Mechanical investigation of rock-proppant interaction with focus on geothermal applications

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Abstract. Since decades proppants have been used to enhance hydraulic pathways for the exploitation of hydrocarbon reservoirs. These technologies may also be adapted for geothermal applications, but geothermal reservoir rocks strongly differ from those typically targeted by hydrocarbon industries. Therefore, the mechanical interaction between conventional proppants and geothermal reservoir rocks and their effect on hydraulic properties need to be investigated in more detail to maximize the success of such method adaption. In principle, two mechanical requirements must be fulfilled: (1) proppants must withstand the stresses that are present in a reservoir, and (2) proppants must not penetrate the rock formation of the reservoir, because this would reduce the fracture conductivity. Fine mobilized rock- or proppant particles can also clog the fracture. For the mechanical suitability of proppants, uniaxial compressive strength tests and long-term creep tests were carried out in the laboratory. The test setup consists of a proppant monolayer placed between two cylindrical rock samples that were axially loaded. We determined Young’s moduli and creep rates for sample stacks with various proppants under different stress conditions. The laboratory tests are part of the ZoKratenS Project, which aims at showing the feasibility of enhancing fractured carbonate rock mass by proppant placement for geothermal applications.

1. Introduction

Due to climate change and neutral climate balance, new developed strategies for the use of renewable energies are needed. Not only the established methods such as wind energy or solar energy should be applied, but also alternatives should be considered.

The collaborative research project ZoKratenS follows an alternative approach for the exploitation of deep geothermal reservoirs. The hydraulic efficiency of proppants, which have not yet been used in deep geothermal systems, is to be demonstrated. So far, proppants have been used in the hydrocarbon industry to stabilize hydraulically stimulated fractures and to increase the permeability of the geological target horizon [1]. To develop a petrothermal system, proppants, possibly in combination with zoned acidizing, could also be introduced into natural fracture zones of deep-seated carbonates. We present results of laboratory experiments conducted to evaluate the technical feasibility of such a pilot project. The experiments aimed at answering the following questions:
Are the proppants capable of withstanding the in-situ stress, or do the proppants fail under stress application in contact with the carbonate formation?
Are the proppants capable of keeping the fractures open, or are proppants pushed into the carbonate formation beyond a tolerable level for the relevant loading?
Will rock fragments be mobilized due to fracture surface damage associated with the proppant compression, resulting in solids discharge that may clog the existing fracture or damage engineering facilities?

2. Material and methods
In this section, the materials and methods are described. In addition to the various proppants, the sample material is also presented. Subsequently, the experimental setup will be described.

2.1. Sample material
The Geretsried research site (approx. 30 km south of Munich) is located in the Northern Alpine Foreland basin. Here, the potential target horizon with the low-permeability carbonates of the Upper Jurassic is encountered at a depth of more than 4 km [2].

Rock samples were prepared from blocks originating from the Pappenheim quarry of Max Balz GmbH, approx. 100 km north of Munich, and used as analog material for the Geretsried geothermal well. The analog material is a thick-bedded bioclast-rich, tuberolithic sponge-biocurrent limestone from the Upper Jurassic of Franconian alb [3]. Stratigraphically it is assigned to the lower part of the middle Kimmeridge layer [3]. In the Pappenheim quarry, the limestone beds are up to 1.5 m thick and nearly horizontally deposited [4]. The degree of fracturing can be described as low. Individual fissures and faults, whose surfaces are covered with a brown-red weathering clay, are partly open in the decimeter range.

Proppants, also called fracture propping agents [5], are essential components of a hydraulic stimulation applied in hydrocarbon exploration. They are transported into a fracture by using viscous fluids and keep it open so that the hydraulically generated permeability can be maintained [6]. Important proppant properties that exert a significant influence on the long-term permeability and stability of the proppant package include strength, grain size, grain size distribution, sphericity and degree of roundness, and specific gravity [7][8]. Three different types of proppants with a diameter range between 0.4 mm and 0.8 mm corresponding to mesh size 20/40 [9] are tested in the present study. The strength category of the proppants provided by their manufacturers increases with increasing density (figure 1).

![Figure 1. Measured grain densities of the different proppant types. In this study high strength proppants (HSP), intermediate strength proppants (ISP) and low strength proppants (LSP) are used.](image-url)

2.2. Rock properties and experimental setup
Before testing stacks of rock samples equipped with proppants, the limestone was geomechanically characterized. Blocks and prepared specimens showed no signs of anisotropy or heterogeneity. The specimens were prepared from a total of six blocks by drilling perpendicular to the bedding and then ground to plane parallelism. Samples for uniaxial compressive strength tests were placed in a stiff 4000 kN loading frame and centered between the loading plates. To determine the radial strain, a radial strain chain was placed in the center of the specimen. According to DGGT [10] / ISRM [11] suggested methods the unconfined compressive strength test was conducted servo-controlled with grade 1 testing equipment. During testing, axial load was applied until failure occurred. The axial piston was advanced with a constant velocity resulting in a strain-rate of about 10^{-5} \text{mm/mm/s}. Experiments were conducted using an MTS TestStar IIm controller. Axial load and axial displacement were recorded with a sampling frequency of 10 Hz using a calibrated load cell and calibrated LVDTs with a resolution of 10^{-7} \text{m}, respectively. During the experiment, uniaxial compressive stress and axial strain were monitored and controlled with a frequency of 10 Hz using the following equations:

\[
\sigma_{\text{ax}} = \frac{4F}{\pi D^2} \quad \text{(MPa)} \tag{1}
\]

\[
\varepsilon_{\text{ax}} = \frac{\Delta l}{L} \quad \text{(mm/mm)} \tag{2}
\]

Uniaxial compressive strength \(\sigma_c\) was derived from the maximum of the stress-strain-relation. The deformation modulus \(V\) and the Young’s modulus from the reloading path \(E_B\) were determined at an axial stress in the range of 40% to 60% of the uniaxial compressive strength unless otherwise specified.

For the Brazilian tensile strength tests [12], the rock disc was placed in a steel loading jaw. After centering the sample an initial load of 100-200 N was applied before sensors were set to zero, i.e., forces and all strains started at zero. Load was applied with a rate of 200 N/s until failure occurred as suggested by ISRM [13]. Tensile stress was determined from load at failure \(P\), diameter \(D\) and sample thickness \(t\) following:

\[
\sigma_t = 0,636 \frac{P}{D t} \quad \text{(MPa)} \tag{3}
\]

Tensile strength \(\sigma_{t,\text{sp}}\) was determined from the maximum in stress-strain-relations provided by Brazilian tensile strength tests. Further characteristic properties such as compressional ultrasound wave velocity and permeability with steady state flow were determined and are presented in table 1.

| UCS, tensile strength | Young’s modulus, GPa | compressional wave velocity, km/s | permeability, m² |
|-----------------------|----------------------|----------------------------------|-----------------|
| 141 ± 23              | 9,4 ± 2,0            | 35 ± 4                           | < 10^{-18}      |

The experimental setup for experiments with proppants is shown in figure 2. During the tests, the proppants were placed between two cylindrical rock specimens. In general, the proppant experiments are composed of two series of tests. One in which the stack of proppants and specimens is loaded axially at a constant deformation rate until the uniaxial compressive strength is reached (uniaxial compressive strength test UCST), and one in which the test specimens were subjected to constant axial stress of 30 MPa while the deformation was recorded over time (uniaxial creep test UCT).
3. Results & Discussion

Figure 3 shows a representative stress-strain-relation for a UCST (left). The point for potential proppant failure and macroscopic failure is indicated. At around 100 MPa, there is a slight drop in axial stress. At the same time, the axial strain of the rock proppant package increases, so that a potential proppant failure can be assumed. The maximum measured axial stress of this UCST is 125 MPa and corresponds to the uniaxial compressive strength of the rock proppant stack. The limestone shows brittle failure by axial splitting.

The results of the UCST are shown in figure 4. In 23 performed tests, the compressive strengths of the stacks show a relation to the proppant strengths. For both blocks 1 and 6, the specimens with the high-strength proppants had the largest uniaxial compressive strengths. Furthermore, for block 6, a trend can be registered between the specimens with medium and low strength proppants. The specimens with medium strength proppants have higher uniaxial compressive strengths than the specimens with low strength proppants. However, this trend can only be partially observed for specimens from block 1.
Figure 4. Uniaxial compressive strength as a function of the used blocks (left) and proppant strength (right) derived from UCST. High strength proppants (HSP) are indicated in blue, intermediate strength proppants (ISP) are shown in red and low strength proppants (LSP) are presented in green.

The uniaxial compressive strengths of the specimens with high strength proppants are relatively constant, i.e., they show a high reproducibility. The averaged value of the uniaxial compressive strength is 120 MPa with a standard deviation of 12 MPa. For specimens with medium and low strength proppants, the uniaxial compressive strength is slightly less reproducible. The UCST results of stacks with medium and low strength proppants is 98 MPa ± 17 MPa and 97 MPa ± 19 MPa, respectively.

The UCT, during which the specimens were axially stressed with an assumed in-situ stress of 30 MPa for more than 17 h, showed the typical primary and secondary creep behaviour without macroscopic failure (figure 3, right). At the beginning of the test, a rapid change in deformation per time can be registered, which decreases as the test progresses. Due to loading, the proppants are initially settled and subsequently minimally penetrate the rock matrix. The creep rates in the later part of the secondary creep are presented in figure 5. In general, the creep rates of the specimens with proppants are in a range of $10^{-8}$ mm/mm/s to $10^{-9}$ mm/mm/s, whereas the specimen without proppants has a lower creep rate of about $10^{-10}$ mm/mm/s. Furthermore, the creep rate increases with a decrease in the proppant strength.

Figure 5. Measured creep rates in mm/mm/s of different proppant types.
Figure 6. Top view of the specimen surfaces provided with proppants after reaching the uniaxial compressive strength (left) and in-situ stress of 30 MPa (right). The arrows correspond to 2 mm, the green markings indicate broken proppant spheres.

For the microscopic examination of the proppants after testing, the surface of the specimen was first examined as a whole, so that a representative area could be selected. In the UCST the proppants with high and medium strength were up to 86 % intact (figure 6a & 6c). For the low strength proppants, a greater portion of broken particles can be registered (figure 6e). Here, the percentage of broken low strength proppants corresponds to about 25 %.

The visual inspection of the creep test samples shows that the high strength proppants are almost exclusively intact (figure 6b). In contrast, broken particles can be identified in the medium and low
strength proppants (figure 6d & 6f). Regardless of the strength, a few broken spheres exhibit the same fracture pattern. In the contact area with the specimen, the spheres are depressed. Splitting cracks appear along the meridional plane. The fracture pattern of the proppant spheres can be attributed to different failure modes [14]. Failure occurs when the tensile stress is not uniformly distributed along the loading axis, resulting in high stress anisotropy. Another potential mode of failure can be caused by the development of a ring crack at the contact surface between rock and proppant. The ring crack is a result of the Hertzian tensile stress prevailing during loading [15][16]. In addition to the ring crack, cone cracks can develop, propagating from the surface of the ring crack along the axis of loading.

Depending on the arrangement, a spacing of 0.2 mm up to 0.4 mm can be observed in between the intact proppant spheres. Fines can be seen in the areas of the fractured proppants and are mainly composed of proppant material, and not rock fragments (figure 6f).

4. Conclusion

In general, the proppants with high and medium strength have fewer broken particles than the proppants with low strength when loaded up to the uniaxial compressive strength of the rock. In no case does the proportion of fractured proppants exceed 25%. During the creep tests, the low strength proppants are more vulnerable and fail more frequently than the medium and high strength proppants, resulting in the increase in creep rate with decreasing proppant strength. However, the percentage of fractured proppant particles is much lower in UCT than in the UCST.

The axial deformation of the rock proppant packages, which is calculated during the creep tests, suggests that the proppants penetrated the carbonate rock matrix to a tolerable degree with respect to the intended application in geothermal systems. Visual inspections also support this conclusion, suggesting that fractures are kept open with intact proppants generating and creating hydraulic pathways. While fines of the carbonate formation and proppants were observed in the tests with loading until uniaxial compressive strength was reached, the creep tests showed fines only from the limestone between the proppants. In the presence of fluids, these fragments can be rearranged and clog the hydraulically conductive fractures [17]. Therefore, a series of tests with a flow cell is intended to simulate clogging and the resulting reduction of the permeability [17][18][19][20].

In addition to that, to make a more precise delimitation of the reservoir properties in connection with proppants, further investigations are planned with focus on proppant tests with stresses up to the uniaxial compressive strength. Further tests could show a clearer relation between the uniaxial compressive strength and the proppant strengths.

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