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Long-term Sustainability of Fracture Conductivity in Geothermal Systems using Proppants

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ABSTRACT

Long-term sustainability of fracture conductivity is critical for commercial success of engineered geothermal system (EGS) and hydrogeothermal field sites. The injection of proppants during stimulation has been suggested as a means of enhancing the conductivity in these systems. Several studies have examined the chemical behavior of proppants that are not at chemical equilibrium with the reservoir rock and water. These studies have suggested that in geothermal systems, geochemical reactions can lead to proppant dissolution and deposition of alteration minerals. We hypothesize that dissolution effects can decrease proppant strength and, thereby, lead to reduced fracture conductivity.

To examine thermal and geochemical effects on the geomechanical strength of proppants, we performed modified crushing tests of proppants that had been subjected to 250 ºC in batch reactor experiments. These preparatory experiments involved heating crushed quartz monzonite rock material and proppants (either quartz sand, sintered bauxite, or kryptospheres) in Raft River geothermal brine for a period of 2 months. After testing a portion of the proppant material was subjected to a modified American Petroleum Institute ISO 13503-2 proppant crushing test. This test is typically used to determine the maximum stress level that can be applied to a proppant pack without the occurrence of unacceptable proppant crushing. We use the test results as a surrogate to examine potential changes in proppant geomechanical properties as compared to samples that have not been subjected to geothermal conditions. Preliminary results may be used to screen proppants for suitability for long-term use in EGS and hydrogeothermal systems.

1. INTRODUCTION

The enhancement of geothermal well productivity and the creation of commercially sustainable fracture conductivity for enhanced geothermal systems (EGS) has been problematic. Efforts to enhance injectivity have had limited success (Entingh, 2000), but have generally been insufficient for commercial production. The geothermal community has lacked an industry specific characterization approach to hydraulic fracturing and proppant placement and has relied on a “brute force” fracture treatment procedure (Aqui and Zarrouk, 2011).

Maximizing fracture conductivity and the long-term sustainability of fractures is critical to maintaining reservoir sustainability in geothermal systems and to enabling commercial success with EGS. Evidence from previous studies suggests that application of proppants during stimulation is an effective means of maintaining high fracture conductivity near the well bore. The DOE’s Geothermal Reservoir Well Stimulation Program (GRWSP) sponsored ten stimulation experiments in the 1980’s. Of these experiments, 7 included addition of proppants (sand, resin coated sand or bauxite) to the reservoir (Entingh, 1999). Post-well evaluation indicated that while some wells showed an increase in the productivity index, others did not. One of the general findings of this study suggests that proppants may degrade over in high temperature and saline environments, however the relevant field testing was of insufficient duration to provide a robust evaluation of long-term stability.

The few EGS field studies that have used proppants to support fractures have consistently indicated improved well productivity with their use (Shiozawa and McClure, 2014). Field studies at Fenton Hill and Le Mayet both indicated that without proppant, simulated fractures were marginally conductive without high borehole pressures, results that are consistent with findings in the oil and gas industry. Fracture stimulations with proppants resulting in higher injectivity/flowback rates suggest that proppants were able to enhance the fracture conductivity near the well bore. Despite successes with EGS fracture stimulation using proppants (Entingh, 2000), there does not seem to be an accepted methodology to estimate the effect of adding proppants during and EGS stimulation project. Some recent studies (Taron and Elsworth, 2009, Ishabashi et al., 2013) have suggested that reservoir rock matrix in EGS applications can dissolve along the fracture face, either reducing the fracture aperture or increasing the fracture conductivity, depending on the injection fluid chemistry, rock type, time, and location in the fracture. Other studies have suggested that proppants may partially dissolve over time, leading to subsequent precipitation of secondary minerals that either plug the fracture or weaken the proppant pack to the point that it can no longer sustain balance closure stress and is crushed (Yasuhara and Elsworth, 2004, McLin et al., 2010). Still others have suggested that certain proppants are chemically inert under EGS conditions (Jones et al., 2014). These contrasting conclusions have led to uncertainty about the value of proppants as a means of sustaining high conductivity of fractures in hydrogeothermal/EGS reservoirs.

The uncertainties about proppant behavior in geothermal systems demonstrate the need for better characterization of the geochemical interactions between proppants, the injected fluid, and the reservoir rock. Unpublished batch studies conducted at the INL, involving bauxite proppants and Raft River geothermal water, indicated significant silica dissolution from the bauxite (Figure 1). Previously, LaFollette and Carman (2011) have also shown the evidence for loss of silica from interior of the bauxite proppant grains and deposition of silica on the external surface.

Proppants in geothermal systems must be able to withstand the effective stress of the EGS reservoir and resist geochemical interactions leading to degradation, over longer time periods, and at higher temperatures, than in the petroleum reservoirs in which they are generally used. Currently, however, the effect of proppants on hydraulic conductivity, and its dependence on in situ stress, is characterized without consideration of long-term stability. To begin to address this issue, we have performed a preliminary investigation to examine the evolution of geomechanical properties of proppants by comparing the relationship between proppant pack conductivity and stress in unreacted proppants and proppants exposed to geothermal conditions in batch geochemical studies.

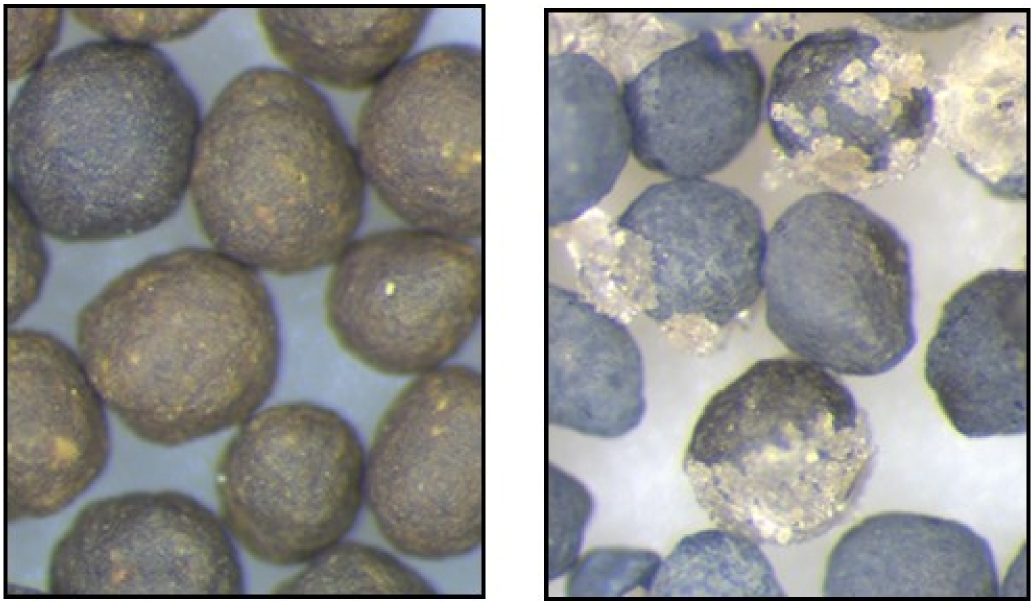
a) b)

Figure 1. Photo of 30/60 mesh bauxite proppants, a) prior to testing, b) after testing.

2. EXPERIMENTAL METHOD

The experimental method consisted of two parts; exposing proppant to geothermal conditions in batch reactor cells and testing the relative strength change of the proppants using a modified American Petroleum Institute (API) proppant crushing test method.

2.1 Batch Reactor Testing

To expose proppants to geothermal conditions in the laboratory, water, rock and proppants were heated to 250°C in a 1-L Parr stainless steel reactor (Table 1). Raft River Geothermal (RRG) water obtained from well RRG-1 was used as the fluid media. The reservoir rock was a granite specimen obtained from the University of Utah. The rock was prepared for testing by crushing with a jaw crusher and sieving to a 30/60 mesh fraction. Each experiment was conducted at a 1:1 fluid-to-solid ratio. Experiment 1 contained only RRG water and the reservoir rock. The remainder of the experiments used RRG water and a 50/50 mixture of proppant and reservoir rock. Proppants tested included sintered bauxite, quartz sand, and kryptospheres. The reactors were sealed, heated to 250°C and maintained at that temperature for a period of 2 months. After that time, the reactors were quickly quenched and opened; fluid samples were obtained for chemical analysis (see Jones et.al. 2016 for results) and the rock/proppant portion was dried for subsequent testing.

Table 1: Proppant-reservoir-rock-water interaction experiments

Experiments	Materials
1	RRG water (150 g) + Reservoir rock (150 g)
2	RRG water (150 g) + Reservoir rock (75 g) + Sintered bauxite (75 g)
3	RRG water (150 g) + Reservoir rock (75 g) + Quartz proppant (75 g)
4	RRG water (150 g) + Reservoir rock (75 g) + Kryptosphere proppant (75 g)

2.2 Proppant Mechanical Testing

To test the strength of the proppant and the granite separately, a procedure was developed to segregate these solid fractions. Because some of the proppant had a similar grain size as the crushed granite rock used as reservoir material, separation by sieving was not an option. The bauxite and kryptospheres are both man-made proppants and are more spherical than the generally angular granite crushed granite. Those proppants were segregated from the granite transport down an inclined plane. Prior to crushing, the proppants were sieved to remove particles less than 60 mesh for the bauxite and 30 mesh for the kryopspheres to create a threshold for each proppant to evaluate the amount of crushing. Unfortunately, we were not able to separate the quartz sand from the crushed granite using this method and therefore were only able to mechanically test the bauxite and kryposphere proppants as proppant-only materials.

ISO 13503-2 *International Standard Petroleum and Natural Gas Industries- Part 2 Measurement of properties of proppants used in hydraulic fracturing and gravel-packing operations* was modified to measure limited quantities of reactive proppants at the INL. Within this standard, Section 11 *Proppant Crush-Resistance Test* is used to determine the amount of proppant crushed at a given stress. This test is designed to indicate the stress level whether proppant crushing is excessive and the maximum stress to which the proppant material should be subjected. We are using this standard to assess changes in the proppant mechanical strength due to the exposure to geothermal conditions.

Due to limited mass of the reacted proppants, the crushing piston was redesigned to test a 5-gram mass that is approximately 1/8th the mass suggested in the procedure. Figure 2 illustrates the stainless steel crushing cell assembly. Previous testing at the INL indicated that the redesign did not affect the fraction crushed as long as the surface area of the piston was proportional to the mass of proppant being tested. For this paper, we are only examining the relative change in the fraction crushed from unreacted proppant to that of proppants exposed to geothermal conditions.

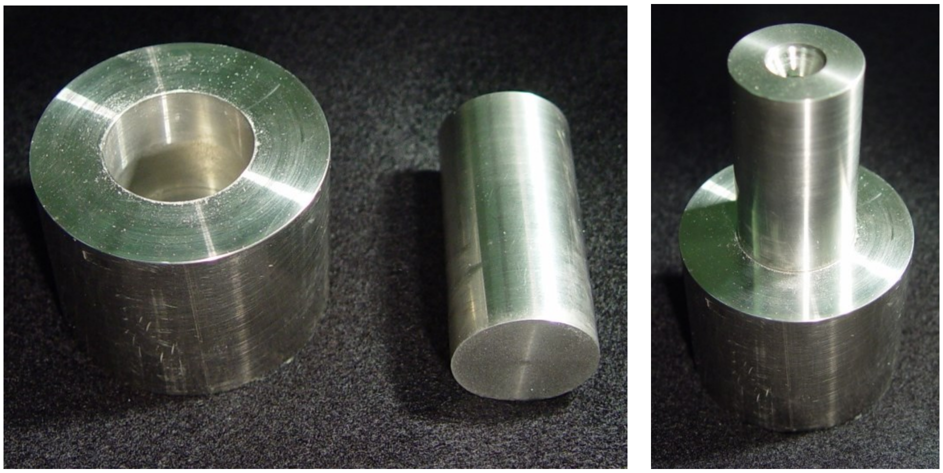

Figure 2. Crushing cell and piston and the assembly.

After the cell was loaded with the proppant sand material, it was placed in a Humboldt load frame to apply a vertical stress that simulates field conditions. The sample was loaded to the desired stress state and held at this stress state for a period to two minutes. The sample was then unloaded and sieved through a 60 mesh (30 mesh used for kryposheres) sieve for 5 minutes. The fraction passing the sieve was calculated and used to evaluate the change of strength of the proppant due to exposure to geothermal conditions.

3. RESULTS

Excess crushing is typically used to determine the stress range appropriate for a proppant, and is dependent on both the mechanical strength of the proppant and its shape. Figure 3 contains photographs of the proppants before and after crushing. The particle shape of the sand/granite mixture (Figure 3a) is angular even prior to crushing. The smaller grain size and the angular nature of the particles result in large percentage of the particles (~ 30 to 40%) being crushed to a size less than a 60 mesh screen even through the mixture was only exposed to approximately one half the applied stress of the proppants. Due to the fact that the sample was a mixture of two materials, , no conclusions on the sand/granite mixture can be made.

Figure 3b and 3c show the bauxite and kryptosphere proppants after separation from the granite before and after crushing. The crushed bauxite and kryptosphere proppants appear to have split into a limited number of pieces and become more angular due to fracturing. Few fines were produced in either proppant pack, suggesting that permeability reduction via fines production would not be an issue in the field.

Crushing test results for bauxite and kryptospheres are shown in Figures 4 and 5. For the unreacted case, both proppants are much stronger than the sand/granite mixture, displaying adequate crushing characteristics (i.e. < 10%) to 13,000 psi. Assuming a lithostatic pressure of 1.4 psi/foot, these proppants can be used to approximately 10,000 feet. This depth exceeds most hydrogeothermal resources and is in the approximate range of suggested EGS sites. In addition, their spherical shape and larger diameter, relative to the sand proppant, should result in higher fracture permeability than sand-propped fractures.

The fraction of bauxite crushed increases with greater applied stress for both the unreacted and reacted cases (Figure 4). These test results suggest that bauxite proppant exposed to geothermal testing conditions is slightly weaker (i.e. greater crushing) than unreacted bauxite for all stress levels. However, the additional degree of crushing due to exposure to the geothermal condition is small. The amount of proppant available for mechanical testing was too limited to allow for evaluation of uncertainty in the crushing results.

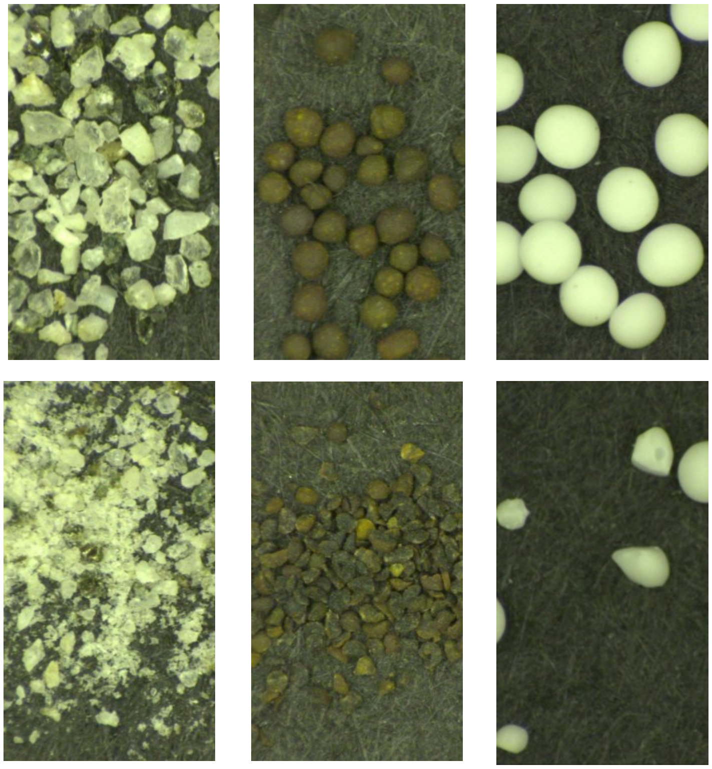
a) b) c)

Figure 3: Proppant pictures before and after crushing a) 30/60 mesh bauxite, b) 60 mesh sand/granite mixture, and c) kryptospheres.

Kryptosphere crushing results (Figure 5) indicate that geomechanical degradation of that proppant occurred under geothermal conditions. Unlike the bauxite proppant, however, the kryptospheres that were exposed to geothermal conditions crushed to a greater extent at higher applied tresses. These results suggest that when choosing a proppant to use under geothermal conditions, not only does the initial geomechanical strength need to be considered but the temporal geomechancial degradation of the proppant should be evaluated as well. Field well stimulation testing programs, such as those conducted by the GRWSP evaluated the post simulation production index immediately after the stimulation and would likely not capture a temporal reduction in the fracture conductivity due to proppant degradation.

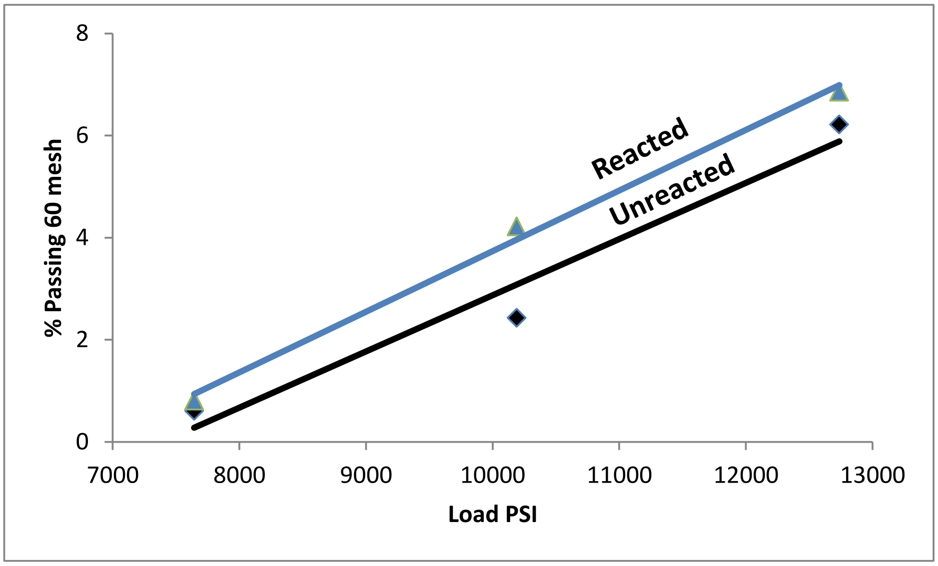

Figure 4: Crush-Resistance test results for unreacted and reacted bauxite proppant.

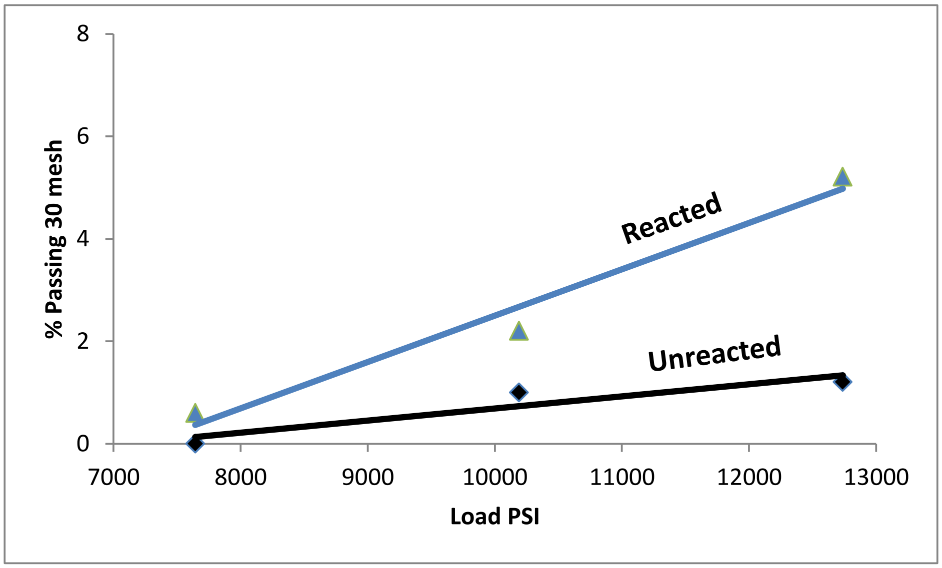

Figure 5: Crush-Resistance test results for unreacted and reacted kryptosphere proppant.

4. CONCLUSIONS

Enhancing productivity in existing hydrogeothermal systems and the creation of high permeability pathways in EGS will likely require the use of proppants to maintain fracture stimulation-enlarged apertures near production and injection wells. Geothermal and EGS reservoir stimulation field testing results have indicated some improvement of performance at least in the short term. However, no long-term performance data of the stimulated wells, with respect to proppant behavior, are available. In addition to development of methodologies to increase reservoir permeability in the field, the materials used to stimulate the reservoir should be evaluated as to their long-term performance in these high temperature systems. Laboratory testing results in this paper suggest that there is a temporal effect on proppant mechanical strength that needs to be incorporated in evaluation of the proppants used in geothermal well stimulation.

The results of this paper are a preliminary scoping study and therefore care should be exercised in making general conclusions. These results were obtained under one set of conditions (i.e. limited proppant types, a single fluid chemistry, temperature, exposure time, and reservoir rock) and may not hold for all geothermal reservoir sites. However, for the two proppants evaluated in this paper that could be segregated from the reservoir rock, the crushing results suggest potential geomechanical degradation of the proppants under the test conditions. Although test results indicated that bauxite had leached silica, little degradation of strength was observed. In contrast, kryptospheres exhibited a large degree of mechanical strength degradation after exposure to identical geothermal conditions. Additional testing is required to understand the long-term behavior of the proppants in hydrogeothermal/EGS reservoirs.

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