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Compression and crushing behavior of ceramic proppants and sand under high stresses

Shuai Man*, Ron Chik-Kwong Wong

Department of Civil Engineering, University of Calgary, Calgary, AB, T2N 1N4, Canada

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ABSTRACT

Proppants play a pivotal role in hydraulic fracturing treatment for oil and gas production in low-permeability hydrocarbon-bearing formations. This paper experimentally investigates the compression and crushing behavior of engineered ceramic proppants and frac sand. Proppants' time-independent and time-dependent mechanical behavior was quantified by conducting displacement-controlled diametrical compression tests and stepwise creep tests on single proppant grains, as well as 1-D compression tests on proppant grain packs. Rock-proppant interaction tests were also performed to mimic the proppants' behavior in a rock fracture under reservoir stresses. Individual ceramic proppants showed higher time-independent crushing resistance than the frac sand. Proppant grains with surface asperities were inferred to be more susceptible to creep behavior under sustained load due to the progressive damage of surface asperities. 1-D compression tests revealed that the frac sand is more compressible and crushing-prone compared with the ceramic proppants. Severe grain crushing and moderate grain embedment were observed in rock-proppant interaction tests under in-situ stresses.

1. Introduction

Natural permeability of tight shale or sandstone formation is usually not sufficiently adequate to allow unrestricted flow of hydrocarbons at economic rates. Hydraulic fracturing rips open tight formations and creates highly-conductive flow pathways through injecting a mixture of fracturing fluids and proppants. Since its premiere in the petroleum industry in 1940s, hydraulic fracturing has become one of the most prevalent operations practiced in the oil field to recover hydrocarbons economically in low-permeability reservoirs (Veatch, 1983a; Mader, 1989; Economides and Nolte, 2000; Adachi et al., 2007). Proppants play a critical role in hydraulic fracturing to maintain the highly-conductive pathways for fluid flow. The function of proppants is to keep the hydraulically-induced fractures open by withstanding the in-situ pressure (also called closure pressure) in the formation (Veatch, 1983b). If proppants are not sufficiently strong, they are likely to experience grain crushing which will result in healing of the created fractures. The proper selection of proppant can make a difference between success and failure in a hydraulic fracturing treatment. Therefore, understanding the compression and crushing of proppant becomes extremely important. To achieve this objective, this paper experimentally investigates the compression and crushing behavior of both engineered ceramic proppants and frac sand.

2. Literature review

2.1. Compression behavior of single grains

2.1.1. Time-independent behavior of single grains

As a foundational step toward the understanding of the compression behavior of proppant packs in hydraulically-induced fractures, studying the crushing behavior of single grains is essential. In the literature of geotechnical engineering, many authors have conducted displacement-controlled diametrical compression tests on individual grains to understand the time-independent compression behavior of sand and other types of crushable soils. It is generally accepted that the failure of a spheroid under diametrical compression is in fact caused by the induced tensile strain. This concept has been adopted to indirectly measure the tensile strength of rock pieces subjected to a pair of concentrated loads (Hiramatsu and Oka, 1966; Jaeger, 1967). The mean value of F/d^2 at failure of an individual spherical particle compressed diametrically is a proper statistical measure of the tensile strength of brittle ceramic particles (McDowell and Bolton, 1998), where F is the crushing force and d is the diameter of the particle. Nakata et al. (1999) diametrically compressed single quartz sand particles and the force-displacement relationship observed before grain failure was approximately linear. Nakata et al. (2001) applied similar

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* Corresponding author. University of Calgary, 2500 University Dr. NW. Calgary, AB, T2N 1N4, Canada.
E-mail addresses: shman@ucalgary.ca (S. Man), rckwong@ucalgary.ca (R. Chik-Kwong Wong).

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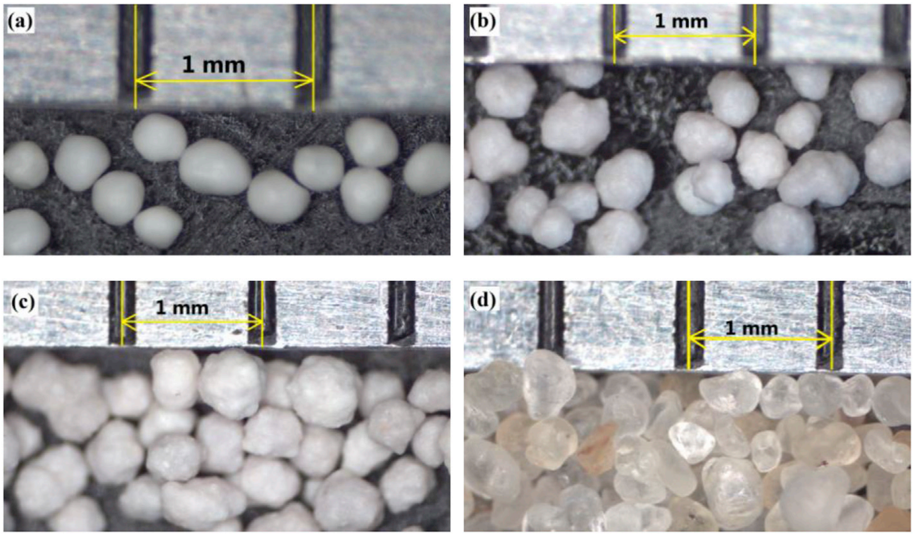

Fig. 1. Proppant materials observed under optical microscope: (a) OxSteel; (b) Hydroprop; (c) SLB; (d) Baylic Sand.

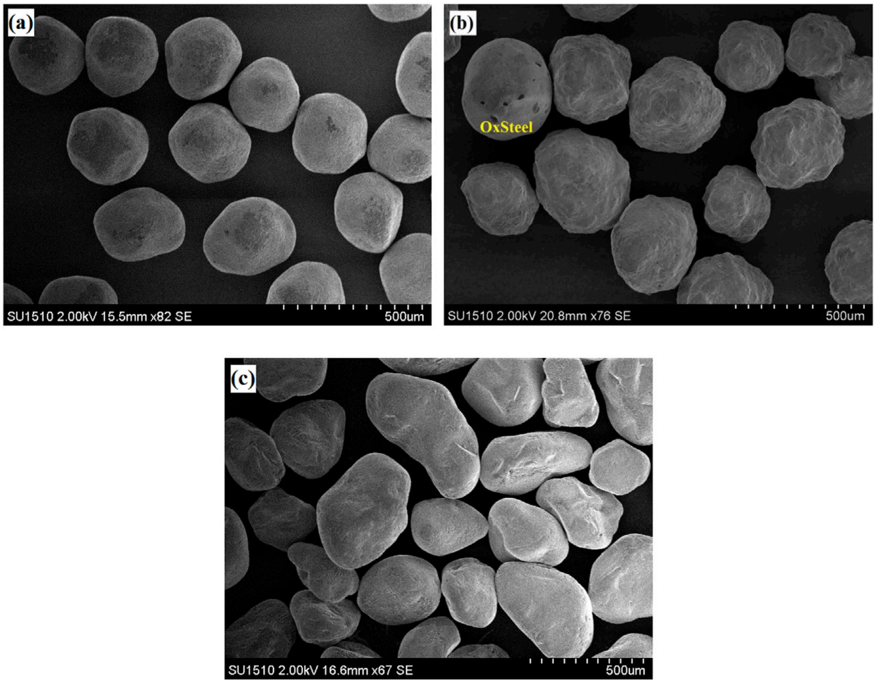

Fig. 2. SEM photos of proppant materials: (a) OxSteel; (b) Hydroprop and SLB; (c) Baylic Sand.

test methods on silica sand but obtained saw-tooth force-displacement relationship because of the successive breakages of sand's surface asperities. Takei et al. (2001) performed compression tests on single angular quartz particles and observed that particles were crushed into a number of pieces along visible discontinuities of crystal structure. Diametrical compression tests on silica sand (McDowell, 2002) and pure quartz sand (Brzesowsky et al., 2011) demonstrated that the single-grain crushing force increased with increasing grain size. Zhao et al. (2015) experimentally showed that the more complex initial particle morphology and micro-structure led to a much richer array of fracture patterns in single sand and decomposed granite grains. In petroleum engineering, mechanical characteristics of walnut shell particles used as proppant (Kulkarni, 2008) and ceramic proppant particles (Kulkarni, 2012) have also been investigated using single-particle compression tests.

2.1.2. Time-dependent behavior of single grains

For time-dependent (creep) behavior of single particles under compression, Michalowski and Nadukuru (2012) proposed that static fatigue (also called stress corrosion cracking) was the primary reason for creep behavior in sand under compression. They experimentally demonstrated the physical consequences of static fatigue of individual silica grains under constant compressive stress. In a follow-up study,

Table 1
Physical properties of proppant materials.

Proppant	Specific gravity	Maximum porosity	Minimum porosity
OxSteel	2.79	0.431	0.349
Hydroprop	2.59	0.440	0.367
SLB	2.61	0.457	0.377
Baylic Sand	2.71	0.443	0.369