

Impact of crushing processes on aggregate morphology: evaluation using *FAA* and *AIMS* tests

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Article

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Abstract

This study evaluates the influence of lithology and crushing processes on the morphology of fine aggregates from five quarries of plutonic igneous and metamorphic origin. Three particle size fractions (0.30, 0.60, and 1.18 mm) were analyzed using the Aggregate Imaging Measurement System (*AIMS*) and the Fine Aggregate Angularity (*FAA*) test according to Brazilian standards DNIT 432/2020 and DNIT 415/2019, respectively. The originality of this study lies in the integrated evaluation of geological anisotropy, crushing technology, and aggregate morphology using both indirect (*FAA*) and image-based (*AIMS*) methods under real quarry operating conditions. The results demonstrated that geological features such as magmatic foliation, mineral orientation, gneissic banding, and cleavage planes influence aggregate shape and angularity by controlling preferential fracture mechanisms during crushing. However, the cone crusher (CC) and, especially, the vertical shaft impact crusher (VSI) were capable of partially mitigating these geological effects, producing predominantly semicircular and subrounded to subangular particles. Aggregates processed by VSI exhibited more uniform 2D shape distributions and lower shape variability than those produced by CC, particularly for metamorphic rocks. Statistical analysis (ANOVA) revealed significant differences ($p < 0.05$) between *FAA* and *AIMS* results, indicating that the indirect nature of *FAA* may lead to angularity interpretations that differ from those obtained through image-based measurements. The findings highlight the importance of considering both lithology and crushing technology in aggregate production, as well as the need for more reliable and standardized protocols for morphological characterization in civil engineering applications.

1. Introduction

Aggregate shape properties – such as form, angularity, flatness, and texture – play a crucial role in the stability and load-bearing capacity of pavements (Chen et al., 2005; Souza et al., 2012; Bessa et al., 2015). The influence of aggregate morphology extends beyond pavements to other civil engineering applications, including concrete production, where particle shape affects workability, compactness, and the aggregate-paste interface (Collares et al., 2012).

Aggregate shape describes the relationships between particle dimensions, classifying them as cubic, flat, elongated, or flat-elongated (Frazão, 2002). The pursuit of more precise morphological characterization has led to the development of advanced techniques, including three-dimensional particle scanning, which enables the quantification of parameters

such as the ‘ellipsoidness ratio’ and provides a more realistic assessment of particle degradation under simulated loading conditions (Gomes et al., 2022). Angularity refers to variations in particle edges, while texture is related to small-scale surface irregularities (Masad, 2005).

Aggregate morphology is influenced by rock formation processes, extraction methods, and crushing techniques (Zheng & Hryciw, 2017). Detailed investigations into the mineralogical and structural characteristics of parent rocks – such as the ‘entablature-colonnade’ compartmentation in basaltic flows – demonstrate that variations in texture and volcanic glass content can significantly affect the technological behavior and durability of aggregates (Gomes & Rodrigues, 2008). Crushing, which breaks particles primarily through compressive or impact forces, plays a major role in defining these properties.

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Jaw crushers (JC) and gyratory crushers apply compressive forces through the periodic approach and separation of a movable surface against a fixed one. In cone crushers (CC), widely used in quarries, particle size reduction occurs due to the eccentric movement of the cone-shaped mantle as it approaches the casing, fragmenting the rock (Griffith & Kallas, 1958). Understanding the micro-mechanisms of particle fragmentation - including the role of heterogeneous bond strength and the size-dependent transition between brittle and ductile failure modes - has been advanced through numerical simulations using the Discrete Element Method. These studies help explain why particles of different sizes and strengths exhibit distinct crushing behaviors under compressive loads (Qiu et al., 2025). However, crushing can follow preferential fracture planes, leading to aggregates with less desirable shapes for civil engineering applications.

Studies have demonstrated that both crushing procedures and parent rock lithology influence aggregate shape characteristics. Hafeez et al. (2016) found that aggregates produced through two-stage crushing—jaw crusher (JC) followed by cone crusher (CC) — exhibited higher cubicity than those produced solely by JC. Rajan & Singh (2017a) investigated the impact of the crushing process on the shape properties of basaltic aggregates, concluding that different crusher combinations (JC, CC, VSI, and HSI) produce aggregates with distinct shape and angularity characteristics. Diógenes et al. (2019) studied rocks from three quarries and two lithologies (biotite gneiss and monzogranite) and found that the first crushing stage with JC resulted in coarse aggregates with better angularity and sphericity. Kamani & Ajalloeian (2019) showed that rock type and crusher type significantly affect aggregate size and shape.

To characterize the morphological properties of fine aggregates, various laboratory testing methods are employed, such as the Fine Aggregate Angularity (*FAA*) test. Although the *FAA* test is considered a useful tool for evaluating fine aggregate quality (Chowdhury, et al., 2001), some researchers have reported significant limitations in its ability to distinguish between high-quality and low-quality aggregates due to its indirect measurement and its dependence on volumetric behavior rather than direct particle geometry (Huber et al., 1998; Lee et al., 1999; Kuo & Freeman, 2000; Fernandes et al., 2000; Gouveia, 2002, 2006; Tutumluer & Pan, 2008; Rodrigues, 2019; Ceccato, 2021). Factors such as aggregate specific gravity, particle drop height during the test, and mass measurement accuracy can also influence *FAA* results.

To overcome these obstacles, digital imaging techniques have recently been applied to measure fine aggregate angularity. The Aggregate Imaging Measurement System (*AIMS*) is recognized as a standard test procedure. *AIMS* has been widely used in the asphalt pavement and railroad ballast

research communities as an alternative for characterizing morphological properties of both fine and coarse aggregates (Tutumluer & Pan, 2008; Mahmoud et al., 2010; Bessa, 2012; Alves, 2014; Ibiapina et al., 2017; Ibiapina et al., 2018; Trotta, 2020; Diógenes et al., 2021; Diógenes, 2021). However, despite being the most current and standardized technique, *AIMS* has limitations that require attention, particularly regarding particle orientation, image binarization, and the inherent constraints of two-dimensional analysis (Al Rousan et al., 2005; Branco et al., 2006; Masad et al., 2007; Ceccato, 2021).

Despite the advances summarized above, significant research gaps remain. First, very few studies have directly compared *FAA* and *AIMS* results for fine aggregates derived from different lithologies (metamorphic and plutonic) processed under real crushing plant conditions. Most comparative analyses have focused on coarse aggregates or single rock types. Second, it is not yet clear whether cone crushing (CC) and vertical shaft impact crushing (VSI) can eliminate the influence of rock fabric — specifically, metamorphic foliation versus magmatic flow foliation in plutonic rocks — on final aggregate shape and angularity. Third, while the individual effects of crusher and rock types have been investigated separately, the interaction between these two factors during fine aggregate production remains poorly understood. Fourth, there is a lack of studies evaluating the impact of crushing processes on fine aggregate morphology using two complementary methods (*FAA* and *AIMS*) to determine whether they yield consistent rankings of aggregate angularity across different lithologies.

In this study, fine aggregates from five quarries of metamorphic and plutonic origins, in three different size fractions (0.30 mm, 0.60 mm, and 1.18 mm), were collected directly from the crushing sites of the respective quarries to evaluate the influence of crusher type and rock type on fine aggregate shape properties. Two types of crushers were used to obtain the final fine material: cone crusher (CC) and vertical shaft impact crusher (VSI).

The angularity and 2D shape of all aggregates were analyzed using *AIMS* according to the DNIT 432/2020 standard (DNIT, 2020). Additionally, the *FAA* of fine aggregates was measured using the corresponding standard (DNIT 415/2019) (DNIT, 2019), allowing a comparative analysis between these two methods. These comparisons aim to provide a more comprehensive and accurate view of the morphological properties of aggregates, assisting in the selection of more suitable materials for specific civil engineering applications.

By comparing aggregates from different geological origins and crushing processes using both traditional (*FAA*) and advanced (*AIMS*) methods, this study aims to provide a comprehensive understanding of how these factors interact and to offer recommendations for more reliable angularity assessment protocols.

2. Research procedure

2.1 Materials

Five quarries in southern Brazil were selected based on three criteria: lithology, crushing technology, and regional representation. Geologically, three plutonic aggregates from Rio Grande do Sul (RS) originate from the Sul-Riograndense Shield (Pelotas Batholith): MIN (Mibersul - Dom Feliciano Granitic Suite, Pelotas/RS), CONP (Compasul - Butiá/RS), and ELD (Eldorado - Eldorado do Sul/RS), with the latter two belonging to the Erval Intrusive Suite (CPRM, 2014). Two metamorphic aggregates from Santa Catarina (SC) belong to the Santa Catarina Granulitic Complex (Luis Alves Granulitic Gneiss): FRAG (Fragosos - Campo Alegre/SC) and VOG (Vogelsanger - Joinville/SC). First, these materials represent distinct lithologies (plutonic and metamorphic) with varying foliation degrees to evaluate fabric influence on aggregate shape. Second, crushing configurations vary: four quarries use cone crushers (CC) as the final stage, whereas VOG utilizes a vertical shaft impact (VSI) crusher, enabling direct comparison of crusher effects. Third, covering two distinct geological regions provides a representative diversity of regional construction materials. This framework allows a systematic assessment of the interactions between lithology, rock fabric, crushing process, and particle size on fine aggregate morphology.

2.2 Characterization of the studied areas

The quarries investigated present distinct lithological, structural, and weathering characteristics. The MIN Quarry (Pelotas/RS; Figures 1a, b) features a massive, medium-to-coarse phaneritic syenogranite (locally monzogranite) from the Pelotas Batholith margin, displaying localized magmatic foliation. Weathering is restricted to upper fractured zones bounded by relief joints. The CONP Quarry (Butiá/RS; Figures 1c, d) exposes a porphyritic monzogranite with tabular potassium feldspar megacrysts in an inequigranular matrix, exhibiting quartz veins and Rapakivi textures. Structurally, it is bounded by relief joints, with highly fractured vertical discontinuities in the upper bench and clay-filled horizontal fractures and magmatic foliation in the lower bench. The ELD Quarry (Eldorado do Sul/RS; Figures 1e, f) consists of a coarse porphyritic syenogranite (~1 cm grains) with massive structures and magmatic foliation. Compared to MIN and CONP, ELD exhibits advanced weathering, with an intensely weathered upper bench and clay-filled, oxidized discontinuities in the lower bench.

Regarding the metamorphic massifs, the FRAG Quarry (Campo Alegre/SC; Figures 2a, b) predominantly comprises dark mafic granulites in the active front and felsic granulites with incipient banding in lower sections. The massif shows intense

deformation, featuring faults, folds, and cataclastic foliation with fragmented minerals. The VOG Quarry (Joinville/SC; Figures 2c, d) consists of biotite gneiss with well-developed gneissic banding (0.5 cm alternating felsic and mafic bands). The structural framework involves multiple faults and fractures that accelerate weathering in the upper benches, while the lamellar mica crystals in the lower intact rock introduce mechanical anisotropy.

2.3 Crushing process

In the production of rock aggregates, each quarry follows similar processing stages, with variations occurring in the tertiary and quaternary crushing stages (VOG quarry). In all quarries, a jaw crusher is used as the primary crusher, whereas the secondary and tertiary crushing stages employ cone crushers (MIN, CONP, ELD, and FRAG). However, due to the geological characteristics of the rock mass, a fourth crushing stage was required at the VOG quarry, where a vertical shaft impact crusher (VSI) was employed. The flowchart presented in Figure 3 illustrates the crushing plant layout adopted at each studied quarry.

The efficiency of the crushing process in producing aggregates with suitable morphological characteristics is supported by studies involving different lithologies. Collares et al. (2012), when comparing jaw crushers and hydrocone crushers for quartzite aggregates, demonstrated that the latter produced particles with significantly improved shape indices, resulting in enhanced mechanical performance in concrete. This finding reinforces the critical role of the tertiary crushing stage, particularly the use of cone and VSI crushers, in mitigating undesirable particle shapes inherited from the parent rock.

Aggregate morphology is primarily controlled by lithology, mineral composition, and internal rock fabric, including foliation, cleavage, and preferred mineral orientation, which define preferential fracture planes during comminution processes (Strzalkowski et al., 2021; Adomako et al., 2021; Gao et al., 2021). However, previous studies have demonstrated that crushing technologies such as cone crushers (CC) and vertical shaft impact crushers (VSI) can partially mitigate these geological controls, producing aggregates with improved cubicity and reduced lamellarity (Rajan & Singh, 2017a; Diógenes et al., 2021; Wang et al., 2021; Duchnowska et al., 2023). Therefore, Table 1 summarizes the expected morphological behavior of the investigated lithologies, and the anticipated influence of the crushing systems adopted in each quarry.

2.4 Methods

Currently, there are two main methods for measuring the shape characteristics of aggregates: direct methods (e.g., *F4A*) and image-based methods (e.g., *AIMS*) (Al Rousan, 2004; Kamani, 2018). Both methods present practical limitations (Lee et al., 2007; Kamani, 2018; Su & Yan, 2018). In this study, aggregate shape properties were determined using

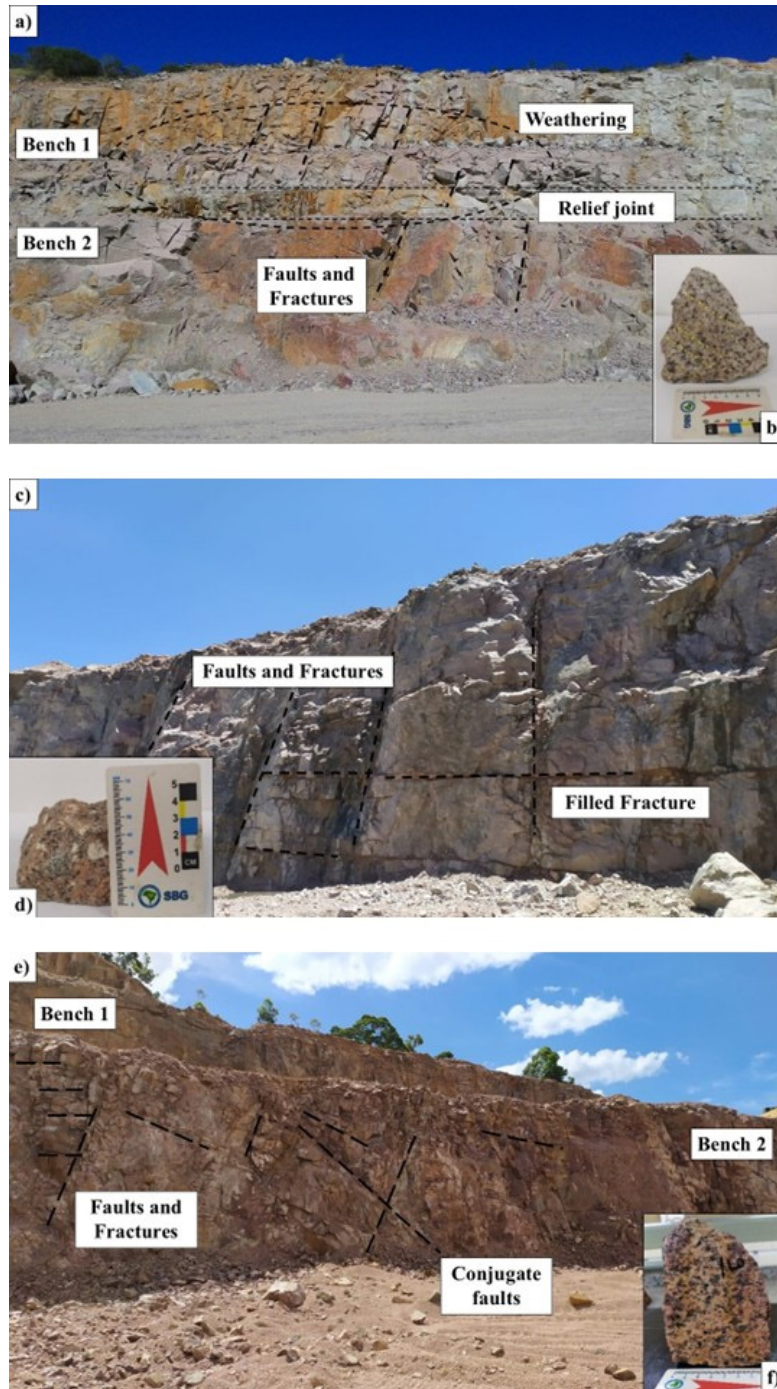


Figure 1. Overview of the quarries and representative hand specimens of the corresponding lithologies studied. (a, c, and e) General views of the MIN, CONP, and ELD quarries, respectively; (b, d, and f) corresponding hand specimens.

these two methods, and their methodologies are described in the following sections.

2.4.1 Measurement of shapes using *AIMS*

The evaluation of aggregate shape using Digital Image Processing (DIP) through the *AIMS* system followed the

methodology established DNIT 432/2020 and was conducted at the Geotechnics and Pavement Laboratory of the Federal University of Rio de Janeiro – COPPE. Aggregates of different particle sizes, ranging from 0.075 mm to 2.36 mm, were washed and oven-dried prior to *AIMS* testing. A representative 200 g sample of each size fraction was selected using the quartering method, and approximately 150 particles were analyzed to

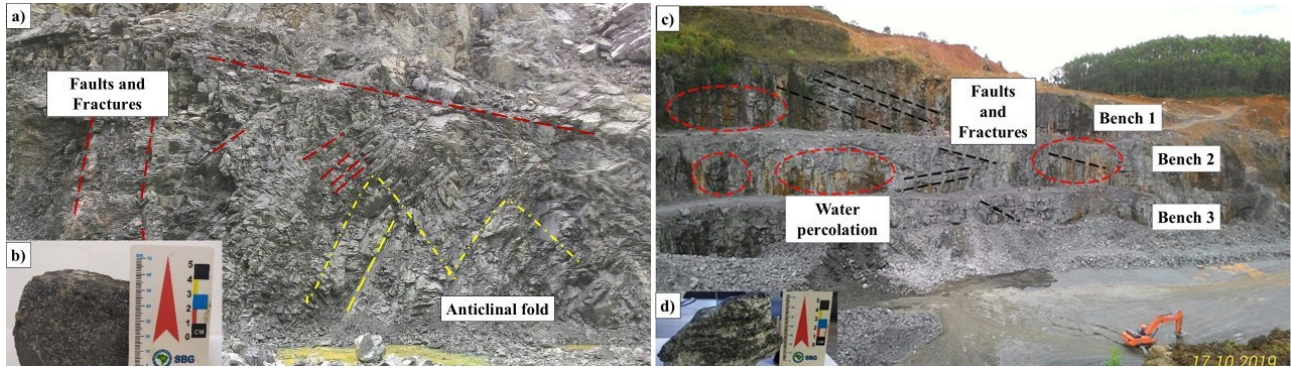


Figure 2. Overview of the studied quarries and representative hand specimens of the corresponding lithologies. (a and b) General views of the FRAG and VOG quarries, respectively; (c and d) corresponding hand specimens.

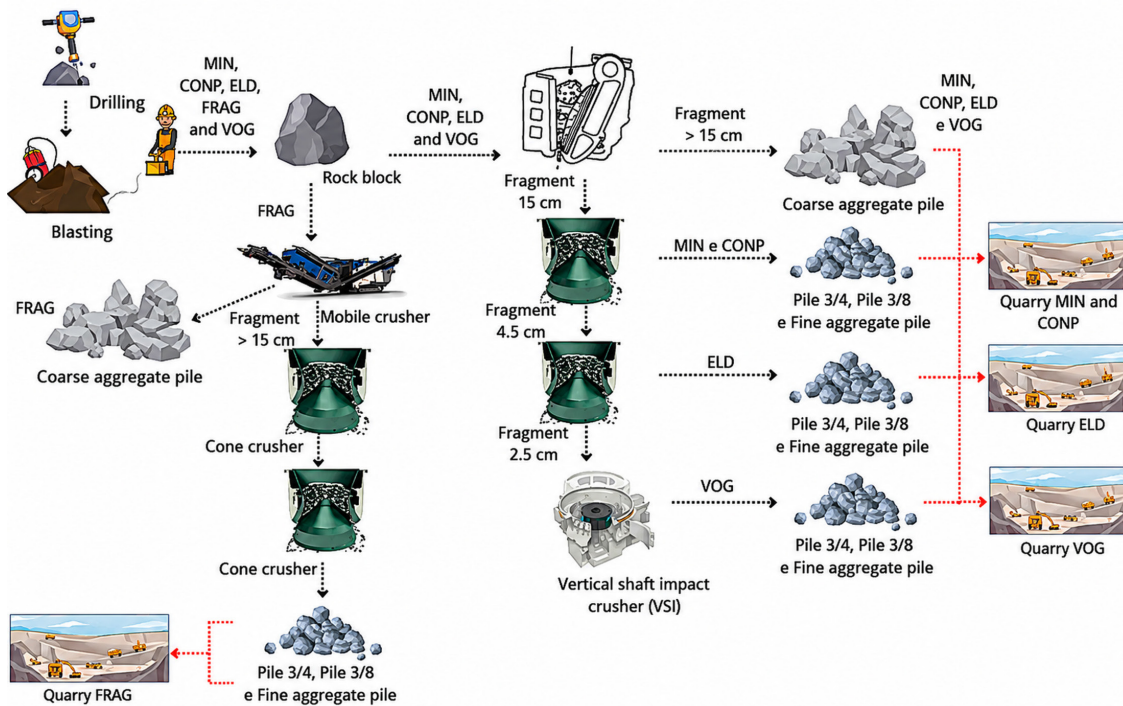


Figure 3. Crushing stages of the quarries.

determine 2D shape and angularity. The selection of 150 particles was based on the recommendations of DNIT 432/2020 and previous studies (Al Rousan et al., 2007; Diógenes et al., 2021), which indicate that this sample size is sufficient to stabilize the mean values of shape and angularity.

The 2D Form parameter is calculated using Equation 1, with values ranging from 0 to 20, where a perfect circle would exhibit a value close to zero. In this study, the classification proposed by Ibiapina et al. (2018) was adopted.

$$\text{Form2D} = \frac{\sum_{\theta=0}^{\theta=360-\Delta\theta} \left[\frac{R_{\theta+\Delta\theta} - R_{\theta}}{R_{\theta}} \right]}{\Delta\theta} \quad (1)$$

Where R_{θ} = radius at an angle θ , $\Delta\theta$ = incremental difference in angle;

In *AIMS*, angularity is defined as the sharpness of the particle corners identified in a two-dimensional image. It is quantified using the gradient method, which evaluates variations in the gradient along the particle boundary based on a binary image (silhouette), as illustrated in Equation 2. The angularity index ranges from 1 to 10,000 (dimensionless).

$$\text{Angularity} = \frac{1}{\frac{n}{3} - 1} \sum_{i=1}^{n-3} |\theta_i - \theta_{i+3}| \quad (2)$$

Table 1. Expected influence of lithology, rock fabric and crushing process on aggregate morphology based on published studies.

Quarry	Lithology/ Structure	Expected Morphological Response	Supporting References
MIN	Syenogranite with magmatic foliation	Flaky and elongated particles; cone crushing may improve cubicity.	Strzałkowski et al. (2021), Adomako et al. (2021), Gao et al. (2021), Duchnowska et al. (2023).
CONP	Porphyritic monzogranite with aligned K-feldspar	Preferential breakage along crystal boundaries; CC tends to homogenize particle shape.	Adomako et al. (2021), Duchnowska et al. (2023), Diógenes et al. (2021)
ELD	Weathered syenogranite with magmatic foliation	High morphological variability; CC only partially reduces anisotropy.	Strzałkowski et al. (2021), Duchnowska et al. (2023), Diógenes et al. (2021)
FRAG	Mafic granulite with cataclastic foliation	High angularity; cone crushing improves sphericity.	Rajan & Singh (2017b), Diógenes et al. (2021).
VOG	Biotite gneiss with mica-rich foliation	Flaky particles; VSI improves cubicity.	Rajan & Singh (2017a), Diógenes et al. (2021), Duchnowska et al. (2023).

Where: θ angle of orientation of the edge points, n is the total number of points, and i denote the i th point on the edge of the particle.

2.4.2 Fine Aggregate Angularity (FAA)

The *FAA* was determined in accordance with the DNIT 415/2019 standard. In this test, a fine aggregate sample is poured into a calibrated cylinder through a standardized funnel, and excess material at the top is carefully leveled. The procedure evaluated three specific methods using 190 g samples (Equation 3). Method A uses a standard gradation combining individual mass fractions retained on specific sieves: 44 g (2.36–1.18 mm), 57 g (1.18–0.60 mm), 72 g (0.60–0.30 mm), and 17 g (0.30–0.15 mm). Method B evaluates distinct 190 g fractions separately for the 1.18, 0.60, and 0.30 mm sieve sizes. Lastly, Method C tests a single 190 g bulk sample passing the 4.75 mm sieve and retained on the 0.075 mm sieve.

$$U = \frac{V_c - \frac{M_a}{\rho_{ap}}}{V_c} \quad (3)$$

Where: U = Uncompacted voids (%); V_c = volume of the cylinder (cm^3); M_a = mass of the aggregate contained in the cylinder (g); ρ_{ap} = bulk density of the fine aggregate (g/cm^3)

2.4.3 Comparison between *FAA* and *AIMS* methods

The choice to combine *FAA* and *AIMS* is based on their complementary characteristics. The *FAA* method, standardized by DNIT 415/2019, is a simple, low-cost approach that requires no sophisticated equipment. However, it provides an indirect measurement based on uncompacted void content, lacks repeatability, and is influenced by density, drop height, and

mass accuracy. Furthermore, *FAA* fails to separate angularity from surface texture, shape, or particle size. Conversely, the *AIMS* method (DNIT 432/2020) utilizes digital image processing to directly and independently quantify shape, angularity, and texture. Its drawbacks include high equipment costs, the need for trained operators, and sensitivity to image resolution and binarization. Additionally, *AIMS* operates on a 2D projection that fails to fully capture 3D angularity and can produce errors if overlapping particle boundaries are incorrectly merged during Results and discussion

2.5 AIMS

Figure 4 presents the *AIMS* results for the distribution of 2D particle shape across different classification ranges, according to the system proposed by Ibiapina et al. (2018): circular, semicircular, semi-elongated, and elongated. Aggregates from different quarries and particle sizes were analyzed, considering two types of final crushing stages: cone crusher (CC) and vertical shaft impact crusher (VSI).

The results indicate that, regardless of lithology or particle size fraction, the aggregates were predominantly classified as semicircular, followed by semi-elongated particles, whereas elongated and circular particles occurred in lower proportions. This behavior suggests that the crushing processes were capable of partially reducing the morphological expression of the geological anisotropy inherited from the parent rocks, including the foliation of metamorphic rocks and the magmatic flow foliation of plutonic rocks.

For plutonic materials, the results demonstrate that the cone crushing (CC) stages were relatively effective in mitigating the generation of flaky particles, even in materials exhibiting structural anisotropy associated with the preferential alignment of feldspars and micas. Despite the location of the MIN quarry at the margin of the batholith — a condition commonly associated with more

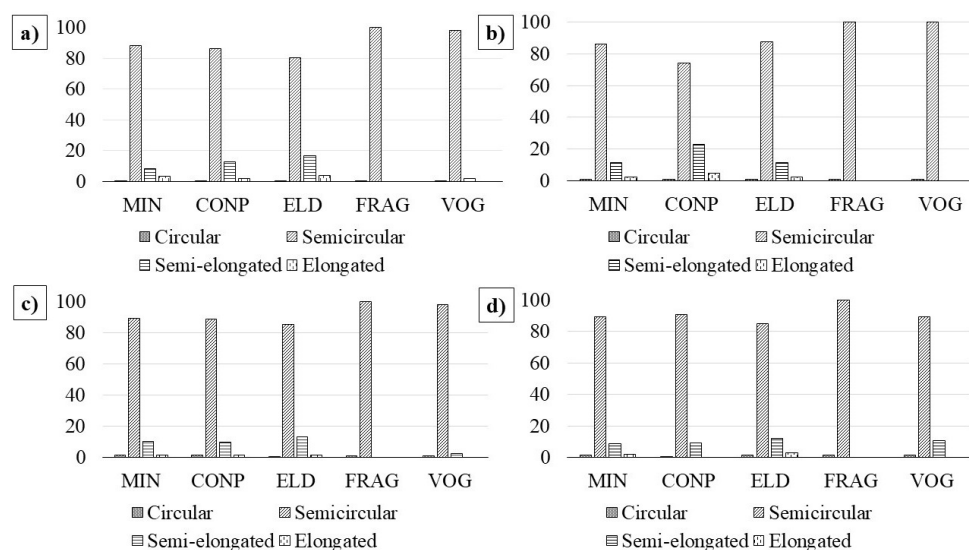


Figure 4. Form 2D – AIMS: a) Size 1.18 mm; b) Size 0.60 mm; c) Size 0.30 mm; d) Size 0.15 mm.

pronounced magmatic foliation — the distribution of 2D particle shapes remained similar to that observed for the CONP quarry, with a predominance of low-aspect-ratio particles. Only minor granulometric variations were observed, particularly in the intermediate fraction (0.60 mm), which exhibited a tendency toward a higher proportion of semi-elongated particles.

This behavior partially contrasts with the expected response of foliated granitic rocks. Granitic rocks commonly exhibit primary structural anisotropy associated with magmatic flow and the preferential crystallographic orientation of tabular minerals, favoring fracture propagation along planes of weakness during crushing. Previous studies have demonstrated that crushed igneous aggregates tend to develop more flaky and elongated particles when fragmentation occurs preferentially along mineral boundaries and aligned minerals (Strzalkowski et al., 2021; Duchnowska et al., 2023). However, the present results suggest that the compressive and abrasive mechanisms associated with cone crushing partially reduced the persistence of these anisotropic discontinuities in the final aggregate morphology.

For metamorphic materials, the results also indicate a significant influence of the crushing process on the final particle morphology, particularly in the VOG quarry, where a VSI crusher was employed during the quaternary crushing stage. Gneissic rocks commonly exhibit strong mineral orientation and mica-rich foliations, favoring preferential breakage along cleavage planes and consequently promoting the generation of elongated and flaky particles. Despite these intrinsic geological characteristics, the aggregates from the VOG quarry remained predominantly semicircular, suggesting that the impact-induced fragmentation mechanisms associated with VSI crushing promoted multidirectional

particle breakage and reduced the influence of the structural anisotropy inherited from the parent rock.

Previous studies have demonstrated that VSI crushers tend to produce more equidimensional particles due to their high-impact energy and more isotropic fragmentation mechanisms when compared with cone crushers (Rajan & Singh, 2017a; Duchnowska et al., 2023). The results obtained in the present study corroborate this interpretation, indicating that crushing technology plays a fundamental role in the final morphology of aggregates and may partially override the controls imposed by lithology and mineral fabric of the parent rock.

Table 2 presents the average 2D shape values for the different aggregate size fractions. In general, the variation among fractions and quarries is relatively small, except for the 1.18 mm fraction from the ELD quarry and the 0.60 mm fraction from the CONP quarry, which exhibited higher average values.

The observed differences in shape characteristics among particle sizes may be intrinsically related to the fragmentation mechanisms described by Qiu et al. (2025). Their numerical simulations suggest that the ratio between weak and strong bond breakage varies according to particle size, influencing both crushing strength and the resulting particle morphology. This size-dependent fragmentation behavior may explain why certain fractions in the present study exhibited distinct shape distributions, even when derived from the same parent rock and subjected to the same crushing process.

However, the FRAG and VOG quarries exhibited lower average values compared with the other quarries. Despite these variations, all aggregates were classified as semicircular based on their mean values. Additionally, the standard deviation values indicate low data dispersion, suggesting that the results are concentrated around the

Table 2. 2D Form parameters by quarry and particle size.

Quarry	Size (mm)	Number of particles	Mean	Standard Deviation
MIN	1.18	151	8.6	2.39
	0.60	151	8.86	2.28
	0.30	150	8.32	2.29
	0.15	151	8.20	2.51
CONP	1.18	150	8.81	2.15
	0.60	150	9.46	2.79
	0.30	151	8.49	2.16
	0.15	151	8.42	1.98
ELD	1.18	148	9.05	2.62
	0.60	151	8.62	2.30
	0.30	151	8.89	2.23
	0.15	148	8.39	2.71
FRAG	1.18	132	7.29	1.32
	0.60	137	7.22	1.46
	0.30	136	7.59	1.32
	0.15	135	6.89	1.32
VOG	1.18	138	7.96	1.53
	0.60	137	7.81	1.48
	0.30	137	7.93	1.69
	0.15	139	7.78	2.30

mean, as illustrated in Figure 4, except for the previously mentioned cases (CONP, 0.60 mm fraction, and ELD, 1.18 mm fraction). The compression and abrasion mechanisms associated with the CC and VSI crushers may have promoted particle polishing, resulting in fine aggregates with a more uniform morphological distribution.

Although 2D image analysis techniques such as *AIMS* provide valuable information regarding particle angularity and shape, three-dimensional approaches offer a more comprehensive morphological characterization. Gomes et al. (2022) demonstrated the application of 3D scanning to evaluate the “ellipsoidness ratio” of steel slag aggregates used as railway ballast, enabling high-precision acquisition of shape parameters before and after mechanical testing. This methodology allows for a more realistic assessment of particle degradation and morphological evolution under loading conditions, complementing the 2D classifications adopted in the present study.

The relative stability of particle shape observed in this study, with aggregates maintaining predominantly semicircular classifications across different fractions, is consistent with the findings reported by Gomes et al. (2022) for steel slag aggregates subjected to cyclic loading. These authors also observed that the particles did not exhibit a clear pattern of morphological evolution after triaxial testing, remaining predominantly cubic even after 250,000 load cycles. This suggests that, for mechanically competent materials processed using appropriate crushing systems, the initial shape characteristics may be largely preserved under mechanical loading, with degradation occurring primarily

through surface polishing and edge wear rather than substantial morphological alteration.

Figure 5 illustrates the angularity distribution of the different particle sizes and quarries analyzed in this study, as determined by the *AIMS* test. In general, a relatively similar angularity distribution was observed among the evaluated fractions and quarries. Most aggregates were classified as subrounded, followed by subangular particles, whereas rounded and angular particles occurred in lower proportions.

As particle size decreased (from 1.18 mm to 0.30 mm), the MIN and ELD quarries exhibited a similar trend, characterized by a reduction in the proportion of subrounded aggregates and an increase in the subangular classification in the 0.60 mm and 0.30 mm fractions. However, in the 0.15 mm fraction, the subrounded classification became predominant again. In contrast, the CONP and VOG quarries exhibited the opposite behavior for these same fractions. The FRAG quarry did not exhibit a clear trend, alternating between reductions in the proportion of subrounded particles accompanied by increases in subangular particles, and vice versa. It is also noteworthy that, in the 0.15 mm fraction, the ELD, FRAG, and VOG quarries presented aggregates classified as rounded.

Table 3 presents the statistical analysis of the mean values and standard deviations for angularity considering the different aggregate size fractions and quarries evaluated in this study. When only the mean values for each fraction are considered, part of the variability in the dataset may be masked, failing to adequately represent the distribution

patterns illustrated in Figure 5, which presents the cumulative percentage of aggregates according to fraction and angularity classification.

According to Table 3, the MIN quarry exhibited aggregates with relatively low average angularity values for both the coarsest (1.18 mm) and finest (0.15 mm) fractions, although this trend does not fully correspond to the distribution patterns observed in Figure 5. This behavior is further supported by the standard deviation values, which quantify the variability or dispersion of the dataset. High standard deviation values

indicate that the data points are distributed farther from the mean, suggesting substantial variability within the sample. In other words, the angularity values exhibit lower consistency and greater heterogeneity.

Typical angularity and 2D form ranges reported in the literature for aggregates produced from granitic, basaltic, and gneissic rocks using *AIMS* or similar image-based systems indicate that aggregates derived from basalt and granite generally exhibit higher angularity and lower sphericity than limestone aggregates, whereas VSI crushing

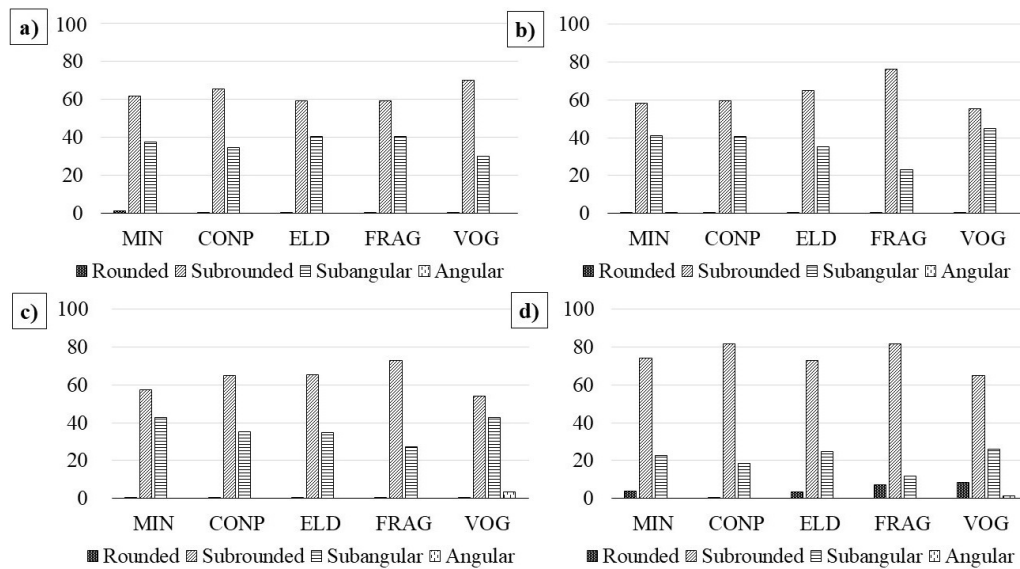


Figure 5. Angularity – *AIMS*: a) Size 1.18 mm; b) Size 0.60 mm; c) Size 0.30 mm; d) Size 0.15 mm.

Table 3. Angularity parameters by quarry and particle size.

Quarry	Size (mm)	Number of particles	mean	Standard Deviation
MIN	1.18	151	3855.18	945.02
	0.60	151	3904.50	1054.61
	0.30	150	3990.44	1014.10
	0.15	151	3230.78	1294.22
CONP	1.18	150	3844.97	988.33
	0.60	150	3928.15	985.50
	0.30	151	3729.68	898.42
	0.15	151	3279.32	931.64
ELD	1.18	148	3914.83	1036.19
	0.60	151	3792.43	997.03
	0.30	151	3765.92	1093.34
	0.15	148	3255.29	1266.39
FRAG	1.18	150	3284.51	842.74
	0.60	151	3510.91	886.16
	0.30	151	3633.16	1037.70
	0.15	151	2827.45	1043.70
VOG	1.18	150	3710.91	993.15
	0.60	150	3969.56	1032.49
	0.30	150	4140.56	1476.85
	0.15	151	3323.09	1527.19

tends to produce more equidimensional particles than cone crushers (Zhang et al., 2012; Rajan & Singh, 2017b; Wang et al., 2021; Xing et al., 2021). The values obtained in the present study are consistent with these previously reported ranges, suggesting that the crushing systems adopted in the investigated quarries were effective in reducing the expression of primary geological anisotropy in the final morphology of the fine aggregates.

This variability in angularity among different particle sizes may be explained by the findings of Qiu et al. (2025), who demonstrated through DEM simulations that the failure mode of particles subjected to compression transitions from brittle to ductile behavior as particle size decreases. Such transitions are expected to generate different angularity characteristics: brittle failure tends to produce sharper and more angular fragments, whereas ductile behavior results in more rounded particles through progressive wear and surface polishing. This mechanism is consistent with the observations of the present study, in which the 0.15 mm fractions from several quarries (ELD, FRAG, and VOG) contained aggregates classified as rounded.

The high standard deviation values observed in Table 3 (ranging from 842.74 to 1527.19) indicate substantial intra-sample variability in angularity. This suggests that, within a single size fraction from a given quarry, particles may exhibit a wide range of angularity characteristics, reinforcing the importance of analyzing distribution patterns (Figure 5) rather than relying exclusively on mean values.

Measurements of aggregate angularity and shape using *AIMS* and other 2D image analysis techniques frequently result in high standard deviation values, reflecting significant intra-sample variability. This variability is influenced by factors such as particle size, mineral size, mineral composition, crushing mechanism, and the inherent heterogeneity of the aggregates (Mahmoud et al., 2010; Rajan & Singh, 2017b; Altuki et al., 2022; Wu et al., 2022; Huang et al., 2023; Liu et al., 2025).

Several studies have demonstrated that even within a single size fraction from the same source, particles may exhibit a wide range of angularity characteristics (Altuki et al., 2022; Wu et al., 2022; Liu et al., 2025).

The literature also highlights that *AIMS* measurements are sensitive to sample handling, particle orientation, and operator-related factors, which may further contribute to data dispersion (Bathina, 2005; Masad et al., 2007; Mahmoud et al., 2010). Furthermore, the fragmentation process during crushing may generate both highly angular and more rounded particles within the same size fraction, particularly as particle size decreases (Rajan & Singh, 2017a; Wang et al., 2021; Huang et al., 2023). These findings support the interpretation that elevated standard deviation values represent the natural variability of aggregate morphology rather than methodological limitation.

2.6 FAA

The *FAA* test was conducted in the laboratory according to DNIT 415/2019 standards. Figure 6 shows the results obtained for Methods A and B. In Method A, the granulometric composition is performed with aggregates of the same sizes previously analyzed in *AIMS*. In Method B, the analysis was conducted separately for three different sizes (1.18 mm, 0.60 mm, and 0.30 mm), and the average is subsequently calculated.

In this test, it is observed that the MIN quarry exhibits higher *FAA* values than the other quarries when using Method A, indicating that its aggregates have greater angularity. However, when evaluating the values using Method B, which consists of a separate analysis of the fractions, it is noted that only for the 1.18 mm and 0.60 mm fractions do the aggregates from the MIN and VOG quarries present higher values compared to the other quarries. For the 0.30 mm fraction, the aggregates from the ELD quarry exhibit greater angularity. It is also observed that *FAA* increased as

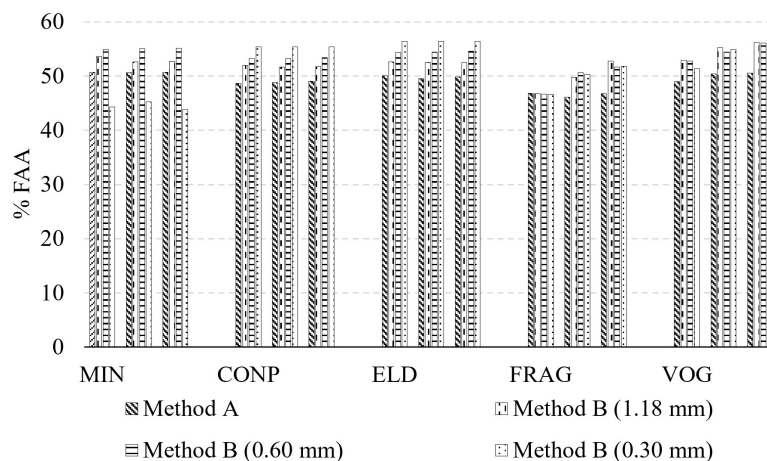


Figure 6. Angularity – *FAA*.

aggregate size decreased for the CONP and ELD quarries, but this trend was not observed in the other quarries.

Method B classified the aggregates in terms of angularity in a way that diverged from the *AIMS* results. In contrast, the comparison with the results obtained using Method A was more representative, indicating that the aggregates from the MIN quarry are the most angular, followed by those from ELD, and finally by those from CONP. Some inconsistencies in the measurement and distribution of angularity may be attributed to the indirect nature of the measurement and the greater subjectivity associated with the *FAA* test, a fact already highlighted in previous studies (Fernandes et al., 2000; Gouveia, 2002; Gouveia, 2006; Rodrigues, 2019; Ceccato, 2021).

2.7 *AIMS* vs *FAA*

The analysis of variance (ANOVA) test was performed to compare the angularity results obtained from the *FAA* and *AIMS* tests under two conditions: (i) considering the total means per quarry (Method A) and (ii) for each granulometric fraction (Method B). The ANOVA analysis revealed statistically significant differences ($p < 0.05$) between the *FAA* and *AIMS* test results for all evaluated conditions, including Method A ($p = 0.003428$) and Method B for the 1.18 mm ($p = 0.004437$), 0.60 mm ($p = 0.009442$), and 0.30 mm ($p = 0.003621$) fractions. These findings reinforce that, although both methods are used to evaluate aggregate angularity, they produce distinct results.

- Method A (total means per quarry): the observed differences reflect the distinct approaches of each method. *FAA* analyzes granulometric fractions collectively, which can capture interactions between particles of different sizes, affecting the perception of angularity. In contrast, *AIMS* performs a detailed analysis of each fraction, resulting in a more precise and specific evaluation of individual angularity.
- Method B (fractions analyzed separately): when fractions are evaluated individually, the significant differences between the methods suggest that *FAA*, due to its more indirect and subjective methodology, may introduce variations that are not captured by *AIMS*. This subjectivity of the *FAA* test has already been highlighted in previous studies (Huber et al., 1998; Fernandes et al., 2000; Gouveia, 2002, 2006; Rodrigues, 2019; Ceccato, 2021).

The results highlight that, although both methods assess aggregate angularity, they have distinct approaches and limitations, leading to significant discrepancies. This reinforces the need for comprehensive characterization protocols, as advocated by Collares et al. (2012), who employed a battery of complementary tests—including shape index, water absorption, Los Angeles abrasion, and alkali-aggregate reactivity—to fully assess the suitability of quartzite waste for construction applications. The present study

similarly demonstrates that relying on a single angularity measurement method may provide an incomplete picture of aggregate behavior.

This underscores the need to consider the specific characteristics of each method when interpreting results. Additionally, the data suggests the importance of adopting complementary approaches or establishing more rigorous standardization to ensure consistent and comparable evaluations of aggregate angularity.

From an engineering perspective, the results demonstrate that aggregate morphology cannot be interpreted exclusively as an intrinsic property of the parent rock, since crushing technology plays a major role in modifying particle shape and angularity. This finding is particularly relevant for pavement engineering, where aggregate morphology directly affects interparticle friction, compaction, rutting resistance, workability, and asphalt binder demand.

The results indicate that cone crushers (CC) and especially VSI crushers are capable of producing fine aggregates with more homogeneous and predominantly semicircular morphologies, even when the parent rocks exhibit strong geological anisotropy, such as magmatic foliation or gneissic banding. This suggests that appropriate crushing strategies can improve aggregate quality and potentially reduce the negative effects commonly associated with elongated or flaky particles in asphalt mixtures and concrete applications.

In addition, the significant discrepancies observed between *FAA* and *AIMS* highlight the importance of selecting suitable characterization methods for quality control. Since *FAA* is an indirect method influenced by particle packing and density effects, it may not fully represent the real angularity and shape distribution of fine aggregates. In contrast, *AIMS* allows a more detailed morphological characterization, making it a potentially more reliable tool for aggregate selection and optimization in civil engineering applications.

3. Conclusion

This study evaluated the influence of lithology and crushing process on the morphology of fine aggregates using *FAA* and *AIMS* methods. The results demonstrated that geological features such as magmatic foliation, mineral orientation, gneissic banding, and cleavage planes influence the expected fragmentation behavior of rocks and the resulting aggregate morphology.

However, the crushing systems, particularly cone crushers (CC) and vertical shaft impact crushers (VSI), were capable of partially mitigating these geological effects, producing predominantly semicircular and subrounded fine aggregates even for rocks with pronounced structural anisotropy. Among the investigated crushing systems, the VSI crusher showed greater potential for improving aggregate cubicity and reducing irregular particle shapes.

The study also demonstrated statistically significant differences between *FAA* and *AIMS* results, confirming

that the indirect nature of *FAA* may lead to angularity interpretations that differ from those obtained through digital image analysis. These findings reinforce the importance of combining geological characterization, crushing technology selection, and advanced image-based methods for a more reliable evaluation of aggregate morphology.

From an engineering perspective, the results highlight that aggregate shape properties are controlled not only by lithology, but also by the crushing strategy adopted during production. Therefore, the appropriate selection of crushing systems and morphological characterization methods is essential for improving aggregate quality and optimizing the performance of construction materials used in pavements and other civil engineering applications.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Haline Dugolin Ceccato: Conceptualization, Investigation, Methodology, Data curation, Visualization, Writing – original draft. Rinaldo José Barbosa Pinheiro: Conceptualization, Data curation, Supervision, Validation, Writing – review & editing. Andréa Valli Nummer: Formal Analysis, Supervision, Validation, Writing – review & editing. César Millan Carraro: Analysis, Validation, Writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

i i-th	edge point of the particle
n	number of points

<i>AIMS</i>	Aggregate Imaging Measurement System
CC	Cone crushers
DIP	Digital Image Processing
DNIT	Departamento Nacional de Infraestrutura de Transportes
ELD	Eldorado
<i>FAA</i>	Fine Aggregate Angularity
FRAG	Fragosos
JC	Jaw crushers
<i>Ma</i>	Mass of the aggregate contained in the cylinder
PUC	Pontifícia Universidade Católica de Minas Gerais
RS	Rio Grande do Sul
R_θ	Radius of the particle
U	Uncompacted voids
V_c	Volume of the cylinder
VOG	Vogelsanger
VSI	Vertical shaft impact crushers
Δ_θ	angular increment difference
θ	orientation angle of the edge points
ρ_{ap}	bulk density of the fine aggregate

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