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Weathering induced Brazilian Tensile Strength and fracture characteristics of sandstone and their prevailing mutual association

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ABSTRACT

This paper evaluates the variation and relationship of Brazilian tensile strength and fracture characteristics of sandstone under different weathering grades. Brazilian tensile strength experiments were performed on Fresh and slightly weathered sandstone specimens using an automated compression measuring machine UTC-5431. Image-based fracture characterization was carried out using public domain open-source software ImageJ. Furthermore, SPSS and Microsoft Excel were used to analyze the relationship between Brazilian tensile strength and fracture characteristics. Results demonstrate that sandstone tensile strength decreases as fracture maximum deviation distance (FMDD), fracture deviation area (FDA) and fracture length (FL), and weathering grades increase. Additionally, FMDD, FDA, and FL increase with an increase in weathering grade. The correlation results revealed that the tensile strength of fresh sandstone has a strong relationship with FMDD, FDA, and FL. Whereas, in the case of slightly weathered sandstone, BTS has a strong correlation with FMDD and FDA. Whereas multiple regression analysis shows that BTS has a strong relationship with fracture characteristics. Therefore, estimating the fracture characteristics of sandstone using its tensile strength is convenient, however, the sensitivity of sandstone strength properties and fracture characteristics to weathering must be acknowledged.

Keywords: Fracture angle, Fracture maximum deviation distance, Fracture deviation area, Fracture length, ImageJ

1. Introduction

Rock fracture propagation mechanism is an attractive research area with potential application in the geotechnical field (Erarslan 2016, Liu et al. 2020). Mechanical properties, especially tensile strength, should be accurately calculated to assess fracture behavior in rock. (Shi et al. 2020). It is also undeniable that a thorough understanding of mechanical responses and fracture behavior is a core component of rock mechanics. (Grechka et al. 2006, Lee et al. 2018, Shah et al. 2020). This complete insight may also be more obvious after evaluating the link between tensile strength and fracture characteristics (fracture maximum deviation distance, fracture deviation area, fracture angle, and fracture length). The fracture deviation area includes the area surrounded by the main fracture and the loading line. Based on the literature, fracture maximum deviation distance refer to the maximum distance between the fracture traces and the diametrical center (Feng et al. 2020). Researchers observed that fracture characteristics have a profound effect on weathering-induced fracture propagation (Lei et al. 2015, Kang et al. 2019, Koohbor et al. 2019). During weathering, fractures are a major infiltration channel that greatly affects the road cut slope (Jiao et al. 2005, Hencher 2010, Regmi et al. 2013). Fracture plays a crucial role in slope water penetration and migration, while significantly decreases the stability of the rock slope (Agam et al. 2016, Jaques et al. 2020, Shah et al. 2020, Zhang et al. 2020). Fracture characteristics anisotropy is thus a well-known phenomenon in rock mechanics, however, its effect on the geotechnical structure is frequently neglected (Zhao et al. 2020). Therefore, knowledge regarding fracture characteristics and their relationship with strength properties is crucial.

According to Whittaker et al. (1992), rock fracture behavior can be analyzed by linking fracture parameters to index test outcomes. Whereas, Bhagat (1985) experimentally analyzes that rock fracture toughness exhibit positive relation with tensile strength. Additionally, Zhang (2002) analyzed the available data in the literature to assess the general relationship between Mode-I fracture toughness and tensile strength. The author proposed an empirical relationship ($\sigma_t = 6.88K_{IC}$) between tensile strength and Mode-I fracture toughness for both soft and hard rocks (Bhagat 1985). Similarly, Wang et al. (2007) determined a relationship between fracture toughness and tensile strength of clay and developed an empirical relationship (K_{IC}=0.3546σ_t). The past decades have seen rapid development in fracture mechanics, where the research is mainly focused on the relationship between fracture toughness and tensile strength. However, the relationship of fracture characteristics with tensile strength deserves the same attention since the final property of geotechnical structures is dependent on fracture behavior. As a result, Li and Li (2015) evaluated the relationship between fracture surface area and tensile strength of cement paste with various supplementary materials. They revealed that the fracture area of cement paste increases with a decrease in tensile strength and proposed that polynomial is the best-fitted model (σ_t=- 3070 a^2+ 27261 a^2- 80234 a + 80367).

Several studies are dealing with evaluating the effect of loading rate

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on the fracture characteristics of rock material Zhou et al. (2010), Feng et al. (2020), and Bažant et al. (1993). Nevertheless, there is a lack of information on how different weathering grades affect fracture characteristics and how they interact with one another and with BTS. This research advances in understanding the compression fracture problem, linking this phenomenon to fracture mechanics induced by tensile loading. Tension fracture induced by compression is the prominent root of fracture genesis. Therefore, by incorporating the FMDD, FDA, FA, and FD, a new relationship has been established between Brazilian tensile strength and fracture characteristics. This study also investigated the sensitivity of weathering-related tensile strength and fracture characteristics correlation.

2. Material and methods

2.1. Brazilian tensile strength measurement

The material tensile strength can be measured either directly or indirectly, however rock tensile strength is often estimated indirectly. The indirect approach (Brazilian test) appears to be the only method for which specimen preparation is not rigorous and experimental data analysis is quite simple. Consequently, in this study, the Brazilian tensile strength test method was used to determine the tensile strength of sandstone considering the weathering grades. The sandstone samples studied in this research were collected from Sor-Range coal mines area Quetta, Pakistan. The area is an active site for underground coal mines and the coal bed is roofed with sandstone up to the outcrop. A haul road is constructed to access each mine by cutting the sandstone in the area. The fresh sandstone samples were acquired from an underground mine while slightly weathered sandstone samples were collected from the outcrop. The fresh sandstone was dark grey in appearance and the slightly weathered sandstone exhibited the brown color shown in Figure1. The weathering grade was analyzed visually similar to the methodology described in International Organization for Standardization (ISO) 14689-1 (2003) and British Standards (BS) 5930 (1981) (BS 1981, BSI 2004, Tating 2015).

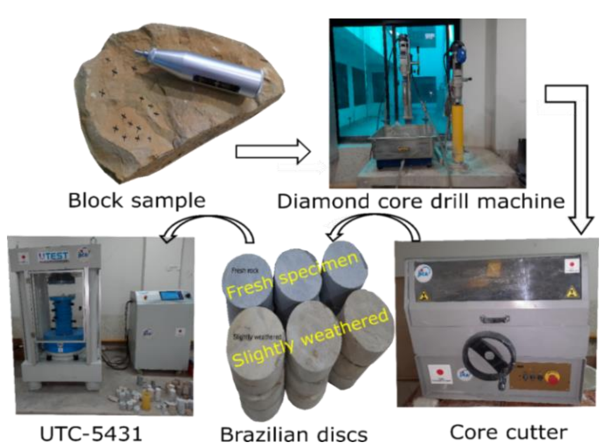

Figure 1. Procedure of sample preparation for the Brazilian test

Block samples are cut by hand from the exposed sandstone according to weathering grade. All the samples were preserved according to the methodology described by BS 5830:1999 (+A2:2010) (BSI 2010). The sandstone cores with a diameter of 54 mm and with dif ferent thicknesses were obtained using a diamond core drill and further cut into Brazilian disk samples of 27 mm, 28 mm, and 29 mm (thickness/diameter ratio of 0.5 to 0.6) thickness respectively. The specimens were categorized into two group's fresh and slightly weathered specimens. Considering the weathering grade of sandstone's Brazilian tests were employed using the UTC-5431 automatic compression testing machine shown in Figure 1.

2.2. Image-based fracture characterization

A close-range camera was used to obtain experimental testing video that was further transformed into frames to capture the fracture propagation images. Fracture characteristics (see Figure 2) such as FMDD, FDA, FA, and FL are analyzed from a digital image using a manual method. Images are reported with fractures that have clear and observable boundaries. An open architecture program ImageJ was used to analyze and process the captured images. ImageJ is a public domain open-source software based on Java 1.5 and a lateral virtual machine. In the initial step image file was uploaded to a new window using File>Open, File>Import, and Drag & Drop. Followed by spatial calibrations that include calibrating a single-pixel image dimension to defined values. By using the line "selection tool" a line over a known length scale bar was drawn, followed by "set scale" from the "analyze" menu. The "known distance" dialog box was entered into the "Global" checkbox to add spatial calibration to all open picture windows. A similar technique was extended to digital camera photos. For image processing algorithms, a binary image (black and white) was generated using the dialog tool "Image>Adjust>Threshold" In binary images, while the backdrop is white, objects are called black. In proper thresholding, the images were translated to 8-bit, 82 grey levels. Afterward, binary images and manually traced fractures were created of distinguishable boundaries. Measurement of fracture characteristics using the ImageJ dialog box "set measurement" Macro fracture research was performed to determine macro fracture involvement. The SPSS and Microsoft Excel is a comprehensive set of analysis tools that were used for regression analysis to evaluate the relationship between fracture characteristics and BTS.

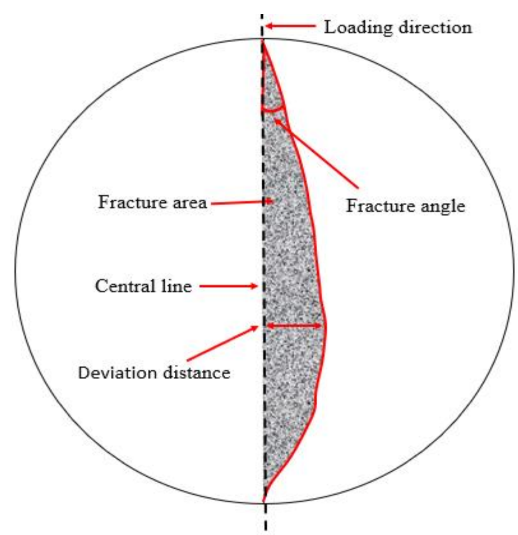

Figure 2: Diagram of fracture maximum deviation distance, fracture deviation area, fracture angle.

3. Results and analysis

3.1. Analysis of Brazilian tensile strength

Indirect tensile tests were performed to evaluate the variability in Brazilian tensile strength of different weathering grades sandstone. Table 1, displays the sandstone tensile strength and fracture characteristics obtained during this analysis. It has been proven that the tensile strength of rock material decreases with increasing weathering grade (Jaques et al. 2020). When analyzing Table 1 the difference between the highest and lowest strength value according to weathering grade is 2.071 MPa and 2.99 MPa. Therefore, sandstone exhibit a moderate impact on mechanical behavior between fresh and slightly weathering sandstone. This may be because physical and chemical weathering did not induce significant mineral alteration that could explain the loss of material strength. In sandstone, the difference in

FMDD is pounced concerning weathering grade. The FMDD in fresh sandstone revealed the largest value of 14.52 mm. However, the FMDD maximum value for the slightly weathered sandstone is 11.23mm, indicating that it is lower than the value for fresh sandstone.

Moreover, FDA exhibits almost similar behavior in both fresh and slightly weathered sandstone with an average value of 141.344 mm^2 and 160.694 mm^2. The results also revealed that FDA might have correspondence with the FMDD. The value of the fracture angle demonstrates no significant changes at the following degree of weathering, although the fracture length in fresh samples is lower relative to that of slightly weathered sandstone. This could be due to the progressive alteration of microstructures with an increment of weathering grade. Consequently, the sample exhibits fracture branches along with the main fracture with an increased weathering grade.

Table 1. Brazilian Tensile Strength and Fracture Characteristics of Sandstone.

Sample name	BTS (MPa)	FMDD (mm)	FDA (mm^2)	FA (°)	FL (mm)
F6	5.532	14.52	506.47	13.9	50.641
F8	2.994	0.989	4.548	0	65.397
F9	7.112	3.65	169.92	7.78	52.859
F50	4.877	1.35	36.36	3.01	109.782
F51	3.946	1.437	21.034	0.81	54
F52	4.55	4.42	130.156	4.88	54.012
F53	4.928	5.73	120.92	7.114	54.135
SW 4	0.404	5.016	84.97	0.42	73.966
SW 5	0.00393	3.53	97.1	11.5	117.767
SW 6	0.022	5.11	88.35	2.18	54.823
Sw51	5.041	7.28	236.49	1.48	109.307
Sw52	2.141	7.31	209.1	9.41	131.309
Sw53	3.46	11.23	350.48	7.68	135.386
Sw54	1.622	2.35	58.37	3.23	54.01

3.2. Fracture characteristics analysis

The damage mechanism in fresh and slightly weathered rock can be characterized by fracture shape, type, and length. In rock, when stress gains the peak strength of a typical specimen, the specimen fails by exhibiting brittle fractures. The findings showed that the fractures are almost straight in fresh rock and approximately pass along loading axis, reaching all loading ends except in specimen F-6. The loading rate and specimen thickness have a slight effect on the shape of the fracture in fresh rock, almost all specimens' exhibit tip-to-tip brittle fracture. The fracture in slightly weathered rock also deviates from the central loading line and exhibits multiple fracture patterns (See Figure 3).

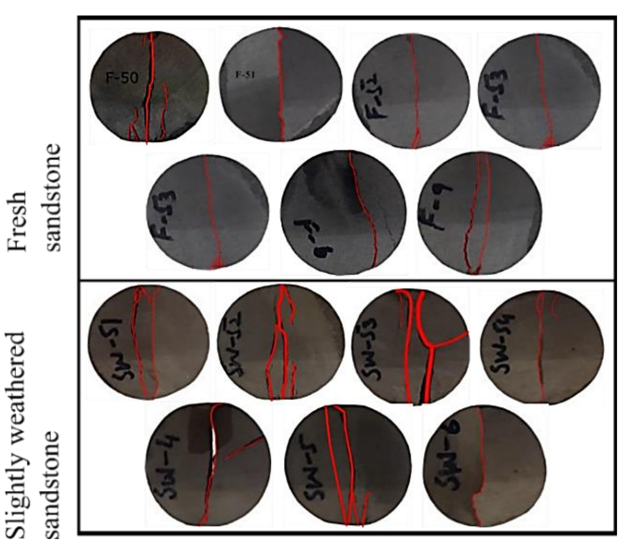

Figure 3. Crack propagation pattern in fresh and slightly weathered sandstone under various loading rates and specimen thickness.

The fracture produced in specimen F-50 starts at the center line and deviates from the center and fractures branches are also created at the lower portion. In specimen F-51, the fractures move through the centerline; therefore, this calculated strength represents the tensile strength of the rock. The fractures propagation in specimens F-6 and SW-53 substantially does not follow the central line, therefore the calculated strength represents strength characterization for the Brazilian test.

When the strength reaches its peak value, the slightly weathered specimen under loading does not fail instantly but degrades as a whole. During fracture propagation, the main tip-to-tip crack is accompanied by numerous small fractures through the specimen. After the post-peak stage of the specimen, the crack that is the main deformation area is moderately induced and the main crack is provided with new fracture areas and the scale of damage is rising and expanding. It can be seen from

Figure **3**, that there are several secondary cracks in specimens SW-52, SW-53, and SW-5; these cracks increase in number with an increase in weathering grade.

4. Correlation

The Brazilian tensile strength of rock decreases and fracture length increases with increasing weathering grade. A correlation was estimated for both fresh and slightly weathered sandstone distinctly to evaluate the effect of weathering on the relationship between Brazilian tensile strength and fracture characteristics.

4.1. Fresh sandstone

The results related to FDA, FMD, and FL indicate that in fresh sandstone, the fracture mostly followed the central loading line. The fractures, on the other hand, were found to be devoid of branches. The correlation coefficient and the regression model were used to determine the relationship between tensile strength and fracture characteristics. The regression model for each type of variable was evaluated based on the R-squared value. The results revealed that there is a moderately strong relation (correlation coefficient=0.77) between the variables. The double reciprocal model is given in Table 2 and Figure 4 is selected as the best model based on the correlation coefficient and R-squared (60.2%) value.

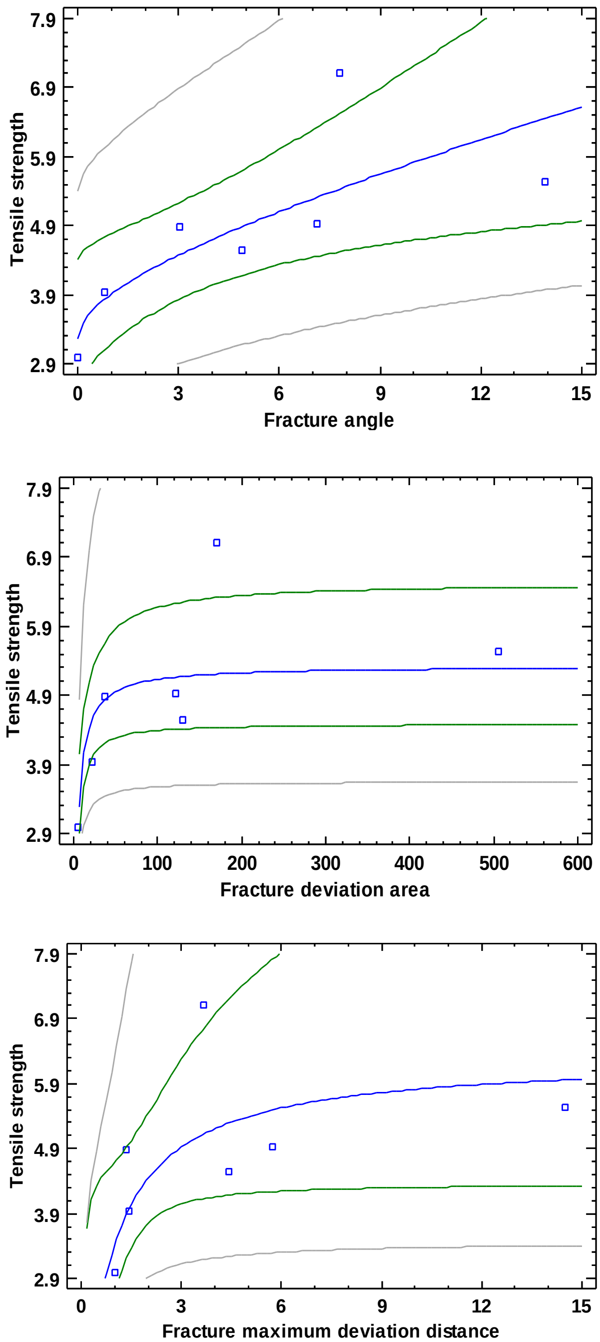

Figure 4. Scatterplot for the fitted model of various relationships in the fresh specimen

The relationship between Brazilian tensile strength and fracture deviation area is perfectly fitted to the double reciprocal model with a 95% confidence interval. For the selected model the correlation coefficient=0.89 and R-squared = 79.1%. Regression analysis of BTS*FA revealed that Logarithmic-Y square root-X is the fitted model, and the ANOVA table indicates that variables exhibit a relatively strong relationship with 95% confidence. The selected model is evaluated, based on correlation=0.85 and R-squared =72.1%. A similar methodology was applied for a relation between indirect tensile strength and fracture length and found that squared-Y reciprocal-X is the fitted model. The model selection constraints correlation coefficient = 0.27 and R-squared =7.23% indicated that there is a relatively weak relationship between BTS and FL. Table **2** gives the mathematical representation of the fitted model for each type of relationship between indirect tensile strength and fracture characteristics of fresh sandstone, while the scatterplot for best-fitted models is given in Figure 4.

4.2. Multiple regression analysis

In multiple regression, the best-fitted model was determined using the ordinary least square approach (OLS). BTS is used as a dependent variable, while FMDD, FDA, FL, and FA are used as independent variables. Choosing the best model requires several criteria. P-value and R-squared were used to select the best model. These values verified the regression model. The ANOVA test p-values are acceptable (0.044), and the R-squared is 97.8%. Therefore, the P-value and R-square value exhibit the accuracy of the regression model, as shown in equation 1.

$$BTS = 4.7 - 0.7 * FMDD + 0.0073 * FDA + 0.57 * FA - 0.0039 * FL \qquad (1)$$

4.3. Slightly weathered rock

The experimental findings showed a comparatively higher fracture length in slightly weathered sandstone compared to fresh sandstone specimens. The results revealed that there is a strong relationship between Brazilian tensile strength and fracture maximum deviation area, based on the correlation coefficient of 0.63 and R-squared = 40.2%. Based on these constraints linear model was selected as a fitted model. Table 3 gives the mathematical representation of the fitted model for each type of relationship between indirect tensile strength and fracture characteristics of fresh sandstone, while the scatterplot for best-fitted models is given in Figure 5.

The regression model which establishes the relationship between BTS and fractures deviation area is squared root-X. The relationship is modeled based on R-squared = 59.4% and correlation coefficient = 0.77. The results show a relatively strong relationship between the variables. In the case of BTS*FA reciprocal-Y logarithmic-X model was adopted, but the relationship between variables is weak based on correlation coefficient = 0.44 and R-squared = 20.1%. Again, to understand the relation between Brazilian tensile strength and fracture length square root-X model is selected based on correlation coefficient 0.48 and R-saqured-23.2%. The results indicate there is a relatively weak relationship between BTS and FL.

4.4. Multiple regression analysis

The ordinary least square method was used to obtain the best-fitted model in the multiple regression analysis. The BTS value is used as a dependent variable, whereas the FMDD, FDA, FL, and FA are used as independent variables in the analysis. Some criteria should be considered when choosing the optimal model. For selecting the optimum model P-value and R-squared values were used. The P-value and R-squared value validated the appropriate regression model. The p-values (ANOVA test) for the models are satisfactory (0.05), and the R-squared value is 97.3%. As a result, all these statistics proved the accuracy of the regression model as shown in equation 2.

$$BTS = 2.0 - 1.24 * FMDD + 0.045 * FDA - 0.3 * FA + 0.015 * FL \qquad (2)$$

5. Discussion

This study establishes the context for the relationship between Brazilian tensile strength and fracture characteristics in rock. Previously few researchers have focused on evaluating this relationship but they are limited to other materials, such as Li and Li (2015) analyzing the relationship between tensile strength and fracture surface area of cement paste under different supplementary materials. However, few studies have explored the relationship between fracture toughness, tensile strength, and process zone (Jin et al. 2011, Dutler et al. 2018).

Table 2. Fitted Model for Various Relationships in Fresh Sandstone Specimen Based on Constraints Selection.

Variable	Model	Equation	Correlation	R-squared
BTS*FMDD	Double reciprocal	BTS = 1/(0.16 + 0.133/FMDD)	0.77	60.23%
BTS*FDA	Double reciprocal	BTS = 1/(0.18 + 0.69/FDA)	0.89	79.1%
BTS*FA	Logarithmic-Y square root-X	BTS = exp(1.18 + 0.18 * sqrt(FA)	0.85	72.1%

Table 3. Constraints-Based Fitted Model for Various Relationships in a Slightly Weathered Sandstone Specimen.

Variable	Model	Equation	Correlation	R-squared
BTS*FMDD	Linear	BTS = − 0.64 + 0.41 * FMDD	0.63	40.2%
BTS*FDA	Square root-X	BTS = − 2.52 + 0.36 * sqrt (FDA)	0.77	59.4%
BTS*FA	Reciprocal-Y logarithmic-X	BTS = 1/(1.58 + 35.7 * ln(FA)	0.44	20.1%
BTS*FL	Square root-X	BTS = − 2.96 + 0.49 * sqrt(FL)	0.48	23.2%

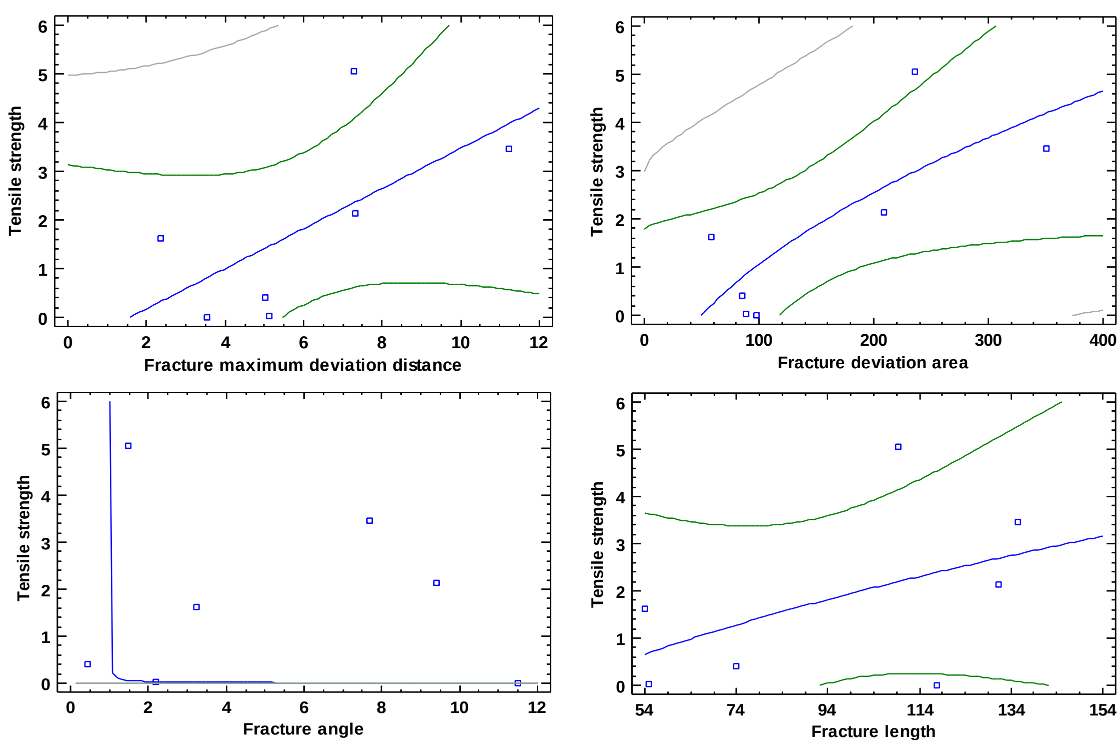

Figure 5. Scatterplot for a fitted model of various relationships in a slightly weathered sandstone specimen.

In this analysis, Brazilian tensile strength and fracture characteristics demonstrated low to a very low association, and further analysis can verify the findings provided.

Additionally, a correlation and regression study was conducted to determine the relationship between fracture characteristics. ANOVA results indicate that there is a significant relationship between FMDD and FDA with a 95% confidence level. Regression analysis reveals that R-squared statistics indicate 96.8% double squared model fitting and a correlation coefficient of 0.985 show a relatively strong relationship between variables. The equation for the fitted model for the relationship between FMDD and FDA is given by equation 3 and this relationship is also represented by Figure 6. Similarly, the relationship between FMDD and FA was evaluated, and the ANOVA results indicate that there is a statistically significant link that exists with a 95% confidence level. The values of R-squared obtained from regression analysis indicate that the double square model is fitted to describe 49.4% of the variability in Fracture maximum deviation distance, also correlation coefficient = 0.70, showing that there is a moderately strong relationship between FMDD and FA. The fitted model is represented by equation 4 and Figure **6** respectively. The relationship between FMDD and FL is also assessed, and the ANOVA table statistics did not show a significant relation. Consequently, a weak relationship was observed that was not statistically relevant (R-squared = 7.23% and P-value>0.05).

$$FMDD = sqrt\,(8.25 + 0.00082 * FDA^2) \quad (3)$$
$$FMDD = sqrt\,(9.57 + 0.71 * FA^2) \quad (4)$$
$$FDA = exp\,(2.85 + 0.83 * sqrt\,(FA)) \quad (5)$$

Moreover, the relationship between fracture deviation area and fracture angle is determined and the relation is found to be moderately strong. From the regression analysis, the resultant logarithmic-Y and square root-X model portray the best relationship between FDA and FA. The fitted model is mathematically and graphically represented by equation 5 and Figure 6. The fitted model is selected based on R-squared (56.2%) and correlation coefficient (0.75). Similarly, the relationship between fracture deviation area and fracture length is also determined.

The regression study summarizes the fitted model's statistics based on the correlation coefficient (0.29) and R-squared (8.66%). The results revealed that there is a relatively weak relationship between FDA and FL. Regression analysis was performed to appraise the relationship between fracture angle and fracture length and the results show that there is a weak relation between variables.

The calculated values were obtained for the coefficient of correlation (0.28) and R-squared (8.1%) and the square root-Y squared-X model was selected based on these statistics.

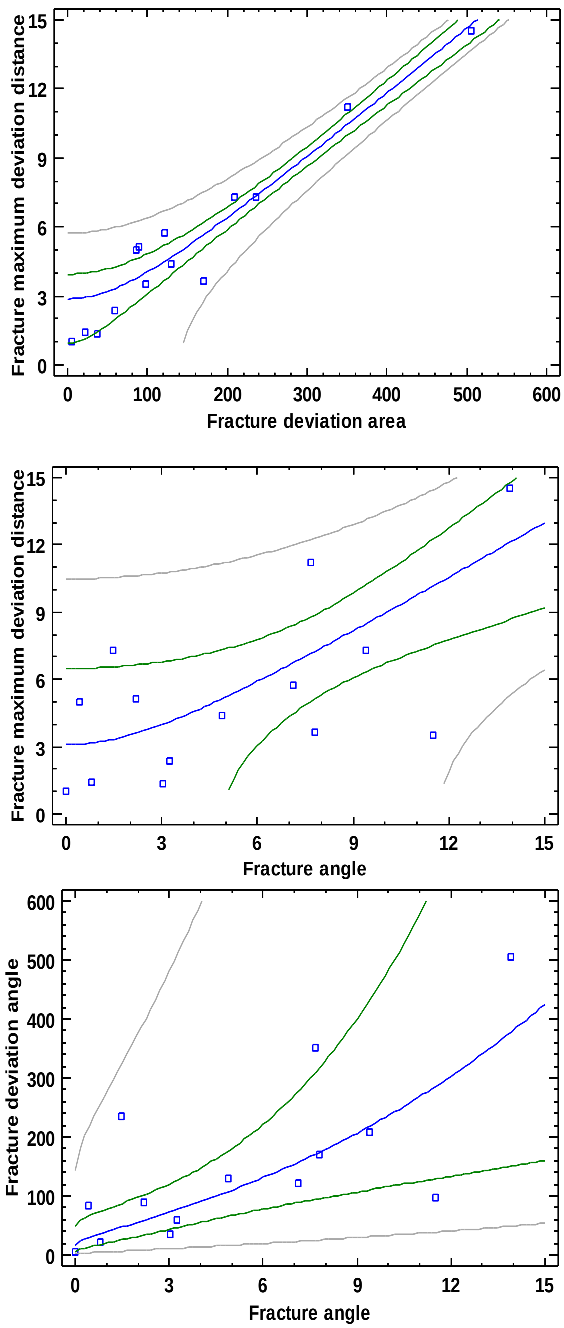

Figure 6. Scatter plot of fitted models among the fracture characteristics

6. Conclusion

The damage behavior in sandstone includes fracture initiation, propagation, and coalescence. Almost all cracks are triggered by shearing and tension, while tensile cracks are the ultimate failure of the tension test. Therefore, there should be a concrete relationship between tensile strength and fracture characteristics. This study has attempted to estimate the relation between indirect tensile strength and fracture characteristics for both fresh and slightly weathered sandstone based on linear regression. The findings obtained allow us to interpret the differences, establish a concept and draw the following conclusions.

1. The fresh sandstone correlation studies show a reasonably strong relationship between Brazilian tensile strength and fracture characteristics, except fracture length. However, multiple regression analysis shows a strong relationship between BTS and fracture characteristics.

2. In slightly weathered sandstone BTS has a relatively strong relationship with FMDD and FDA and a weak relationship with FA and FL. Conversely, multiple regression analysis reveals a significant correlation between BTS and fracture characteristics.

3. It was concluded that the fracture and strength characterization with progressive weathering and their relationship is essential to evaluate the impact of weathering on the propagation of fractures and mechanical response in sandstone. Among the sandstone properties that represent the strength characteristics and fracture behavior was found to be the most sensitive to weathering.

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