PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

FRACTURE CONDUCTIVITY OF A BAUXITE-PROPPED GEOTHERMAL SYSTEM AT IN-SITU CONDITIONS

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ABSTRACT

Fracture conductivity is one of the most important properties of geothermal systems - conventional or enhanced. One of the areas of research in enhanced geothermal systems (EGS) involves using proppant to increase retained fracture conductivity - retained and maintained after hydraulic fracturing. Proppant is natural or manmade particulates that are injected concurrently with hydraulic fracturing fluids while creating an EGS fracture system. After fracturing operations the proppant remains in the fractures and "props" them open to ensure retained conductive pathways that would otherwise close under prevailing in-situ stresses. The primary purpose of this study is to investigate the effect of proppant on fracture stability and the effect of temperature on fracture conductivity in both a saw cut (nominally smooth, low friction) and wedge-split (higher friction, fractured) case.

Proppant was placed in a surrogate fracture, temperature applied and hydraulic confining pressure was also applied to provide a normal stress acting to close the fracture. Pressure drop was measured for flow of water through this stressed and propped fracture allowing calculation of conductivity with time and inference of degradation via mechanical affects (such as embedment or chemomechanical alteration of the fracture surface).
In addition to baseline tests that were run at ambient temperature, a range of tests at temperatures of 90°C, 150°C and 200°C have been run to determine the effect of increase in temperature on fracture conductivity and permeability. Even at a moderate temperature of 90°C, the conductivity is greatly reduced by this increase in temperature from ambient (~22°C).

Baseline tests at ambient temperature were completed for comparison to all subsequent results and to determine the effect of increasing temperature on fracture conductivity. Future and ongoing testing is being conducted at a temperature of 200°C to simulate in-situ conditions representative of a moderate temperature scenario within a geothermal reservoir.

To determine the effect of fracture roughness on conductivity, testing was done on both a nominally smooth, saw-cut fracture in a granitic sample and a rough-faced sample that was fractured with a mechanical wedge. Results have shown that temperature may have an impact on lowering the permeability and conductivity through the proppant pack. It was also found that surface asperities have little to do when there is a maximum concentration of proppant filling the fracture.

Key Words: EGS, proppant, bauxite, geothermal, fractures

INTRODUCTION

The purpose of this study is to look at the effectiveness of propping fractures in geothermal systems under in-situ conditions. Low-permeability granite samples were saw cut and split using a wedge and filled with 30/60 bauxite proppant. Both the saw cut and wedge-split tests were run at ambient conditions to use as a baseline for the conductivity measurements to be taken at temperature throughout the testing program. In addition, the differences between surface asperities and low friction saw cut faces were tested to determine the effect of the surface asperities on proppant breakage and embedment,[1] (Cooke, 1977) and whether there is an effect on lowering the conductivity through the sample because of this. It was found that increased temperature decreased the conductivity through the fracture when compared to the literature values published for the equivalent proppant. This may be attributed to thermal expansion (although the effect of thermal expansion, when compared to the confining pressure is assumed to be negligible) or the order in which the tests were run. Tests were run by "ramping" the temperature up from ambient: during the ambient testing the proppant may have compacted and pathways for the water were closed or re-rerouted. Although it was hypothesized that the surface asperities of the wedge-split sample would decrease the permeability and conductivity below the saw cut values, the increase in fracture width (same concentration of proppant in saw cut and rough samples, but nominally greater effective width for rough fractures) allowed for additional pathways that the water travelled through without interacting with the rough face of the wedge-split sample. At adequate concentrations of proppant the surface asperities of the rock are not the controlling factor of permeability through the fracture. At lower concentrations, as may be a realistic scenario, the roughness may promote greater conductivity but this is speculative.

Conductivity measurements on the saw cut and wedge split samples were obtained at an effective confining pressure of 2000 psi.

PROCEDURE

A saw cut (smooth surface) and a wedge-split (rough surface) sample were tested under conditions of 2000 psi confining pressure and ambient (~22°C), 90°C, 150°C, and 200°C temperatures. The pressure vessel and end caps that were used for the testing are shown in Figures 1 and 2.

The rock slabs were filled with proppant and placed on the endcaps with screens covering the faces of the end caps to prevent proppant from clogging the tubing. A Teflon jacket was placed over the sample and end caps and this assembly was placed in the vessel. Brass shim stock was placed over the sides of the fracture and at the rock- end cap interface to prevent jacket failure from the confining pressure. Threaded rings were then used to retain the end caps in the vessel.

Figure 1: End Caps

Figure 2: Pressure Vessel

The saw cut sample means that the sample was cut down the middle using a saw and the fracture surface was nominally smooth—there were relatively few interacting asperities. Figure 3 shows the saw cut sample used for the testing at all temperatures.

Figure 3: Saw Cut Sample

The wedge-split sample means that the fracture was created in the core sample by scoring the edges of the rock and using a wedge to mechanically fracture the sample. The wedge-split sample has a rough surface along the entire length of the core, simulating fractures encountered underground. Figure 4 shows the wedge split sample used for testing at all temperatures.

Figure 4: Wedge-Split Sample

The saw cuts down the side of the wedge-split sample decreased the area of proppant coverage in the fracture to 1.75 inches (down from 2.5 inches). In order to prevent channeling of water down the saw cut grooves on the side of the wedge-split sample, strips of silicone gasket rated to high temperatures were placed in the grooves. A visual inspection of the gasket strips post-test revealed that no proppant passed out of the rough faced fracture and into the saw cut grooves on the sides.

Deionized water was flowed through the samples and the pressure drop through the fracture was measured using a differential pressure transducer. The flow rate of the water through the samples was varied. In both the saw cut and wedge-split sample the flow rates were varied between 1, 2, 3, 4, 5, 10, 15, 20, 25 and 30 mL/min.

The standard proppant weight to be used in a granite sample, for comparison with other experiments in the public domain, was calculated to be 2.74 pound mass per square foot.

The length of the saw cut sample was 9 inches and the length of the wedge split sample was 5.69 inches. The initial fracture width of the saw cut sample was approximately 3.25 mm, filled with 194 grams of 30/60 bauxite proppant. For the wedge-split sample the fracture width was approximately 5 mm, filled with 88 grams of 30/60 bauxite proppant. The proppant was distributed as evenly as possible across the fracture.

The head losses through the tubing and end caps of the pressure vessel were found to be significant. In order to correct for the head losses in the vessel the system was set up with the end caps connected and water was flowed through at various flow rates and pressure drop was measured. A friction correction curve was generated at all the tested temperatures and was applied to the data obtained in the tests.

THEORY

Permeability (conductivity) of the fracture was calculated using Darcy's Law, given in Equation (1).

$$k = \frac{Q\mu L}{A\Delta p} \qquad (1)$$

where

k…...…fracture permeability fracture, Darcy or m^2;
Q………………..flow rate through the fracture, m^3/s;
μ…………………….……viscosity of the fluid, Pa-s;
L………………………length of the test section, m;
A……………cross-sectional area of the fracture, m^2;
Δp……..pressure differential through the test section, psi or Pa.

Conductivity through the fractures was calculated by multiplying the permeability by the fracture by the aperture, as in Equation 2.

$$C = kW_f \qquad (2)$$

where

C..…..conductivity through sample, mD-ft or mD-m;
k…………….……..permeability of the fracture, mD;
W_f………...…….width of fracture in sample, ft or m;

RESULTS AND DISCUSSION

Several tests were run at the various temperatures and the results were averaged. Table 1 shows the averaged permeability values for temperature tests on the saw cut sample. All values presented in the tables and figures in this paper are corrected for friction losses in the tubing and end caps.

Table 1: Average Saw Cut Permeability Summary Table

	Temperature			
	Ambient (~22°C)	**90°C**	**150°C**	**200°C**
Flow Rate (ml/min)	**Permeability (Darcy)**			
1	110.0	9.2	50.0	6.1
2	123.3	16.9	54.1	16.0
3	125.0	20.0	185.5	44.1
4	133.4	27.8	85.2	32.0
5	163.2	21.3	88.9	53.2
10	160.5	24.8	85.2	68.8
15	150.4	25.1	74.7	158.6
20	176.3	43.2	68.3	123.3
25	146.4	40.8	64.2	143.9
30	145.9	37.2	63.6	107.3

Permeability of the 90°C saw cut tests were the lowest values seen in all of the tests. One of the reasons that these values were so low can be attributed to the fact that a back pressure regulator was not used on this set of tests. "Bubbling" of the water must have occurred and the relative permeability of the two phases reduced the effective permeability of the water flowing through the sample. Permeability values of the tests at 150°C were approximately one-half of those at the baseline ambient temperature. It appears that bubbling may have occurred at the lower flow rates of the 200°C test, as in the 90°C case, leading to a relative permeability of the water flowing through the proppant pack being established, despite application of back pressure to maintain single phase conditions.

The permeability values were also averaged over several tests at the various temperatures in the wedge-split sample; the results are presented in Table 2.

Table 2: Average Wedge-Split Permeability Summary Table

	Temperature			
	Ambient (~22°C)	**90°C**	**150°C**	**200°C**
Flow Rate (ml/min)	**Permeability (Darcy)**			
1	66.6	101.5	111.5	6.0
2	154.1	104.3	129.1	34.3
3	193.8	97.6	294.7	9.3
4	269.8	109.4	134.4	39.8
5	236.7	106.0	134.7	17.4
10	215.6	93.6	136.8	76.8
15	193.4	89.6	130.6	56.1
20	183.2	88.1	96.6	49.0
25	172.2	84.8	82.3	98.7
30	162.7	85.8	73.0	61.4

Permeability values at 90°C were again approximately one-half those for the baseline ambient permeability conditions. It also appears that bubbling may have occurred in the wedge sample at the lower flow rates at 200°C, leading to a low relative permeability. Although there was a back pressure regulator on the tests at 200°C, the flow rates may have been low enough to allow for some bubbling to occur.

A comparison plot of the averaged permeability values at all of the temperatures for the saw cut case is presented in Figure 5.

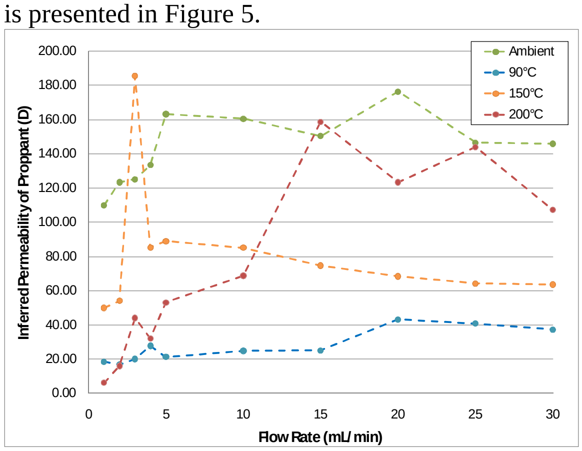

Figure 5: Saw Cut Permeability Summary Plot

Ambient permeability and the permeability of the higher flow rates at 200°C for the saw cut sample approach the values in the published literature for the bauxite proppant used in the testing, although they are still well below them. Interestingly, the permeability around the boiling point of water stays at a constant low value. At the intermediate temperatures of 90°C and 150°C and even the lower flow rates at 200°C, temperature appears to have an effect on the permeability of the proppant pack in the saw cut tests.

A comparison of the averaged permeability values at all the temperatures for the wedge-split case is presented in Figure 6.

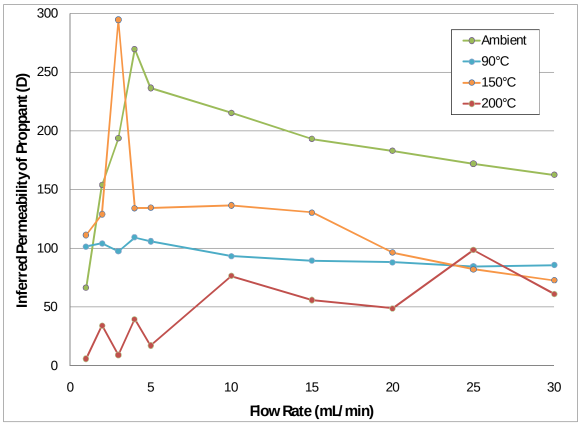

Figure 6: Wedge-Split Permeability Summary Plot

As with the saw cut tests the ambient permeability approaches the published literature values. In the wedge-split cases the permeability for 90°C and 150°C approach nearly constant values of approximately 100 Darcy and 120 Darcy, respectively. Permeability values at 200°C are lowest in the wedge-split case; at higher flow rates they appear to rise to just below the permeability values of the other temperature tests. A back pressure regulator was used for the wedge-split tests at 90°C, and while the values are higher than in the saw cut case they are still low compared to the baseline ambient test. In the wedge-split tests, the measurements at temperature appear to show that there may be temperature effect on the permeability of the proppant pack.

Figure 7 is a comparison of the averaged permeability values for saw cut and wedge split scenarios.

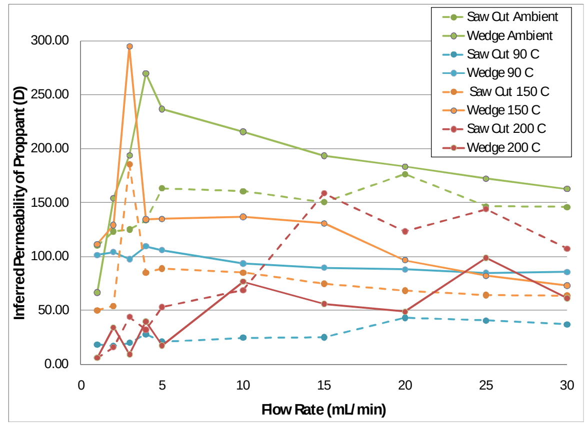

Figure 7: Saw Cut vs. Wedge-Split Permeability Summary Plot

In the 200°C temperature set, the saw cut sample had higher permeability values than in the wedge-split case; in all other temperature sets the wedge-split sample averaged higher permeability values than the corresponding temperature saw cut test. It was originally hypothesized that the surface asperities on the surface of the wedge-split sample would increase the friction through the proppant pack, thereby decreasing the permeability values when compared to the saw cut tests. Since this was not exclusively the case, alternative hypotheses were also formulated.
One of the reasons that the permeability of the wedge-split tests was greater than the saw cut tests can be attributed to the difference in the width of the fracture in the wedge-split tests. The width of the gasket material that was placed in the saw cut edges on the wedge-split faces held the fracture open approximately 1.5 mm more than in the saw cut case. This would have increased the number of pathways that water could take through the proppant, limiting exposure to the apertures on the faces of the wedge-split sample. Fredd et al. (2006) found in a similar study that the higher the proppant concentration, the less the fracture relies on aperture effects in maintaining permeability and conductivity.[3]

Temperature, even at the low scenario of 90°C appears to have a great effect on lowering the permeability of the system; all of the permeabilities measured at temperature are much lower than the baseline permeabilities found at ambient temperature. One of the reasons the permeability may decrease with an increase in temperature from ambient could be attributed to the thermal expansion of the rock and proppant, decreasing some of the void space that was available in the ambient testing. A more likely scenario is that in running the tests they were run in order of increasing temperature. During any one of the tests the proppant pack may have compacted, and prevented flow in the manner that it was flowing in the previous tests. Restarted tests (after reloading of the proppant following a jacket failure) did appear to have higher permeability values than the later tests run. Though that may be one of the main reasons for the decrease in permeability through the sample, at increasing temperature, it is still believed that temperature has an effect on the permeability of the sample, though the extent of this is not known.

Average conductivity values obtained in the saw cut tests at the various temperatures is presented in Table 3.

Table 3: Average Saw Cut Conductivity Summary Table

	Temperature			
	Ambient (~22°C)	**90°C**	**150°C**	**200°C**
Flow Rate (mL/min)	**Conductivity (mD-ft)**			
1	1172.8	197.2	533.0	65.3
2	1315.1	207.6	577.3	170.8
3	1333.8	275.0	1978.2	470.1
4	1423.2	316.5	908.7	341.8
5	1740.3	244.4	947.8	567.0
10	1712.0	282.9	908.3	733.6
15	1604.1	296.2	796.8	1692.0
20	1880.7	479.6	728.8	1315.4
25	1561.9	454.2	684.7	1534.5
30	1556.3	415.3	678.3	1144.0

Average conductivity values at the various temperatures for the wedge-split case are presented in Table 4.

Table 4: Average Wedge-Split Conductivity Summary Table

	Temperature			
	Ambient (~22°C)	**90°C**	**150°C**	**200°C**
Flow Rate (mL/min)	**Conductivity (mD-ft)**			
1	1073.0	1587.6	1672.5	98.2
2	2410.6	1624.0	1937.2	558.1
3	3017.7	1511.2	4420.9	150.5
4	4157.4	1700.1	2015.3	646.7
5	3657.6	1658.7	2020.8	283.4
10	3343.9	1443.8	2051.7	1247.7
15	3009.5	1382.1	1959.1	912.3
20	2853.8	1356.2	1449.4	795.8
25	2683.5	1306.7	1233.8	1604.2
30	2537.3	1325.3	1094.6	997.2

A summary plot comparing the saw cut and wedge-split conductivity values is presented in Figure 8.

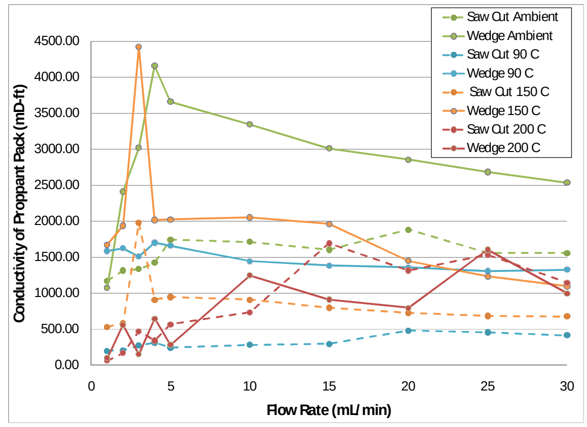

Figure 8: Average Saw-Cut vs. Wedge-Split Conductivity Summary Plot

Of note in Figure 8 is the widening gap in conductivity values between the saw cut and wedge-split samples. This is attributed to the wider fracture gap of the wedge-split sample. The conductivity of the ambient baseline wedge-split test is much greater than all of the other average conductivity values obtained (~1000 mD-ft greater than the next closest values at all flow rates). Intuitively it makes sense that the wider the fracture, and consequentially the more layers of proppant in the fracture, the higher the conductivity.

Other studies on proppant in hydraulic fractures at extreme conditions have concluded that geochemical reactions occur to both the rock and proppant pack under extreme temperature and that the effect of which is lowering of conductivity and porosity.

Weaver et. Al (2006), in a study on sustaining fracture conductivity found that "Geochemical reactions can lead to rapid, dramatic loss of porosity of proppant packs exposed to high temperature and stress conditions, leading to significant loss of fracture conductivity. This mechanism is functional at lower temperatures and closure stresses, but may be sufficiently slow to not be a significant factor in production. The use of high-strength proppants may actually exacerbate porosity filling reactions by forming clay-like minerals. This may partially mitigate the advantage of using stronger proppants." (Weaver et. Al, 2006).[4]

Yasuhara et al. found that geochemical reactions occur within hydraulic fractures where high stress and high temperature conditions already exist. Yasuhara et al. (2003) reported, "At effective stresses of 5,000 psi, with temperatures in the range 170 to 570°F, the rates of porosity reduction and ultimate magnitudes of porosity reduction increase with increased temperature."[5]

Geochemical reactions within the fracture may attribute to the decrease in permeability and conductivity with increase in temperature.

Proppant Appearance (Pre-test)

The proppant was analyzed under an optical microscope both before and after testing in both the saw cut and wedge-split cases. Figure 9 shows the appearance of the proppant before it had undergone any testing. As shown in Figure 9 the surface of the bauxite proppant is rough and uneven.

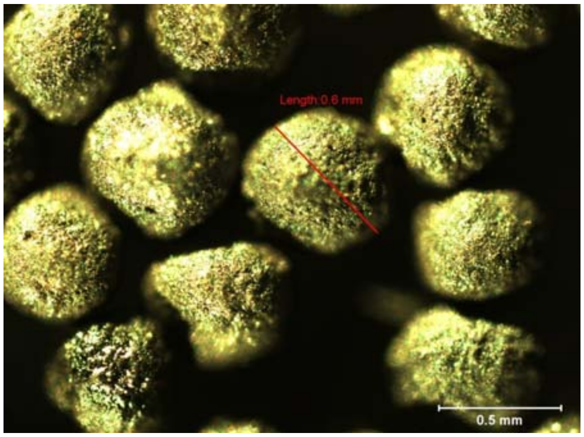

Figure 9: Untested Proppant, 5x Magnification

Proppant Appearance (Post-test)

There was some breakage of proppant and embedment seen following the sets of tests on both the saw cut and wedge-split cases. Figure 10 shows some clumping of the proppant and a broken fragment off the face of a sample. Note that this degradation occurred at low closure stress (2000 psi).

In both the saw cut and wedge-split cases, after the proppant had been removed from the vessel and allowed to dry, the proppant was clumped, due to the confining stresses in the fracture and potentially chemical effects. Other optical microscopy analyses show proppant breakage, with more proppant being seen broken in the wedge-split case than in the saw cut tests. This is most likely attributed to the fact that there is more surface area in which the proppant particles are in contact with, and are crushed against. Very limited proppant breakage was seen following the saw cut sample testing.

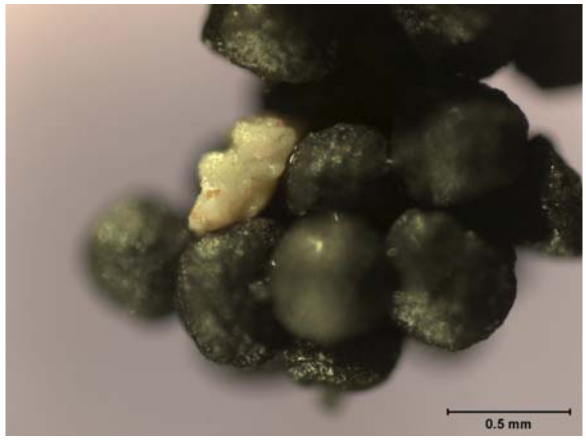

Figure 10: Tested Proppant, 5x Magnification

Optical microscopy also confirmed that in some of the earlier measurements the system entrained oxygen/air, forming rust on some of the proppant particles. Figure 11 shows rust formation on a proppant particle.

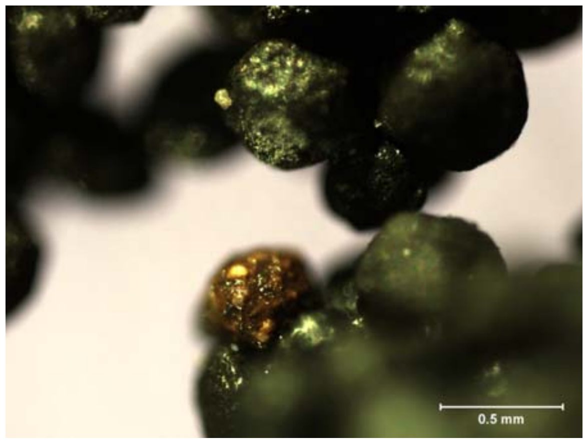

Figure 11: Rust Formation on Tested Proppant, 5x Magnification

Figure 11 further illustrates the fact that the proppant clumps under the confining stress in the fracture. The proppant oxidation can justify a hypothesis that two fluid phases in the proppant pack lowered the effective permeability of water through the proppant pack.

CONCLUSIONS

Conductivity values were measured through a manufactured fracture - both a saw cut and wedge-split sample - under a confining pressure of 2000 psi. The fracture conductivities were lower than published values. All tests at temperature lowered the permeability and conductivity well below the ambient baseline values. At elevated temperature, the proppant apparently does not retain the conductivity values that are characteristically found in the literature. This may be attributed to thermal expansion of the core and proppant. Alternatively, time-temperature dependent compaction of the pack could be an issue. The tests were run by progressively increasing the temperature, allowing stabilization and then flowing. The proppant pack may have compacted in such a way that the flow was hindered for the later tests at higher temperature. Limited geochemical reactions may also have occurred in the proppant pack, lowering the conductivity at higher temperatures.

Conductivity and permeability decreased in the saw cut tests due to the aperture width. This is completely reasonable since the nominal width for the rough samples was higher because of the surface asperities. In addition, since the gaskets holding the edges of the wedge-split sample opened the wedge-split fracture nearly 50% greater than in the saw cut case, there were more potential pathways for the flow through the sample and less possibility of any surface interaction with the rough wedge-split face.

Some of the deviation from published values might also be attributed to the added friction created by the surface asperities. The surface roughness for the wedge-split sample increased frictional pressure loss (much greater than the friction of a flat metal plate on which they are often tested) and this lowered the fracture conductivity. Even the saw cut sample had an increase in friction when compared to the flat metal plates often used to test proppant conductivity in the laboratory.

Geothermal systems typically deal with low permeability rocks with a high compressive strength. Experimentally it was seen that there was little embedment of the proppant into a granite sample, even at a confining pressure of 2000 psi. Proppant entrapment in the surface asperities of the wedge-split sample was noticeable across the entire fracture. Although it was not quantified, there was some proppant breakage in both the saw cut and wedge split cases, with more proppant being broken in the wedge-split sample. Clumping of the proppant was observed in both the saw cut and wedge-split cases, with more clumping of the proppant that had been trapped in the surface asperities of the wedge-split sample than in the saw cut fracture.

Solution or local phase change within the proppant pack reduced the effective permeability values for both the saw cut and wedge-split experiments, particularly at low flow rates where the water was not flowing into, and through, the fracture enough to remove all air in the system. Lower observed permeability values at the low flow rates can be attributed to this effective permeability reduction.

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