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Dilation of rock joints based on quantified surface description

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Summary

Rock dilation process is a complex behaviour that is influenced by material properties, stress conditions, and surface characteristics. In this study, we used twenty direct shear tests on four rock types under a constant normal load (CNL) condition to investigate rock dilation. Shear and normal displacements measured in these tests were used to understand shear induced dilation as a function of surface geometry. We focus our investigation on the ultimate dilation (ξ_{ult}), which is defined as a constant value that the dilation (ξ) approaches with increasing shear displacement (δ). Results show that ξ_{ult} is influenced by compressive strength, applied normal stress, and surface geometry.

Introduction

Rock dilation describes the increase in joint aperture during shear. Although shear induced dilation is minimal compared to direct tensile opening of a joint, according to the cubic law, that suggests doubling fracture aperture increases the permeability by a factor of eight, dilation can significantly affect the overall permeability of the rock mass (Koyama et al., 2006). Since source mechanisms computed from recorded microseismic events during hydraulic fracturing show a significant amount of shear failure during treatment, the ability to properly account for shear-induced dilation is of considerable importance in assessing the transmissivity of fracture networks and hydrocarbon deliverability of stimulated reservoirs (Warpinski & Du, 2010).

This study focuses on investigating the dilation value at the later portion of the dilation curve, termed ultimate dilation (ξ_{ult}). Using twenty direct shear tests conducted on fresh rock joints from different materials by Grasselli (2001), the ultimate dilation is associated with surface characteristics, material properties, and testing conditions. Surface characterization is done using an advanced topometric sensor (ATS) that captures light fringe patterns from two digital cameras to compute the object coordinates (Grasselli & Egger, 2000). Material properties and testing conditions have been recorded by Grasselli (2001). Findings of this study have implications on more accurate assessment and modelling of hydraulic fracturing treated reservoirs.

Theory and Method

Four types of rocks have been used for this study, they are Magny limestone (C), Tarn granite (G), gneiss (Gn), and serpentinite (S). Direct shear tests have been performed under a constant normal load (CNL) condition with a servo-hydraulic equipment, the hydraulic jacks applying the shear and normal loads have capacities of 150 kN and 2000 kN respectively. Vertical and horizontal measurements of the shear box displacements have been done with four vertical linear variable differential transducers (LVDT) and one horizontal LVDT directly linked to the sample (Grasselli, 2001).

Roughness of these surfaces have been calculated according to Tatone & Grasselli (2009) approach. In this approach, point clouds obtained from the ATS measurements are meshed with triangles using a triangulation algorithm built into the ATS software (Figure 1). This approach gives a quantitative and directional measurement of surface geometry. Another surface description is called surface amplitude. It is defined as the maximum vertical distance of the point cloud from the calculated average plane.

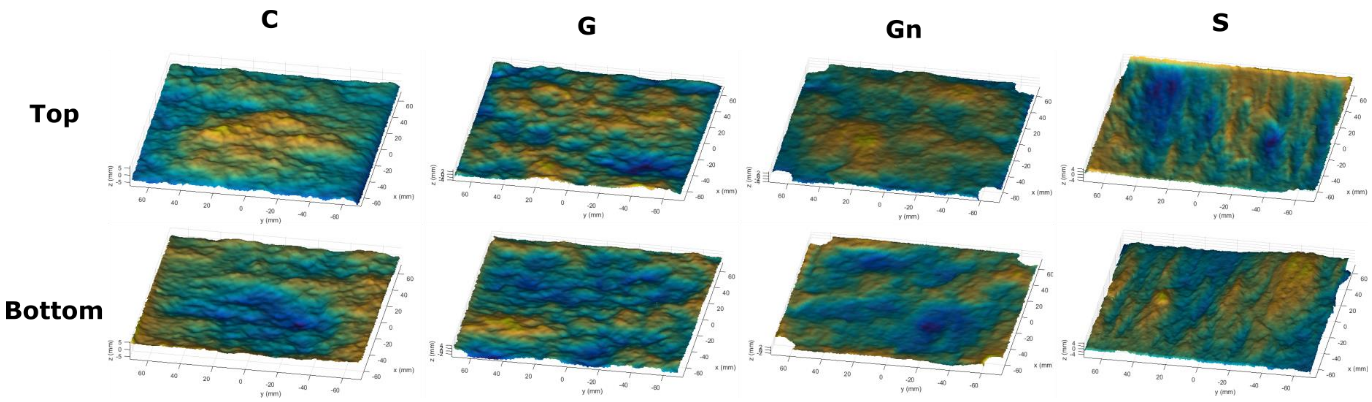

Figure 1 Example surface topographic scans. Color scale represents elevation.

Examples

One surface from each rock type with their corresponding material properties, testing conditions and surface characteristics are listed in Table 1.

Dilation versus shear displacement responses extracted from the direct shear tests show that at the end of the test dilation is still increasing. Therefore, an equation is needed to fit the dilation curve to predict the ultimate dilation value. The dilation curves from the experiment show that at the onset of dilation, the rate at which dilation increases is high, as shear progresses, the rate of dilation decreases and eventually dilation plateaus (Figure 2). Taking into account these observations, we propose the following negative exponential growth expression for the dilation curve.

$$\xi = a(1-e^{-b*(\delta-c)})$$

Where ξ is dilation in mm, δ is shear displacement in mm; and a, b, and c are fitting parameters. The expression approaches a as δ tends toward infinity, thus defining an ultimate dilation value (ξ_{ult}) also listed in Table 1.

Table 1 Properties and test conditions of selected example surfaces: compressive and tensile strengths (σ_c and σ_t), testing normal stress (σ_n), surface roughness (R), surface amplitude (A_{max}), and ultimate dilation (ξ_{ult}).

Surface	σ_c (MPa)	σ_t (MPa)	σ_n (MPa)	R (-)	A_{max} (mm)	ξ_{ult} (mm)
C1	20.9	2.42	1.07	10.04	7.10	1.789
G5	172.53	8.77	1.12	8.77	4.10	1.754
Gn3	183.8	9.5	3.09	6.28	3.58	1.058
S2	115.6	5.99	0.95	15.28	5.32	1.987

It is observed that ξ_{ult} is linked to the surface amplitude and it is expected that ξ_{ult}/A_{max} is a function of compressive strength, normal stress, and roughness. Stronger rock with high compressive and tensile strengths has asperities that break at higher stresses, thus sustains greater dilation. On the other hand, a higher normal stress applied to a surface supresses dilation. Higher roughness, indicative of steeper asperities, concentrate more of the shear load in the direction normal to the asperity surfaces, resulting in a scenario favourable in shearing the asperities off rather than dilation. Therefore, ξ_{ult}/A_{max} should be directly related to compressive strength, and inversely related to normal stress and roughness. Our test results showed good agreement with the abovementioned trend that ξ_{ult}/A_{max} decreases with increasing normal stress; however, the relation between ξ_{ult}/A_{max} and roughness is not pronounced (Figure 3). This suggests that material heterogeneity limits us in obtaining accurate material strengths, and that other factors such as joint normal stiffness which are not measured at the time of the direct shear tests can also impact the ultimate dilation.

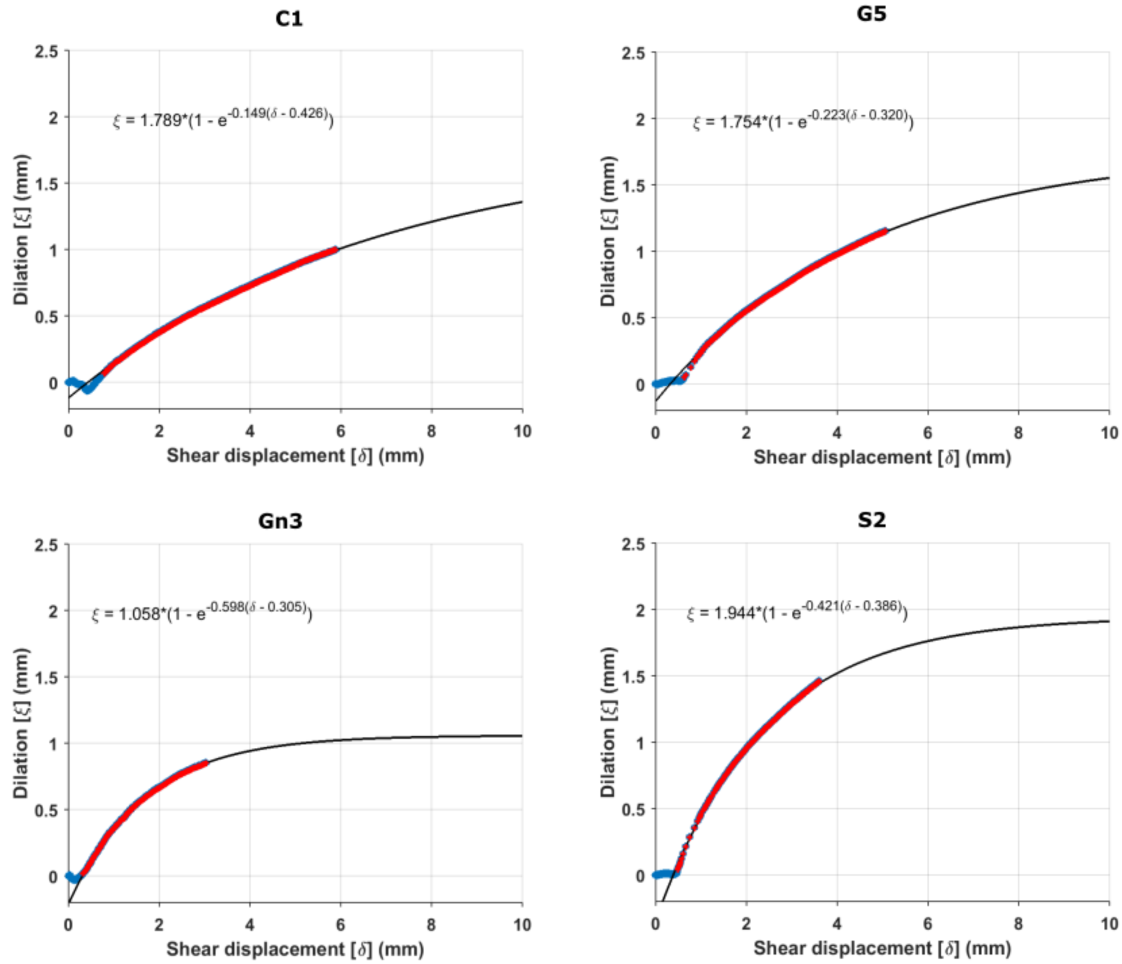

Figure 2 Dilation responses of example surfaces from each rock type (only data points in red are used in fitting)

It is also noticed that each factor influencing the ultimate dilation has various degrees of significance, one surface can have noticeably low roughness, but a slightly higher normal load can result in a noticeably low ξ_{ult}/A_{max}. It is, therefore, more reasonable to assume that the fraction applied to surface amplitude is a summation of the factors considered instead of a product.

$$\xi_{ult} = A_{max}*(n_1*\text{f}(\sigma_c) + n_2*\text{f}(\sigma_n) + n_3*\text{f}(R))$$

Where $n_{1,2,\&\,3}$ are the coefficients of the corresponding factors σ_c, σ_n, and R respectively.

Conclusions

From a series of direct shear tests, dilation as a function of shear displacement responses were extracted. The measured responses were used to fit an equation that provided the ultimate dilation value. The negative exponential growth equation produced an accurate fit to the laboratory data. The ultimate dilation was examined as a function of roughness and normal stress. Our results suggested that the ultimate dilation decreases with increasing normal stress; however, the influence of material properties, surface roughness, and stress conditions as a whole appeared to be more complex. Future work involves conducting more shear tests using replica materials with controlled material and surface properties, and improving the data acquisition capability of the experiment to incorporate additional measurements such as joint normal stiffness. This can simplify the correlation process allowing for assessment of factors independently of each other and incorporate additional properties and parameters in the equation.

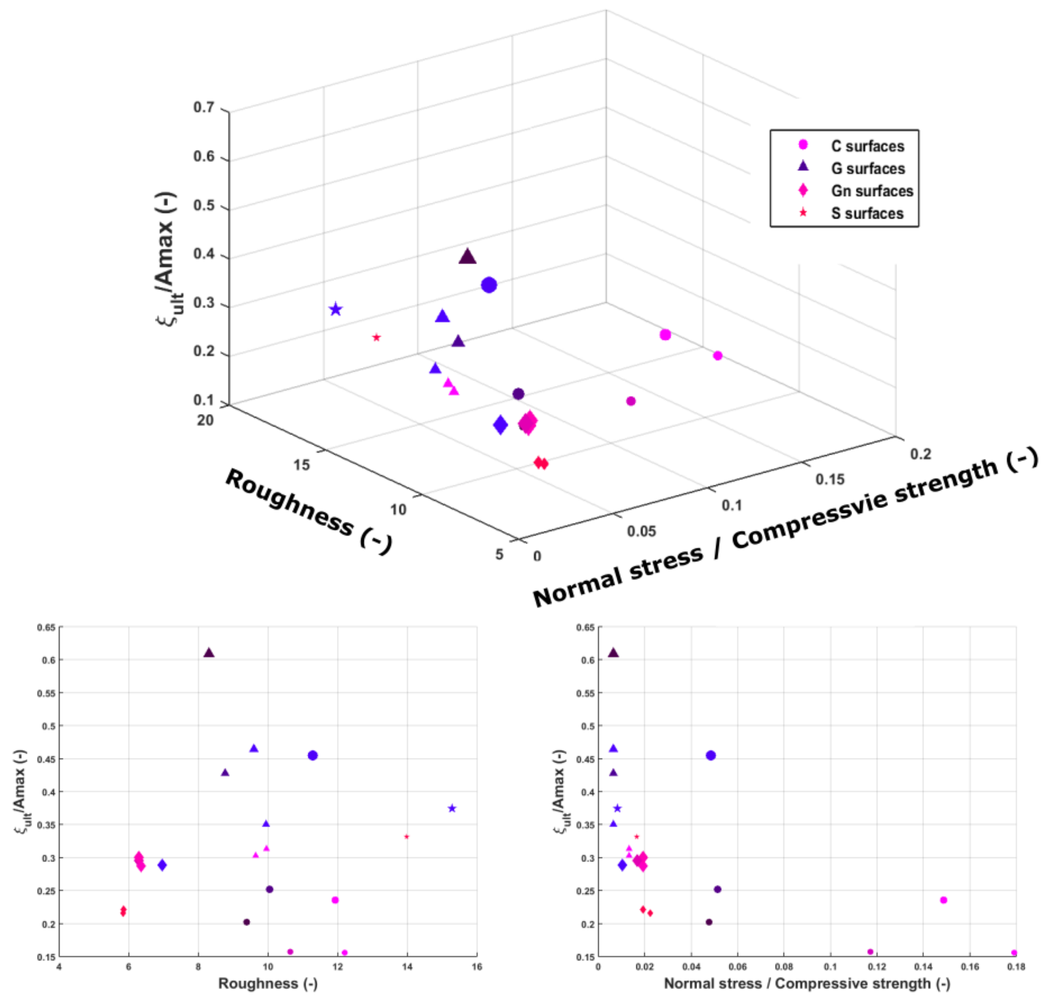

Figure 3 Dilation correlation of the four rock types: higher blue intensity = higher roughness, higher red intensity = higher normal stress / compressive strength, larger marker size = higher ξ_{ult} / A_{max}

Acknowledgements

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