PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP-TR-224

Selection and Testing of Proppants for EGS

Sunghyun Ko[1], Ahmad Ghassemi[1], Matt Uddenberg[2]

[1]Reservoir Geomechanics and Seismicity Research Group, The University of Oklahoma, Norman, OK 73069

[2]Alta Rock Energy Inc., Seattle, WA 98103

ahmad.ghassemi@ou.edu

Keywords: High temperature proppant, EGS, Proppant crush resistance, Polymer coated proppant, Acoustic emission.

ABSTRACT

In this paper, we present the results of investigating proppant pack performance when subjected to high temperatures (up to 320 °C) in the presence of water for one to two weeks. Crush resistance and proppant packing strength in dry and heated conditions were studied to understand the proppant performance in high temperature EGS environments. AE response was utilized to estimate the approximate packing strength and fines percentage was used to evaluate the crush resistance. In addition, surface features and fracture mechanisms were studied under magnification using SEM. Fluid heated with proppant was collected to observe proppant dissolution or chemical alteration. The results show that the heated proppant in EGS conditions has a lower approximate packing strength and yields a higher fines percentage, indicating reduced conductivity after its exposure to high temperature fluid for 14 days. The capability of polymer coating, encapsulating and trapping fines within polymer coating, is reduced by coating degradation in high temperatures fluid, resulting in significant increase in fines percentage compared to non-coated proppants.

1. INTRODUCTION

Hot subsurface rock can provide a viable source for renewable energy. The concept of EGS involves circulating cold water through cracks in the hot subsurface rock and extracting thermal energy. High grades of geothermal resources above 300 °C can occur in formations that consist of igneous rock and metamorphic rock with low permeability. Hydraulic stimulation is required to enhance the low permeability of rock masses and those fractures become the main pathway for fluid flow to a production wellbore (Ghassemi et al., 2005). This process requires cracks to remain open under the earth's stress and it can be achieved by placing solid materials called proppants. Thus, understanding proppant pack behavior in the subsurface is crucial to improve fluid flow in EGS. When proppants are placed between cracks, they tend to form a proppant pack and fluid can flow through their porous volume and in channels around distributed packs as shown in Figure 1 (a). As the proppant pack is subjected to in-situ stress, proppants can get crushed and the fracture closes leading to conductivity decreased over time in Figure 1 (b). The proppant conductivity is a product of proppant pack permeability and pack width. The crush resistance controls porous volume around distributed packs, affecting proppant pack permeability and the packing strength controls how much width can be secured under in-situ stress. Thus, two important parameters should be considered for the proper selection of proppant: proppant crush resistance and proppant packing strength. The crush resistance can be measured by following ISO 13503-2 but no available method to approximate packing strength. In addition, the standard crush resistance test only evaluates proppant crush resistance under surface conditions. We introduce the new methodology to evaluate approximate proppant packing strength and carry out heated tests to assess proppant performance under representative reservoir conditions of EGS.

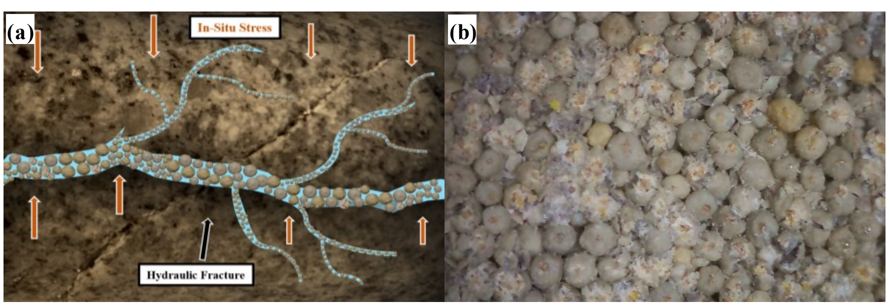


Figure 1: (a) Hydraulic fracture schematic in granite formation and (b) reduced conductivity after proppant pack failure.

In this work, we conducted a crush test using dry and heated proppants to understand the change in proppant pack behavior. First, we characterize bulk density, elemental composition, sphericity, and roundness. Next, the proppant was heated in a water-filled pressure vessel for up to two weeks and then it was subjected to a wet crush resistance test. The crush resistance (K-Value) and packing strength results of heated proppants were then compared to the test results of dry proppants. The crush resistance is evaluated by following the prescribed guidelines in ISO 13503-2 and the proppant packing strength is estimated by monitoring AE (acoustic emission response). Lastly, heated proppant was investigated under magnification and water sample heated with proppant was analyzed to observe dissolution or chemical alteration. These experimental test results provide insights into proppant pack behavior in EGS above 300 °C and can help design advanced proppants for geothermal applications.

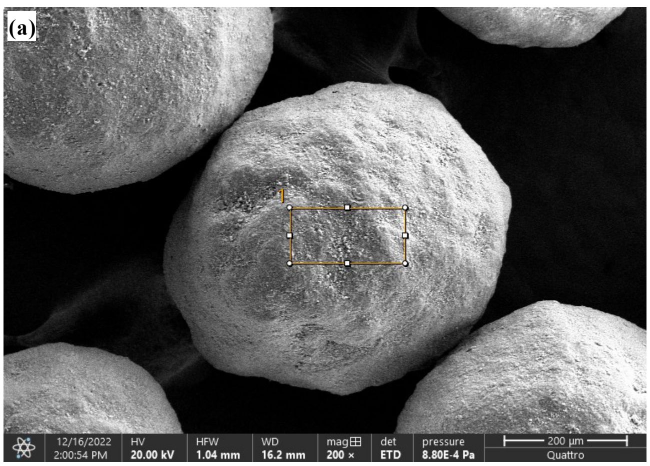
2. MATERIAL PREPARATION

Five different proppants were prepared for this research: non-coated ceramic (NC), hydrophobic polymer coated ceramic (HC), resin coated ceramic (RC), petroleum coke (PC), and white sand (WS). Samples were sieved in two different mesh sizes, 35/60 and 60/120, using an RO-TAP RX-29 sieve shaker. The sieving procedure follows the prescribed guidelines in ISO 13503-2. Before running the crush resistance test, elemental composition, bulk density, sphericity, and roundness were first characterized. The bulk density of the proppant controls the required mass of the proppant that is needed to pump into the well. Same for the proppant crush resistance test, the bulk density is used to calculate the required mass to achieve the volume, 24.7 cm^3, in the test cell. A denser proppant requires more mass to fill the same volume in the cell. Sphericity and roundness are determined based on magnified images of the proppant. These are important parameters that affect the quality of the proppant. A more spherical and rounded proppant can resist closure stress with less fines by evenly distributing an applied stress among neighbor proppants. Lastly, proppants were sputter coated and SEM-EDX (energy dispersive X-ray) analysis was performed to determine their elemental composition.

2.1 Ceramic

Ceramic is a man-made proppant and is considered one of the strongest commercial proppants for hydraulic fracturing applications. This ceramic is non-surface coated proppant. Shown in Table 1, it has a high roundness and sphericity, 0.9 and 0.9 each. The main elements were determined as aluminum, silicon, and oxygen as shown in Figure 2 (b). The bulk density was determined to be close to that of white sand (~1.5g/cc).

(a)



(b)

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	2.8	0.1	1.6	0.1
O	60.2	0.2	47.1	0.2
Al	20.8	0.1	27.5	0.1
Si	14.8	0.1	20.3	0.1
Ti	0.6	0	1.5	0
Fe	0.8	0	2.1	0

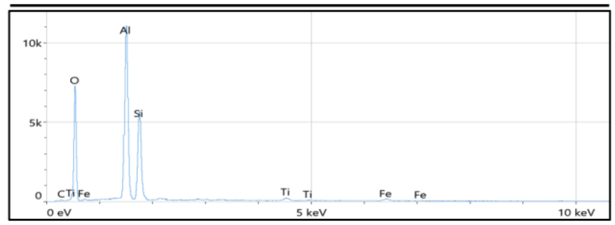
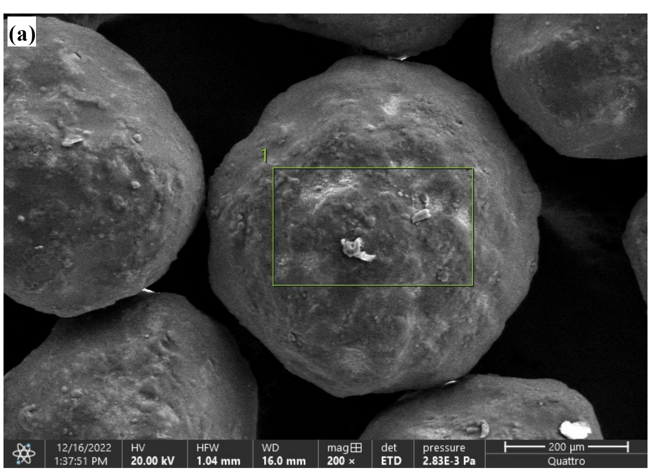


Figure 2: (a) SEM image of ceramic and (b) SEM EDX analysis results.

2.2 Hydrophobic Polymer Coated Ceramic

This polymer coated ceramic has a much lower density (~1.1g/cc) than the other three ceramics (~1.5g/cc) as shown in Table 1. It is designed for high transport in fracture pathway for better propping efficiency. The low bulk density is achieved by making ceramic porous and its surface is coated by hydrophobic polymer to prevent reservoir fluid from entering pores and enhance the crush resistance. The durability of the coating is very important to achieve good mobility and proppant pack integrity at reservoir conditions. The roundness and sphericity were both 0.9. Due to the polymer coating, SEM-EDX analysis results show that it contains C and O on the surface shown in Figure 3.

(a)



(b)

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	71.5	0.2	60.8	0.2
O	20.3	0.1	23	0.2
Al	4.1	0	7.8	0
Si	3.8	0	7.6	0
Ti	0.2	0	0.5	0
Fe	0.1	0	0.2	0

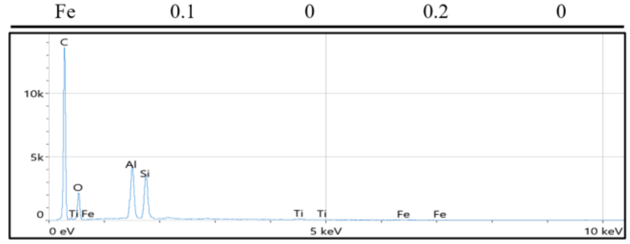
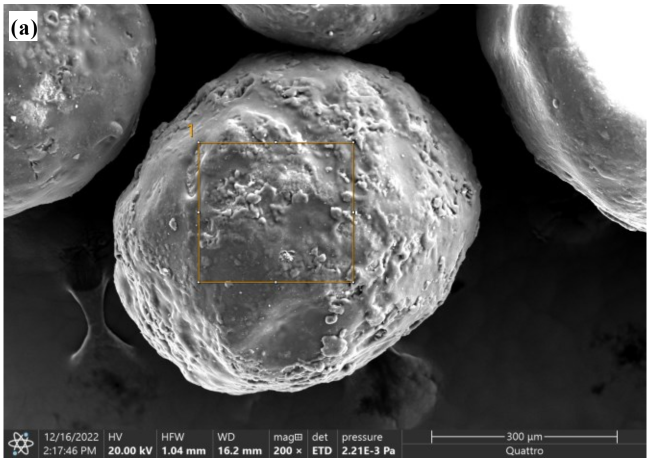


Figure 3: (a) SEM image of hydrophobic polymer coated ceramic and (b) SEM EDX analysis results.

2.3 Resin Coated Ceramic

Resin coated proppants can maintain a good conductivity in deep hydraulic fractures by enhancing the crush resistance and bonding between proppants. Resin coating can encapsulate or trap fines within coating, generating less fines under closure stress (Sinclair et al., 1983; Underdown and Das, 1985). The resin requires a curing process to form cross linked structures, which enhance its mechanical properties. The resin coating can be either curable or precured. Curable resin coating is used to prevent proppant flowback issue, which happens when placed proppant is washed out of fractures along reservoir fluid. The reservoir provides temperature and pressure to cure resin in fractures and the proppant pack is consolidated with a cured resin, forming a bond between proppants (Liang et al., 2016). Precured resin coating is already exposed to the conditions that resin can cure and add an additional crush resistance and strength. The 60/120 size is coated with a much thicker layer than the 35/60 as shown in Figure 4 and 5. Due to the polymer coating, SEM-EDX analysis results also show that proppants contain C and O on the surface.

(a)



(b)

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	64.4	0.2	56.6	0.1
N	12	0.5	12.3	0.5
O	19.3	0.2	22.5	0.2
Al	2.5	0	5	0
Si	1.8	0	3.6	0

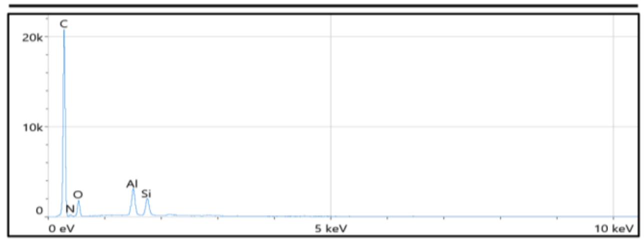
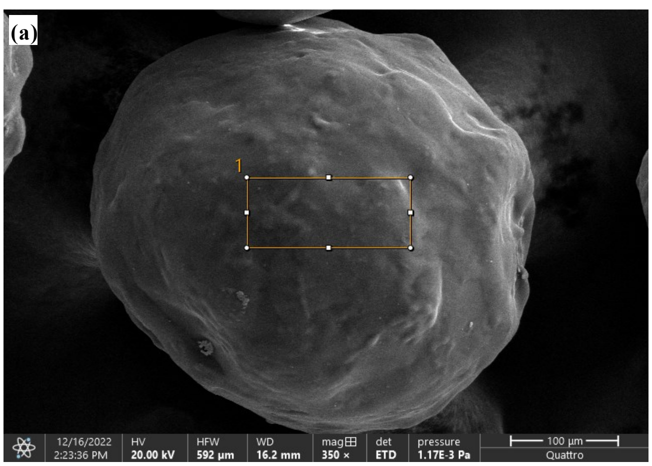


Figure 4: (a) SEM image of curable resin coated ceramic and (b) SEM EDX analysis results.

(a)



(b)

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	62.2	0.1	56.5	0.1
N	14.8	0.5	15.6	0.6
O	22.9	0.2	27.6	0.3
Al	0.1	0	0.3	0

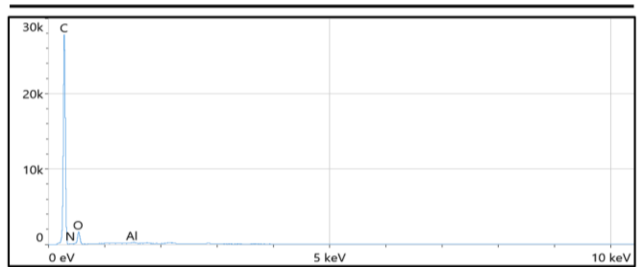
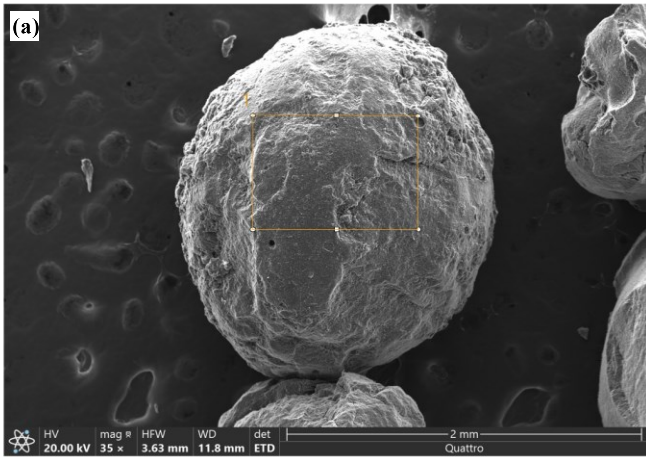


Figure 5: (a) SEM image of precured resin coated ceramic and (b) SEM EDX analysis results.

2.4 Petroleum Coke

Petroleum Coke is a carbon rich material derived from oil refining processes and is often used for fuel or aluminum manufactures. The SEM-EDX analysis in Figure 6 (b) shows it consists of 96 % carbon and 3 % sulfur. The biggest advantage of this material is its very low bulk density (~0.8g/cc), which is almost half of white sand and ceramic as it was measured in Table 1. This lighter petroleum coke could lower the required mass for hydraulic stimulation. In addition, it can be transported farther than other proppants with lighter fracking fluid. However, samples have a high heterogeneity and show the lowest sphericity and roundness among all proppants. SEM image in Figure 6 (a) displays gas released pores on its uneven surface.



(b)

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	96.2	0.3	90.1	0.2
Na	0.1	0	0.3	0
Al	0.1	0	0.2	0
S	3.2	0	8.1	0
Ca	0.1	0	0.3	0
V	0.1	0	0.6	0
Fe	0.1	0	0.4	0.1

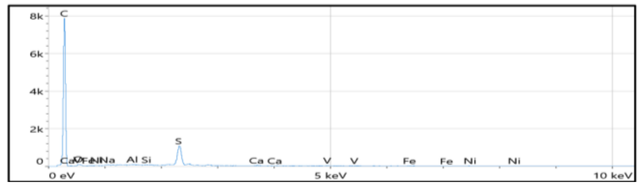
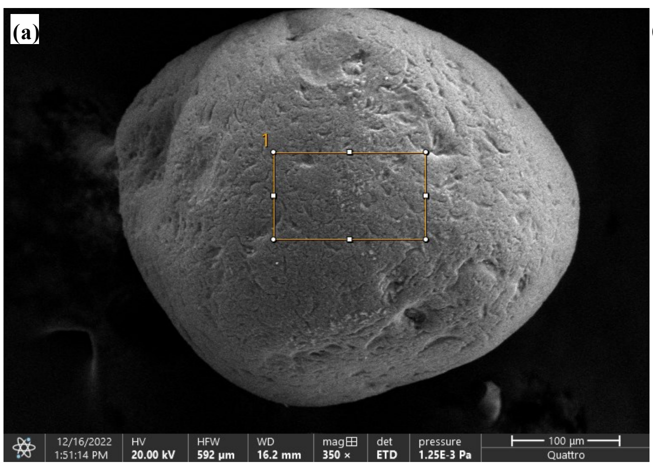


Figure 6: (a) SEM image of petroleum coke and (b) SEM EDX analysis results.

2.5 White Sand

Frac sand is the most widely used proppant for general hydraulic fracturing operations due to its accessibility and low cost. The quality of the sand is determined by the amount of quartz percentage, sphericity, and roundness. SEM EDX analysis results in Figure 7 (b) show that it is composed of silica (SiO_2) rich elements. The bulk density was around 1.5 g/cc.



(b)

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	1.9	0.1	1.1	0.1
O	64.1	0.2	51.2	0.1
Mg	0.2	0	0.2	0
Al	0.5	0	0.7	0
Si	33.2	0.1	46.6	0.1
Ca	0.1	0	0.1	0

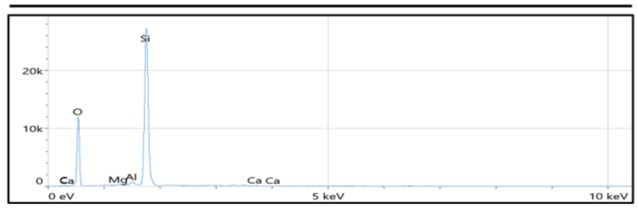


Figure 7: (a) SEM image of white sand and (b) SEM EDX analysis results.

Table 1: Summary of bulk density, sphericity, and roundness of proppant.

Proppant Type	Bulk Density (g/cc)	Sphericity	Roundness
PC 35/60	0.815	0.5-0.7	0.3-0.5
HC 35/60	1.172	0.9	0.9
WS 35/60	1.520	0.7-0.8	0.7-0.8
NC 35/60	1.543	0.9	0.9
RC 35/60	1.445	0.9	0.9

Proppant Type	Bulk Density (g/cc)	Sphericity	Roundness
PC 60/120	0.792	0.3-0.5	0.3-0.5
HC 60/120	1.191	0.9	0.9
WS 60/120	1.544	0.7-0.8	0.7-0.8
NC 60/120	1.555	0.9	0.9
RC 60/120	1.560	0.9	0.9

3. CRUSH RESISTANCE TEST

The primary test procedure follows ISO 13503-2 guidelines. The standard requires 2,000 psi/min rate of compressive force until the final stress level is achieved, and the final stress level should be maintained for 2 minutes. In this work we used the MTS 816 hydraulic load frame to carry out the crush resistance test. The force command (lbf/min) is used to apply the constant rate by changing the load frame's piston displacement. The compressive force (lbf) was later converted to stress (psi), dividing by the inner area of the crush cell. After applied closure stress, the crushed proppants were sieved for 10 minutes and the mass of fines was determined. Any proppant size smaller than the original size is considered as fines. With the known total mass used for the crush test, the fines percentage is calculated. ISO 130503-2 evaluates crush resistance using K-Value. The K-value is the maximum stress level where the proppant pack generates no more than 10% fines. The initial stress level is chosen based on a reasonable guesstimate and the stress level is increased in the increment of 1,000 psi until the fines reach nearly 10%. If the proppant pack exceeds 10% fines, the next lower stress level is selected as K-value (ISO 13503-2, 2006). Tests were repeated three times and those results were averaged for fines percentage calculation.

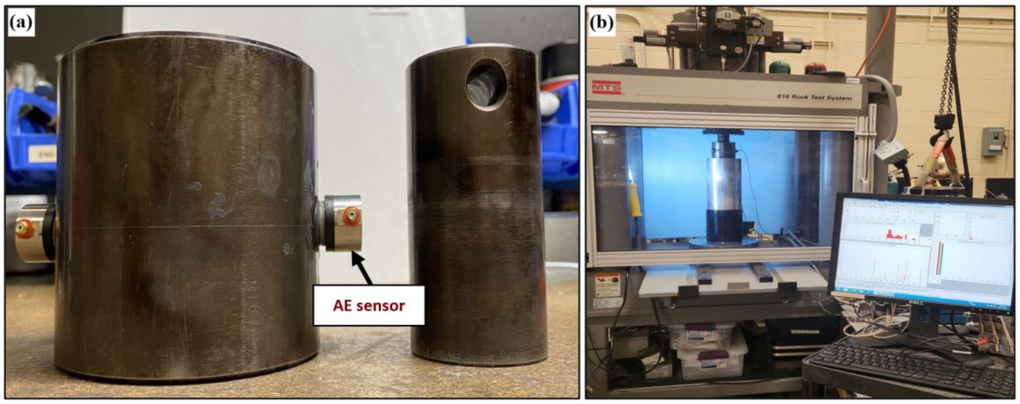


Figure 8: (a) Crush test cell and piston on the left and (b) overall crush test set-up with hydraulic frame and AE configuration.

During proppant crush, AE response was monitored to approximate proppant packing strength. Two commercial AE sensors were attached to the crush cell and MISTRA Group's AEwin software was used to collect soundwaves data. Data filter was used to filter low-mid amplitude noise induced by frictional sliding between proppants. The AE data were post-processed and synced with the stress profile from the hydraulic load frame. The cumulative AE hit was utilized by other researchers to approximate the initial failure of the proppant pack (Hampton et al., 2015), but the cumulative hit approach could mislead the approximation depending on how much AE data are filtered. Furthermore, when it comes to much smaller proppants, no dramatic surge in AE or gradual piston displacement makes interpretation difficult. To improve this, AE hit rate was supplemented by interpretation of the proppant pack AE generation profile. It was observed that the proppant pack cannot maintain the same hit rate after a severe crush happens and the hit rate starts to deflect when the proppant pack experiences a severe crush. So, we define this stress level as critical stress approximating proppant packing strength. This deflection can be observed before the target stress value chosen for the crush resistance test. If the AE rate continues to increase, the target stress level can be increased until the deflection is observed. The two parameters, critical stress and piston displacement, were also used to evaluate the proppant packing strength because they are changed by proppant pack failure.

3.1 Dry Test Results

The AE profile of non-coated ceramic in Figure 9 is much skewed to the right compared to the AE profile of hydrophobic polymer coated proppant in Figure 10, white sand in Figure 11, and petroleum coke in Figure 13, indicating a stronger approximated proppant packing strength. Shown in Table 2, the piston displacement of non-coated ceramic is also lower than piston displacements of those proppants, indicating stronger packing strength.

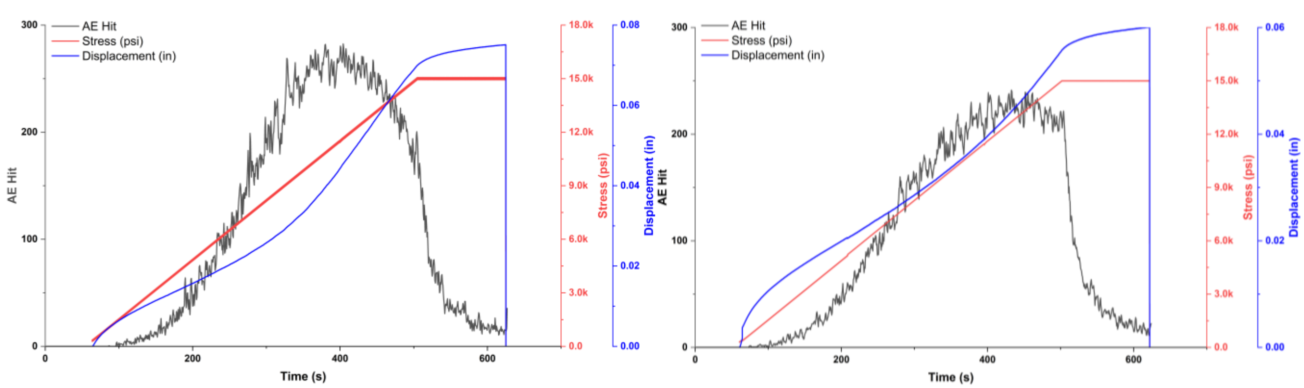


Figure 9: AE, piston displacement, and stress profile of NC 35/60 (left) and NC 60/120 (right).

Figures 10 and 11 show that white sand has a slightly higher packing strength and lower piston displacement than those of hydrophobic polymer coated ceramic, but crush resistance test results in Table 2 show that the crush resistance (K-Value) of hydrophobic polymer coated proppant is superior to that of sand. Hydrophobic polymer coated proppant has a good crush resistance, 10K and 18K each, due to the surface coating. However, the proppant packing strength is low due to its porous nature to achieve its low density. Thus, the crush resistance and proppant packing strength are not always necessarily proportional to each other. This demonstrates the advantage of running a crush test along AE monitoring.

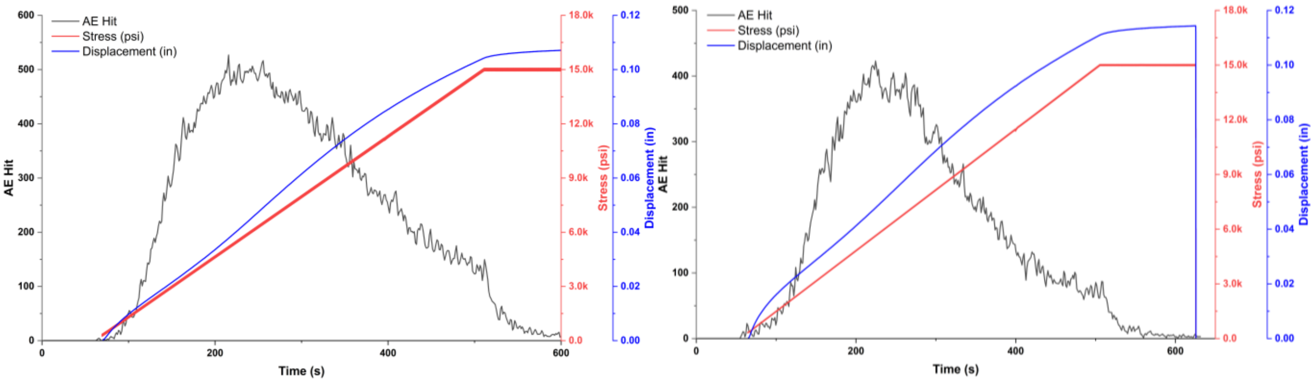


Figure 10: AE, piston displacement, and stress profile of HC 35/60 (left) and HC 60/120 (right).

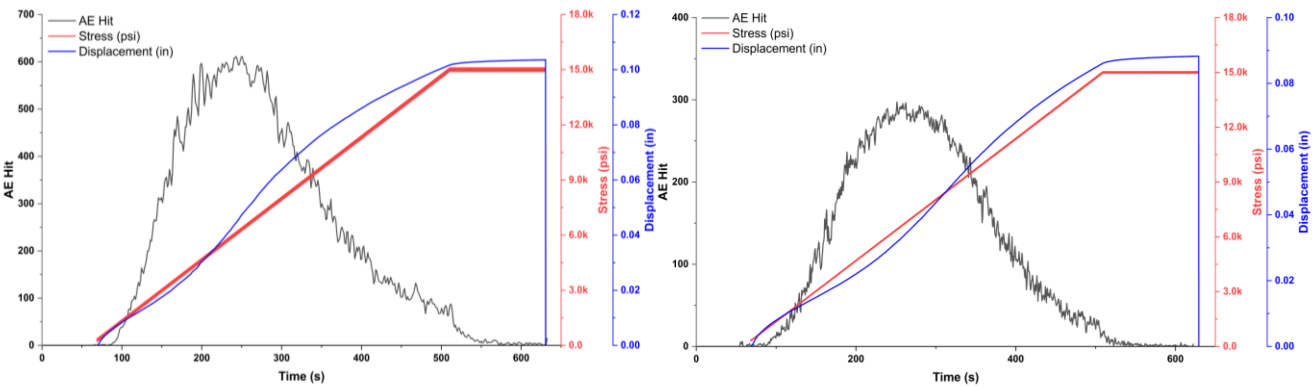


Figure 11: AE, piston displacement, and stress profile of WS 35/60 (left) and WS 60/120 (right).

Resin coated proppant shows very high estimates of packing strength and crush resistance as shown in Figure 12 and Table 2. The final stress level of 15,000 psi was applied first, but the AE response was continually increased until the end. The final stress level was elevated to 30,000 psi and the deflection in the AE rate was observed at the stress level of 18,000 psi. In Figure 12 (a), the first spike in the AE profile, 8,600 psi, is where the initial proppant failure occurs and a sudden increase in piston displacement was also observed due to the proppant failure. In figure 12 (b), the 60/120 size does not show large spikes due to its much smaller proppant size than the 35/60 size proppant. The piston displacement of the 60/120 size, 0.194 in, compared to that of the 35/60 size, 0.264 in, implies the 60/120 size has a better proppant packing integrity.

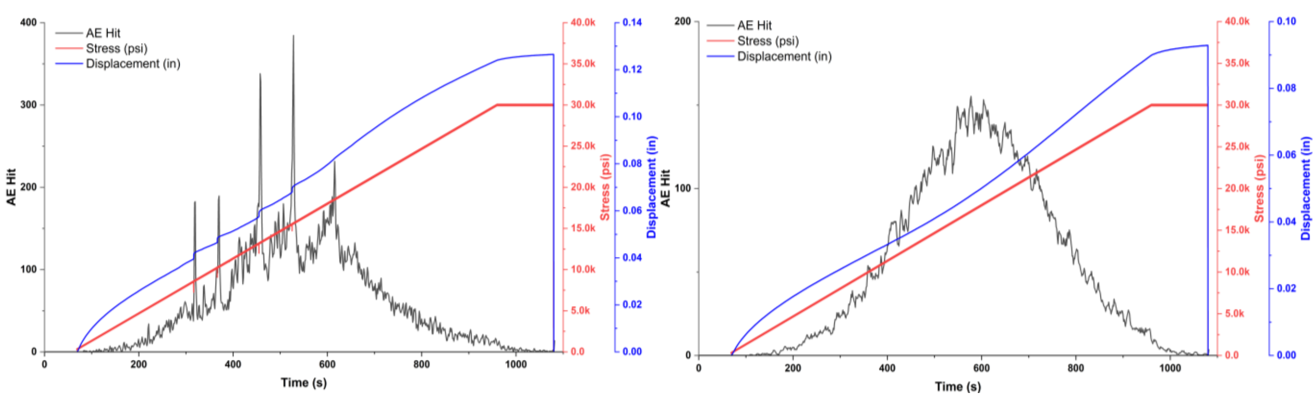


Figure 12: AE, piston displacement, and stress profile of RC 35/60 (left) and RC 60/120 (right).

Petroleum coke was determined to be the weakest material in terms of crush resistance and packing strength as shown in Table 2. The deflection of the AE rate was observed at approximately 1,300 psi. The AE profile shows a steep decline even before reaching the 2 minutes holding stage (horizontal red line) in Figure 13, indicating severe crush occurrence at the very low stress level. The displacement of the piston at 5,000 psi were 0.152 in and 0.104 in each, indicating the weakest packing integrity among all proppants tested as it is shown in Table 2.

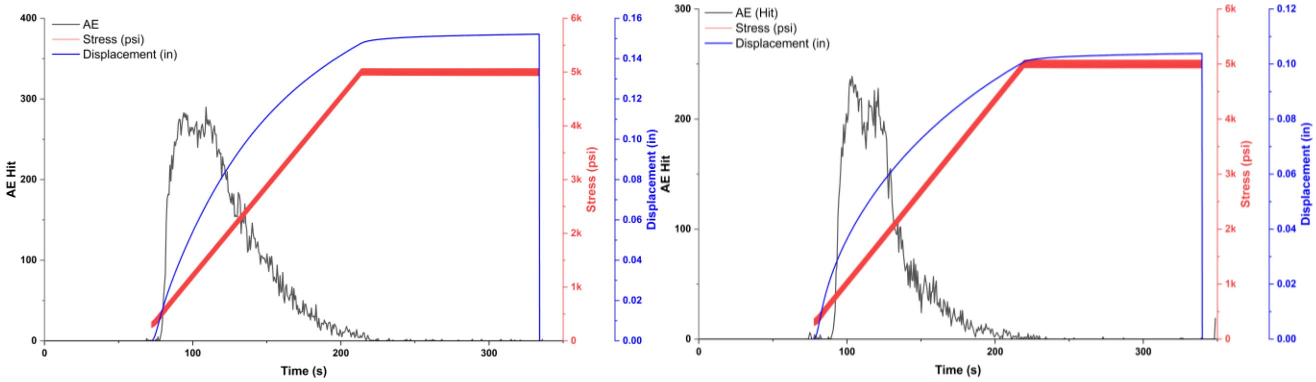


Figure 13: AE, piston displacement, and stress profile of PC 35/60 (left) and PC 60/120 (right).

Table 2 shows the summary of proppant test results of dry proppants. The final stress level means the stress level ended at the end of the test. Critical stress indicates the approximation of the proppant packing strength estimated by AE. K-Value is the stress level where the fines percentage reaches nearly 10%. All ceramic samples have 10K or higher crush resistance, implying it yields less than 10 percent of fines at 10,000 psi. Hydrophobic polymer coated ceramic shows a high crush resistance, 10K and 18K each but low pack strength of around 6,000 psi. Resin coated proppant has an extremely high crush resistance of 18K and 33K each and a very high packing strength of around 18,000 psi. Petroleum coke has the lowest K-Value, 1K and 3K each and the lowest packing strength of around 1,000 psi.

Table 2: Summary of dry proppant test results.

Proppant Type	Final Stress Level (psi)	Displacement (in)	Critical Stress (psi)	K-Value	Average Fines % at K-Value
PC 35/60	5K	0.152	1,300	1K	6.26
HC 35/60	15K	0.107	6,000	10K	7.85
WS 35/60	15K	0.104	6,500	5K	9.59
NC 35/60	15K	0.075	11,500	10K	6.43
RC 35/60	30K	0.127	18,000	18K	8.68

Proppant Type	Final Stress Level (psi)	Displacement (in)	Critical Stress (psi)	K-Value	Average Fines % at K-Value
PC 60/120	5K	0.104	1,300	3K	8.86
HC 60/120	15K	0.114	6,000	18K	9.58
WS 60/120	15K	0.088	7,000	7K	7.39
NC 60/120	15K	0.059	12,000	15K	9.33
RC 60/120	30K	0.093	17,500	33K	8.80

4. HEATED TEST

To simulate high temperature EGS conditions in the laboratory, proppant material was heated with tap water at 320 °C. Steam and high temperature water should not leak during the heating process. As shown in Figure 14, a pressure vessel was used to tolerate high temperature and pressure in the furnace. Stainless metal was machined and was designed to be fully sealed using high pressure screws and sealing materials. The pressure capacity of the vessel was checked by injecting water into the vessel up to 10,000 psi and waiting for a day to check its zero flow rate. The following heating duration was used: 7 days and 14 days. Once the heating duration was achieved, the vessel was cooled in water. The heated proppant was transported to the test cell and a wet crush test was performed. Fluid should be presented between proppant grains when the pressure vessel is opened. Otherwise, samples should be re-prepared. The stress level at K-Value from the dry test is used for the heated test. For example, if proppant has the K-Value of 10K, 10,000 psi is also used for the heated test and the change in fines percentage were compared. Proppant saturated water was collected to investigate the proppant dissolution in water. The crushed sample was collected and dried until it fully lost moisture. Before the crushed sample was sieved, the total mass was recorded again to consider mass loss during heating and transportation. Otherwise, the percentage of fines could be underestimated by the initial total mass, which is higher than the actual mass after heating. SEM EDX analysis was also performed to investigate changes in surface features.

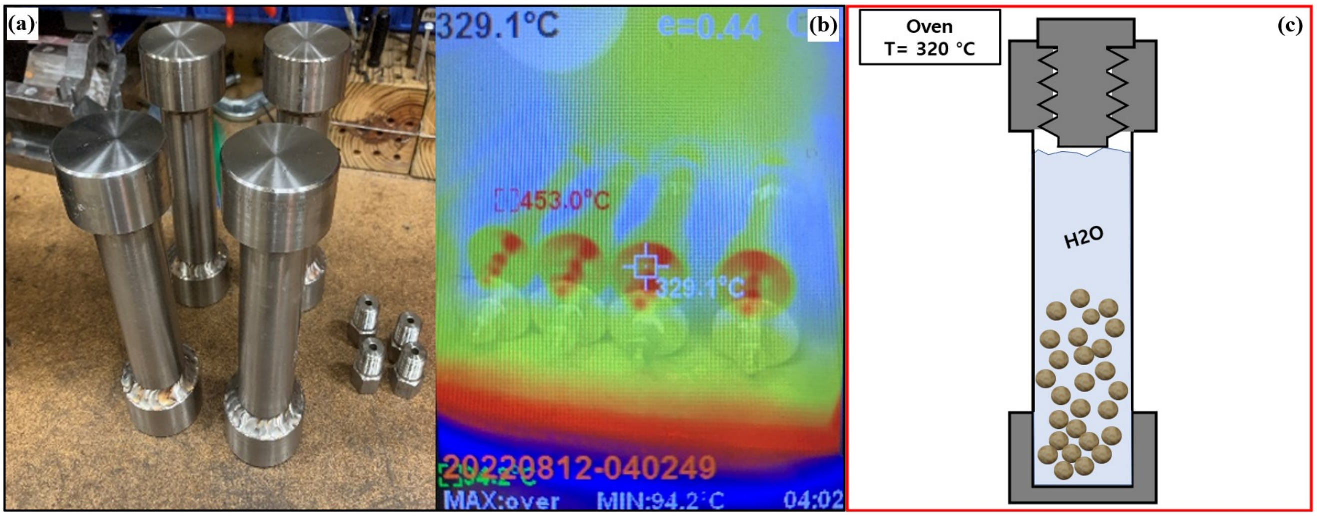


Figure 14: (a) Pressure vessels used for heating proppants with water. (b) thermal capture image inside of the oven showing temperature of the vessel is around 320 °C and the side wall of the oven reaching up to 450 °C. (c) overall schematic of pressure vessel in the oven.

4.1 Heated Test Results

Figures 15, 16, and 17 show 14 days heated proppant has a different AE profile because of water. The AE induced by frictional sliding was decreased and a lower amplitude or no data filter was needed. All ceramics show an increase in piston displacement shown in Table 3. Even though dry and heated samples were tested at different final stress levels, the same or higher piston displacement is recorded at the lower stress level as shown in Table 3, demonstrating lower packing integrity of heated proppants. The degree of increase in piston displacement also shows a similar trend as the degree of decrease in critical stress.

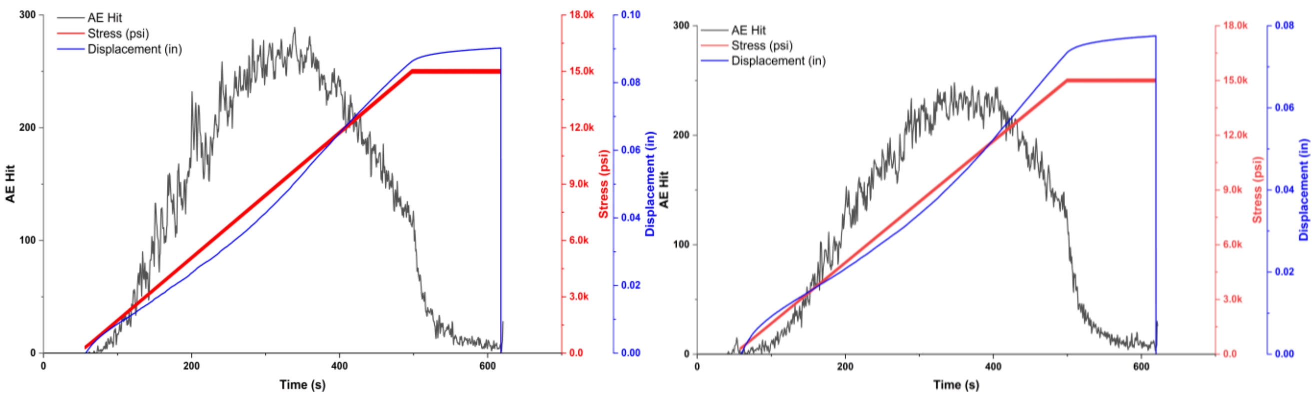


Figure 15: AE, piston displacement, and stress profile of NC 35/60 (left) and NC 60/120 (right) after heating for 14 days.

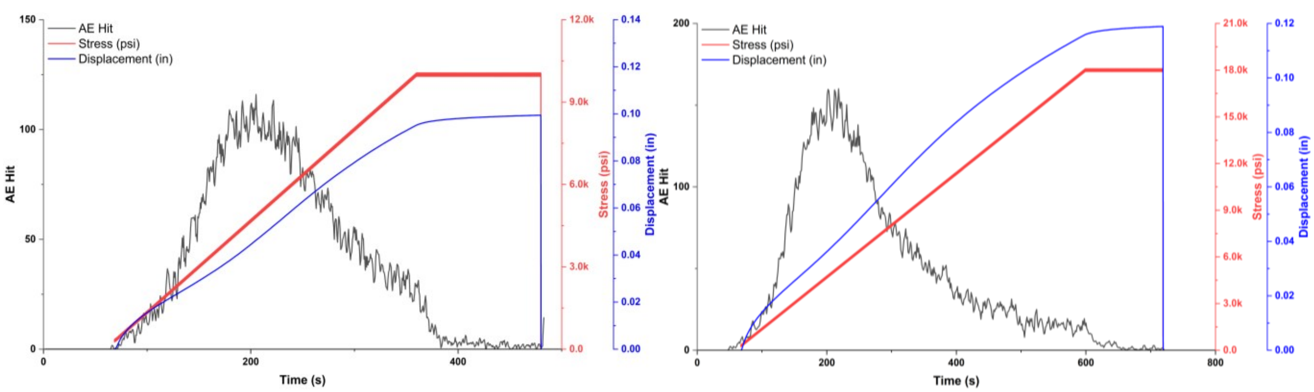


Figure 16: AE, piston displacement, and stress profile of HC 35/60 (left) and HC 60/120 (right) after heating for 14 days.

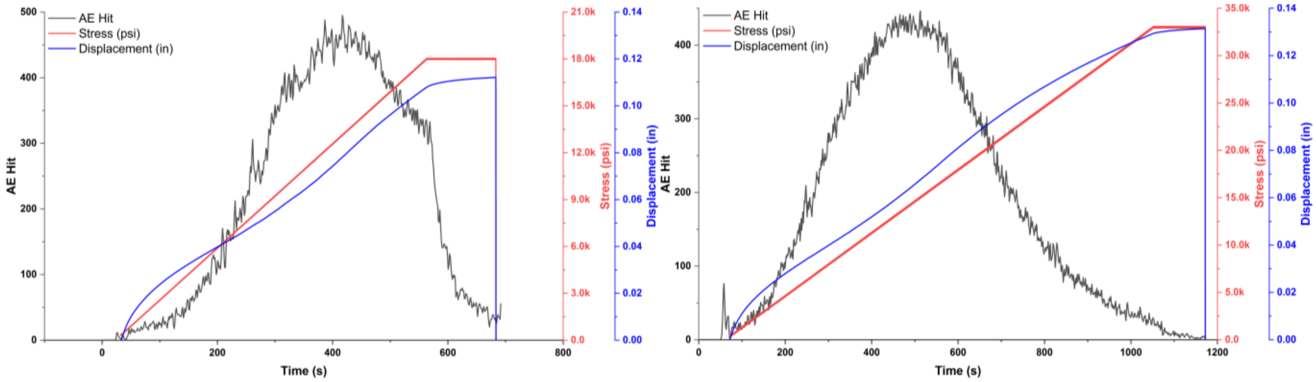


Figure 17: AE, piston displacement, and stress profile of RC 35/60 (left) and RC 60/120 (right) after heating for 14 days.

Both dry and heated proppant AE profiles are shown in Figure 18. It presents that the red AE curve (14 days heated) shows deflection earlier. Hydrophobic polymer coated ceramic shows the least change in not only packing stress but also total piston displacement. This again demonstrates that the proppant packing strength estimated by AE presents a correlation to piston displacement (change in the proppant pack width). Table 4 is the summary of crush resistance results, showing decrease in proppant crush resistance as proppant is heated with water. 0 days % means fines percentage of dry proppant and 7 and 14 days % are fines percentage after 7 days and 14 days of heating. All proppants show an increase in fines percentage except the petroleum coke 35/60. The primary reason could be the low final stress (1,000 psi) applied for testing due to its low crush resistance in surface conditions. The non-coated proppants show an addition of 3 ~ 4 fines % and coated proppants show an addition of 8~15 fines %. The experimental results showing change in approximated proppant packing strength, piston displacement, and fines %, demonstrate the proppants' diminished performance after they were subjected to EGS condition (320 °C) for 14 days.

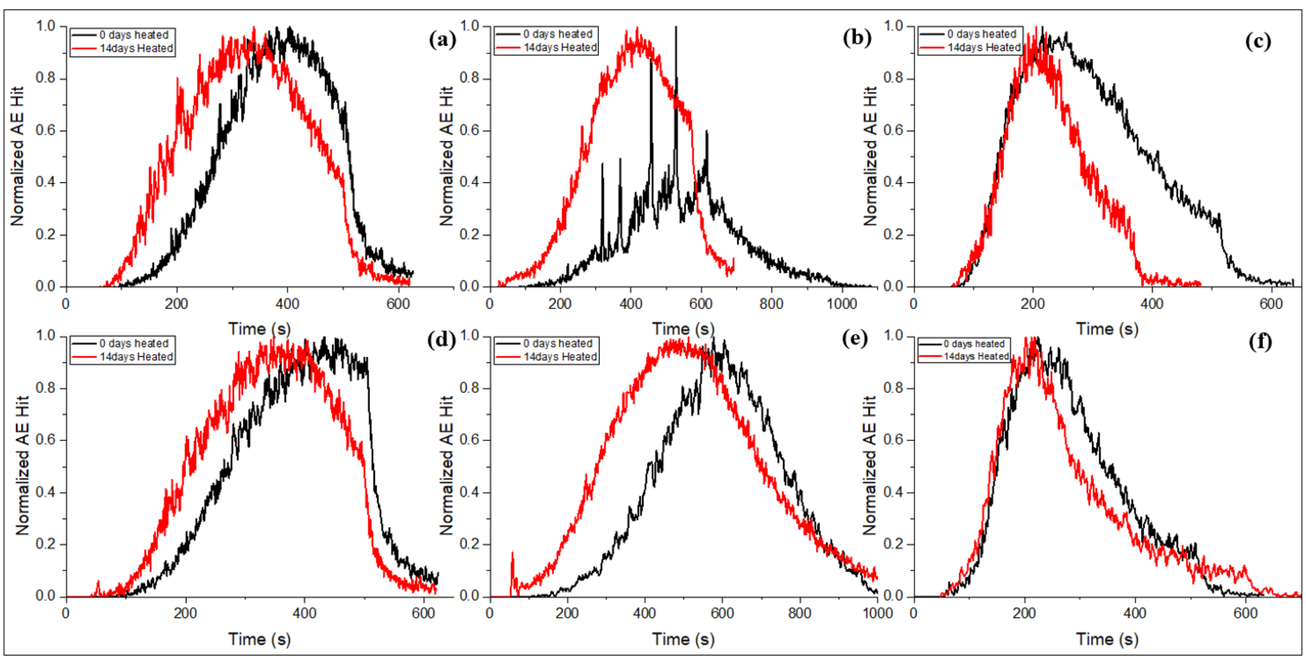


Figure 18: (a) NC 35/60 (b) RC 35/60 (c) HC 35/60 (d) NC 60/120 (e) RC 60/120 (f) HC 60/120. The red AE curve is 14 days heated proppant and the black AE curve is 0 days heated (dry) proppant. AE hit on y-axis is normalized to 1 for comparison purpose.

Table 3: Critical stress and piston displacement of ceramic proppant pack after heating for 14 days.

Proppant Type	Final Stress Level (psi)	Critical Stress (psi)	Displacement (in)
HC 35/60	10K	4,000	0.099
NC 35/60	10K	9,000	0.090
RC 35/60	18K	13,000	0.112

Proppant Type	Final Stress Level (psi)	Critical Stress (psi)	Displacement (in)
HC 60/120	18K	5,000	0.119
NC 60/120	15K	10,000	0.078
RC 60/120	33K	14,500	0.131

Table 4: Summary of fines percentage at different heating durations.

Proppant Type	Stress Level (psi)	0 days %	7 days %	14 days %
PC 35/60	1K	6.26	6.80	6.19
HC 35/60	10K	7.85	22.19	23.18
WS 35/60	5K	9.59	12.57	13.63
NC 35/60	10K	6.43	10.64	10.38
RC 35/60	18K	8.68	20.59	21.44
Proppant Type	Stress Level (psi)	0 days %	7 days %	14 days %
PC 60/120	3K	8.86	13.66	12.07
HC 60/120	18K	9.58	16.38	18.14
WS 60/120	7K	7.39	10.66	11.15
NC 60/120	15K	9.33	13.37	12.67
RC 60/120	33K	8.80	19.08	17.70

4.2 Investigation of Heated Proppants under Magnification

Figures 19 and 20 show coated proppants have different surface features after exposure to heat for 14 days. These images were captured before running the crush resistance test. The SEM image in Figure 19 presents cracks and an uncovered portion of a substrate. Proppant diagenesis or scale growth on the proppant surface is a factor that reduces the proppant conductivity by tightening the porous channel between proppant packs. Unknown scale growth was observed on both resin and hydrophobic polymer coated ceramics as shown in Figure 20. Considering coated proppants' diminished performance in crush resistance and packing strength in Table 3 and 4, it can be concluded that the effect of coating is reduced throughout the heating process. Considering the response in short duration heating, longer heating cycles, such as a month, 6 months, and a year could severely affect the proppant performance.

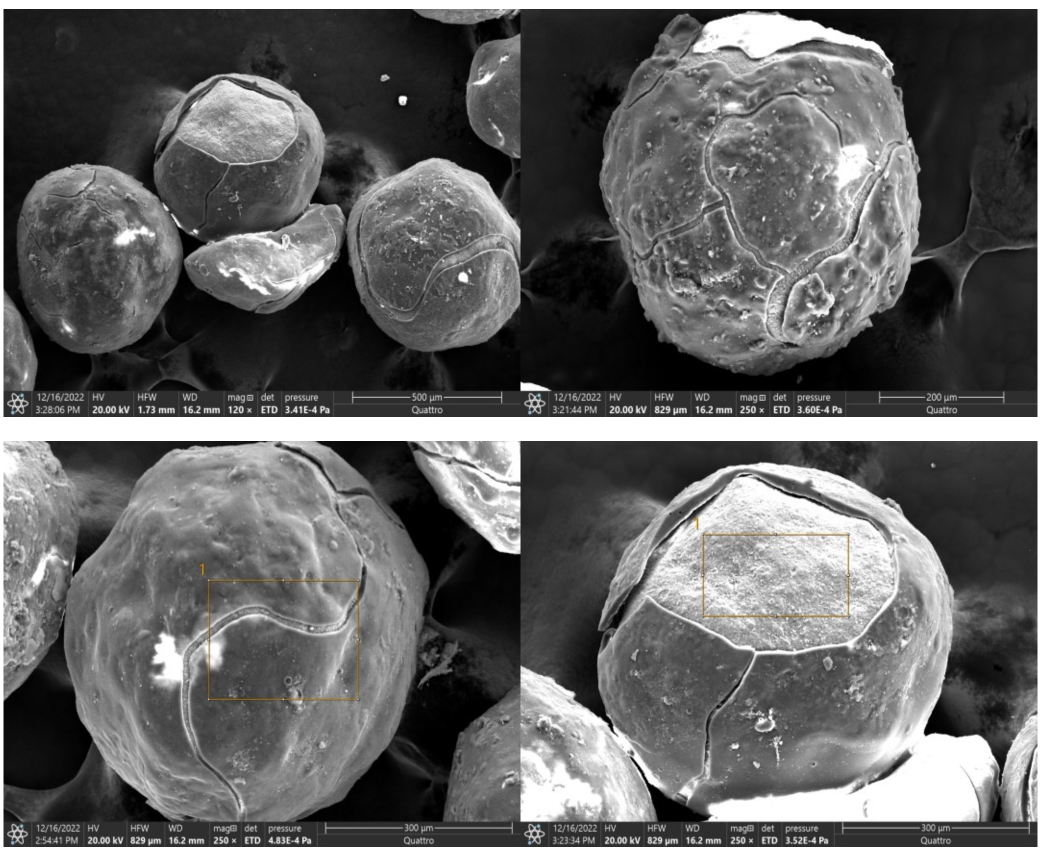


Figure 19: SEM images of resin coated ceramics after heating for 14 days.

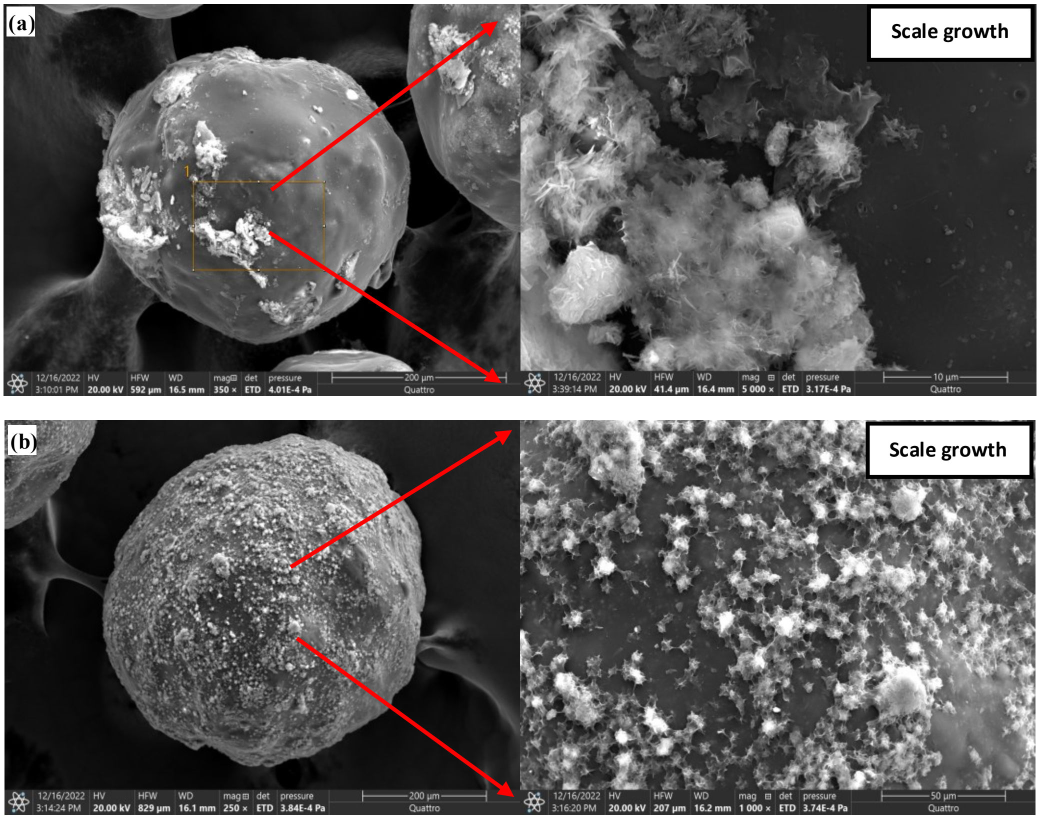


Figure 20: (a) SEM images of resin coated ceramic and (b) hydrophobic polymer coated ceramic after heating for 14 days.

4.3 Proppant Water Analysis

Some dissolved proppant materials are settled to the bottom and unknown cloudy materials are suspended in solutions in Figure 21. Non-coated proppants, WS, PC, and NC, show no significant color change, while polymer coated proppants, HC and RC show yellowish to dark brown color of fluid, indicating qualitative amount of polymer coating dissolution in water. Figure 22 shows the change of chemicals in water after 14 days of heating. The original water used for the test is labeled as Tap Water. Non-coated proppant fluids contain higher calcium while coated proppant fluids have much lower calcium and magnesium after 14 days of heating.

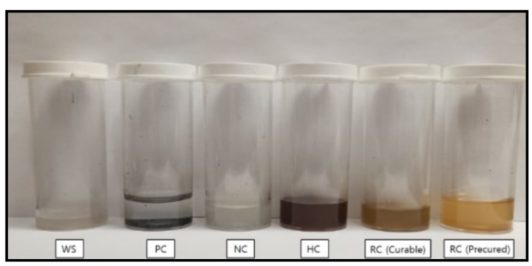


Figure 21: Water samples collected from proppants.

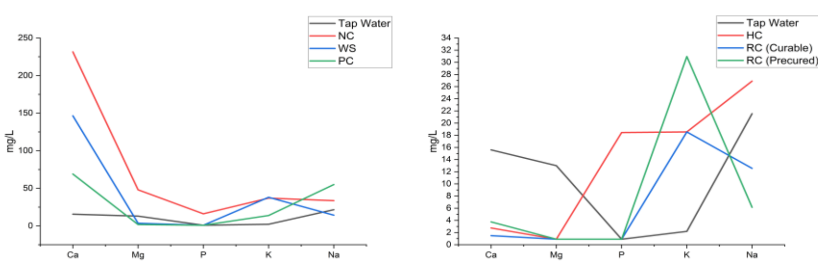


Figure 22: Water analysis results of non-coated proppants (left) and polymer coated proppants (right) after heating 14 days.

5. FRACTURE MECHANISM

Through investigation under magnification, the main fracture model is determined to be tensile. The brown stains in Figure 23 (a) present the contact zone with the piston. This zone shows a severe crush and the proppant is cleaved into wedges by tensile fracture. Under closure stress, proppant particles are subjected to shear movement and the outer surface of the proppant is chipped or failed by shear fracture. The failed proppant starts to plug the porous proppant pack. Those fines are compacted over time and build a less porous and permeable proppant pack, reducing proppant pack width and permeability. This ultimately reduces the conductivity of the proppant pack. Figure 23 (b) presents that the primary fracture mechanism of wet proppants is also a tensile fracture.

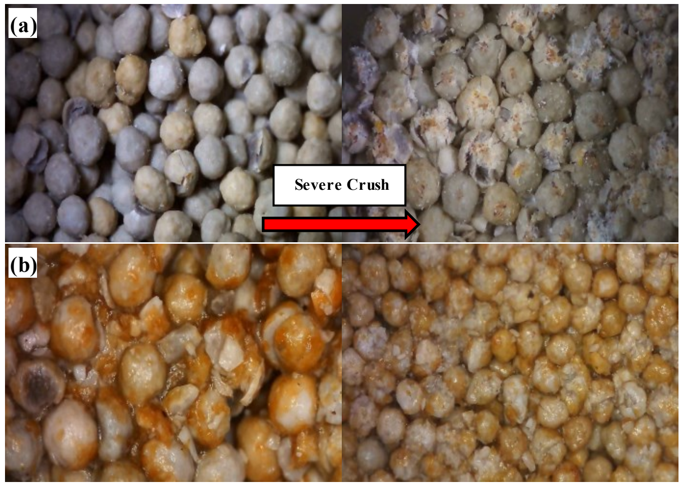


Figure 23: (a) The progress of proppant pack crush. (b) the crushed polymer coated proppant (14 days heated).

CONCLUSION

In this study, we proposed an experimental workflow to characterize proppant pack behavior and assess its thermal stability in representative reservoir conditions of EGS. The elemental composition, bulk density, sphericity, and roundness were characterized first. Then, a crush resistance test was performed to determine K-Value and the AE hit rate was monitored to approximate packing strength. Tests were repeated with heated proppants. It was found that petroleum coke has a desirably low density (~0.8g/cc), which is almost equivalent to half densities of other proppants so that it can be transported farther and suspended well along fracking fluid. It has shown a relatively lower K-value and additional tests are needed to fully assess its long-term endurance in rock fracture. Non-coated proppants such as ceramic, white sand and petroleum coke generated an additional 3~4 fines % at the same stress level after it was heated in EGS conditions, indicating lower crush resistance of the proppant pack. Non-coated ceramic showed lower packing strength and attained less proppant pack width. The fines percentage change decreased over time, implying that the effect of heat stabilizes once the proppant pack reaches a certain level of thermal damage. Polymer coated proppants with resin and hydrophobic polymer showed poor stability under high temperature (320 °C) due to their polymer coating integrity. An additional 8~15 fines % was generated with less proppant pack width, indicating lower conductivity of the proppant pack. The SEM image of heated proppants displays cracking and uncovering of resin coating. The interior ceramic was exposed through cracks, allowing partial contact with fluid during heating. It is shown that the capability of polymer coating to encapsulate and trap fines within coating is reduced by coating degradation in high temperature fluid, leading to decreased crush resistance and packing integrity. The capability of resin polymer to bond proppants should be revisited by conducting a proppant flowback test.

ACKNOWLEDGEMENT

The authors sincerely acknowledge the support from the OU Reservoir Geomechanics and Seismicity Group. The authors also would like to thank Dr. Zhi Ye for valuable discussions and the help from the lab manager Stephen Dwyer.

REFERENCES

Ghassemi, A., Tarasovs, A., and Cheng, A.D.-H: Integral equation solution of heat extraction induced thermal stress in enhanced geothermal reservoirs, Int. J. Num. & Anal. Methods in Geomechanics, 29, (2005), 829-844.

Hampton, J.C., et al.: Acoustic Emission Monitoring Elucidates Proppant Pack Strength Characteristics during Crush Testing, Proceedings, 49th U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, CA (2015).

ISO 13503-2: Petroleum and Natural Gas Industries-Completion Fluids and Materials-Part 2: Measurement of Properties of Proppants Used in Hydraulic Fracturing and Gravel-Packing Operations, Genova, Switzerland (2006).

Liang, F., et al.: A comprehensive review on proppant technologies, Petroleum, 2, (2016), 26−39.

Sinclair, A.R., Graham, J.W., and Sinclair, C.P.: Improved Well Stimulation with Resin-Coated Proppants, Proceedings, SPE Production Operations Symposium, Oklahoma City, OK (1983).

Underdown, David R., and Das, Kamalendu: New Proppant for Deep Hydraulic Fracturing, J Pet Technol, 37, (1985), 98–104.