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An experimental and analytical study of the effects of shear displacement, fluid type, joint roughness, shear strength, friction angle and dilation angle on proppant embedment development in tight gas sandstone reservoirs

Y. Tang, P.G. Ranjith*

Deep Earth Energy Laboratory, Department of Civil Engineering, Monash University, Building 60, Melbourne, Victoria 3800, Australia

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ABSTRACT

Proppant embedment is one of the most common proppant degradation mechanisms during the hydraulic fracturing process, and it can greatly reduce fracture width and conductivity. Shearing and the corresponding displacement caused by rock shearing and fault activation during hydraulic fracturing may enhance proppant embedment, and the influence may vary under different fluid and joint roughness conditions. Rock shear performance is worthy of study as it has an important role in the development of proppant embedment. In this study, a direct shear machine is utilized under constant normal load, and proppant embedment and rock shear strength are recorded by transducers with increasing rock horizontal displacement. Based on the experimental results, rock shearing has a detrimental effect on proppant embedment, and proppant embedment increases almost linearly with increasing horizontal displacement. Fluid affects proppant embedment by altering the interaction between the proppant and the rock mass, and fluid with high viscosity helps improve proppant embedment by maintaining even proppant distribution, especially for rock shearing along undulating surfaces. Rock shear strength, associated with rock friction angles, decreases with the addition of proppant. The addition of proppant also greatly alters rock dilatancy, enhancing rock dilation angle reduction through a large amount of proppant embedment. The reduction of rock shear resistance is believed to be a threat to proppant behaviour. The results may assist the understanding of proppant degradation mechanisms during potential shearing failure, and optimise proppant behaviour for fracture joints.

1. Introduction

Horizontal well drilling and hydraulic fracturing are recognised as one of the most successful methods for the extraction of natural gas from unconventional reservoirs.[1,2] Tight gas sandstone, classified as sandstone with average permeability lower than 1mD,[3] is one of the potential unconventional reservoirs with large amounts energy storage.[4,5] Blanket sandstone is one main type of tight gas sandstone with extensive and laminated deposits, which need to be drilled horizontally to contact as many bodies as possible to optimise production.[6] According to Myers and Potratz,[7] Reinicke et al.[8] and Shekhawat and Pathak,[9] economic production of tight gas sandstone can be achieved through horizontal drilling and hydraulic fracturing. In the fracturing process, proppant, small particles with high strength, has an essential role in propping the fractures open after pumping ceases in order to permit gas flow. However, proppant degradation mechanisms cannot be avoided, due to the extreme conditions deep underground, including high in-situ pressures and temperatures, and one of the most common types of proppant degradation is proppant embedment.[10–13] Proppant embedment is defined as proppant particles being indented into the rock mass under pressure, causing a reduction of fracture width and conductivity,[14–22], and effective stress plays a dominant role in proppant embedment, as the mechanism worsens with increasing stress.[11,12] In addition, rock shearing may worsen proppant embedment, although no study has ever focused on this. Specifically, hydraulic fracturing may induce rock shearing with relative movement, and lead to shear failure at the fracture tip.[23–30] Faults may be activated at the same time, which may enhance the rock's relative movement.[31–34] Furthermore, according to studies by Liu et al.[35] and Parker et al.[36] the stress in packed granular materials, like the proppant pack, is concentrated along chains, and stress chains transmit force along the contact points of grains. This means the force is not perpendicular to the rock surface, and some portion of the force may be in the direction of the wellbore, causing rock movement. As rock shearing is inevitable during hydraulic fracturing, its effect on proppant behaviour should be studied. Theoretically, the mechanism of joint shearing and displacement increases

* Corresponding author.
E-mail address: ranjith.pg@monash.edu (P.G. Ranjith).

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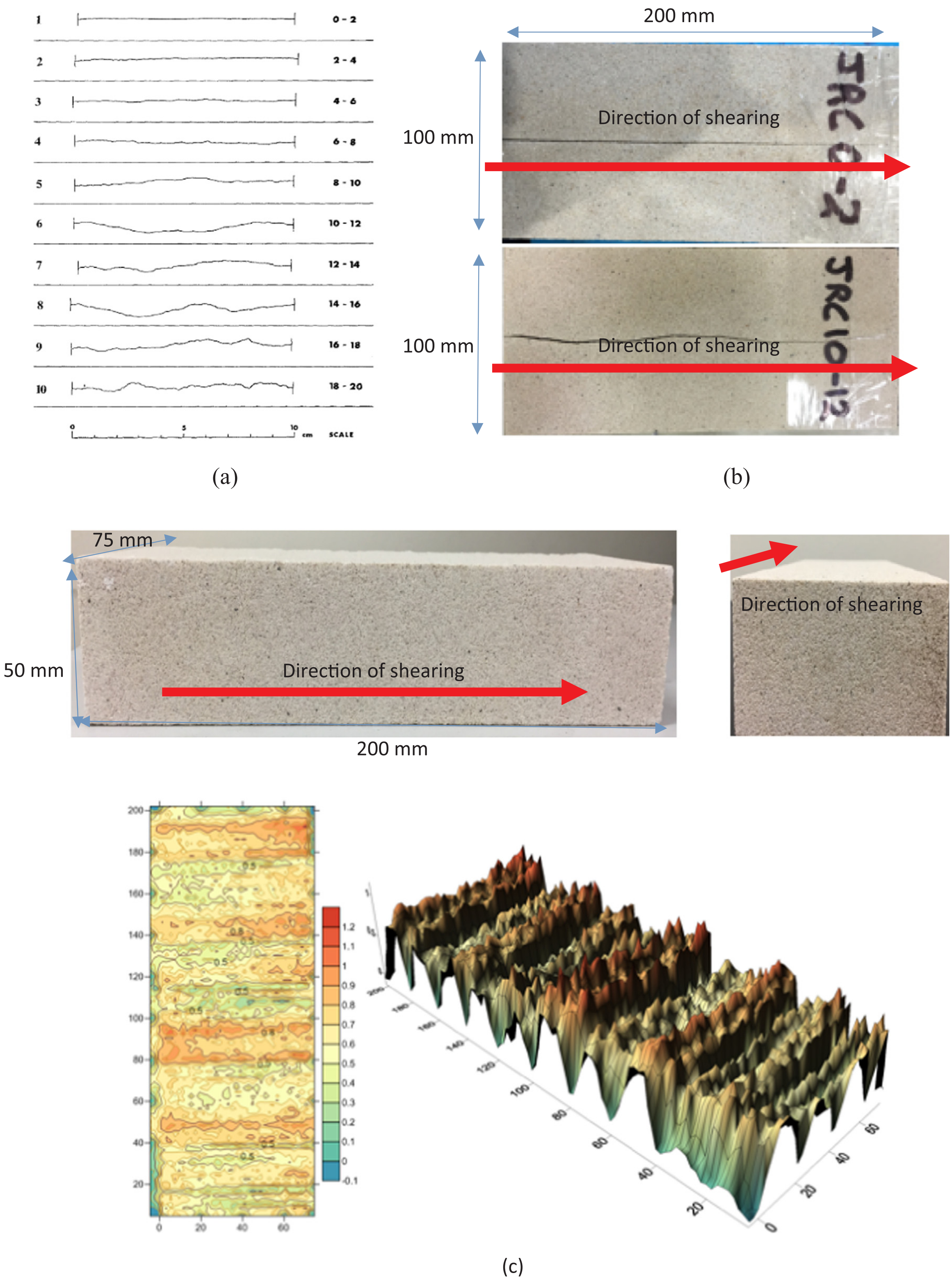

Fig. 1. (a) JRC profile by Barton and Choubey[44]; (b) Front view of rock joints after water-jet cutting in 2-D; (c) Front view of smooth rock joints in 3-D with Surfer; (d) Front view of rough rock joints in 3-D with Surfer.

the effective stress due to the reduction of the contact area,[37] which may further enhance proppant embedment. Fracture conditions, including various fluids and rock surface roughnesses, may alter proppant embedment under rock shearing, and their influences on proppant embedment need to be identified.

Rock shear performance is worthy of study as it has a close relationship with proppant behaviour, and is helpful in explaining the development of proppant embedment. Specifically, rock shear strength, representing the shear resistance of the rock mass, plays an important role in preventing relative movement of rock, and is therefore essential for proppant behaviour. According to Eshiet and Sheng,[38] rock friction angle and dilatancy are strongly related to shear strength development