Update on Artificial Fracture Experiments at B+Tech

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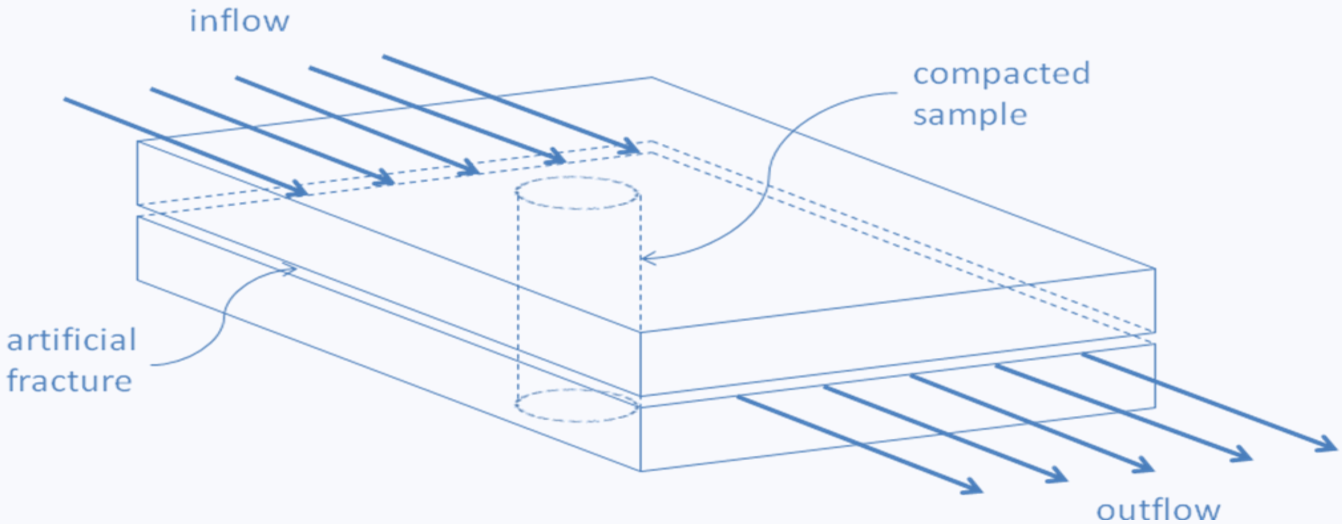
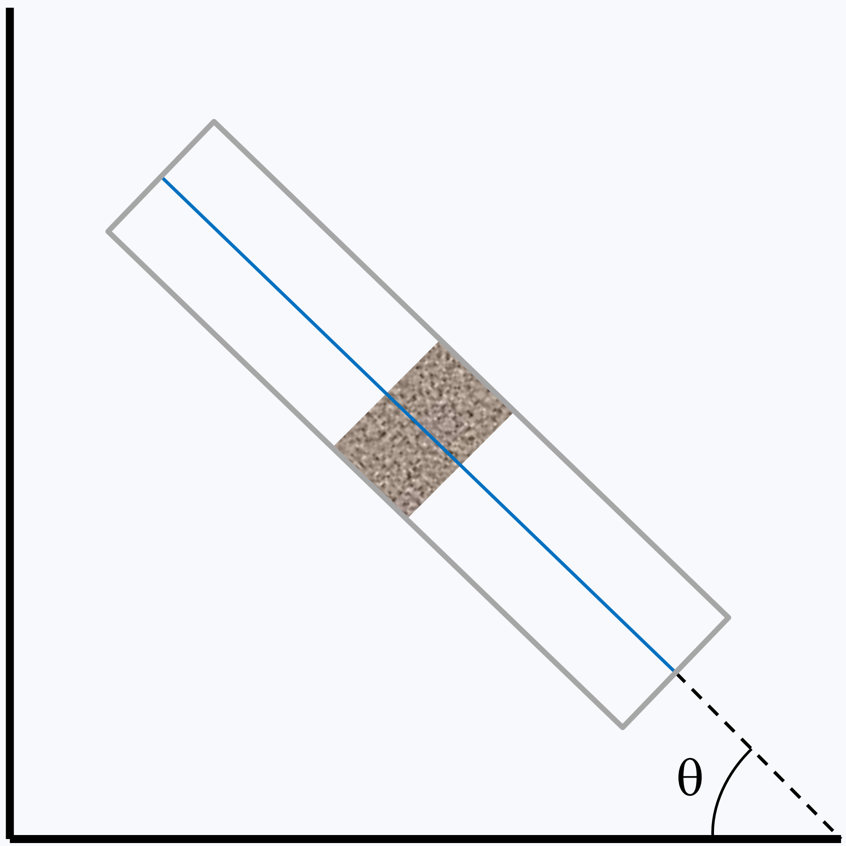
Artificial Fracture Experiments



- Directly probe buffer erosion in a ”fracture environment” under flow-through conditions relative to:
    - buffer composition
    - groundwater composition
    - groundwater velocity
    - fracture geometry
    - surface roughness

EFFECT OF FRACTURE SLOPE

Fracture Position

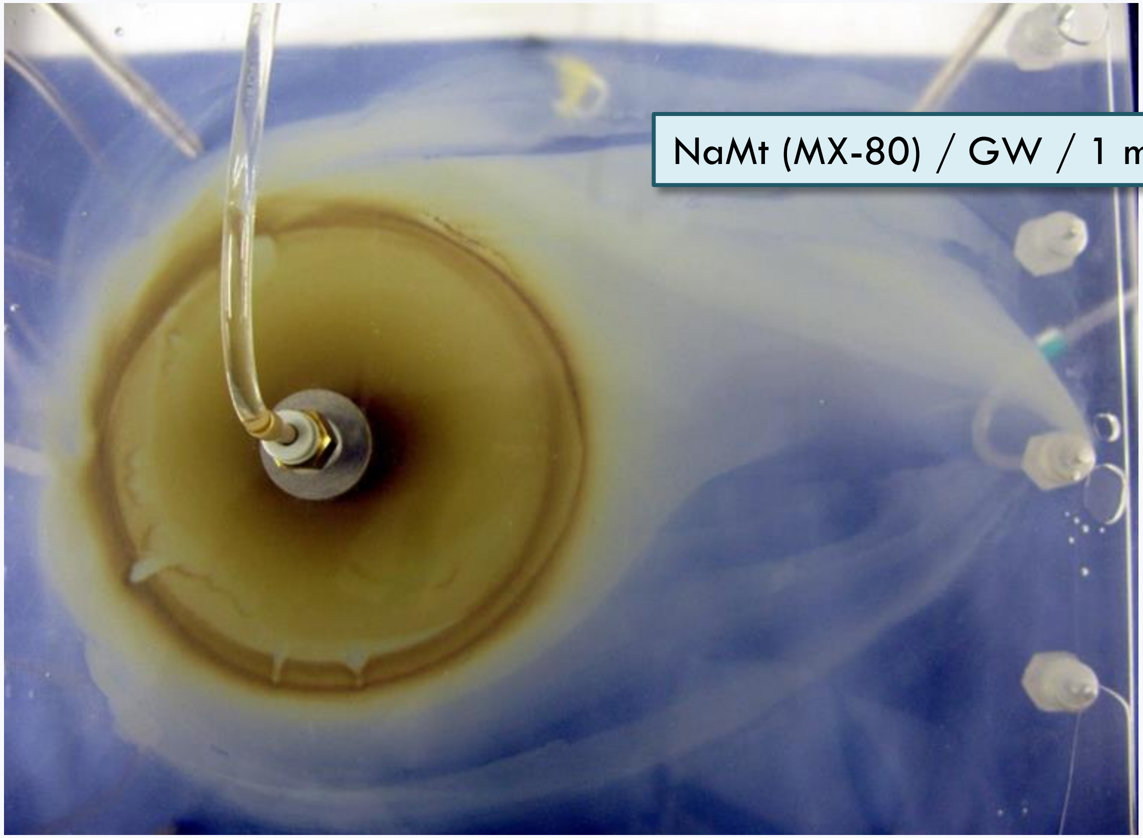


- a series of artificial fracture tests were conducted in fractures positioned at steep slope angles ($\theta \geq 45°$).

- sodium montmorillonite or 50/50 calcium/sodium montmorillonite (all from MX-80 type bentonite) against deionized water or Grimsel groundwater simulant.

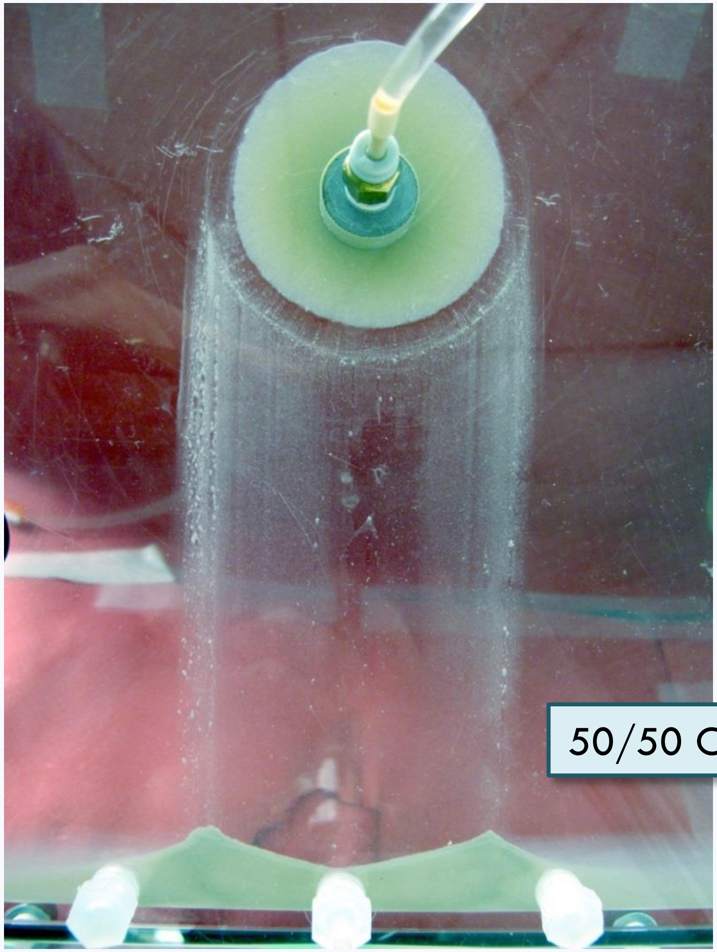
- downhill, stagnant (no) and uphill flow conditions.

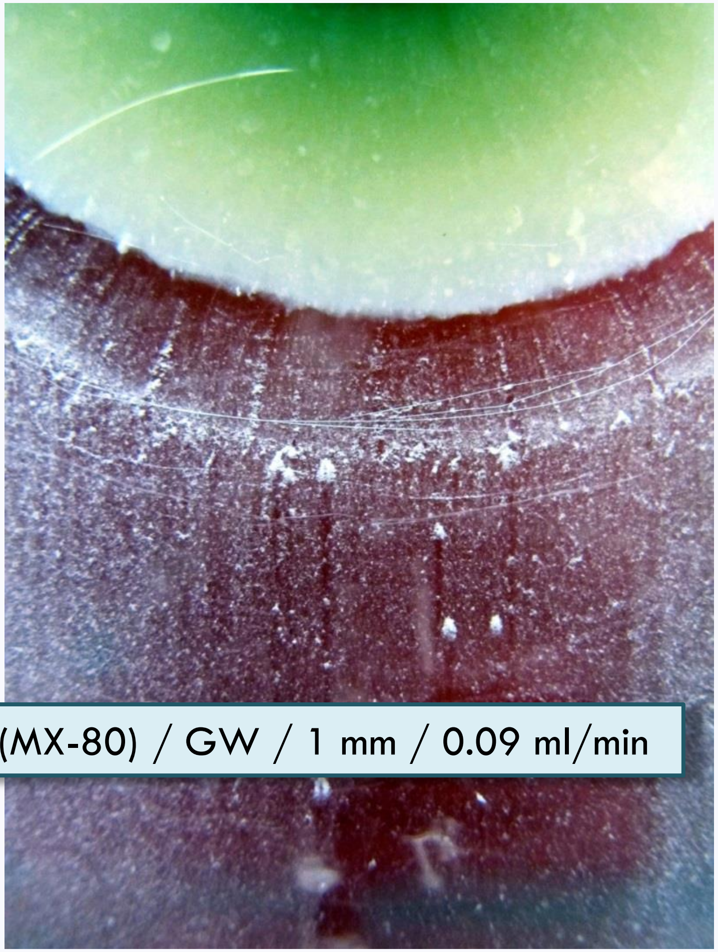
Horizontal Fracture


NaMt (MX-80) / GW / 1 mm / 0.09 ml/min

- Mass loss by dispersion at solid/liquid interface into passing flow.
- Steady state extrusion distances observed.

45° Sloped Fracture



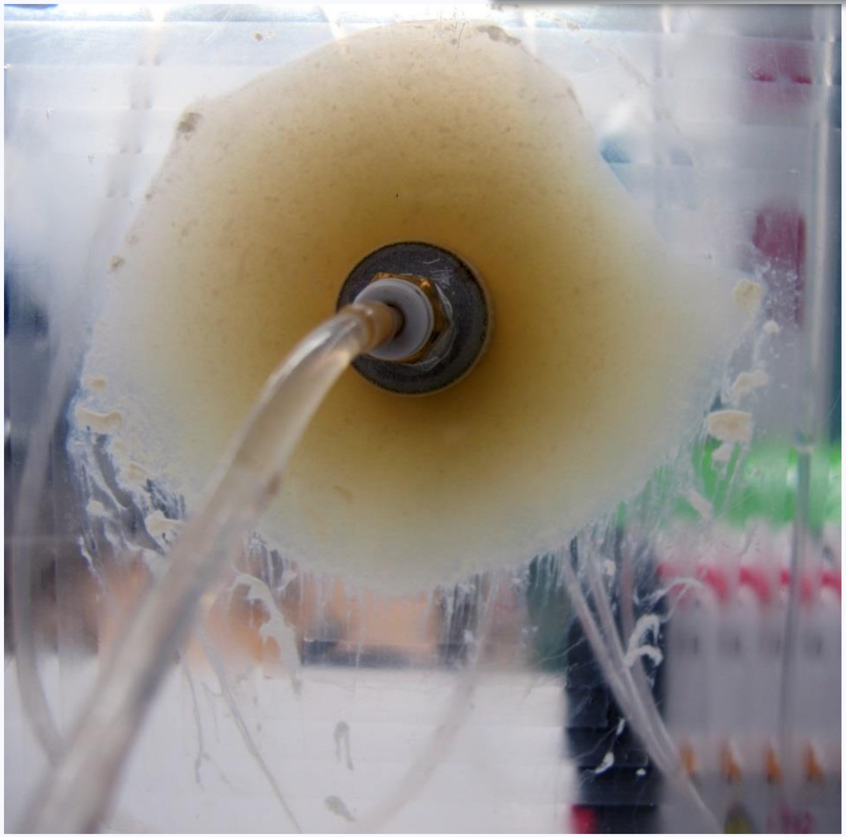


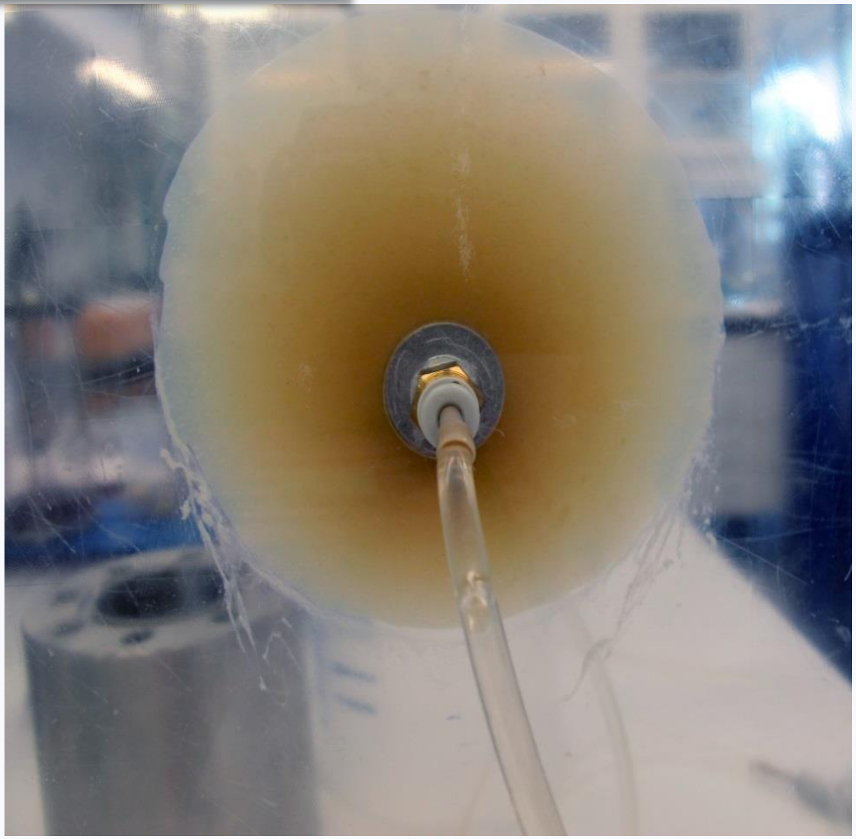
50/50 Ca/NaMt (MX-80) / GW / 1 mm / 0.09 ml/min

- Mass loss by sedimentary process at solid/liquid interface.
- Extrusion distances recede with mass loss over time.

90° Fracture

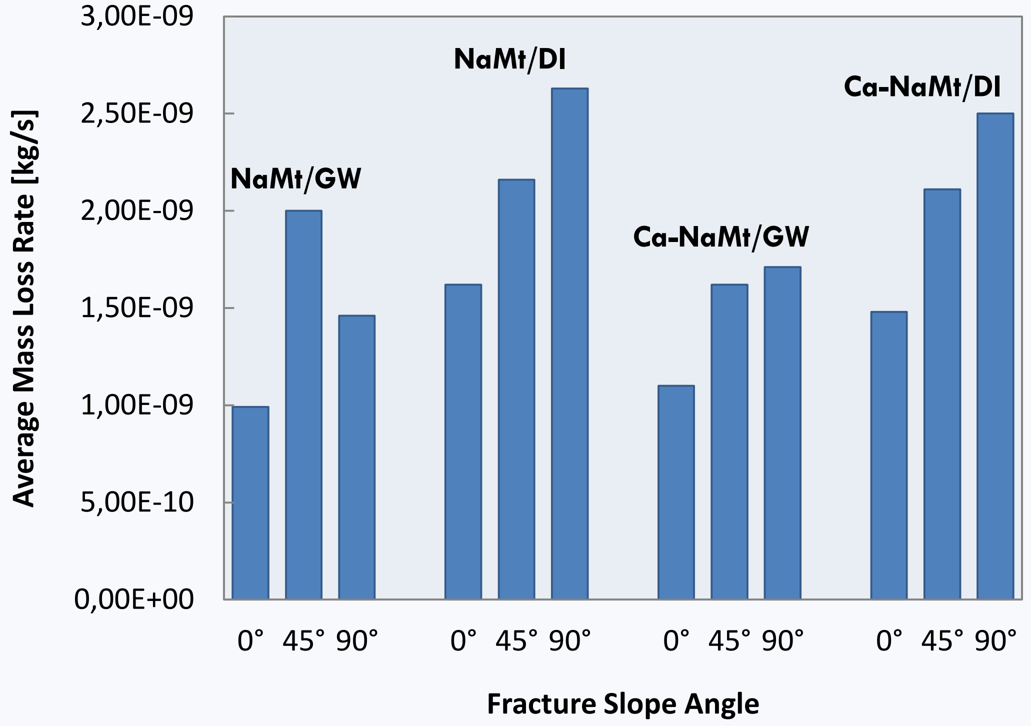
NaMt (MX-80) / 1 mm / 0.09 ml/min





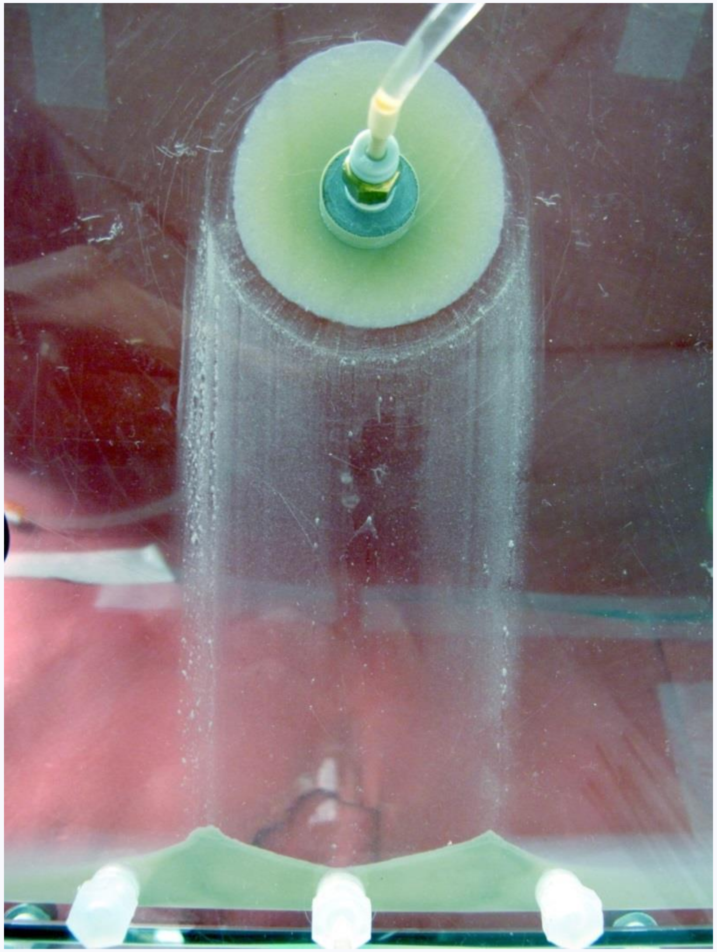
- Ribbons of gel-like material falling from solid/liquid interface.
- Extrusion distances recede with mass loss over time.

Effect of Fracture Slope

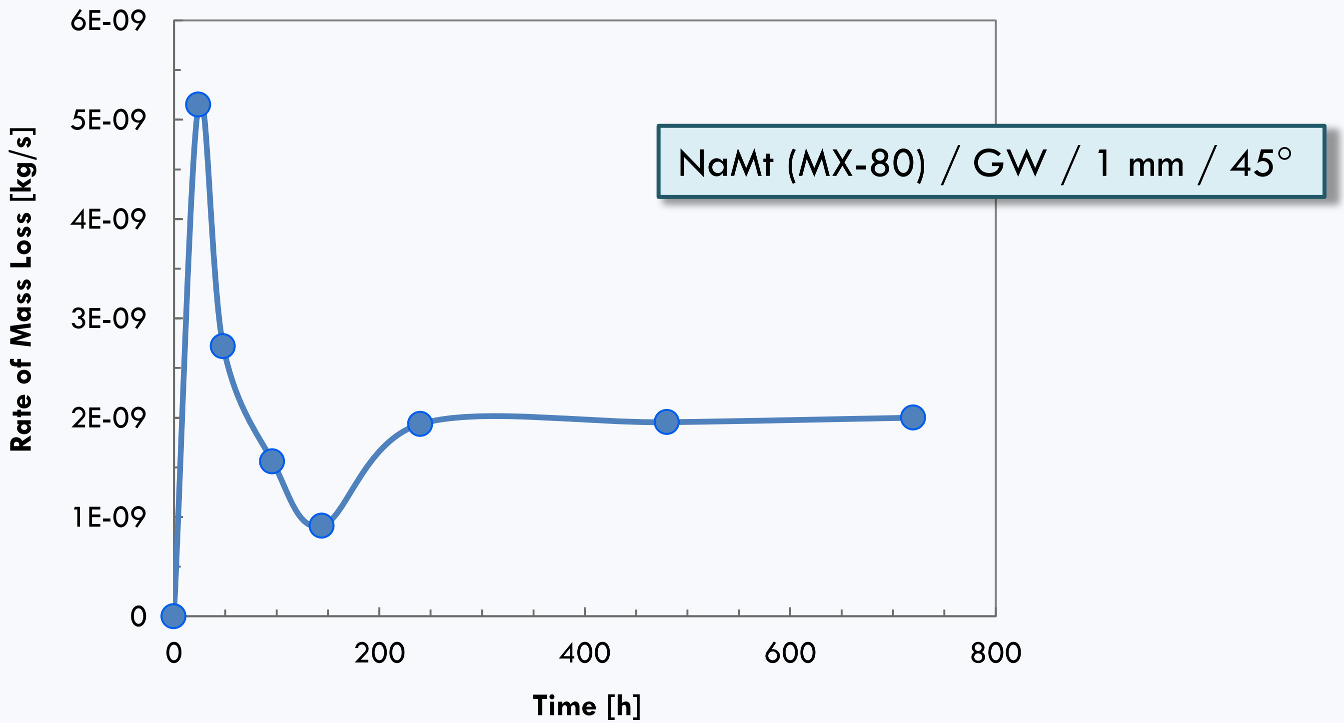


- All tests conducted in 1 mm aperture fracture using 0.09 ml/min solution flow.
- Mass loss is always higher in sloped fractures relative to horizontal.
- Larger slope angle generally leads to increased mass loss.

Mass Loss in Sloped Fractures

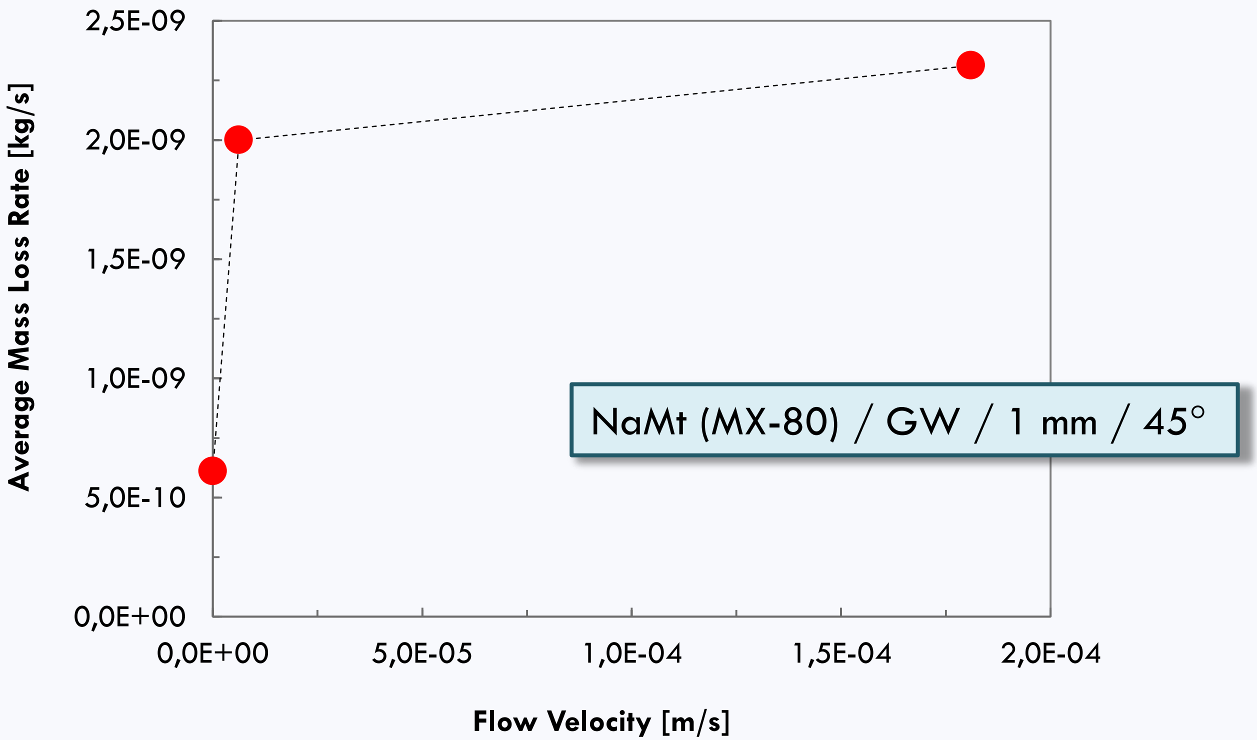


Steady-State Mass Loss in Sloped Fracture



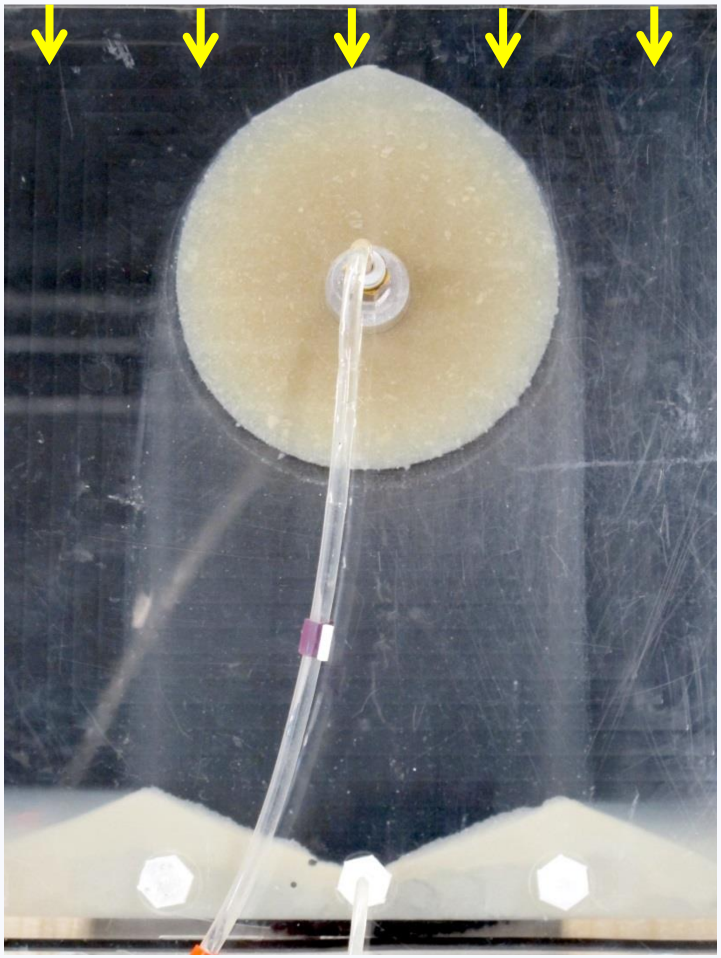
- Individual tests run over various durations at 0.09 ml/min solution flow.
- Steady-state mass loss established after 200 to at least 720 h.
- No corresponding steady-state extrusion distance.

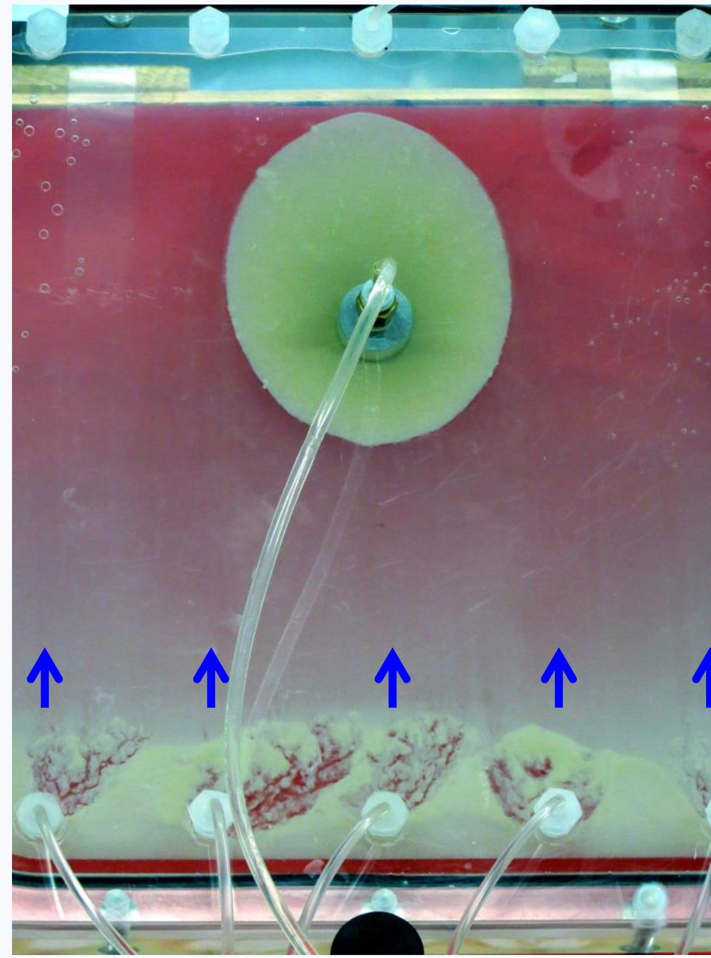
Effect of Flow Rate in Sloped Fractures



- Increasing the flow down the fracture from zero (stagnant) to 10^{-6} m/s results in a 3x increase in mass loss; further increasing the flow velocity by roughly two orders of magnitude yields only a 15% additional increase in mass loss.
- By contrast, a similar, two order of magnitude flow velocity increase in horizontal fracture systems leads to an 80% increase in mass loss.

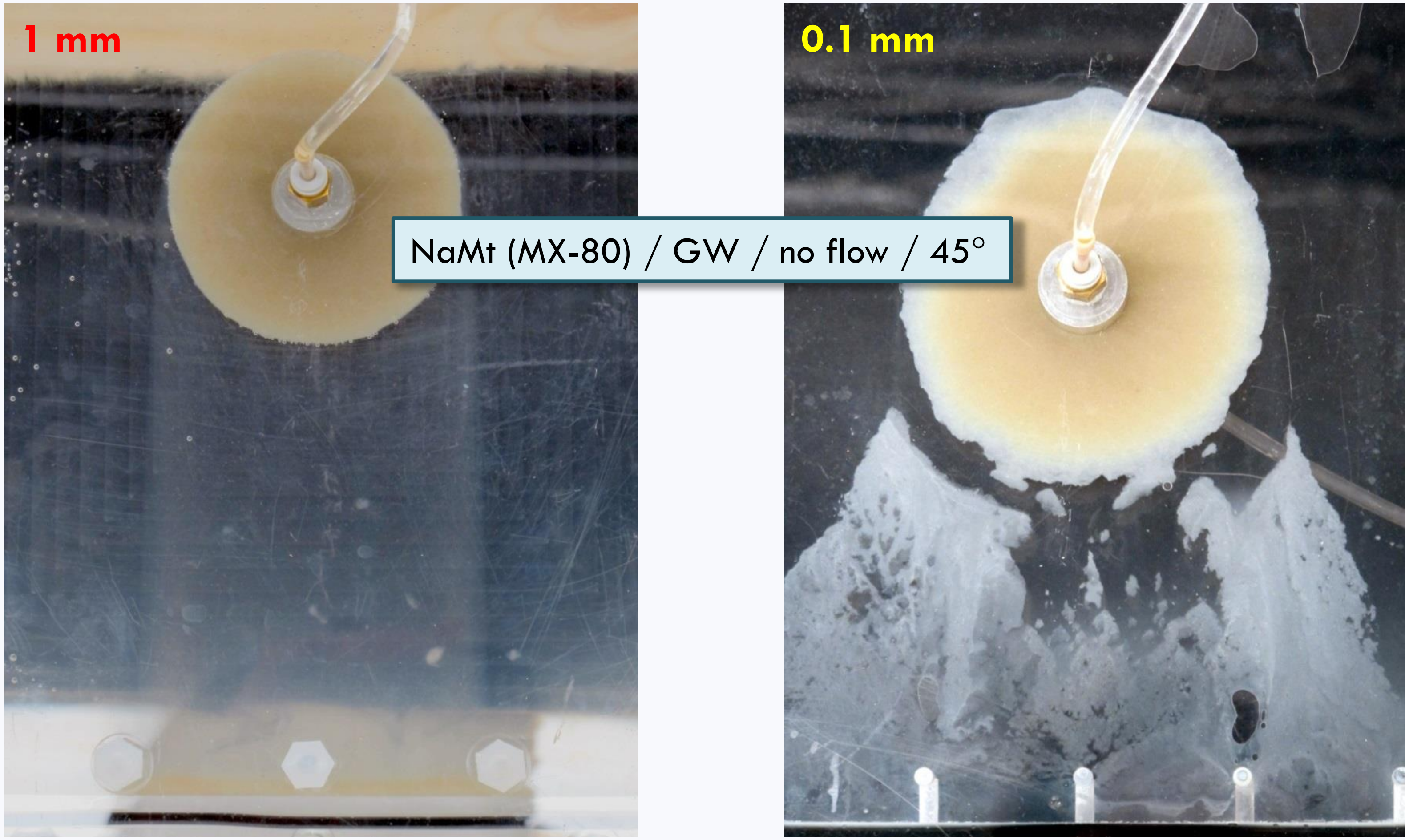
Effect of Flow Direction





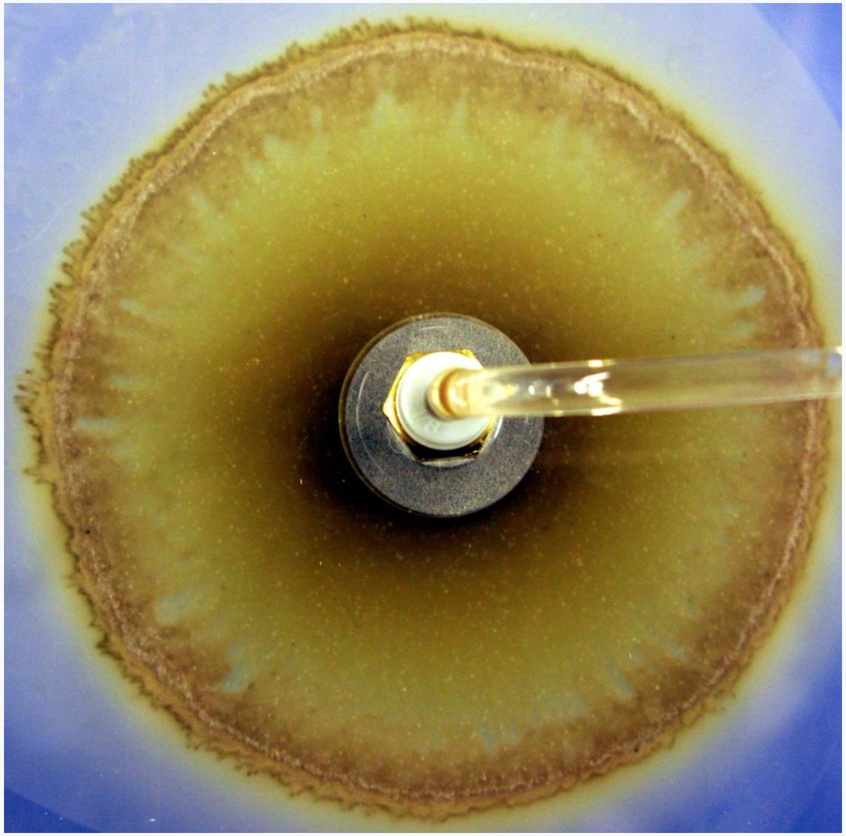
- NaMt (MX-80) / GW / 1 mm / 0.09 ml/min / 45°
- Essentially equivalent average mass loss in either flow direction.

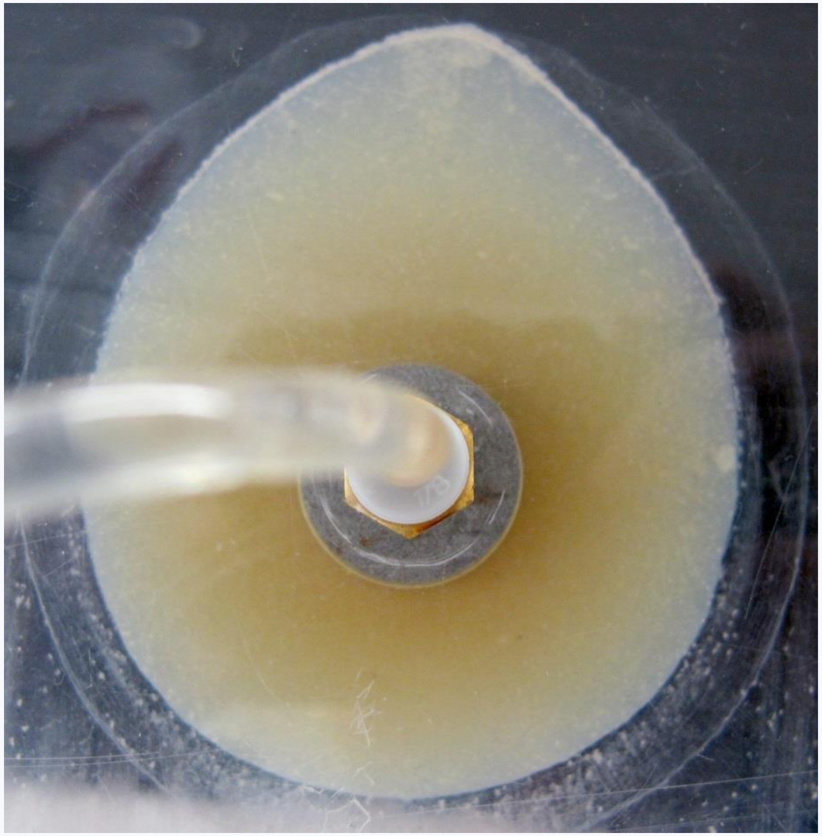
Effect of Aperture in Sloped Fractures



- Mass loss in 0.1 mm aperture fracture system determined to be more than an order of magnitude lower than in the 1 mm aperture fracture system.
- Consistent with the assumption that interfacial surface area has controlling influence on mass loss and scales linearly.

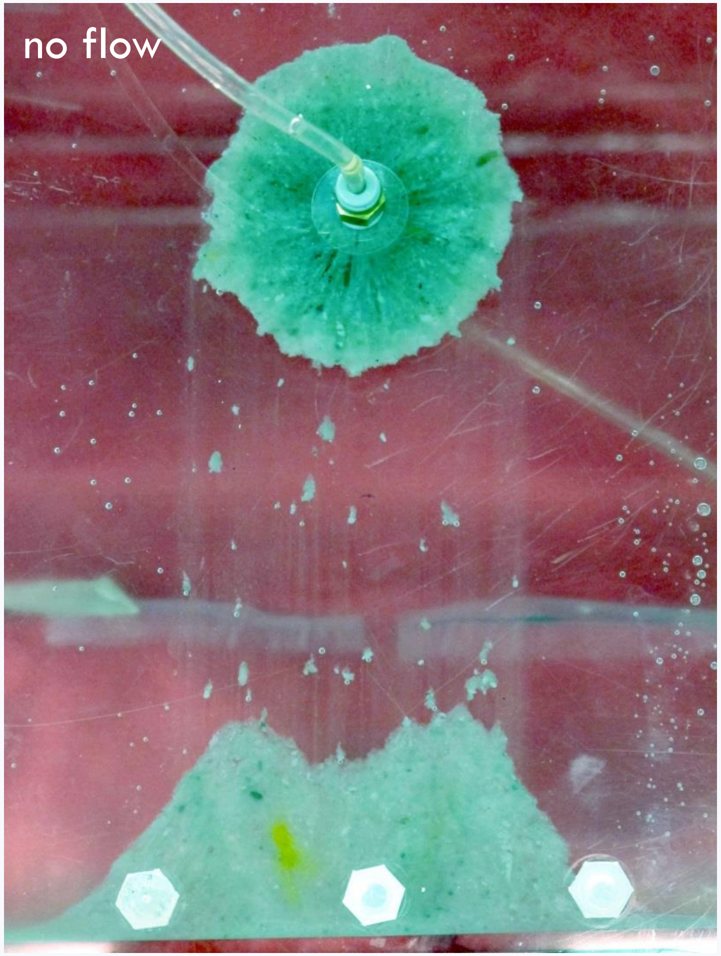
Presence of Accessory Material





- In the horizontal fracture (left), only montmorillonite is lost (disperses into passing flow).
- In the sloped fracture (right), both montmorillonite and sand are lost (by sedimentation) from the extrusion interface.

MX-80 at 45°



- Significantly more mass is lost from as-received MX-80 bentonite against dilute groundwater in sloped fractures versus horizontal.
- Increased mass loss in the presence of imposed flow.

Additional

- Stabilty to mass loss at increased salinity.
- Similar to horizontal tests, hysteresis effects observed in sloped fractures.

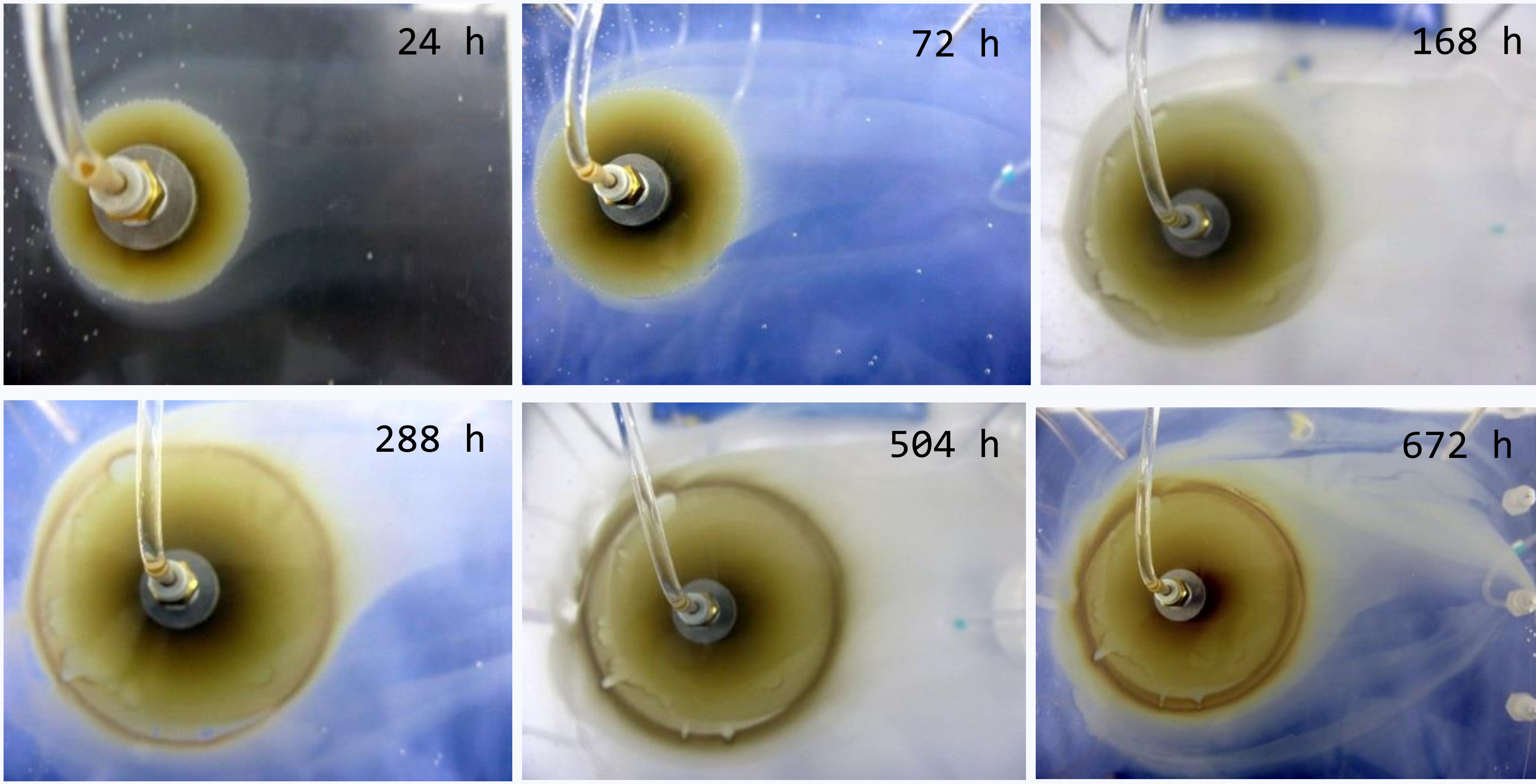
EFFECT OF MONTMORILLONITE COMPOSITION

Overview

- A set of comparable tests were performed using identically prepared sodium montmorillonites from Milos, Kutch and MX-80 bentonites.

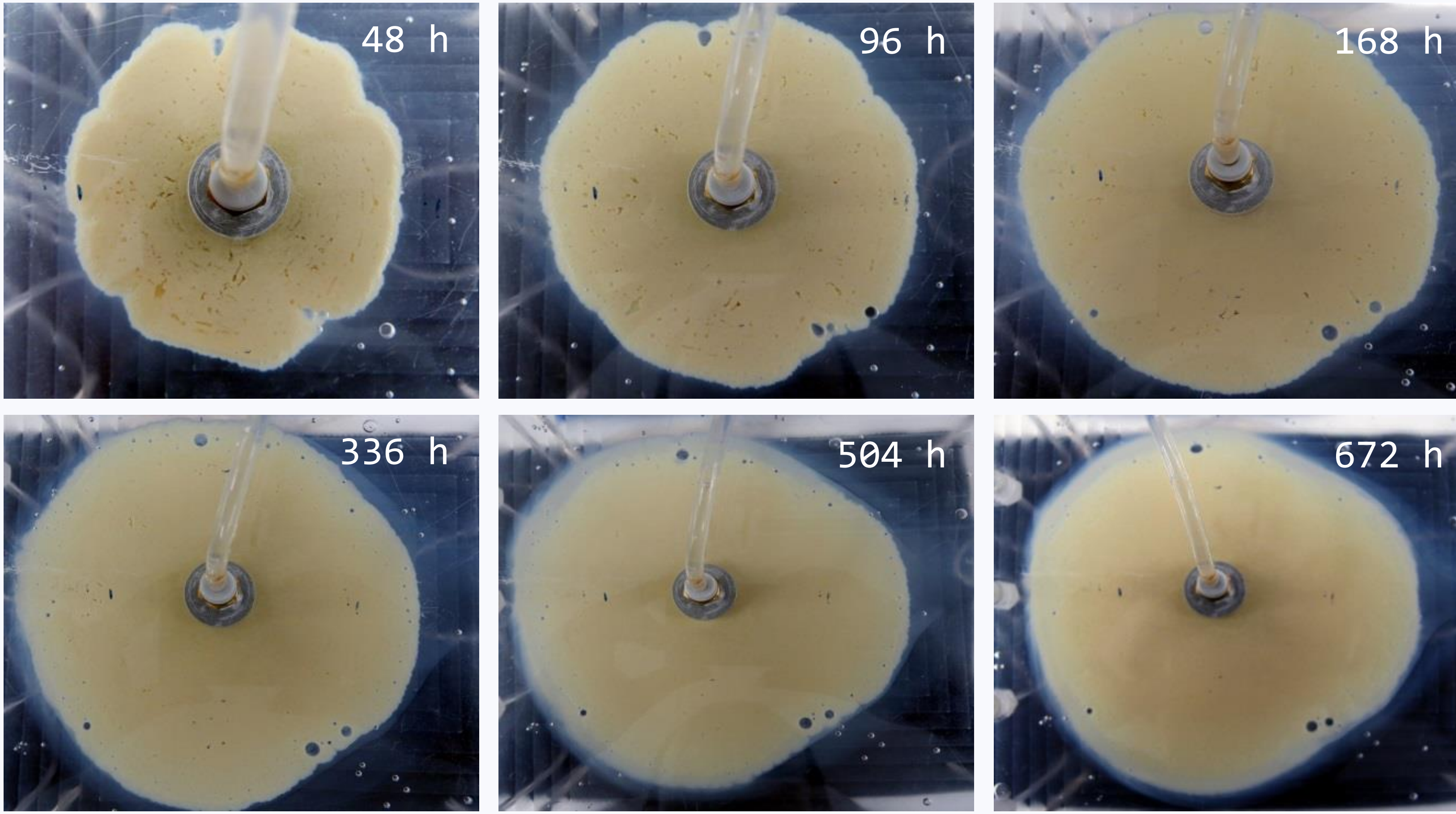
- Artificial fracture tests were conducted with these sample materials (compacted to 1.6 g/cm^3) in contact with Grimsel groundwater simulant ($[Na^+]$ and $[Ca^{2+}]$ only) at an average flow rate of 0.09 ml/min through a horizontal, 1 mm aperture fracture.

sodium montmorillonite (MX-80)



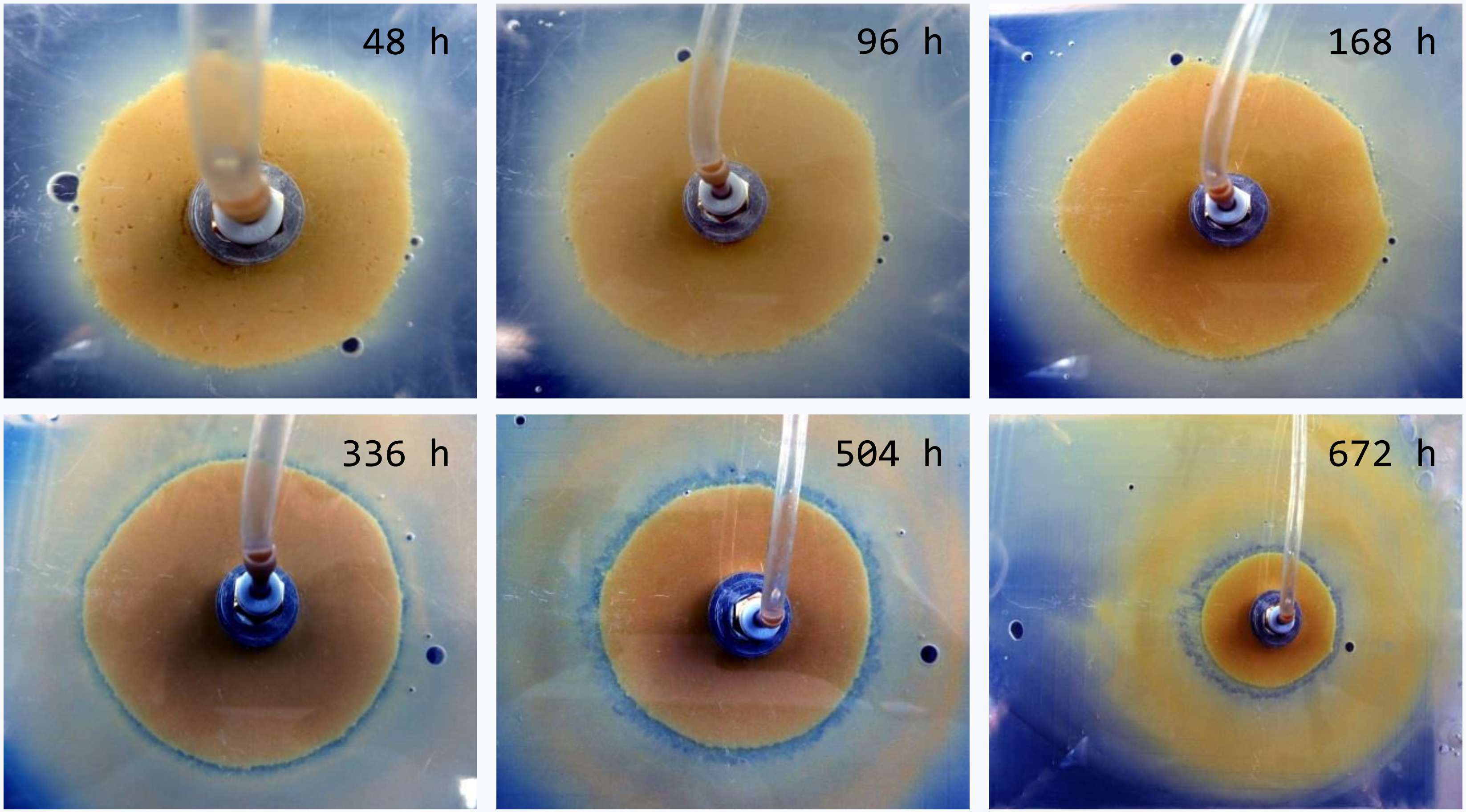
Extrudes to a steady-state distance (factor of four radial increase) after half of the test duration and shows a clear eroding flow of dispersed material over the course of the test.

sodium montmorillonite (Milos)



Continuously extrudes (factor of seven radial increase) into the fracture over the course of the test and shows only a thin eroding flow of dispersed material during the latter stages.

sodium montmorillonite (Kutch)



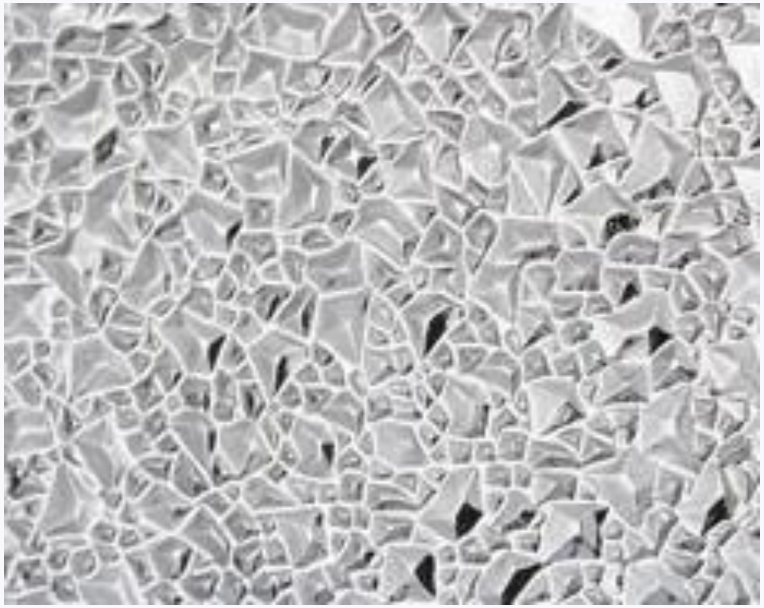
Extrudes to a maximum distance after a quarter of the test duration but the continuosly recedes as material is lost from the interface; the dispersed material forms a rather dense, possibly associated zone which is not readily transportable by the flow.

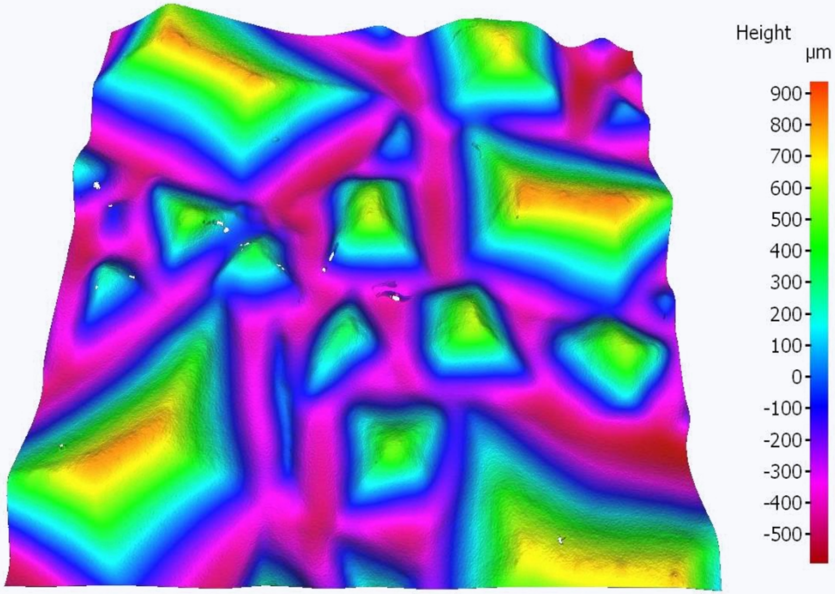
Summary

- Average mass loss is faster from the Kutch material by a factor of 2.5 over the MX-80 material and a factor of 16 over the Milos material.
- Although the sample materials are all ostensibly sodium montmorillonite, they exhibit quite different quite different extrusion/erosion behavior.
  - should stem from inherent differences in the clay minerals themselves.
- Montmorillonites from these source bentonites are reported to differ with respect to layer charge and charge location as well as content of iron and titanium (Karnland et al. 2006).
  - Specifically the Milos and Kutch montmorillonites are indicated to have higher total charge than the MX-80 montmorillonite including significantly higher tetrahedral charge fractions.

EFFECT OF FRACTURE SURFACE ROUGHNESS

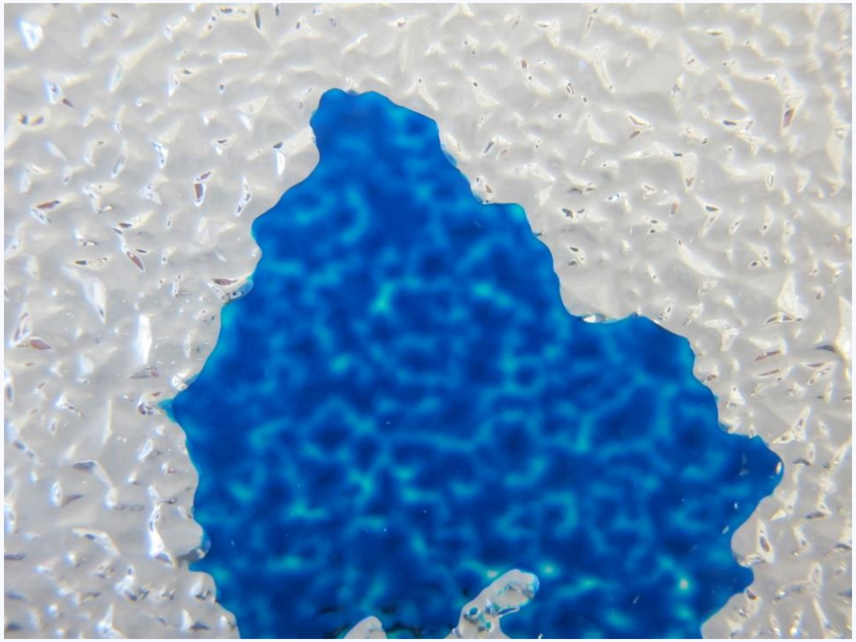
Fracture Surface Material





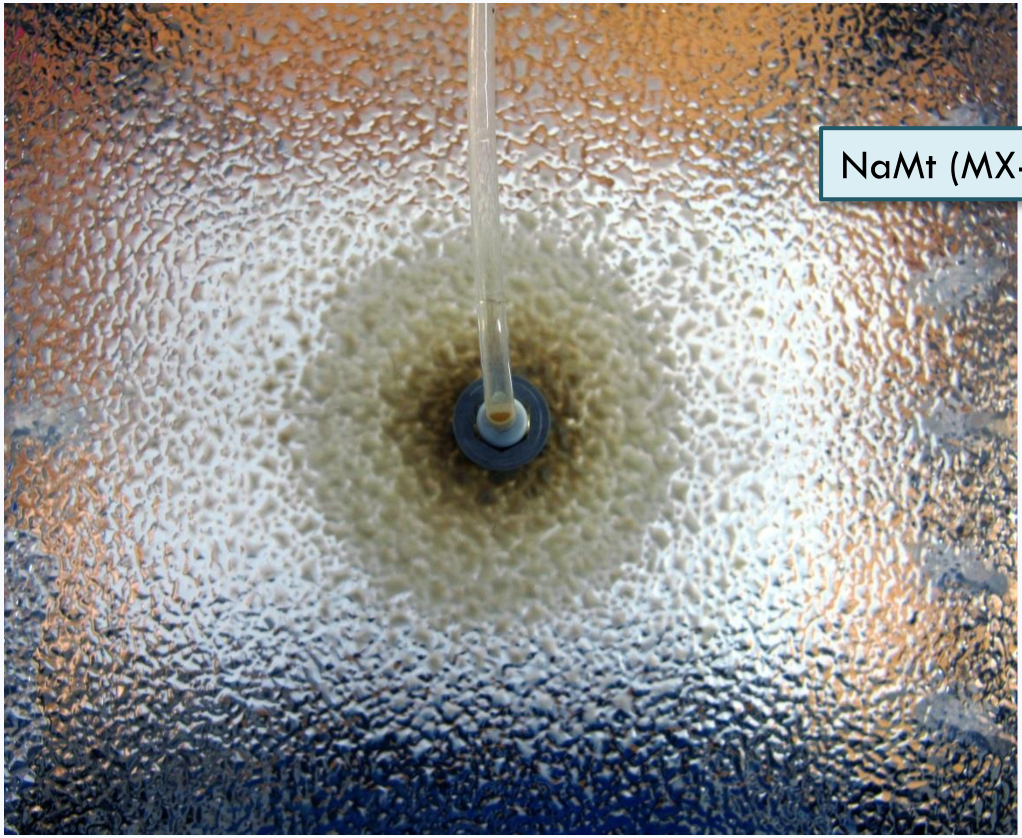
- In order to begin to examine the effect of surface roughness on the extrusion/erosion behaviour of bentonite buffer material at a transmissive fracture interface, a rough-walled artificial fracture cell was built which incorporates structured acrylic material covering the fracture surfaces.
- Topographical features from the micron to millimeter scale.

Rough-walled, Artificial Fracture System



- Plates covered with structured material are placed over one another to form a heterogeneous (tortuous) fracture space.
- Average aperture of the rough-walled, artificial fracture system is 0.95 mm (void volume measurement).

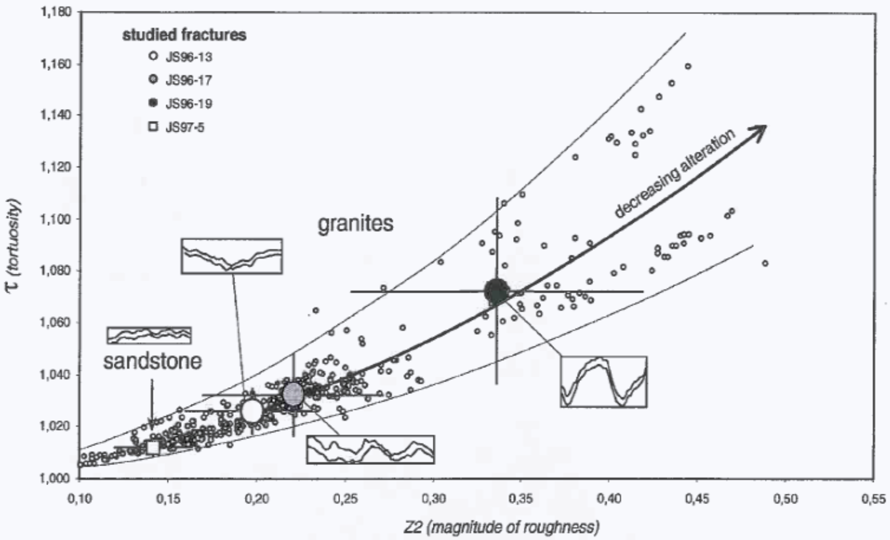
Rough-walled, Artificial Fracture Test

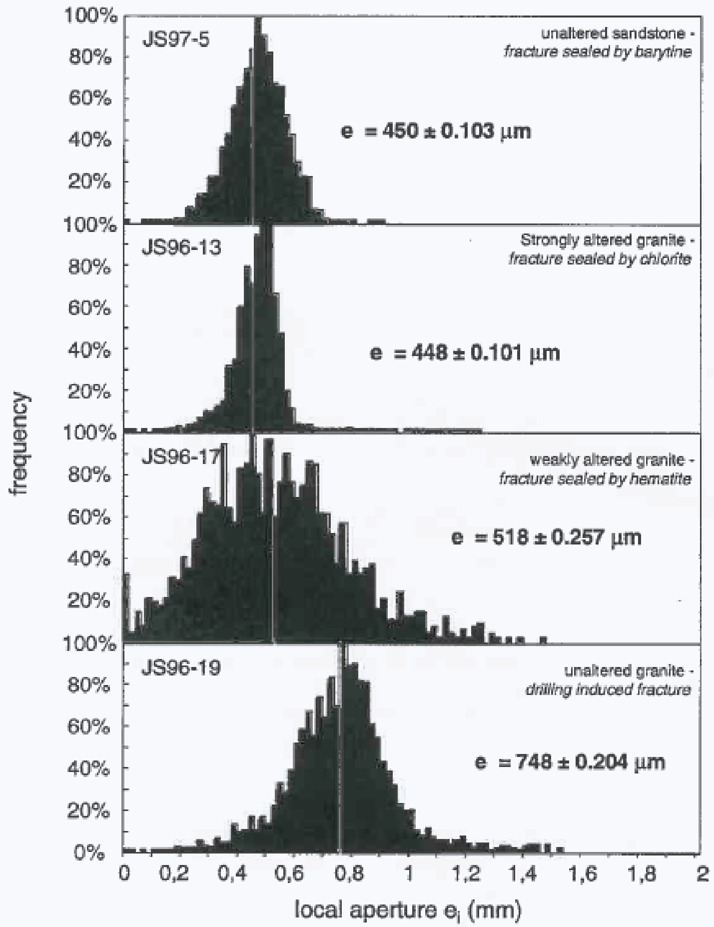


NaMt (MX-80) / DI

- Average mass loss rate lower by more than a factor of 2 compared to tests run in smooth-walled fractures at 1 mm aperture with the same material, solution and inflow rate.
- Lower rate of extrusion; steady-state not observed.

Natural Fracture Surfaces





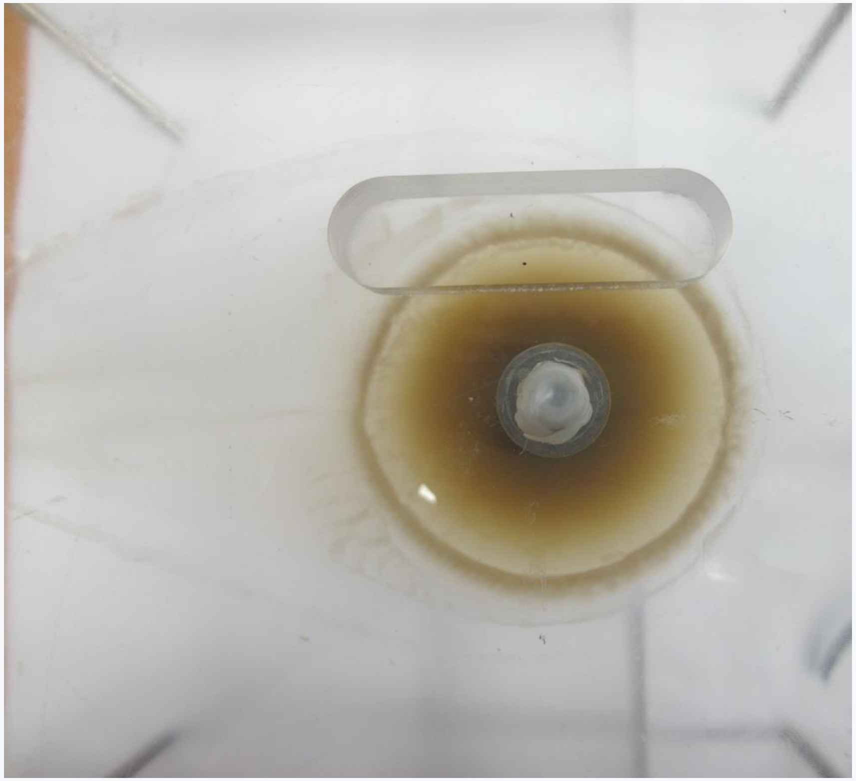
Natural fractures are characterized by rough surfaces. Large distributions of apertures and the presence of contact points produce heterogeneous flows.

As the previous data indicate, buffer mass loss in rough-walled fracture systems may significantly differ from parallel and smooth plane experiments and models.

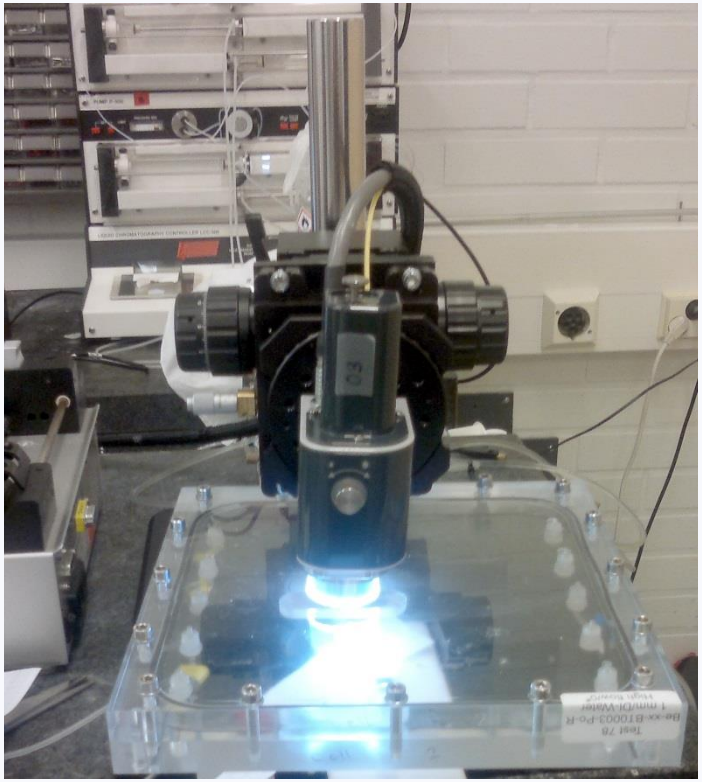
Figures 7 and 8 from Sausse, J. 2002, Tectonophysics, 348, 169-185

OCT IMAGING OF ARTIFICIAL FRACTURE TEST

OCT Imaging of Fracture Test

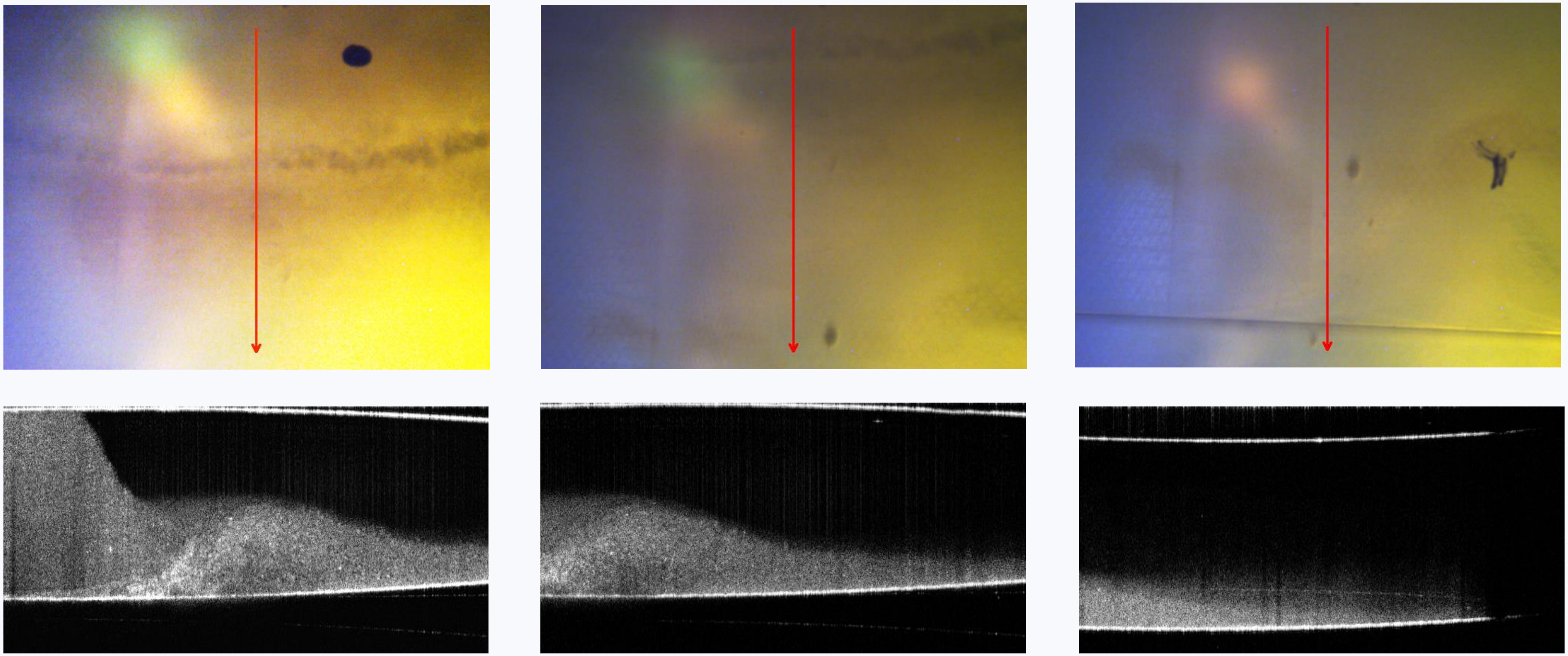


Imaged test was sodium montmorillonite against DI water in a 1 mm fracture after one week of flow at 1 ml/min.



Optical Coherence Tomography (OCT) imaging provides structural information of a sample based on backscattered light from near infrared wavelengths.

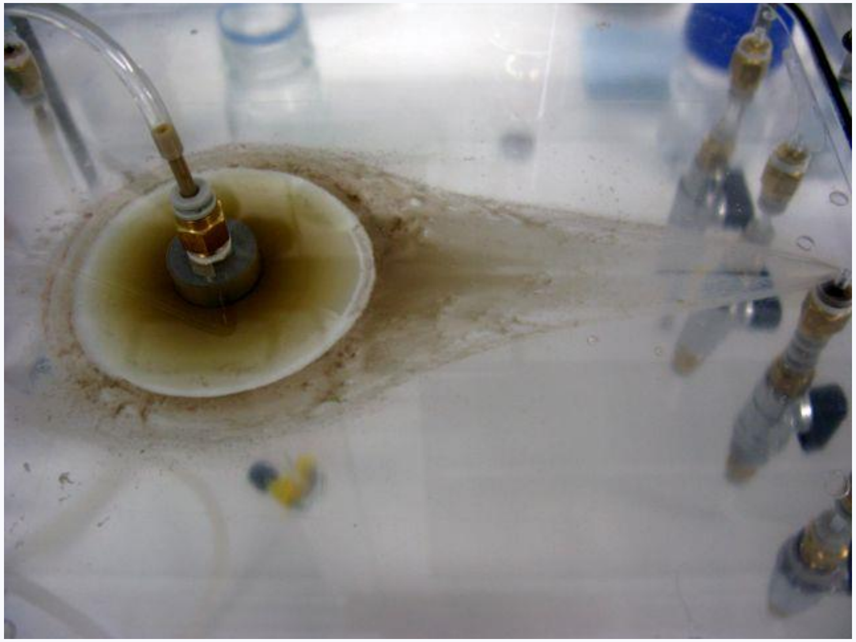
Situation after one week of flow



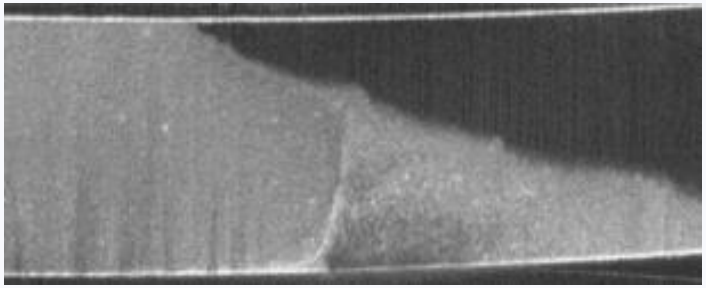
- B-scan line position marked with red arrow; scan line is 8 mm long
- Scans were taken at increasing distances into fracture.
- In top images original flow direction is left to right; in bottom images original flow direction is into image.
- 2D structural images (bottom) show the interface between the fracture-filling homogeneous extruded zone (left most image) and sedimented, eroded material which is deposited further and further into fracture space on the bottom surface.
  - Aggregation and sedimentation of the eroded (colloidal) material occurs downstream of the source
  - Some fraction of the initially eroded mass becomes sedimented and will not be readily transported out of the near-field.

Clay Sediment in Flow Path

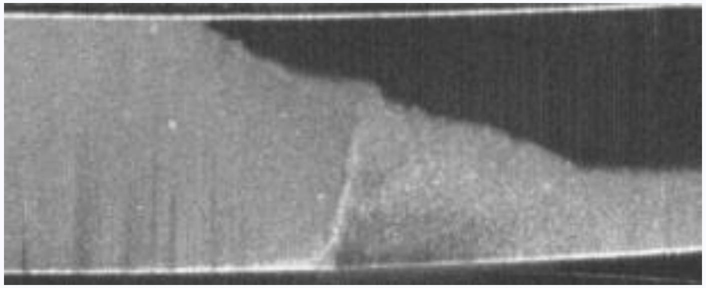
NaMt (MX-80) / DI / 1 mm / 2.6 ml/min



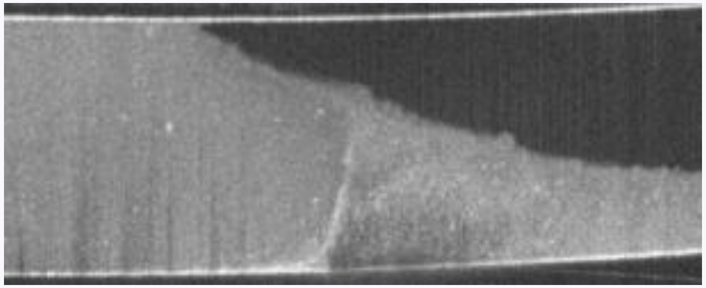
Presence of flow to high rates



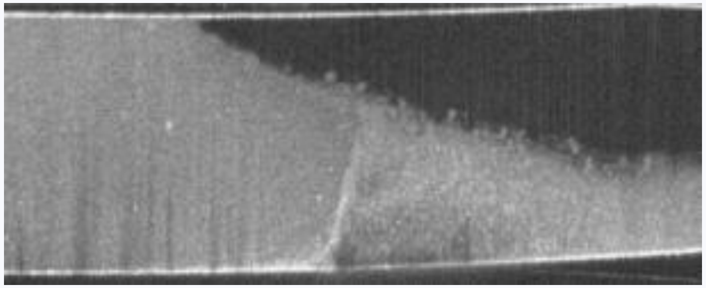
1 ml/min



10 ml/min



5 ml/min



200 ml/min

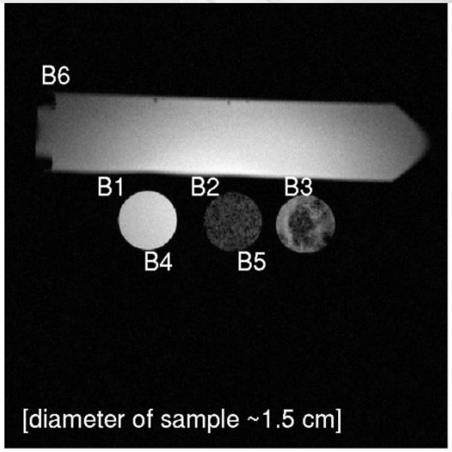
- Both the extruded and sedimented regions are rather stable to flow through the fracture system; slight motion observed in the sediment and at the solid/liquid interface but no volume change.
- Only an extreme flow condition (200 ml/min) appears to produce mechanical shear effects.

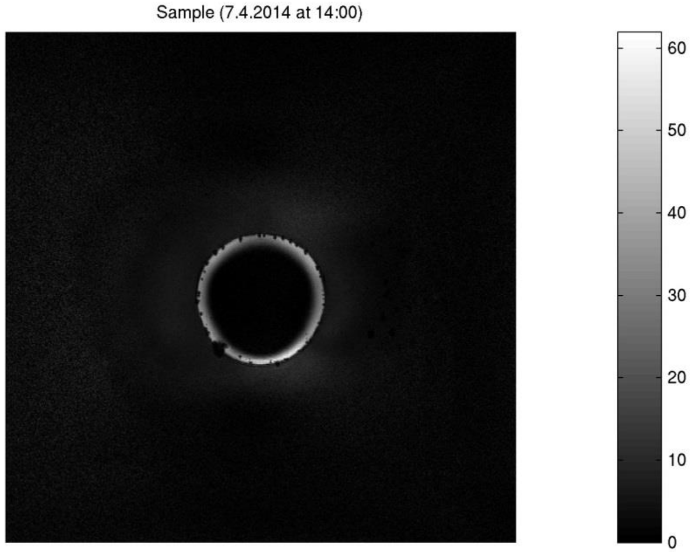
MRI APPLICATION TO ARTIFICIAL FRACTURE TESTS

Status


SIEMENS

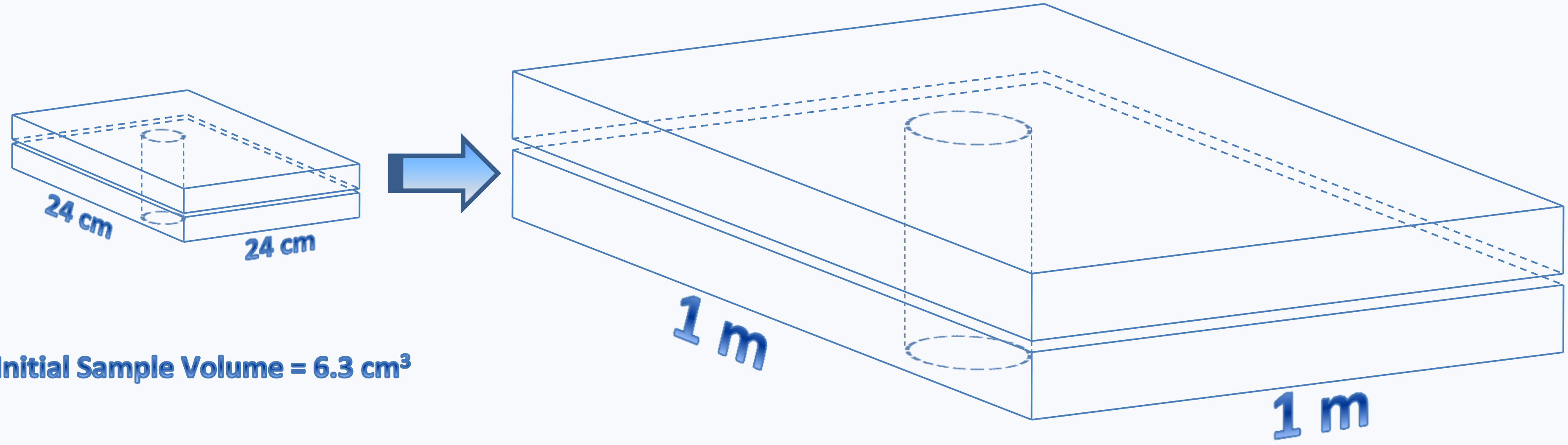

SIEMENS
SIEMENS
SIEMENS


B6
B1
B2
B3
B4
B5
[diameter of sample ~1.5 cm]


Sample (7.4.2014 at 14:00)
60
50
40
30
20
10
0

STATUS OF LARGER FRACTURE TEST

Larger Artificial Fracture System



Initial Sample Volume = 6.3 cm^3

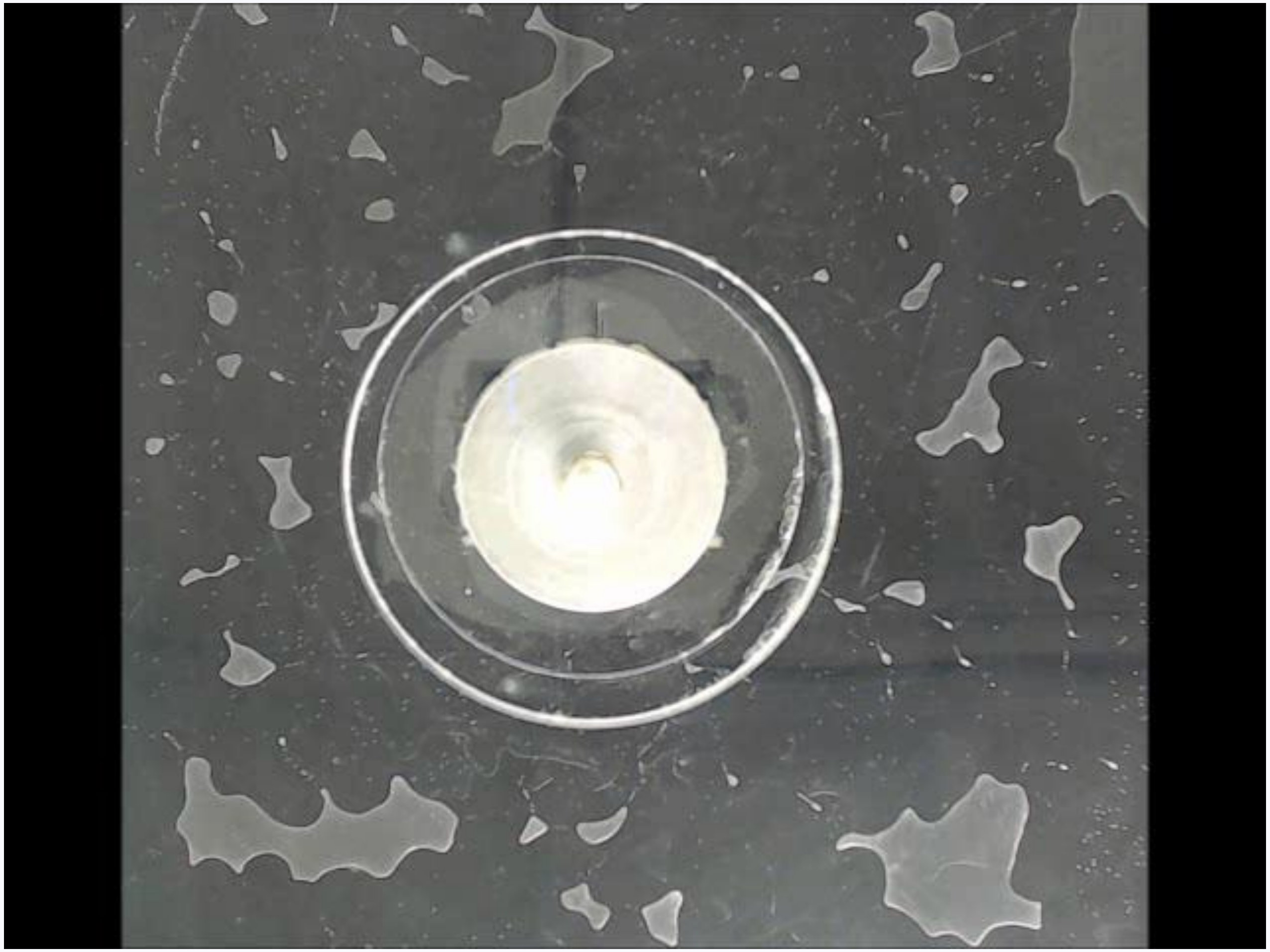
Initial Sample Volume = 98.2 cm^3

Scale Effects?

Current Situation

- Test is ongoing with conditioned MX-80 bentonite
- Experienced problems with deformation and nonuniform flow through the fracture
- Extrusion distance still increasing, but remains well below (on a relative basis) extrusion distances observed in smaller systems regardless of aperture.
- Flow of dispersed material out of the fracture.

40 days in 40 seconds



STATUS OF BENCHMARK TESTS