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FormaG: mobile application for measurement of 2D shape of coarse aggregates using digital image processing

FormaG: aplicativo móvel para medição da forma 2D de agregados graúdos utilizando processamento digital de imagens

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ABSTRACT

This paper presents FormaG, a mobile application designed to measure two-dimensional form and angularity indices of coarse aggregates using digital image processing. The tool advances a previous prototype, moving from Technology Readiness Level (TRL) 4 to TRL 8 and becoming a robust, validated, and ready-to-use system. Improvements include enhanced particle detection through the CIE LAB color space and the use of Principal Component Analysis for efficient computation of the elongation index. Sensitivity and reproducibility tests were performed with different aggregate types, using multiple mobile devices operated by four users, to assess reliability under diverse capture conditions. The results demonstrate high sensitivity to real variations in morphological indices and consistent reproducibility. Available on Google Play Store, FormaG provides a practical and accessible solution for scientific studies, quality control of construction materials, field inspections, and large-scale data acquisition for Data Science applications in civil and heavy construction engineering.

RESUMO

Este artigo apresenta o FormaG, um aplicativo móvel desenvolvido para medir índices bidimensionais de forma e angularidade de agregados graúdos utilizando processamento digital de imagens. A ferramenta representa uma evolução de um protótipo anterior, avançando do Nível de Maturidade Tecnológica (Technology Readiness Level — TRL) 4 para o TRL 8, tornando-se um sistema robusto, validado e pronto para uso. As melhorias implementadas incluem o aprimoramento da detecção de partículas por meio do espaço de cores CIE LAB e o uso da Análise de Componentes Principais (Principal Component Analysis — PCA) para o cálculo eficiente do índice de alongamento. Testes de sensibilidade e reprodutibilidade foram realizados com diferentes tipos de agregados, utilizando múltiplos dispositivos móveis operados por quatro usuários, com o objetivo de avaliar a confiabilidade do sistema sob diversas condições de captura de imagens. Os resultados demonstram elevada sensibilidade às variações reais dos índices morfológicos e reprodutibilidade consistente das medições. Disponível na Google Play Store, o FormaG oferece uma solução prática e acessível para estudos científicos, controle de qualidade de materiais de construção, inspeções de campo e aquisição de dados em larga escala para aplicações de Ciência de Dados nas construções civil e pesada.

1. Introduction

Permanent deformation and fatigue cracking are among the main deterioration mechanisms in asphalt mixtures and are therefore widely investigated in the literature (Bastos, Babadopulos & Soares, 2017; Ferreira, Soares & Bastos, 2016; Ferreira *et al.*, 2020; Silva *et al.*, 2024). Based on the analysis of 99 asphalt mixtures in the laboratory, Gomes, Soares & Bastos (2019) identified aggregate characteristics as key factors in resistance to permanent deformation (Figure 1). However, in the case of polymer-modified binders, the binder itself is likely to play the major role in preventing the defect (Gomes, Soares & Bastos, 2020), and despite aggregate gradation, it often provides the mixture with sufficient resistance capacity.

Obtaining a stable aggregate skeleton with good interlocking requires not only a proper aggregate gradation (Stakston & Bahia, 2003), but also the selection of particles with appropriate morphological

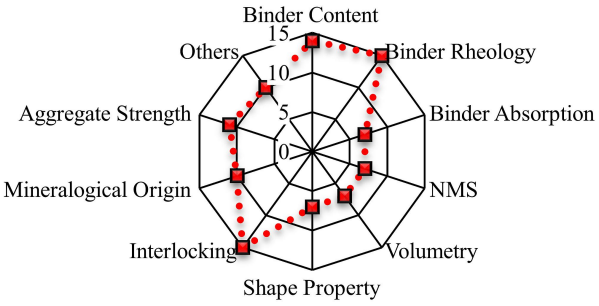

Figure 1 • Possible contribution to Permanent Deformation Resistance (Gomes, Soares & Bastos, 2019).

parameters (Bessa *et al.*, 2015). Recently, Chen *et al.* (2023) demonstrated that aggregate shape significantly influences the mechanical stability and workability of asphalt mixtures, as well as the thickness of the binder film coating the aggregate particles following the homogenization process.

The influence of aggregate shape extends beyond asphalt mixtures and has been reported in several other civil and heavy construction studies. One example is railway ballast (heavy construction), for which Orosz, Farkas & Tamás (2023) investigated the mechanical behavior of ballast assemblies composed of three different aggregate-shape configurations: exclusively cubic particles, exclusively flat/elongated/bladed particles, and a mixture of both. The authors observed that ballast composed of a mixture of particle shapes exhibited higher shear resistance. In civil construction, for example, aggregate shape also influences the properties of permeable concrete. Pimentel *et al.* (2024) showed that the use of more polished, angular, and spherical aggregates results in concrete with higher flexural strength and lower permeability coefficients.

In Brazil, the characterization of coarse aggregate shape can be carried out using standardized methods such as circular and reducer sieves (DNIT, 2020b), calipers (DNIT, 2020c), and digital image processing (DIP). The latter can be performed using the AIMS (Aggregate Image Measurement System) device, which quantifies sphericity, angularity, and texture for coarse aggregates, as well as 2D form and angularity for fine aggregates, which is standardized in Brazil by DNIT ME 432 (DNIT, 2020a) and documented in the United States of America by the Federal Highway Administration (FHWA).

Despite its technical and scientific potential, explored in several studies (Bessa *et al.*, 2015; Diógenes *et al.*, 2021; Ibiapina *et al.*, 2020; Lucas Jr., Babadopulos & Soares, 2020), the AIMS device is not widely available in countries such as Brazil and many others (Ibiapina *et al.*, 2020). In an attempt to produce data similar to AIMS with low-cost equipment, a prototype Android application (referred to here as FormaG-pilot) was developed in 2021 to determine the 2D form and angularity indices of coarse aggregates, proposing a fast and accessible alternative for morphological characterization (Gomes, 2021).

The FormaG-pilot presents limitations, such as difficulties in recognizing particles in environments with heterogeneous lighting (which is common in laboratories) and a high computational cost for form calculation. Part of the processing involves exhaustively computing the Euclidean distances between all contour points of a grain, a process repeated for each particle in the image. Despite this, the application is currently at the so-called level 4 of the Technology Readiness Level (TRL): functional validation of components in a laboratory environment (Mankins, 2004; MCTI, 2022), since the mobile application (App) has only been validated under controlled conditions.

This paper presents FormaG, an enhanced version of the App designed for the 2D morphological characterization of coarse aggregates through DIP. Its name combines “Forma” (Portuguese for “shape”), referring to the morphological indices analyzed, with “G”, representing *graúdo* (Portuguese for “coarse”), thereby emphasizing its application to coarse aggregates. The aim of the paper is to propose a practical, functional, and validated tool, advancing to TRL 8 (qualified and completed system), designed to be robust, reliable, and ready for use in measuring particle 2D form and angularity, with the following specific objectives: (*i*) to investigate optimization methods for particle recognition and segmentation, as well as efficient computational strategies for calculating form; (*ii*) to assess the sensitivity of mobile devices (smartphones) in detecting morphological differences between aggregates with distinct shape

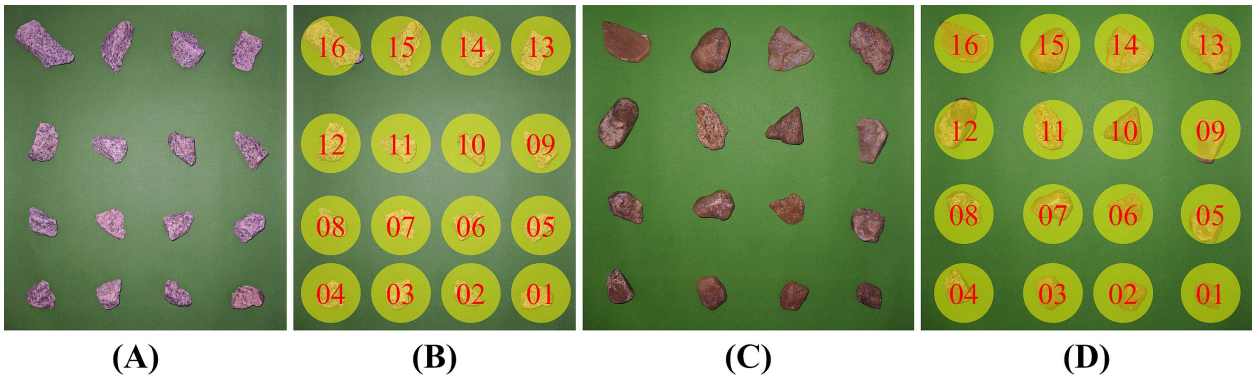

Figure 2 • Aggregate images used in the development of FormaG-pilot. (A) Crushed aggregates on a green background (2869 × 3299 pixels). (B) Numbered crushed aggregates. (C) River pebbles on a green background (2710 × 2656 pixels). (D) Numbered river pebbles.

characteristics; and (*iii*) to analyze the reproducibility of parameters obtained from images captured by different mobile devices, testing the tool's reliability under different usage conditions.

2. Methodology

For this study, images of crushed aggregates and river pebbles from Morada Nova, Ceará, Brazil (Figure 2) were used to compare the processing time between FormaG, FormaG-pilot and the AIMS average time. The images were also employed to evaluate the sensitivity of FormaG regarding 2D form and angularity (detailed in section 2.2), as they include both crushed aggregates (higher angularity) and river pebbles (lower angularity).

For a reproducibility assessment, a sample of 50 phonolitic aggregate particles from a quarry in the municipality of Eusébio (also from Ceará state) was used. The aggregates had a gradation between retained on 4.75 mm and passing on the 9.5 mm sieve. They were arranged on a table with a green background, and four volunteers photographed the sample using different smartphones (with and without the device's lighting system – flash), aiming to keep the device as parallel as possible to the table surface. The smartphones used were a Samsung Galaxy S20 FE, a Samsung Galaxy S23, a Xiaomi Redmi Note 14 and a Motorola Moto G05.

2.1. Android platform and algorithm

For the development of the application, Android Studio was used as the Integrated Development Environment (IDE). The algorithm was implemented using Java – utilizing the Android Software Development Kit (SDK) – and XML (Extensible Markup Language), resulting in an application compatible exclusively with the Android operating system. For digital image processing (DIP), the OpenCV (Open Source ComputerVision Library) API was employed to perform optimized image processing. Additionally, the Native Development Kit (NDK) was required to enable coding in C/C++, which are included in the OpenCV API.

The following processing logic was implemented to obtain the contours of the aggregates:

(*i*) after selecting an image from the smartphone's gallery, it is converted to the LAB color space (L: lightness channel; A: channel ranging from green to red; B: channel ranging from blue to yellow);
(*ii*) based on either the A or B channel (depending on the background color – as a chroma key – on which the aggregates are placed: green or blue), the image is binarized to highlight the particles;
(*iii*) with the black-and-white image, a morphological opening followed by closing is applied to remove noise from segmentation;
(*iv*) the contours of the aggregates are then obtained and numbered using OpenCV's findContours function;
(*v*) finally, inspired by Masad *et al.* (2001), who used images with a resolution of 80 pixels/mm and particles of approximately 1.5 mm diameter to measure 2D form and angularity, a criterion was

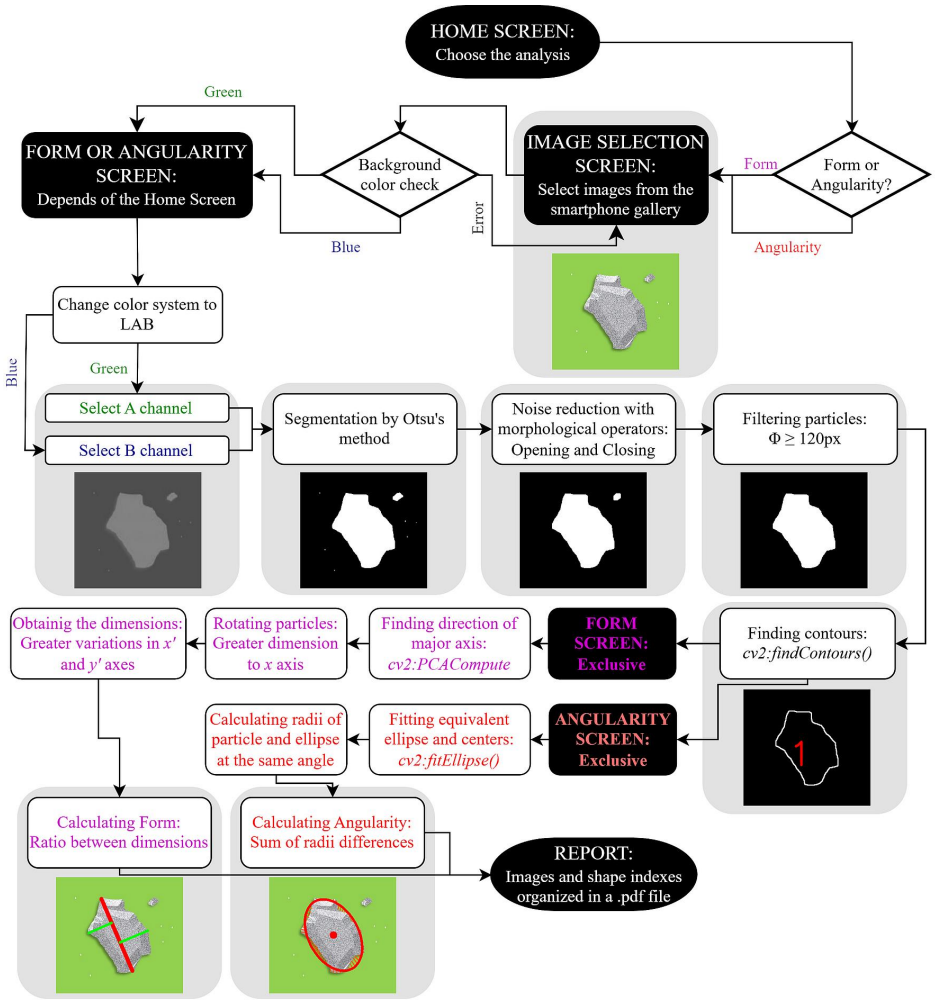

Figure 3 • Flowchart of FormaG and its algorithm.

added to exclude from processing particles with a circumscribed diameter (obtained with OpenCV's minEnclosingCircle function) smaller than 120 pixels.

Once the contours are obtained, FormaG proceeds with two distinct processing approaches:

- **Form**: The length (L) is calculated as the greatest distance between pixels along the particle's contour, and the width (W) as the greatest perpendicular distance. Principal Component Analysis (PCA) is used to identify the direction of maximum variation in the plane (with xy coordinates), which is assumed to be the particle's principal axis. The contour is then rotated to align with this axis (new x'y' coordinates), and L and W are obtained from the differences between the extremes of the x' and y' coordinates, respectively. The 2D form is given by the ratio L/W, representing the degree of elongation of the particle in the 2D image.
- **Angularity**: The radii of the particle contour (R_θ) and of an ellipse equivalent to the contour (R_{EE_θ}) are calculated at the same angular positions (θ), with θ increasing in 5° increments. Thus, angularity is expressed by the index in Equation 1 (Masad *et al.*, 2001):

$$\text{Angularity} = \sum_{\theta=0}^{355} \frac{\left|R_\theta - R_{EE_\theta}\right|}{R_{EE_\theta}} \quad (1)$$

The equivalent ellipse is fitted using the fitEllipse function from the OpenCV library. In the paper, Masad *et al.* (2001) observed angularity values between 1 and 14 for the fine aggregate particles analyzed. Higher values obtained from Equation 1 indicate greater particle angularity.

Figure 3 shows a flowchart summarizing the FormaG application and the operation of its algorithm.

2.2. Sensitivity analysis regarding shape indices

From Figure 2, it is apparent that some particles are more elongated than others, and it is generally known that river pebbles are less angular than crushed aggregates. It was tested whether FormaG could capture these differences, with the expectation that the form index would align with visual analysis and that the angularity would show higher values for the crushed aggregates than for the river pebbles.

Specifically for angularity, representations of aggregates were created using regular polygons (Figure 4) to validate the robustness of the algorithm. The angularity of an aggregate defines how rounded the particle is (Masad & Button, 2000), providing a measure of the aggregate's corners, which can also be interpreted as how sharp the corners are. The greater the number of sides of the polygon, the larger the internal angles at the vertices, the more rounded the geometry, and consequently, the lower the angularity.

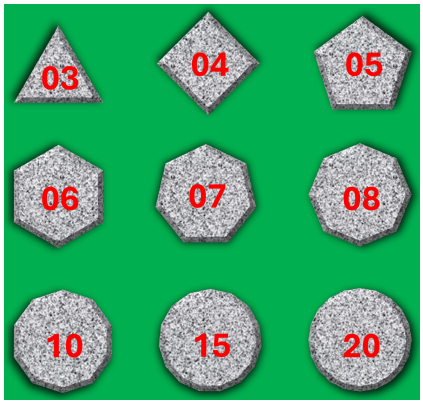

Figure 4 • Regular polygons with identified number of sides.

2.3. Reproducibility analysis

Figure 5 shows the eight images used to evaluate the reproducibility of the aggregate shape indices calculations, as previously mentioned. FormaG processed the images to obtain the form and angularity indices. The reproducibility analysis was performed using a hypothesis test, where, at a 5% significance level, it was assessed whether all results could be considered equal (null hypothesis) or if at least one result was truly different from the others (alternative hypothesis).

One alternative for performing the hypothesis test is through analysis of variance (ANOVA), provided that the assumptions of observation independence, residual normality and homoscedasticity are met. If these assumptions are not satisfied, another option is to verify whether the non-parametric Kruskal-Wallis test can be applied, considering its assumptions of data independence, ordinal or continuous data, and similarity in the shape of distributions. All statistical analyses were performed using the Python programming language, with the aid of the SciPy and Statsmodels libraries for statistical analysis.

3. Results and discussion

Figure 6 shows the screens of the FormaG Android application. The screen in Figure 6a allows the user to select which index will be measured, and also includes options to access the: User Manual, which provides instructions on how to use FormaG; About FormaG, which displays information on how the indices are calculated (including the equations); and Send Feedback, allowing users to provide feedback on FormaG to the developers.

The Image Selection screen (Figure 6b) follows the Home screen, where the user can access the smartphone's gallery and select up to four photos to be processed. The 2D Form and Angularity screens (Figure 6c and 6d, respectively) appear last in the navigation sequence. Based on the processing choice made on the Home screen, the user can obtain the measured results for form and angularity for each particle in the selected image(s).

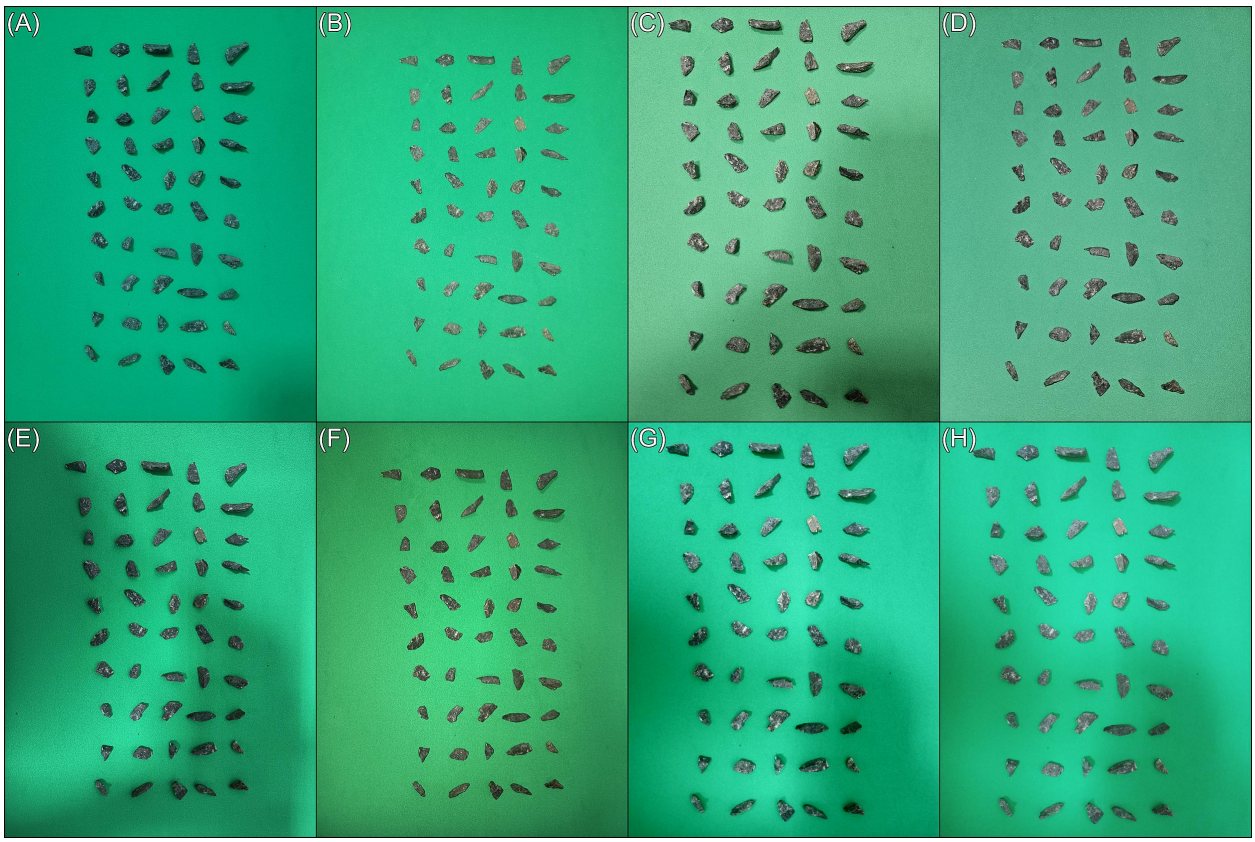

Figure 5 • Aggregate images photographed by different volunteers using different smartphones, with and without flashlight. (A) S20 FE. (B) S20 FE – flashlight. (C) S23. (D) S23 – flashlight. (E) Note 14. (F) Note 14 – flashlight. (G) G05. (H) G05 – flashlight.

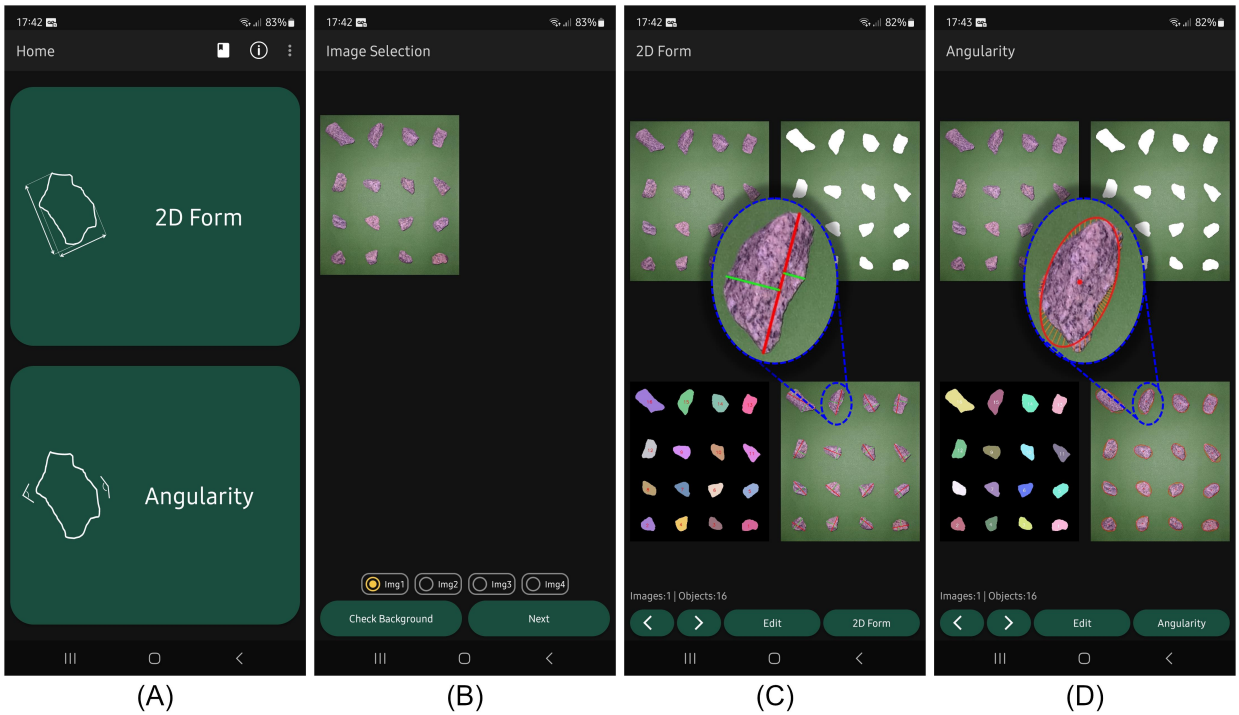

Figure 6 • FormaG's screens: (A) Home; (B) Images selection; (C) Form Analysis of Figure 2a; (D) Angularity Analysis of Figure 2a.

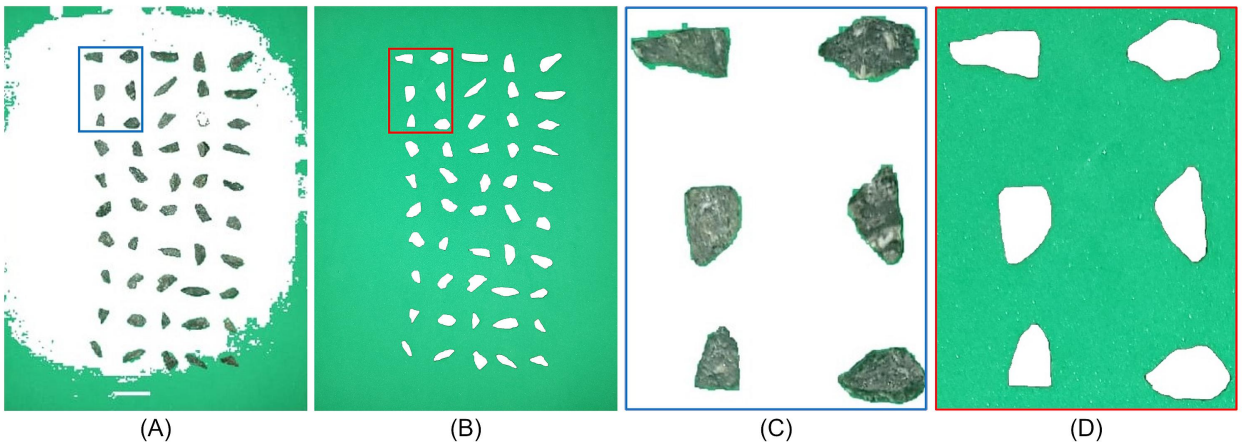

Figure 7 • Figure 5b segmented by different Apps. (A) Segmentation in FormaG-pilot. (B) Segmentation in FormaG. (C) Particles from the upper left corner of Figure 7a. (D) Particles from the upper left corner of Figure 7b.

Figures 6c and 6d also highlight particle 15 (from Figure 2b), which has already been processed, shown here solely to display the visual results of the 2D shape indices. In Figure 6c, the red line represents the particle's maximum length, and the green lines combined indicate its width. In Figure 6d, the fitted equivalent ellipse is shown in red, and the radius segments ($R_\theta - R_{EE_\theta}$) at every 5 degrees are displayed in orange.

3.1. Advances in digital image processing algorithms

FormaG-pilot uses segmentation in the RGB color space to distinguish the background (green or blue), requiring a combined analysis of all three channels. In contrast, FormaG employs the LAB color space, which allows the background to be isolated in a single channel and directly segmented using Otsu's method (Otsu, 1979). As shown in Figure 7, FormaG successfully segmented the green background, whereas FormaG-pilot failed to detect the particles in Figure 5b. The images in Figure 5 were captured in a common area, without controlled lighting and by untrained individuals, which allows FormaG to be classified here at TRL 8 (System qualified and completed) (MCTI, 2022).

Regarding computational cost, when processing the 2D form index on a Samsung Galaxy S20 FE smartphone with both FormaG and FormaG-pilot for a duplicate of the images in Figure 2 (the Apps can process up to four images at once), FormaG took about 1.5 s, while FormaG-pilot took 3.5 s, demonstrating that the PCA technique significantly reduces processing time. Although faster, PCA may present slight differences in the length value, which is extracted with greater accuracy by FormaG-pilot. Pazos (2015) estimated that the AIMS system requires about 15 minutes to process the form index of an aggregate sample, as it captures images particle by particle. This demonstrates that FormaG is more practical and faster.

3.2. Sensitivity analysis results

In terms of sensitivity, FormaG showed consistency in the 2D shape indices obtained from smartphone images. Table 1 presents the morphological indices calculated by the App. For particles 3 and 16 of the crushed aggregates (Figure 2a), the estimated values were 1.09 and 1.92, respectively, showing an expected difference since particle 16 is visually more elongated than particle 3. Regarding angularity, FormaG yielded an average of 6.20 for crushed aggregates and 5.23 for pebbles, indicating that, on average, crushed aggregates are more angular than river pebbles, which is consistent with the literature (Aragão *et al.*, 2016).

When Masad *et al.* (2001) proposed the angularity index, they obtained values ranging from 1 to 14 for the 22 aggregates analyzed. This range is similar to the angularity of the regular polygons measured in this study with FormaG (see Table 2), where the relationship between the number of sides (#Sides) and the angularity index follows a power-law curve and is inversely proportional (see Figure 8).

Table 1 • 2D Form and Angularity of the Aggregates in Figure 2 Measured by FormaG.

	Crushed aggregate		Pebble aggregate	
Particle	Form	Angularity	Form	Angularity
1	1.43	5.01	1.35	2.68
2	1.22	6.51	1.23	3.45
3	1.09	6.48	1.23	3.08
4	1.64	5.43	1.37	5.42
5	1.45	4.12	1.16	3.18
6	1.29	7.35	1.19	7.01
7	1.45	8.61	1.37	6.50
8	1.62	4.79	1.56	3.63
9	1.75	8.59	1.42	7.62
10	1.55	6.29	1.30	12.31
11	1.38	6.46	1.58	4.98
12	1.63	6.19	1.72	3.23
13	1.45	5.40	1.54	4.30
14	1.40	3.34	1.09	8.01
15	1.92	6.38	1.39	3.04
16	1.92	8.24	1.64	5.23
Mean	1.51	6.20	1.38	5.23
Std dev	0.23	1.52	0.18	2.57

Table 2 • Results of angularity for the polygons in Figure 4.

#Sides	Angularity
3	15.91
4	7.23
5	4.09
6	2.72
7	1.98
8	1.47
10	0.86
15	0.42
20	0.33

Since there is still no classification system adapted for the shape indices obtained by the FormaG method – such as those developed by Al-Rousan *et al.* (2005) and Ibiapina *et al.* (2018) for AIMS equipment and aggregates from the United States of America and Brazil, respectively –, a comparison with regular polygons serves as a metric to quantify the level of roundness of the particles. Additionally, regular shapes can be used as inspiration to produce two-dimensional computational models of aggregates used in simulations of composite materials such as asphalt mixtures (Almeida *et al.*, 2019) or railway ballast (Torquato e Silva *et al.*, 2024), allowing a better representation of the angularity of real aggregates in computational models.

Although some river pebbles exhibited higher angularity than crushed particles, the angularity algorithm applied to the regular polygons in Figure 4 reinforces the consistency of the results, i.e., the greater the number of sides of a regular polygon, the lower its angularity (Figure 8). Observing river pebble no. 10 (the particle with the highest angularity among all samples), it can be noted that its geometry resembles a triangle and that its angularity is indeed close to that of the polygon with the highest calculated angularity index (12.31 for the pebble and 15.91 for the triangle).

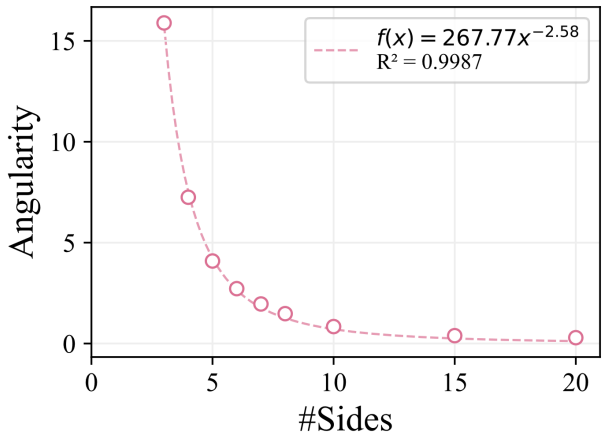

Figure 8 • Dispersion and tendency: Angularity *vs.* #Sides of the polygons in Figure 4.

3.3. Reproducibility analysis results

Figure 9 presents the histograms of the 2D shape indices, as well as the corresponding means and Coefficients of Variation (CV) for 50 phonolitic particles photographed by four different people, with and without the use of the smartphone flashlight. From these results, it can be observed that the aggregate in Figure 5 is more elongated compared to the aggregates in Figure 2 and has an average angularity similar to that of the aggregates in Figure 2a (crushed).

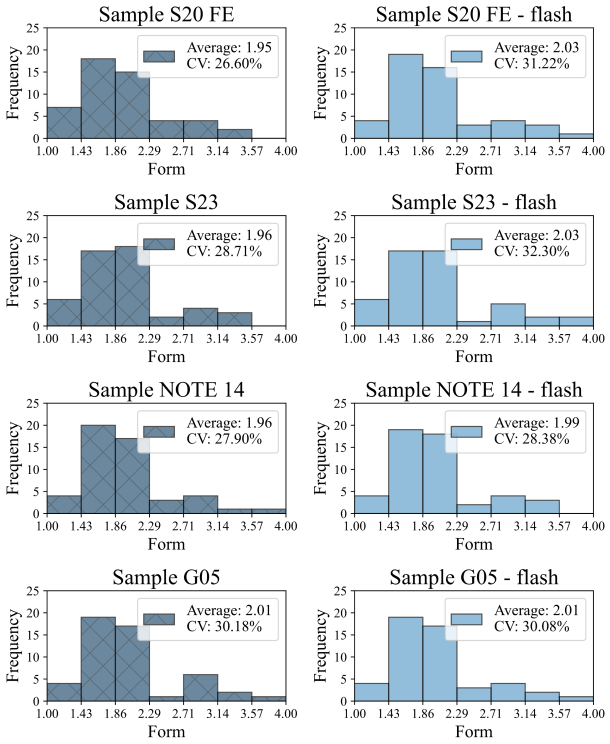

Figure 9 • Histograms of Form data calculated by FormaG.

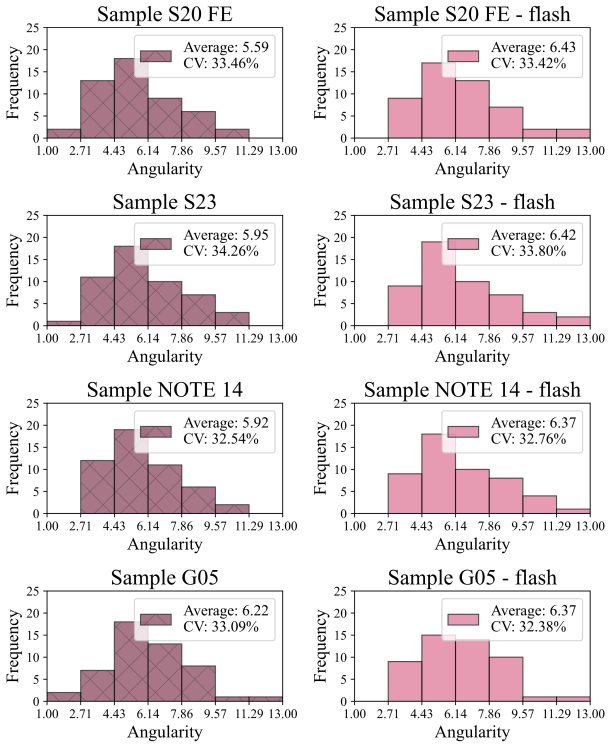

Figure 10 • Histograms of Angularity data calculated by FormaG.

In the comparative test to evaluate the reproducibility of 2D form, it was found that the residuals of the Ordinary Least Squares (OLS) model did not follow a normal distribution (Shapiro-Wilk: p-value < 0.01). Therefore, the nonparametric Kruskal-Wallis test was adopted, with its assumptions met (independence, continuity, and visually similar distributions with right skewness). The test result (p-value ≈ 0.999) indicated no significant differences among the samples.

Reproducibility was also evaluated for angularity, with the histograms shown in Figure 10. Similarly to form, ANOVA was discarded due to non-normality of the residuals (Shapiro-Wilk: p-value < 0.01). In this case, the Kruskal-Wallis test yielded a p-value ≈ 0.33, indicating no significant differences among the samples.

Although no statistically significant differences were detected, Figures 9 and 10 reveal a consistent tendency for images acquired with the smartphone flashlight to yield slightly higher form and angularity values. This behavior is likely associated with the reduction of shadows around particle boundaries, allowing FormaG to detect contours more accurately.

The effect was most evident for the Samsung S20 FE images (Figures 5a and 5b), whereas the Motorola G05 images (Figures 5g and 5h) showed virtually no change. Although the flashlight generally increased the coefficient of variation for form, these variations remained small and were insufficient to produce statistically significant differences, as confirmed by the Kruskal-Wallis tests.

Although the results indicate high reproducibility, it is important to note that the analysis was conducted by comparing sample distributions rather than individual particles. The FormaG algorithm

does not maintain the same particle identification order when processing different images, which hinders particle-level analyses that could provide a more detailed assessment of reproducibility.

4. Conclusions

FormaG is a ready-to-use application available on the Google Play Store, developed to efficiently quantify the 2D form and angularity indices of coarse aggregate particles used in civil construction and heavy infrastructure. The results demonstrated that FormaG meets the three proposed objectives: (*i*) it incorporates optimized segmentation and geometric calculation methods, reducing computational cost and ensuring functionality in environments with uncontrolled lighting; (*ii*) it presents adequate sensitivity to detect morphological variations among different types of aggregates; and (*iii*) it maintains good reproducibility of results even when operated by different users and mobile devices, provided usage guidelines are followed. By fulfilling these objectives, FormaG can be classified as TRL 8 (System qualified and finalized), meaning it can be used by anyone with access to an Android smartphone.

In addition to providing fast processing and effective segmentation under common lighting conditions, the application stands out for its usability and accessibility. Due to its ability to generate reliable data quickly and efficiently, FormaG proves to be a promising tool not only for supporting construction quality control, inspection, monitoring, and education, but also for advancing research in aggregate morphological characterization and data science applications in civil construction and heavy infrastructure, paving the way for future investigations.

Finally, as suggestions for future work, this paper encourages the widespread use of FormaG to build a significant database that may support the development of an appropriate classification system for aggregate shape indices evaluated through this new, accessible, and low-cost tool. Furthermore, a particle-level analysis is recommended to assess how image acquisition differences affect the measurements of individual particles.

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CRediT authorship contribution statement

Otávio José de Freitas Gomes: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing. *Juceline Batista dos Santos Bastos*: Conceptualization, Supervision, Investigation, Methodology, Project administration, Funding acquisition, Writing – review & editing. *Jorge Barbosa Soares*: Conceptualization, Investigation, Supervision, Writing – review & editing.

Use of artificial intelligence-assisted technology

ChatGPT (OpenAI) was used as an auxiliary resource during the revision stage for proofreading and correcting spelling errors in the manuscript. The authors reviewed the outputs generated by this AI tool and take full responsibility for any material resulting from its use.

Competing interests statement

No competing interests have been declared with regard to this paper or its contents.

Data availability statement

All data generated or analyzed during this study are included in this published article.

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