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Microcapsule Transport in Porous Media for Treatment of Non-Ideal Flow Zones

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ABSTRACT

Flow through permeable zones in the subsurface is the key to modern energy production. In geothermal systems, this involves injecting fluid along ideal flow pathways such as fractures and faults to extract heat. However, the efficiency of the heat extraction may be greatly diminished if the injected fluid travels in part through non-ideal flow zones which are excessively permeable or not well-connected to the withdrawal well. To treat these non-ideal flow paths in geothermal reservoirs, a porous polymer has been developed that can restrict flow by partially sealing these non-ideal flow zones. This polymer will be distributed through a temperature-activated microcapsule release. The focus of this work is how these microcapsules will flow and become trapped in a network system in the subsurface. We develop a high-temperature high-pressure flow loop for injecting microcapsules into a porous network. Using polyethylene microcapsules to simulate the final microcapsules developed in this study, we injected the microcapsules into a porous reservoir material while varying parameters during testing such as injection fluid viscosity, gravel size, and microcapsule properties. The results indicated that the developed microcapsules will be able to enter the network, but that most of the injectates will block the matrix near to the porous media rather than penetrate throughout. Future work will use X-ray CT to reveal how the microcapsules are trapped in the pore spaces and what channel parameters control microcapsule trapping.

1. INTRODUCTION

Geothermal energy has significant potential for producing renewable low-carbon producing energy to meet global demand. However, despite the broad acceptance of geothermal energy and its potential, to date its usage makes up only ~1% of the total renewable energy produced globally (Krieger et al. 2022). Part of this gap is due to the low availability and uneven distribution of subsurface resources, as viable economic production of geothermal energy requires sufficiently high temperatures near the surface which are not often present. Another limitation to maximizing geothermal energy production is the necessary hydrologic conditions. Geothermal energy requires sufficient permeability in a hot reservoir for fluids to transmit between wells and accumulate heat that can be utilized at the surface for energy extraction. Most lithologies with sufficient heat for production are low-permeability crystalline rocks such as granites (Lu 2018). To make such heat sources viable, reservoir permeability must be engineered in-situ to create sufficient flow between wells to enable heat production. Such engineered geothermal systems (EGS) require the use of hydraulic fracturing technologies to generate sufficient permeability, but the implementation of artificial geothermal reservoirs could enable the upscaling of geothermal energy production by several orders of magnitude globally. To reduce the costs of EGS development, it is thus necessary to develop new technologies to reduce the high upfront costs incurred during drilling and reservoir development.

One issue in geothermal systems is thermal short-circuiting (Parker 1999), which is the formation of non-ideal flow pathways in EGS systems that lead to reduced energy production. In most cases, short-circuits are attributed to thermo-mechanical effects that cause the matrix blocks to contract because of cooling (Fu et al. 2016). As cold water is injected into a geothermal reservoir along an ideal flow path such as a fracture or shear zone, the heat extraction by the injected fluid causes the surrounding rock to contract near the flow zone. Matrix contraction can open adjacent fractures, thus opening alternate fluid flow pathways with higher permeability and non-ideal flow directions. This can result in large losses of injected fluid and reduced production rates in geothermal systems, reducing their viability for long-term energy production. Since short-circuiting appears to be a natural thermal-hydrological-mechanical process in reservoir rocks and geothermal energy extraction, alternative methods for blocking these non-ideal flow paths are needed in order to maintain long-term heat extraction in EGS.

Various researchers have proposed injecting particles to reduce flow in these non-ideal zones in geothermal reservoirs. The injected materials proposed include high temperature preformed polymers (Darko et al. 2024), hydrogels (Nakagawa et al., 2023), and urea (Rose et al. 2010). The main challenges limiting use of materials are: 1) how to deploy the diversion agents such that they seal only the undesired flow zones; 2) timing of the diversion agent taking effect; 3) survivability of the agent(s) at EGS conditions (e.g., 200-300 ˚C acidic formation fluids); 4) reducing fluid flow without creating high fluid pressurization and thus generating undesired fracturing/damage that further enhances non-ideal flow. To address these conditions required for a successful diverter in geothermal systems, a porous polymer was specially developed to partially block flow in thermal short-circuits created during geothermal production (Tetteh et al. 2023). A time-released microcapsule system has also been developed to transport the adhesive polymers to these flow zones. Successful deployment of this polymer sealant in thermal short-circuits will require that the microcapsule transport and trapping in these zones be understood and accounted for when designing the technology. To inform this development, we have conducted several tests with a high pressure high temperature (HPHT) flow loop system of microcapsules with similar physical properties to the developed microcapsules to evaluate their transport. Analogue microcapsules were injected into porous gravel matrices in a high-pressure high-temperature flow loop for a period of 3 days. Parameters such as fluid composition, gravel size, and microcapsule size were varied during the different tests to evaluate how microcapsule properties can be tuned to best achieve successful blockage. Examination of the samples through 2D and 3D imaging post-test allowed us to characterize the controls on microcapsule transport in the gravel matrices.

2. MATERIALS AND METHODS

Because of the risks of the developed microcapsules "releasing" the polymer and the number of microcapsules needed, in this study we conducted tests with two sets of microcapsules from Cospheric (Figure 1a). Both sets of microcapsules are composed of red fluorescent polyethylene, are hollow inside their shells, and have densities around 0.998 g/cm^3. The difference between the two is size: the first set of microcapsules have diameters ranging from 425 to 500 µm while the second set have diameters ranging from 850 to 1000 µm. The microcapsules developed for this project are designed to have 450 to 550 µm diameters and densities ~1 g/cm^3, so the microcapsules used here are a good simulacrum for the newly developed acrylic microcapsules in terms of physical properties.

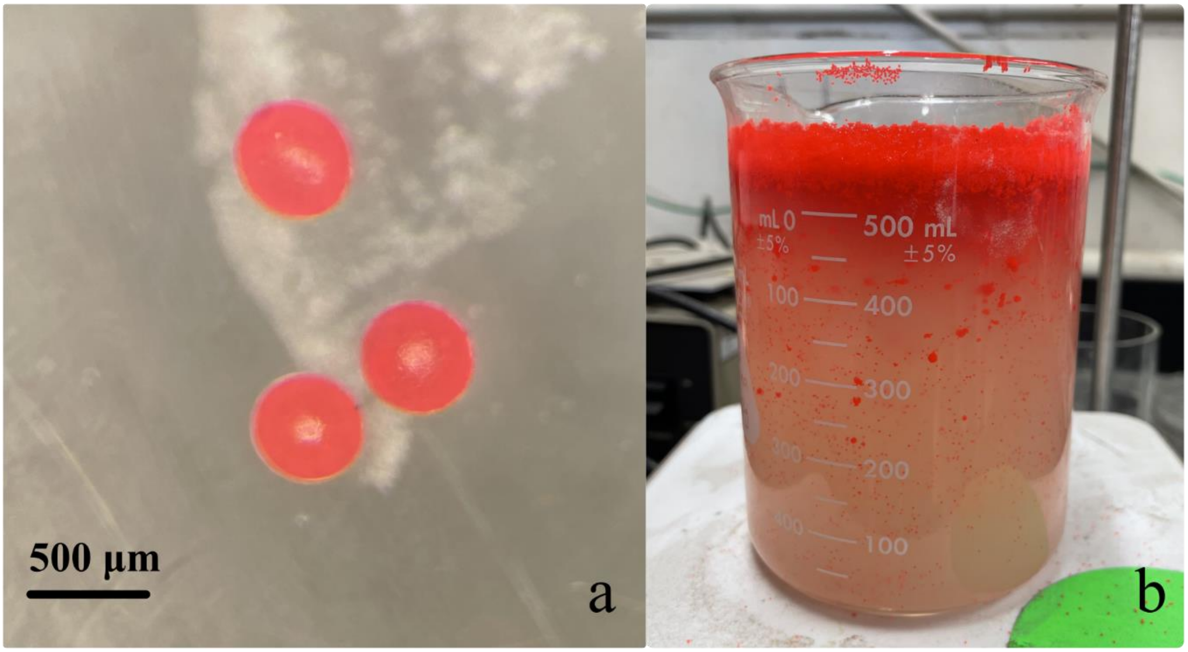

Figure 1: Example of ~500 µm microcapsules in microscopic view (a) and initial mixture of 30 g of microcapsules in the xanthan gum carrier fluid (b).

The test setup utilized in this study is a modified version of the one described by Kibikas et al. (2024). To summarize, our HPHT flow loop system is designed to inject water in a continuous loop through a porous matrix material held at temperatures and pressures up to 250 ˚C and 17.5 MPa. An image of the modified system is shown in Figure 2a. In this system, water is held in a catchment basin that is pumped into the system by the external Hydrorex pump system. The pressure system pushes water into the batch reactor where the injected materials (in this case microcapsules) are contained and by pressurizing the reactor force the materials to flow out of the reactor and into the gravel pack. A cylindrical sample holder (Figure 2b), with internal dimensions of 101.6 mm by 203.2 mm, is filled with gravel (the "sample") and the holder is placed inside a special heating system. The injected materials are pushed along the loop and into this sample. Ideally, the materials remain trapped in the gravel while the fluid leaves the sample. Two pressure transducers are used to measure pressure around the sample during testing; one transducer is mounted at the inlet point for the gravel pack (e.g., upstream) while the second transducer is mounted at the outlet point for the gravel pack (e.g., downstream). The fluid (with any materials that pass through the gravel) then transmits through a coolant loop before reaching an external pressure relief valve (PRV). The PRV in our setup is set at 9.7 MPa (~1400 psi), which enables pressure to build up during the test so any effect from the trapped particles can be detected through pressure changes. Once through the PRV, the fluid passes through an external flow meter (Figure 2) that records the rate of flow through our system, before finally returning to the catchment basin where any particles exiting will remain trapped and can be separated from the re-injected fluid.

Figure 2: Setup of modified HPHT flow loop system (left) and opened sample holder prior to testing (right).

The test procedure used was as follows:

1. The system was initialized with the gravel pack and microcapsules sealed in batch reactor.
2. Recording of data was initiated for the test (2 Hz).
3. Water was injected through the system without heating to evaluate and seal any leaks.
4. Once sealed, flow was halted, and temperature was externally set to ~100-110 ˚C. Temperature around the sample holder was allowed to equilibrate overnight.
5. The next morning, the system was pressurized, and microcapsule injection was initiated.
6. Flow was continued for ~8 hours, then the pressure system was halted, and temperature was allowed to return overnight.
7. Steps 4-6 are repeated twice.
8. After the third day of testing, once flow was ended the external heater was deactivated and temperature was allowed to return to ambient conditions overnight.
9. Data recording was halted, and the test was concluded.

Using this procedure, 7 tests were conducted (Table 1). Test #1 was a preliminary test using only water to check system operationality. Test #2-7 were all tests where microcapsules were injected into the system. Three parameters were varied during the tests: 1) gravel size; 2) carrier fluid viscosity; 3) microcapsule size. To show the effect of different gravel sizes, 2 gravels were procured from Buildology in Albuquerque, NM for testing. Both are a predominantly crushed felsic rock composed of subangular grains. The main difference is the grain size: one gravel had grains between 3 and 6 mm in diameter and the other had grains between 6 and 9 mm in diameter. Gravel 1 was used for Tests #1/2/4/6 while Gravel 2 was used for Tests 3/5/7. Since microcapsule transport will depend upon the fluid properties, Tests #1-3 were injected only using water as a carrier fluid. Tests 3/4-7 used a carrier fluid in the batch reactor composed of water-xanthan gum mixture with xanthan gum making up 0.5 wt% of the mixture (Figure 1b). Xanthan gum is a common viscosifying agent used during drilling, and rheometer tests confirm this mixture should have a viscosity in the range of 40-60 mPa·s during our tests. Finally, we also varied the microcapsule size during our tests; 30 g of microcapsules were used for each test, added to the batch reactor prior to testing. During Tests 2-5 microcapsules with diameters of 0.425 to 0.500 mm were injected, while during Tests 6-7 microcapsules with diameters of 0.850 to 1.000 mm were injected. This allowed us to compare the effects of microcapsule size on transport through our gravel pack.

Table 1: Information for conditions of each flow loop test conducted.

Test #	Gravel Grain Diameter (mm)	Max Temperature (˚C)	Microcapsule Diameter (mm)	Viscosity (mPa·s)
1	3-6	110	0.425-0.500	1
2	3-6	110	0.425-0.500	1
3	6-9	110	0.425-0.500	1
4	3-6	110	0.425-0.500	50

5	6-9	110	0.425-0.500	50
6	3-6	110	0.850-1.000	50
7	6-9	110	0.850-1.000	50

Once each test was concluded, the sample holders were removed from the heating system and the downstream end was opened. The opened holder was then placed in an oven to dry at ~70 ˚C overnight to remove the water. After drying, EpoxyCast Deep Pour was mixed and poured into the now-dry sample. This was done to preserve as best possible the position of the gravel and any trapped microcapsules. After 3 days the epoxy had dried, and the gravel samples were removed from the holder using a hydraulic press to slide out the now epoxied samples. These epoxied samples were then inspected to determine the microcapsule trapping behavior that occurred during each test.

3. RESULTS AND ANALYSIS

3.1 Flow loop tests

The preliminary Test #1 of the system was successful in allowing for continuous circulation of fluids at high temperature over a period of 3 days. The temperature, flow rate, and upstream/downstream pressure data for Tests #2-7 are shown in Figure 3.

Once microcapsule injection began at the start of each day, a temperature drop across the sample occurred whereby the temperature decreased from ~110 ˚C to 60-70 ˚C after ~30 minutes of injection. The system was designed with this temperature drop in mind, as this more accurately reflects the thermo-poro-mechanical phenomena such as contraction that would occur in geothermal systems when the microcapsules are injected into permeable zones. The temperature would remain at this lower bound for each test until flow was halted after ~8 hours, whereby it would rapidly recover to its pre-injection high. Flow rate and pressure data in Figure 3 offers insights into the transmission of microcapsules during our tests. Tests #2 and #3 tended to have higher flow rates than the other tests. Flow rates are similar for Test #4, but appear to be lower for Test #5 with slight decreases as testing continues. Interestingly, Test #6 and #7 both have the lowest flow rates which decrease permanently with each subsequent day of microcapsule injection. The pressure measurements appear to follow an inverse trend to the flow rates, with the lowest pressures on average occurring for Test #2 and #3 and the highest occurring for Test #6 and #7.

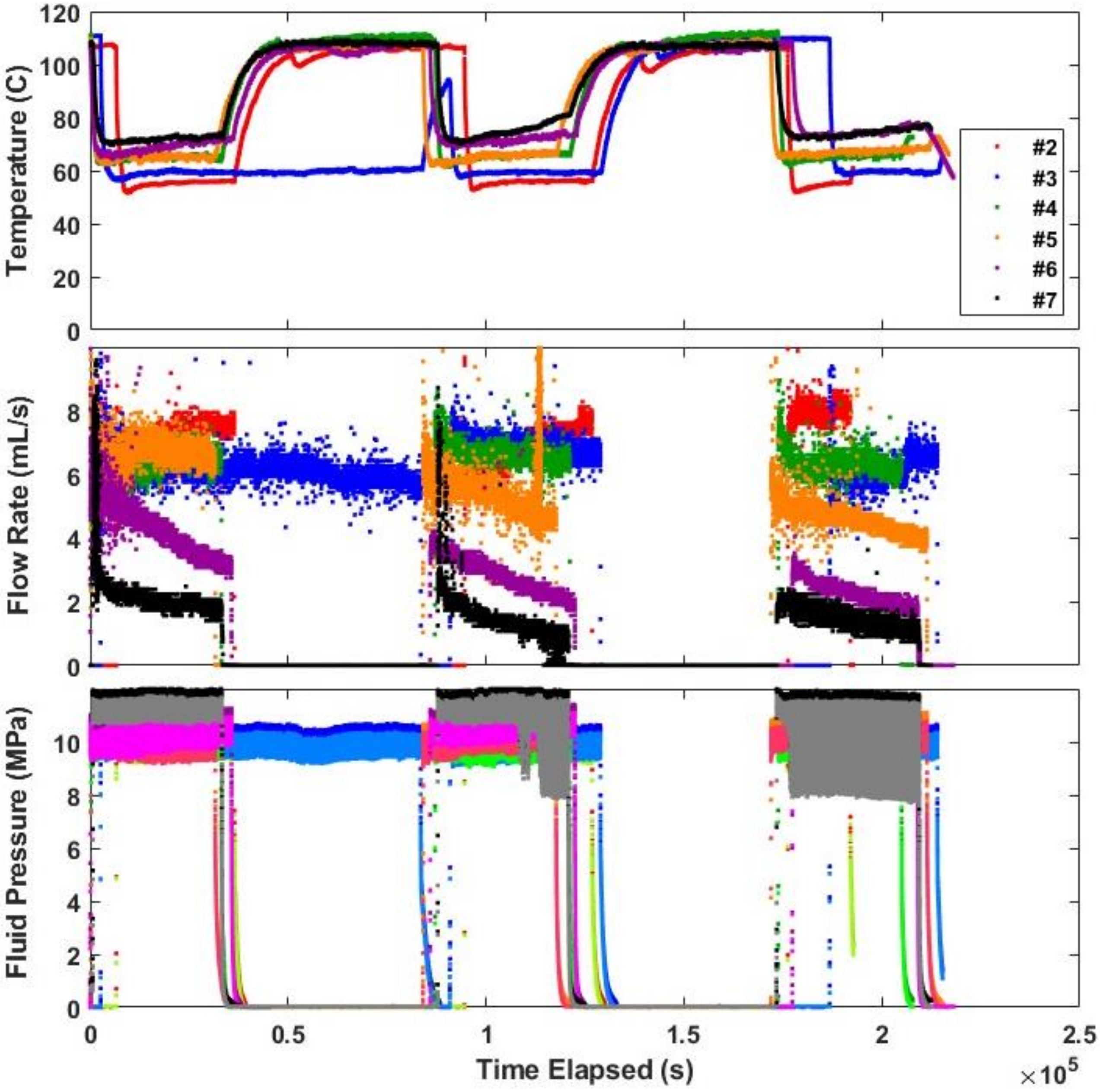

Figure 3: Flow loop test data for the 3 days of injection showing the changes in temperature, flow rate, and fluid pressure.

The initial data suggests that the test conditions have altered the transmissibility of fluid through our gravel packs. To more effectively elucidate the difference, we calculated the pressure difference ΔP (i.e., upstream fluid pressure – downstream fluid pressure) and permeabilities across the sample during our tests. Darcy's law was used to determine the permeability for our tests. Since temperature affects the dynamic viscosity μ of the fluid carrying the microcapsules, a temperature-dependent formulae for water and a 0.5% xanthan gum mixture were used for the permeability calculations (Reid et al. 1987). Determined values for both are shown in Figure 4.

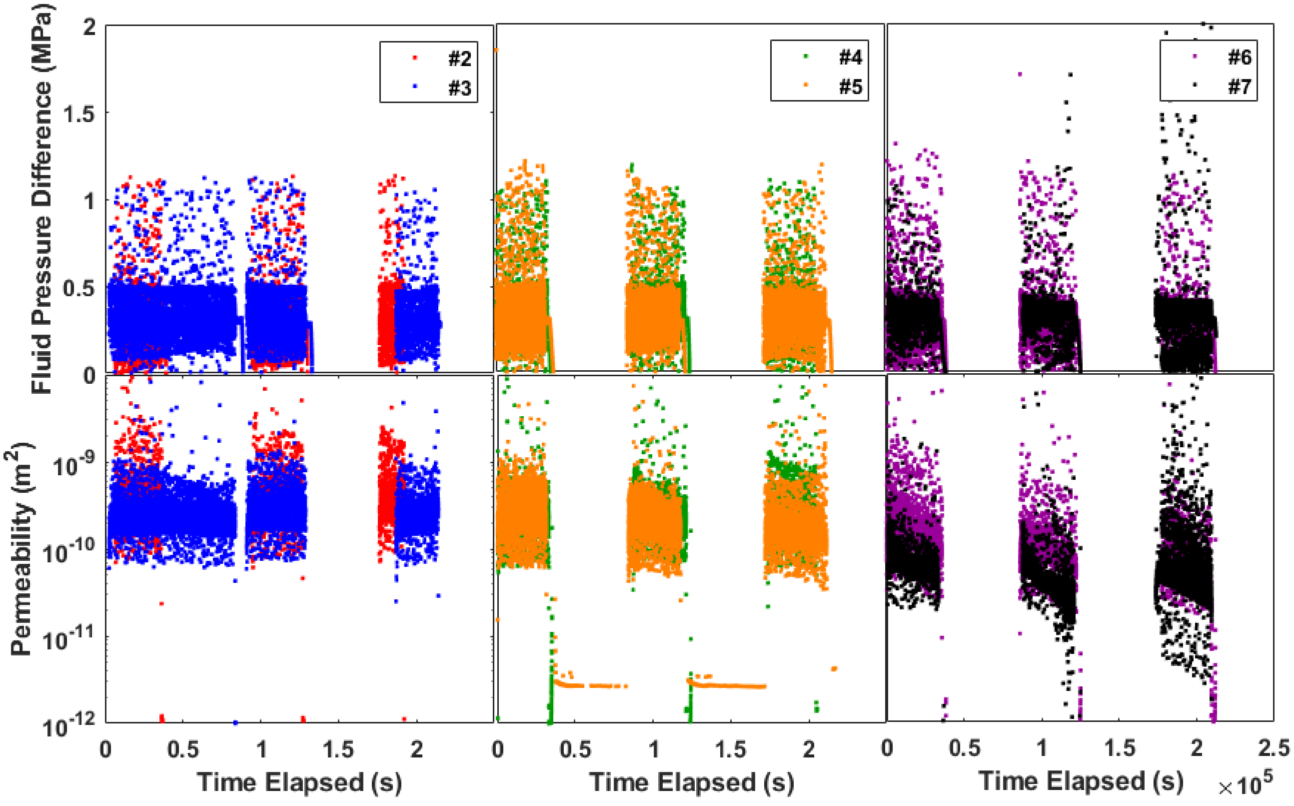

Figure 4: Pressure difference and permeability determinations for each flow loop test over a 3 day period.

The pressure data indicates that, regardless of the test conditions, the predominant pressure difference for all tests was between 0.1 and 0.5 MPa. Although there are outlier values, ΔP tends to have a mean around 0.28 MPa during our tests indicating relatively low pressure variation across our sample lengths. This result is interesting, as fluid pressures shown in Figure 3 indicate both the upstream and downstream pressures increase with both carrier fluid viscosity and microcapsule size. It can be seen however that there are more ΔP values above ~0.5 MPa for Tests #4-#7 than were observed for Test #2 and #3.This appears to occur regardless of the gravel size used.

The effect on permeability of different injection conditions is somewhat clearer. Permeability for Tests #2 and #3 does not significantly vary from 10^{-4}-10^{-3} m^2 for the duration of tests, implying a low effect from the microcapsule injection. Permeability for Test #4 and #5 are slightly lower than Test #2 and #3, but more interestingly appear to experience slight decreases as injection continues. Test #6 and #7 appear to experience large decreases in permeability as injection continues, with each day flow rates starting lower than previous the previous injection cycle (Figure 4). These results strongly imply that permeability continued injection decreases permeability when both carrier fluid viscosity and microcapsule size increase.

Additionally, it appears that the average grain size of the gravel influences flow and restriction as well. The permeability measurements of each test were average per each day of injection. We thus determined the impact of gravel size by finding the permeability ratio k_r, which was the ratio of the fine gravel permeability average measurements to the coarse gravel permeability average measurements for the same test conditions(e.g., mean permeability of Test #2/Test #3, Test #4/Test #5, Test #6/Test #7). k_r for Test #2/#3 was 1.27, k_r for Test #4/#5 was 1.34, and k_r for Test #6/#7 was 2.22. These results indicate that 1) the coarser gravel has an intrinsic permeability less than the coarse gravel and 2) doubling the microcapsules size (i.e., 0.425-0.500 mm vs. 0.850-1.000 mm) can increase the permeability reduction more for the coarse gravel sample than the finer gravel sample.

3.2 Post-test observations

The degree of microcapsule trapping in our samples could not be quantitatively determined at this time. However, through post-test examination of the samples we were able to qualitatively observe how different variables related to microcapsule trapping.

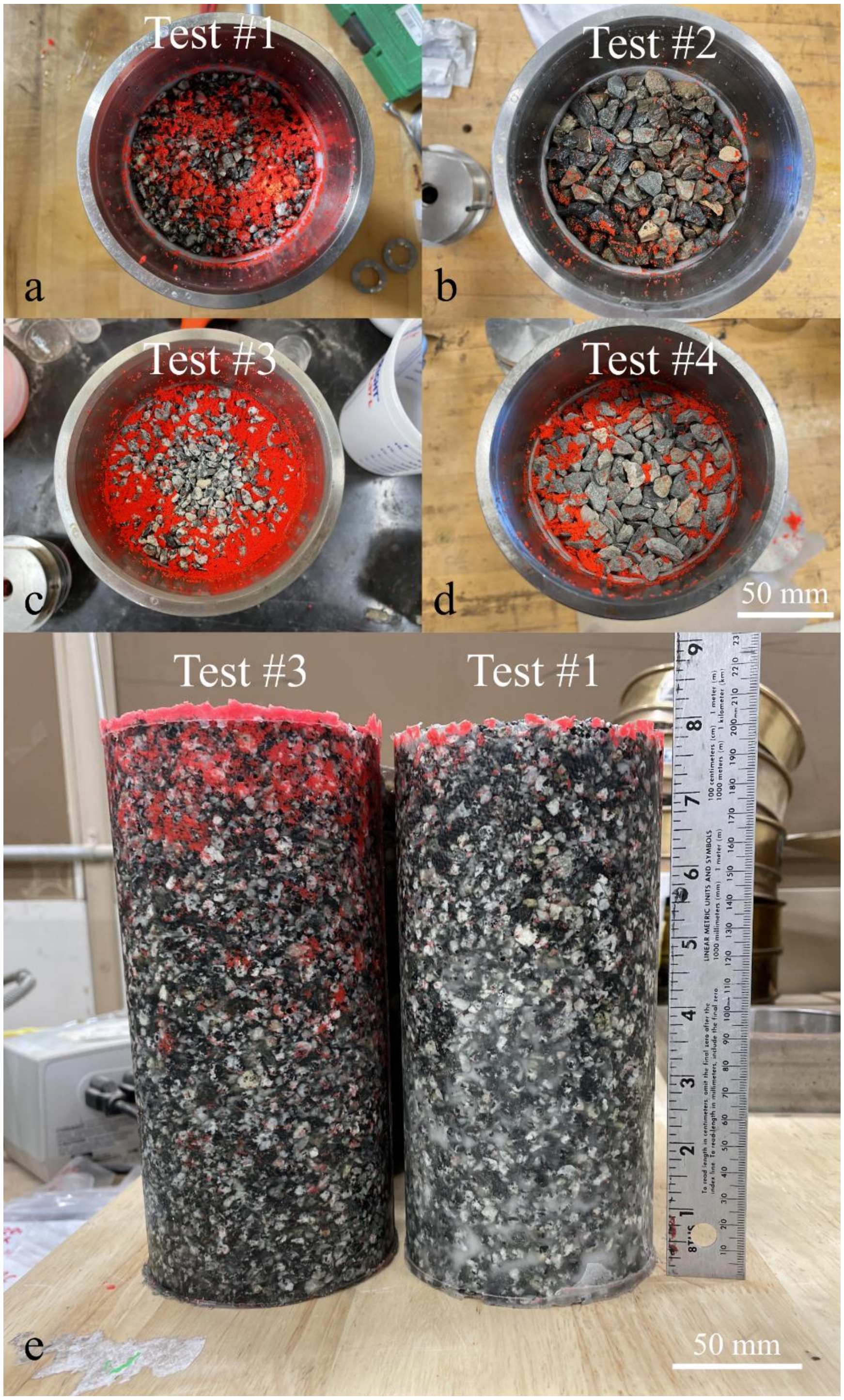

Figure 5: Upstream end of samples post-test (a-d) and examples of epoxied samples for Test #1 and Test #3 (e).

As shown in Figure 5, the amount of microcapsules varied for each test, indicating that the pressure and flow data were due to physical alteration of the matrix flow paths by the microcapsules. Test #2 had the lowest observable amount of microcapsules post-test, while Test #3 had the highest number of microcapsules post-test. Overall, three trends were observed:

1) The samples with water as the carrier fluid had the lowest amount of trapped microcapsules, with the xanthan gum carrier fluid tests having more than twice the microcapsule concentrations per sample.
2) For the 500 μm microcapsules, the finer gravel samples had far more microcapsules trapped in the matrix than in the coarser grained gravel.
3) For 1000 μm microcapsules, the coarser gravel had more microcapsules trapped in the matrix than in the finer gravel.

Future analysis will look to quantify the degree and nature of the microcapsule trapping in the system using 2D and 3D imaging methods.

4. DISCUSSION AND CONCLUSIONS

The transport of solids in the subsurface in porous and fractured media is a well-studied phenomenon (Bear, 2013), and understanding the dynamics of injected material flow and trapping has been of great interest to various subsurface engineering projects. For example, the transport and plugging of lost circulation zones with various granular, fibrous, and flaky materials has been a crucial focus for poromechanical studies of the subsurface. It has led to the development of various theories around solid and liquid properties of drilling fluids and particles that affect the sealing capability of the materials (Kibikas et al., 2024a). Most prominently, it has led to various prescriptive rules such as the Abram's rule (e.g., the median particle size of the bridging additive should be equal to - or slightly greater than - one-third the median pore size of the formation) wherein the injected materials size distribution can be matched to the lost circulation zones size. The treatment of thermal short-circuits presents different requirements than for lost circulation treatment. For treating thermal short-circuits, it is required that our microcapsules travel away from the wellbore successfully without becoming trapped. They need to flow through successfully to the microfracture and micropore zones that will be opened up as the rock cools, then remain in these zones when flow is halted. The microcapsules will then ideally degrade and the polymers will partially block the flow paths. However, the microcapsules cannot restrict flow too much or pressure buildup could result in fracture growth and increased flow.

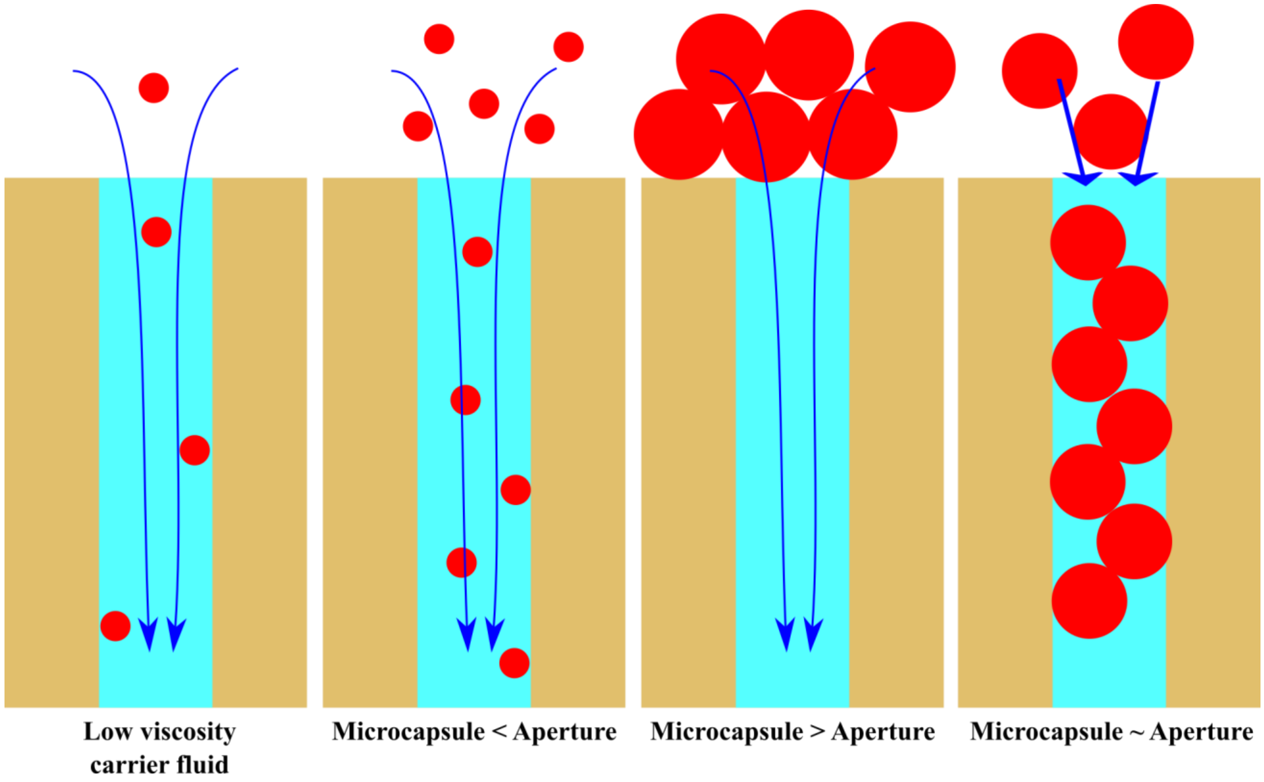

Figure 6: Schematic of different microcapsule injection scenarios.

Thus, it is necessary to achieve partial flow of microcapsules with some blockage. Based on the flow loop tests conducted and the post-test sample analysis, we describe the different scenarios in Figure 6. The different scenarios based on fluid viscosity, microcapsule size, and aperture width are as follows:

1) If the carrier fluid viscosity is too low or diluted, the microcapsules will settle out of suspension and their numbers will be insufficient to modify thermal short-circuit permeability.
2) If the microcapsules are much smaller than the flow aperture, no impingement will occur, and the polymer will not be distributed.
3) If the microcapsules are equal or greater than the flow aperture width, they will block the entrance of the flow path and restrict permeability completely as the polymer seals off fluid flow.
4) If the microcapsules are near or slightly lower than the aperture width, partial blockage of the flow path will occur because the microcapsules will form a non-restricting force chain, allowing for the polymer to coat the flow path sufficiently once rupture of the microcapsules occurs.

Of these scenarios, 2) is the optimal situation for our proposed microcapsule treatment of thermal short-circuits. Based on our experiments, it appears that if the microcapsules are too large, they will only block the upstream end of the samples. If the microcapsules are small enough, they will flow through microfractures and not obstruct flow. If the viscosity of the carrier fluid is low, most microcapsules will not flow into the system. It appears then that the average size of the non-ideal flow zones must be known before treatment is attempted. Once the range of non-ideal flow zone sizes can be determined, the microcapsule size should be tailored to match the appropriate size for achieving a partial flow and partial blockage in these flow paths.

These experiments provide new insight into how microcapsules will be transported in porous networks in the subsurface. We determined that the microcapsule size, network grain size, and fluid viscosity all affect the dynamics of microcapsule transport and trapping. However, these are not the only properties that play a role in microcapsule transport; volume of microcapsules injected, microcapsule friction, microcapsule morphology and various other properties could all play a role in how efficiently the particles will be transported through geothermal reservoirs. Future work will need to expand on the potential flow path scenarios and the effect of these different properties for microcapsule injection for treating thermal short-circuits.

REFERENCES

Bear, J.: Dynamics of fluids in porous media. Courier Corporation, (2013).

Darko, C.K., Liu, Y., Wei, M., Bai, B. and Schuman, T.: Enhancing geothermal efficiency: Experimental evaluation of a high-temperature preformed particle gel for controlling preferential fluid flow, Renewable Energy, 235, (2024), 121417.

Fu, P., Hao, Y., Walsh, S.D. and Carrigan, C.R.: Thermal drawdown-induced flow channeling in fractured geothermal reservoirs. Rock Mechanics and Rock Engineering, 49, (2016), 1001-1024.

Kibikas, W., Chang, C., Bauer, S.J., Nakagawa, S., Dobson, P., Kneafsey, T. and Samuel, A., 2024. Time-dependent thermal degradation of lost circulation materials in geothermal systems. Geothermics, 121, p.103038.

Kibikas, W., Nakagawa, S., Ingraham, M., Bauer, S., Chang, C., Dobson, P., Kneafsey, T. and Samuel, A.: Evaluation of Lost Circulation Material Sealing for Geothermal Drilling, Energies, 17(11), (2024), 2703.

Krieger, M., Kurek, K.A., and Brommer, M.: Global geothermal industry data collection: A systematic review,. Geothermics, 104, (2022), 102457.

Lu, S.M.: A global review of enhanced geothermal system (EGS). Renewable and Sustainable Energy Reviews, 81, (2018), 2902-2921.

Nakagawa, S., Kibikas, W., Chang, C., Kneafsey, T., Dobson, P., Otto, A.S.M., Bruce, S., Kaargeson-Loe, N. and Bauer, S.J.: Stability and Breakdown of Acid-Induced Hydrated Silicate Gels and Metal Silicates under Geothermal Conditions: A Preliminary Laboratory Study, 48th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2023).

Parker, R.: The rosemanowes HDR project 1983–1991, Geothermics, 28(4-5), (1999), 603-615.

Reid, R.C., Prausnitz, J.M. and Poling, B.E.: The properties of gases and liquids, (1987).

Rose, P., Fayer, S., Petty, S. and Bour, D.: The in situ formation of calcium carbonate as a diversion agent for use in engineered geothermal systems, In Proceeding of the 35th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2010).

Tetteh, P.A., Seaburn, B., Goering, D. and Stormont, J.C.: Microcapsule Transport in Transparent Rough Fractures for EGS Fracture Modification, (2023).