Abstract

This study explored the performance evaluation for resin-coated proppants through a customized tri-axial test. By validating the accuracy of the test setup and simulating the test condition with numerical modeling, the protecting effect of the resin coating on the proppant was verified through this compression test under a tri-axial stress state as well as microscopic analysis by SEM.

Introduction

In hydraulic fracture for shale gas, micro-cracks created inside the rocks are maintained by proppants to allow natural gas and other petroleum reserve to migrate towards the well [1]. As shown in Figure 1, proppants, typically polymer coated silica sands, are pumped into the fractured rocks during or following a fracturing treatment. After the fracturing pressure is withdrawn, the interstitial space between proppant particles should be sufficiently large, yet have the mechanical strength to withstand closure stresses to hold fractures open [2]. The main function of the polymer based coating, such as phenolic-formaldehyde coating, polyurethane coating, and epoxy coating, is to improve the performance of proppant in terms of flow conductivity and service life.

Figure 12. Example of resin-coated proppant – from Fairmount Santrol SEC Filing [3]

The overall performance of the proppant is usually evaluated by a long term (50 hours) conductivity test (ISO Method 13503-5), in which proppants are heated to 121 °C under a compression loading [4]. As this conductivity test is expensive and time consuming, and also not readily reproducible quantitatively, it is not suitable for developmental research to improve proppant coating; rather, it is used mainly for monitoring proppant coating property and quality of already commercial grades of proppants in a manufacture environment.

In the past, several proppant coating characterization methods have been proposed, such as individual proppant compression test [5], proppant coating property measurement by atomic-force microscopy and dynamic fracture test [6]. Modeling of proppant flow permeability, and thus flow conductivity, of spheres or ellipsoids of narrow size dispersity have also been done in the past, for the uncoated rigid proppant case [7]. However, very few studies have been published to correlate the overall proppant performance with its polymer coating behavior in micro-scale.

By developing a customized tri-axial compression test, this study explored a multi-scale performance evaluation for resin coated on the proppant through both macro compression test and micro-scale evaluation by SEM. In the following sections, the overall test design is discussed. Then, protective effect of the resin coated on the proppant is explored in this study.

Tri-axial Test Setup for Resin-coated Proppant

The tri-axial test is aimed at determining the compression and creep of the samples that are constrained in two dimensions (axial and radial). A typical tri-axial test setup based on ISO standard 12736 is shown in Figure 2 [8].
One major advantage of using the tri-axial geometry is that it closely mimics the true nature of the forces and degrees of freedom that apply onto polymer or granular materials which will be used in a constrained space. With properly designed test setup, this test allows not only bulk material property measurement, such as compressibility and creep behavior, but also evaluation of complex interstitial properties, such as shear strength and packing of a discontinuity [9].

The proposed tri-axial compression test design for resin-coated proppant is shown in Figure 3. It is composed of a pressure loading component, a compression punch with pin design for easy assembling, a removable testing chamber, a base for holding the proppant sample and a protection housing with pressure release design. During the test, the tri-axial test setup was loaded into a hydraulic driven Instron™ to perform the compression test, as shown in Figure 4.

The weight of the resin-coated proppant sample was precisely controlled during the loading process with an accuracy of 0.01g. The sample height was tracked during the test with a built-in position sensor in the hydraulic driver, and its accuracy is around 50 μm.

Macro Scale Tri-axial Test on Resin-coated Proppant and Numerical Verification

The resin-coated proppant was first evaluated through this macro-scale tri-axial test. In order to ensure measurement accuracy, the customized tri-axial tester was also modeled by numerical simulation for its effectiveness. Both test fixture geometry change due to the applied temperature and the expected stress distribution in the resin-coated proppants were evaluated through finite element analysis (FEA).

Compressive Behavior at Elevated Temperature

The tri-axial compression test was carried out in a temperature-controlled environmental chamber (see Figure 5). The test fixture was expected to expand due to the applied temperature. For example, a proppant sample under controlled 1000 psi preloading, as its temperature was heated from room temperature to 121°C, the expected thermal expansion for the test fixture was about 8.333 mm based on FEA modeling, as shown in Figure 6.
This 0.833mm fixture expansion was considered in tracking actual proppant sample height in the test. For a selected pressure loading profile shown in Figure 7, the corresponding fixture displacement during the heating up process with 1000 psi preloading was 0.824 mm (see Figure 8), which was about the same as the predicted value (0.833mm) from FEA modeling. The actual proppant height change in the tri-axial test was then adjusted based on its temperature and the thermal expansion from the fixture. As shown in Figure 9, majority of proppant sample deformation occurred as pressure increases from 1000 psi to 6000 psi. Creep behavior also contributed to the sample height reduction. By repeating this tri-axial test on the same type of resin-coated proppant samples, it was verified that final sample height is very repeatable, as shown in Table 1.

Table 1. Sample Final Height in the Test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Measured Final Height [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>4.871</td>
</tr>
<tr>
<td>Sample 2</td>
<td>4.859</td>
</tr>
<tr>
<td>Sample 3</td>
<td>4.851</td>
</tr>
</tbody>
</table>

By validating this test method, the effect of adding lubrication in the resin-coated proppants was explored in this study. With same resin-coated proppants, tri-axial tests were repeated with and without silicone oil under same temperature and pressure condition shown in Figure 7. As shown in Figure 10, it was found that silicone oil affected the packing of the resin-coated proppant in the initial stage. As compression pressure increased from 1000 psi to 6000 psi, the final sample height was very close. This suggests that silicone oil reduced the friction between the resin-coated proppant and allowed more interstitial space reduction during the initial packing.

**Stress Distribution on Resin-coated Proppant**

The stress distribution in the proppants in this tri-axial test was explored by FEA simulation, where 336 spherical proppants were simulated in this case under 1000 psi pressure loading, as shown in Figure 11. It was found that stress on individual proppants could be different due to the packing effect. Consequently, loading force on each proppant would be different, and some proppant could fail earlier due to the higher force it undertook, as shown in Figure 12.
Figure 11. Simulation of compression test on Resin-coated proppant: (a) Initial Model Configuration (b) Simulated Stress

Figure 12. Force distribution on the Resin-coated Proppant

Protection Effect from Resin Coating through Micro-scale SEM Analysis

The protection effect from the resin coating on the proppants was evaluated through SEM for the tested sample. Instead of breaking the tested sample for SEM analysis, the whole proppant sample pack was directly potted by a low viscosity epoxy resin after the test. Then, it was cross sectioned using a diamond saw after it was fully cured. With this approach, the tested proppants held their original positions in the tri-axial test for coating performance evaluation, as shown in Figure 13.

Figure 13. Whole resin-coated proppant sample potted by epoxy after compression test
By looking into individual proppants in SEM (see Figure 14), the resin coating can be easily distinguished from the proppant and epoxy resin for potting. It can be observed that resin coating near the proppant contact locations were pushed away and result in penetration. However, the cushion effect provided by the 10~15 µm thick resin coating was sufficient to prevent proppant from cracking.

In very small amount of proppants, cracks were observed near the proppant contacting area. This is likely related to the sand packing effect shown in Figures 11-12, in which some high contacting stress would always occur to cause some proppants to fail earlier.

![Figure 14. Resin-coated proppant after tri-axial test](image)

Conclusions

In summary, this study explored resin coating performance evaluation through tri-axial test for proppant application. With a customized tri-axial test, Resin-coated proppant sample height change can be precisely evaluated under compressive loading. From macro-scale test, most of the proppant sample height reduction occurred as pressure increased from 1000 psi to 6000 psi at the elevated temperature. By adding silicone oil based lubrication into the resin-coated sample, it was confirmed from this study that this led to more sample height reduction in the initial packing. The protective effect of the resin coating on the proppant sand was verified in this study by performing SEM analysis on the tested sample in its original loading configuration. The cushion effect from the 10~15 µm thick resin coating prevented most proppants from cracking under compressive loading. Small amount of Resin-coated proppant fractured during the test, and this is related to the stress variation in the sand packing process based on the FEA simulation.

References

8. ISO/FDIS 12736, Petroleum and natural gas industries — Wet thermal insulation coatings for pipelines, flow lines, equipment and subsea structures.
9. BS 1377-9:1990 Part 8: Shear strength tests (effective stress) Triaxial Compression Test