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Application of Stochastic Simulation in Assessing Effect of Particle Morphology on Fracture Characteristics of Sandstone

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Abstract

Indirect tensile testing is used in order to investigate the effect of particle morphology (shape and size) on the various weathering grade sandstone fracture characteristics. Several fracture characteristics are discussed in depth in this work including the fracture length (FL), fracture deviation area (FDA), fracture angle (FA), and fracture maximum deviation distance (FMDD). A tabletop microscope (TTM) is used to measure the particle morphology. The image analysis techniques induce the uncertainty-related particle shape and size. Therefore, the Monte Carlo simulation (MCS) is used in order to incorporate the inherent uncertainties-related particle morphology. The results obtained reveal that the sandstone fracture angle presents an unclear relationship with the particle shape and size. The effect of particle size on FL is completely obvious, and FL increases with the particle size. In contrast, the particle shape and size have an unclear relationship with the fracture characteristics. Furthermore, the sandstone porosity affects the fracture characteristics, which increase with the weathering grade. Moreover, the findings reveal that the Monte Carlo simulation is a viable tool for integrating the inherent uncertainties associated with the particle shape and size.

1. Introduction

Rocks are composed of mineral particles of various shapes and sizes [1, 2]. The particle shape may be categorized as quantitative and qualitative [2, 3]. The quantitative description shows the particle and dimensional characteristics, whereas the qualitative description measures the shapes of the particles. A qualitative description of the particle shape can be derived from a quantitative description. The researchers have further classified the particle shapes into sub-quantities such as shape/morphology, roundness, and surface texture. The axis length, surface area, and volume of the particles are used to describe the particle morphology. Additionally, the particle edges may be described in term of roundness (rounded), angularity (angular), and surface texture (rough or smooth) [3-5]. The particle shape has been defined in a variety of ways in the literature including roundness, aspect ratio, sphericity, and Feret diameter but there is no standard terminology. This loophole can be filled by simultaneously using several forms of shape descriptors, which is impossible due to various types of shapes.

Numerous methods have been used in order to determine the particle shape [2-6]. The particle shape has been initially measured through the hand method before being replaced by the map method [2, 3, 7, 8]. The sieving method has been proposed in order to analyze the particle elongation and flakiness but this approach is restricted to small particles [2, 3, 9]. The computer-based image processing tools impart the goal of ongoing the development related to the particle shape evaluation due to speed and automation. Numerous

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methods including fractal dimension, orthogonal image analysis, Feret diameter, Fourier method, laser-aided tomography, and Laser scanning techniques have been used for image processing [10, 11]. The surface image of the required sample has been scanned by an image processing tool such tabletop microscope (TTM). The strength of an image processing method can be considered from zero subjectivity, and the same findings from the same micrograph can be obtained. The micrograph provides more details in less time than the aforementioned approaches. Therefore, TTM is an ideal tool for analyzing the effect of particle morphology on the fracture characteristics of sandstone. On the other hand, the image-based approaches, specifically TTM for particle morphology, generate images with limited sensing, causing uncertainty [12-14]. Therefore, several researchers have proposed the statistical approaches in order to deal with the particle morphological uncertainties [2, 15-17].

The bond between the mineral particles plays a crucial role in the fracturing process, and is influenced by the particle shape and size. Therefore, evaluating the effect of particle shape and size on the fracture characteristics is significant. Various researchers have studied the influence of particle morphology related to various aspects. Das and Cleary [18] have used Smooth Particle Hydrodynamics (SPH) in order to evaluate the influence of rock shape on the fracture mechanisms. Uniaxial compression tests (UCS) have been used for modelling, and have then been matched with the experimental results in order to validate the models. The results obtained reveal that the rock shape significantly affects the fracture mechanism. Han et al. [19] have used a clump particle model in the 2D particle flow code (PFC^{2D}) to produce the square, strip, and triangle shape particles. The results obtained show that tensile fracturing increases as the particle changes from strip and triangle to square shape. Li et al. [20] have evaluated the damage and fracture mechanism of rock under dynamic loading. They proposed a grain-based discrete element method (GB-DEM) in order to analyze the rock fracturing behavior realistically. The required micro-parameters are acquired by calibrating the stress-strain curve, elastic modulus, fracture characteristics, and quasi-static strengths of igneous rocks. Furthermore, the authors validated the numerical models with the experimental results acquired from the split Hopkinson pressure bar (SHPB). The results obtained showed that the single fracture associated with fracture branches was controlled by intergranular fracture. Similarly, Sabri et al. [21] have studied the effect of particle size on the rock crack propagation. They used the Single-Edge Crack Brazilian Disks (SECBD) specimens of granite rock in order to evaluate the failure mechanism. The findings showed that the number of fractures increased with particle size increases. In general, the previous studies have concentrated on the impact of particle morphology on the mechanical behavior and fracture mechanism of rock and rock-like materials, and fracture characteristics have constrained them. Han et al. [19] have used 2D particle flow code (PFC2D) in order to evaluate the effect of the square, strip, and triangle shape grains. They revealed that grain shape significantly affected the elastic modulus, peak strength, and rock porosity. Shah et al. [2] have reviewed the effect of particle morphology on the mechanical behavior of rock mass. They concluded that the particle shape had a distinct effect on the geotechnical properties of rock; conversely, each descriptor is case-sensitive to a specific shape attribute. Eberhardt et al. [22] have evaluated the effect of grain size on the stress-induced brittle fracture in crystalline rocks. They revealed that the grains size did not significantly affect the fracture response. Fracture response is significantly affected by the strength of grains.

The fracture in rocks can be differentiated by its type, length, and shape [23]. As the rock specimen gains peak strength during loading, it fails and presents fractures [24]. Therefore, it is essential to understand the fracture characteristics such as FL, FA, FDA, and FMDD for their identification. The sum of fracture extensions through the specimen is called fracture length. Similarly, the angle between the central loading line and primary fracture is known as the fracture angle. In contrast, FDA refers to the point of maximum deviation of the main fracture in accordance with the central loading axis. The area enclosed by the main fracture with the center loading line is known as FDA [23]. The literature has explained that the particle morphology could affect fracture mechanisms; therefore, it is essential to investigate the effect of particle shape and size on the fracture characteristics.

The effect of particle shape and size on the fracture characteristics of various weathering grade sandstone under Brazilian tensile testing is investigated in this work. Three different types of particle shape (circularity, aspect ratio, and roundness) descriptors were used in order to acquire the effect of particle morphology on the fracture characteristics. A tabletop microscope

(TTM) was used to acquire the micrographs of the sandstone samples. Furthermore, ImageJ, an image processing program, was used in order to determine the particle shapes and size distributions from the micrographs obtained. However, the image analysis techniques produce uncertainty related to the particle shape and size. Therefore, the uncertainties associated with rock particle shape and size parameters were statistically integrated using the Monte Carlo simulation.

2. Materials and methods

The studied area comprises a sandstone body on the road cut slope in the Sor-Range coal mines near Quetta, Pakistan. The rock samples reveal a moderately weathered to fully weathered sandstone on the outcrop. The extensive BTS tests were conducted on the fresh, slightly weathered, and moderately weathered sandstone collected from various locations in order to determine the fracture characteristics. The weathering grades were estimated using the simple means approach recommended by the international organization of standards (ISO)-14689-1 (2003)) and (British Standard (BS) 5930. (1981)) [25, 26]. The fresh sandstone samples were acquired from an underground mine, while the slightly and moderately weathered sandstone samples were collected from the outcrop. The bulk samples collected from the site were preserved, as recommended by BS 5830:1999 (+A2:2010). The core samples of NX size (54 mm in diameter) with various thicknesses were drilled, maintaining the thickness/diameter ratio of 0.5 to 0.6. The Brazilian tensile strength tests were carried out using UTC-5431 (see Figure 1) in order to evaluate the mechanical response and fracture characteristics of fresh, slightly, and moderately weathered sandstone.

2.1. Image analysis

TTM is a low-vacuum scanning electron microscope (SEM) that makes testing and analysis simple without preparing the specimen. This instrument is widely applied, particularly in the particle analysis. The TTM automated design allows the data to be collected over several depths of the field. The micrographs with distinguishable particle boundaries were saved. The particle analysis was performed using the ImageJ software. The manual analysis was used in order to evaluate the particle morphology due to bright and contrast issues in automated thresholding. The In manual analysis, the acquired micrograph was initially uploaded into a new window of ImageJ. The picture was then calibrated in pixel value against a known distance. A binary image was produced to identify the particle boundaries effectively. After that, the particles with distinct boundaries were manually traced.

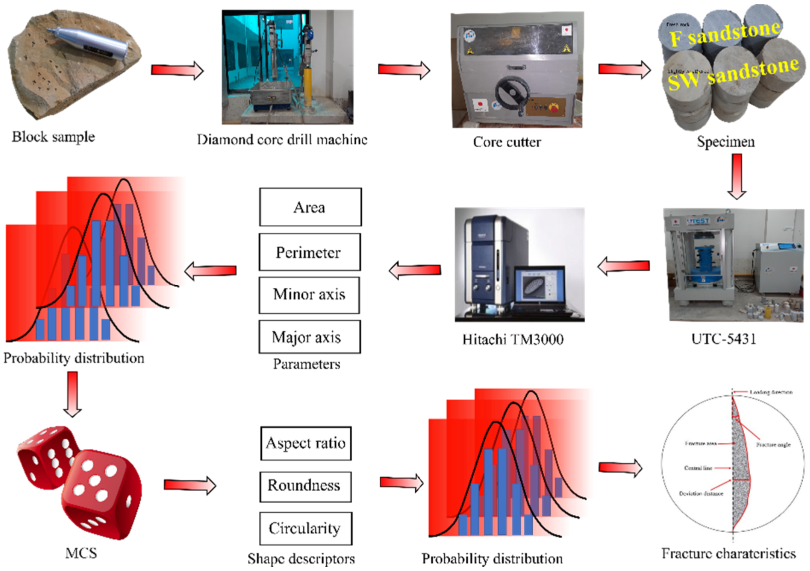

Figure 1. Framework diagram used to assess the effect of particle morphology on fracture characteristics with simulation by Monte Carlo method.

2.2. Particle shape descriptors

The literature has reported various shape descriptors; however, this research work focused on the aspect ratio, circularity, and roundness. The reason for this is that the researchers present numerous shape descriptors; therefore, it is not possible to use several descriptors simultaneously. Hence, the emphasis of this research was on the shape descriptors that can be obtained using the ImageJ software. As mentioned earlier, a quantitative description of particle shape can be used to derive a qualitative description of particle shape. The provided quantitative descriptions are the major and minor axis (mm), perimeter (mm), and area (mm^2). These quantitative descriptors are used in order to calculate the three qualitative descriptors (aspect ratio, circularity, and roundness) using Equations 1, 2, and 3.

$$\text{Aspect ratio}=\frac{(\text{Major axis})}{(\text{Minor axis})} \tag{1}$$

$$\text{Circularity} = 4\pi\frac{(\text{Area})}{(\text{Perimeter})^2} \tag{2}$$

$$\text{Roundness} = 4\frac{(\text{Area})}{\pi(\text{Major axis})^2} \tag{3}$$

2.3. Monte carlo simulation

Monte Carlo simulation (MCS) is a method for incorporating uncertainty into the data and displaying the potential scenarios. Similarly, MCS is also used to model the probability distribution of various outcomes. MCS may ensure a viable alternative instead of replacing uncertain results with a single average value when faced with uncertainty during estimating or forecasts. MCS can be used in rock mechanics for stochastic modelling due to the randomness involved in the data. Stochastic modeling comprising random variables and such input variables for a model is obtained from a probability distribution. The values obtained are in a specific range, and the samples should be obtained with the highest probability. MCS can replicate the input distribution through thousands of iterations, and offers the potential scenarios. In this work, we use MCS in order to evaluate and integrate the inherent uncertainty related to the particle size and shape descriptors.

3. Results and discussion

3.1. Uncertainty incorporation using stochastic simulation

The primary objective of this section is to measure the particle shape distribution for the sandstone samples. The principal elements of this analysis are particle shape measurement using ImageJ and using Equations 1, 2, and 3, the statistical modelling of the shape descriptors of the sample data, the Monte Carlo simulation of size parameters using a reference probability distribution, and fitting distribution to the simulated data. Rhe sandstone samples were tested for particle shape distributions. The Chi-square test was used in order to determine the particle shape distribution before and after MCS. Figure 2 shows the histograms with a model and frequency distribution of the input parameters of fresh sandstone. The largest extreme value reference model fits the area, whereas the loglogistic distribution fits the perimeter. The major and minor axis represents the aspect ratio of the particle shape descriptors, which follow the Birnbaum-Saunders and Gamma distributions. The frequency distribution of the input values was utilized to calculate the circularity, aspect ratio, and roundness of the particles. The shape descriptor values were first calculated by the deterministic method. After that, the shape descriptors best-fitted distribution was evaluated. Figure 3 shows the histogram with the best-fitted frequency distribution for deterministic shape descriptors. The results obtained show that circularity follow the smallest extreme value distribution.

As it can be seen in the graph, the quality of the fit for circularity is quite acceptable. The circularity of the particle varies considerably for the fresh sandstone. Figure 4 also demonstrates that the aspect ratio is best fitted with the largest extreme value. As it can be seen from the graph, the aspect ratio is negatively skewed. Figure 4 demonstrates that the Weibull distribution best describes roundness. The particle size of fresh sandstone followed the Birnbaum-Saunders distribution.

MCS was utilized to account for the inherent uncertainty associated with the particle shape descriptor (PSD) distributions. In this work, 10,000 iterations were performed for each model. MCS demonstrates that the smallest extreme value, largest extreme value, and Weibull distributions are best fitted with circularity, aspect ratio, and roundness. In addition, the frequency distributions of simulated PSD show a significant resemblance to deterministic PSD.

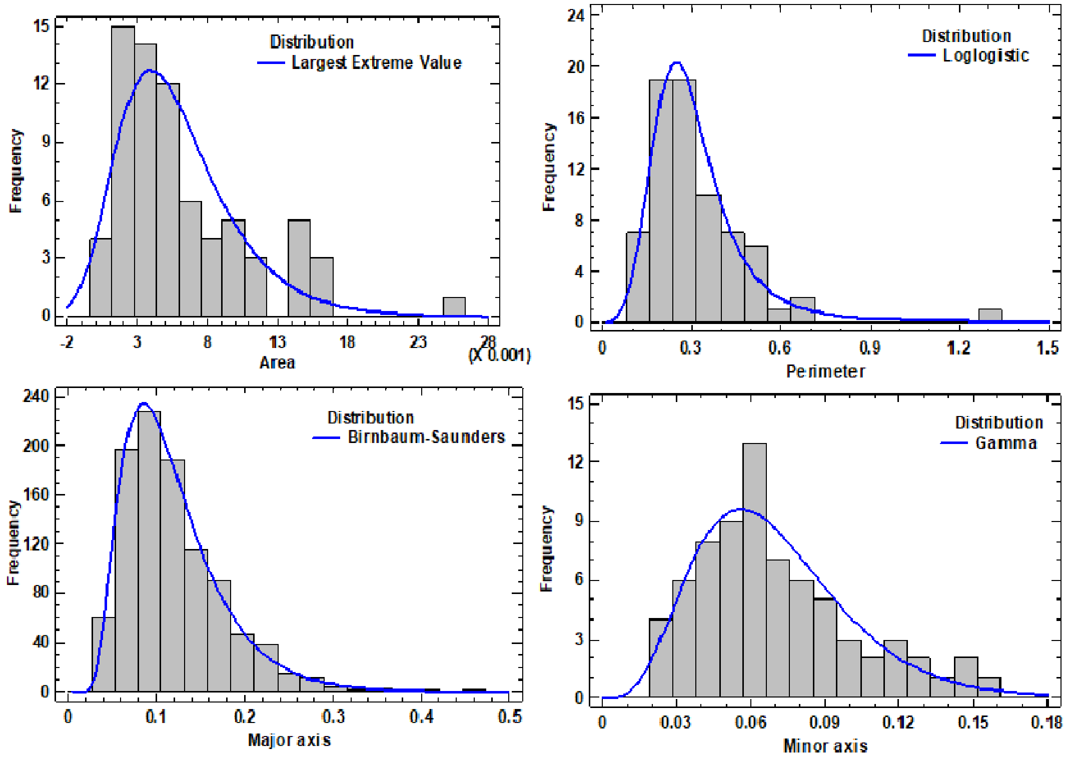

Figure 2. Best-fitted frequency distribution of input parameters of fresh sandstone.

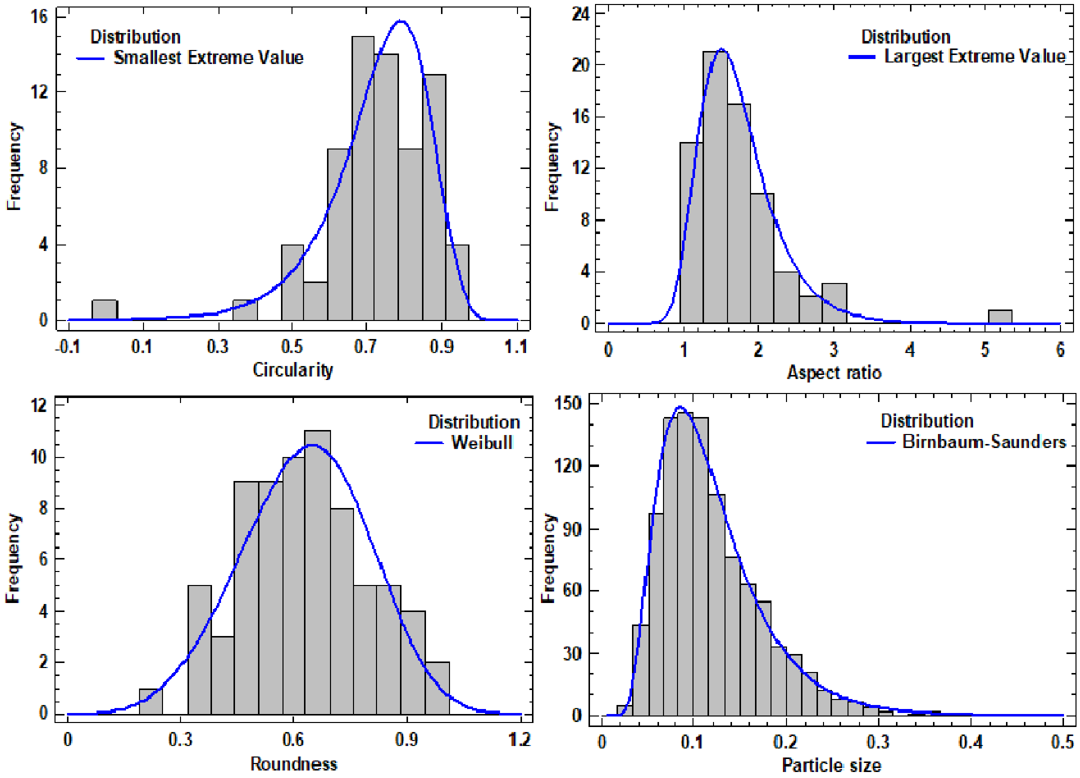

Figure 3. Fitted frequency distribution of deterministic particle size and shape descriptors of fresh sandstone.

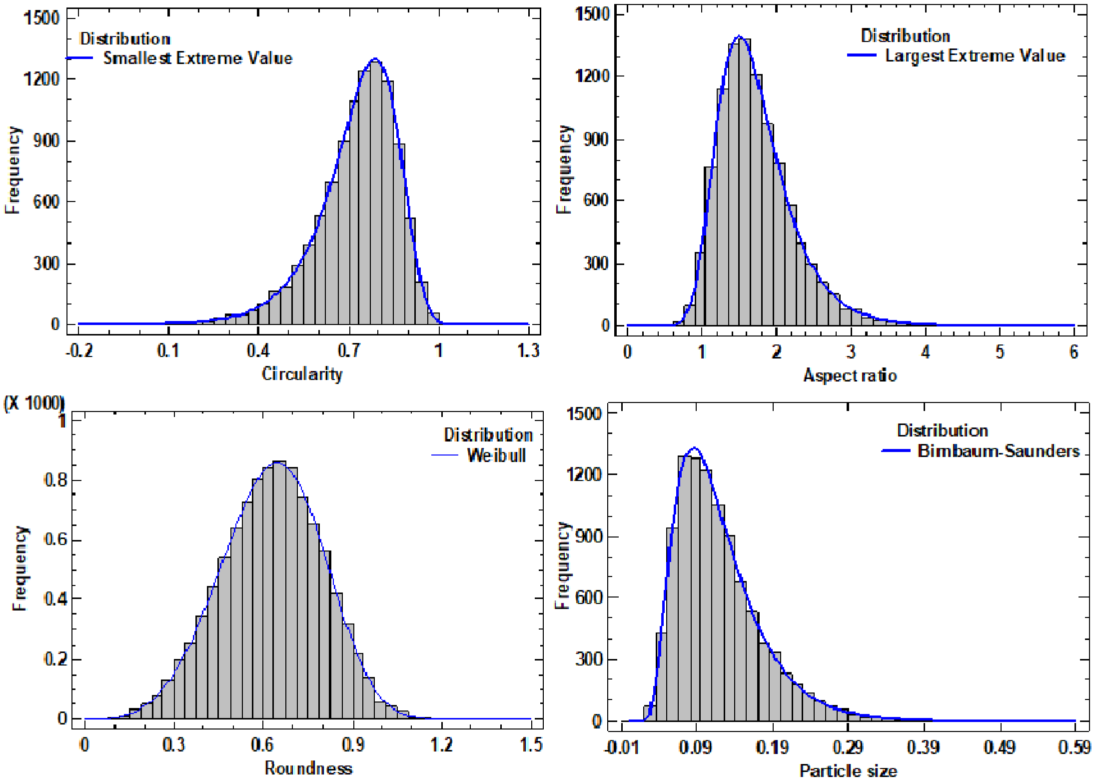

Figure 4. Fitted model of MCS-based PSD values and their optimal frequency distribution of fresh sandstone.

Traditionally, comparing the statistics of PSD of the simulated and deterministic values show small variations. The simulated roundness average value is 0.62, which is close to the deterministic procedure value (0.63). The other statistics results also show small differences such as standard deviation reduced from 0.146 to 0.13, and coefficient of variation decreased from 20.1% to 18.6%. The quotient obtained by dividing the standard deviation (SD) by the mean is called the coefficient of variance (COV), and depicts the uncertainty. Similarly, the average simulated aspect ratio is decreased from 1.75 to 1.72. SD and COV show a small reduction from 0.64 to 0.5 and from 36.7% to 29.3%, respectively. Similarly, by comparing the simulated and deterministic circularity values, the SD and COV values reduced from 0.2 to 0.17 and 27.1% to 27.0%, respectively. In contrast, the average value decreased from 0.63 to 0.62. The average particle size is 0.12, which remains constant for both the deterministic and simulated methods. In comparison, both SD and COV increases from 0.056 to 0.057 and 47.2% to 48.1%, respectively.

The histograms with a model and frequency distribution of the input parameters of slightly weathered sandstone are shown in Figure 5. The area is best fit by the exponential reference model, while the inverse Gaussian distribution best fits the perimeter, whereas the major axis is best with the inverse Gaussian distribution and the minor axis is best with the Birnbaum-Saunders distribution. The histogram with the best-fitted frequency distribution for the deterministic shape descriptors of slightly weathered sandstone is given in Figure 6. According to the findings, the circularity of slightly weathered sandstone followed the smallest extreme value distribution. The circularity of the particle varies greatly in slightly weathered sandstone. Figure 6 also shows the largest extreme value best fits of the aspect ratio, whereas the roundness of slightly weathered sandstone is also best described by the Weibull distribution. The particle size of slightly weathered sandstone followed the inverse Gaussian distribution.

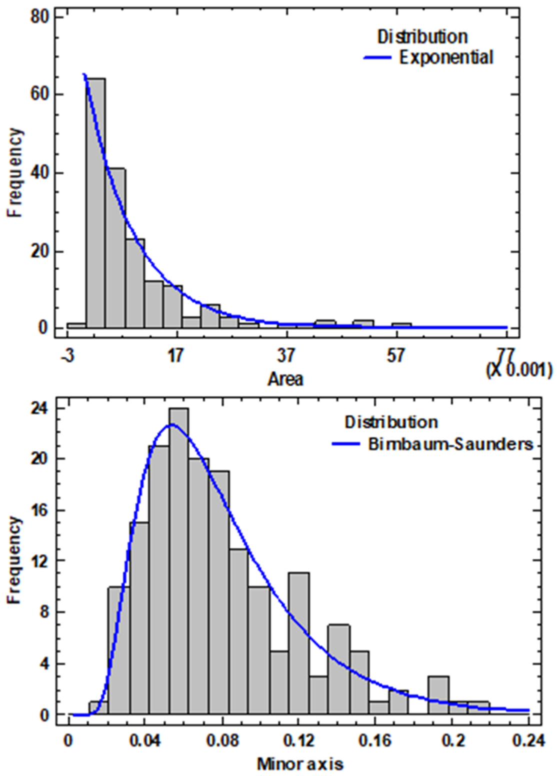

Figure 5. Best fitted frequency distribution of input parameters of slightly weathered sandstone.

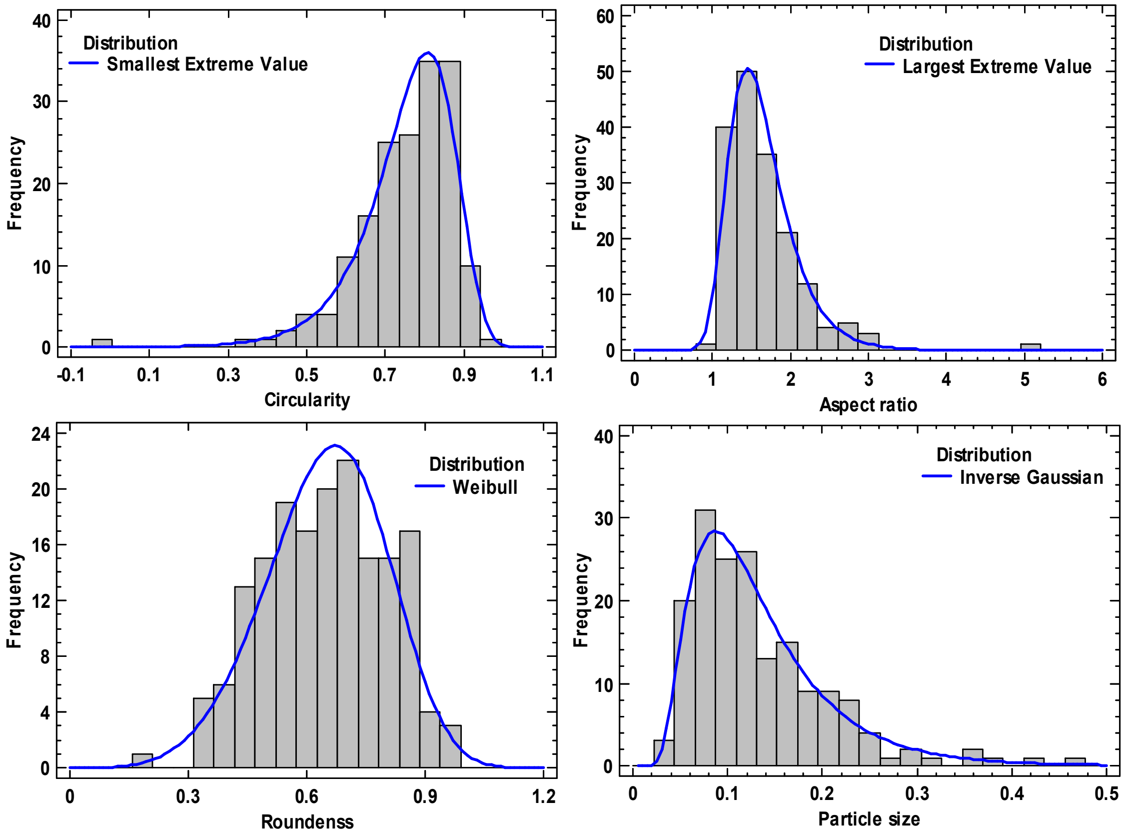

Figure 6. Best fitted frequency distribution of deterministic shape descriptors of slightly weathered sandstone.

Figure 7 shows that MCS for circularity, aspect ratio, and roundness yield best-fitted distributions of smallest extreme value, largest extreme value, and Weibull. The frequency distributions of simulated PSD exhibit a close agreement with the deterministic PSD. Typically, assessing the statistics of the particle shape descriptors of simulated and deterministic values reveals minor differences. For both the simulated and deterministic methods, the average value of circularity is 0.75, whereas the other statistics for circularity exhibit small variation such as standard deviation reduced from 0.13 to 0.11 and coefficient of variation reduced from 17.1% to 15.5%, respectively.

Similarly, the average simulated aspect ratio is decreased from 1.65 to 1.64, and SD and COV show a significant change from 0.51 to 0.42 and from 30.7% to 25.5%. The simulated and deterministic procedures for roundness yield the same average, standard deviation, and COV values of 0.65, 0.15, and 23.7%, respectively. The average particle size is 0.13, which remains constant for both the deterministic and simulated methods, whereas both SD and COV slightly decrease from 0.074 to 0.072 and 55.6% to 55.5%, respectively.

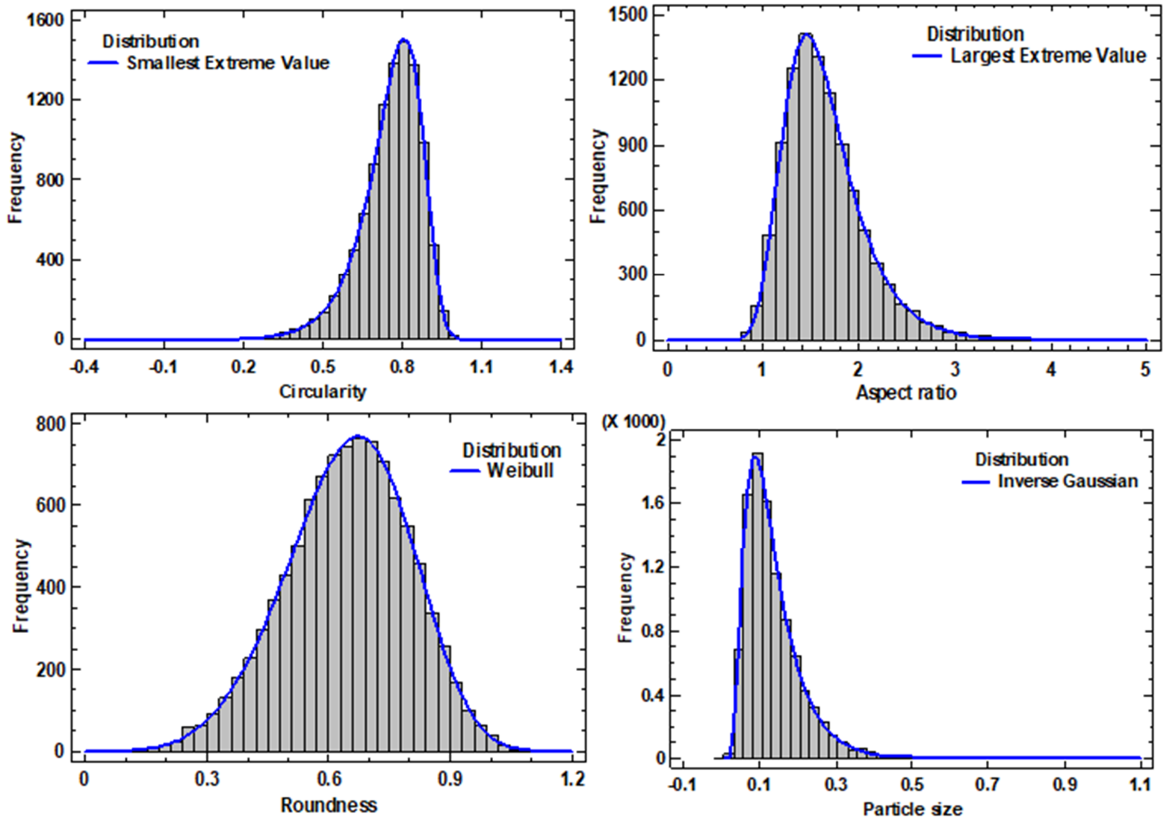

Figure 7. Fitted model of MCS-based PSD values and their optimal frequency distribution of slightly weathered sandstone.

Figure 8 depicts the histograms based on a model and frequency distribution of the input parameters of moderately weathered sandstone. The area is the best fit with the gamma distribution, while the perimeter is the best fit with the Birnbaum-Saunders distribution, whereas the major axis is best with the Birnbaum-Saunders distribution and the minor axis is best with the gamma distribution.

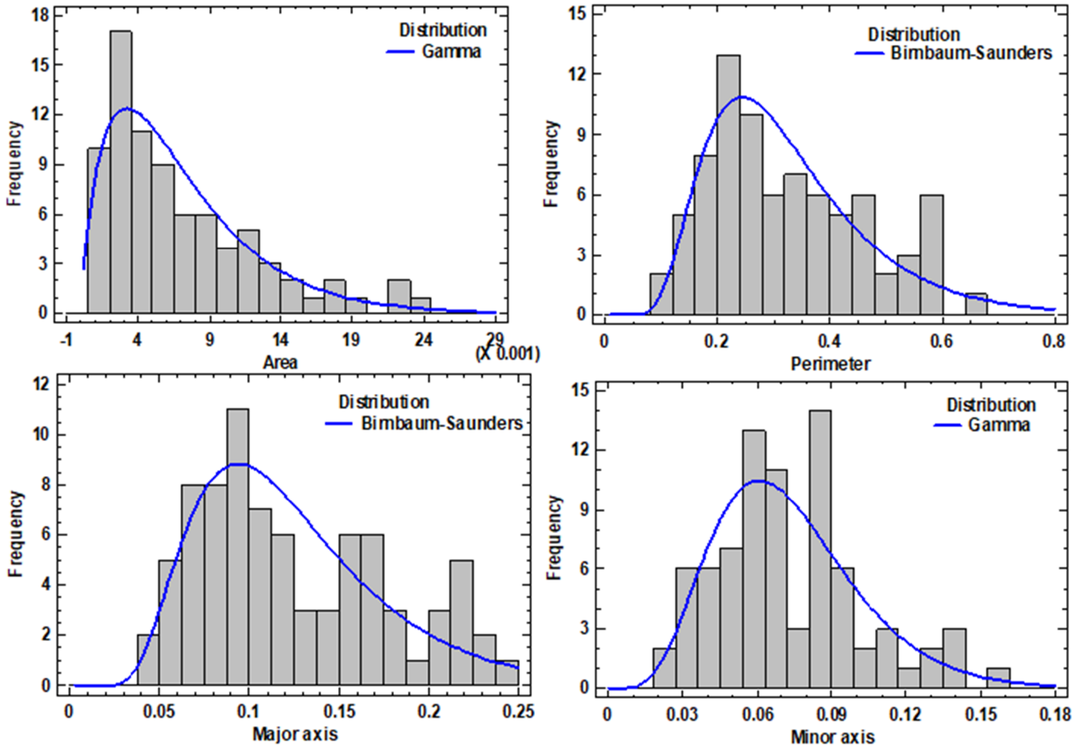

Figure 8. Best fitted frequency distribution of input parameters of moderately weathered sandstone.

Figure 9 depicts the histogram with the best-fit frequency distribution for deterministic form the descriptors of moderately weathered sandstone. According to the findings, the circularity of moderately weathered sandstone followed the Weibull distribution. Figure 9 also shows that the largest extreme value best fits the aspect ratio, whereas the roundness of moderately weathered sandstone is also best described by the gamma distribution. The roundness of the particles varies greatly in moderately weathered sandstone. The particle size of moderately weathered sandstone followed the Birnbaum-Saunders distribution.

As shown in Figure 10, the MCS of circularity, aspect ratio, and roundness provide the data that best with Weibull, largest extreme value, and gamma distribution. The simulated particle shape descriptor (PSD) frequency distributions match the deterministic PSD's. By comparing the statistics of the simulated and deterministic particle shape descriptors, relatively small differences were observed. Circularity has an average value of 0.75 for both the simulated and deterministic circularity. Similarly, for both types of techniques, the standard deviation (SD) of circularity is 0.098. The coefficient of variation (COV) of circularity of moderately weathered sandstone increases slightly from 13.1% to 13.2%. In the case of aspect ratio, the average value remained 1.73, while the SD and COV values decreased slightly from 0.46 to 0.45 and 26.5 to 26.3, respectively. The average and standard deviation for roundness remain unchanged at 0.62 and 0.15, respectively but COV increases slightly from 24.7% to 25.03%. The average particle size and SD are 0.13 and 0.05, which remain constant for both the deterministic and simulated methods. In contrast, COV increases from 41.7% to 44.1%.

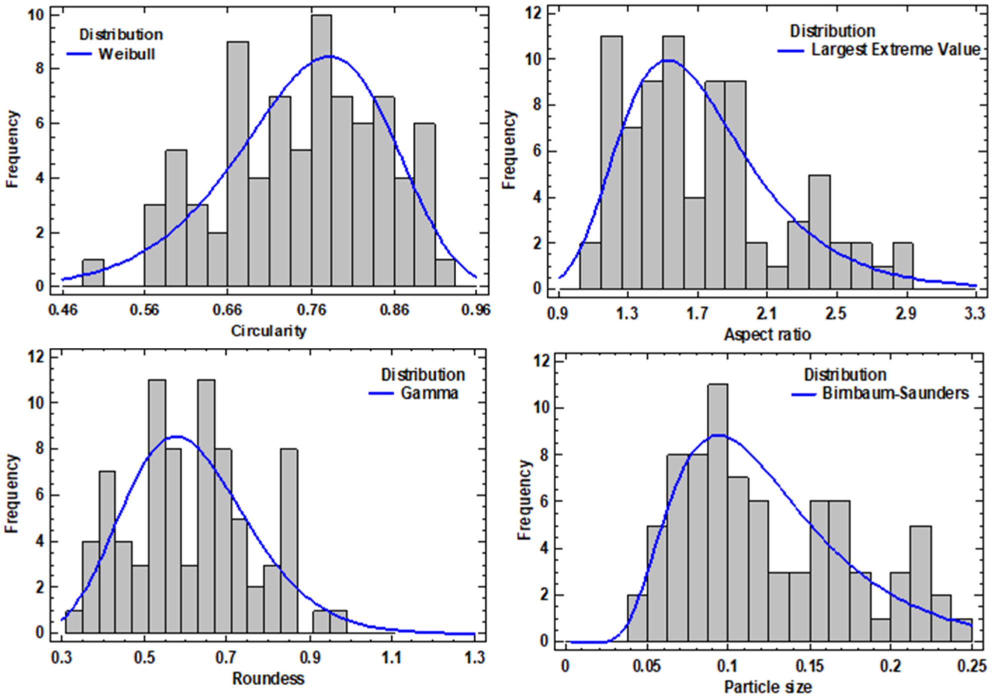

Figure 9. Best fitted frequency distribution of deterministic shape descriptors of moderately weathered sandstone.

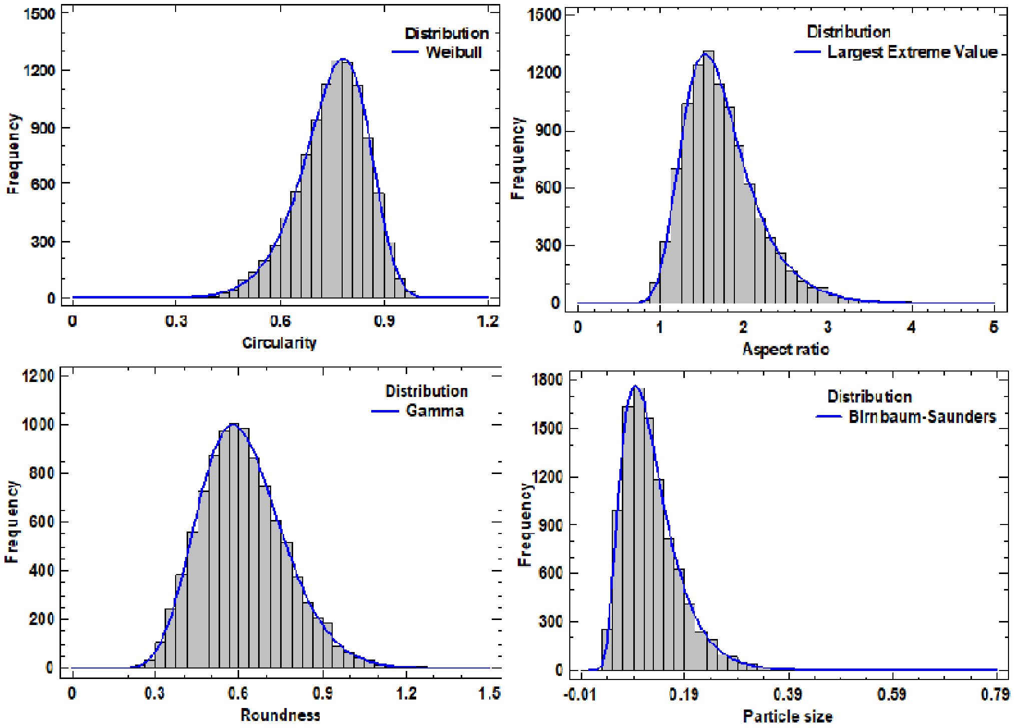

Figure 10. Fitted model of MCS-based PSD values and their optimal frequency distribution of moderately weathered sandstone.

3.2. Effect of particle morphology on fracture characteristics

The particles within the rock samples are present in an extensive range of shapes and sizes, their characterization and analysis existing with a considerable diversity. Therefore, this research work focused on integrating the inherent uncertainty associated with the particle shape and size. The inherent uncertainty associated with the particle shape and size was incorporated using MCS for each sample. Furthermore, the average particle shape and size values were used to investigate the effect of particle morphology on the fracture characteristics of various weathering grade sandstone.

The particle shapes are determined using Equations 1, 2, and 3 and compared to the fracture characteristics of fresh sandstone, as shown in Figure 11 and Figure ***12***, respectively. Figure 11(a) and 11(b) illustrate the relationship of fracture angle (FA) with circularity, roundness, aspect ratio, and particle size. The findings indicate an indirect relationship of FA with particle circularity, roundness, and particle size. However, FA slightly increases as the aspect ratio increases. This is because when the particle size, circularity, and roundness increase, the pore space expands. As a result of the coalescence of micro-flaws in the loading direction, the fracture propagates with a lower fracture angle. The relation between the fracture length and particle shapes and size is presented in Figure 11(c) and 11(d). Figure 11(c) depicts that the fracture length is inversely proportional to the aspect ratio. In contrast, FL increases as the particle size increases. Similarly, the fracture length is directly proportional to both roundness and circularity. As already mentioned, the pore spaces in rock increase with an increase in particle size, circularity, and roundness. As pore spaces increases, the micro-flaws interact with the neighboring incipient discontinuities, resulting in an increase in the fracture length.

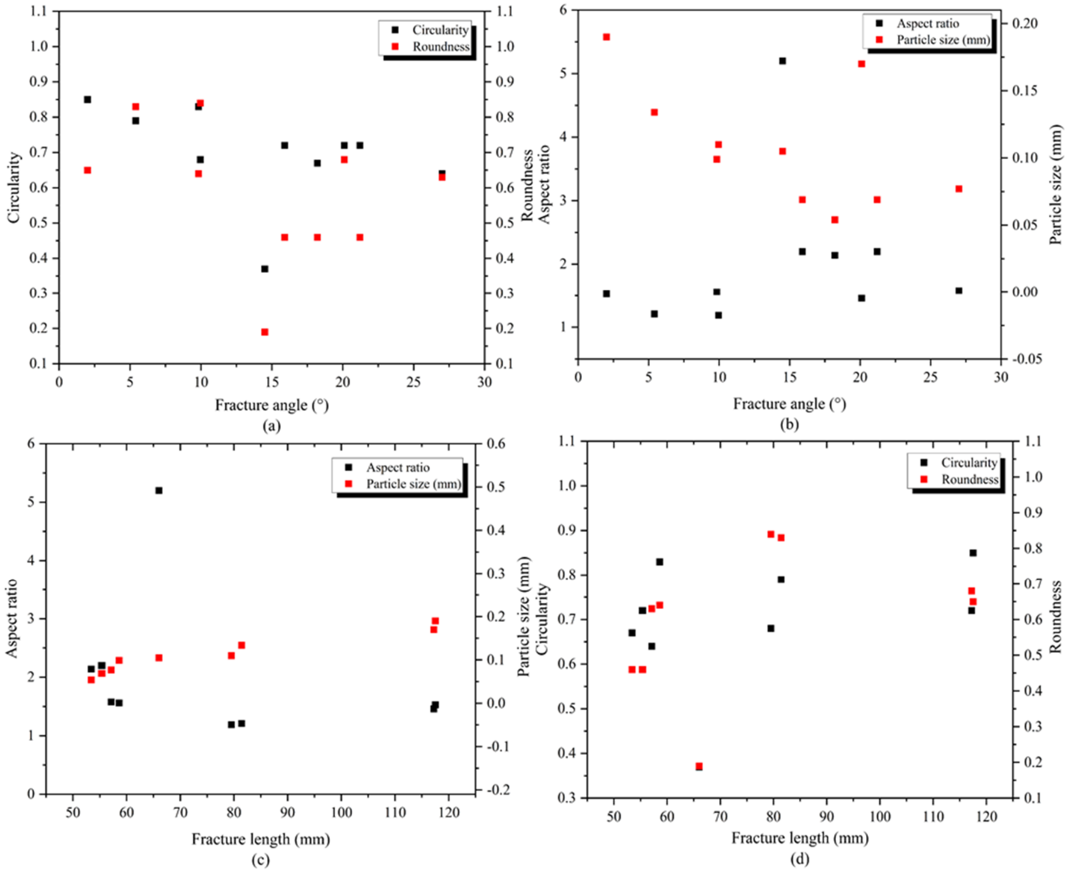

Figure 11. Relationship of fracture angle and fracture length with particle shape and size of fresh sandstone.

Figure 12 presents the findings of the fracture characteristics such as the fracture deviation area (FDA) and fracture maximum deviation distance (FMDD) of fresh sandstone. Figure 12(a) and 12(b) show that FDA of fresh sandstone decreases as the roundness, circularity, and particle size increases. Conversely, FDA slightly increases with an increase in the aspect ratio of sandstone particles. Figure 12(c) and 12(d) present the relationship of the fracture maximum deviation distance (FMDD) and the fracture characteristics and particle size. The results obtained indicate that FMDD of fresh sandstone decreases slightly with increasing circularity, roundness, and particle size. Conversely, FMDD nearly remains the same as the aspect ratio rises.

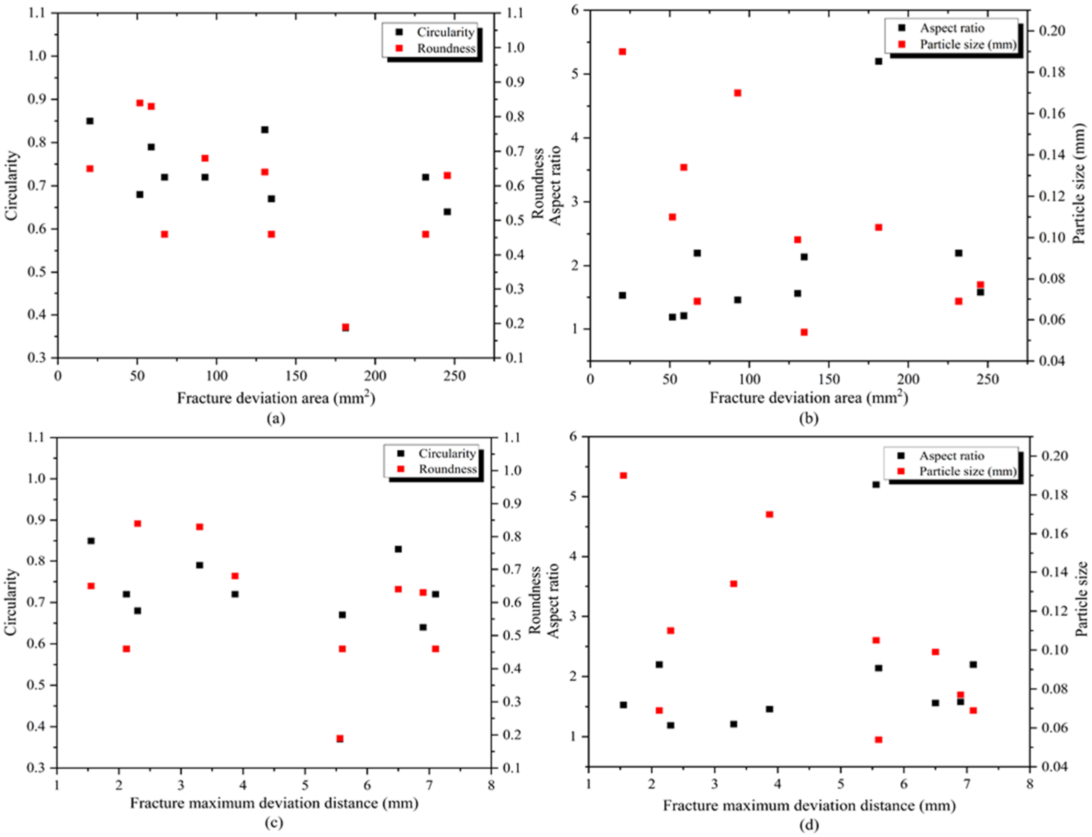

Figure 12. Relationship of fracture deviation area and fracture maximum deviation distance with particle shape and size of fresh sandstone.

A progressive increase in the particle size is an evidence of decreasing the crack damage threshold and crack coalescence. This is because a particle with a length boundary and a higher number of intergranular cracks results from particle size increment, which ensures an additional route of weakness for cracks growth to propagate through and assist a prompt damage. Therefore, the fracture characteristics were identified to increase with an increase in the particle size. From the results obtained, the fracture characteristics increase with an increase in particle roundness and circularity. The reason for that is the effect of roundness and circularity is closely related to the porosity model. According to the literature, as the roundness and circularity increase, the porosity of rock also increases [27]. On the basis of the pore structure, it can be classified into the spherical pores and flat cracks. The pores in the rocks behave like a defect or incipient discontinuity. As a result, increasing porosity increases the chances of increasing fracture length, roundness, and angularity.

In comparison to the fresh sandstone, slightly weathered sandstone exhibits fractures with a higher number of branches. The effect of particle shape and size on the fracture characteristics in slightly weathered sandstone is an evidence with minor variation compared to fresh sandstone. Figure 13 depicts the relationship of the fracture length and fracture angle with particle shape and size in a slightly weathered rock. The results in Figure 13(a) and 13(b) show that the fracture angle presents random results with an increase in roundness, circularity, aspect ratio, and particle size. The reason for this is that the frequency of pore spaces increases as the weathering grade of sandstone increases. Therefore, the effect of stresses in the loading direction increases. In addition, the coalescence of neighboring micro-flaws causes a slight increase in the fracture angle as compared to fresh sandstone. Fracture length (FL) gets more random as particle circularity and roundness increases, as shown in Figure 13. The reason for this is that the frequency of pore spaces is not substantially dependent on the circularity and roundness of particles. However, FL of slightly weathered sandstone increases as the particle size increases. Furthermore, FL rises randomly as the aspect ratio increases.

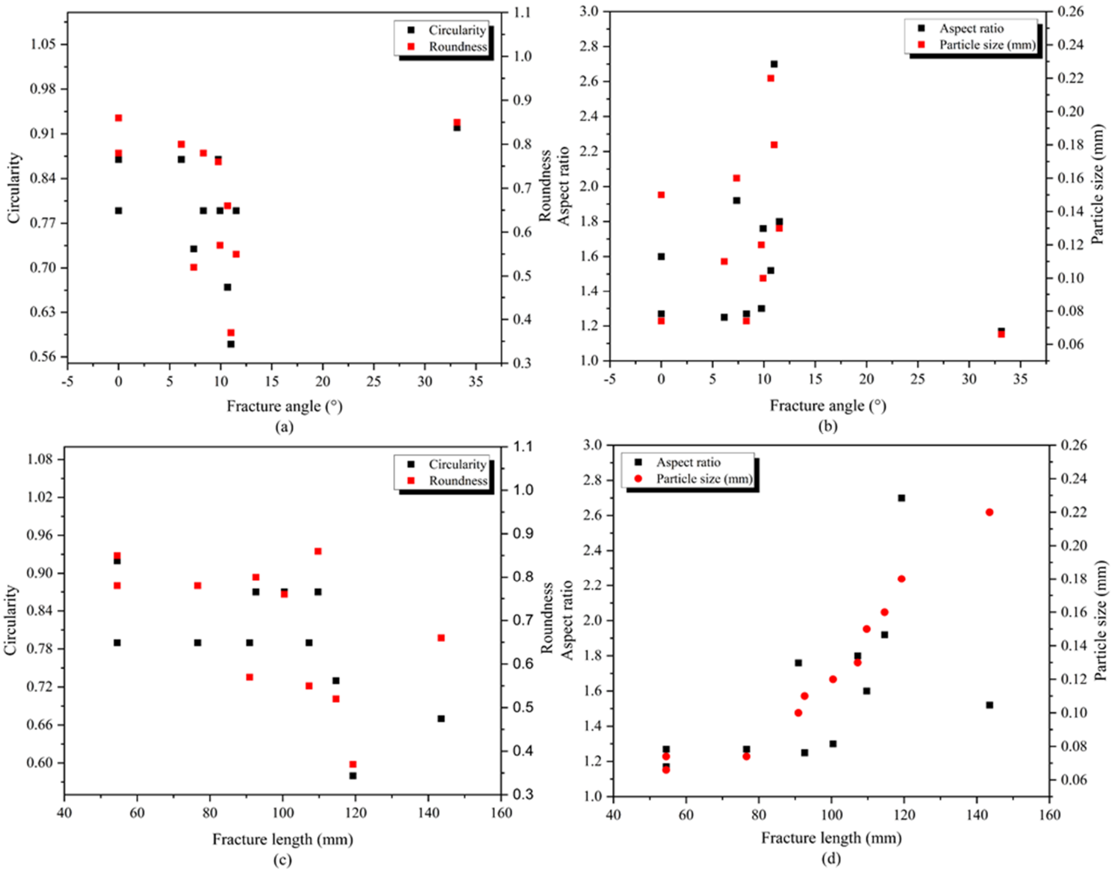

Figure 13. Relationship of fracture angle and fracture length with particle shape and size of slightly weathered sandstone.

Figure 14 depicts the relationship of the fracture deviation area (FDA) and fracture maximum deviation distance (FMDD) with the particle shape and size of slightly weathered rocks. The results in Figure 14(a) reveal that FDA slightly decreases as the particle circularity and roundness increases. According to Figure 14(b), FDA of slightly weathered sandstone produces erratic outcomes as the particle size and aspect ratio increases. Figure 14(c) shows that FMDD of slightly weathered sandstone decreases slightly as the circularity and roundness of slightly weathered sandstone particles increases, whereas FMDD increases slightly with increasing particle size and aspect ratio, as illustrated in Figure 14(d). As discussed earlier, an increase in porosity enhances the probability of fracture characteristics development. According to a previous research work, the voids ratio of a rock rises with increasing weathering grade [28].

Figure 15 depicts the effect of particle shape and size on the fracture angle (FA) and fracture length (FL) of moderately weathered sandstone. The results in Figure 15(a) and 15(b) show that the fracture angle increases randomly with particle circularity, roundness, and particle size. The results also demonstrate that the fracture angle decreases as the aspect ratio of moderately weathered sandstone increases. Figure 15(c) shows that the fracture length of moderately weathered sandstone increases as the particle roundness and circularity increases. Nevertheless, as illustrated in Figure 15(d), FL reduces with an increase in the aspect ratio, although it increases with an increase in the particle size.

Figure 16(a) and 16(b) depict that FDA of moderately weathered sandstone remains almost the same with an increase in the particle circularity and roundness, particle size, and aspect ratio. Similarly, the results obtained also reveals that FMDD remains almost the same as the particle circularity, roundness, particle size, and aspect ratio increase, as shown in Figure 16(c) and 16(d). The reason for this is that as the weathering grade increases, the porosity of sandstone increases. As a result, the chances of specimen breakage along with the loading line increase but as the number of micro-flaws increases outside the loading line, the main fracture deviates from the loading line.

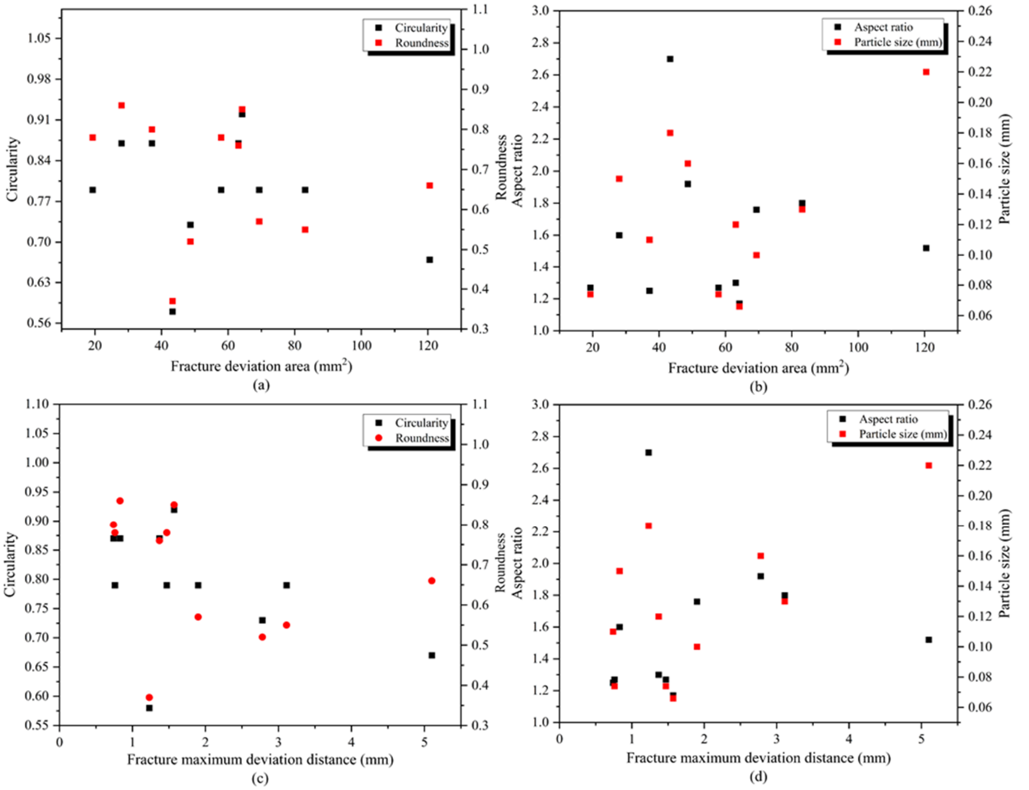

Figure 14. Relationship of fracture deviation area and fracture maximum deviation distance with particle shape and size of slightly weathered sandstone.

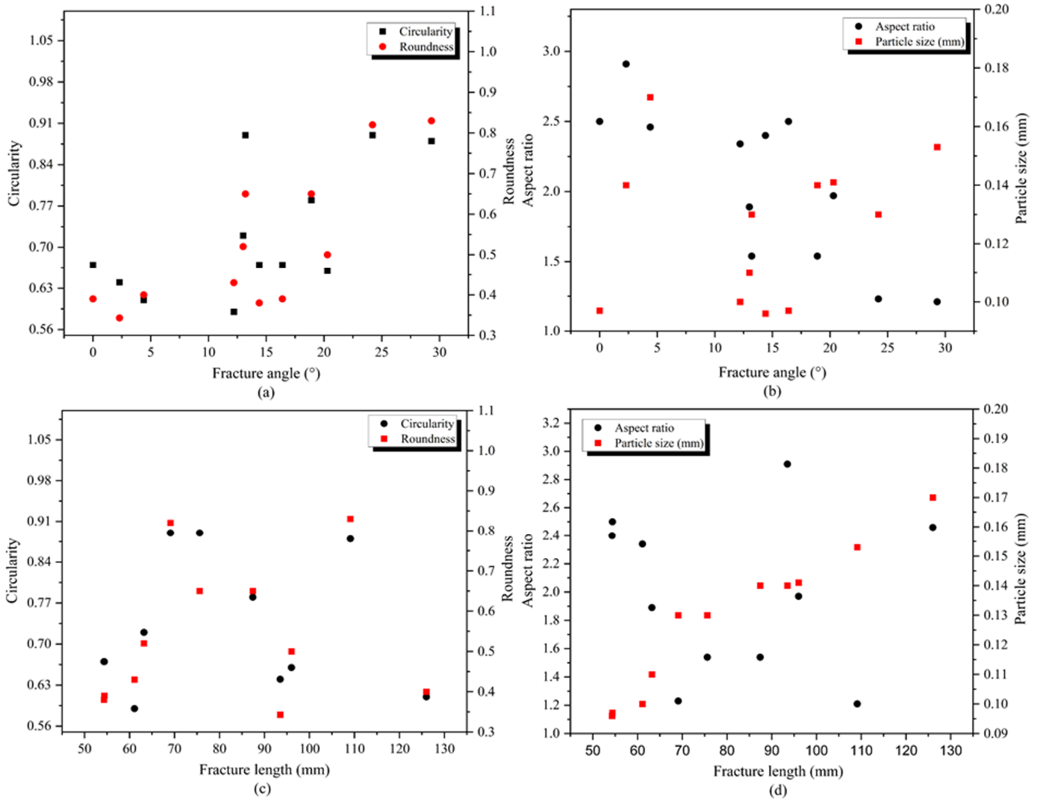

Figure 15. Relationship of fracture angle and fracture length with particle shape and size of moderately weathered sandstone.

As aforementioned, micro-flaws have an effect on the mechanical behavior and the fracture characteristics of sandstone. Similarly, sandstone frequently presents a wide range of fracture characteristics and mechanical responses due to variations in the weathering grades and the existence of natural fractures. These natural fractures in sandstone are regularly cemented by different minerals or cementation removed by weathering and/or stained with iron, which can affect the stress-induced fracture pattern and rock. These effects along with fracture orientation and location on the mechanical behavior and failure modes resulting from dynamic loading are essential to understand.

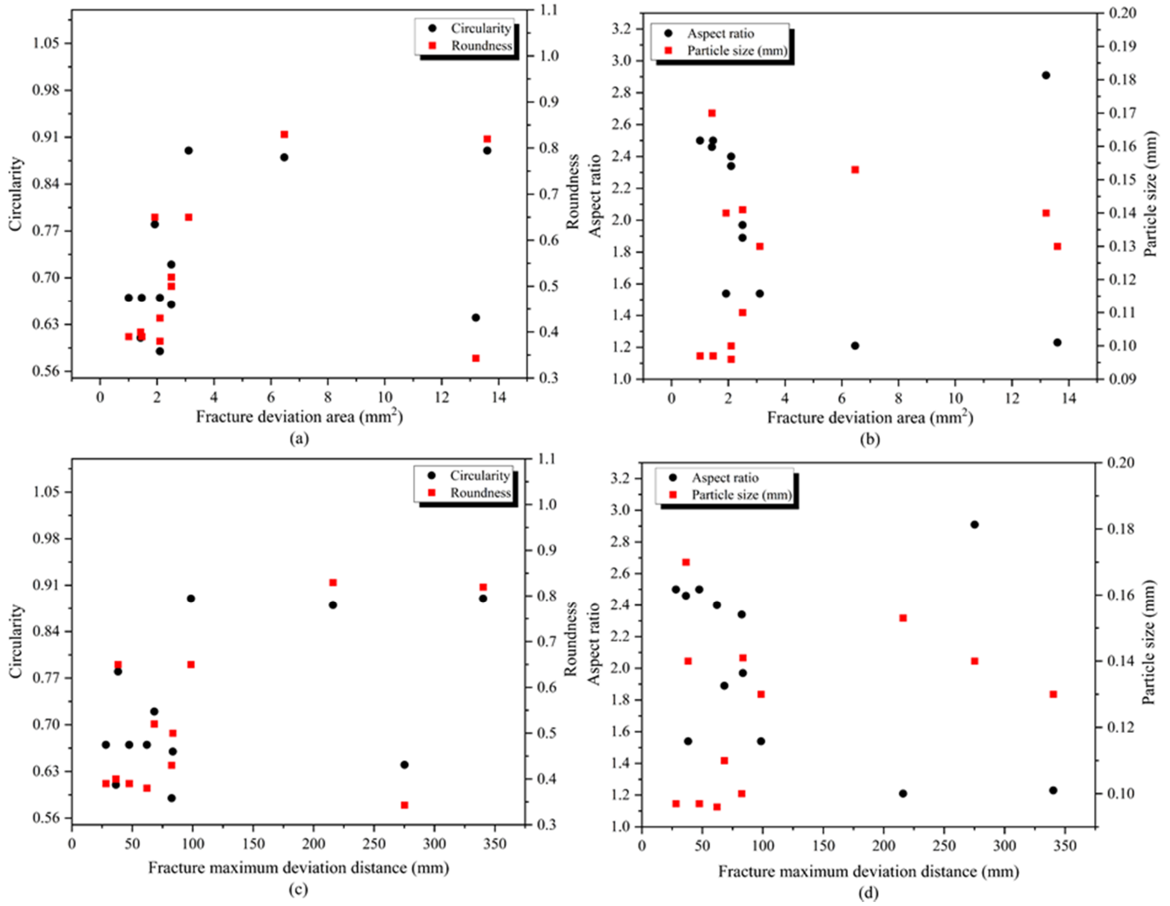

Figure 16. Relationship of fracture deviation area and fracture maximum deviation distance with particle shape and size of moderately weathered sandstone.

4. Discussion

The behavior of rocks is the response to the particle-to-particle interaction. Consequently, evaluating the effect of the particle shape and size on the fracture characteristics is significant in terms of the rock damage. In the literature, several researchers have used the discrete element method (DEM) and PFC in order to evaluate the mechanical behavior of rocks. Unfortunately, the application of these methods has a limitation of correspondence of the simulated particle shape and size distribution to the rock particles. In order to simulate the rock particles in PFC and DEM, it is essential to consider the real particle shape and size.

The literature presents several particle shape descriptors such as elongated, flakey, spherical, sphericity, roundness, circularity, aspect ratio, and roughness [29]. This work mainly focuses on the shape descriptors such as circularity, roundness, and aspect ratio since it is impossible to use all the shape descriptors simultaneously. The reason for that is the particle shape described by various researchers in several forms. Therefore, this work focused on the shape descriptor that could be acquired from micrographs using the ImageJ software.

A suitable number of particles should be analyzed from a statistical perspective, acquiring appropriate and optimistic outcomes. The techniques and instruments used for particle measurement are also fraught with complications. The image analysis-based techniques such as scanning electron microscopy (SEM) have a limited sensing range to the depth of flow. This problem can be solved using the artificial intelligence (AI) based methods such as a neural network, genetic algorithm or fuzzy logic. The AI-based approaches require extensive coding, whereas the image analysis-based techniques require less time, and also give faster and more consistent results. Therefore, MCS is a viable tool to incorporate the inherent uncertainty related to particle shape and size [2].

5. Conclusions

In this research work, the effect of particle morphology on the fracture characteristics of fresh, slightly weathered, and moderately weathered sandstone was investigated. According to the literature, three types of shape descriptors were preferred: circularity, aspect ratio, and roundness. This work demonstrated that the fracture angle of sandstone had an unclear relationship with the particle shape and size. The effect of particle size on the fracture length (FL) was obvious, and it was concluded that FL increased with increase in the particle size. The fracture length provides random outcomes regarding the particle shape, which suggests that the particle shape has essentially little influence on the fracture length. The fracture deviation area and the fracture maximum deviation distance were observed to have no association with the particle shape or size. The results obtained also revealed that Monte Carlo simulation was a viable tool for integrating the inherent uncertainties related to the particle shape and size.

Furthermore, the results obtained also revealed that the sandstone fracture characteristics were as weathering sensitive as most other properties. Fresh, slightly weathered, and moderately weathered sandstone present slight differences in the fracture characteristics. Overall, the fracture length increases as the weathering grade increases.

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کاربرد شبیه سازی تصادفی در ارزیابی اثر مورفولوژی ذرات بر ویژگی های شکست ماسه سنگ

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چکیده:

آزمایش کشش غیرمستقیم به منظور بررسی اثر مورفولوژی ذرات (شکل و اندازه) بر ویژگی‌های درزه‌های ماسه سنگ با درجه هوازدگی مختلف انجام شد. چندین ویژگی شکستگی به طور عمیق در این کار از جمله طول شکستگی (FL)، ناحیه انحراف شکستگی (FDA)، زاویه شکست (FA)، و حداکثر فاصله انحراف شکستگی (FMDD) مورد بحث قرار گرفت. یک میکروسکوپ رومیزی (TTM) برای اندازه گیری مورفولوژی ذرات استفاده می شود. تکنیک‌های تحلیل تصویر شکل و اندازه ذرات مرتبط با عدم قطعیت را القا می‌کنند. یک میکروسکوپ رومیزی (TTM) برای اندازه گیری مورفولوژی ذرات استفاده شد. پردازش تصویر شکل و اندازه ذرات مرتبط با عدم قطعیت را القا می‌کنند. بنابراین از شبیه‌سازی مونت کارلو (MCS) به منظور ترکیب مورفولوژی ذرات مرتبط با عدم قطعیت‌های ذاتی استفاده شد. نتایج به‌دست‌آمده نشان داد که زاویه شکست ماسه‌سنگ رابطه نامشخصی با شکل و اندازه ذرات نشان می‌دهد. تأثیر اندازه ذرات بر FL کاملاً آشکار است و FL با اندازه ذرات افزایش می یابد. در مقابل، شکل و اندازه ذرات رابطه نامشخصی با ویژگی‌های شکست دارند. علاوه بر این، تخلخل ماسه سنگ بر ویژگی های شکست تأثیر می گذارد، که با درجه هوازدگی افزایش می یابد. علاوه بر این، یافته‌ها نشان می‌دهند که شبیه‌سازی مونت کارلو یک ابزار مناسب برای ادغام عدم قطعیت‌های ذاتی مرتبط با شکل و اندازه ذرات است.

کلمات کلیدی: مورفولوژی ذرات، ماسه سنگ، ویژگی های شکست، شبیه سازی مونت کارلو، درجه هوازدگی.
