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Competing Effects of Proppant and Surface Roughness on the Frictional Stability of Propped Fractures

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Abstract

Proppant is often used to enhance reservoir stimulations, such as hydraulic fracturing and hydraulic shearing; however, the influence of proppant on the shear deformation of fractures and the potential consequent-induced earthquakes are rarely explored. We explore the systematics of frictional behavior, deformability and dilatancy of proppant-filled fractures to define the complex response to different fracture roughness and proppant mass loadings. Shear experiments on rough granite fractures show that proppant reduces cohesion and internal friction, reduces the shear stiffness, delays the shear displacement to a diminished peak strength, reduces the magnitude of shear dilation, and promotes ductile shear failure that is analogous to aseismic creep. A systematic transition in shear behavior occurs from fracture-roughness-dominant to proppant-dominant with increased proppant mass loading that is augmented by increased grain size. Long-wavelength fracture undulations may engage at large shear displacements, causing increased frictional resistance—identifying an intrinsic-scale effect. The presence of proppant reduces the shear dilation. Thus, the convolved interactions between proppant and fracture roughness require careful assessment in their impact on creating and sustaining permeability and modes of aseismic versus seismic ruptures.

Highlights

- Frictional behavior systematically transitions from fracture-dominated to proppant-dominated response as proppant mass loading increases.
- Proppants promote ductile shear failure that is exacerbated by increased proppant mass loading and increased grain size.
- The transition of frictional behavior caused by proppant could impact permeability and stability of the stimulated fractures.

Keywords Shear behavior · Proppant · Surface roughness · Frictional stability

1 Introduction

Reservoir stimulation methods, such as hydraulic fracturing and hydraulic shearing, are used to improve the efficiency of resource extraction from fractured hydrocarbon and geothermal reservoirs (e.g., Ahamed et al. 2021; Dempsey et al. 2015; KC and Ghazanfari 2021; Rinaldi and Rutqvist 2019; Schoenball et al. 2020; Zimmermann and Reinicke 2010). Hydraulic fracturing involves the injection of fluid into a reservoir at a pressure higher than the minimum principal stress to create new hydraulic fractures that increase permeability. Conversely, hydraulic shearing reactivates shear deformation on pre-existing fractures by reducing the effective normal

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stress through fluid injection, promotes shear dilation (i.e., self-propping) that enhances permeability, but at a fluid pressure less than the minimum principal stress. Proppants are often injected with the fluid to maintain fracture permeability after injection. These stimulation processes modify the stress conditions on rock discontinuities, may generate shear deformation that could induce earthquakes (Guglielmi et al. 2015) with the presence of proppant making the stress state in fractured rock mass more difficult to predict.

Commonly used proppant types include silica sands, ceramic particles and resin-coated sands, among other high-strength natural and artificial granular materials. The sizes of such proppants are generally between 8 and 140 mesh (105–2.38 mm) (Liang et al. 2016). Silica sand is the most commonly used proppant for reservoir stimulation because of its low cost and adequate performance, while engineered proppants may offer better stimulation results but at higher costs. Much interest has been applied to the permeability enhancement resulting from proppant treatment. The evolution of permeability of a propped fracture using shearing-concurrent measurements of permeability at constant velocity shearing shows permeability of a propped fracture to be mainly governed by the normal stress, the proppant thickness, and the proppant size (Zhang et al. 2017). However, few studies have focused on the frictional stability of propped fractures, in particular where the proppant loading is low relative to the roughness of the native fracture—and hence—the competition between the proppant pack and native fracture will be important. Proppant embedment during rock shearing under different rock roughness conditions indicates that proppant caused a reduction of the rock fracture mechanical properties including peak shear strength, shear stiffness and friction angle, and enhances surface damage (Tang and Ranjith 2018; Tang et al. 2019). Cornelio and Violay (2020) performed a parametric analysis that described the Sommerfeld number, which is a key parameter assessing the effectiveness of elastohydrodynamic lubrication during seismic sliding and observed that the injection of proppant can allow the fault to slip into the fully elastohydrodynamic lubrication regime with a small friction coefficient.

Conversely, studies on the shear behavior of filled rock discontinuities in geophysics and rock mechanics also provide valuable insights. Early studies suggested that filled rock discontinuities exhibit lower strengths and effective frictional coefficients than unfilled discontinuities (Barton 1974). Later studies on the shear behavior of filled rock discontinuities identified similar effects for different rock types, filling materials and stress conditions. de Toledo and de Freitas (1993) reviewed studies related to the shear strength of infilled rock joints in the literature, discussed the main parameters controlling the shear strength of infilled joints and provided a framework for understanding the failure mechanisms involved in the shearing of such discontinuities. They concluded that the shear mechanisms were controlled by the grain size, the thickness of filler material and the rock itself. Indraratna et al. (2010) presented possible shearing mechanisms that may occur in soil-infilled rock joints and proposed a corresponding joint shear strength criterion that considers the effects of a series of governing parameters, such as the friction angle of the infill material, the basic friction angle of the rock joint, the degradation of asperities, and the infill thickness-to-asperity height ratio. Jahanian and Sadaghiani (2014) performed a series of constant normal load direct shear tests to investigate the shear strength of artificial samples with in-filled rough joint surfaces having different asperity and infill characteristics. They found that the normal stress on the joint played an important role in the shear behavior of in-filled rock joint samples. Meng et al. (2017) studied the shear behaviors of joints with thin layers of different infillings and found that the maximum shear strength of the filled joints was significantly reduced compared with the clean joints. Moreover, when the joint infill was of large granular particles, the particles rotated and were crushed. Tang et al. (2020) studied the shear behavior and mechanisms of clean and filled rough joints under direct shear tests using experimental and numerical approaches with the mechanisms of the shear stress and shear dilatancy behavior significantly altered by the infilling material. Zhao et al. (2020) performed direct shear experiments on sand and clay in-filled joints prepared by reproducing the standard Joint Roughness Coefficient (JRC) profiles on a rock-like material and placing the infill material inside the joint. Their results showed that the shear behavior and strength of the infilled joints were affected by the JRC, the infill material type, the infill thickness to joint asperity amplitude ratio and the applied normal stress.

These observations are congruent to those of fault gouge where the gouge, itself, dominates the frictional response of mature faults. For example, Marone (1998); Marone et al. (1990) discussed shear localization in fault gouge. Their data highlight differences in the shear behavior of bare rock surfaces as compared to shear within granular fault gouge that can dilate and deform. An investigation of the frictional properties and stability of frictional sliding was presented, and the effect of surface roughness, gouge thickness, and slip rates was studied.

Surface roughness of the fractures is an important factor controlling the frictional stability of rock discontinuities across a large range of scales. Bandis et al. (1981) noted the significance of scale effects on both the shear strength and deformation characteristics with both the geometrical and strength characteristics of surface roughness presented as potential sources of scale effects. At large fault scale, Brodsky et al. (2016) quantified the slip surface roughness

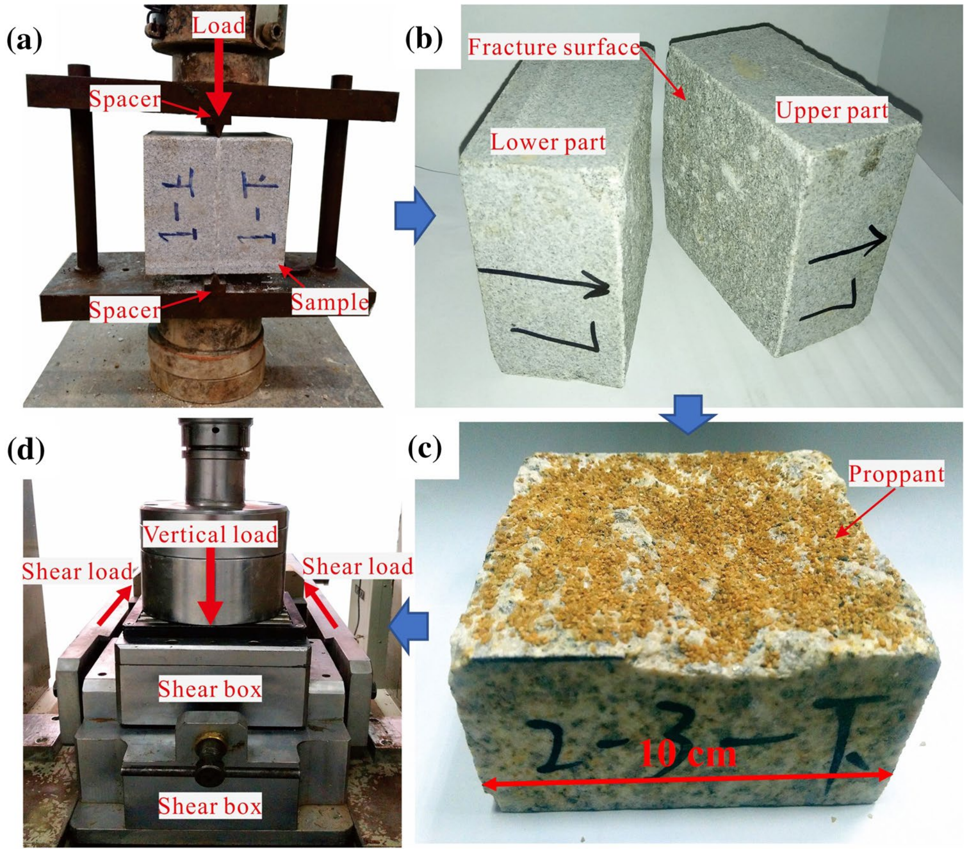


Fig. 1 Preparation process for the rough granite fractures used in the direct shear tests. **a**, **b** Indirect tensile fracture loading to create a fresh rough fracture with matching surfaces. **c** Silica sand proppant placement on the fracture surface using dry pluviation. **d** Test setup of the direct shear test

by measuring the aspect ratio and pointed out that faults have scale-dependent roughness. Surface roughness also influences proppant embedment under shear deformation and in turn influences the shear behavior of fractured rocks. Tang and Ranjith (2018) studied proppant embedment during rock shearing under different fluid and rock roughness conditions. They found that a rough surface achieves a higher embedment increment than smooth rock due to severe dilation. However, the influences of proppant relative to the roughness of the encasing fractures have yet to be systematically evaluated and their impact on shear strength and frictional stability determined.

Reservoir stimulation aided by proppant plays an important role in the efficient and safe extraction of hydrocarbon and geothermal energy from fractured reservoirs, which are critical to the energy transition toward carbon neutrality. Therefore, to resolve the ambiguous impact of proppant-fracture roughness interaction on the frictional stability of propped fractures, we systematically explore the frictional behavior of rough rock fractures under different proppant and normal stress conditions and use quantitative surface roughness analysis to elucidate the underlying mechanisms.

2 Materials and Methods

Outcrop samples of granite were collected that are representative of the Gonghe geothermal site (Gonghe basin, Qinghai province, China). The granite mainly consists of quartz (20–30%), plagioclase (25–35%), alkaline feldspar (30–38%) and mica (5–7%), with a dry density of 2.62–2.65 g/cm^3. The rock samples were cut into 100 mm sized cubes and then split into two equal-sized halves using indirect tensile (knife-edge) loading. This created the matching rough fractures that we examined in this study (Fig. 1).

Three quartz sand samples with monomodal grain size ranges (0.1–0.5 mm, 0.5–1.0 mm, and 1.0–2.0 mm) were used as proppant and sandwiched between the rough fracture surfaces. For each proppant sample, 2 g of the proppant was placed on the fracture surface by dry pluviation. Proppant placement in narrow and rough fractures under reservoir conditions is equivocal and likely patchy, as the proppant interacts with the flow of the injection fluid and the specifics of the local fracture roughness (Wang et al. 2018). Our method provides a pragmatic and repeatable procedure to create a heterogeneous proppant layer partially covering the fracture, which is preferred in practice because it drastically increases the fracture conductivity (Bolintineanu et al. 2017; Medina et al. 2018).

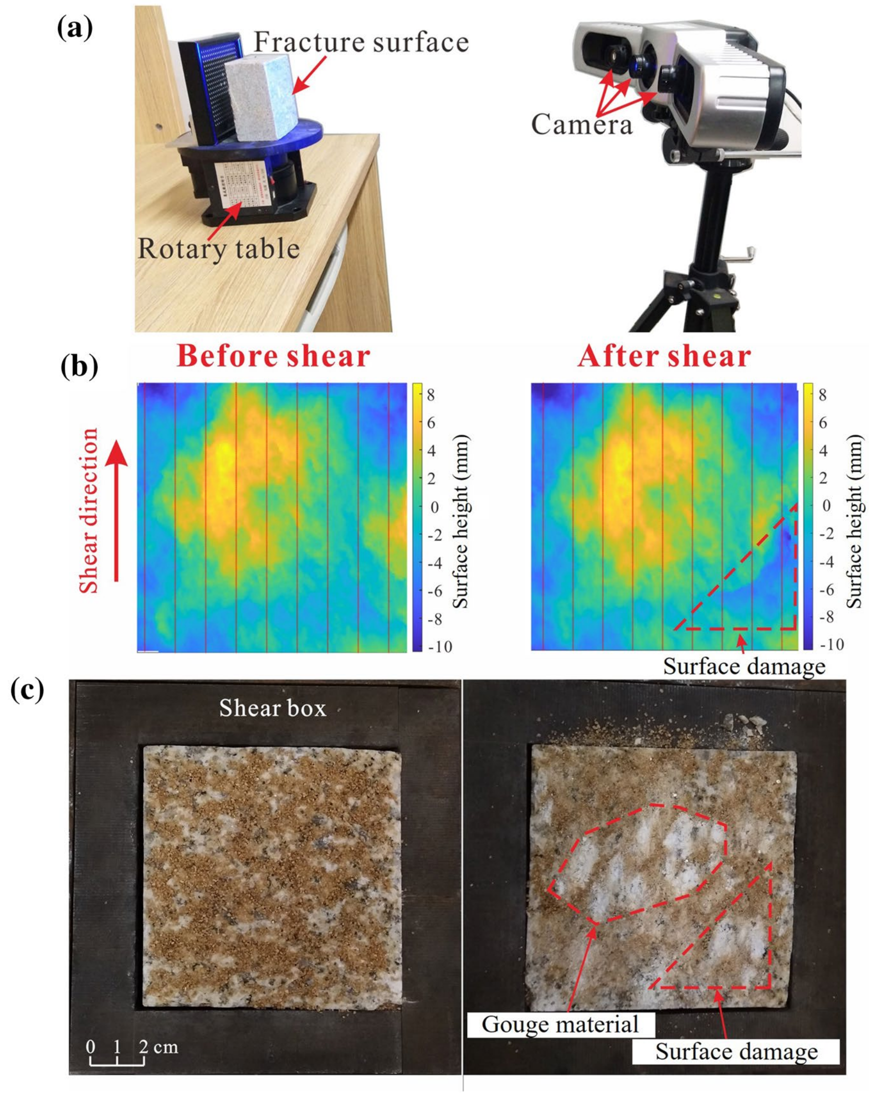


Fig. 2 Fracture surface roughness measurement and calculations. **a** Surface scan setup. The surface was digitized into a point cloud with 30 μm spatial resolution. **b** Example results of the surface scan showing the morphological information pre-then post-test (post-test scan was conducted after removing the gouge). The averaged surface roughness was calculated based on nine profiles measured along the shear direction. **c** Example of actual surfaces pre- and then post-test, corresponding to (**b**)

Before the direct shear tests, tilt tests were conducted on the rough fractures with four proppant conditions as well as on a planar, smooth and pristine fractures to measure the basic friction angle (ϕ_b) of the fractures under low stress. Then, three suites of direct shear experiments under constant normal stresses were conducted at a constant shear rate of 0.01 mm/s to a maximum shear displacement of 15 mm. The first suite comprised 16 shear experiments representing combinations of four normal stresses ($\sigma_n = 2$ MPa, 3 MPa, 4 MPa, and 5 MPa) and the four proppant conditions (no proppant and three abovementioned proppant samples, referred to as P0.0, P0.1, P0.5, and P1.0, respectively). To ensure the reliability of the data, the second suite of 6 experiments was conducted under the conditions where anomalous frictional behavior was observed. The third suite of experiments examined the role of proppant mass loading (i.e., the amount of proppant by weight)—all at 4 MPa and with P0.1 proppant, but with different mass loadings of proppant at 4 g, 6 g, and 8 g. During the direct shear experiments, shear stress (τ), shear displacement (δ_s) and dilation (δ_v) were simultaneously monitored at a sampling rate of 2.5 Hz. The apparent friction coefficient is calculated as $\mu = \tau/\sigma_n$. Note that we conducted constant normal stress direct shear tests; thus, the overall variations of the shear stress and the apparent friction coefficient are identical.

We used a surface scanner to digitize the two sides of the surfaces of each fracture, both pre- and post-experiments, at a spatial resolution of 30 μm. The comminuted gouge material on the specimens' post-experiments was removed with a soft brush before scanning. Each surface scan generates a point cloud representing the fracture surface geometry, and we calculate the roughness amplitude (H) as the difference between the highest peak and lowest trough on the surface. We re-sampled the point cloud onto a 50 μm-sized regular mesh. Then, a total of nine equal-spaced profiles were extracted from the surface along the shear direction (Fig. 2).

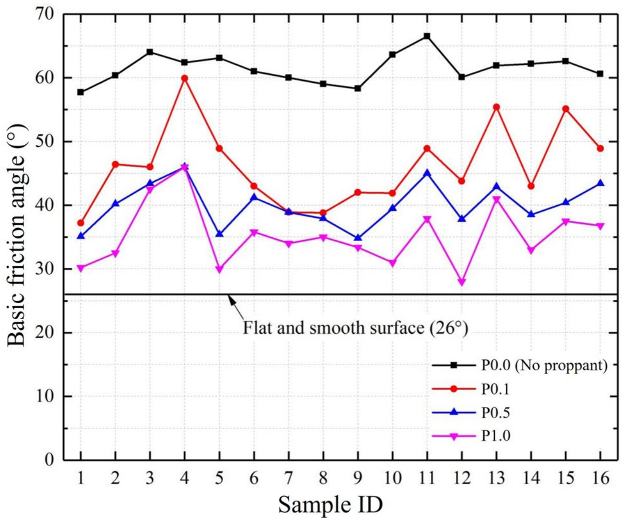


Fig. 3 Tilt tests results on rough fractures with four proppant conditions (P0.0, P0.1, P0.5, and P1.0) as well as on a flat, smooth, and pristine fracture to measure the basic friction angle (ϕ_b)

We examined the roughness of the extracted profiles quantitatively using the RMS roughness (i.e., Root Mean Square of the profiles amplitude) and Z_2 (i.e., RMS of the second derivative of the profiles amplitude) (Magsipoc et al. 2019; Myers 1962; Tse and Cruden 1979). Then, the roughness parameters Z_2 and RMS of the profiles were averaged to obtain the mean roughness of the surface. Finally, the variation of surface roughness both pre- and post-tests (ΔZ_2 and ΔRMS) for both sides of the fractures was evaluated from the differences in these roughness parameters.

3 Results

The averaged ϕ_b values from the tilt tests for proppant conditions P0.1, P0.5, and P1.0 were 46.13°, 40.03°, and 35.29°, respectively, all lower than the averaged ϕ_b of the non-propped specimens at 61.46° but higher than the averaged ϕ_b obtained on a flat saw cut surface with no proppant of 26° (Fig. 3).

In the non-propped direct shear experiments, the apparent friction coefficient, μ, increased linearly with the shear displacement, δ_s, to a peak value, μ_p (i.e., static frictional strength) followed by an abrupt drop (Fig. 4a–d). Then, μ decreased to a residual value. In the propped direct shear experiments, μ also increased with δ_s; however, the rate of increase was decreased, that is, the proppant reduced the shear stiffness of the fracture. When $\sigma_n < 5$ MPa, the reduction of shear stiffness increased with increasing proppant size. When $\sigma_n = 5$ MPa, the grain size of the proppant did not show a clear influence on the shear stiffness–the fractures had similar shear stiffness values regardless of the proppant grain size. Non-propped specimens had μ_p values close to 2, significantly higher than those of the propped specimens, with greater reductions resulting from larger sized proppants.

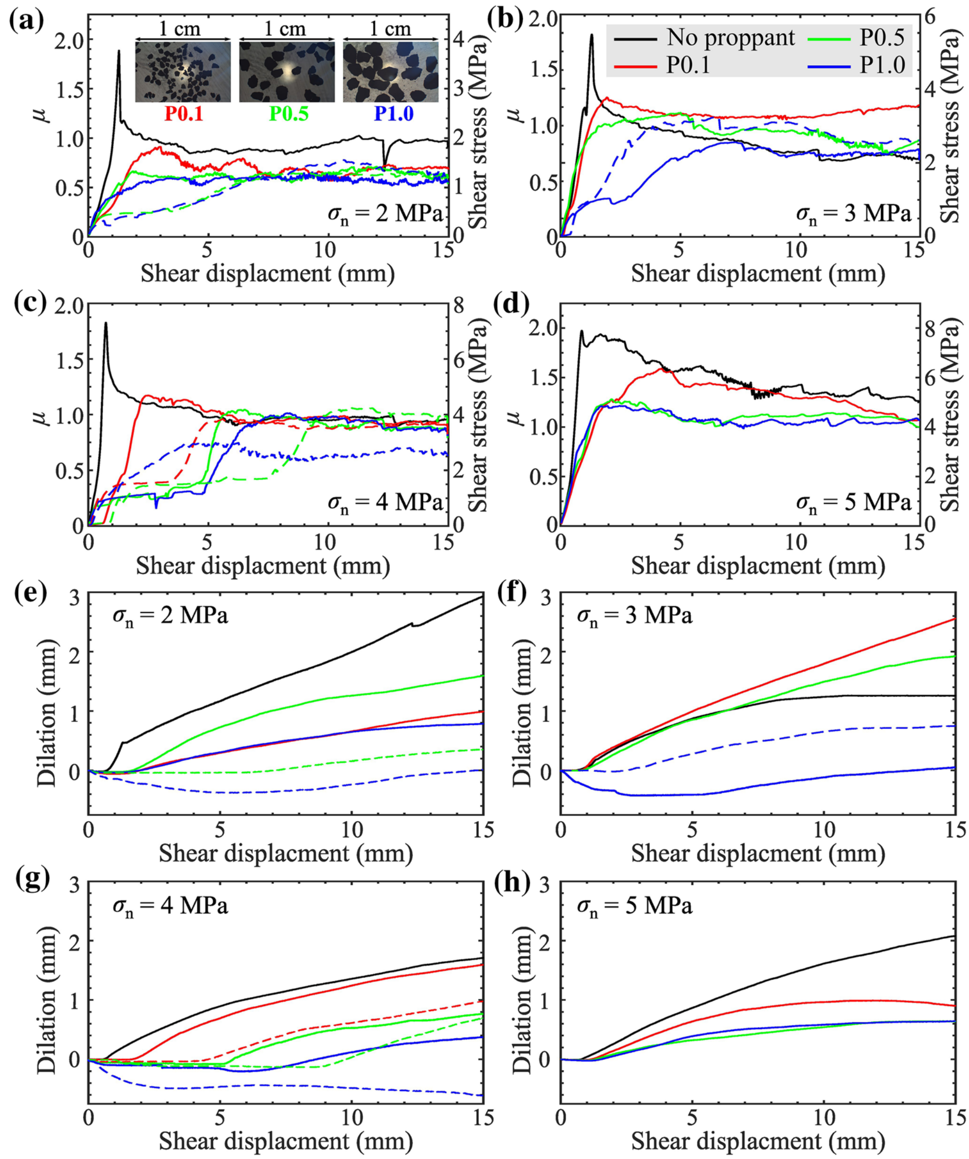
The peaks of the apparent friction coefficient–shear displacement (μ–δ_s) curves for the propped samples became less pronounced relative to residual μ (i.e., less brittle), and the larger the proppant grain size, the more significant was this effect. Several experiments with proppants P0.5 and P1.0 returned a flat peak response (with δ_s). Instead, the μ stabilized around the reduced μ_p. In addition, the occurrence of μ_p was delayed by the proppant; and the larger the proppant grain size, the larger the delay, except for the experiments conducted under 5 MPa, in which the delay showed no obvious correlation with proppant grain size.

In a typical direct shear experiment, the vertical displacement, δ_v, experienced a transition from compaction (negative δ_v) to dilation (positive δ_v) with increased shear displacement. The non-propped experiments lack the compaction phase with the propped experiments showing compression over an extended δ_s (Fig. 4e–h). Most observations followed this general trend, but the forms of the δ_v–δ_s dilation curves were altered. The larger the proppant grain size, the more significant was the compression phase, with correspondingly less dilation. Overall, experiments with low σ_n had higher dilation values than those under high σ_n. Also, in experiments with low σ_n, the dilation was generally still increasing at the end of the experiments after $\delta_s > 15$ mm. Only propped experiments conducted at 5 MPa showed plateaus at the end of experiments, suggesting that ultimate dilation had been reached.

The shear strength of the first two suites of experiments can be described with linear failure envelopes (Fig. 5a): $\tau_p = s + \mu_i \sigma_n$, where the intercept s is the cohesion and μ_i is the internal friction that describes the rate that shear strength (τ_p, see Table 1 for peak shear stress values) increases with σ_n. The s values for the four sets of experiments with different proppant conditions (P0.0, P0.1, P0.5, and P1.0) were 1.28 MPa, − 0.84 MPa, − 1.00 MPa, and − 0.62 MPa; respectively; and the μ_i values were 1.40, 1.38, 1.29, and 1.09, respectively. With the introduction of the proppant, the internal friction and the cohesion were reduced, and the larger the proppant grain size, the more significant were the two effects. The flattened and lowered failure envelope, together with injection fluid pressure, would render the stimulated fractures in the field more susceptible to shear failure (Fig. 5b). In addition, the dilation at μ_p ($\delta_{v,\,p}$) showed no obvious correlation with normal stress or proppant conditions (Fig. 5c); whereas, the dilation at 15 mm of shear displacement ($\delta_{v,\,15\,mm}$) decreased with increasing proppant grain size (Fig. 5d).

For the six experiments with apparently anomalous frictional behavior in the first suite of experiments, a significant

Fig. 4 Apparent friction coefficient (**a**–**d**) and dilation (**e**–**h**) as functions of shear displacement of the fractures under different normal stress and proppant conditions. Solid lines and dashed lines are from the first and second suites of repeated experiments, respectively. Inserts in (**a**) show the example proppant grains under the microscope. PX.X mnemonics indicate the grain size of the proppant in mm



increase of δ_s occurred with negligible variations of τ or δ_v. This shear behavior was repeated in most of the second suite of experiments; ruling out the extrinsic origin of this behavior. Such sliding behavior with substantial shear displacement at relatively constant shear stress was analogous to aseismic creep observed in earthquake studies (Rathbun and Marone 2010). This stable sliding behavior had no apparent correlation with proppant size and was absent in experiments under $\sigma_n = 5$ MPa.

The increased mass loading of proppant caused a larger area of proppant coverage on the fracture surface as well as an increased thickness of the proppant layer, especially in the troughs (Fig. 6a). The third suite of experiments showed that the larger and thicker proppant caused the aseismic creep behavior. The more proppant, the longer the creep distance, the gentler the peak of the μ–δ_s curve, and the smaller the shear dilation (Fig. 6b, c).

The variation of surface roughness due to the shear deformation showed a clear correlation with proppant conditions (Fig. 7, see Table 2 for detailed roughness values). The non-propped samples showed the largest variation in roughness with the samples propped by P0.1 and P0.5 proppants experienced only minor changes in roughness. The samples propped by P1.0 proppant showed a greater variation in roughness relative to the other two proppant size experiments, but less than the non-propped experiments.

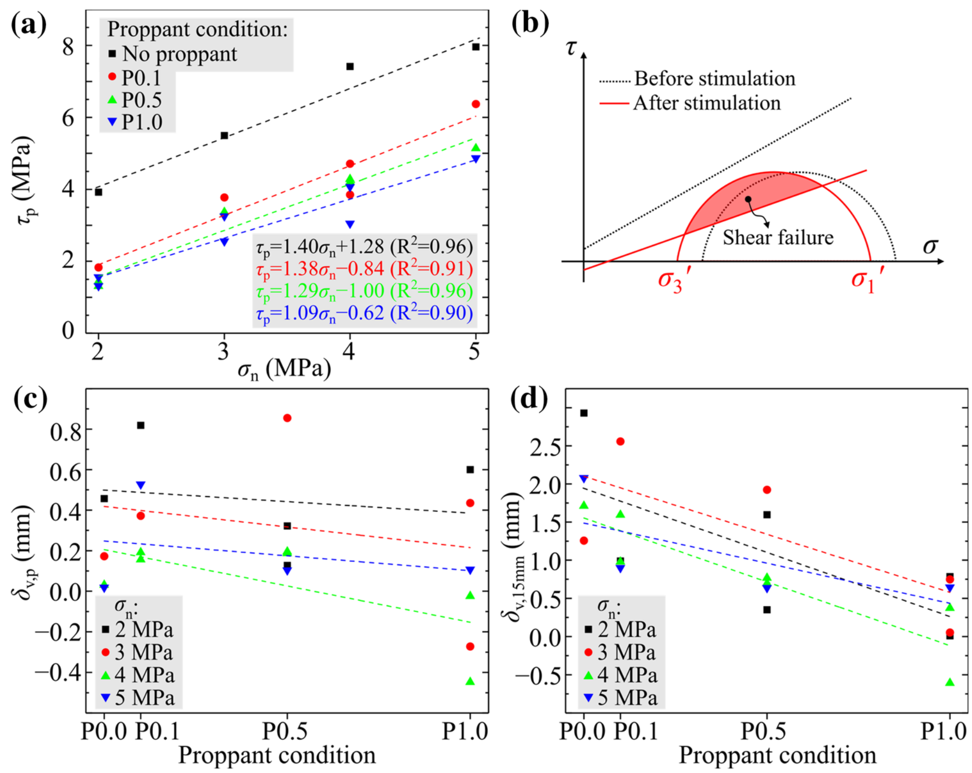


Fig. 5 Summary of shear behavior for different normal stress and proppant conditions. **a** Peak shear stress (τ_p) as a function of normal stress (σ_n). **b** Schematic of failure envelope relative to effective principal stresses (σ_1' and σ_3'). **c** Dilation at peak shear stress. **d** Dilation at 15 mm of shear displacement. Dashed lines are linear regressions

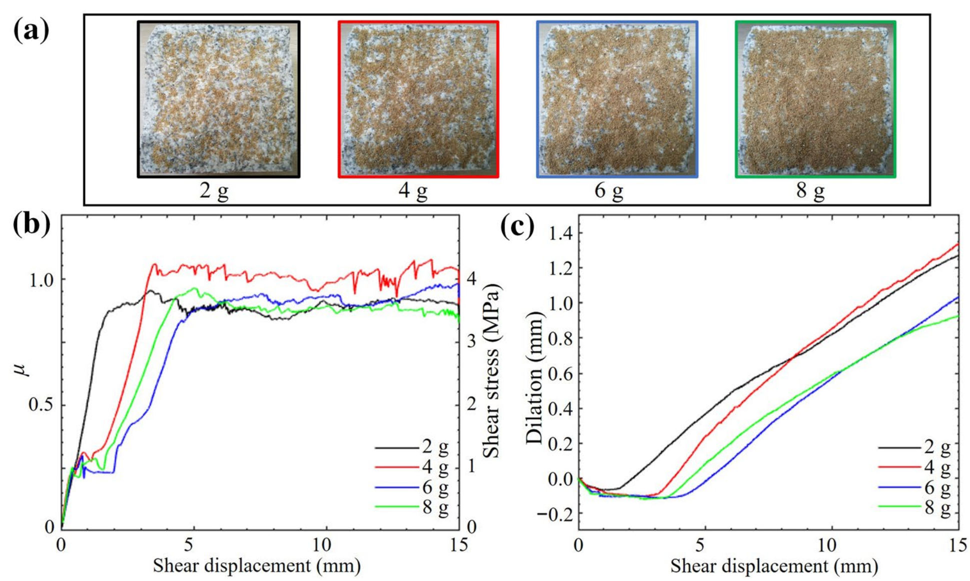


Fig. 6 Results of the direct shear experiments conducted under 4 MPa normal stress and with different mass loadings of P0.1 proppant. **a** Illustration of different mass loadings of proppant at 2, 4, 6 and 8 g mass loading per fracture. **b**, **c** Shear stress and dilation curves

4 Discussion

The frictional behavior was significantly altered by proppant. Proppant reduced the shear stiffness of the fractures, extended the shear displacement, δ_s, to the occurrence of peak friction, μ_p, and diminished the peak response. In the non-propped experiments, the abrupt drop of μ indicates brittle shear failure, which is related to the sudden release of strain energy associated to asperity breakage. Shear failure of the propped fractures is ductile and lacks such a rapid energy release process–the ductility increases with increased proppant grain size and mass loading.

The failure envelopes can be used to determine the proximity to failure, the value of s represents the shear strength at no normal stress and is related to the interlocking of the asperities. The non-propped fractures returned positive s values and the propped fractures negative s values. This

Table 1 Peak shear strengths recovered from the shear tests

Proppant size (mm)	Normal stress (MPa)	Peak shear stress (MPa)
No proppant	2	3.92
No proppant	3	5.49
No proppant	4	7.41
No proppant	5	7.96
0.1–0.5	2	1.83
0.1–0.5	3	3.77
0.1–0.5	4	3.85
0.1–0.5	5	6.37
0.5–1.0	2	1.31
0.5–1.0	3	3.37
0.5–1.0	4	4.28
0.5–1.0	5	5.14
1.0–2.0	2	1.56
1.0–2.0	3	2.56
1.0–2.0	4	3.05
1.0–2.0	5	4.87

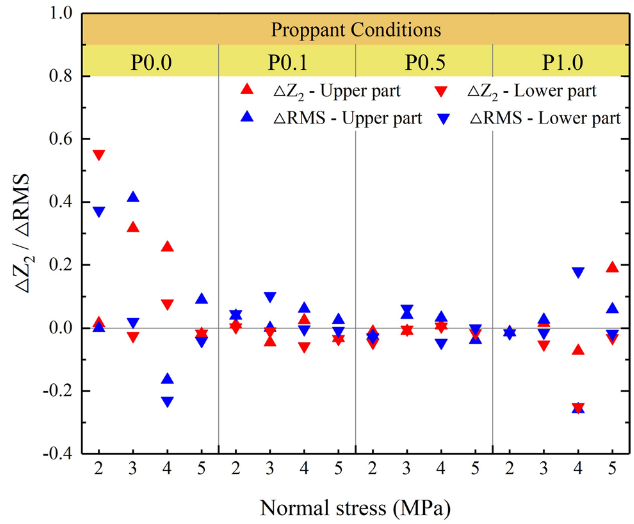


Fig. 7 Change in fracture surface roughness (ΔZ_2 and ΔRMS) from pre- to post- experiments and for different normal stress and proppant conditions

indicates that the proppant not only prevents the asperity from interlocking but also creates an additional lubrication effect that makes the fracture mobile—analogous to acting as a ball-bearing race. This conjecture is also supported by tilt tests, where we observed a systematic decrease of the basic friction angle with the increase of proppant size (Fig. 3). These adverse influences on the frictional stability of propped fractures are more prominent when the proppant grain size was relatively large and/or when the mass loading of the proppant was relatively high.

Both shear stiffness and peak response are related to the interlocking of asperities at the initial stage of shearing. Propped fractures showed similar shear behavior to rock fractures under cyclic, repeated, or continuous shear steps (e.g., Grasselli and Egger 2003; Lee et al. 2001; Zhao et al. 2018). In such tests, the fracture surfaces are damaged, and the asperities worn. For our proppant-filled fractures, however, the surface roughness analysis showed that the fractures experienced insignificant damage. This suggests that proppant protected the asperities by preventing their interlocking and interactions. For the same proppant mass loading, this protective effect is more noticeable as proppant size decreases. The surface roughness of the tested specimen with proppant grain size > 1 mm showed variations of roughness, especially at relatively high σ_n, suggesting surface damage. This may be because small proppant grains readily infill the troughs, while larger grains tend to engage with asperities that eventually cause damage. Moreover, high normal stress intensifies the asperity-asperity and asperity-fracture interactions.

In all the propped experiments, the thickness of the proppant layer was smaller than the roughness amplitude, which introduced an extra degree of complexity due to the interactions between proppant and fracture surfaces. This is manifested as the creep behavior that has not been investigated in previous studies. Previous studies considered fractures that are either clean or fully covered by granular layers, which may not be representative of actual proppant placement conditions. We found that partially filled fractures may not exhibit typical stress–strain curves, and thus, cannot be described with formerly established constitutive relations. The complex shear behavior of propped fractures can be explained by the interaction of proppant with roughness at different scales (Fig. 8a–e). Bare fractures experience asperity–asperity interlocking, causing significant shear resistance, dilation, and surface damage (Fig. 8a). With a low mass loading of proppant, proppant grains buffer the small-scale asperities (i.e., unevenness) from direct contact, and the rolling of proppant grains may also contribute to the shear behavior (Pereira 1997), thus lowering the shear strength and preventing the damaging of asperities (Fig. 8b). The creep behavior appears as the proppant layer is sufficiently thick to fill the troughs on the rough surface, allowing the fracture to slide on proppant alone (Fig. 8c). However, as the shear displacement increases, large-scale fracture undulation (i.e., waviness) allows the opposite fracture faces to engage and the creep behavior stops. The more proppant, the longer the creep displacement that can occur. The ultimate form of this creep behavior would occur when a thick proppant bed covers the entire fracture surface and obviates the influence of the long wavelength roughness by preventing the fracture asperities from engaging, even at

Table 2 Surface roughness statistics measured both pre-and post-tests

Proppant size (mm)	Normal stress (MPa)	Sample no.		Before			After		
				H (mm)	Z_2	RMS	H (mm)	Z_2	RMS
No proppant	2	1–1	Upper	23.22	0.62	3.93	23.52	0.60	3.93
			Lower	41.49	1.17	4.08	22.71	0.61	3.71
No proppant	3	1–2	Upper	18.18	0.55	1.23	5.63	0.23	0.82
			Lower	5.82	0.21	0.85	5.64	0.24	0.83
No proppant	4	1–3	Upper	18.24	0.49	1.35	8.64	0.24	1.52
			Lower	21.96	0.33	1.27	8.53	0.25	1.50
No proppant	5	1–4	Upper	12.92	0.25	2.39	12.27	0.27	2.29
			Lower	13.29	0.25	2.26	12.59	0.27	2.30
0.1–0.5	2	2–1	Upper	6.09	0.17	0.97	5.98	0.16	0.93
			Lower	5.73	0.17	0.96	5.71	0.17	0.91
0.1–0.5	3	2–2	Upper	15.09	0.23	1.83	10.22	0.28	1.83
			Lower	10.77	0.24	1.91	10.32	0.25	1.81
0.1–0.5	4	2–3	Upper	13.65	0.55	1.84	10.10	0.52	1.78
			Lower	10.12	0.47	1.77	10.17	0.53	1.78
0.1–0.5	5	2–4	Upper	8.23	0.24	1.44	8.62	0.27	1.41
			Lower	8.66	0.25	1.38	8.60	0.28	1.38
0.5–1.0	2	3–1	Upper	12.01	0.44	1.52	12.12	0.45	1.54
			Lower	10.08	0.40	1.42	10.32	0.45	1.45
0.5–1.0	3	3–2	Upper	6.78	0.24	1.16	6.66	0.25	1.12
			Lower	7.07	0.23	1.15	6.81	0.24	1.08
0.5–1.0	4	3–3	Upper	18.79	0.52	3.05	18.87	0.51	3.02
			Lower	19.58	0.56	3.13	19.55	0.55	3.17
0.5–1.0	5	3–4	Upper	6.05	0.23	0.77	5.56	0.27	0.81
			Lower	5.97	0.25	0.83	5.61	0.26	0.83
1.0–2.0	2	4–1	Upper	16.08	0.52	2.56	16.62	0.53	2.57
			Lower	16.96	0.52	2.48	17.53	0.54	2.49
1.0–2.0	3	4–2	Upper	14.23	0.55	2.33	14.26	0.54	2.31
			Lower	14.19	0.47	2.29	14.21	0.53	2.30
1.0–2.0	4	4–3	Upper	18.30	0.53	3.13	19.32	0.60	3.39
			Lower	20.25	0.53	3.44	19.14	0.78	3.26
1.0–2.0	5	4–4	Upper	22.99	0.47	1.28	6.62	0.28	1.22
			Lower	8.18	0.26	1.25	7.62	0.29	1.27

maximum shear (Fig. 8d). This will result in a much flatter μ–δ_s curve with much lower shear strength than for bare fractures. This phenomenon is evident from the numerous shear tests on fully filled fractures reported in the literature (e.g., de Toledo and de Freitas 1993; Indraratna et al. 2010; Jahanian and Sadaghiani 2014; Meng et al. 2017; Tang et al. 2020; Zhao et al. 2020). This transition in shear behavior from fracture response to proppant response is favored by increasing the mass loading of proppant and by increasing proppant grain size.

Fluid injection during reservoir stimulation may promote aseismic creep on rock discontinuities that could ultimately translate to seismic rupture (Guglielmi et al. 2015; Zoback 2012). Our study shows that proppant-filled fractures can also respond in this manner with ductile shear failure occurring through the asperity-shielding mechanism. The ductile shear failure, if generated in situ, will be invisible to seismic monitoring methods and absent from the seismic energy budget. This may be especially important for fractures only partially infilled by proppant that are under shear deformation, for example, natural fractures obliquely intersecting the main driven hydraulic fracture and intentionally hydro-sheared fractures.

Shear dilation due to the surface roughness, i.e., self-propping, can keep fractures open even at high effective normal stress (Brace 1980; Durham and Bonner 1994). This is desired in reservoir stimulation but will be suppressed by the presence of proppant—where the shear dilation potential of the fracture will be ceded to that of the proppant. Even though proppant placement can increase the fracture aperture, our results demonstrated that the propped fracture also experiences less shear dilation,

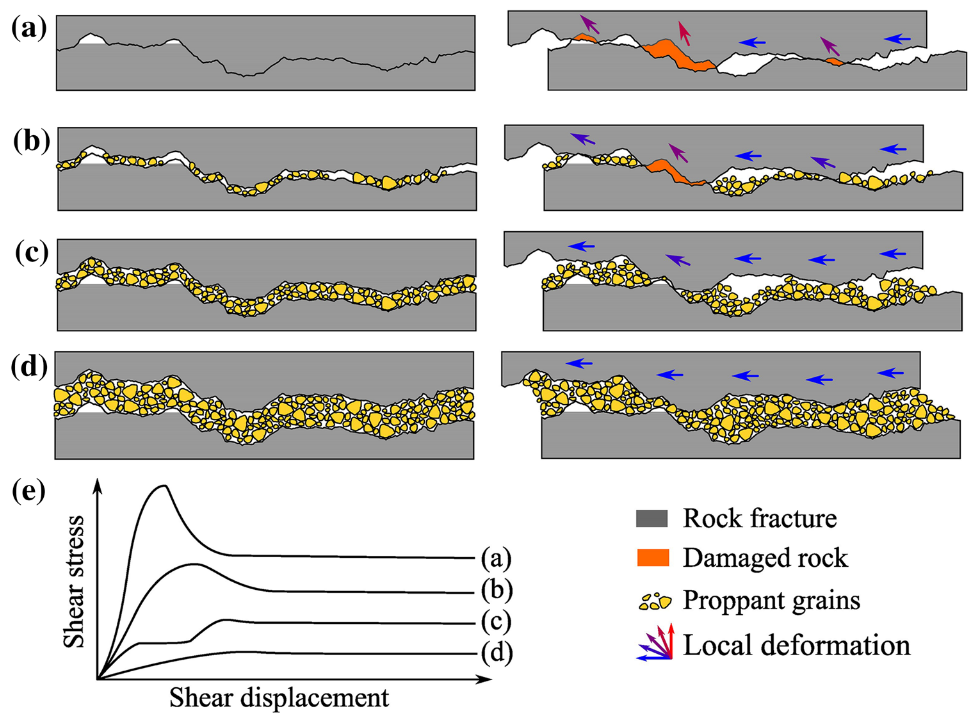


Fig. 8 Schematic of mechanisms describing the transition of fracture shear behavior from control by fracture roughness (**a**) to control by proppant strength (**d**) with increasing mass loading of the proppant. **a**–**d** Mechanistic illustration of shear behavior with increasing proppant mass loading. (**e**) Representative τ–δ_s curves corresponding to (**a**–**d**)

especially at large shear displacement. This effect needs to be considered for effective shear stimulations.

The results we obtained in this study are from fractures with different initial roughness values. The fact that we observe the transition of frictional behavior without controlling the surface roughness of the fracture specimens indicates that these are systematic first-order dependencies that override the impacts of the specific variabilities in fracture roughness. However, at higher stresses (> 5 MPa), the presence of proppant does not significantly alter the shear behavior, relative to that at lower normal stresses. These observations suggest that there is an interplay among the influences of fracture surface roughness, proppant conditions, and normal stress. Understanding this relationship may be the key to optimally increasing permeability in stimulated reservoirs and in concurrently mitigating induced seismicity. Although our experiments are conducted under dry conditions and at relatively low effective stresses, the overall trends in proppant response will apply at the reservoir scale.

5 Conclusion

We systematically investigate the influence of proppant on the frictional behavior of rough granite fractures. Importantly, we observe that proppant plays an opposing role to surface roughness: thick proppant layers prevent asperities from interlocking and protect the surface from damage but render the fracture weaker in shear. We summarize the influences of proppant on shear behavior into four key observations: (i) reduction of the cohesion and internal friction; (ii) reduction of shear stiffness and extension of the shear displacement to reach the diminished peak strength; (iii) reduction of shear dilation; and (iv) promotion of ductile shear failure—all are exacerbated by increased mass loading and increased mean grain size of the proppant. Proppant placement and fracture shear dilation can both enhance the permeability of the stimulated fractures, but the presence of proppant reduces the dilation; thus, the interaction between proppant and fracture self-propping requires careful assessment. In addition, the ductile shear failure that is analogous to aseismic creep on propped fractures is likely at high proppant mass loadings. As proppants are widely used in hydrocarbon and some geothermal reservoir stimulations, it is important to understand the interplay of surface roughness, effective normal stress, and proppant conditions on rock discontinuities to ensure the efficiency of energy extraction and alleviation of hazardous-induced seismicity.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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