lm}| \tag{8}$$

$$\text{angularity} = \sum_{l=6}^{25} \sum_{m=-l}^{l} |a_{lm}| \tag{9}$$

$$\text{surface texture} = \sum_{l=25}^{l_{max}} \sum_{m=-l}^{l} |a_{lm}| \tag{10}$$

In this study, the spherical harmonic analysis form index (Equation 8) was used to quantify the aggregates and compared with the form indices computed based on the physical aggregate properties obtained from 3-D laser scanning system. The form indices based on the physical properties include sphericity computed from surface area and volume, sphericity computed from three orthogonal dimensions, and flat and elongated ratio computed from the longest and shortest dimensions of an aggregate particle as described in Equations 1–5.

LASER-BASED SCANNING OF AGGREGATES

3-D Laser Scanning Device

The 3-D laser scanning device used for this study is an LPX-1200, originally designed by Roland DGA Corporation USA for solid shape modeling in medical and manufacturing applications. The device uses a laser beam moving horizontally and vertically to scan objects at a pre-defined resolution. The maximum scanning resolution is 0.1 mm (100 µm). In order to ensure good quality scans, maximum resolution was used in this study. The laser scanner operates in rotary and planar scanning modes. Rotary scanning mode is suitable for scanning spherical objects, whereas planar mode is used for scanning non-spherical objects such as aggregates. The laser scanning device has been integrated with Rapidform data acquisition and processing software. Figure 2 shows a photograph of the laser scanning device at CSIR.

The scanning device has been evaluated with 15 spherical objects of different materials including steel, ceramic, rubber and plastics, and 12 cubic objects of steel, aluminum and brass for direct measurement of aggregate properties including surface area, volume and the three orthogonal dimensions (*15*). The capacity and precision of the scanning device to accurately measure surface properties of irregular objects was verified through measurement of volume of aggregate in a previous study (*17*). Therefore, validation of the laser scanning device was excluded from this study.

Aggregate Materials and Scanning

Sample Preparation

Six types of aggregate materials commonly used in South African pavements and sourced from six commercial quarries were selected for this study. The aggregates included four crushed stones (granite, tillite, quartzite and hornfels), alluvial gravel and a recycled aggregate (RA). Representative samples were obtained for each aggregate source by means of rifling, and sieve analysis was conducted on the aggregates. A total of 30 particles were sampled from each coarse aggregate fraction (i.e., retained on 4.75, 6.7, 9.5, 13.2 and 19.0 mm sizes) for laser scanning. Thus, 150 particles from each source or 900 aggregate particles overall, representing all coarse aggregate fractions for the six types of aggregates were scanned. For each aggregate source, flat, elongated, angular, round, rough and smooth aggregate particles were visually identified and sampled from a population of aggregates.

Aggregate Scanning

A laser-based scanning protocol (*27*) developed at CSIR for aggregate scanning was followed in this study. Using the planar mode of scanning, four side surfaces of the aggregate particles were scanned first and then the particles were turned to scan the top and bottom to model 3-D aggregates with the six scanned planes. As mentioned earlier, a maximum scanning resolution of 0.1 mm was used in order to ensure high data quality. On average, approximately 30 minutes was required to scan a 19.0 mm aggregate particle (largest particle size for this study) and approximately five minutes for a 4.75 mm aggregate particle (smallest particle size).

The laser scan data constitute surface point (point clouds) data. The Rapidform software was used to process the scan data to reconstruct a 3-D model of the aggregate particles. The process involves aligning, combining and merging the four side surfaces and top and bottom surfaces. A scanned and modeled aggregate is a 3-D particle with triangular shell elements (mesh). Each element consists of x, y, z Cartesian coordinates that can be exported to other data processing software such as MATLAB and Microsoft Excel for further processing.

Scanned Aggregate Results

After processing individual aggregate particles, the surface area, volume, and the three orthogonal dimensions (length, width and height) are obtained directly from the software. In addition, 3-D coordinates of the surface points and coordinates of the mass center of the particle are obtained. These parameters provide the basic data for the analysis to determine sphericity, flat and elongated ratio of the aggregates. Figure 3 shows the photograph of actual aggregate particles and their corresponding modeled aggregates of 19 mm size for granite, tillite and quartzite, hornfels, alluvial gravel and recycled aggregate. In Figure 3, it is demonstrated that the aggregates can be modeled in the 3-D laser system to produce the same shape as the actual, and therefore, accurately quantify their physical properties.

ANALYSIS TO QUANTIFY AGGREGATE FORM

Three main steps i.e. data acquisition, processing and analysis were followed to quantify the aggregate form properties. Figure 4 is the schematic presentation of these steps. The data acquisition involved capturing surface points of an aggregate particle from the 3-D laser scanning system. The surface points were processed to reconstruct a 3-D model of an aggregate particle.

Two analyses approaches were followed to quantify sphericity, and the flat and elongated ratio form properties of the aggregate. In the first approach, aggregate sphericity was quantified based on the three orthogonal dimensions of the aggregate (see Equation 1), and on surface area and volume (see Equation 5). Similarly, the flat and elongated ratio of the aggregate particles was quantified as one of the form properties using Equation 4. In the second approach, a spherical harmonic analysis was used to quantify the aggregate form. The spherical harmonic analysis method is described in a more detail in the following section.

Aggregate Form Using Spherical Harmonic Analysis

Pre-processing of Aggregate Laser Scan Data

The scanned aggregate surface points (x, y, z) Cartesian coordinates were exported into MATLAB software to perform the analyses. The coordinates of the mass center of the scanned aggregates were computed directly using the 3-D laser scanning software. The spherical harmonic analysis technique uses polar coordinate system. Accordingly, the first analysis step involved conversion of the scanned aggregate surface points into a polar coordinate system, and these points are defined in terms of the radius (*R*) measured from the mass center, the horizontal angle (α) and the vertical angle (β) as presented in Figure 5. Since the coordinates of the surface points and that of the center of mass were known, the radii of all aggregate surface points were computed using the distance formula presented in Equation 11. The angles α and β were computed using the spherical polar coordinate relation defined by Equation 12 (*28*).

$$R = \sqrt{(x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2} \tag{11}$$

$$\alpha = \text{arc tan}\frac{y}{x}; \beta = \text{arc cos}\frac{z}{R} \tag{12}$$

where
x, y, z = surface point coordinates, and
x_c, y_c, z_c = mass center coordinates.

Determination of Spherical Harmonic Coefficients and Aggregates Form Indices

The spherical harmonic function (see Equation 6) describes the radii of an aggregate particle at each corresponding α and β angles. The function can be written in terms of summation of the product of the harmonic coefficients a_{lm} and harmonic function, $Y_l^m(\beta,\alpha)$ evaluated at each degree (*l*) and order (*m*) as presented in Equations 13 and 14.

$$R(\beta,\alpha) = a_{00}Y_0^0(\beta,\alpha) + a_{1-1}Y_1^{-1}(\beta,\alpha) + a_{10}Y_1^0(\beta,\alpha) + a_{11}Y_1^1(\beta,\alpha) + \ldots + a_{lm}Y_l^m(\beta,\alpha) \tag{13}$$

$$R = a_{lm} \times Y_l^m \tag{14}$$

where
R = column vector representing radii at each corresponding α and β,
a_{lm} = vector representing the coefficients to be determined, and
Y_l^m = spherical harmonics.

In Equation 14, the radius at each corresponding vertical and horizontal angles was obtained numerically from the laser scan results using Equation 11. The unknowns in Equation 14 are the coefficients (a_{lm}) which could be obtained by optimization using least square method or by solving a linear matrix system. In this study, the coefficients were determined using a linear matrix method. It should be mentioned that the number of rows in the matrix defined by Equation 14 is equal to the number of aggregate surface points to be analyzed. A complete set of surface points for typically large aggregates were over 60, 000 data points using the scanning resolution of 0.1 mm. Solving a_{lm} by common computer programs such as Microsoft Excel could be tedious. Therefore, MATLAB™ software was used to determine the coefficients for each aggregate particle, and subsequently compute the spherical harmonic form index using Equation 8. The harmonic function was also evaluated numerically using Condon-Shortley Phase (*28*). The equations for computation of the spherical harmonics up to $l = 2$ are presented in Table 1.

In order to establish the optimum number of degrees at which aggregates could be differentiated in terms of form, a spherical object and four different aggregate particles of varying shapes (round to flat and elongated) were analyzed using *l* values ranging from 1 to 5. The results are presented in Table 2, along with the models obtained from the 3-D laser scanning. It can be seen that moving vertically down in Table 2, the form indices increase from approximately 1 for the spherical steel to about 3.3 for the flat and elongated granite. For $l = 5$, the form index of a round aggregate differed significantly from that of flat and elongated aggregate, indicating that at this degree value the spherical harmonic analysis can clearly differentiate aggregates with different forms. Therefore, a degree of 5 was used for the analysis of all aggregates studied.

Shape Properties Results and Discussions

Distribution of Aggregate Form Indices

Figure 6 shows plots of the distribution of form indices for the six types of aggregates. Results of the 15 spherical objects with different sizes and material types were included in Figures 6 (a), (b), and (c) to demonstrate that ideal spherical objects have sphericity value closer of one. The spherical objects were used as control sample to compare the shapes of the aggregate particles. Figure 6a shows the distribution for sphericity computed from surface area and volume. The alluvial gravel has higher sphericity values (*0.70–0.95*) when compared with the other five aggregates. It is important to note that the RA has sphericity higher than the four crushed aggregates. This is probably expected, since the RA material has already been used in the road, and appears to have degraded during the course of time. With respect to the four crushed aggregates, tillite was generally more spherical followed by hornfels, granite and quartzite in decreasing order of sphericity. Similar trend was observed for the sphericity values based on the three orthogonal dimensions for the six aggregate types (see Figure 6b).

Figure 6c shows the distribution of flat and elongated ratio form parameter. It can be seen that quartzite has high flat and elongated particles, followed by hornfels, granite, tillite, RA and alluvial gravel in a decreasing order in terms of flat and elongated ratios. In Figure 6d, the spherical harmonic form index ranked the six sources of aggregates the same as the flat and elongated ratio form parameter. The distributions of the form indices for the four crushed aggregates were similar to each other. Overall, the aggregate form indices could be used to distinguish the shapes of all six types of aggregates.

Correlations of the Form Indices

Figures 7–9 show plots of the spherical harmonic analysis form index against the three indices obtained from the 3-D laser based physical properties of all six aggregates types. The goal was to investigate if there exist correlations between the spherical harmonic analysis form index and the sphericity, flat and elongated ratio computed based on the physical properties of the aggregates. Overall, good correlations were observed for all aggregate types, i.e., the coefficient of correlation values (R^2 values) range from approximately 0.5 to 0.9. The correlation between the spherical harmonic form index and the laser-based sphericity values computed from surface area and volume was the strongest for all aggregate types, when compared with correlations with sphericity obtained from the three orthogonal dimensions. Also, strong correlations exist between the harmonic form index, and flat and elongated ratio of all six aggregate types.

In comparison with the other aggregate types, the correlation between the spherical harmonic form index and the laser-based form indices (sphericity, flat and elongated ratio) for the alluvial gravel was the weakest among all aggregate types. Among the four crushed stones, the correlations were weaker for the granite when compared with quartzite, tillite and hornfels aggregates.

CONCLUSIONS

Aggregate shape properties (form, angularity, surface texture) play a major role in the overall performance of pavements. Therefore, better characterization techniques are essential. This paper presented a reliable three-dimensional (3-D) laser-based scanning technique to describe aggregate form indices (sphericity, flat and elongated ratio). Four form indices based on aggregate dimensions, surface area and volume as well as spherical harmonic analysis were successfully used to describe shape properties of aggregate materials selected from six different sources in South Africa. Based on the results presented in this paper, the following conclusions are drawn:

- The 3-D laser scanning technique is capable of producing data required for the determination of form indices for coarse aggregates. As demonstrated, the laser scanning technique is versatile, and can accurately describe the shape characteristics of aggregates.
- Good correlations observed between spherical harmonic form indices and the form indices obtained from the physical properties of the aggregates clearly indicates that sphericity, and flat and elongated ratio determined from surface area, volume and three orthogonal dimensions can be used with confidence to describe the shape of aggregates.
- The spherical harmonic analysis technique is applicable to the aggregate types used in South African pavements or similar aggregates, and can be used to validate aggregate data obtained from the 3-D laser scanning system.

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Table Titles

TABLE 1 Spherical Harmonics (Condon-Shortly Phase) (*28*)
TABLE 2 Form Indices for Different Degree (*l*) Values

Figure Captions

FIGURE 1 Fundamental aggregate shape properties (*20*).

FIGURE 2 Photograph of 3-D laser scanning set-up at CSIR.

FIGURE 3 Actual and 3-D Laser-based modeled aggregate particles.

FIGURE 4 Schematic Procedures for the laser-based quantification of aggregate form.

FIGURE 5 Relationships between Cartesian and polar coordinate.

FIGURE 6 Distributions of form indices.

FIGURE 7 Correlation between harmonic index and sphericity based on surface area and volume.

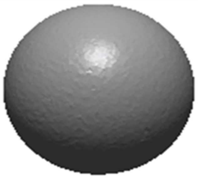
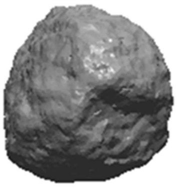
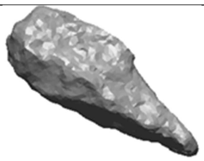
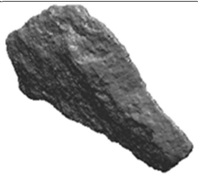
FIGURE 8 Correlation between harmonic index and sphericity based on orthogonal dimensions.

FIGURE 9 Correlations between harmonic index and flat & elongated ratio.

TABLE 1 Spherical Harmonics (Condon-Shortly Phase) (*28*)

Degree (*l*)	Order (*m*)	Function
0	0	$Y_0^0(\beta,\alpha) = \frac{1}{\sqrt{4\pi}}$
1	-1	$Y_1^{-1}(\beta,\alpha) = \sqrt{\frac{3}{8\pi}} \sin\beta e^{-i\alpha}$
1	0	$Y_1^0(\beta,\alpha) = \sqrt{\frac{3}{4\pi}} \cos\beta$
1	1	$Y_1^1(\beta,\alpha) = -\sqrt{\frac{3}{8\pi}} \sin\beta e^{i\alpha}$
2	-2	$Y_2^{-2}(\beta,\alpha) = \sqrt{\frac{5}{96\pi}} 3\sin^2\beta e^{-2i\alpha}$
2	-1	$Y_2^{-1}(\beta,\alpha) = \sqrt{\frac{5}{24\pi}} 3\sin\beta\cos\beta e^{-i\alpha}$
2	0	$Y_2^0(\beta,\alpha) = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos\beta - \frac{1}{2}\right)$
2	1	$Y_2^1(\beta,\alpha) = -\sqrt{\frac{5}{24\pi}} 3\sin\beta\cos\beta e^{i\alpha}$
2	2	$Y_2^2(\beta,\alpha) = -\sqrt{\frac{5}{96\pi}} 3\sin^2\beta e^{2i\alpha}$

TABLE 2 Form Indices for Different Degree (*l*) Values

Description	Model	$l = 1$	$l = 2$	$l = 3$	$l = 4$	$l = 5$
Spherical steel		1.0003	1.0008	1.0014	1.0016	1.0016
Round granite		1.0283	1.1555	1.3379	1.4586	1.5144
Cubical granite		1.0295	1.1351	1.2560	1.3268	1.4028
Elongated granite		1.0968	1.6624	1.9302	2.1936	2.3079
Flat and elongated granite		1.0987	2.8833	3.5230	3.0995	3.2838

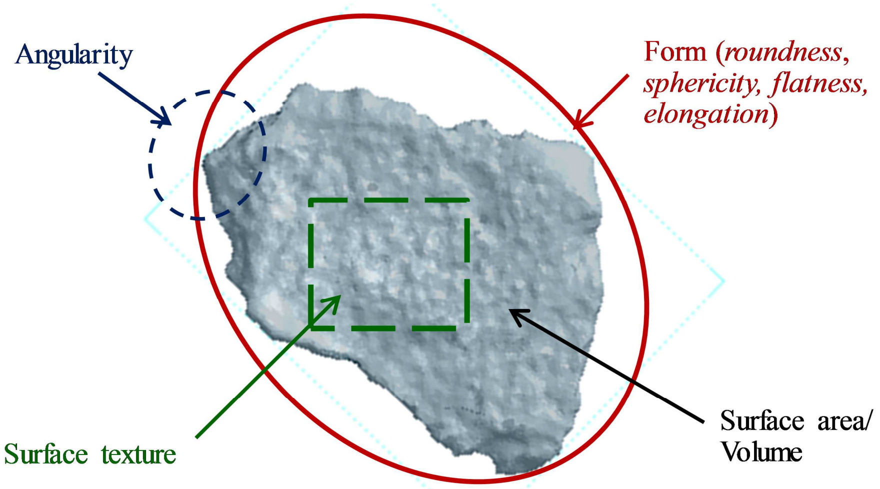


FIGURE 1 Fundamental aggregate shape and surface properties (*20*).

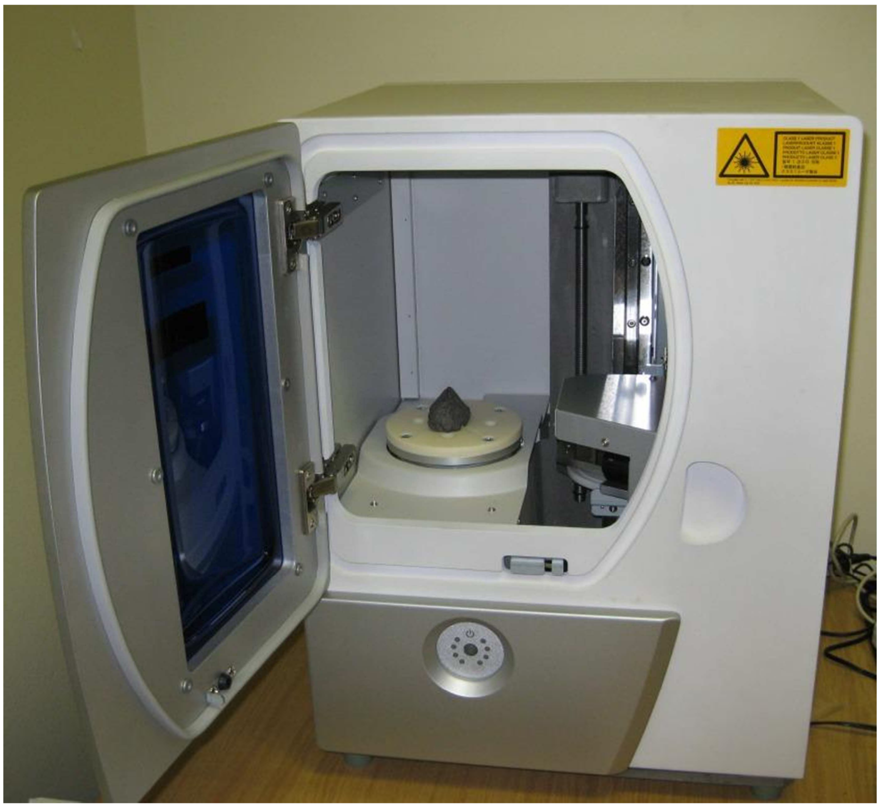
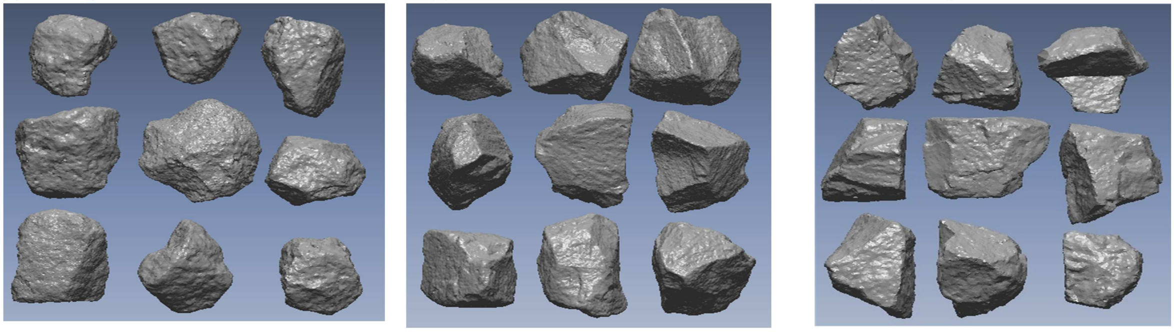


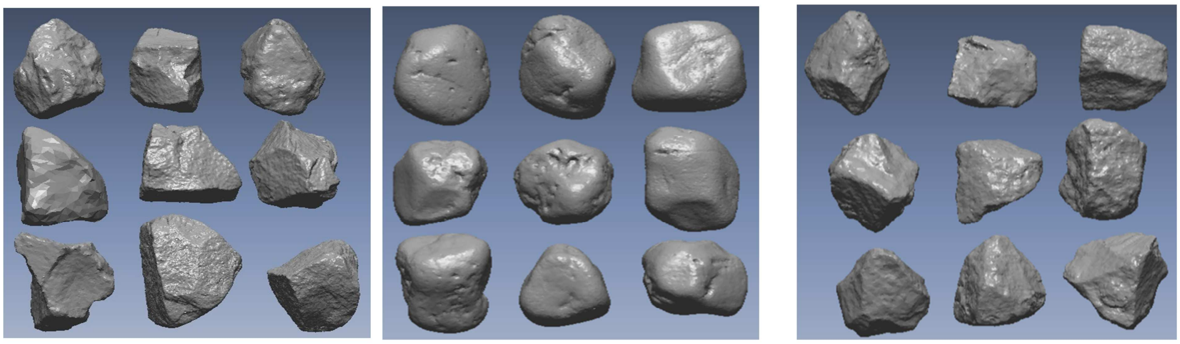
FIGURE 2 Photograph of 3-D Laser scanning setup at CSIR.

(a)Actual granite (b)Actual tillite (c)Actual quarzite



(d) modeled quartzite (e)modedled tillite (f) modeled quarzite

(g) Actualhornfels (h) Actual gravels (i) Actual RA



(j) modeled hornfels (k) modeled gravels (l) modeled RA

FIGURE 3 Actual and 3-D Laser-based modeled aggregate particles.

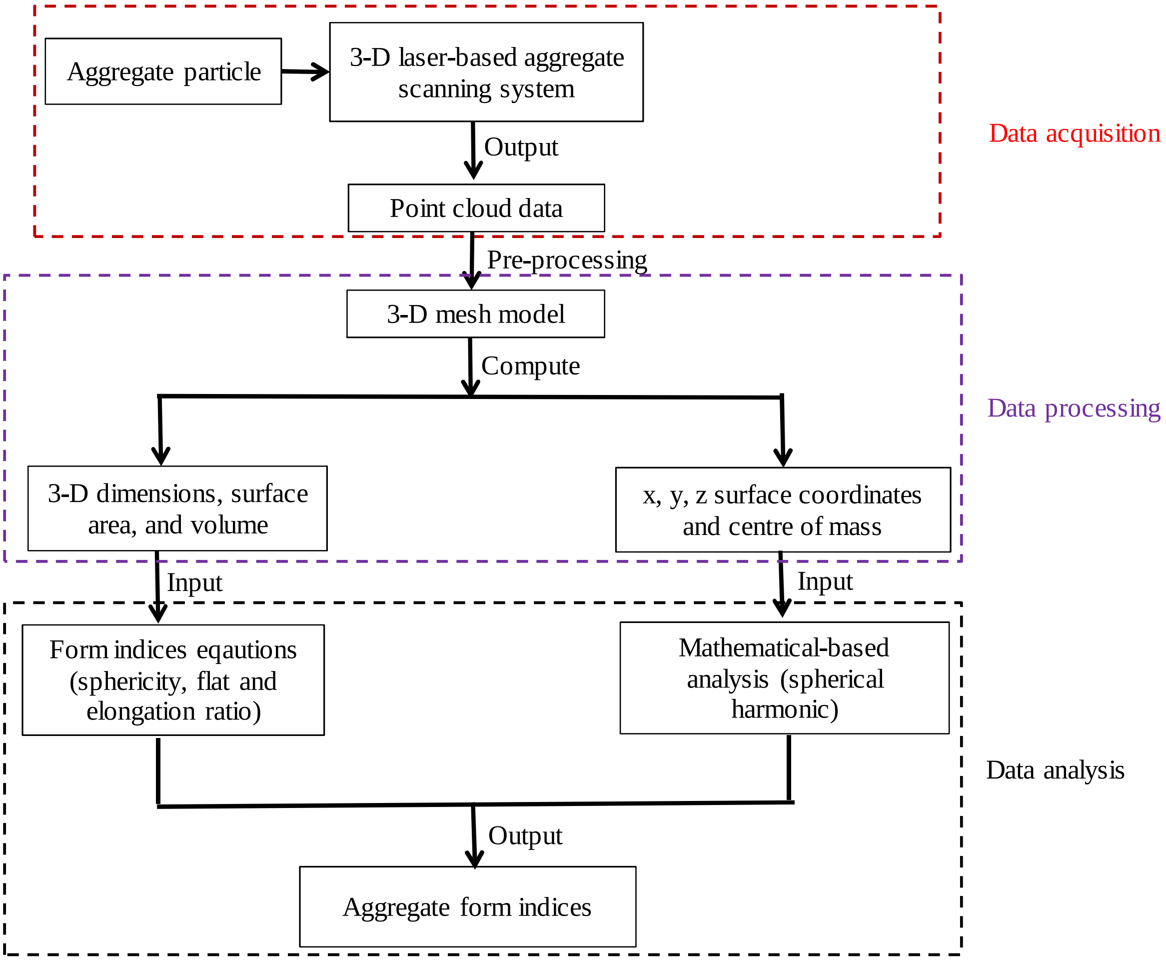


FIGURE 4 Schematic procedures for the laser-based quantification of aggregate form.

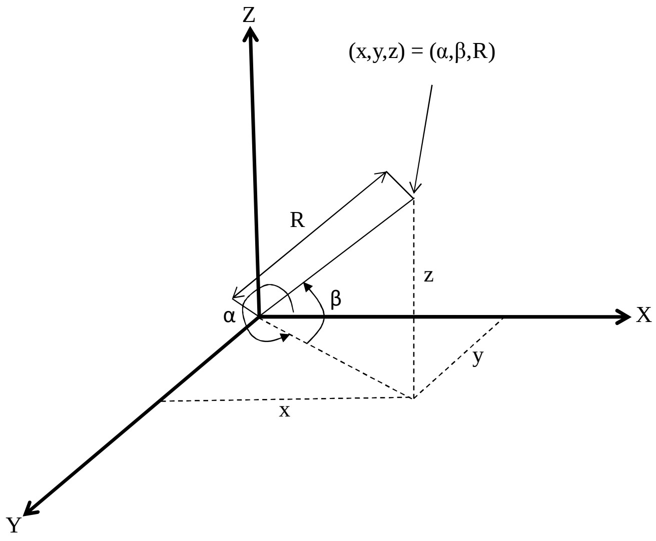


FIGURE 5 Relationships between Cartesian and polar coordinate.

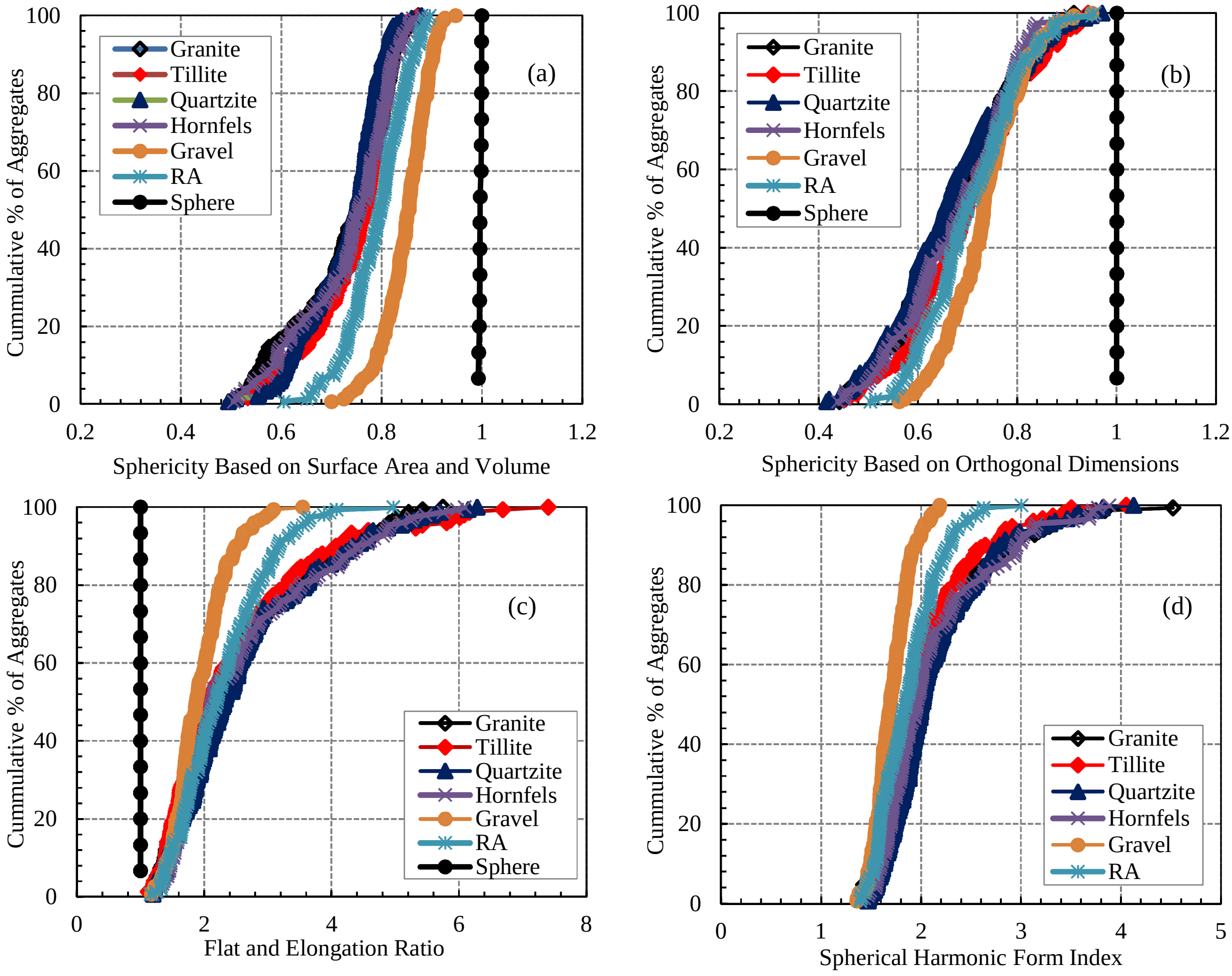


FIGURE 6 Distributions of aggregate particles with form indices.

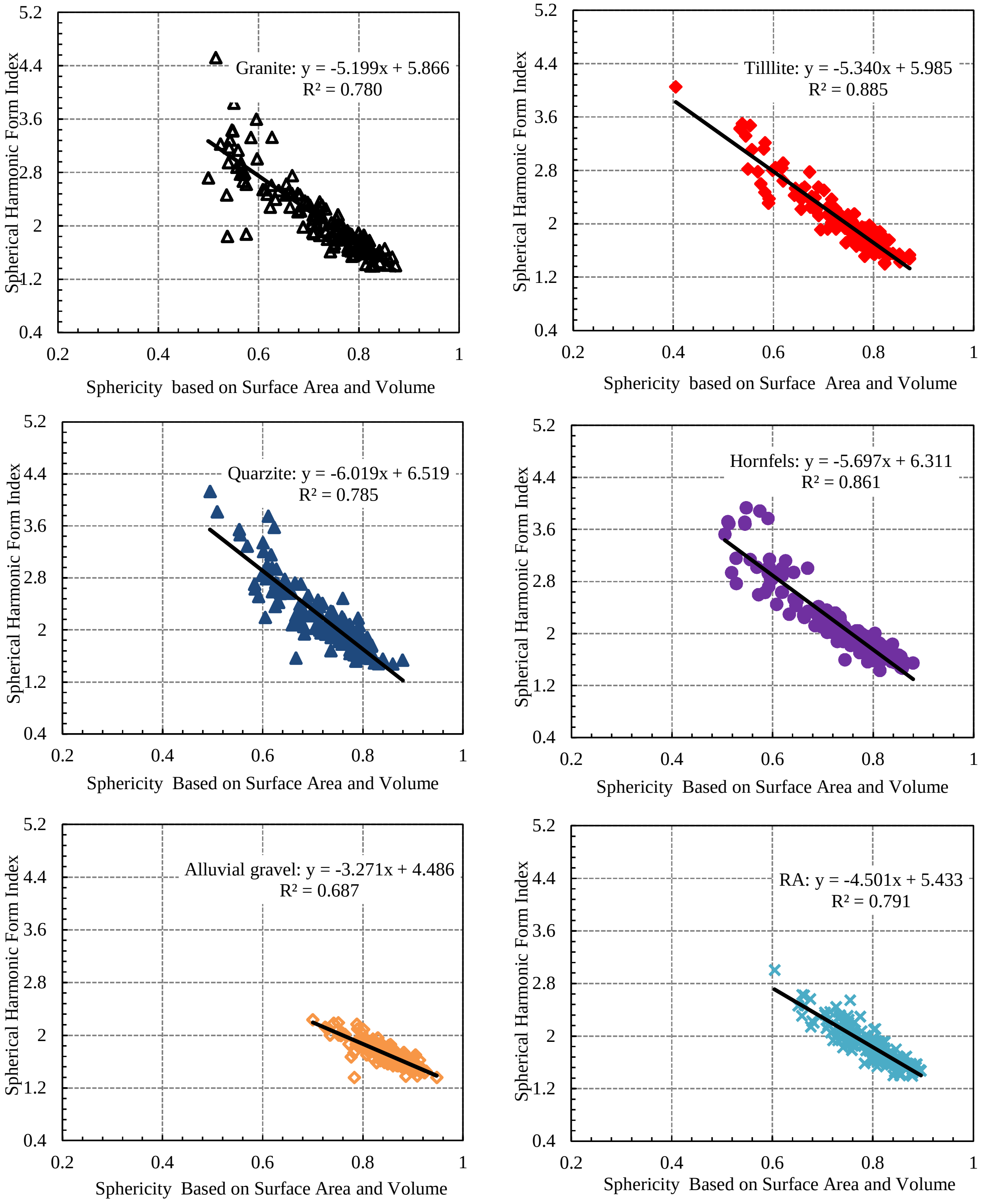


FIGURE 7 Correlation between harmonic index and sphericity based on surface area and volume.

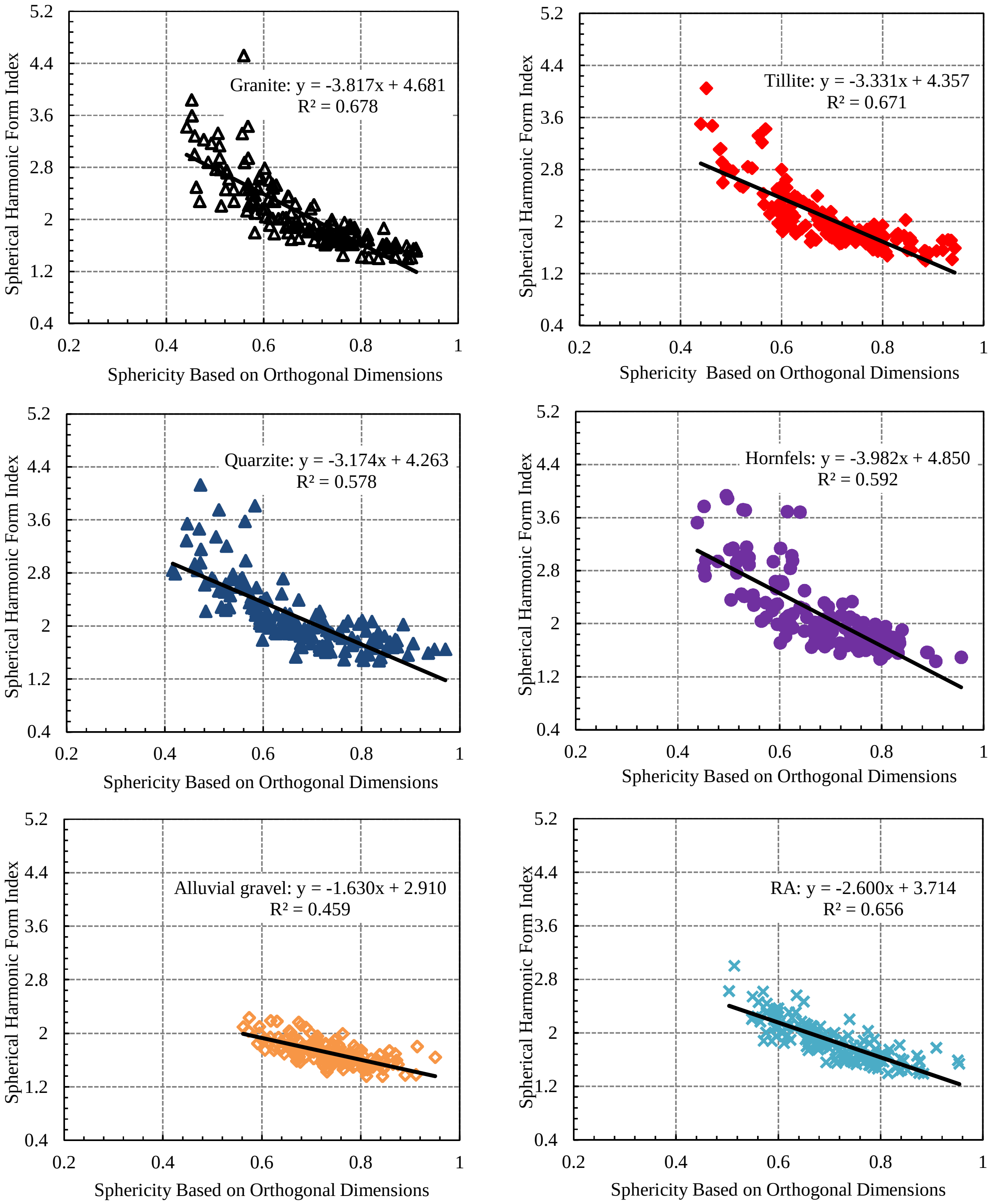


FIGURE 8 Correlation between harmonic index and sphericity based on orthogonal dimensions.

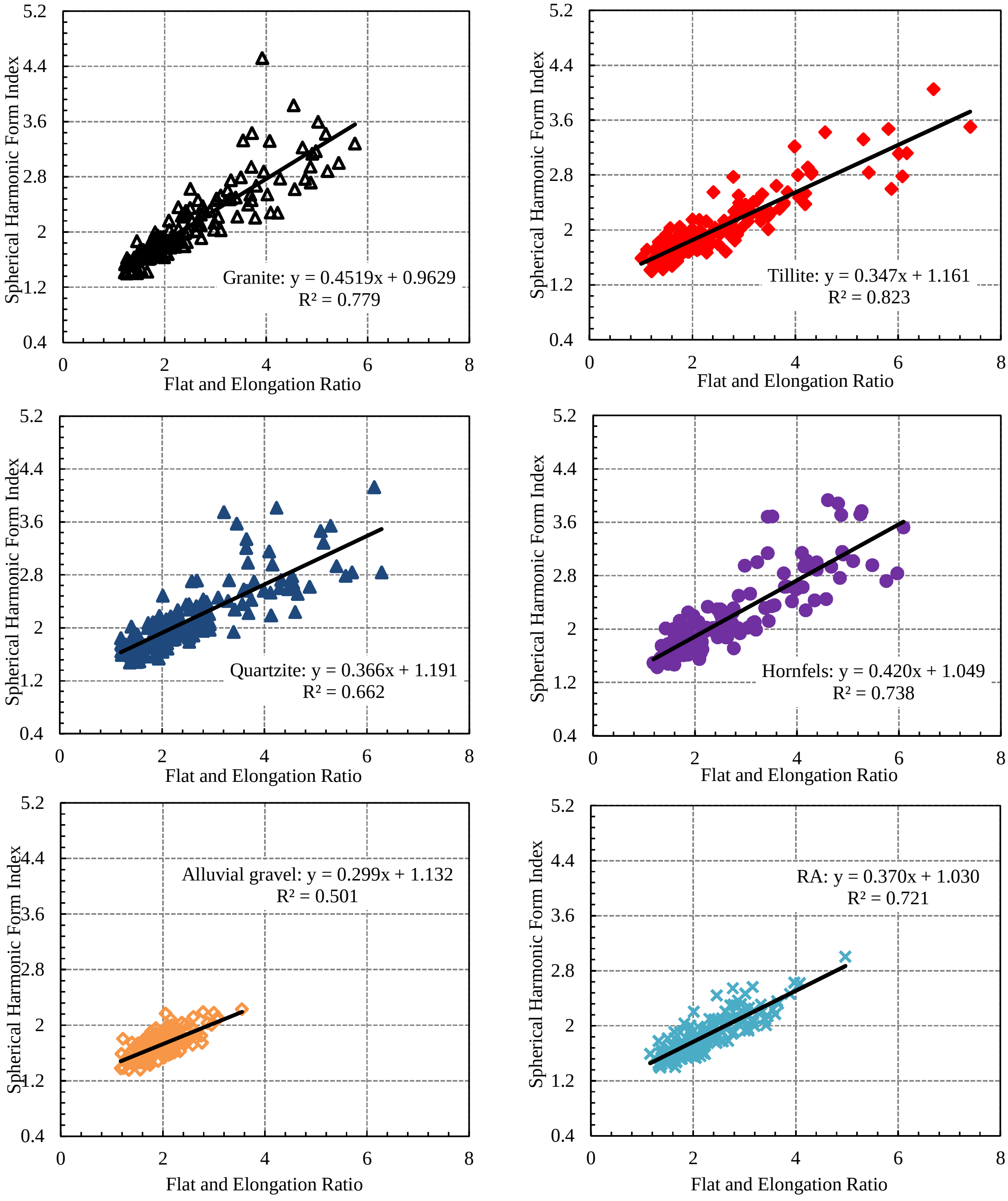


FIGURE 9 Correlation between harmonic index and flat & elongated ratio.