Enhanced Imaging Analysis of Aggregates for Roads and Railways Applications

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ABSTRACT

The South African pavement community has shown a keen interest in the use of imaging techniques to characterize the morphological characteristics of aggregates used in road and railway construction. This interest arises from the need to overcome the limitations of traditional methods currently employed to quantify the shapes of these materials. Recent advancements and the use of enhanced aggregate imaging techniques for quantifying the shapes of crushed stone and ferro slag materials from 10 sources across the country are presented in this paper. A wide range of railway track ballast and road aggregates were selected from various quarries and sources across different provinces for this study. As part of this research, an improved protocol was developed to standardize imaging acquisition and ensure the repeatability of shape property measurements, thereby providing meaningful results and facilitating data analysis. The imaging analysis conducted in this study, which involved close to 2,000 aggregate particles, revealed valuable insights into angularity, surface texture, and flat and elongated ratio properties of coarse aggregates. Preliminary specification limits for these shape properties have been established. This contribution represents an initial step towards supporting the South African road and railway industry in adopting advanced techniques for the selection of aggregate materials.

Keywords: Aggregate, Imaging, Angularity, Surface Texture, Flat & Elongated Ratio

INTRODUCTION

There is a general interest in South Africa to explore the use of modern and advanced imaging techniques to characterize the shape properties of aggregates utilized in roads and railways. These techniques are being considered as replacements for current empirical methods, which are known to have significant limitations, thus failing to provide results that can be confidently utilized in the design and construction of road and railway infrastructure (*1*). In the United States, imaging technology has garnered support from state departments of transportation, research institutions, industry, and academia. It has been actively promoted by esteemed bodies such as the Transportation Research Board (TRB), the International Centre of Aggregates Research (ICAR), and the National Stone, Sand and Gravel Association (NSSGA).

Recently, three prominent organizations in South Africa, namely the Council for Scientific and Industrial Research (CSIR), Tshwane University of Technology (TUT), and Transnet Freight Rail (TFR), have embarked on an exploration of an innovative three-dimensional (3D) laser scanning system. This system aims to determine the shape and surface properties of aggregates and ballast materials, while also evaluating their impact on the performance of roads and railways. The fundamental influence of aggregate and ballast shape characteristics on the performance of these infrastructures has been substantiated, leading to significant proposals for improvements in the current specifications regarding the characterization of shape properties of aggregates used in roads and railways (*2–5*). Moreover, efforts are underway to develop imaging techniques and algorithms that hold promise for various potential applications in other engineering disciplines, such as coastal and hydro-engineering, particularly in determining the shapes of riprap.

The CSIR, in collaboration with the University of Pretoria in South Africa, supported by the South African National Road Agency Limited (SANRAL), is currently in the process of upgrading its advanced materials testing laboratory for road and track ballast modelling. As part of this initiative, the aggregate laboratory is undergoing modernization using imaging and advanced numerical techniques. In line with this development, an aggregate imaging analyzer has been procured to complement the ongoing work conducted with 3D laser scanning devices. This analyzer aims to quantify individual particle characteristics such as surface area, volume, angularity, surface texture, flatness, and elongation. One of the key advantages of utilizing an aggregate imaging analyzer is its ability to expedite particle scanning (imaging acquisition) and computations, particularly when obtaining the shape properties of larger ballast/aggregate particles. Moreover, the acquisition of this equipment further strengthens the international collaboration between researchers in South Africa and the USA.

This paper presents a recent study conducted in March 2023, aimed at upgrading an advanced aggregate imaging system obtained from the University of Illinois. The purpose was to enhance its capabilities for research and development activities in aggregate imaging characterization within South Africa. The objective was to utilise the imaging system to establish the morphological characteristics, including angularity, surface texture, flatness, and elongation ratio, of aggregate materials sourced from 10 locations across five of the nine provinces in the country. These aggregates, including crushed stones and ferro slags, are commonly used in road and railway construction projects throughout South Africa. A total of six ballast stones and four road aggregates were examined. These materials were deliberately selected to reflect the diverse mineralogical properties typically found in crushed stones available in the country. Images of 1,929 ballast particles were captured and analysed using an Enhanced University of Illinois Image Analyzer (E-UIAIA) system. A specific protocol was developed for the acquisition of aggregate imaging data.

BACKGROUND

Aggregates for Roads and Railways Construction in South Africa

Materials used in the construction industry in South Africa range from some of the oldest rocks on earth (more than 3.6 billion years) to sands that have developed in the past 10 or 20 000 years. A study conducted by the Department of Mineral Resources of South Africa (*6*) indicated that the primary applications of sand and aggregate utilization in the country are mortar, plaster, and screed (40%); concrete products (30%); road bases and surfacing layers (25%), and others, mainly ballast (5%).

Rock aggregates may be of igneous, sedimentary, or metamorphic origin. The way these rocks are formed through different processes, the mineralogical composition of the constituents, and the tectonic history each rock formation had seen in a geological time scale, collectively play a role in the internal structure as well as secondary features such as weaker planes and fractures, and thus how they crush/break during aggregate production. For instance, igneous rocks formed from the solidification of molten material (magma or lava), tend to have interlocking mineral crystals and might produce angular fragments when crushed. Sedimentary rocks, which originate from the accumulation and compression of sediments, may have a more layered or fragmented structure, influencing how they break when crushed. On the other hand, metamorphic rocks, which are formed from the alteration of existing rock due to heat and pressure, can have varying degrees of hardness and durability, affecting how they break down into aggregates. Each aggregate thus has unique properties that affect its performance. In addition to this, the type and degree of processing during preparation of the material for use in construction affects its properties.

The type of rock being extracted in the quarry can impact particle shape. Certain rock types may naturally fracture along planes, producing flat and elongated particles when crushed. Some rocks may contain weak planes or natural fractures that are prone to breakage during the crushing process. When these weak planes are oriented in specific directions, they can generate flat and elongated particles. The type and configuration of the crushing equipment used in the quarry can affect particle shape. Different crushing methods, such as impact crushing or cone crushing, can lead to varying degrees of particle elongation. Improper adjustment or inadequate maintenance of the crushing machinery can also contribute to the production of flat and elongated particles. However, there is a lack of objective and fundamental assessment of aggregate shapes in the country. Often, traditional specifications such as (*7*) and (*8*) are the dominant specifications for the selection of aggregates used in roads and railways, respectively. Although these specifications have supported the construction industry for some time, there are obvious limitations including the lack of a realistic approach to determining the shapes of aggregates. Anochie-Boateng et al. (*9*) expressed concerns about the inability of South African specifications to directly address the measurement of shape properties, thus leading to inconsistent interpretation of test results and performance of road and railway infrastructure. Mvealse (*5*) indicated that if rounded ballast is to be avoided then an even more restrictive specification of ballast shape properties would be required.

Aggregates Shape Characteristics and Performance

The type of parent rock could influence the size and shape of aggregates, which in turn affect the performance attributes of the aggregates in roads and railways (*10–12*). Angularity, for instance, has been strongly linked with the frictional resistance and interlocking properties of aggregates used in road and railway applications. Particles with angular shapes have better interlocking capabilities, creating a strong skeleton of aggregates in the road and ballast structures. This interlocking enhances load distribution, prevents particle movement, and improves the overall structural integrity and durability of the road or railway. Raymond (*13*) emphasized the importance of aggregate selection and indicated that the aggregate's particle shape and surface (i.e., cubical shapes and a high percentage of fractured faces) is of utmost importance and has long been recognized as having a major effect on track stability. While aggregate production from stone quarries cannot control the geology of the rock, they can control the quality in terms of size and shape. Screening of aggregates in the quarry is a process that produces various sizes of road stones, and track ballast, and these are checked against standard specifications for selection and utilization. The widespread use of aggregates in South Africa is due to their availability and economic considerations (significant use of industrial by-products such as steel and ferro slags) when compared with other construction materials. Aggregate of good quality is commonly available near most construction sites in the country at a relatively low cost.

There are several shape descriptors and various techniques to capture the particle profile (3D and 2D). Three-dimensional (3D) is the technique that provides more information about the particle shape, but the precision also lies in the resolution. Some image-based techniques provide only 2D information about the aggregate particles, which makes it difficult to accurately determine if the surface of the aggregate shape is a three-dimensional property. The 2D method has recently become a concern for most agencies and stakeholders in the road industry. In the late 1990s and early 2000s, researchers attempted to analyze aggregate shape properties using imaging techniques and video imaging systems (*14–16*). These methods are generally rapid and efficient, offering the added benefits of automation, which mitigate the subjectivity associated with traditional manual methods. However, a significant limitation of many of these techniques is their reliance on capturing 2D images of the aggregates, providing only 2D information about the geometry of the aggregate particles. Consequently, measuring aggregate shapes in terms of mass or volume becomes challenging. Moreover, it is well-known that the standard methods for aggregates, such as ASTM and AASHTO, primarily rely on 2D, lacking an effective approach to accurately capture profiles of irregular and non-ideal shapes of aggregate particles, leading to poor approximations. These methods often approximate aggregate particles as spheres when determining bitumen film thickness and other engineering properties. Such approximations can significantly influence the durability and performance of asphalt pavements. Kutay et al (*17*) presented a detailed discussion about 2D and 3D aggregate shape parameters including form and angularity indices. The comparison was made using 2D and 3D images of five different types of aggregates whose images were obtained using AIMS and X-ray CT, respectively. The researchers observed that the trend of 2D and 3D form indices computed for five different types of aggregates was similar. They, however, observed that the relative ranking based on the 3D angularity index was not always the same as the rankings based on the 2D angularity index of the aggregate samples. Based on the radius method, the 2D angularity indices suggested by Masad et al. (*18*) and the study by Wang et al. (*19*) correlated very well with the 3D angularity indices. However, gradient angularity indices (*18*) and a study by Wilson and Klotz (*20*) did not correlate 2D angularity indices well with the 3D angularity indices of the aggregate materials investigated.

Aggregate shape properties are important for understanding the suitability and performance of aggregates in various engineering applications, such as construction materials, pavement, concrete, and railway ballast. Changes to the particle morphological characteristics will therefore affect the performance of the matrix of aggregates in a road or railway structure (*21*). The shape of aggregate particles can influence their mechanical properties (*22*). It is well known that angular or irregularly shaped particles tend to provide better interlocking and frictional resistance, leading to improved strength and stability in compacted materials. For railway ballast, the breakdown of particles due to fragmentation, chipping, and abrasion is a primary cause of the accumulation of fine material within the voids of the unbound aggregate layer. This process is commonly known as ballast fouling, as described by (*23, 24*). Ballast fouling refers to the undesirable build-up of fine materials within the ballast layer, which can have adverse effects on the performance of the ballast bed. There are several reasons for ballast fouling, including the infiltration of material from the ballast surface, such as spillage from trains, and the wear of sleepers. Additionally, material infiltration from underlying granular layers or the subgrade can contribute to ballast fouling (*24*).

Enhanced University of Illinois Image Analyzer (E-UIAIA)

Studies conducted on South African railway track ballast highlight the challenges faced when using 3D laser scanning for aggregate analysis (*5*). The time required to scan a large number of aggregates can be significant, especially when considering the size and complexity of the aggregates being scanned. This motivated the decision of the CSIR to acquire an aggregate imaging system to supplement an existing 3D laser scanning device in aggregate imaging. By acquiring an aggregate imaging system, the CSIR can benefit from a more efficient and streamlined process for aggregate analysis. While aggregate imaging systems may not provide the same level of detailed 3D information as laser scanning devices, they offer a practical solution for capturing aggregate shape properties promptly.

The E-UIAIA system at the CSIR was commissioned at the CSIR just before the COVID-19 pandemic and upgraded and recalibrated in March 2023. This system is now available at the CSIR for an R&D project addressing challenges related to characterizing aggregate shape and surface properties. The first generation of the University of Illinois Image Analyzer (UIAIA) system, developed by (*15*) had certain limitations in the speed and efficiency of image processing and analysis algorithms, potentially leading to longer processing times or limited real-time capabilities. Moaveni (*25*) made improvements to the E-UIAIA system to capture projections of coarse particles as they move on a conveyor belt. To obtain high-resolution colour images of aggregates, a blue background is used on the conveyor. An advanced colour thresholding scheme is implemented to enable the measurement of different types of aggregates with varying colours. This scheme optimizes light intensity and minimizes the impact of shadows during the imaging process. One notable advantage of the E-UIAIA system is its efficiency in capturing images of aggregate particles. This enhanced imaging speed offers potential benefits to the quantity of large-size aggregate and road ballast particles. By utilizing the E-UIAIA device, researchers and practitioners in South Africa can be able to efficiently characterize aggregate shape properties.

This innovation will place South Africa among the leading countries in employing cutting-edge technology to quantify the characteristics of aggregates and quantitatively relate these characteristics to the performance of roads and railways. There are several benefits to gain from the proposed technique for the road and railway industry in using the E-UIAIA system in characterising aggregate shape properties. The successful implementation of this technique will lead to new opportunities dealing with the development of improved national and international standards for road and railway construction materials. These standards will have a significant impact on pavement/ track structure and the construction industry to provide better-performing roads and railways. The major benefit for stakeholders will be an improved understanding of how these infrastructures perform through better materials characterization using the E-UIAIA system. This will enable more effective management of assets in terms of maintenance/rehabilitation costs and the user costs of the infrastructure. It is expected that the tools/guidelines developed using the E-UIAIA system will allow stone quarry output and recycled material to be used, instead of being wasted. Overall, the E-UIAIA system will have an impact on the road and railway design solutions for South Africa's transport infrastructure.

It should be mentioned that similar imaging systems such as Aggregate Imaging System (AIMS-1 and AIMS-2) have been utilized for quantifying aggregate shapes. NCHRP 555 (*26*) research project highlighted UIAIA and AIMS as two of the most reliable imaging systems for evaluating the shape, angularity, and texture of coarse aggregates. However, it's essential to recognize that the E-UIAIA system and AIMS-2 utilize different software and hardware components to capture and process images of aggregate particles for morphology characterization. According to findings from NCHRP Report 539 (*16*), both UIAIA and AIMS systems could be utilized to classify aggregates based on imaging-based indices including angularity, surface texture index, and F&E Ratio. For more comprehensive details regarding the hardware and software technical components of these systems and their performance in morphology characterization of the different aggregate sources, additional resources are available (*27*). Additionally, a study by Wang et al. *(28*) compared the results obtained from Fourier Transform Interferometry (FTI) with those from AIMS-II and UIAIA systems. They concluded that when angularity and texture between two aggregate sources are significantly different, these three imaging systems may exhibit sensitivity to differentiate them, with a similar order of ranking observed.

DEVELOPMENT OF A PROTOCOL FOR IMAGING ACQUISITION

Aggregate/Ballast Image Acquisition Process

As of now state, there is no established standard protocol for data acquisition/capturing of aggregate images from the E-UIAIA system. Consequently, as part of this study, an aggregate image-capturing protocol was developed to standardize imaging acquisition and ensure the repeatability of the data and images acquired from the system. Adopting a systematic and standardized approach enables researchers to mitigate biases and enhance the reliability of subsequent analyses and findings. **Figure 1** illustrates the E-UIAIA system utilized for this study, highlighting the importance of implementing a standardized protocol to ensure consistency and accuracy in image capturing processes.

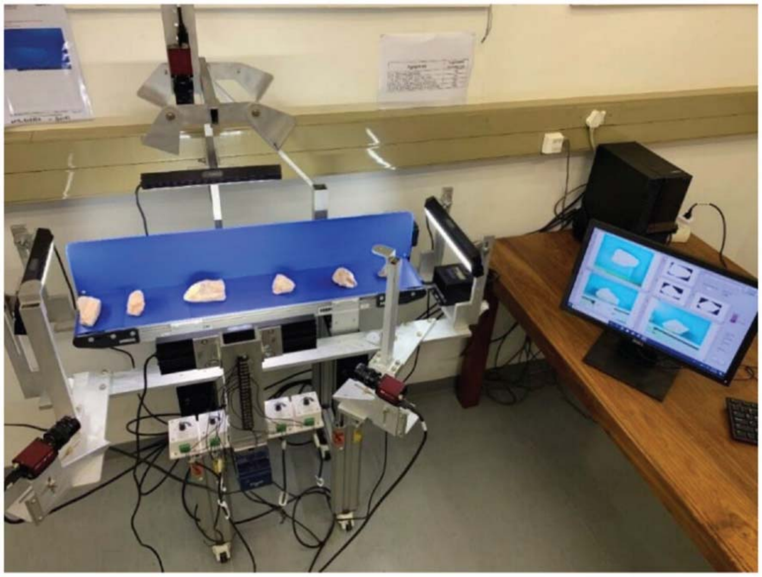


Figure 1 Photograph of the E-UIAIA Set-up at the CSIR

The image acquisition protocol involves the following steps:
Step 1: The imaging system is prepared by configuring the hardware components, adjusting camera settings, and ensuring proper lighting conditions.
Step 2: The aggregate particles are then positioned on the conveyor belt of the imaging system in a manner that allows for clear imaging. This step involves a camera setup and calibration of the E-UIAIA.

- The user is to set up the computer and wait a few seconds for images to appear on the screen.
- The calibration material (25.4 mm plastic ball) is to be placed on the conveyor belt. The top camera interface is used to align the ball at the centre of the frame.
- The camera zoom and focus are to be adjusted to the desired pixels (this is determined by the size of the particle to be scanned). The user is to ensure the resolution requirements are met for all three cameras.
- An adjustment is required on the (gains) to reduce any noise/unwanted reflections from the binary images if required. The top LED lamp dimmer can be adjusted physically.
- The user should then use the camera setup the calibration module, and the variable focal lengths of the camera lenses to adjust the system to capture images at 160 pixels per inch (ppi) to 430 ppi spatial resolution based on the size of the aggregate particles. The spherical calibration ball with known diameters is used to verify the achieved number of pixels per inch for each of the three cameras. The user should specify the targeted spatial resolution depending on the typical aggregate size: 4.75 to 9.5 mm (0.19 to 0.38 in) - 160 ppi, 13.2 to 19 mm (0.53 to 0.75 in) - 230 ppi, 26.5 to 37.5 mm (1.06 to 1.5 in) - 330 ppi and above 50 mm (2 in)- 430 ppi when capturing the particle.
- After the final adjustment of all three cameras and achieving the desired identical number of pixels per inch in addition to identifying camera gain levels, the user should use the calibration controller on the front panel to save the calibration file. The system records and saves the calibrated values in a text file named “calibration”. This calibration file is later used in the image analysis module to convert the size, surface area and volume of aggregate particles into real engineering units of length, area, and volume.

Step 3: Remove the calibration ball and place the aggregate particle to be scanned. Centre the particle in the top camera frame. Pay attention to any noise on each of the camera frames and adjust the orientation of the particle until all noise has been eliminated.

- Select the suitable capturing mode ("Continuous" or "Trigger") and wait a few seconds until images show up on the screen.
- To capture many aggregates at a time the Trigger mode is selected. The conveyor belt speed, camera delay and laser sensor need to be adjusted relative to each other so that the cameras can be triggered at the right moment to capture the images of the aggregate particles. Experience has shown that (Continuous Mode) is preferred to get the best quality datasets.

Step 4. The captured images are processed using software algorithms to extract relevant information about the aggregates, such as size, shape, texture, and grading.

- The "Analyse Images" module is used to select the folder that includes the acquired images, and the associated calibration file that is automatically loaded.
- The user is to check the folder on the ("Image Folder") to ensure it is the correct folder and should save and ensure the lighting system of the device turns green.
- The user should return to the folder that was created to save the scanned images. An MS Excel file containing the scanned particle data will also be saved in this folder.
- After loading the acquired images, if the user pushes the "start analysis" controller on the front panel, the shape properties are computed, and the numerical results are stored in an MS Excel file for any post-processing analysis.
- Aggregate shape properties associated with each grading sieve size are then recorded.
- Usually, the original results are sorted (ranked) and their cumulative percentiles are tabulated.

Step 5: The software calculates various aggregate parameters based on the processed images and the predetermined algorithms or formulas.

Step 6: The results of the image acquisition and analysis process are presented to the user, typically in the form of numerical data, graphical representations, or visualizations.

EXPERIMENTAL PROGRAMME AND IMAGING ACQUISITION

Materials and Sample Preparation

For this study, it was necessary to obtain a diverse range of materials reflecting various rock types and processing techniques. Through collaboration with the Aggregate and Sand Producers Association of South Africa (ASPASA), materials were sourced from different geographic locations across the country, encompassing a wide distribution of geological genesis and age, including two commonly used slag materials for construction. A total of six ballast stones and four road aggregates were collected from 10 different sources spanning five provinces in South Africa, ensuring representation across various geological characteristics. These naturally occurring materials were carefully selected to encompass the diverse mineralogical properties typical of crushed stones found in the country.

For road construction aggregates, two rock types, granite (AGS1) and norite (AGS2), were sourced from quarries in Gauteng province. Additionally, two by-product aggregates, chrome slag (AGS3), and Coarse Residual Disposal (CRD) slag (AGS4) were obtained from mines located in Mpumalanga and Free State provinces, respectively. The six rock ballast materials were sourced from various quarries located in Gauteng, Mpumalanga, Northwest, and Limpopo provinces. **Table 1** presents the types and applications of all aggregate materials studied. To prepare the aggregate particles for imaging, standard procedures including scalping, riffling/quartering, and sieve analysis were conducted to ensure uniformity and accuracy in particle size distribution. These steps were essential to obtain representative samples for subsequent imaging analysis.

Table 1 Aggregate Material Types Selected for the Study

Source/ Province	Source ID	Aggregate Application	Sample Description	Total Particles Imaged	Mode of Image Acquisition
Gauteng	TBS1	Ballast Stones	Meta Quartzite	131	Continuous
Gauteng	TBS2	Ballast Stones	Dolerite	143	Continuous
Mpumalanga	TBS3	Ballast Stones	Felsite	156	Continuous
Limpopo	TBS4	Ballast Stones	Granite	172	Continuous
Gauteng	TBS5	Ballast Stones	Dolomite	97	Continuous
Northwest	TBS6	Ballast Stones	Quartzite	98	Trigger
Gauteng	AGS1	Road Aggregates	Granite	373	Trigger
Gauteng	AGS2	Road Aggregates	Norite	332	Trigger
Mpumalanga	AGS3	Road Aggregates	Chrome Slag	393	Continuous
Free State	AGS4	Road Aggregates	CRD Slag	34	Trigger

Track Ballast Stones
The following steps were undertaken to prepare a representative sample of the track ballast:

- Approximately 100 kg (220 lb) of ballast material was collected from each source and transported to the CSIR aggregate laboratory.
- The 100 kg of ballast material was reduced in size to 21 kg (46 lb) using a suitable method such as riffling or quartering. This process aimed to obtain a smaller subsample that still accurately represented the overall characteristics of the bulk material.
- The representative ballast sample was carefully poured into a 14-liter capacity stainless steel bucket, ensuring no material loss during the process. Compaction was then performed as per the TFR S406 specification (8).
- The compacted sample was transferred from the bucket onto the 0.075 mm (No. 200) sieve. A spatula or scoop was used to carefully transfer the sample to ensure no material loss.
- The sample was washed to remove fines (particles passing through the 0.075 mm sieve) adhering to individual particles. The washed samples were subsequently dried in an oven at 110°C (230°F) for 24 hours.
- The dried samples were prepared using critical sieve sizes: 13.2 mm (0.53 in), 19 mm (3/4 in), 26.5 mm (1.06 in), 37.5 mm (1-1/2 in), 53 mm (2.12 in), and 63 mm (2-1/2 in).
- The prepared representative ballast samples were appropriately labelled and stored in a controlled environment to preserve their integrity until further analysis.

Road Aggregates
For road aggregates, the sample preparation process was similar, with the following differences:

- A relatively smaller sample size of 3 kg (6.6 lb) was prepared for the study.
- The critical sieve sizes used were 5 mm (0.2 in), 14 mm (0.56 in), 20 mm (0.8 in), 28 mm (1.10 in), 37.5 mm (1-1/2 in), and 50 mm (2 in).

As illustrated in **Figure 2,** the prepared aggregates were subjected to standard procedures including scalping, riffling (quartering), and grading to ensure uniformity and accuracy in particle size distribution. Grading played a crucial role in aggregate imaging analysis by providing essential information about particle size distribution and distinguishing between fine and coarse aggregates. Following sample preparation, representative aggregate particles were scanned with the E-UIAIA to obtain morphological properties.

Figure 2: Sample preparation before imaging capturing

Aggregate Imaging Capturing

Aggregate particles were individually positioned on the conveyor belt, and sensors were employed to detect the presence of a particle at specific locations on the conveyor belt. Upon detection, the sensors triggered the cameras to capture three projections of the particle individually. This process was repeated for each aggregate particle, ensuring comprehensive imaging coverage. **Figure 3** shows a visual representation of the E-UIAIA setup at the CSIR laboratory and illustrates a typical aggregate imaging capture of samples analyzed for this study.

Figure 3 E-UIAIA system at the CSIR laboratory performing aggregate imaging acquisition

RESULTS AND DATA ANALYSES

Grading Results and Analysis

The initial tests conducted on the track ballast and road aggregates involved grading to ascertain if the aggregates met the necessary size distribution requirements outlined in the relevant specifications. Grading was carried out at the CSIR laboratory using their respective test methods (*7, 8*). **Figure 4(a)** depicts the particle size distribution of the six-track ballast samples, demonstrating compliance with the requirements specified in the TFR S406 (*8*) grading specification for heavy haul tracks. The figure illustrates that the particle sizes of the samples predominantly fall within the range of 9.5 mm (3/8") to 37.5 mm (1.476 "). Similarly, **Figure 4 (b)** displays the particle size distribution of the four road aggregates, as per reference (*7*), indicating that aside from the CRD slag sample, almost all particle sizes of the road aggregates ranged between 4.75 mm (0.187") and 37.5 mm (1.476"). It's noteworthy that grading is primarily employed for aggregate imaging analysis to differentiate between fine and coarse aggregates. This information is subsequently utilized to determine the necessary number of particles to be scanned from each size, ensuring the acquisition of a representative imaging sample from each source. While all particles of the track ballasts were included in the imaging because the minimum size for all six samples was 13.2 mm (**Figure 4b**), the CRD slag contributed approximately 30% (retained on the 4.75 mm / No. 4 sieve) to the total aggregate particles studied, compared to 90% (chrome slag, AGS3) and 100% of the natural rock aggregates (AGS1 and AGS2). As previously mentioned, the E-UIAIA can only process images of coarse aggregates (i.e., 4.75 mm and above).

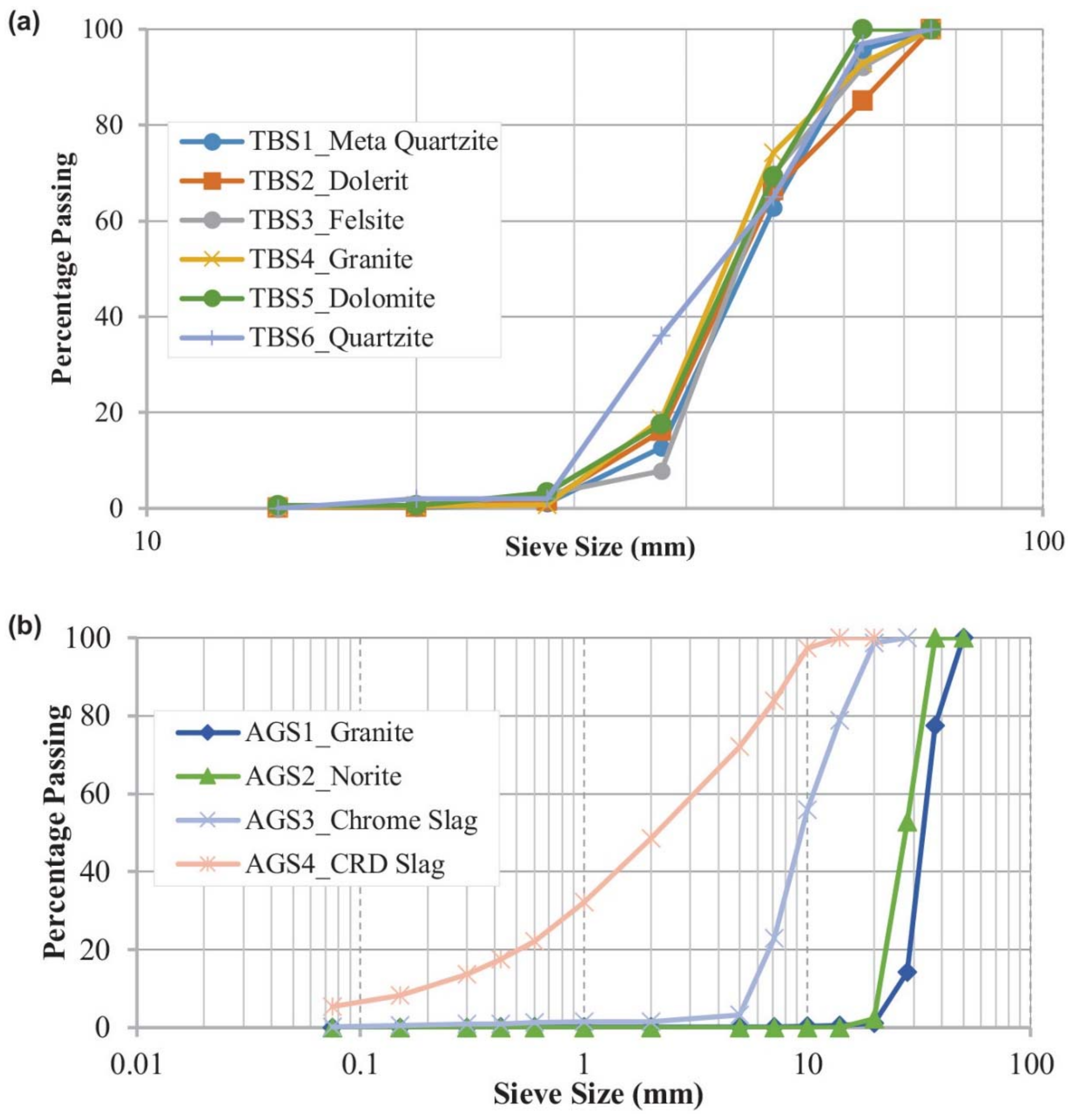


Figure 4 Grading curves of railway ballast and road aggregate materials

Aggregate Shape Indices

Proven analytical techniques and equations were employed to analyze the various aggregate shape indices of the materials in this study. These techniques have been developed and refined over decades, drawing upon the collective expertise of numerous researchers (*26, 29-31*).

Analysis of Flat and Elongated Ratio

To properly characterize the flat and elongated ratio (F&E Ratio) of an aggregate particle, information about the overall 3D shape of the particles is required. The F&E Ratio is calculated using **Equation 1**, which involves measurements related to the particle's dimensions. The F&E Ratio calculation involves measurements from three orthogonally positioned camera images (top, side, and front images) obtained using the E-UIAIA system.

$$\text{F\&E Ratio} = \frac{Longest\ Dimenstion}{Shortest\ Perpendicular\ Dimension} \tag{1}$$

These dimensions have been widely defined by researchers as follows:

- *Longest Dimension* refers to the longest measured dimension of the aggregate particle obtained from the three orthogonally positioned camera images. This dimension represents the maximum extent of the particle in one direction.
- *Shortest Perpendicular Dimension* is the shortest dimension among the three measured dimensions from the orthogonally positioned camera images. This dimension is perpendicular to the longest dimension and represents the shortest extent of the particle in a direction perpendicular to its longest dimension.

E-UIAIA Analysis of the Angularity Index

The assumption behind this approach is that the angularity elements observed in 2D are a good representation of the 3D angularity of the particles. Achieving the necessary image resolution for angularity analysis has become easier with the availability of automated systems for capturing high-resolution images. Masad (*31*) specified that an image resolution with a pixel size less than or equal to 1% of the particle diameter is required for accurate angularity analysis. This criterion ensures that the details of the particle outline and angular features are captured with sufficient clarity. In the case of the E-UIAIA system, quantitative angularity analysis was developed based on the images captured by the system (*15*). This method involves tracing the change in slope of the particle image outline obtained from the top, side, and front images. The angularity for each 2D projection is determined by extracting the image outline and approximating it with an n-sided polygon. **Equation 2** is then used to calculate the angularity of each projected image. In this equation, e represents the starting angle value for each 10-degree class interval, and *P(e)* denotes the probability that the change in angle α falls within the range from e to (e+10).

$$Angularity = A = \sum_{e=0}^{170} e * P(e) \tag{2}$$

Then, a final angularity index (AI) is established for the particle according to **Equation 3**, by taking a weighted average of its angularity determined for all three sides.

$$AI = \frac{\sum_{i=1}^{3} A_i \times Area_i}{\sum_{i=1}^{3} Area_i} \tag{3}$$

The quantitative angularity index developed using this approach allows for a numerical assessment of the angularity characteristics of the aggregates based on the 2D projections obtained from the E-UIAIA images. It provides a valuable metric for quantifying the angularity of the particles and contributes to a better understanding of their shape properties.

E-UIAIA Analysis of Surface Texture

The surface texture index measurement in E-UIAIA is based on the concept of erosion and dilation, commonly used in binary image morphology analysis, which is described by **Equation 4**. For each 2D image (top, front, and side orthogonal views), denoted by the index *i*, the surface texture parameter (*STi*) and the corresponding area (*Ai*) are determined. The surface texture index measurement is based on the difference in area, measured in terms of pixel counts, before and after an equal number of erosion and dilation operations.

$$ST = \frac{A_1 - A_2}{A_1} \times 100 \quad (4)$$

where
A_1 =Initial area (in pixels) of the 2-D image of the particle.
A_2 = Area (in pixels) of the particle after performing a sequence of "*n*" cycles of erosion followed by "*n*" cycles of dilation.

Then, a surface texture index (STI) is established for the particle by taking a weighted average of each STI determined from three sides, which measures the overall surface irregularities of a particle. The surface texture of the particle is computed according to **Equation 5**. The STI is a dimensionless quantity, as it measures the ratio of the areas before and after erosion and dilation.

$$STI_{particle} = \frac{\sum_{i=1}^{3}(ST_i \times A_i)}{\sum_{i=1}^{3} A_i} \quad (5)$$

Where *i* take values from 1 to 3 for top, front, and side orthogonal views. ST*i* is the surface texture parameter for each 2D image and Area *i* is the corresponding area of each 2D image. Therefore, STI measurement in E-UIAIA is performed based on a familiar concept in binary image morphology analysis that is called "erosion and dilation." The difference in the area in terms of pixel counts for 2D images before and after an equal number of erosion and dilation is directly related to the surface micro-irregularities and involves modifying the binary image by shrinking and expanding the foreground regions, respectively (*32*). The erosion operation erodes the boundary pixels, while the dilation operation expands the boundary.

The representative images of three orthogonal views (front, top, and side) of the aggregate particles and the corresponding binary images before and after processing in the E-UIAIA system are presented in **Table 2**. These images were compared with visual assessment charts developed by (*33*). After visually checking particle angularity from the 10 sources, it was observed that samples TBS1 and AGS3 generally demonstrate a higher angularity than samples from the other sources. This type of visual assessment of particles only gives an idea of the particle shape (i.e., angularity and roundness) but does not indicate the fine surface characteristics. It is important to highlight that the use of any visual assessment chart to describe particle shape properties has a high degree of subjectivity.

In the E-UIAIA system, monochrome digital images are generated through an image processing technique called thresholding procedure that is performed on individual grayscale images such as described by (*34*). The colour/digital images of aggregate particles are then converted to array pixels. This process generates the corresponding binary images (see **Table 2**). Extracting the pixel coordination of the boundaries of an aggregate particle therefore makes it possible to define the mathematical-based shape indices and quantify the morphological properties using AI, STI and F&E Ratio of the particles. The visual inspection of the generated binary images of the aggregate particles confirms the satisfactory performance of the developed protocol in thresholding the black and grey particles. Note that these images were captured at 160 to 430 ppi spatial resolution.

Table 2 Images and Visual Classification of Aggregate Samples

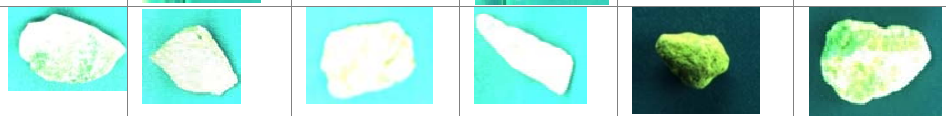
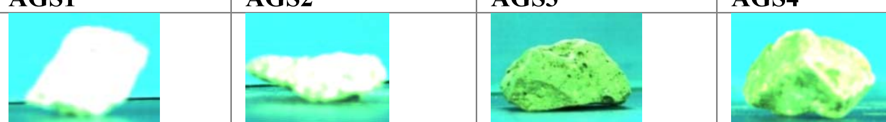
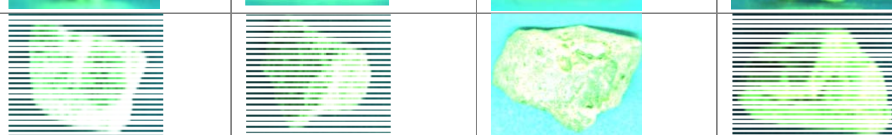
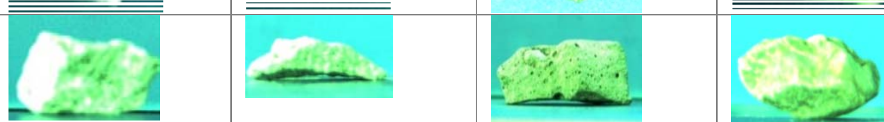
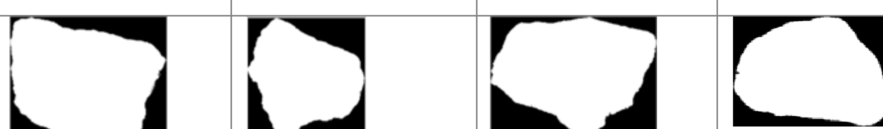
Image Type	**Ortho. Views**	**Sample TBS1**	**Sample TBS2**	**Sample TBS3**	**Sample TBS4**	**Sample TBS5**	**Sample TBS6**
Particle Colour (Digital Image)	Front						
	Top						
	Side						
Particle Binary Images	Front						
	Top						
	Side						
Visual classification		Very Angular	Angular	Angular	Angular	Sub-angular	Angular

Image Type	**Ortho. Views**	**Sample AGS1**	**Sample AGS2**	**Sample AGS3**	**Sample AGS4**
Particle Colour (Digital Images)	Front				
	Top				
	Side				
Particle Binary Images	Front				
	Top				
	Side				
Visual classification		Very angular	Angular	Very Angular	Sub-Angular

DISCUSSION OF RESULTS

The morphological characteristics of six ballast stones and four road aggregates were assessed using E-UIAIA imaging technology. A total of 1,929 particles larger than 4.75 mm (0.187 in) in size (coarse aggregates) were captured and analyzed for their shape properties. **Table 1** presents the number of particles studied from each source/province in South Africa.

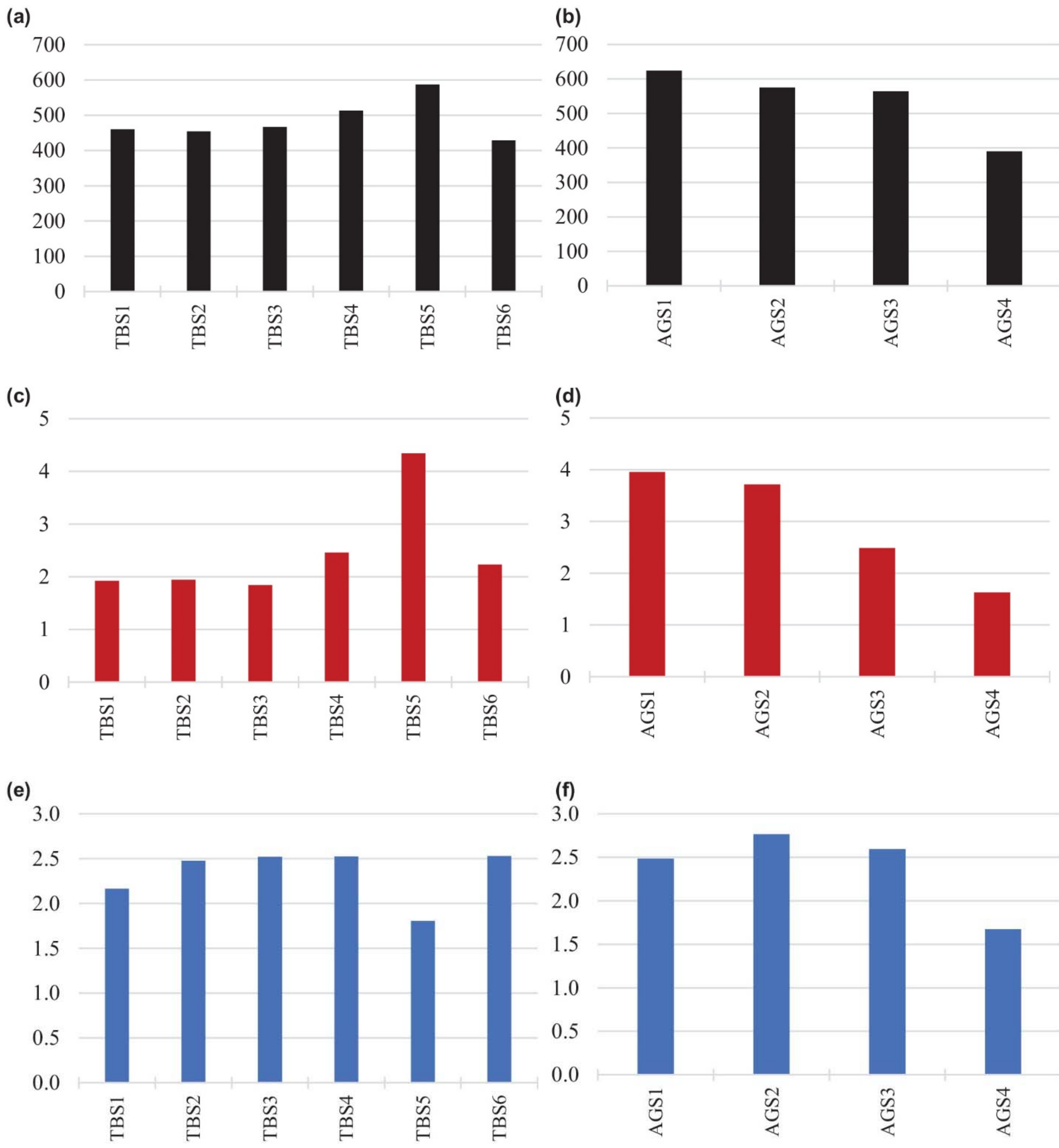


Figure 5 Comparison of morphological properties of different samples

Figure 5 compares the angularity, surface texture indices, and F&E Ratios of the track ballast and road aggregate samples, with corresponding values listed in **Table 3**. The results indicate a reasonable coefficient of variation (COV) in the angularity, surface texture, and F&E Ratio values of all samples, suggesting high confidence in the data obtained from E-UIAIA. Variations observed among the samples can be attributed to either the mode of imaging acquisition or material sampling from the source, although COV values are mostly below 30%.

Table 3 Morphology Properties of Track Ballast and Road Aggregates

Application	Type of Material	Morphology Properties	MEAN	STDEV	COV
Ballast Stones	TBS1_Meta Quartzite	AI	460.1	90.9	19.7
Ballast Stones	TBS2_Dolerite	AI	454.1	57.5	12.7
Ballast Stones	TBS3_Felsite	AI	467.2	62.5	13.4
Ballast Stones	TBS4_Granite	AI	512.8	70.6	13.8
Ballast Stones	TBS5_Dolomite	AI	587.0	93.4	15.9
Ballast Stones	TBS6_Quartzite	AI	428.8	82.3	19.2
Road Aggregates	AGS1_Granite	AI	623.9	30.6	4.9
Road Aggregates	AGS2_Norite	AI	575.0	45.3	7.9
Road Aggregates	AGS3_Chrome Slag	AI	564.4	68.0	12.0
Road Aggregates	AGS4_CRD Slag	AI	390.0	65.8	16.9
Ballast Stones	TBS1_Meta Quartzite	F&E Ratio	2.2	0.6	25.4
Ballast Stones	TBS2_Dolerite	F&E Ratio	2.5	0.5	19.6
Ballast Stones	TBS3_Felsite	F&E Ratio	2.5	0.6	22.9
Ballast Stones	TBS4_Granite	F&E Ratio	2.5	0.6	24.3
Ballast Stones	TBS5_Dolomite	F&E Ratio	1.8	0.2	13.5
Ballast Stones	TBS6_Quartzite	F&E Ratio	2.5	0.9	37.2
Road Aggregates	AGS1_Granite	F&E Ratio	2.5	0.3	10.2
Road Aggregates	AGS2_Norite	F&E Ratio	2.8	0.5	19.0
Road Aggregates	AGS3_Chrome Slag	F&E Ratio	2.6	0.6	23.1
Road Aggregates	AGS4_CRD Slag	F&E Ratio	1.7	0.2	11.5
Ballast Stones	TBS1_Meta Quartzite	STI	1.9	0.7	34.9
Ballast Stones	TBS2_Dolerite	STI	1.9	0.4	20.5
Ballast Stones	TBS3_Felsite	STI	1.8	0.6	30.2
Ballast Stones	TBS4_Granite	STI	2.5	0.6	24.0
Ballast Stones	TBS5_Dolomite	STI	4.3	1.7	38.8
Ballast Stones	TBS6_Quartzite	STI	2.2	0.7	31.1
Road Aggregates	AGS1_Granite	STI	4.0	1.2	30.5
Road Aggregates	AGS2_Norite	STI	3.7	0.7	18.9
Road Aggregates	AGS3_Chrome Slag	STI	2.5	0.7	26.4
Road Aggregates	AGS4_CRD Slag	STI	1.6	0.5	31.1

Except for the TBS5_Dolomite material, which exhibited higher surface texture and angularity and lower F&E Ratio values compared to other track ballast materials, the remaining five track ballast stones had similar shape properties. Similarly, apart from the AGS4 CRD slag material, all three road aggregates displayed comparable shape properties in terms of angularity, surface texture, and F&E Ratio values. These results confirm that the sample sizes of 21 kg (ballast stones) and 3 kg (road aggregates) were appropriate representations for imaging acquisition with E-UIAIA. Additionally, the grading of materials plays a crucial role in obtaining suitable samples for aggregate imaging analysis and provides vital information about particle size distribution. The variations in the shapes of road materials were not significant for angularity and F&E Ratio properties and were generally comparable with ballast materials. Dolomite track ballast stones exhibited the highest angularity index among the samples, while quartzite was the least angular rock material. The mode of imaging acquisition did not significantly affect the shape properties of the materials, as both continuous and trigger modes yielded similar results. It's noteworthy that the occurrence of high texture in aggregates could significantly influence angularity, as observed in this study. A high texture index generally resulted in a higher angularity index of the samples, underscoring the relationship between surface characteristics (i.e., texture) and the sharpness of the particle's edges and corners (i.e., angularity).

The provided information explains the distributions of the Angularity Index (AI), Surface Texture Index (STI), and Flat and Elongated Ratio (F&E Ratio) for different samples, as depicted in **Figure 6**, **Figure 7, and Figure 8**, respectively. These plots offer a more detailed understanding of the variability in shape indices across sample sources compared to the bar charts in **Figure 5,** as they display individual measurements of shape indices from particles.

Figure 6 reveals that the dolomite ballast sample (TBS5) exhibited highly angular particles, suggesting it could serve as a reference for setting a maximum limit for angular aggregates in road and railway construction. Conversely, the AGS4 CRD slag material, characterized by the lowest angular particles, could be considered for setting the lowest limit for angular aggregates. This observation aligns with expectations, given that the slag material was not crushed, leading to limited control over particle shape. More than 85% of the TBS5 sample had an angularity index of 500, while more than 85% of the AGS4 CRD slag had an angularity index of 350.

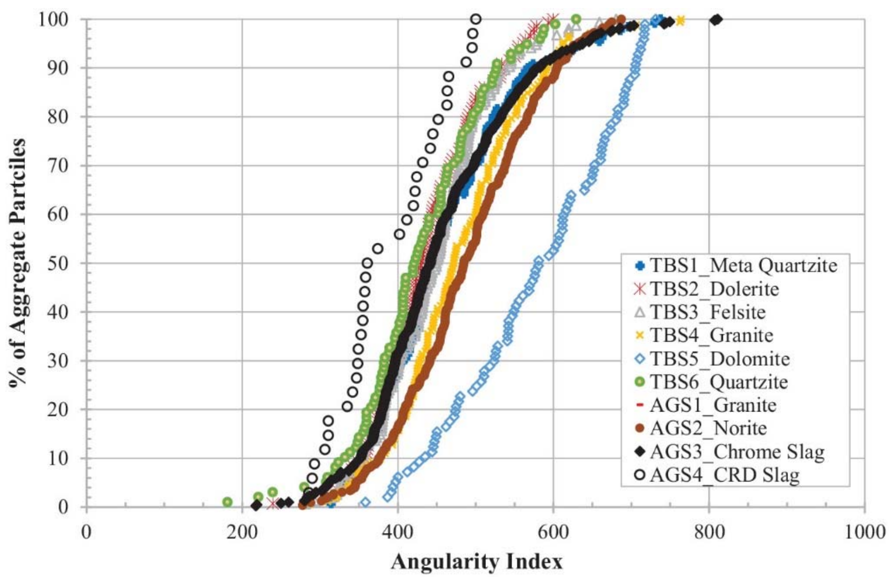


Figure 6 Distribution of angularity index of the aggregates

A similar trend was observed for the surface texture index, with the dolomite ballast sample (TBS5) exhibiting the highest surface texture index and the AGS4 CRD slag material displaying the lowest. This indicates that more than 85% of the dolomite ballast sample had a surface texture index of 2.5, while more than 85% of the AGS4 CRD slag material had a surface texture index of 1.0. Consequently, these materials can be used to set the maximum and minimum limits for surface texture, respectively, in aggregates.

Regarding the F&E Ratio, the AGS4 CRD slag exhibited the lowest ratio, whereas the AGS2 norite sample demonstrated a higher ratio. More than 85% of these materials had F&E Ratios of 1.4 and 1.9, respectively. This implies that the values of AGS2 norite can be used to set the minimum specification limit, while those of AGS4 CRD slag can be used to set the maximum specification limit for F&E ratios in materials selection for roads and railways. Notably, the F&E Ratio distributions exhibited a wider range of values compared to the AI and STI values, suggesting that the presence of flat and elongated particles may be influenced by various factors related to geological formations and the crushing process.

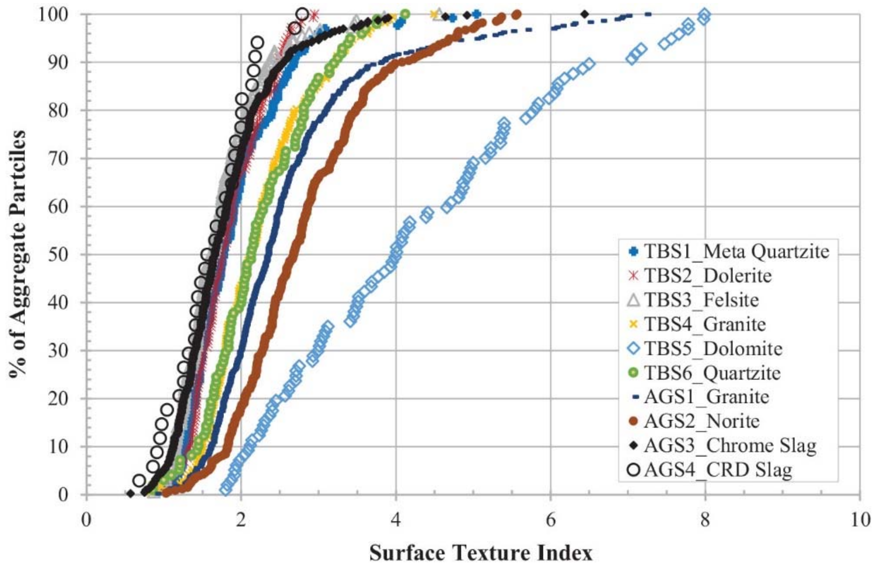


Figure 7 Distribution of surface texture index of the aggregates

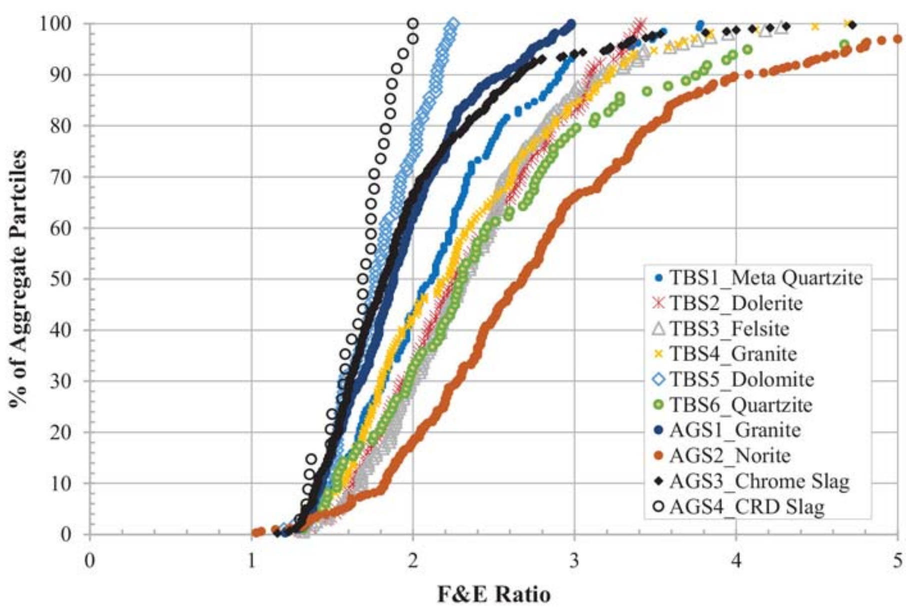


Figure 8 Distribution of flat & elongation ratios of the aggregates

Correlation between Surface Texture and Angularity

A similar trend was observed for the angularity and surface texture values across most of the investigated aggregates, suggesting a potential correlation between these two shape parameters. It was deemed worthwhile to explore whether such a relationship exists for the two parameters. In practice, agencies typically prefer aggregates with higher angularity and surface texture for roads and railways to improve performance while minimizing flat and elongated particles, which are undesirable in transport infrastructure projects. Hence, understanding the relationship between surface texture and angularity was essential compared to the relationship between either of these shape properties and the Flat and Elongated (F&E) Ratio.

The correlation between surface texture and angularity was investigated to understand their relationship across various aggregate types. **Figure 9** presents a plot depicting surface texture against angularity for both ballast materials and road aggregates. This analysis aimed to determine if there exists a correlation between these two parameters. Across all aggregate types, strong correlations were observed, with coefficient of correlation (R^2) values reaching 0.86 for road aggregates and 0.80 for ballast stones. These strong correlations indicate a significant relationship between surface texture and angularity. **Figures 6 and 7** further illustrate this relationship, showing consistent trends in the angularity and surface texture indices for both ballast stones and road aggregates.

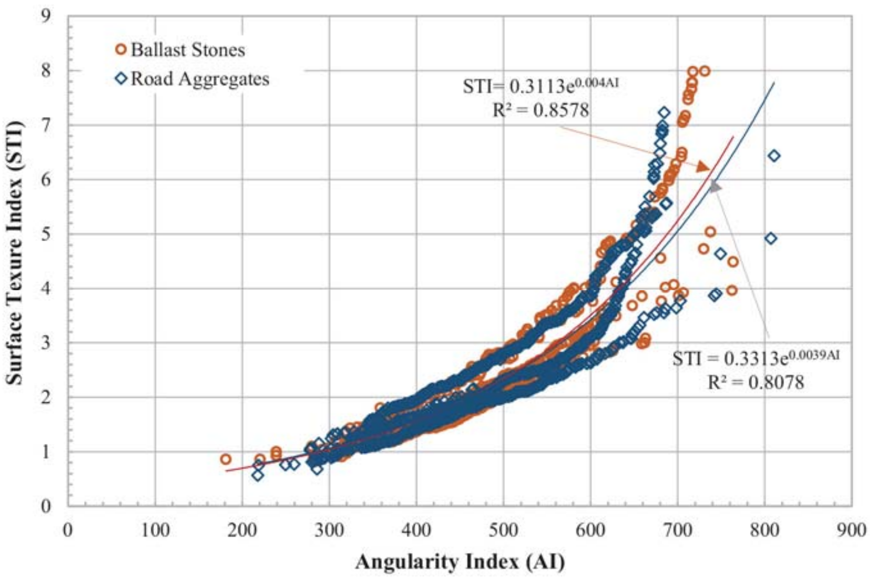


Figure 9 Correlation between surface texture and angularity indices

FINDINGS AND CONCLUSIONS

This study employed the recently acquired EUIAIA system to evaluate the morphological characteristics of nearly 2,000 railway ballast stones and road aggregates, with a specific focus on angularity, surface texture, and flat and elongated ratio. The findings provide insights into the factors influencing aggregate morphology and their implications for road and railway construction in South Africa. Presented below are the study's findings and conclusions.

- The implementation of the E-UIAIA technology in South Africa has been successful, enabling the establishment of interim specification limits for the shape properties of ballast and road aggregates.
- The choice of rock type significantly impacts the morphological properties of aggregates. For instance, quartzite ballast stones (TBS6) tend to exhibit lower angularity, possibly indicating more rounded shapes compared to other ballast stones. Conversely, dolomite ballast stones (TBS5) display higher angularity and surface texture. Similarly, granite road stones (AGS1) demonstrate high angularity and surface texture.
- Various factors, including rock type and the crushing process, influence the presence of flat and elongated particles in a sample. These factors contribute to the wide range of Flat and Elongated Ratio (FER) distributions observed among different samples investigated in this study.

- The railway ballast and road aggregates examined in this study are suitable for construction in at least five provinces in South Africa, suggesting potential cost savings in material selection through the utilization of this imaging technology.

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AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: J. Anochie-Boateng, G. M. Mvelase, and M. Moaveni; data collection: All authors; analysis and interpretation of results: All authors; draft manuscript preparation: All authors reviewed the results and approved the final version of the manuscript. The authors do not have any conflicts of interest to declare.

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