Proppants for Fracture Conductivity Enhancement and Reservoir Characterization in EGS

1. **Design Development and Testing of Tagged Proppant for Fracture Conductivity Enhancement and Reservoir Characterization in EGS**
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   - Project Start and End Date: 04/01/2024-09/31/2026

2. **Project Objectives and Purpose**
   - Test and develop new proppants that can be used in geothermal conditions of at up to 250 ˚C and differential pressures of 35-70 MPa
   - Characterize the materials and carry out conductivity tests under HTHP
   - Test a few proppant materials e.g., garnet, petcoke, and polymer, etc. The polymer material will be used to generate sub-100 mesh light and high strength proppant. This proppant will also be doped with conductive agents having electromagnetic sensitivity for potential diagnostics
   - Designing and testing of new proppants and interrogating their performance in HTHP condition of interest to EGS would provide the means for sustaining hydraulic fracture conductivity and enabling effective heat production from EGS concepts relying on multi-stage fracturing.
3. **Technical Barriers and Targets**
   - Select, test and develop proppants that can sustain high temperatures and pressures encountered in EGS.
   - Phase 1 targets are: obtain proppant materials and consider modifications if necessary and determine their index properties and durability in the presence of geothermal fluids at high temperatures; determine crush resistance (K-value) and crush strength for both dry and wet-heated samples for the uncoated/untagged proppant materials; and determine long-term hydraulic conductivity of the uncoated/untagged proppant materials at various stress and temperature conditions.
4. **Technical Approach**
   - Conduct proppant crush tests on heated proppants. Procure proppant materials and consider modifications if necessary and determine their index properties. Examine the durability of selected proppant materials in the presence of geothermal fluids at high temperatures.
   - Conduct conductivity tests at high temperature and pressure using standard and new test geometries. Determine long-term hydraulic conductivity of the uncoated/untagged proppant materials at various stress and temperature conditions.
   - Develop new polymer materials that can sustain high temperatures and pressure.
   - Conduct simulation modeling to study controls on proppant resistance. Modeling the effect of particle size, size distribution, shape, and type on crush resistance and deformational as well as hydraulic (permeability evolution) of particulate packs to inform lab developments and field implementations.
   - Examine the hydraulic conductivity, and electrical detectability of the coated/tagged proppant materials in large fracture(s) created in granite blocks.
   - Conduct modeling on proppant transport and deposition in fracture networks

5. **Project Timeline (list milestones achieved and/or decision points)**
   - We have multiple milestones in Year 1 and there is a Go/NoGo at the end of Year 1.

	Budget Year	Year 1			
	Actual Qtr.	Q2 24	Q3 24	Q4 24	Q1 25
	Project Qtr.	Q1	Q2	Q3	Q4
Project Milestones	Deliverable				
Task 0 – Project Management and Planning			●		
Task 1 – Procure proppant materials and consider modifications if necessary and determine their index properties. Examine the durability of selected proppant materials in the presence of geothermal fluids at high temperatures					
Milestone 1.1 -Review the selected proppant materials and determine their index properties.					X
Sub Task 1.2 – Characterize the resistance of selected proppant materials to geothermal fluids and high temperatures.					X
Milestone 1.2 -Characterize the resistance of selected proppant materials to geothermal fluids and high temperatures.					X
Task 2 – Design, synthesis, and characterization of polymeric proppant					
Milestone 2.1-A new high temperature thermoset is designed, synthesized, and tested.					x
Milestone 3.3 -Complete the determination of crush strength of the uncoated/untagged proppant materials through the modified triaxial crush testing. Simulations of controls on proppant and pack strength completed					
Task 4 – Determination of crush resistance (K-value) and crush strength for both dry and wet-heated samples for the uncoated/untagged proppant materials; study failure mechanisms and modes using modeling and comparison with test results					
Milestone 4.1 -Completion of long-term hydraulic conductivity under HTHP conditions for the uncoated/untagged proppants, and correlation of conductivity, closure stress, and temperature. index properties.					
Sub Task 4.2 –Quantify/map the impact of proppant size, shape, packing on strength and potential failure modes, as well as the stress-dependent thermo-hydromechanical behavior of selected particulate materials under high-stress (35-70 MPa) and at least 250C					
Go/No-Go Decision Point #1: Selected and manufactured proppants characterized, crush tests and long-term conductivity tests completed (at least 2 tests per proppant type) under pressure and temperature conditions of 35-70 MPa, and up to 250C.					X

6. Technical Accomplishments

- We have obtained proppant materials (e.g., petcoke and ceramics) and have conducted crush tests to obtain K-values for petcoke and low-density ceramics (LDC) and resin-coated Ceramic proppants (RC) subjected to different heat treatments (duration). The crush resistance of LDC, RC, and petcoke have been determined after exposure of up to 30 days of heating at up to 300°C. We have performed conductivity testing using two different geometries. We resolved challenging leak issues with triaxial and conventional conductivity testing and carried out a few tests on select proppants. The former relies on two cylindrical pieces of rock with proppant between them. The assembly is subjected to triaxial compression and water flows from one side to the other under different loading and temperature conditions. In addition, we successfully eliminated leaks in the conventional conductivity cell set up and performed a test at temperature higher than 225°C and an axial load exceeding 9000 psi. The proppant pack conductivity was assessed in each test. The leak resolution is a major step forward enabling additional tests at desired conditions.

- We have synthesized and tested the mechanical properties of a new high temperature thermoset polymer (HTTP) both at room temperature and 250 °C, 260 °C, and 270 °C. We fabricated the HTTP panels and crushed and ball milled them into particles and powders in the range between 0.074 mm ~ 2.16 mm and will use it for testing. We have also developed DEM models using PFC2D to study the effects of particle size and shape and micromechanical parameters on the mechanical response of granular packs. We have also started working on adding magnetic properties to the high temperature thermoset polymer. Different from the ball milling method of machining the bulk polymer into particles and powders, we also started to use emulsion polymerization to directly produce sphere particles. The HTTP material was also tested after it was heated in a KCl solution. The particles lost their strength significantly. The LSU group is considering alternatives to address the issue by exploring small spherical polymeric particles which can survive the very hot water environment for several weeks. To demonstrate stability under the hot water system, we have designed two types of polymers and evaluated their stability under 200 °C water environment. The first group is fabricated UV cured tris(2-(acryloyloxy)ethyl) isocyanurate (TAI) which was coated by dicumyl peroxide (DCP) cross-linked fluoro-gum to demonstrate the form-stability under the superhot water environment for several weeks. The other group was polyether ether ketone (PEEK) particles under the same very hot water environment for several weeks. To further prove the chemical stability, the FTIR measurements were conducted for sample exposed for 1~4 weeks. Results show fluoro-gum can protect the TAI particles effectively under the hot water system.
- Furthermore, we worked on modeling strength and crush resistance for different particle shapes and sizes. We used three particle shapes: spherical, elongated, and angular. In addition, we performed oedometer test on a pack of 5mm spherical particles using a rigid cell with fixed lateral boundaries (zero lateral strain) with a diameter D of 63 mm. The axial stress–strain response of the pack was used for model calibration. The UU team focused on the quantitative analysis of particle shape effects on the deformational behavior using the PLA fabricated particulate packs representing spherical and angular particles. Laboratory oedometer and direct shear tests have been completed and used to calibrate and validate the DEM models in PFC3D.

7. Challenges to Date

- Several technical challenges associated with leaks and material performance at high temperatures were faced and have been mostly resolved. Water under pressure decreases polymer proppants performance significantly.

8. Conclusions and Plans for the Future

- Proceed to carry out the tasks outlined in the SOPO. Continue to perform conductivity cell test using different proppant and loading conditions. Improve polymer proppant performance.

9. Geothermal Data Repository

- NA

10. Publications and Presentations, Intellectual Property (IP), Licenses, etc.

-Sutradhor, A.S., Ghassemi, A. 2025. Hydraulic Fracture Propagation and Proppant Transport in Anisotropic Rock Formations. 59th US Rock Mechanics/Geomechanics Symposium held in Santa Fe, New Mexico, USA.

-Sutradhor, A.S., Ghassemi, A. 2025. Crush Resistance and Packing Strength of Candidate Proppant for Enhanced Geothermal Systems. PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, CA
-Liu, B., Ghassemi, A. 2024. Modeling proppant transport and settlement in 3D fracture networks in geothermal reservoirs. Geothermics.
-Alasadi, A., Potyondy, D., Ghassemi, A., and Roshankhah, S. (2025). DEM-Based Analysis to Reveal the Effects of Particle Size Distribution on Deformational Behavior of Particulate Packs, Stanford Geothermal Workshop, Palo Alto, CA, February 10-12.
-Alasadi, A., Potyondy, D., Ghassemi, A., and Roshankhah, S. (2026). Influence of Particle Shape on Deformational Behavior of Particulate Packs Using Experimental and DEM Modeling, GeoCongress, Salt Lake City, UT, March 9-12.

11. Publicity and outreach (Optional)

- NA.

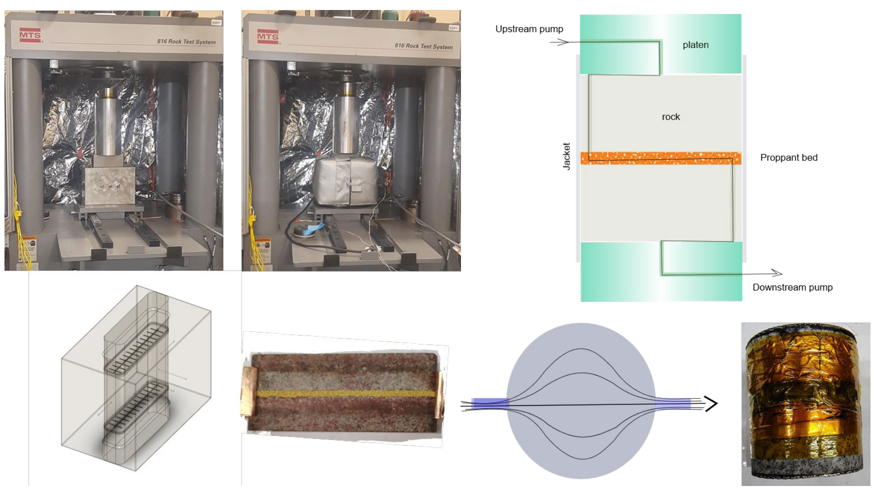
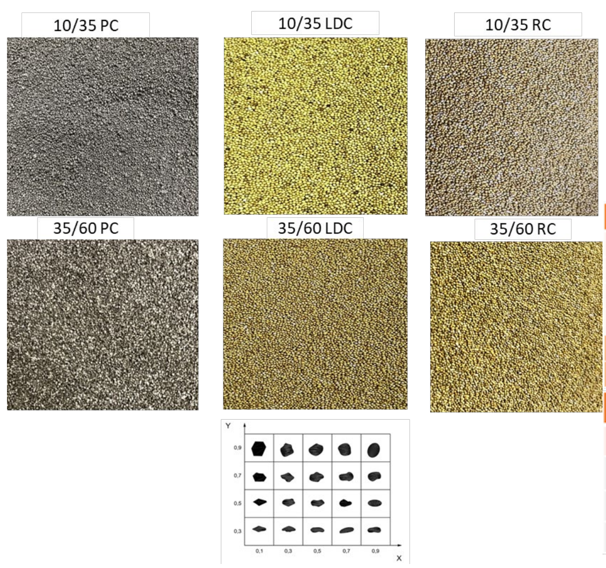


Figure 1. Test assemblies.

Proppant Type	Sizes	Bulk Density (gm/cc)	Proppant shape (X=Roundness, Y=Sphericity	Packing strength (psi)	K-value	Fine generates at K-value (%)
PC	10_35	1.09	(0.7, 0.7)	2100	2K	6.67
	35_60	0.99	(0.3, 0.5)	1800	2K	8.90
LDC	10_35	1.21	(0.9, 0.9)	3600	4K	7.77
	35_60	1.27	(0.9, 0.9)	5700	7K	9.70
RC	10_35	1.60	(0.9, 0.9)	10200	15K	7.50
	35_60	1.53	(0.9, 0.9)	12100	17K	9.03

Sample ID	Proppant type	Proppant bed shape	Proppant bed thickness (mm)	Proppant bed weight (g)	Host rock dimension (mm)	
					Top section	Bottom section
Sample A	LDC	circular	5.00	22.00	30.50	30.80
Sample ReA	LDC	rectangular	4.00	35.00	30.30	28.50
Sample B	RC	circular	5.00	25.40	30.80	29.00
Sample ReB	RC	rectangular	3.30	39.00	30.30	28.50
Sample C	PC	circular	5.00	35.50	26.50	33.00



Density Measurement of Petroleum Coke proppants

Test Number	5/10	10/35	35/60
1	0.837	1.089	0.989
2	0.851	1.086	0.983
3	0.861	1.099	0.996
Avg Density	0.850	1.091	0.989
Mass required	21.0 gm	26.95 gm	24.43 gm

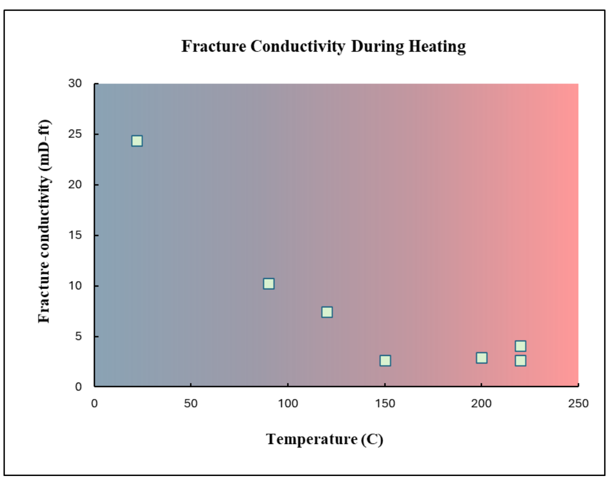
Density Measurement of Ceramic proppants

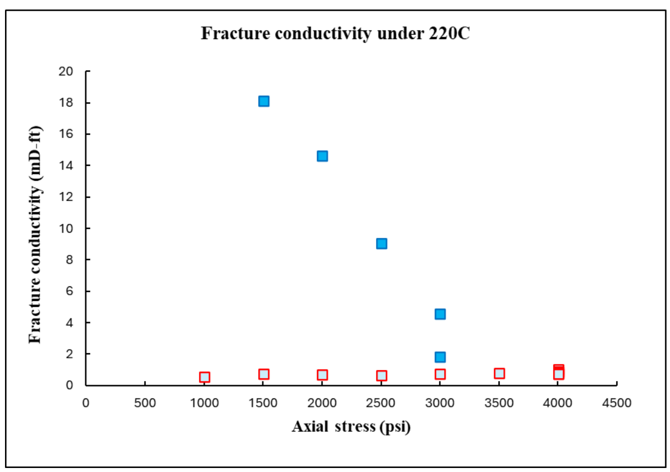
Test Number	LDC 10/35	LDC 35/60	RC 10/35	RC 35/60
1	1.233	1.297	1.613	1.542
2	1.213	1.291	1.597	1.540
3	1.196	1.232	1.578	1.506
Avg Density	1.214	1.273	1.596	1.529
Mass required	30 gm	31.45 gm	39.42 gm	37.76 gm

Shape of the proppants

Proppant type	10/35	35/60
PC	(0.7,0.7)	(0.3,0.5)
LDC	(0.9,0.9)	(0.9,0.9)
RC	(0.9,0.9)	(0.9,0.9)

Figure 2. Proppants selected for testing to date.





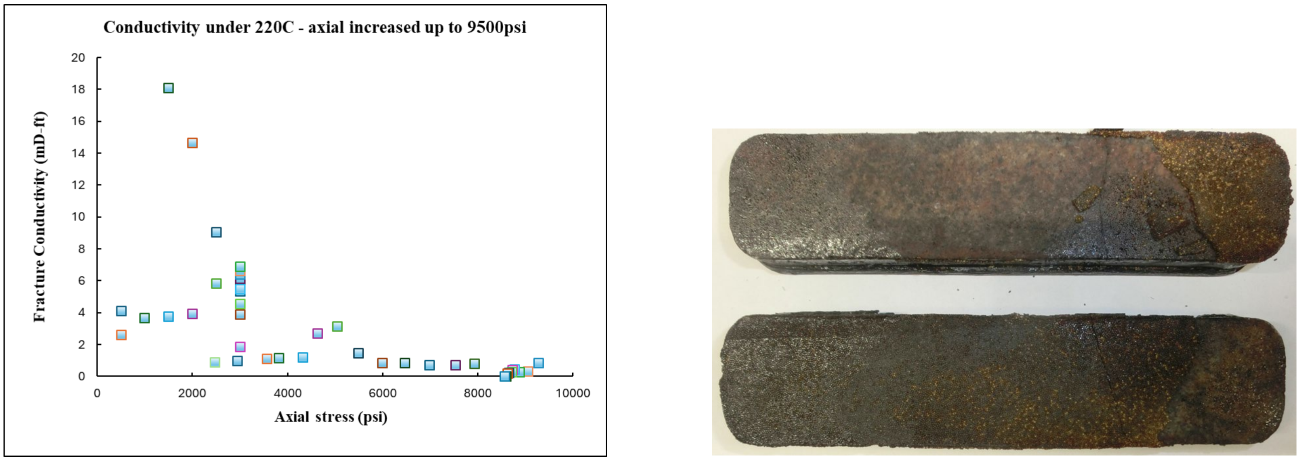


Figure 3. Propped fracture (Sample ReA, LDC proppant) conductivity response during heating under a constant axial stress and a fixed pressure differential between upstream and downstream pumps. The axial load was maintained at 1000 psi, the upstream and downstream pressure difference is about 2~3psi. Conductivity decreases as temperature increases.

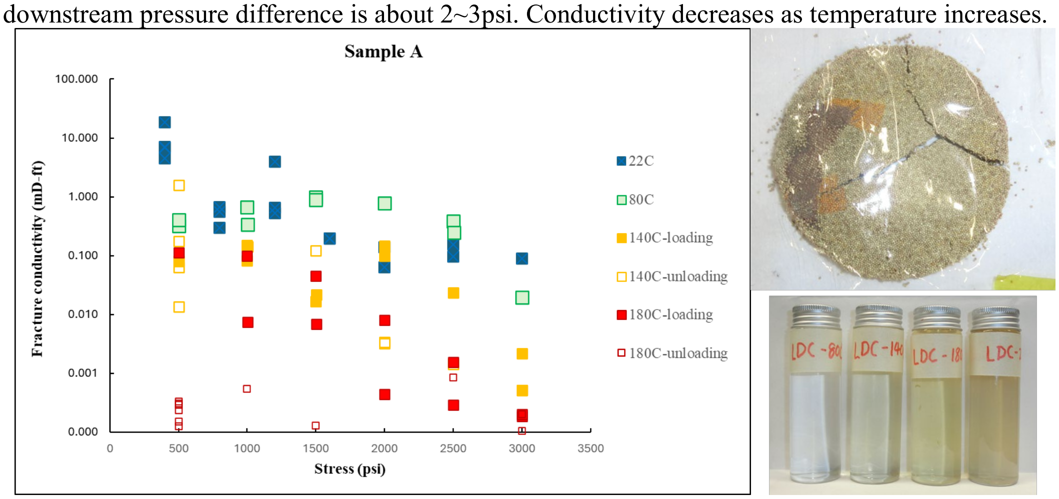


Figure 4. Propped fracture conductivity decreases with both increasing temperature and applied stress. While data shows some scattering - indicative of unstable flow behavior characteristic of proppant packs -a decreasing trend is evident. Notably, permeability reduction at elevated temperatures appears irreversible, persisting even during stress unloading cycles (180°C - unloading). Sample ReA, LDC proppant.

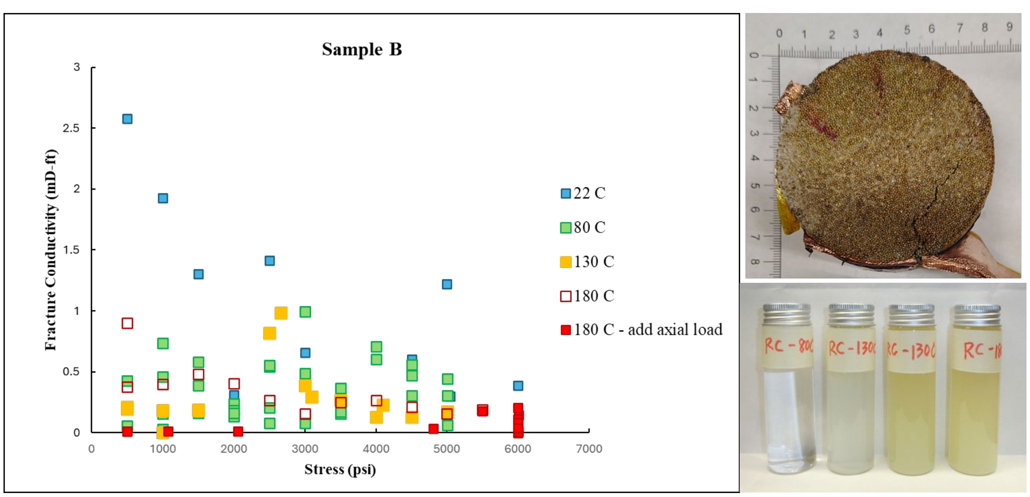


Figure 5. Sample B (RC proppant).

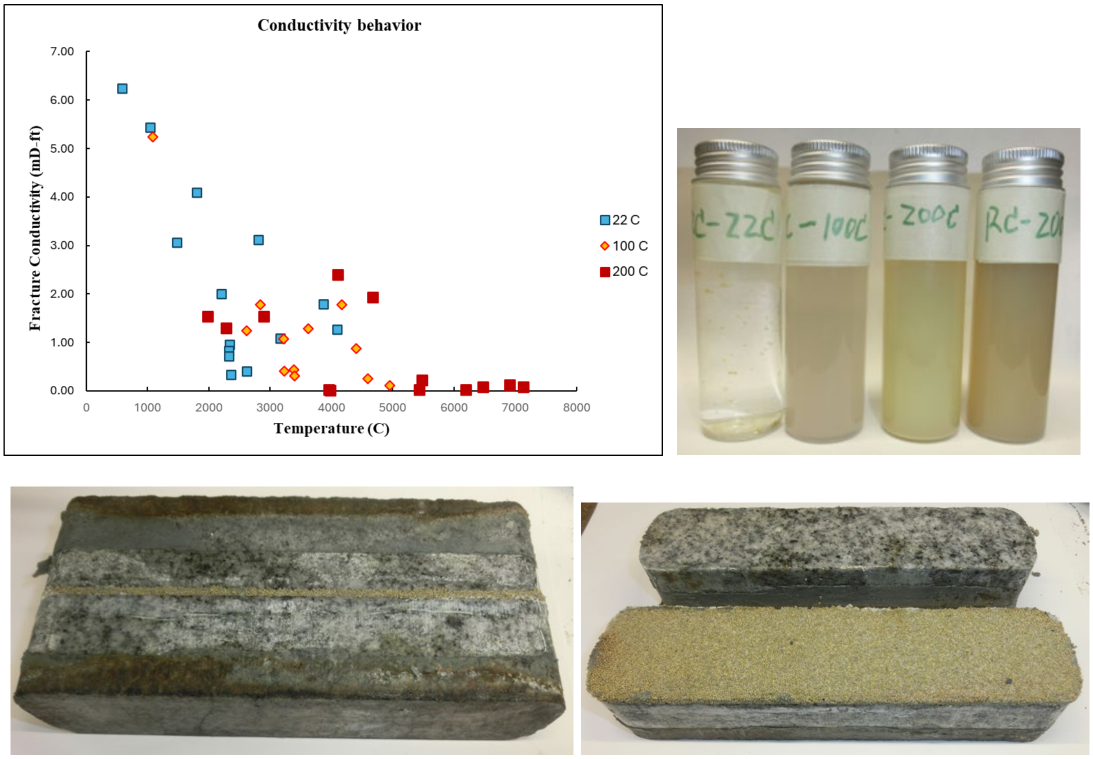


Figure 6. Sample ReB (RC proppant). Propped fracture conductivity decreases with both increasing temperature and applied stress. Data scatter is due to unstable flow behavior characteristic of proppant packs.

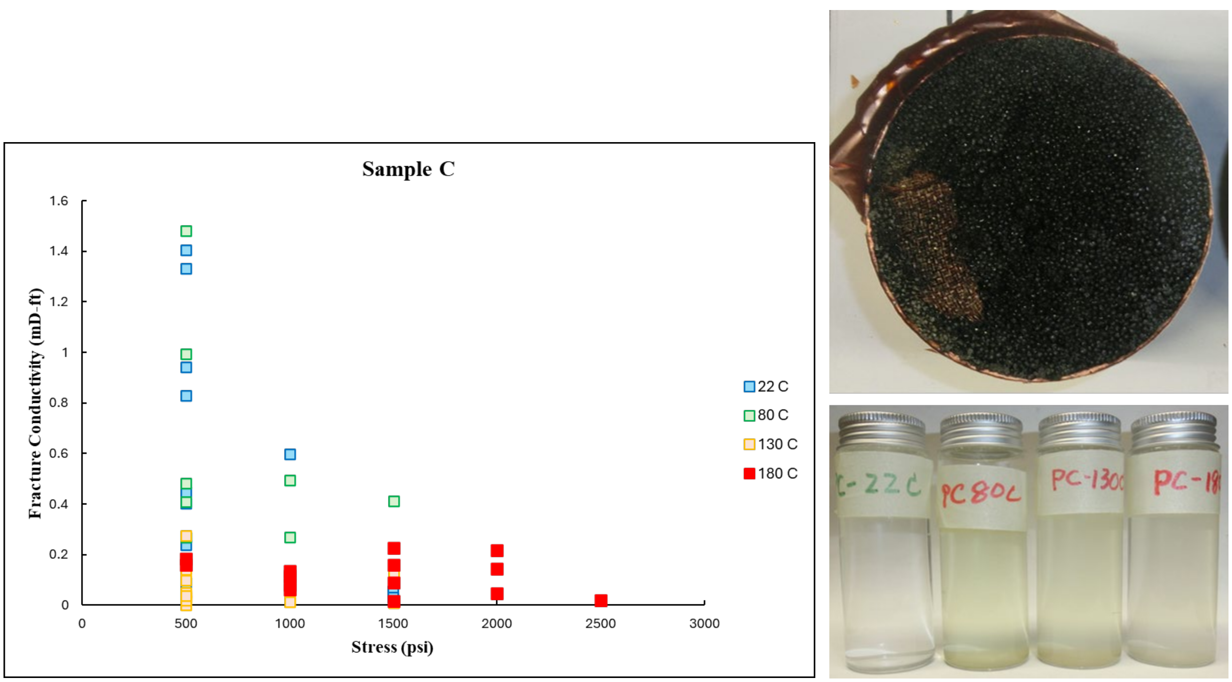


Figure 7. Sample C (Petcoke proppant). At lower temperatures (22°C and 80°C), conductivity is more sensitive to stress changes, while at 180°C, it remains low even under low stress—indicating possible irreversible thermal effects on proppant structure.

Sample ID	Proppant type	Proppant bed shape	Test summary
Sample A	LDC	circular	Fracture conductivity drops from 20 md-ft at room temperature to that below 1E-3 at 180 °C
Sample ReA	LDC	rectangular	Fracture conductivity drops from 20 md-ft at room temperature to that below 1E-2 at 220 °C
Sample B	RC	circular	Fracture conductivity drops from 10 md-ft at room temperature to that below 1E-2 at 180 °C
Sample ReB	RC	rectangular	Fracture conductivity drops from 10 md-ft at room temperature to that close to 1E-2 at 200 °C
Sample C	PC	circular	Fracture conductivity drops from 5 md-ft at room temperature to that close to 1E-2 at 180 °C

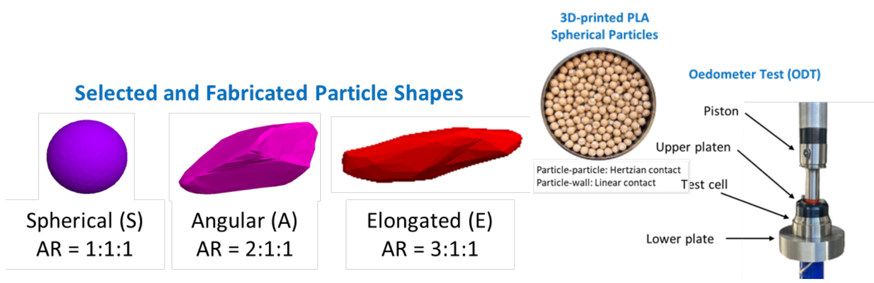


Figure 8. Three particle shapes were printed with PLA material to obtain different aspect ratios as shown and were tested in the laboratory setup for the oedometer and direct shear tests. The model parameters are calibrated based on the oedometer test results conducted on the pack of spherical particles (shown in the middle) and used to model other particle shapes under oedometric and direct shear test conditions. In the models, particle-particle contacts are simulated based on Hertzian formulation (non-linear force-displacement relation), and particle-wall contacts are modeled based on the linear formulation.

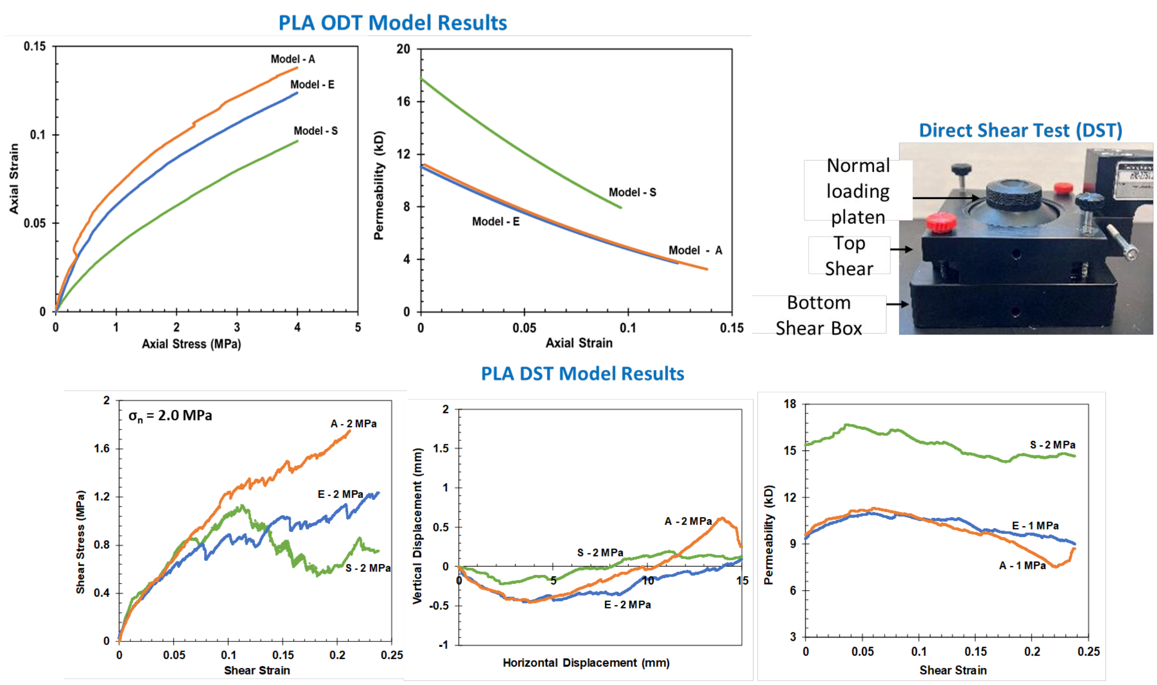


Figure 9. Larger (~2 mm) spherical particles show higher initial permeability and lower reduction in permeability under uniaxial loading. Under shear loading, these particles experience higher dilation and increase in permeability. While these attributes seem to be ideal for the proppant candidate, the crushing and creep behavior of such packs of coarse spherical particles of various types/materials must be investigated further under HTHP conditions to come up with the final recommendations.

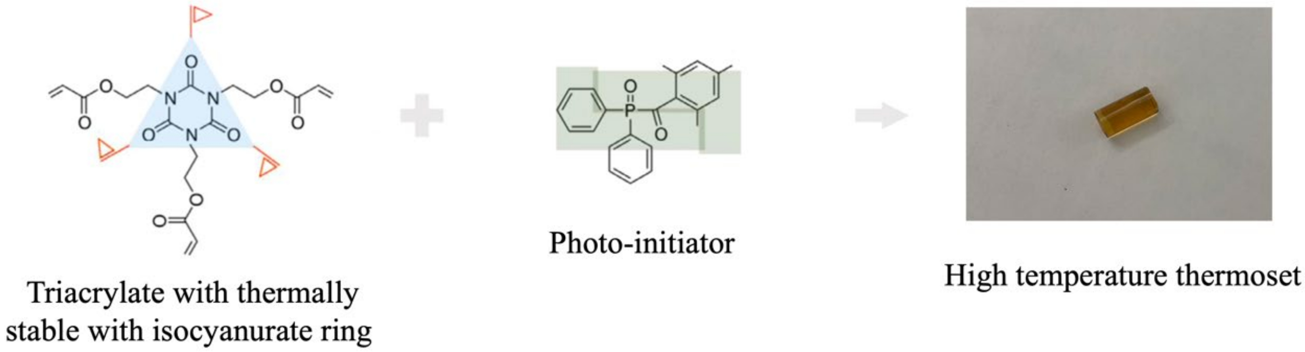


Figure 10. Preparation of high temperature thermoset polymer (HTTP). Chemical structures of tris[2-(acryloyloxy)ethyl] isocyanurate (TAI) monomer and photo-initiator diphenyl(2,4,6-trimethylbenzoyl)phosphine oxides (TPO). The weight percentage of TAI was 93% and the weight percentage of TPO was 7%. The curing was completed by two steps: ultraviolet curing for 40 seconds followed by thermal curing at 310 °C for 3 hours.

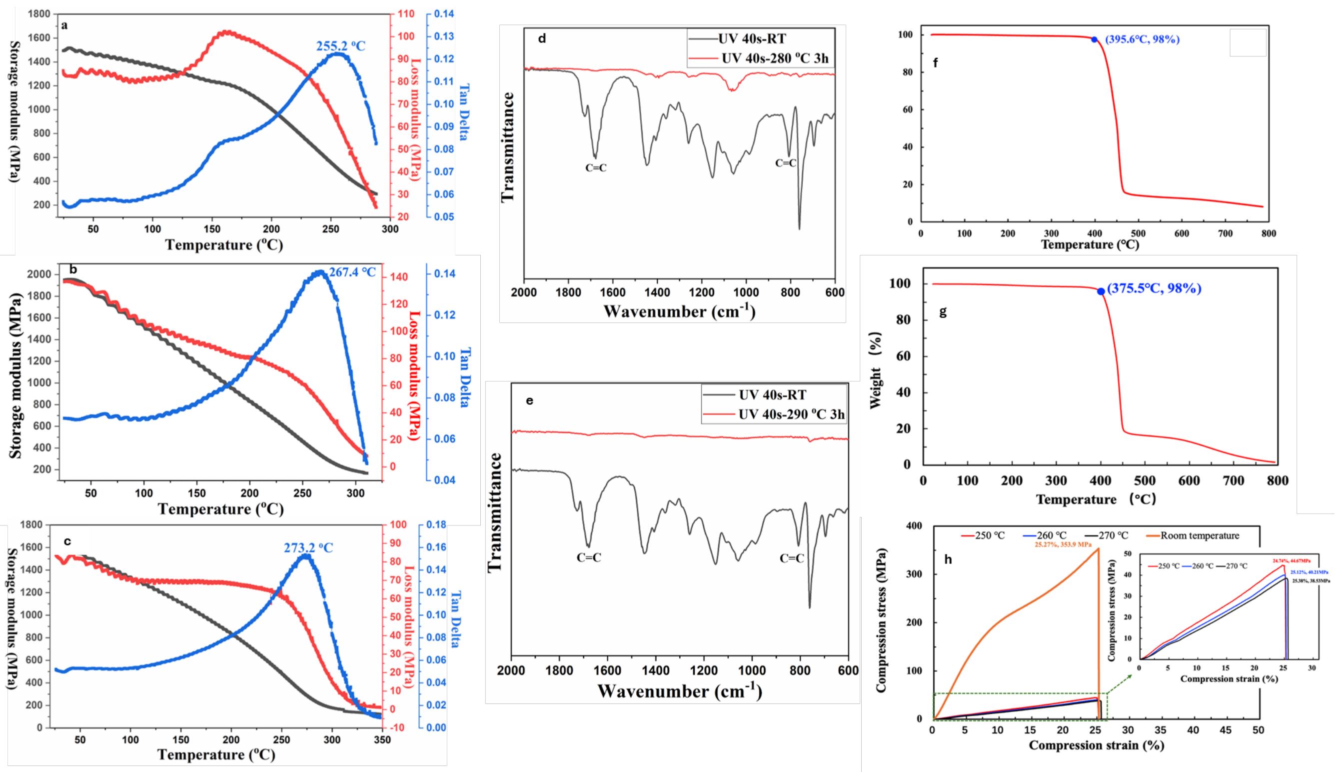


Figure 11. (a) DMA test results of the HTTP post-cured at 280 °C for 3 hours. (b) DMA test results of the HTTP post-cured at 290 °C for 3 hours. (c) DMA test results of the HTTP post-cured at 310 °C for 3 hours. (d) FTIR characterization of the HTTP post-cured at 280 °C for 3 hours. (e) FTIR characterization of the HTTP post-cured at 290 °C for 3 hours. (f) TGA test results of the HTTP post-cured at 280 °C for 3 hours. (g) TGA test results of the HTTP post-cured at 290 °C for 3 hours. (h) Uniaxial compressive stress-strain test results of the HTTP post-cured at 290 °C for 3 hours. The compression test was conducted at 250 °C, 260 °C, and 270 °C, respectively.

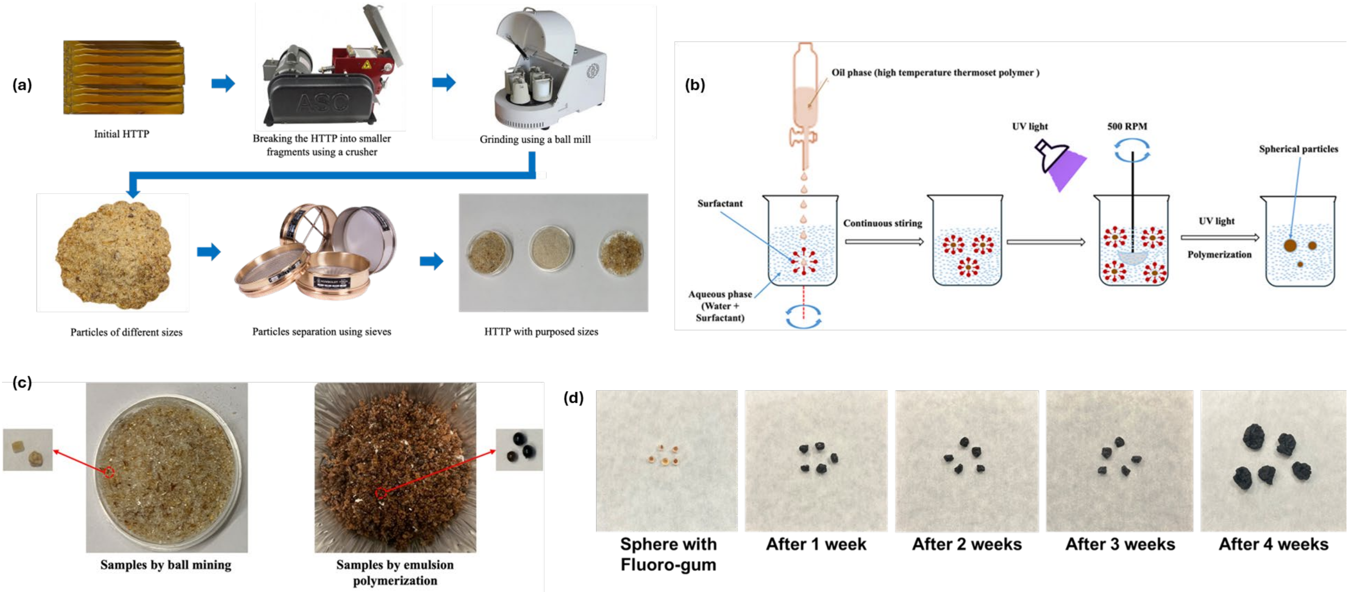


Figure 12. (a) Procedures to convert HTTP bulk to particles through ball milling. (b) Procedures to produce HTTP particles directly using emulsion polymerization. (c) The prepared HTTP particles as proppants. (d) The HTTP particles were immersed in superhot water (200 oC) for different time periods (original, 1 week, 2 weeks, 3 weeks, and 4 weeks). The HTTP particles were coated by a crosslinked fluorinated rubber layer. It is seen that the rubber coating layer darkened and swelled overtime.

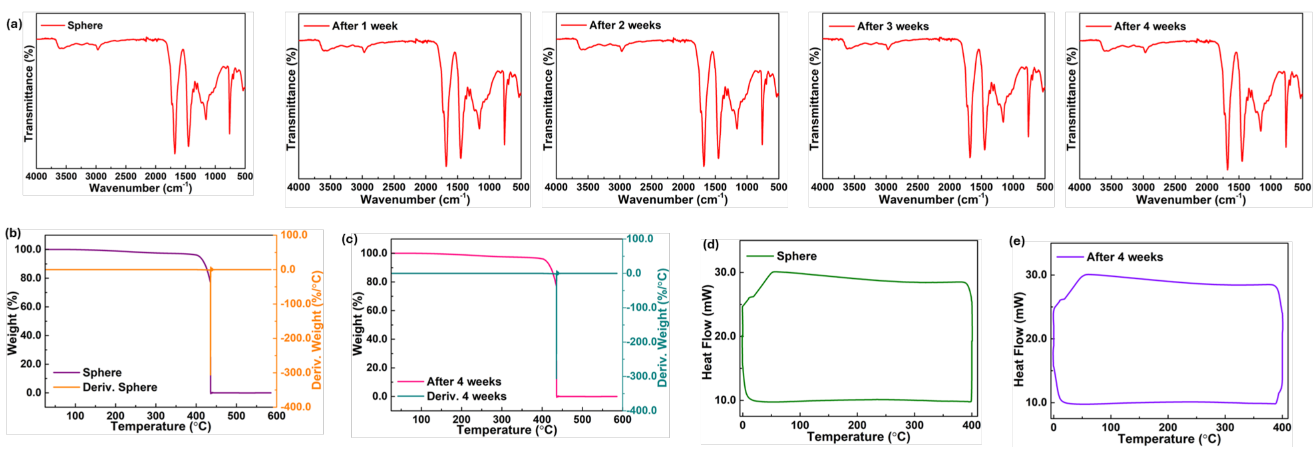


Figure 13. (a) FTIR characterization of the fluorinated rubber coated HTTP particles after immersing in 200 ^{o}C water for 1 week, 2 weeks, 3 weeks, and 4 weeks. The test results show that the polymer is chemically stable. However, we saw the change in surface color and swelling of the coating rubber layer. We will continue to improve the coating layer. (b) TGA test results of the original HTTP particles. (c) TGA test results of the fluorinated rubber coated HTTP particles after immersing them in 200 ^{o}C water for 4 weeks. (d) DSC test results of the original HTTP particles. (e) DSC test results of the fluorinated rubber coated HTTP particles after immersing them in 200 ^{o}C water for 4 weeks.