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Geothermal Proppants: Qualification for use in Superhot Reservoirs

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ABSTRACT

Superhot Rock (SHR) geothermal reservoirs represent a promising frontier in renewable energy, offering vast potential for sustainable heat and power generation. The development of SHR systems necessitates sophisticated engineering solutions, particularly in the realm of reservoir stimulation and how to maintain power generation. Early approaches to establishing SHR reservoir networks relied on innovative techniques such as hydroshearing and novel pumping methodologies to induce fractures, facilitate fluid circulation without needing proppants, and rely on created permeability. However, as SHR technology advances, the need for effective proppants to maintain fracture permeability and integrity becomes increasingly apparent. This paper investigates the critical process of proppant selection and qualification in SHR applications, addressing the adaptation of existing commercial products and the development of novel materials tailored to SHR conditions.

The selection process for proppant materials in SHR systems is a complex task, involving careful consideration of various factors, including thermal stability, mechanical strength, and chemical compatibility. The unique challenges of SHR systems, such as extreme thermal and mechanical stresses, require proppants with exceptional performance. One approach is to test existing commercial proppants from the oil and gas industry, which require no modification but must be tested to ensure suitability for SHR environments. Alternatively, creating novel proppants from raw materials presents an opportunity to tailor material properties to specific SHR conditions, potentially optimizing performance and sustainability.

Following the selection of candidate proppants, the next crucial step is the qualification process, which rigorously assesses their suitability for SHR applications. This paper outlines an exploratory methodology for proppant qualification, drawing upon industry standards such as API Std 19 and adapting them to SHR-specific conditions.

The qualification process provides valuable insights into the strengths and weaknesses of current proppants in SHR applications and sheds light on areas needing improvement and innovation. By identifying promising candidates and assessing their performance through laboratory testing, this research contributes to the ongoing advancement of SHR proppant technology.

1. INTRODUCTION

Recently industry leaders such as Fervo (Norbek et al. 2023) have applied conventional stimulation methods to geothermal projects by adapting oil and gas industry workflows and using proppants widely available for current use. Similarly in FORGE (Jones et al. 2023), various proppants are being tested in field demonstration experiments to study their ability to maintain permeable pathways for subsurface heat exchange in a moderate temperature Engineered Geothermal Systems (EGS) test site.

The use of proppants in SHR, where water is injected in reservoirs with rock temperatures and fluid pressures exceeding the critical point of water is a new frontier for EGS (CATF 2022). This paper will consider an SHR reservoir as having temperatures above 375°C, where water becomes supercritical at pressures above 22 MPa. SHR conditions create significant challenges for proppant selection, both considering potential issues with proppant delivery due to low fluid viscosity, and with regard to chemo-mechanical stability at conditions where data for conventional proppants is not available. One strategy for the initial selection is to screen materials developed previously for high temperature oil and gas applications with the hope that some of these materials can be applied to SHR systems with minimal additional R&D and thus reduced costs. A second option is to identify new proppant materials that have the potential to exceed performance of the current proppants on the market and can be processed to have the desired physical properties (e.g. shape, size, density) for use as proppants at SHR conditions.

2. PROPPANT SELECTION

There have been prior experiments to understand the geochemistry of proppants in geothermal settings (Brinton et al. 2011), but the testing presented would be at almost 200°C higher and with stresses that mimic a particular reservoir condition. Candidate materials were selected, including commercial proppants and a range of other potential materials to gather a baseline and screen their response to

SHR conditions including stability at temperature, water pressure, and net closure stress. Studied proppants included commercially available natural sands and high strength ceramics commonly used in the oil and gas industry as well as novel materials selected for their chemical and physical properties. The goal of the testing was to further aid the selection and development of proppants that are optimized for SHR EGS, while also understanding the potential and limitations of current commercially available proppants.

2.1 Test Criteria

The criteria that qualify a proppant to be used in SHR include a complex combination of chemical and mechanical stability. Assessment must take into consideration the potential for non-linear chemo-mechanical couplings and time dependent deformation. Currently, for a proppant to be used in a geothermal application, an operator will make a decision based on their own testing and decide on a well-to-well, EGS-to-EGS system approach. The inspiration for testing proppants was based on the American Petroleum Institute (API), which provides guidelines for proppant characterization that are accepted by the O&G industry. API Std 19 offers a well-established standard for testing proppants for a range of oil and gas applications, however direct application of standard testing procedures at SHR conditions is not practical using the same equipment and protocols and may overlook variables specific to EGS applications. Even within the oil and gas industry, the qualifications of proppants are an ever-evolving process (e.g. Simo et al. 2013).

2.2 Test Set-Up

An early part of this study involved design of test protocols that would provide comparisons between candidate proppants to down-select materials for more in-depth study. Initially, our first challenge was to create a testing set-up and procedure that would enable the measurement of crushing resistance at the temperatures, pressures, and fluid chemistries relevant to SHR reservoirs. The work started with an existing apparatus originally designed for another application that was able to reach temperatures of 450°C, confining and pore pressures of 50MPa, and axial loads of up to 250 MPa. These initial capabilities satisfied the parameters that will be seen at the Newberry EGS project location. (Cladouhos et al. 2016). Barre granite was selected as the rock material for testing, allowing for realistic rock/water/proppant chemical interactions. A schematic diagram of the apparatus is shown in Figure 1a.

Two sample configurations were developed to enable testing of proppants (Figures 1b,c). In one configuration, the proppant layer was accessed by pore fluid from one end while allowing for flow through the surrounding granite at the other end. This scenario enables testing using fluid in various states of equilibrium with the proppant, rock, or proppant+rock, as well as the ability to monitor the permeability of the rock in the vicinity of a stressed proppant layer. The second configuration allows for short circuiting the fluid flow through the rock, enabling controlled studies of variable fluid chemistry and the potential to measure steady-state permeability of the proppant pack.

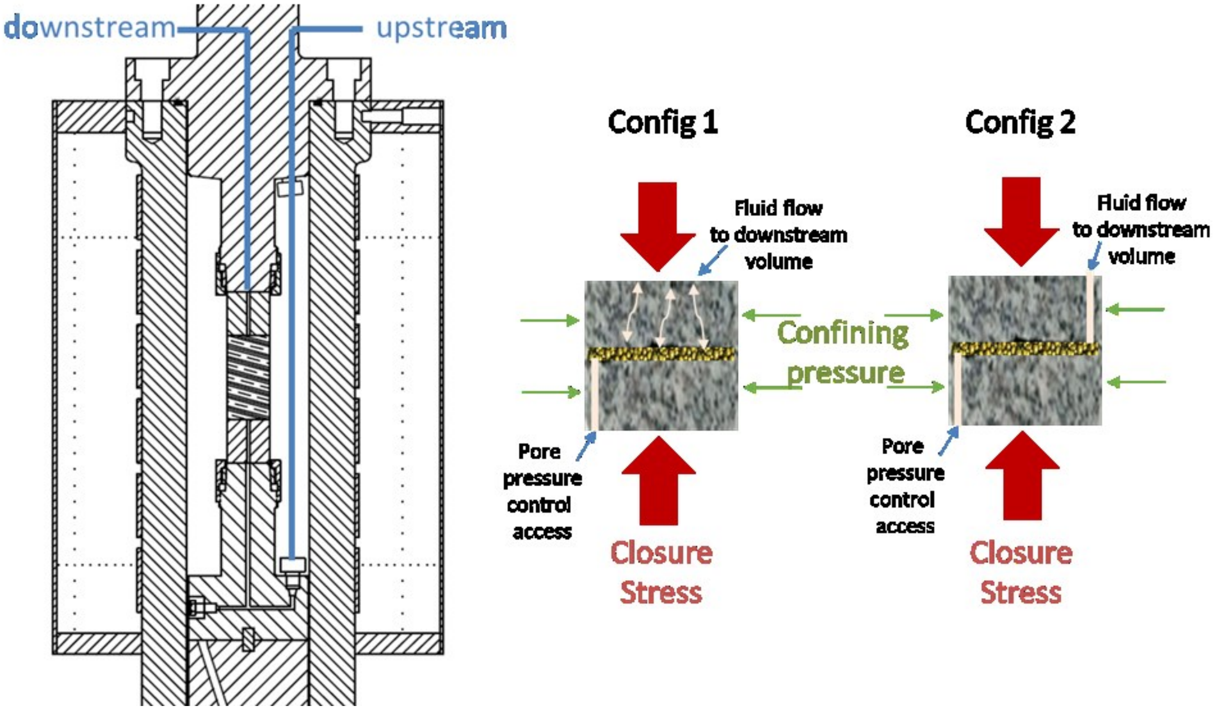

Figure 1 Schematic illustration of test apparatus and sample configurations used in the study.

For our initial testing a general protocol was developed that consisted of up to 5 steps to test and qualify the proppants (Figure 2). For testing using configuration 1, tests were performed using steps 2,3, and 4. For tests using configuration 2, steps 1 and 5 were added to quantify the permeability of the proppant layer before and after the high temperature compaction.

Multilayer testing protocol

1) Measure permeability vs axial load at room temp
2) Load to target pressure while heating to 400C
3) Add axial load to target net closure pressure, hold for 40 hours
4) Remove axial stress and cool down with reverse protocol as in step 2
5) Measure permeability vs axial load at room temperature

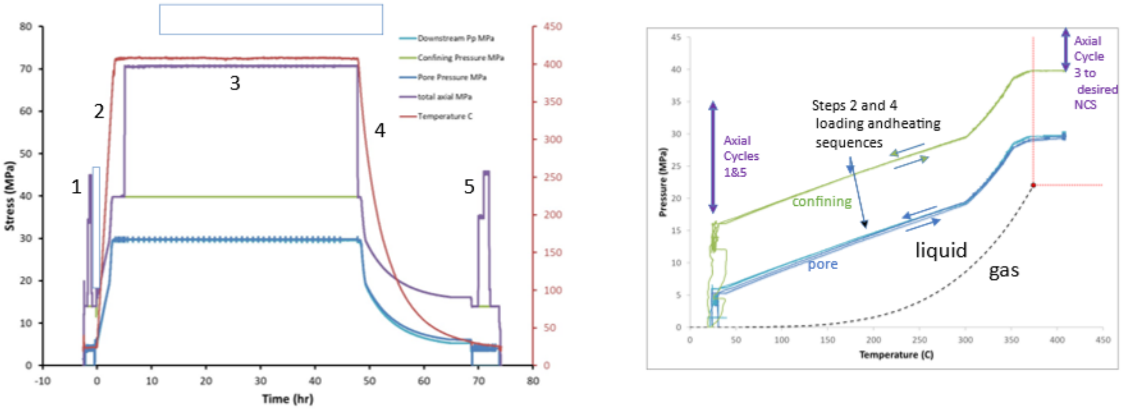

Figure 2 The standard testing procedure involved a 5-step process with 40 hrs at temperature and net closure stress. Permeability of the proppant pack was measured during load cycling in steps 1 and 5. Compaction of the proppant pack was measured continuously throughout the experiment.

3. TESTING RESULTS

In the first phase, testing consisted of a monolayer of proppant pressed between two end-ground granite core samples using configuration 1. This was done to test the material properties of the grains in just one monolayer. Multiple samples were tested using this monolayer testing procedure to assess the materials chemical and mechanical stability at SHR conditions and to look for evidence of proppant embedment and crushing.

Testing monolayers gave the ability to focus testing on proppants that show promise for mechanical and chemical stability. During monolayer testing the axial displacement and stress (axial load) and how the displacement changed over time with temperature was monitored. Post test CT scans were used to visualize proppant behavior and post-test microscopic analysis of the proppant was performed to quantify degree of crushing and look for evidence of chemical reaction (Figure 3).

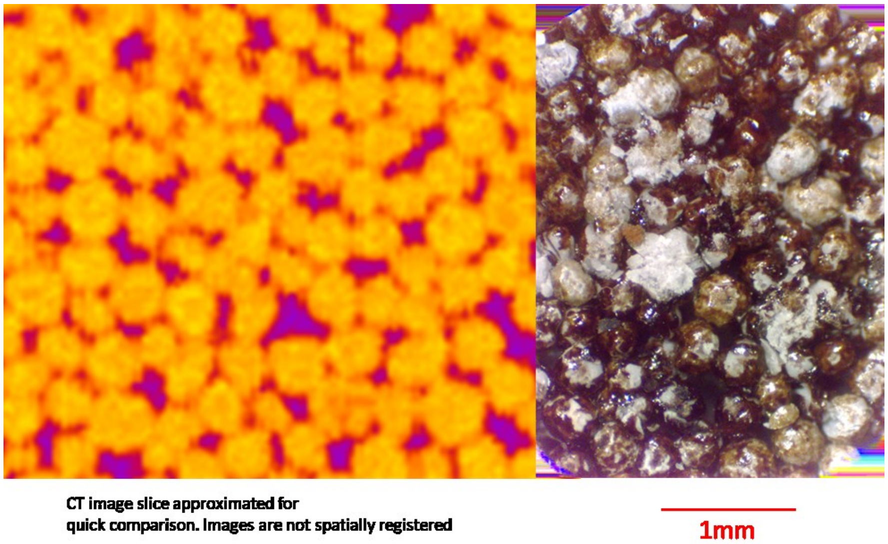

Figure 3 Post test CT in the plane of a monolayer of coated ceramic proppant alongside a post test photo showing coating degradation and grain crushing.

The second phase of testing consisted of testing multilayer proppant packs and quantifying permeability and porosity maintenance as well as degree of crushing and fines generation. Considering that the use of various proppants with a wide range of grain densities, and being limited to a small cell geometry, for this testing a fixed initial thickness was used as the controlled starting condition. A starting thickness of 6.4 millimeters was adopted for the standard multilayer testing reported here. As an illustrative example, **Error! Reference source not found.**4 shows a representative ceramic proppant pack after testing.

Figure 4 Example of a ceramic proppant pack after testing

Two contrasting examples of the axial displacement measured during multilayer testing are shown in Figure 5. On the left are results from a test on a proppant that is very strong and stiff at room temperature, but undergoes significant time dependent creep and mechanical degradation at supercritical conditions. On the right are results from a comparatively weak proppant at room temperature but after crushing is mechanically stable at supercritical conditions. Numbers in Figure 5 correspond to the stages of the test protocol described in Figure 2. Both proppants exhibit equally strong and elastic behavior post-test (cycle 5).

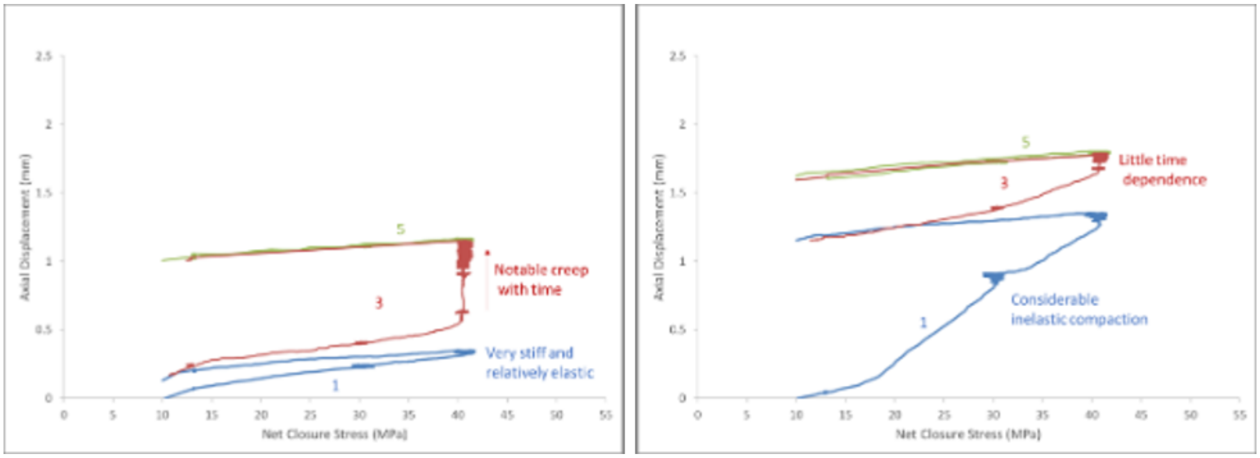

Figure 5 Axial Displacement during the testing procedure for two contrasting proppants. See text for discussion.

Error! Reference source not found. illustrates another contrasting comparison of the two proppants with very similar initial compaction at SHR conditions. A ceramic proppant (black) shows good thermal and compaction properties and stability over time. In contrast, natural sand (green) exhibits noticeable creep over time.

The final testing parameters to analyze were the permeabilities and porosities of the multilayers pre- and post-test. **Error! Reference source not found.** shows a comparative cross-plot of permeability and porosity performance for selected proppants from testing illustrating the range of responses observed. The measurements that are graphed are the room temperature (RT) values at fixed net closure stress both pre- and post 40-hour test at 400°C (e.g. steps 1 and 5 from figure 2). The results are the first step in selecting proppants based on the operational requirements for SHR EGS, illustrating a range of behaviors among the materials studied.

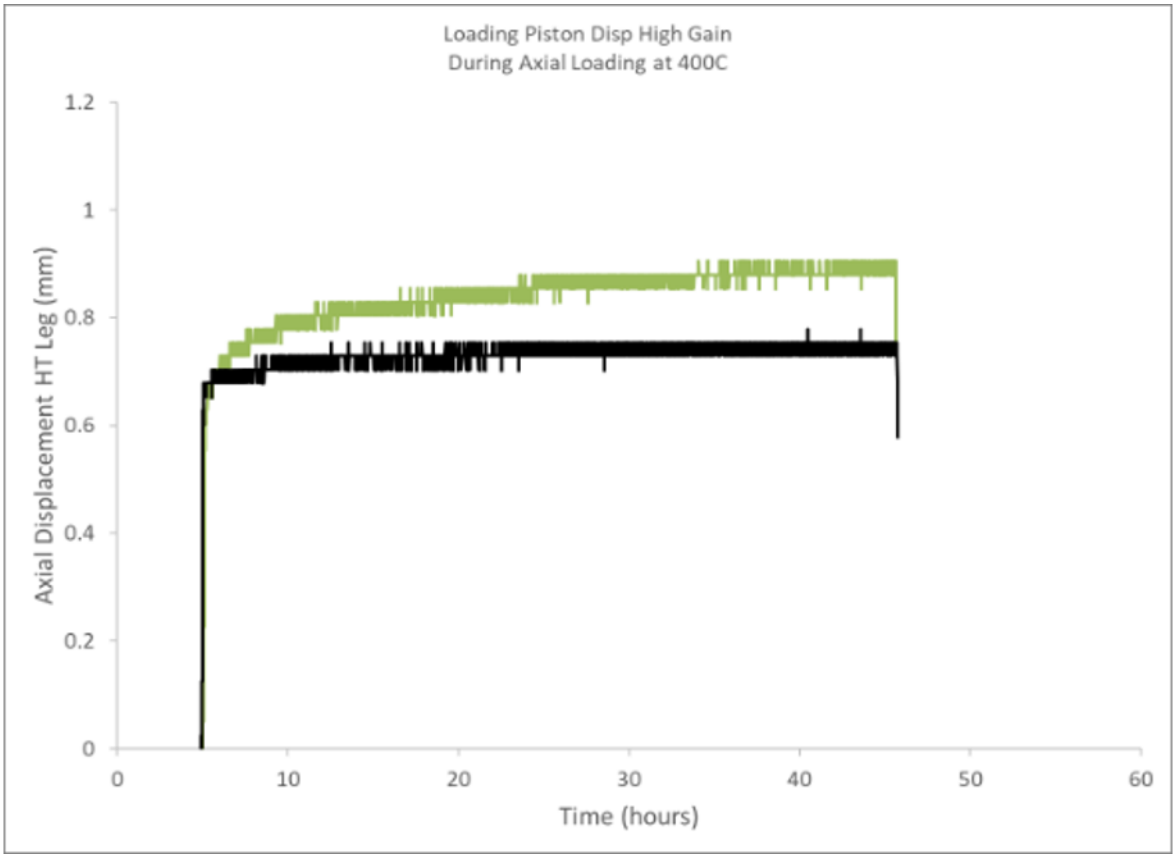

Figure 6 Axial displacement of two contrasting proppants over time at supercritical conditions, one exhibiting time dependent creep and the other remaining relatively stable at the conditions tested.

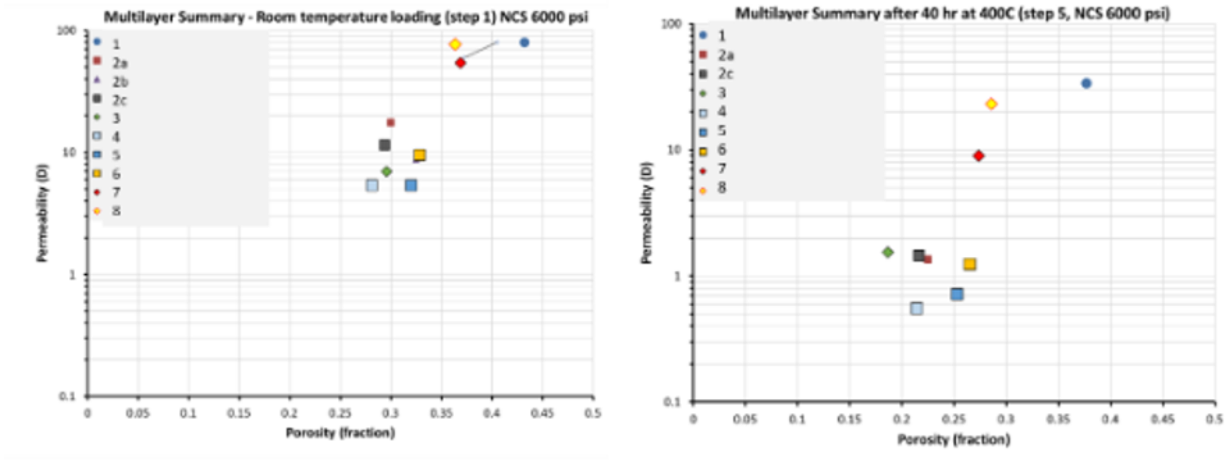

Figure 7 Permeabilities and porosity of various proppant packs before and after 40 hours at supercritical conditions. Reported permeabilities are intrinsic values corrected for variable layer thickness.

CONCLUSION

The primary focus of this testing was to provide a pathway for the initial evaluation and selection of proppants for SHR EGS. Current geothermal projects, at the time of writing this paper, can only rely on current proppants and some experimental proppants. As SHR is becoming more relevant in the geothermal project development, the industry needs to qualify materials and proppants in order to optimize their use in maintaining fracture permeability at these reservoir conditions. Our testing is limited in terms of the materials that have been tested and the specific conditions to our SHR reservoir, but these learnings will serve as a useful guide for proppant selection and future development of standards for proppant qualifications at SHR conditions.

The testing showed that a currently available ceramic proppant held up well at SHR conditions over the time duration tested, and that natural sands can have good intrinsic early stage properties in the short term but degrade over time at the temperatures and stresses studied. Other experimental proppants illustrated good long term stability at SHR conditions but suffered from tendency to crush even at room temperature.

Building on these early findings and experiences to guide testing of new and current materials designed for SHR stimulation design and field trials is the ultimate goal. The testing procedures will be updated for new conditions, and additional studies and equipment modifications will be made to improve our understanding of proppants in SHR reservoirs.

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