

HEAT-ACTIVATED EPOXY FOAM FOR PERMEABILITY ALTERATION IN FRACTURED GEOTHERMAL FIELDS: *PROOF OF CONCEPT*

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ABSTRACT

This Supplementary Material provides additional details supporting the main paper. **Section A** (Heat-activated epoxy resin foam) presents the formulation and characterization of the resin system, including foaming behavior, curing kinetics, mechanical strength, and resistance to thermal degradation. **Section B** (Fracture model permeability measurements) describes the experimental procedures used to determine the permeability of the fracture models prior to resin injection. This includes details of the closed-loop flow system, measurement of pressure drop and flow rate, and calculation of permeability over a range of Reynolds numbers, along with comparisons to theoretical predictions.



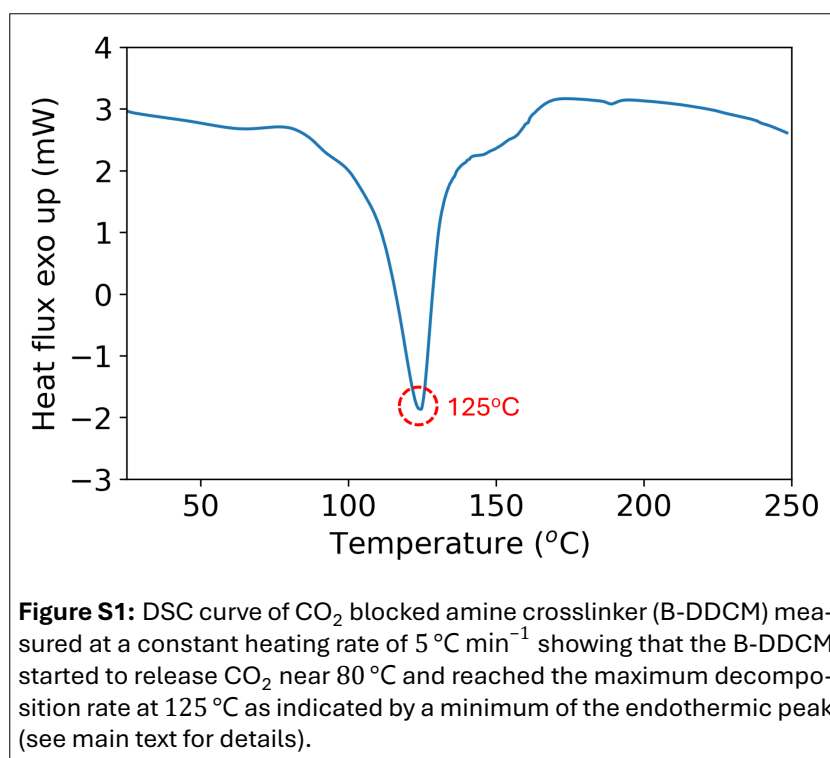
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A. HEAT ACTIVATED EPOXY RESIN FOAM

In this appendix we summarize details of the heat-activated resin foaming, curing rate, mechanical strength and ability to withstand thermal degradation. First, we evaluated the critical temperature for peak foaming (release of CO₂) when the resin travels from ambient temperatures to elevated temperatures in a geothermal field. The thermal stability of the CO₂-blocked amine crosslinker B-DDCM was characterized using differential scanning calorimetry (TA instruments DSC Q100) as depicted in **Figure S1**. The sample was heated at a heating rate of 5 °C min⁻¹ from 25 °C to 250 °C. The results showed that CO₂ gas release started at around 80 °C and as temperature increased, resin activation reached the maximum at 125 °C as indicated by the minimum of the endothermic peak (**Fig. S1**). We thus established the critical temperature for activation of the heat-sensitive epoxy to be approximately 125 °C.

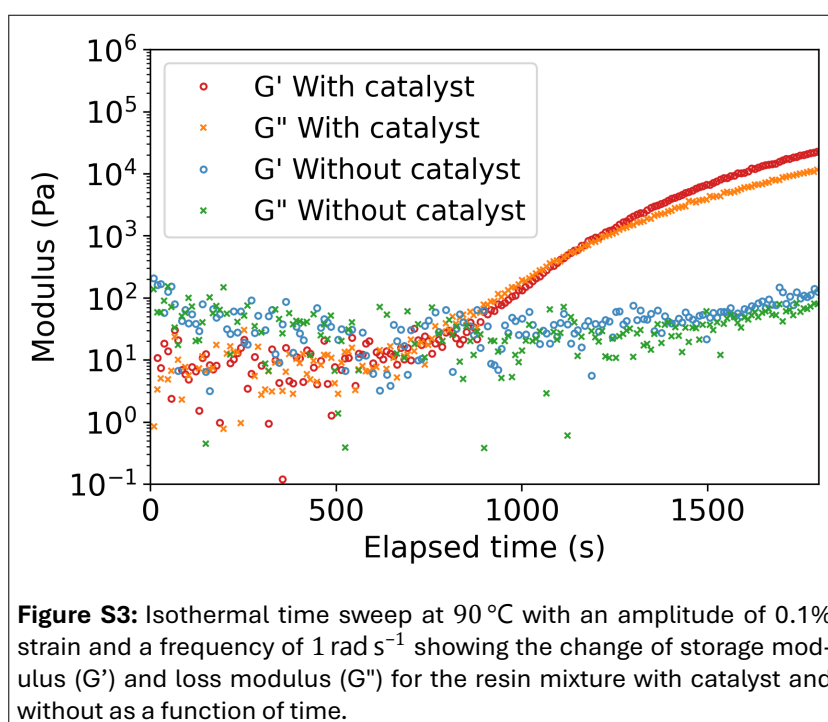
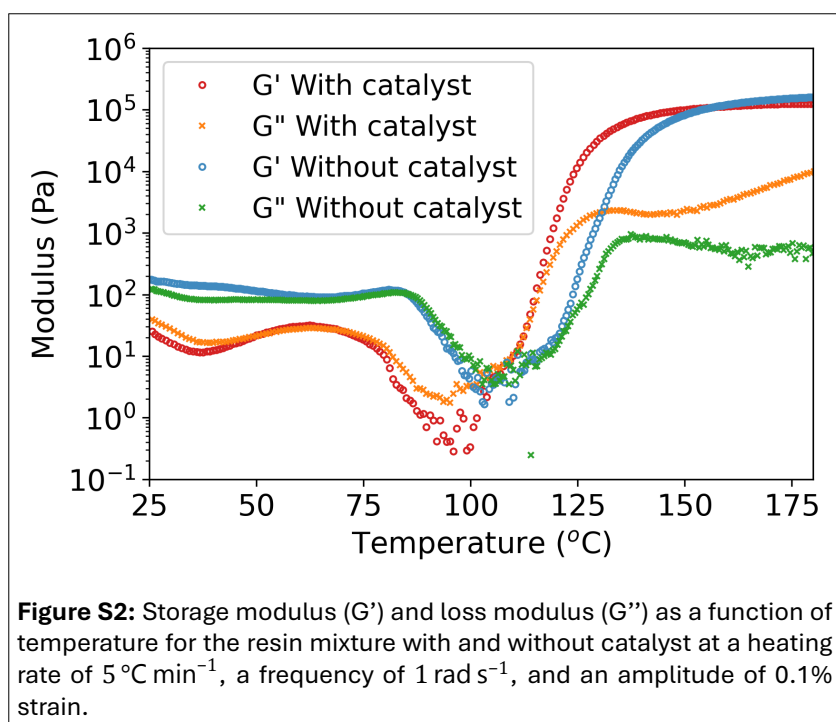
In several experiments, we observed that at 125 °C without using a catalyst, the curing rate was slow relative to the rate of gas release causing loss of CO₂ bubbles from the resin and resulting in collapsing of the foamed resin and lower volume expansion. This phenomenon is attributed to a rapid foaming rate

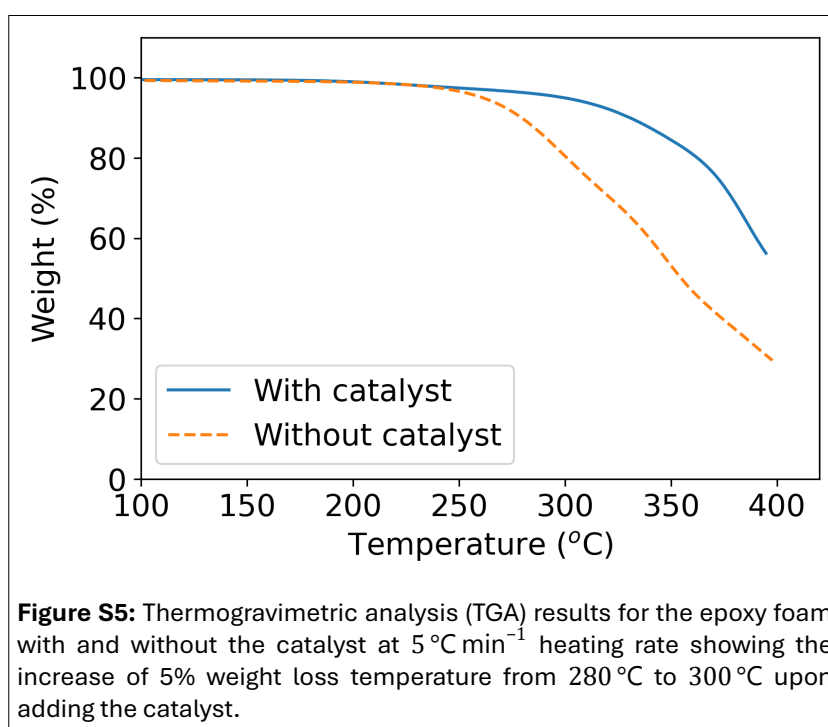
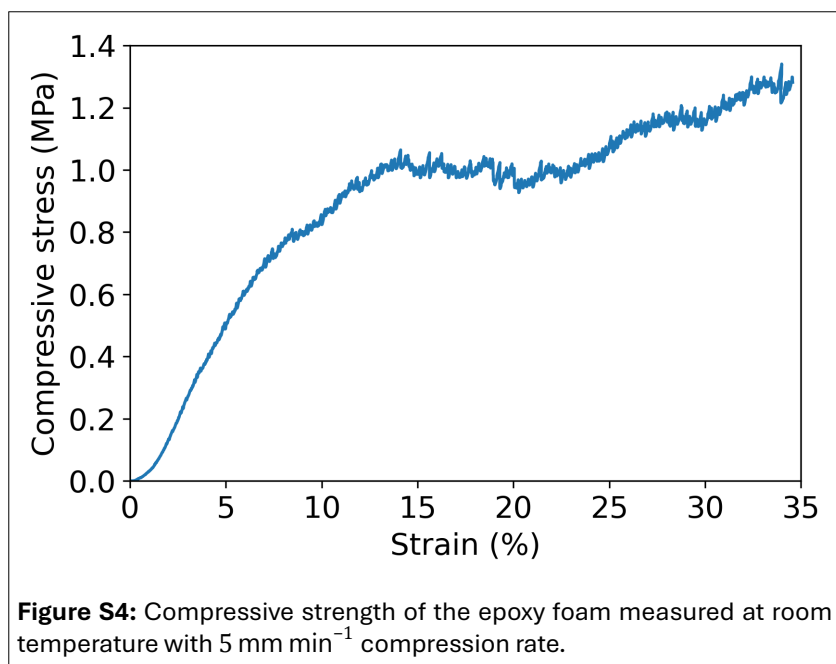


without sufficient increase in resin stiffness (or curing). To accelerate the rate of curing, we added 2,4,6-tris(dimethylaminomethyl)phenol as a catalyst (1). The catalyst not only improved CO₂ bubble retention within the foam, but also improved the overall thermal stability of the stiff foam. The effects of the catalyst on curing kinetics were analyzed using a rheometer (TA Instruments Discovery HR-2). The resin mixture was loaded onto the 25 mm stainless steel parallel plates and tested with an oscillation temperature ramp for which the dynamic moduli, including the storage and loss moduli (G' is the elastic component and G'' the viscous component), were measured as a function of resin temperature. The results are shown in **Figure S2**. For an epoxy resin containing 1 wt.% of catalyst, both G' and G'' show a drop around 80 °C, followed by large fluctuations while moduli drop to the minimum (these reflect resin foaming before curing). As temperature continued to increase at a rate of 5 °C min⁻¹, G' and G'' started to increase, indicating curing. A plateau was reached at 160 °C where curing was completed and a rigid foam was formed. The catalyst induced an earlier release of CO₂ (the stiffness levels were similar as seen in **Fig. S2**). To show the enhanced rate of curing reaction in the presence of the catalyst, we conducted an isothermal time sweep, where the temperature was kept at 90 °C and G' and G'' were measured as a function of elapsed time (**Fig. S3**). Without the catalyst, foaming was observed from the fluctuation of the dynamic moduli. The release of CO₂ nearly completed after 1800 s without any indication of curing. With the catalyst, curing took place at 600 s shown by the increase of G' and G'' .

We therefore have used the catalyst throughout the experiments reported here. The epoxy foam formed by heating in an oven at 125 °C for one hour was subjective to compression test using Shimadzu AGS-X testing frame at a rate of 5 mm min⁻¹. The compressive strength at the plateau region was 1.0 MPa at 14% strain as shown in **Figure S4**. The plateau region represents the stress level at which the foam mechanically collapses under compression.

We also evaluated the thermal stability of the epoxy foam using thermogravimetric analysis (TA Instruments TGA Q50) with a temperature ramp from room temperature to 400 °C at a heating rate of 5 °C min⁻¹. As shown in **Figure S5**, the foam remained thermally stable up to 280 °C, with no detectable mass loss under (N₂) atmosphere. The inclusion of catalyst increased the degradation onset temperature, shifting the 5% weight loss point from 280 °C to 300 °C.





B. FRACTURE MODEL PERMEABILITY MEASUREMENTS

Prior to the experiment, the permeability of each model was determined by measuring the pressure drop across the model at various prescribed flow rates, corresponding to Reynolds numbers ranging from 0.1 to 0.5. The setup uses for permeability measurements, shown in **Figure 4** (main text), is same to the experimental configuration but conducted at room temperature (approximately 25 °C). It consists of a closed-loop system driven by a peristaltic pump circulating silicone oil (viscosity $\eta = 50 \text{ mm}^2 \text{ s}^{-1}$ at 25 °C). By measuring both the pressure drop and flow rate of silicone oil, the permeability k of the model can be calculated using:

$$k = v \frac{\eta \Delta x}{\Delta p} \quad (\text{S1})$$

where v is the average flow velocity, $\Delta x \approx 280 \text{ mm}$ is the distance between model inlet and outlet, Δp is the pressure drop across the model.

For comparison, the theoretical permeability k_T between two infinite parallel plates is given by:

$$k_T = \frac{b^2}{12} \quad (\text{S2})$$

where b is the aperture between the plates. For the model containing square obstacles, (2) provides an expression that relates the effective 2D permeability k_2 (only the viscous resistance of the fluid around the cylinder is considered) to the 3D permeability with obstacles k_{T0} :

$$k_{T0} = k_2 \left[1 - \frac{2\sqrt{k_2}}{\phi b} \tanh \left(\frac{\phi b}{2\sqrt{k_2}} \right) \right] \quad (\text{S3})$$

Where ϕ is the porosity of the model (the fraction of space in the model plane that is not occupied by obstacles). The hyperbolic tangent term accounts for additional shear resistance of the fluid in z-direction (through the thickness direction). The effective 2-D permeability k_2 can be estimated using a lubrication-type approximation for flow between adjacent cylinders, as derived by (3):

$$k_2 = \frac{a^2}{3.34(1-\phi)} \left[1 - 1.10\sqrt{1-\phi} \right]^{\frac{5}{2}} \quad (\text{S4})$$

where a is the radius of the cylinders. In our model, since the obstacles are rounded square, we use an equivalent radius to approximate their hydraulic effect.

Figure S6 illustrates typical values of fracture model permeability for 0.75 mm and 1.50 mm apertures (predicted and measured). The pressure drop ranged between 0.6 kPa to 21.8 kPa for flow rates in the range from 20 g min^{-1} to 90 g min^{-1} for the different fracture models. Measured permeability values remain nearly constant for all flow rates and fracture models. We note that measured permeability values

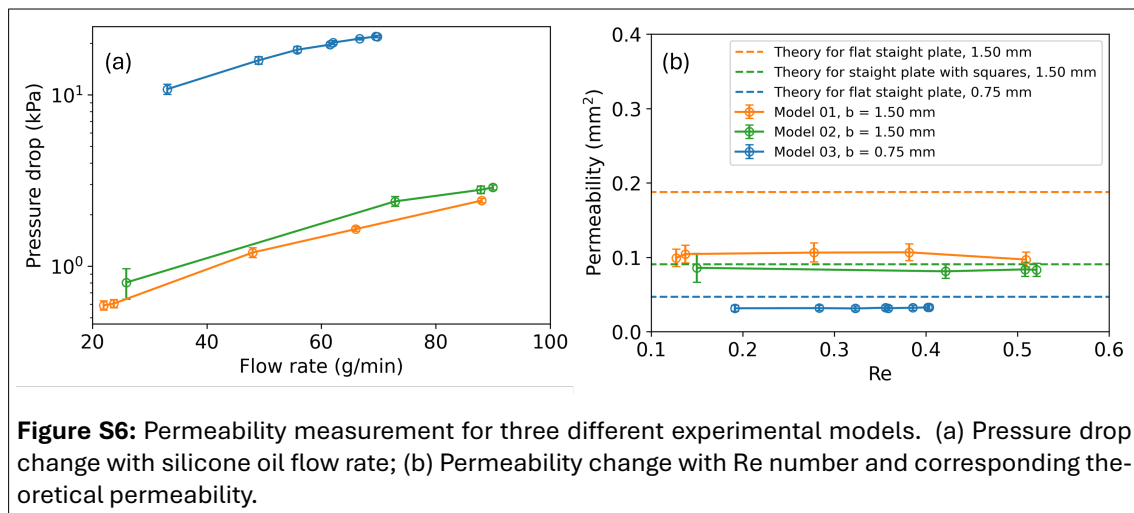


Figure S6: Permeability measurement for three different experimental models. (a) Pressure drop change with silicone oil flow rate; (b) Permeability change with Re number and corresponding theoretical permeability.

for all models were lower than their theoretical counterpart probably due to resistances and flow behavior at the model entrances and aperture manufacturing errors. For the permeability of Model 03 (u-shape configuration) simulation results indicate that, for low Reynolds numbers ($Re < 0.5$), the permeability is comparable to a flat straight fracture with a similar aperture (i.e., the u-shaped flow field had little effect on the fracture permeability).

REFERENCES

1. Mohammadnabi Hesabi, Ali Salimi, and Mohammad Hosain Beheshty. Effect of tertiary amine accelerators with different substituents on curing kinetics and reactivity of epoxy/dicyandiamide system. *Polymer Testing*, 59:344–354, 2017. doi:[10.1016/j.polymertesting.2017.02.023](https://doi.org/10.1016/j.polymertesting.2017.02.023).
2. Sunil Kumar, Robert W Zimmerman, and Gudmundur S Bodvarsson. Permeability of a fracture with cylindrical asperities. *Fluid Dynamics Research*, 7(3-4):131–137, 1991. doi:[10.1016/0169-5983\(91\)90053-L](https://doi.org/10.1016/0169-5983(91)90053-L).
3. Ashok S Sangani and C Yao. Transport processes in random arrays of cylinders. II. viscous flow. *The Physics of fluids*, 31(9):2435–2444, 1988. doi:[10.1063/1.866596](https://doi.org/10.1063/1.866596).