



# Benchmarking Exercise of Clay Erosion in Artificial Fracture Tests

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Christopher Reid, Frank Friedrich, Franz Rinderknecht  
& Kari Koskinen

# BELBaR Benchmarking Participants

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- **CIEMAT** (*Ursula Alonso & Tiziana Missana*)
- **B+Tech**
- **KIT / INE** (*Frank Friedrich & Franz Rinderknecht*)
- **University of Strathclyde** (*Chris Reid*)
- **Posiva** (*Kari Koskinen*)

# BELBaR Benchmark Test Method

## ❑ Material

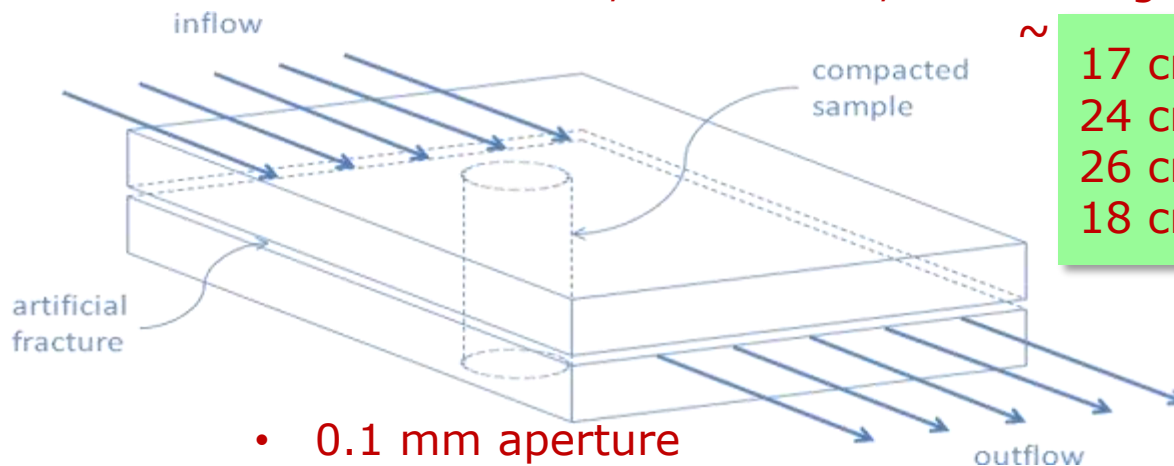
- commercial sodium montmorillonite (Nanocor, PGN grade)

## ❑ Samples

- dry density – 1400 kg/m<sup>3</sup>
- dimensions (height, diameter) ~
  - 10 mm × 19 mm (CIEMAT)
  - 20 mm × 20 mm (B+Tech)
  - 10 mm × 19 mm (UniStrath)
  - 25 mm × 80 mm (KIT/INE)
- pre-saturated (1 mM NaCl)

## ❑ Fracture

- custom-made, small-scale, flow-through artificial fracture cells



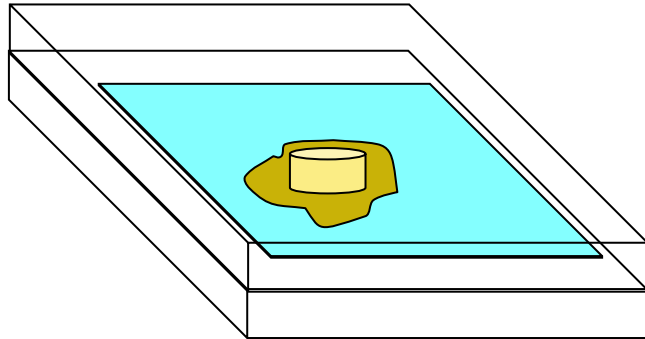
- ~
  - 17 cm × 17 cm (CIEMAT)
  - 24 cm × 24 cm (B+Tech)
  - 26 cm diameter (UniStrath)
  - 18 cm diameter (KIT/INE)

## ❑ Solution

- 1 mM NaCl

# BELBaR Benchmark Test Protocol

## Phase 1: stagnant conditions (30 days)

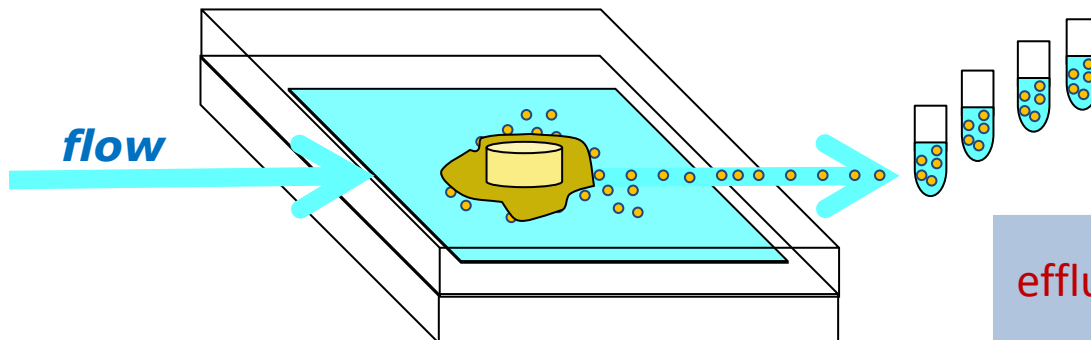


extrusion distance

Swelling  
pressure  
measurements  
performed by  
UniStrath and  
KIT/INE

## Phase 2: low flow conditions (14 days at $10^{-6}$ m/s)

## Phase 3: high flow conditions (14 days at $10^{-4}$ m/s)



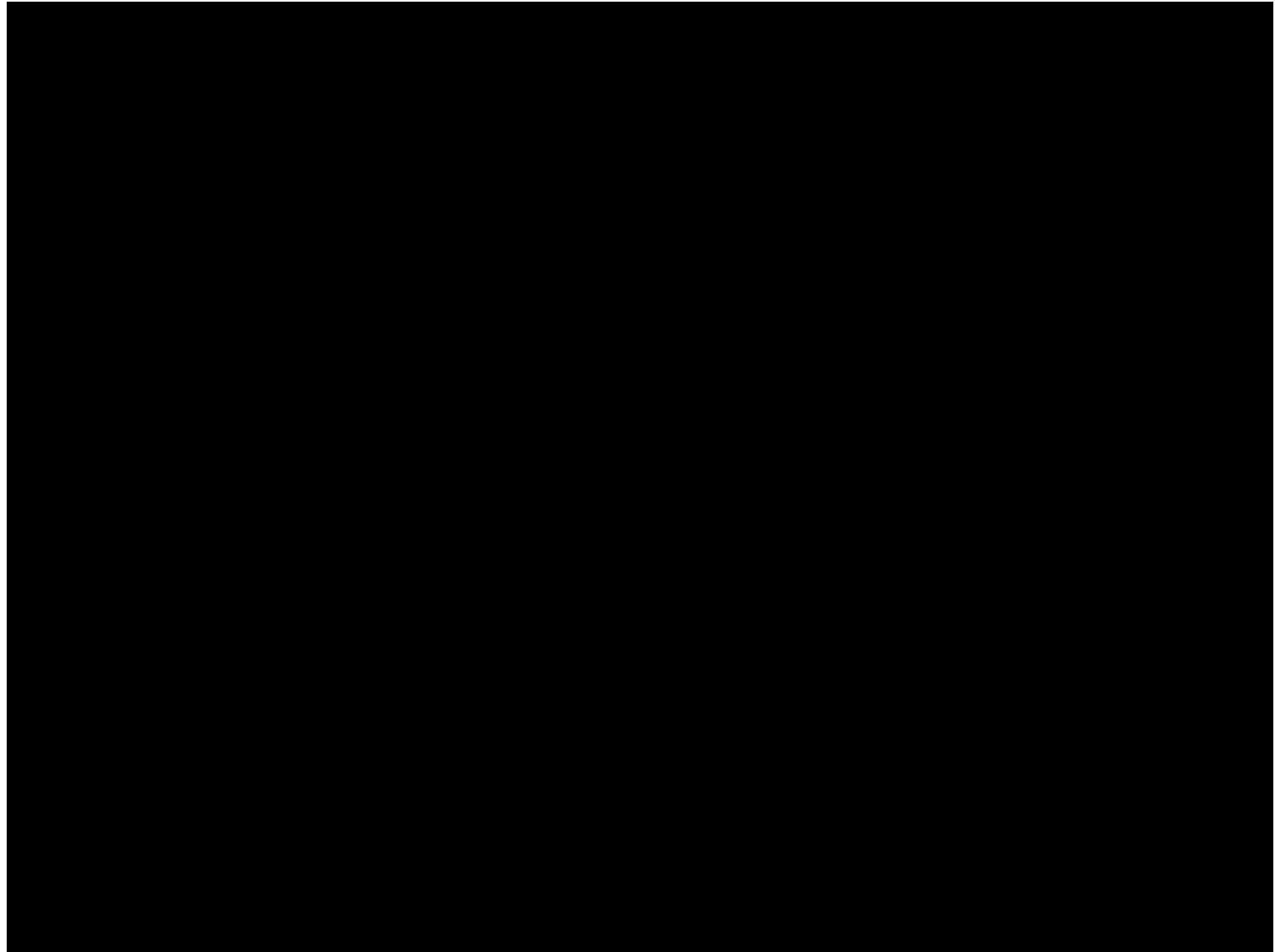
effluent solids content

# BELBaR Benchmark Test Set-up



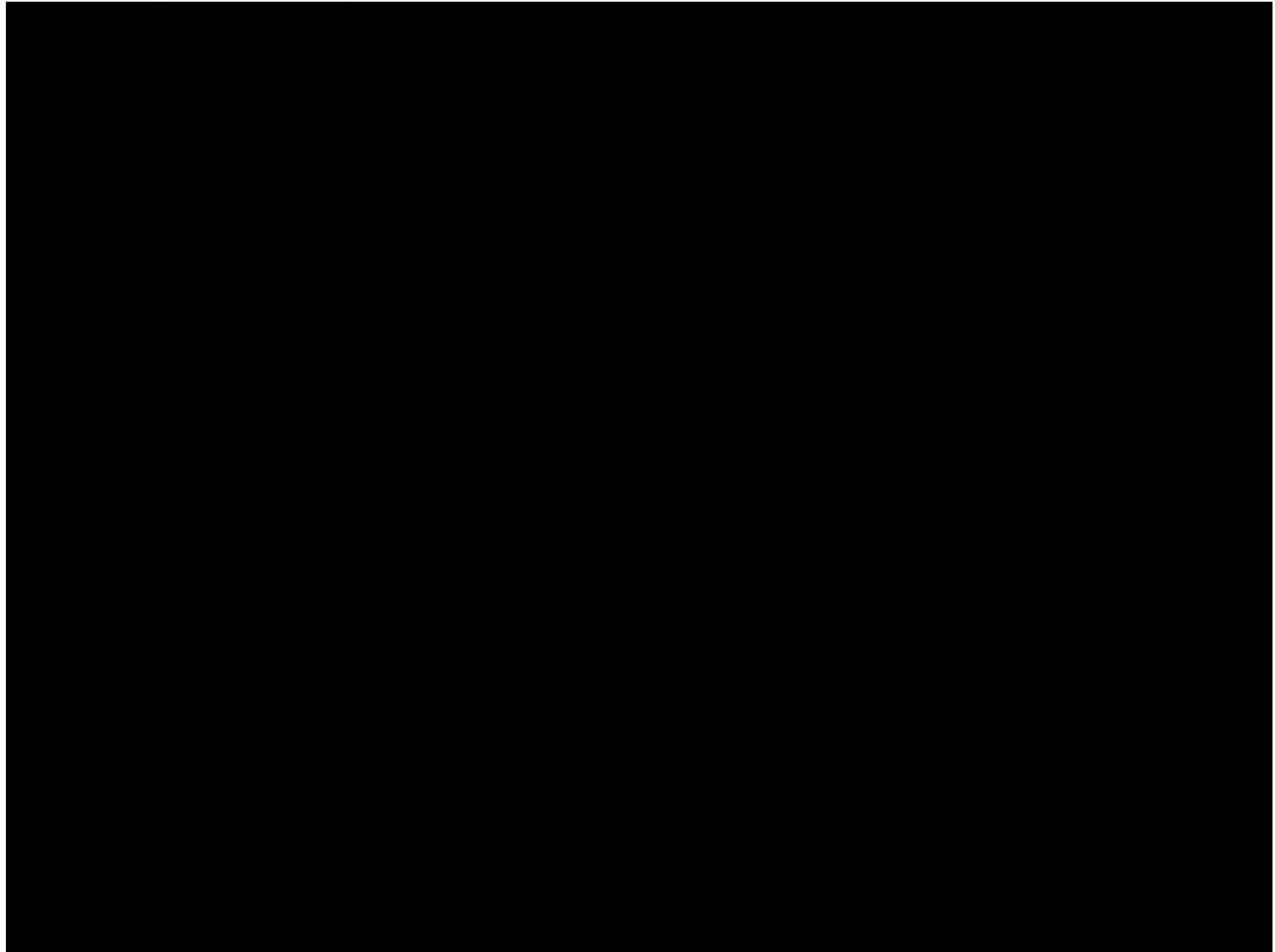
# BELBaR Benchmark Test (time lapse)

B+Tech

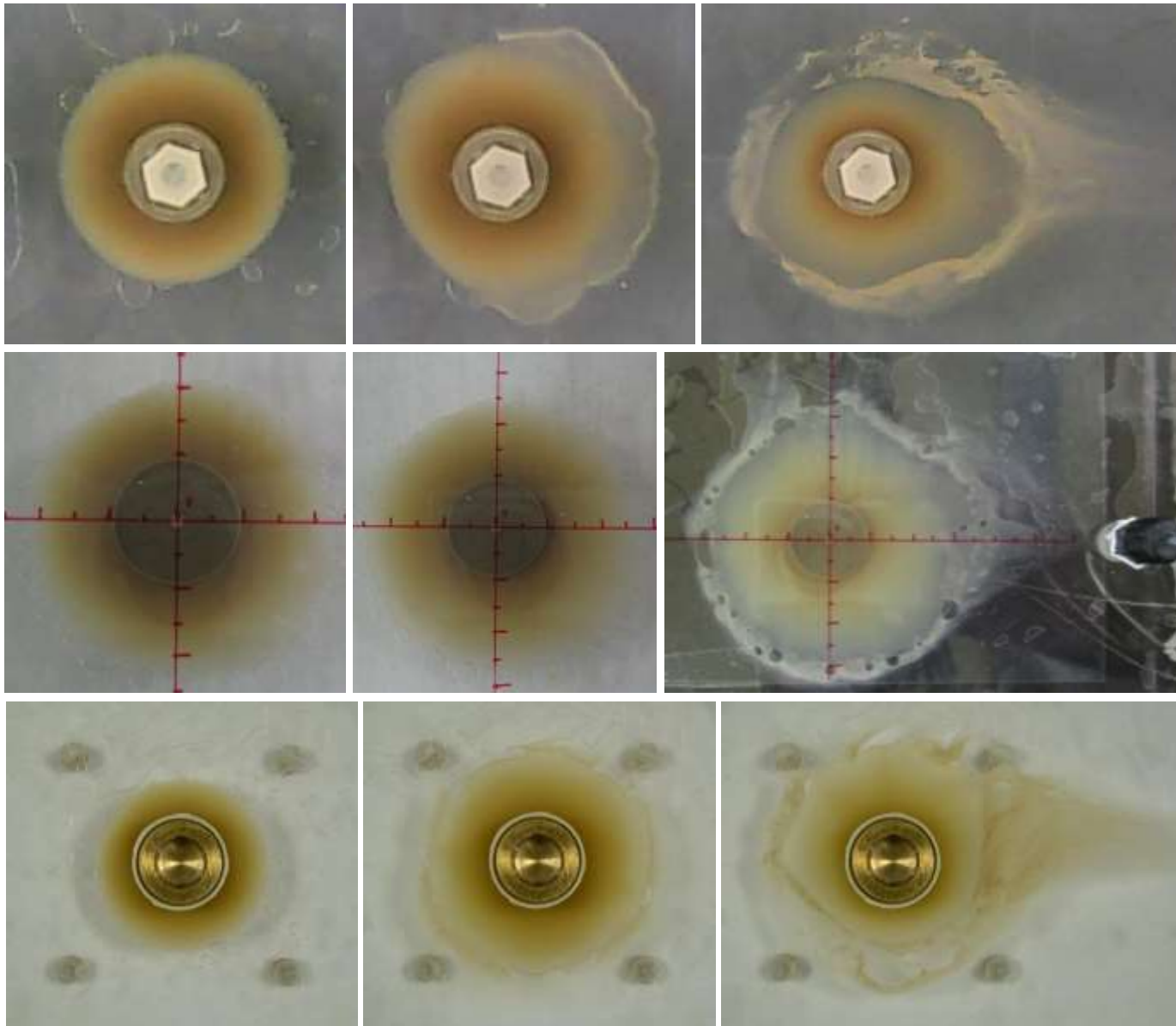


# BELBaR Benchmark Test (time lapse)

University of Strathclyde



# Benchmark Test Observations



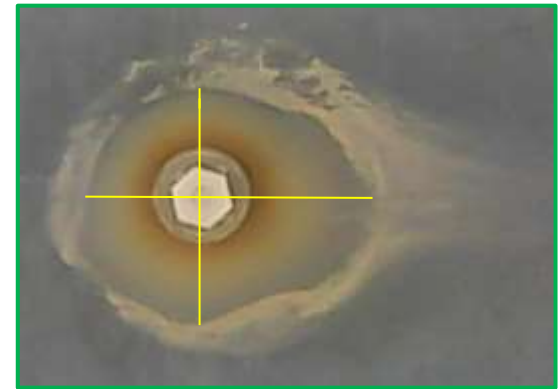
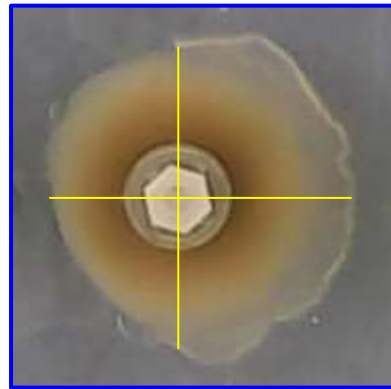
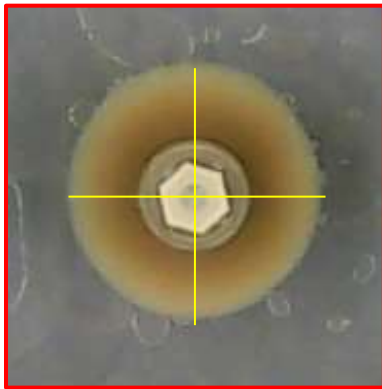
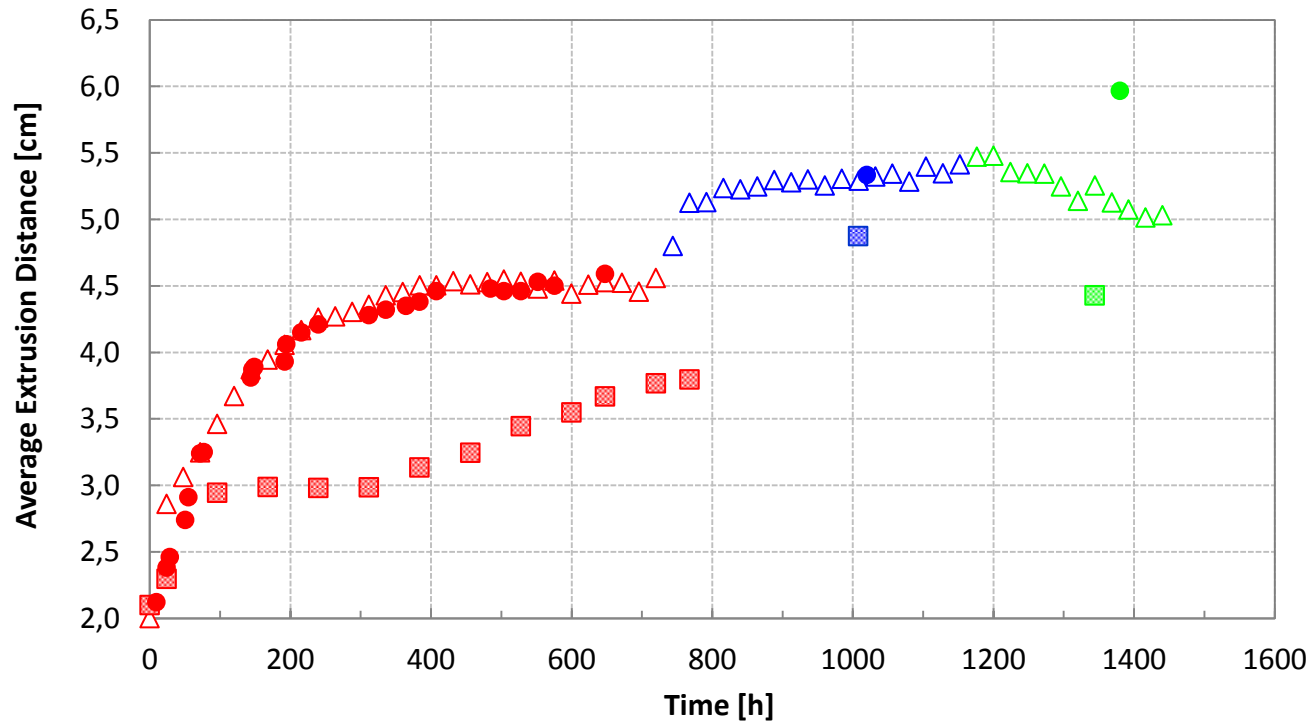


# Phase Characteristics

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- ❑ Phase 1 of the tests (stagnant period) was characterized by symmetric extrusion of emplaced sample material to steady-state distances into the fractures.
- ❑ Phase 2 of the tests (low flow velocity) was characterized by rather abrupt, asymmetric increases in extrusion and the formation of distinct solid material regions.
- ❑ Phase 3 of the tests (high flow velocity) was characterized by further development of the sharp boundary between the inner continuous solid material zones and the outer discontinuous particulate material zones, and, in two cases, erosive loss of the inner zone.
  - Clear flow patterns of entrained/dispersed eroding solid material from around the extrudates were visible during phase 3.

# Extrusion Distances

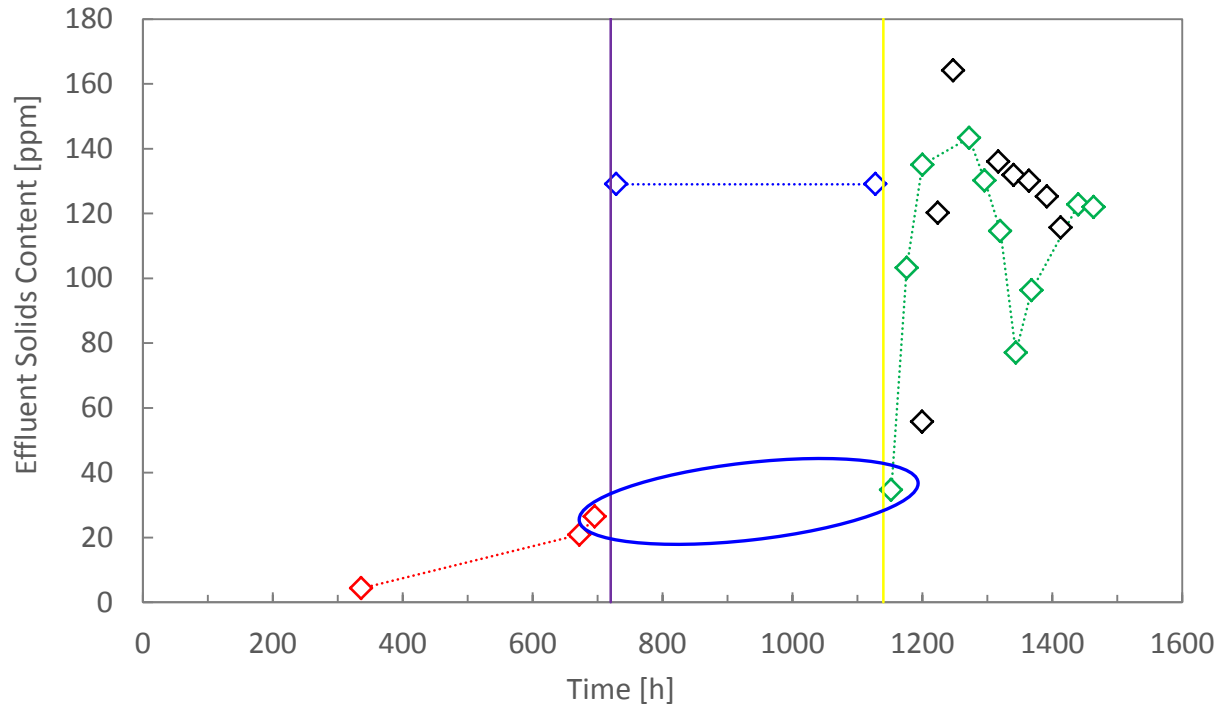


# Extrusion Behaviour

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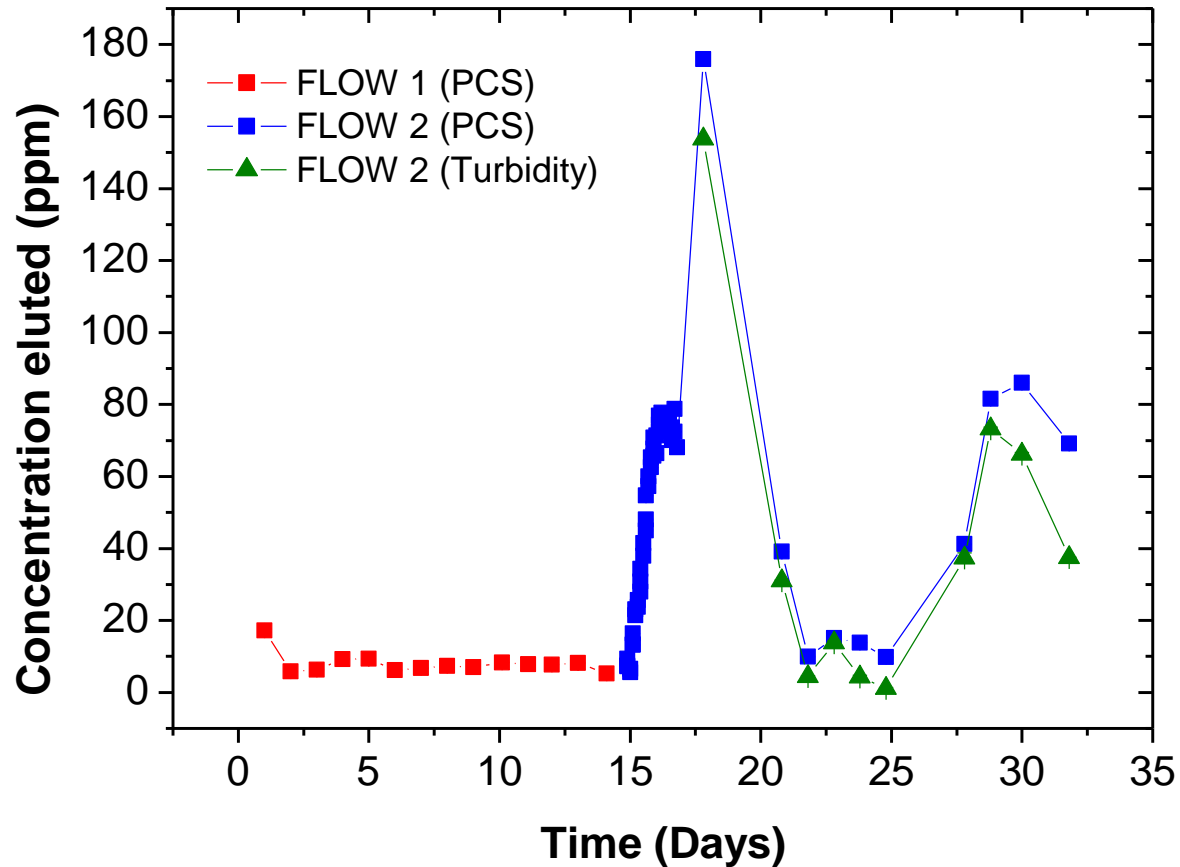
- ❑ Overall the benchmark tests showed extrusion distances, considered as averages of the horizontal and vertical lengths across the extruding, continuous phases in the fracture space, of:
  - ❑ 3.8 to 4.6 cm at the end of phase 1,
  - ❑ 4.9 to 5.3 cm at the end of phase 2,
  - ❑ 4.4 to 5.9 cm at the end of phase 3.

# Effluent Solids (B+Tech)



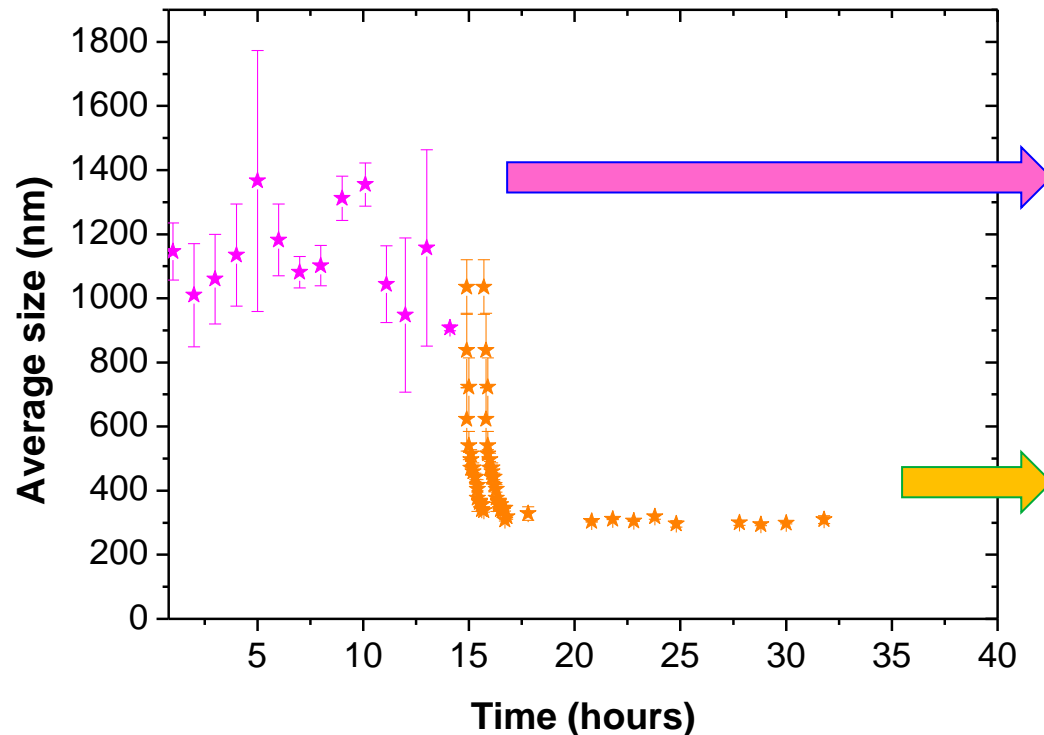
- ❑ Average effluent concentration of 30 ppm during phase 2.
- ❑ Effluent concentrations from 35 to 160 ppm during phase 3.

# Effluent Solids (CIEMAT)



- ❑ Average effluent concentration of 8 ppm during phase 2.
- ❑ Effluent concentrations from 8 to 180 ppm during phase 3.

# Effluent Particle Size (CIEMAT)

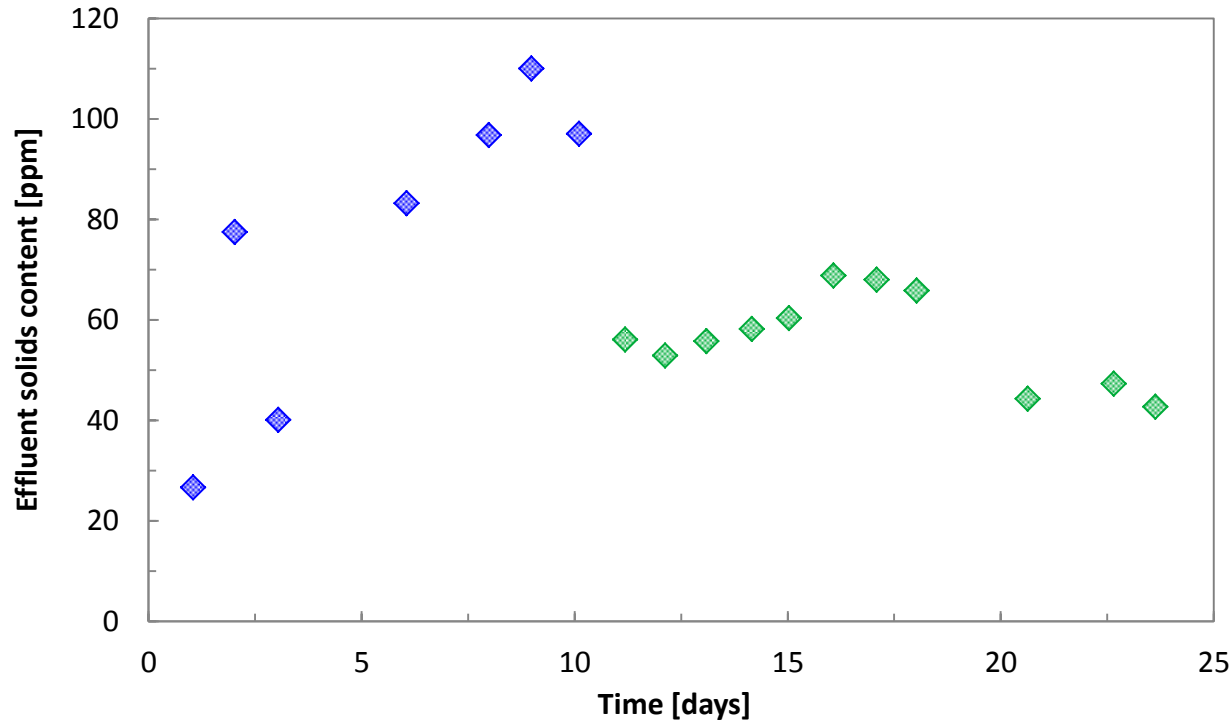


larger particles are eluted during phase 2 flow

smaller particles are removed during phase 3 flow

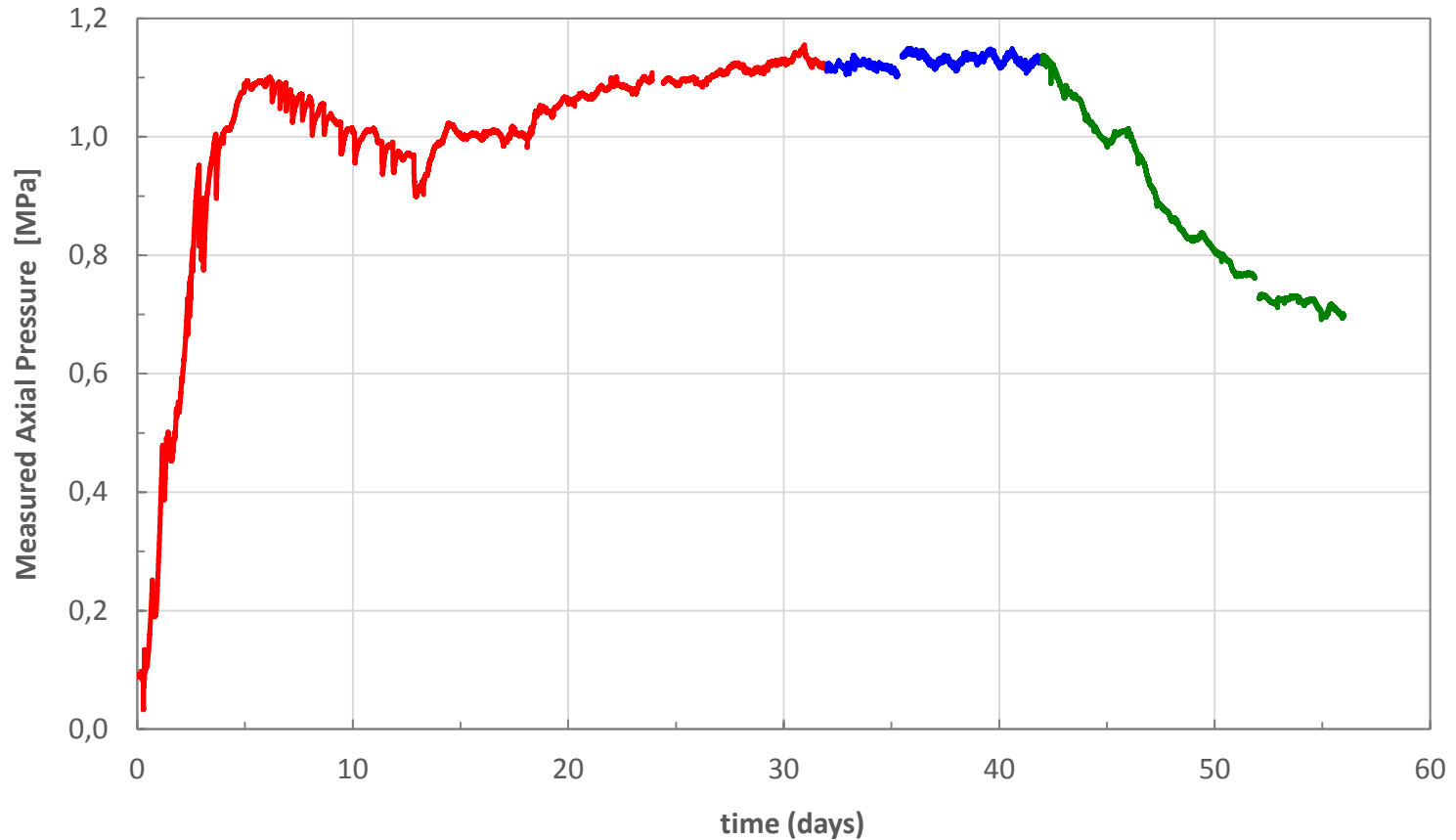
- ❑ Distinct particle size populations or disaggregation?

# Effluent Solids (UniStrath)



- ❑ Effluent concentrations from 27 to 110 ppm during phase 2.
- ❑ Effluent concentrations from 42 to 69 ppm during phase 3.

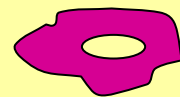
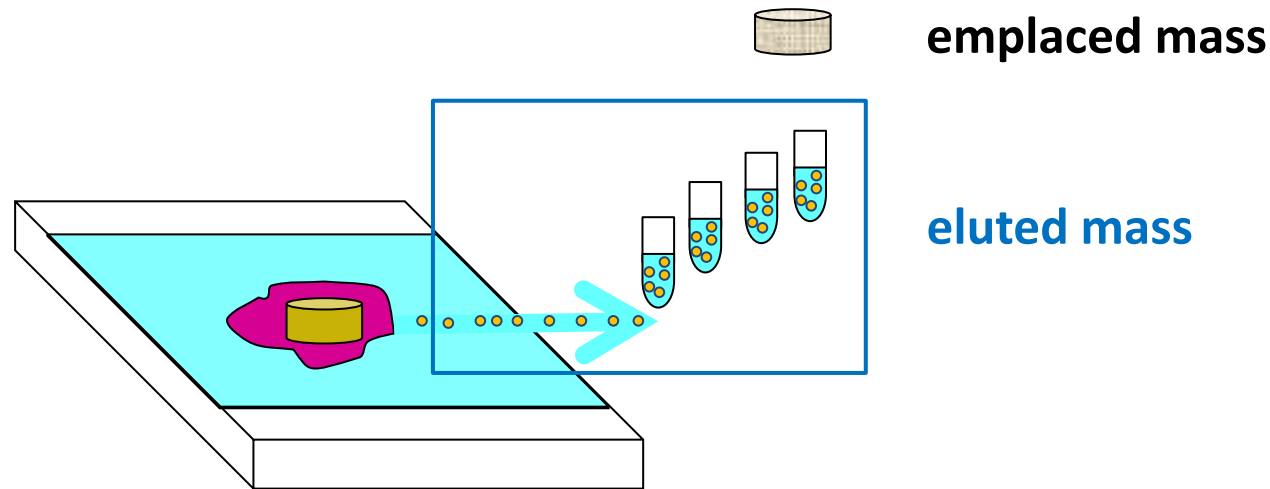
# Swelling Pressure (UniStrath)



- ❑ Relatively constant pressures observed during phases 1 and 2.
- ❑ 40% drop in pressure during phase 3 (erosion).



# BELBaR Benchmark Test Post-Mortem







**extruded mass (post mortem)**



**remaining mass (post mortem)**

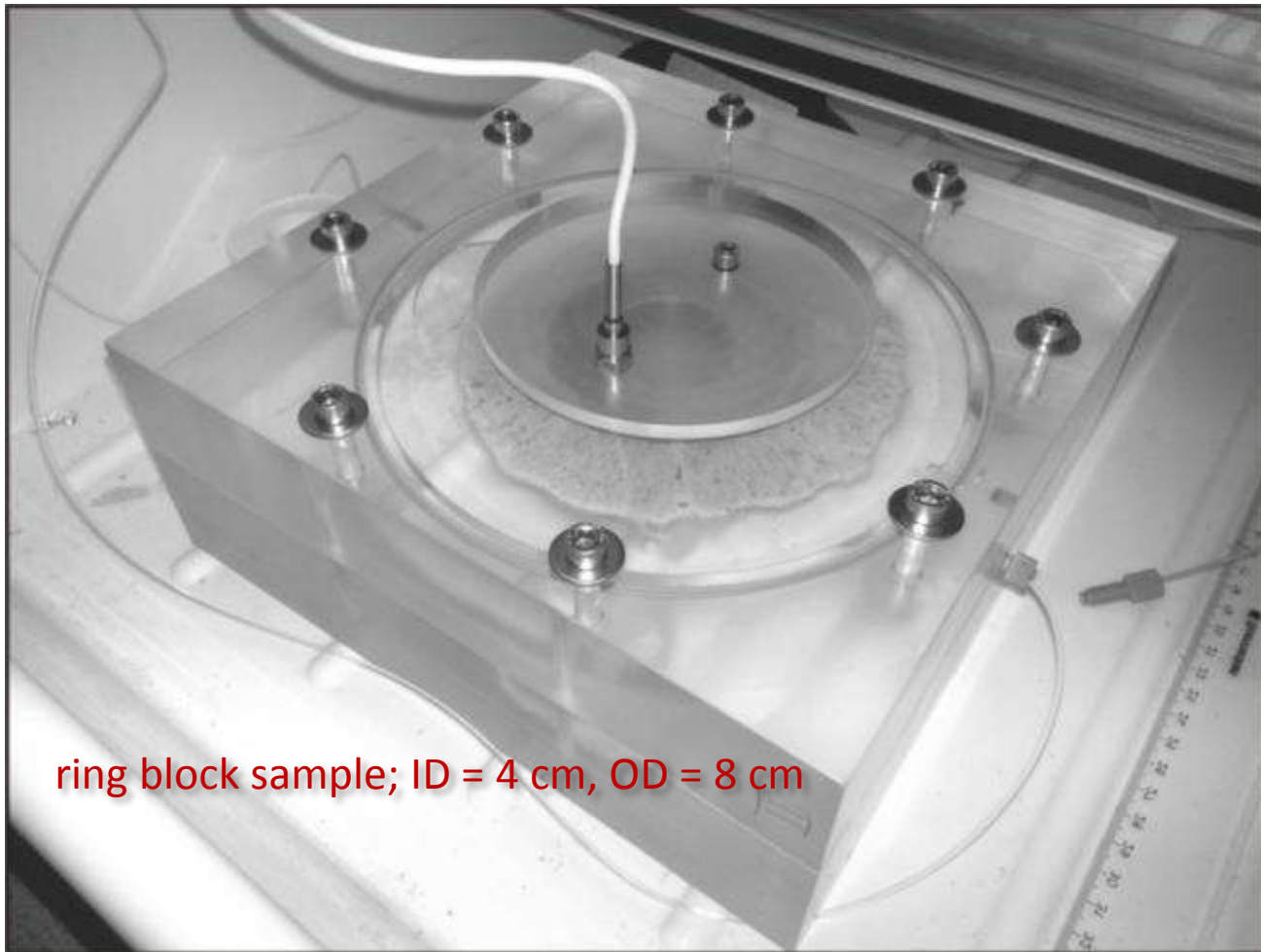
$$\text{emplaced mass} - (\text{remaining mass} + \text{extruded mass}) = \text{eroded mass}$$

# Erosion Comparison

			
Emplaced mass	3.8554	7.7023	4.3000
Extruded mass	0.3640	0.3090	0.3137
Remaining mass	3.4040	6.4977	3.2479
Eroded mass	0.0874 (2.3%)	0.8956 (11.6%)	0.7384 (17.2%)
Eluted mass	0.1180	0.5622	0.5576

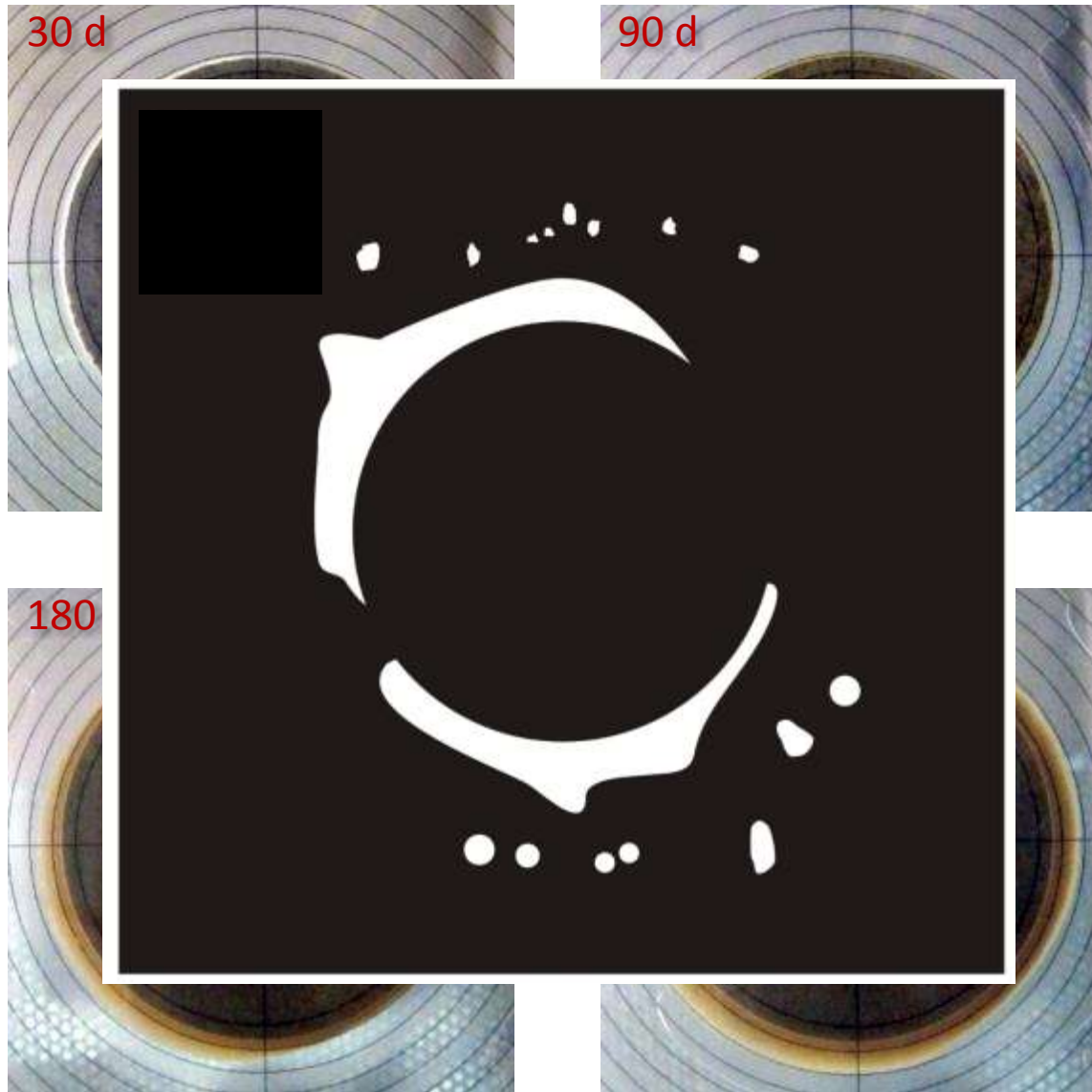
- ❑ Post-mortem analysis of remaining mass and extruded mass relative to emplaced mass indicates total losses of 2 to 17%.

# BELBaR Benchmark Test at KIT/INE

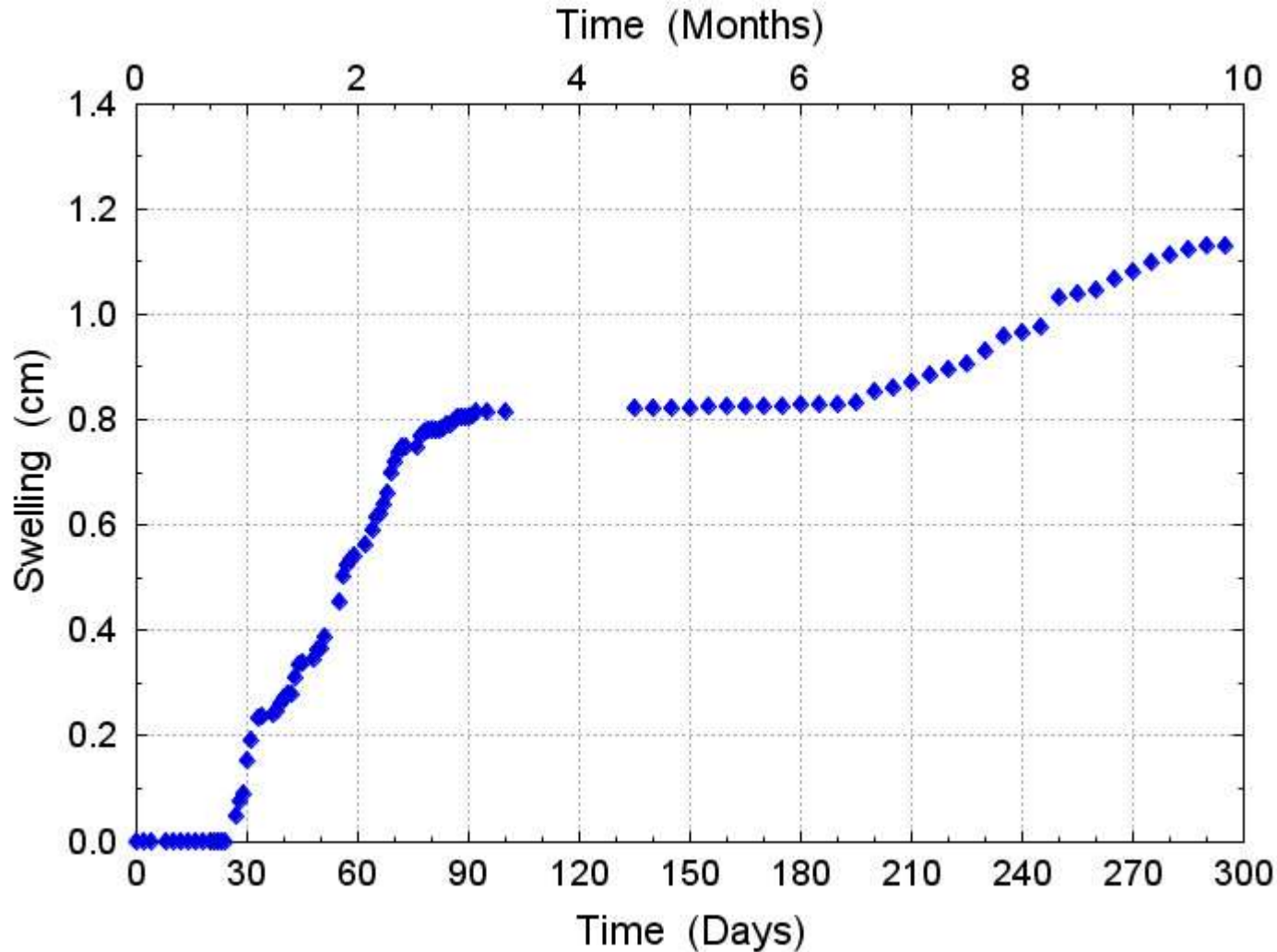


- ❑ Fracture volume could not be filled with solution; phases 2 and 3 of the benchmark tests protocol were not initiated.

# Extrusion Observations (KIT/INE)

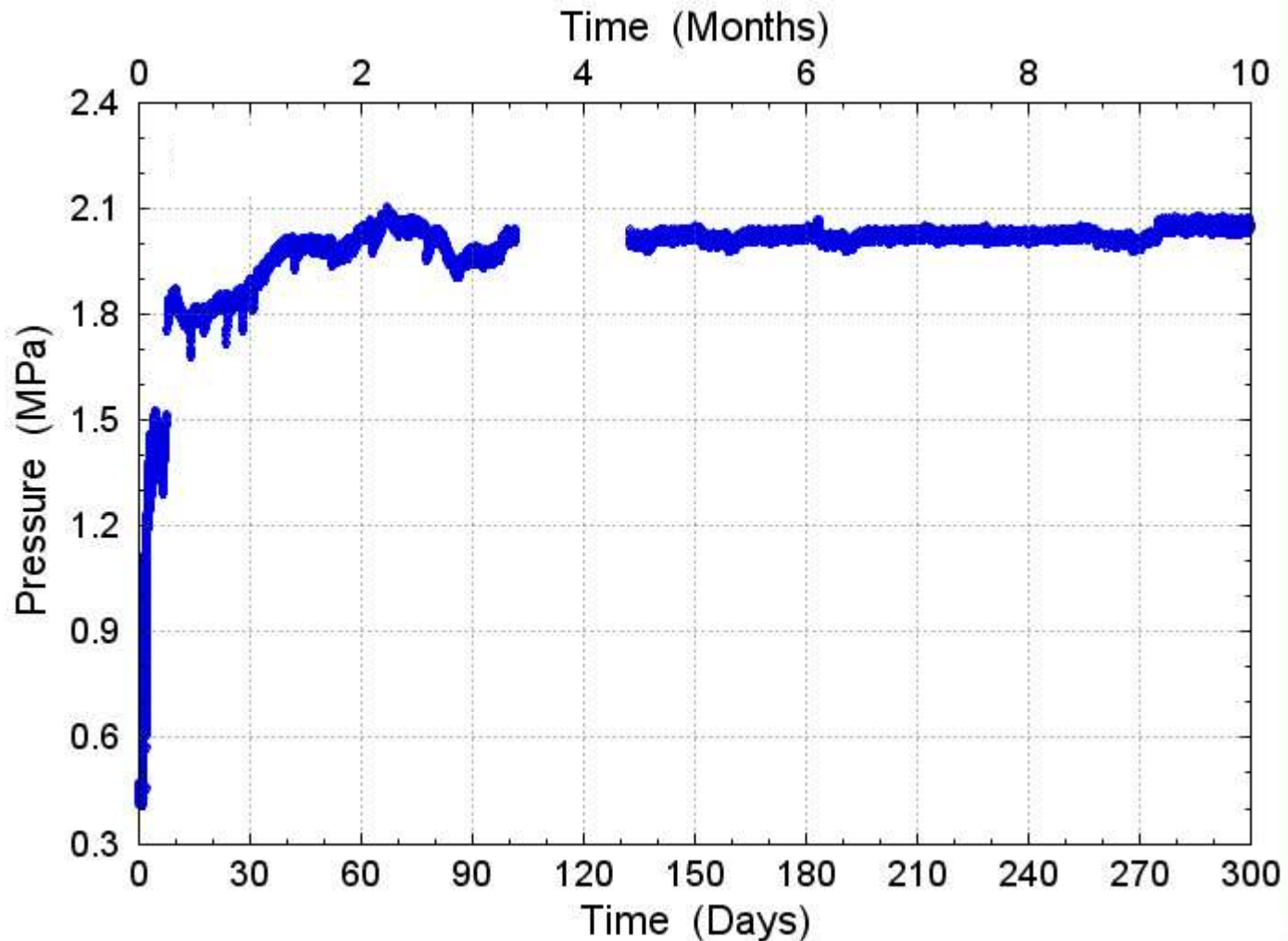


# Extrusion Distance (KIT/INE)



- ❑ Limited extrusion in time and distance relative to smaller sample tests.

# Swelling Pressure (KIT/INE)



- Relatively constant pressures observed after 60 days.

# Summary

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- ❑ In general, the results of the benchmark tests performed on similarly sized samples are relatively consistent with one another.
  - Extrusion distances were in agreement to within 15% over all three tests phases.
  - Minimum to maximum eluted solids concentration ranges measured during phase 3 were found to be favorably overlapped
  - Relative erosion was determined to be from 2 to 17%
- ❑ With a more rigorously detailed protocol, artificial fracture tests could be more tightly benchmarkable.
- ❑ The behaviour of the larger test system (and elsewhere) indicates that comparison between tests even at these modest scaling increases may not be straightforward.