Investigation of the Effects of the Type of Crusher on Coarse Aggregate Shape Properties Using the Three-Dimensional Laser Scanning Technique

Julius Komba[1]; Martin B Mgangira[2]; and Luckyboy Mohale[3]

[1]Senior Research Engineer, Council for Scientific and Industrial Research (CSIR), P.O. Box 395, Pretoria 0001, South Africa. E-mail: JKomba@csir.co.za
[2]Principal Research Engineer, Council for Scientific and Industrial Research (CSIR), P.O. Box 395, Pretoria 0001, South Africa. E-mail: MMgangira@csir.co.za
[3]Research Technician, Council for Scientific and Industrial Research (CSIR), P.O. Box 395, Pretoria 0001, South Africa. E-mail: LMohale@csir.co.za

Abstract: The fundamental shape/morphological properties of coarse aggregates including form, angularity, and surface texture are known to influence the performance of pavements. The coarse aggregate shape properties are affected by many factors, amongst others, the properties of the parent rock and the type of crusher or crushing operations. Therefore, quantification of the effects of the crusher type on the aggregate shape properties is important as it influences the bulk properties of pavement materials and therefore performance. Recent studies have demonstrated that laser scanning technique can be employed to better quantify the three-dimensional (3-D) shape properties of aggregate materials used in pavements. In this paper, the shape properties of quartzite aggregates crushed by using four different types of crushers were investigated. The results have demonstrated the extent to which the aggregate shape indices computed using laser scan results can be used to distinguish aggregate by-product from different crushers.

INTRODUCTION

Coarse aggregate shape/morphological properties are known to influence the performance of pavements (Al-Rousan et al, 2007). The shape of an aggregate particle is distinguished by using three independent fundamental properties; the 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, which defines the sphericity, roundness, flatness and elongation. Angularity of an aggregate particle describes the sharpness of corners, whereas surface texture describes the smoothness or roughness of an aggregate particle (Masad, 2003; Al-Rousan et al, 2007). An illustration of the three fundamental aggregate shape properties is presented in (Anochie-Boateng et al, 2011).

The coarse aggregate shape properties are affected by many factors, amongst others, the properties of the parent rock and the type of crusher or crushing operations (Prowell et al, 2005; SBM, 2015). Crushers used for the production of aggregates are commonly grouped into two main categories. These categories are compression-type and impact crushers (Collis and Fox, 1985). Compression-type crushers, which include Jaw, Gyratory and Cone crushers, compress a rock until it breaks. On the other

hand, an impact crusher consists of rotating hammers which transfer kinetic energy to a rock by striking it until it breaks (Collis and Fox, 1985 and SBM, 2015). Thus the mechanism in which the crushing load is applied affects the shape properties of the produced aggregates. Compression-type crushers tend to produce flat and elongated particles and impact crushers produce cubical aggregates (Prowell et al, 2005).

The objective of the study being reported in this paper was to investigate the effects of the type of crusher on the coarse aggregates shape properties using three-dimensional (3-D) laser scanning technique. A 3-D laser scanning device was used for scanning quartzite aggregate particles crushed by using four different types of crushers, namely: Jaw crusher; Cone 1 crusher, Cone 2 crusher and Impact crusher. The laser scans results were used to compute sphericity and flat and elongated particle ratio indices, which are commonly used to measure the quality of quarry product.

STUDY APPROACH

Aggregate Source and Crushing Process

Quartzite aggregate was sourced from Afrisam Ferro quarry in Pretoria, South Africa. This commercial quarry supply aggregate for pavement construction and production of concrete. The quarry uses four different types of crushers, which was ideal for the study (i.e. same geological material crushed using four different crushers). The aggregate crushing at the Afrisam Ferro quarry is carried out in stages, starting with the primary, followed by the secondary and then the tertiary using four different types of crushers. The blast materials (usually greater than 110 mm rock boulders) are fed into a Jaw crusher (primary crusher). The Jaw crusher is used to provide size reduction sufficient for the secondary crushing stage. Aggregate product larger than 40 mm from the Jaw crusher is further crushed using Cone 1 crusher (secondary crusher). The Cone 1 crusher reduces the size of aggregate materials to a maximum size of 40 mm. Aggregate material from Cone 1 crusher is further crushed using a Cone 2 crusher and Impact shaping crusher to obtain road aggregate products.

Aggregate Sampling and Preparation

Aggregate sampling was carried out at the end of each crushing stage (i.e. aggregate crushed using each of the four crushers). The bulk samples were delivered to the Council for Scientific and Industrial Research (CSIR) pavement material testing laboratory where the study was conducted. Representative samples were obtained from each bulk sample from the different crusher type by means of rifling. The samples were washed, oven dried and screened to obtain four particle size classes namely: material passing 37.5 mm sieve but retained on 26.5 mm sieve; material passing 26.5 mm sieve but retained on 19.0 mm sieve; material passing 19.0 mm sieve but retained on 13.2 mm sieve, and material passing 13.2 mm sieve but retained on 9.5 mm sieve. Following the screening of the aggregates, a total of 30 particles were randomly selected from each of the size class for laser scanning. The aggregate screening ensured that different sizes of aggregate particles are selected for laser scanning. A total of 120 particles from each crusher type or overall 480 aggregate particles were scanned for the four types of crushers.

Other standard tests performed on the aggregate samples included sieve analysis, Bulk Relative Density, Apparent Relative Density and Water Absorption. Table 1 provides a summary of the properties of the aggregate used in the study.

Table 1. Properties of Aggregates Used in the Study

Crusher Type	Jaw	Cone 1	Cone 2	Impact
Bulk Relative density	2.623	2.608	2.625	2.604
Apparent Relative Density	2.645	2.648	2.656	2.642
Water Absorption (%)	0.290	0.578	0.469	0.556

Laser scanning of aggregates

In this study, three dimensional (3-D) laser scanning device available at the CSIR was used to scan individual aggregate particles. The laser scan data constitute surface point (point clouds) data which are further processed to reconstruct a 3-D model of an aggregate particle. The process involves aligning, combining and merging the sides of aggregate particles scanned separately. After reconstructing the 3-D models, the physical properties of individual aggregate particles including the surface area, volume, and orthogonal dimensions can be directly computed. The schematic aggregate scanning process is presented in Figure 1. From the figure, it is clear that the laser scanning technique is capable of producing an aggregate model, similar to the actual aggregate particle. Therefore, it is reliable to analyze the aggregate model to get an indication of the shape properties of the actual aggregate particle. Detailed procedure for the laser scanning of aggregates and processing of the scans data can be found in (Anochie-Boateng and Komba, 2010; Komba et al, 2013; Komba, 2013).
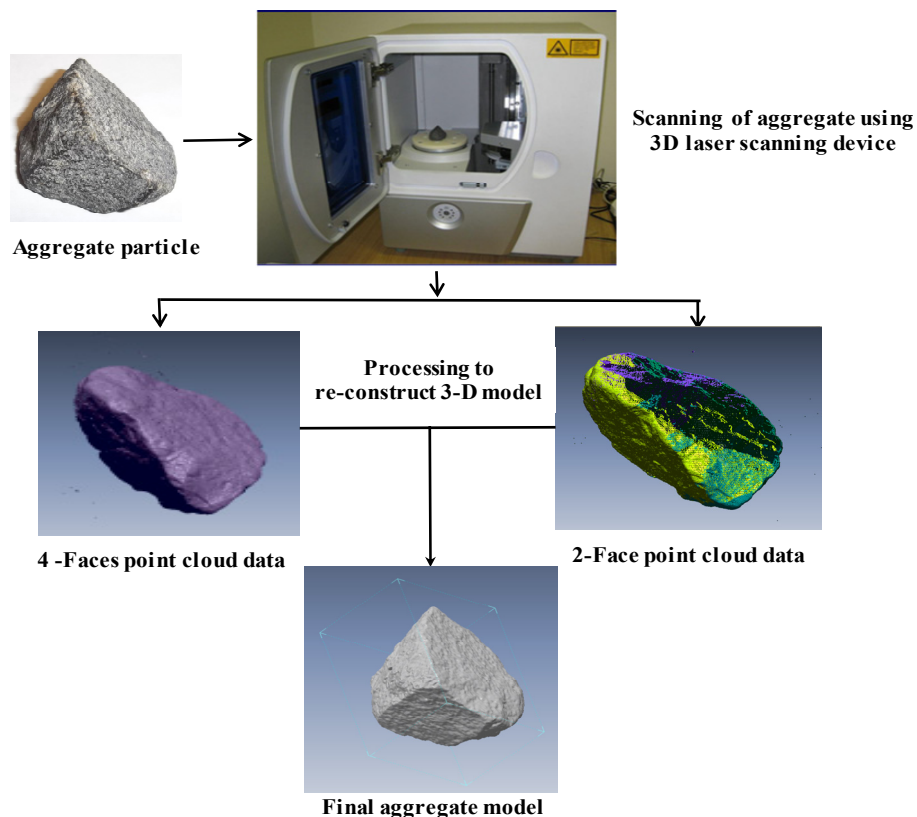
FIG. 1. Aggregate Scanning Process

Determination of Aggregate Shape Properties

The physical properties of individual aggregate particles (surface area, volume, and orthogonal dimensions) were used to compute three indices to describe the overall shape/form of aggregates. The three computed indices are defined as follows:

(a) Sphericity computed by using the aggregate surface area and volume as defined by Equation 1(Lin and Miller, 2005).

$$Sphericity\ (\psi) = \frac{\sqrt[3]{36\pi V^2}}{A} \tag{Eq. 1}$$

Where, V =Volume of an aggregate particle; A = Surface area of an aggregate particle

(b) Sphericity computed by using orthogonal dimensions of the aggregate as defined by Equation 2 (Masad, 2003).

$$Sphericity = \sqrt[3]{\frac{d_s.d_I}{d_L^2}} \tag{Eq. 2}$$

Where, d_L =longest dimension; d_I = intermediate dimension; d_s = shortest dimension;

(c) The flat and elongated particle ratio computed using the longest and smallest dimensions of the aggregate as defined by Equation 3 (Rao et al, 2001).

$$FER = \frac{d_L}{d_s} \tag{Eq. 3}$$

Where, d_L =longest dimension; d_I = intermediate dimension;

For equal dimensional particles such as round or cubical aggregates, the sphericity values computed using Equations 1 and 2 are expected to approach a maximum value of 1. On the other hand, the flat and elongated particle ratio values computed using Equation 3 approaches a minimum value of 1, for equal dimensional particles. As an aggregate particle becomes flatter, the flat and elongated ratio increases.

RESULTS AND DATA ANALYSIS

Laser Scanning Results

After scanning individual aggregate particles, the particle physical properties including, surface area, volume and orthogonal dimensions can be computed directly. These aggregate physical properties forms basic data used for the analyses presented in this paper to determine aggregate shape properties. Figure 2 shows plots of the surface area and volume of aggregate particles crushed using Jaw Crusher. The plots show that the surface area and volume of aggregates decrease with decreasing size of the sieve on which they are retained, which is the expected trend. It is also observed that the surface area and volume of aggregate particles retained on the same sieve size varies significantly. Table 2 shows a summary of the coefficient of variation (CoV).

Table 2. Coefficient of Variation of Surface area and volume (%)

Sieve size	Jaw		Cone 1		Cone 2		Impact	
(mm)	CoVSA[1]	CoVV[2]	CoVSA[1]	CoVV[2]	CoVSA[1]	CoVV[2]	CoVSA[1]	CoVV[2]
26.5	24	37	24	37	21	26	25	40
19.0	21	32	19	27	21	34	18	26
13.2	24	35	28	47	19	32	21	33
9.5	20	33	25	38	24	39	25	37

[1]: CoVSA is coefficient of variation of surface area; [2]: CoVV is coefficient of variation of volume
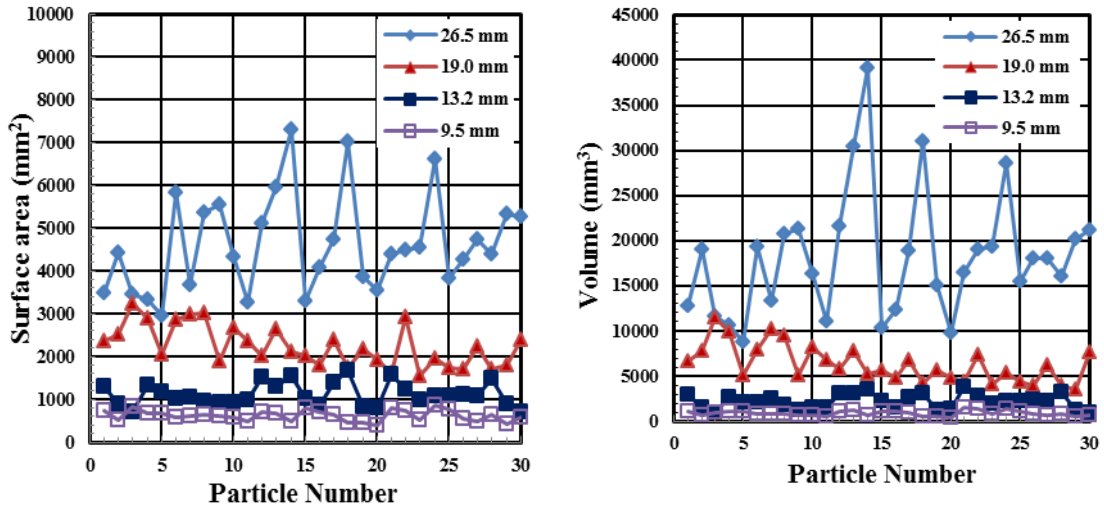
FIG. 2. Surface Area and Volume of Aggregates Crushed by Using Jaw Crusher

Effect of Crusher Type on Aggregate Shape properties

Table 3 shows the statistical parameters (average and standard deviation) of shape properties indices for aggregates crushed using the four types of the crushers. For each crusher type the statistical parameters were computed by using results of 120 aggregate particles (i.e. a total of 30 particles retained on each of the 9.5, 13.2, 19.0 and 26.5 mm sieve size). The results presented in Table 3 indicate that the average sphericity of aggregates crushed using Impact crusher is higher compared to the other crushers. As expected, a high sphericity is an indication of compactness of the particle and the average flat and elongated particle ratio is lower for aggregates crushed using Impact crusher.

Figure 3 shows plots of the distribution of aggregate shape indices. The results are a better illustration of the impact of crusher type on the shape properties. Aggregates crushed using Impact crusher can clearly be differentiated from the aggregates crushed using Jaw, Cone 1 and Cone 2 crushers. It can also be seen that aggregates crushed using Impact crusher have lower flat and elongated values, compared to aggregate particles crushed using the other types of crushers. Cone 2 crusher produces aggregates with greater variation in particle size and shape. The results are consistent with previous studies, specifically with respect to impact-type crushers that they tend to produce cubical/spherical aggregate particles (Prowell et al, 2005).

Table 3. Statistical Parameters of Aggregate Shape Properties

Crusher Type	SAV[1]		SD[2]		FER[3]	
	Average	STD[4]	Average	STD[4]	Average	STD[4]
Jaw	0.710	0.057	0.696	0.096	2.271	0.647
Cone 1	0.715	0.055	0.702	0.090	2.253	0.646
Cone 2	0.712	0.064	0.708	0.106	2.286	0.783
Impact	0.763	0.048	0.780	0.080	1.770	0.427

[1]: SAV is sphericity computed by using surface area and volume; [2]: SD is sphericity computed by using orthogonal dimensions; [3]: FER is flat and elongated particle ratio; [4]: STD is standard deviation
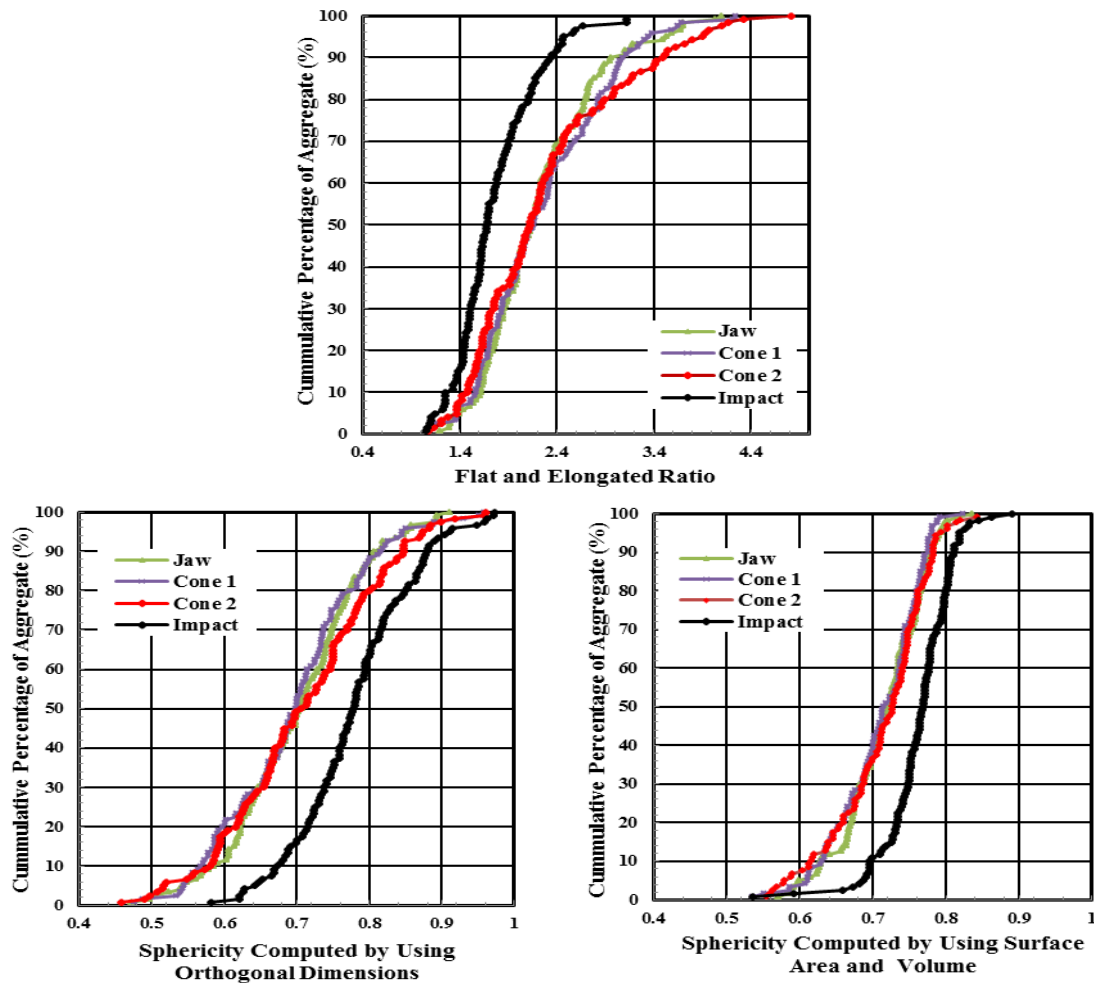
FIG. 3. Distribution of Shape Indices (Combined Aggregate Sizes)

Effect of Particle Size on Aggregate Shape Properties

To gain a better understand of the influence of the aggregate particle size on the shape properties, the shape indices distributions were plotted for each size separately. Utilizing the advantage of the 3-D laser scanning technique, Figure 4 shows plots of the distribution of sphericity computed using surface area and volume of aggregate particles. It can be seen that regardless of particle size, the sphericity values of the aggregates crushed using Impact crusher are higher than those of the other types of crushers. Although the ranking of the distributions of the sphericity of the aggregate particles crushed using Jaw, Cone 1 and Cone 2 crushers is not consistent, it is observed that the differences in shape indices are more noticeable when comparing the results of each particle size separately. It should be pointed out that based on the aggregate crushing process described earlier in the paper, aggregate particles may be influenced differently, by previous crushing process involving the different crushers hence contributing to the observed inconsistence in the distribution of shape indices. However, the effect of shaping mechanism of the Impact crusher is evident in all particle sizes. Similar trend was observed for the sphericity computed by using surface area and volume (SAV) and flat and elongated particle ratio (FER).
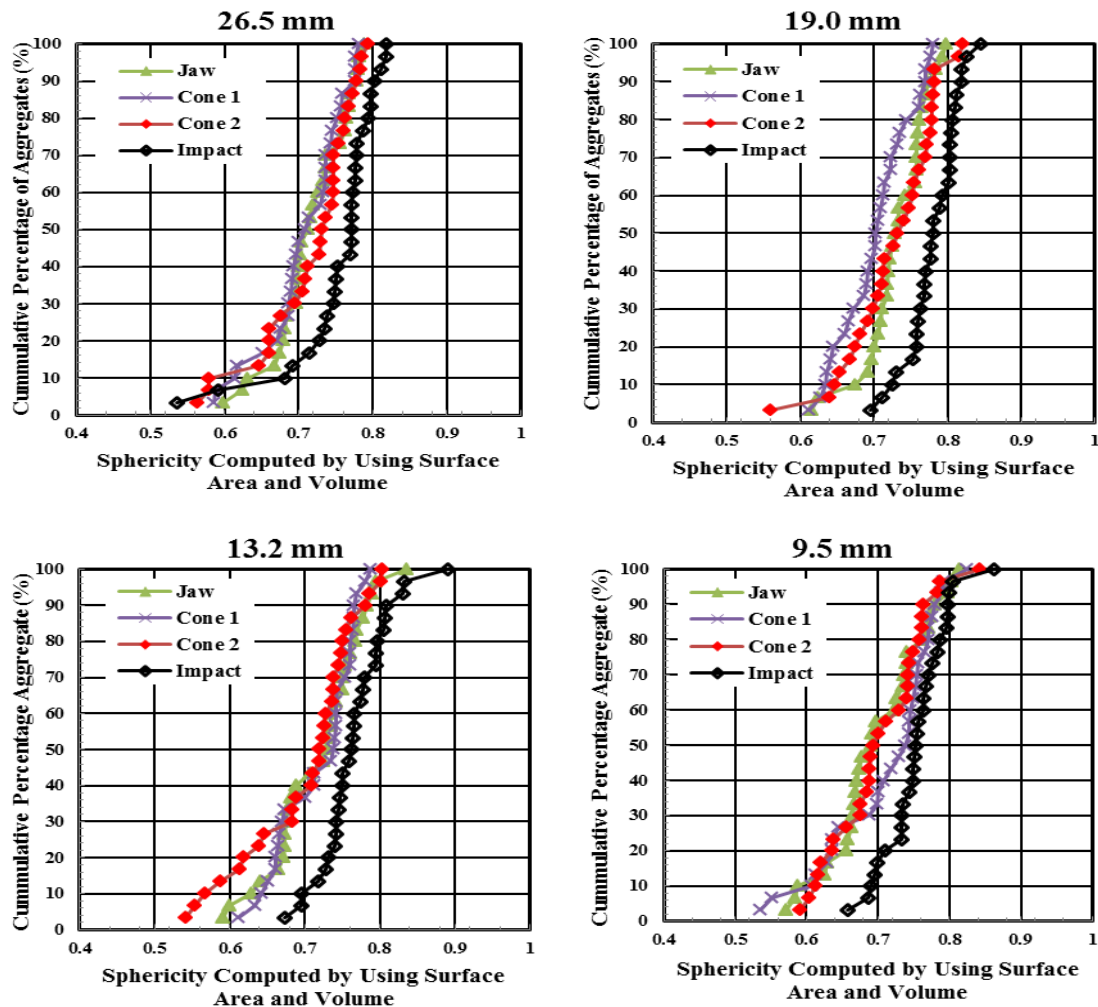
FIG. 4. Distribution of Sphericity (Individual Aggregate Sizes)

CONCLUSIONS AND RECOMMENDATION

The paper investigated effects of the type of crusher on the coarse aggregates shape properties using 3-D laser scanning technique. Quartzite aggregates crushed through four different types of crushers, namely: Jaw crusher, Cone 1 crusher, Cone 2 crusher and Impact crusher were investigated. Based on the results presented in this paper, the following conclusions are drawn with a recommendation:

- The study has demonstrated how computed aggregate shape indices can be used to distinguish aggregates crushed using different crushers. Evidence base knowledge on the effect of crusher type on aggregate shape properties has been presented;
- The distribution in aggregate shape indices for different crusher types is not consistent when comparing the results of each particle size separately;
- The effect of aggregate shaping has been quantified. Regardless of particle size, the sphericity values of the aggregates crushed using Impact crusher are higher than that of the other types of crushers, providing an indication of cubical aggregates which are preferred for road construction, and
- Only one aggregate type was used in this study. It is recommended that future

studies should include different aggregate types, based on geology of parent rock to validate the concept.

ACKNOWLEDGMENTS

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