Selection Method of Surfactant Foam for Enhanced LNAPL Recovery in Contaminated Soils

Mélanie Longpré-Girard[1], Richard Martel[1], Thomas Robert[1], René Lefebvre[1] & Jean-Marc Lauzon[2]

[1]Institut National de la Recherche Scientifique, Centre Eau, Terre et Environnement [2] Technorem Inc.

The Project

Introduction

Foams have advantages when compared with injection of surfactant solutions:

- Cheaper since they are used in low concentrations and mainly made of air;
- Better mobiliser since they are more viscous;
- Shear thinning behavior, so no need of polymers
- Collapse in contact with NAPL and increase sweep efficiency of contaminated areas

Context:

This project will lead to the application of foam technology on LNAPL contaminated sites. This study presents the first steps towards this objective. Different surfactants have been selected and sand column tests were made.

Objectives:

- **Select the best surfactant for foam production**
- **Enhance mobilization potential in sand columns**
- **Enhance mobility control of the displacement front**

Surfactant Selection

Criteria

1- Toxicity and Biodegradability

Most products tested are FDA approved

2- Capacity to produce foam

Quantified with Ross Miles test

3- Interfacial tension with LNAPL

Measured with pendant drop method

Ross Miles Test (ASTM D1173)

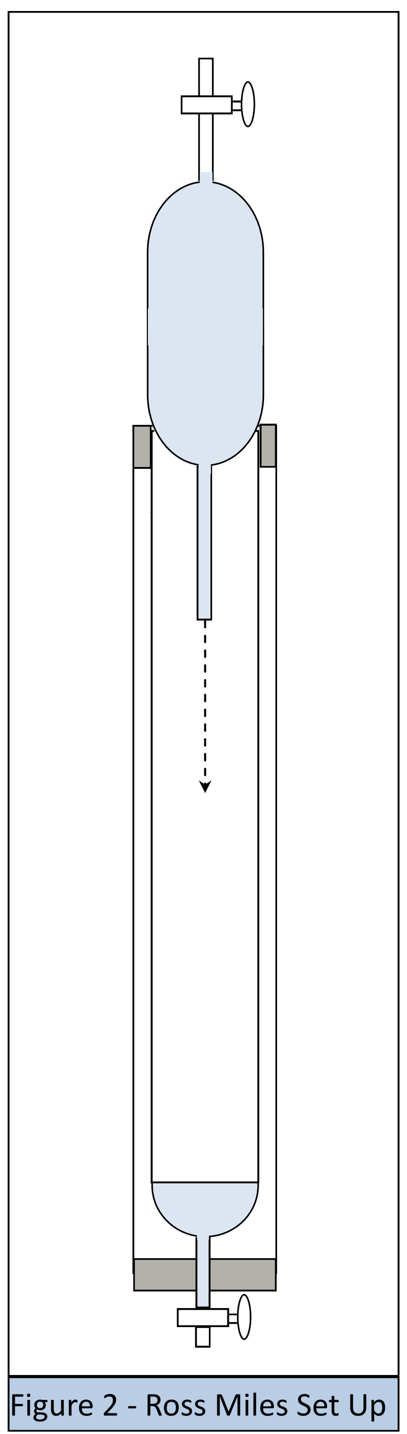


Figure 2 - Ross Miles Set Up

Objective:

Qualitative comparison of foams

Methodology:

- walls of the glass receiver are rinsed with 50 ml of surfactant solution
- 200 ml pipet filled with surfactant solution is placed on top of the receiver
- pipet's stopcock is opened allowing surfactant solution to flow in the receiver creating a foam
- foam's height is measured at different times: 0, 1, 3, 5 and 15 minutes

Mobilisation Process

It consists in pushing the LNAPL with a displacing front of foam and then recovering high concentrations of NAPL when the front exits the porous media.

Capillary number (N_c): ratio of viscous to capillary forces

$$N_c = \frac{q\mu}{\sigma cos\theta} \geq 10^{-5}$$

Where: - q is the flux (m/s)

- μ is the viscosity (Pa·s)
- σ is the interfacial tension (mN/m)
- Θ is the wettability angle (°)

Mobilisation happens at $N_c \geq 10^{-5}$, when viscous forces are great enough to overcome capillary forces.

This study is focused on maximising μ and σ in order to increase N_c

Mobility Control

Polymers are commonly used to enhance the mobility control during surfactant injection and minimize fingering.

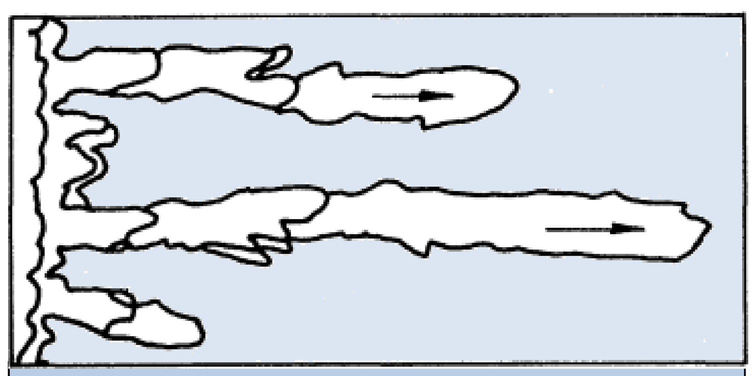


Figure 1 - Fingering (modified from Panko and Cherry 1996)

Fingering happens when the displacing fluid is less viscous than the displaced fluid. This condition is encountered when the mobility ratio (M) is above 1.

$$M = \frac{k_{r1}/\mu_1}{k_{r2}/\mu_2} = \frac{\mu_2}{k_{r2}} \cdot \frac{k_{r1}}{\mu_1}$$

The only parameter that is possible to optimize is the foam's viscosity (μ_1).

Pendant drop method

Objective:

Maximise capillary number by minimizing interfacial tension

Methodology:

- Camera takes pictures of LNAPL drops in surfactant solution
- Drop shape indicates the interfacial tension between the two immiscible liquids

Figure 3 - LNAPL drop

Surfactant Selection

- 16 surfactants were compared with both tests
- 3 surfactants were chosen to be tested in sand columns
- Concentration tested in sand column is 0,1% w/w

Surfactant	Type	Ross Miles Rank	IFT Rank
A	Anionic	2	1
B	Anionic	1	2
C	Nonionic	3	3

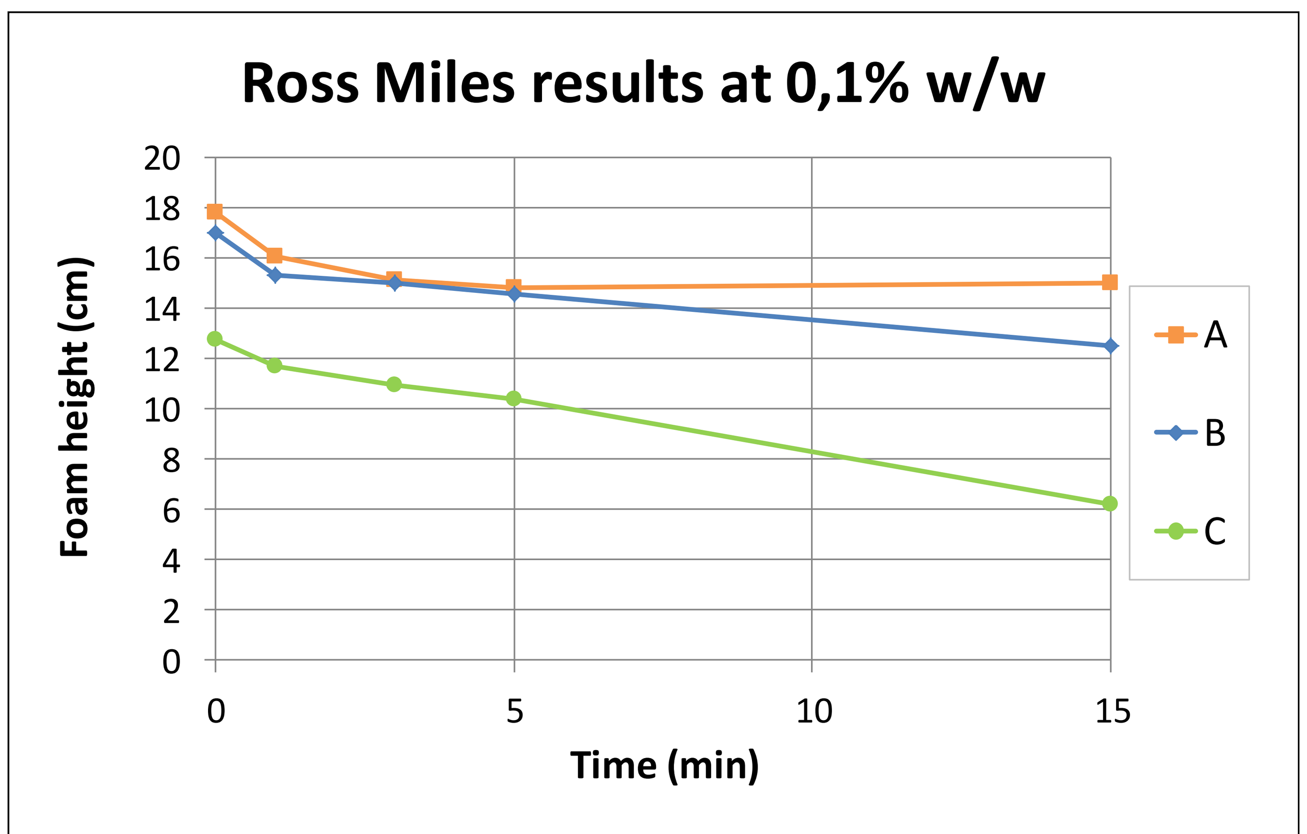


Figure 4 - Results of Ross Miles Test for 3 chosen surfactants

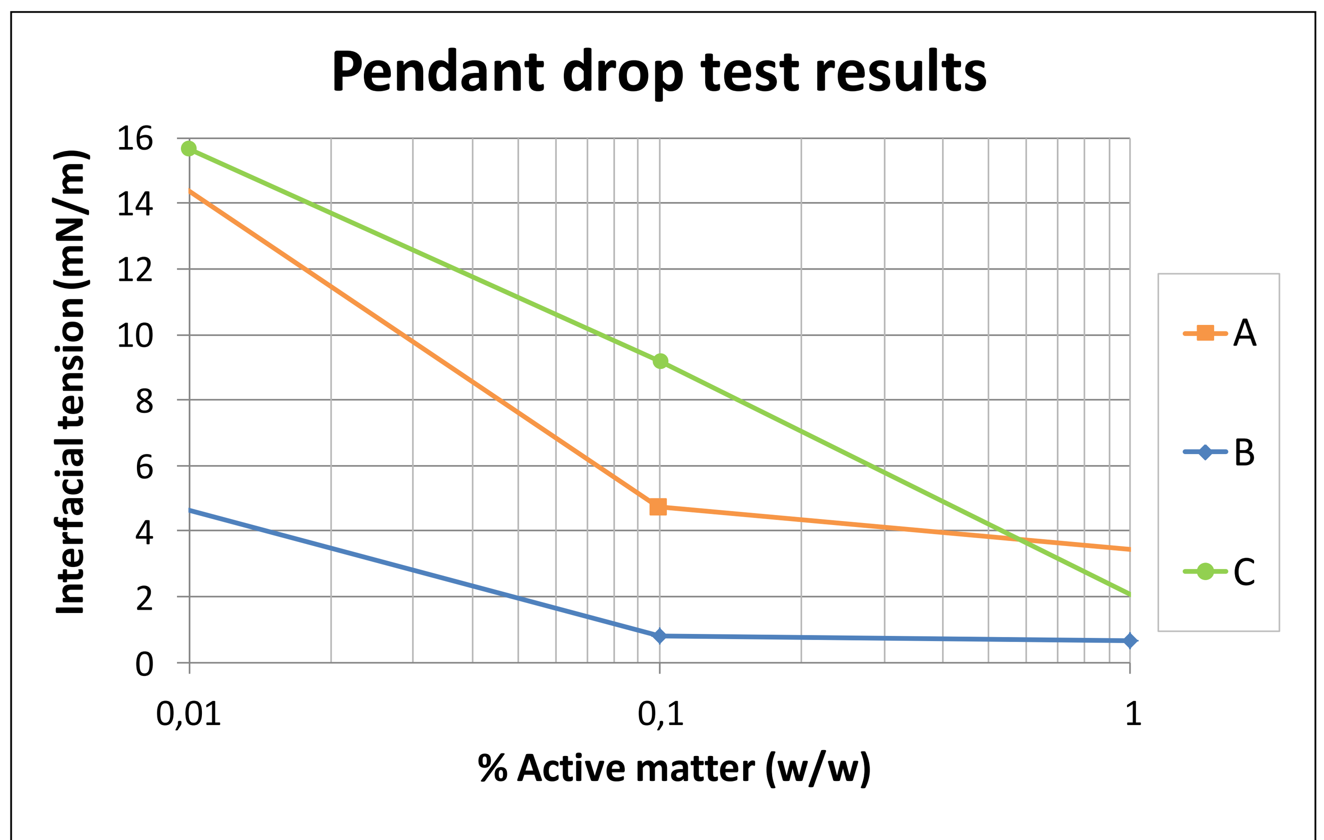


Figure 5 - Results of Pendant Drop for 3 chosen surfactants

Sand Column Test Setup

Foam production:

Foam is produced by alternating injection of surfactant solution and air at the same pressure in a glass beads column connected to the sand column

Data Collecting

- Pressure transducers in the set up record pressure variations throughout the experiments
- Video camera allows to visualize the foam advancing front

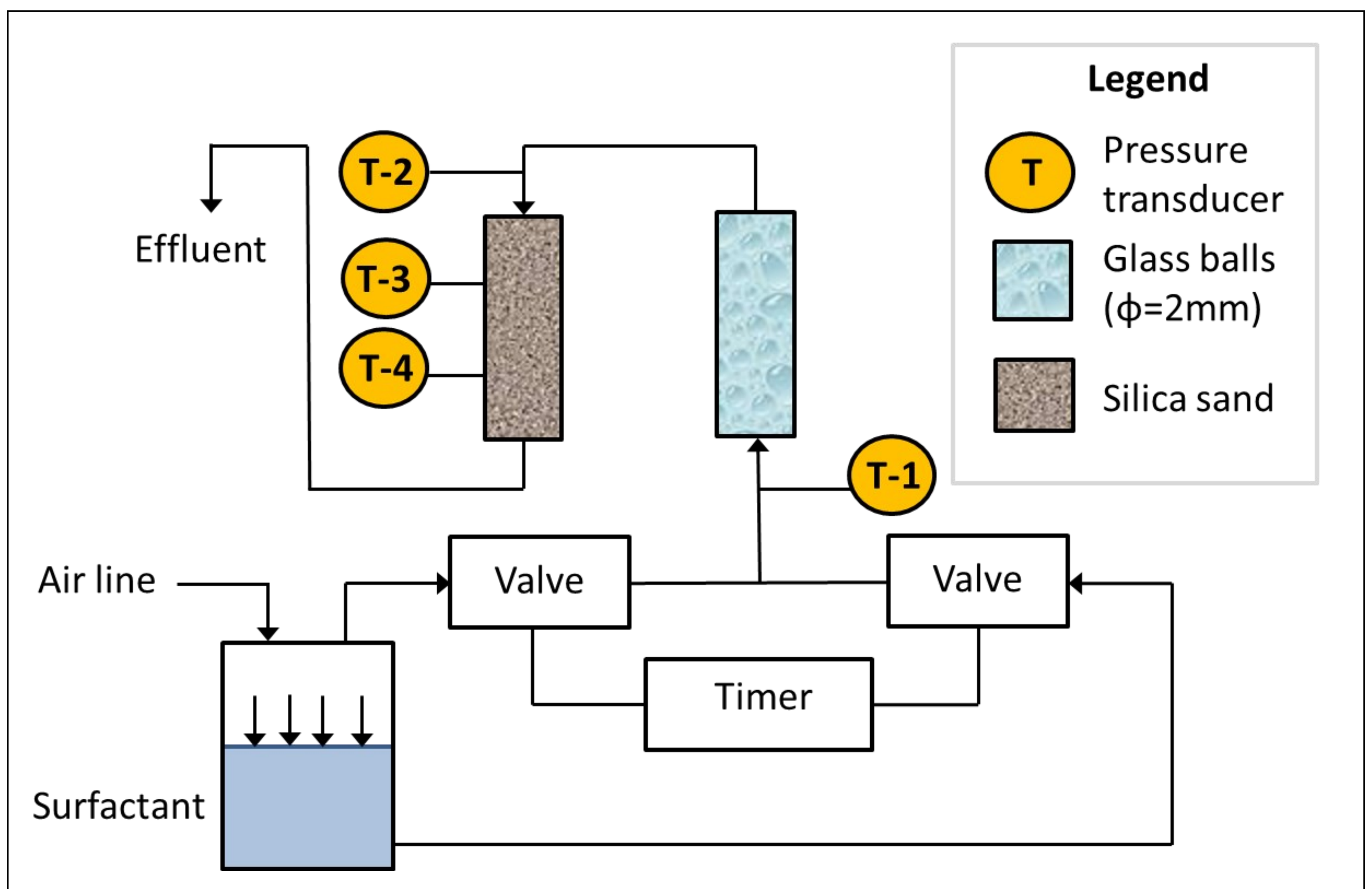


Figure 6 - Column test experimental setup

Column Tests

- **Silica sand pre-flushed with water or surfactant**
- **Different injection pressures (210 cm H_2O or 350 cm H_2O)**
- **3 Surfactants tested**

Column Pre-Flush

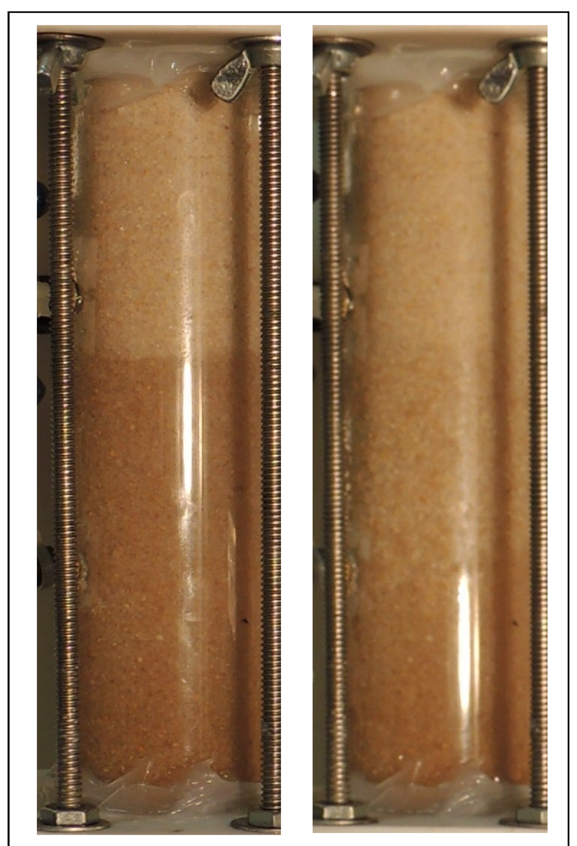


Figure 7 - Column pre-flush test
A) Surfactant B) Water

Before foam injection, a pre-flushed is needed to saturate the column

A pre-flush with surfactant solution creates a stable foam front (Column A)

A pre-flush with water creates two fronts (Column B): 1) an air front less viscous and ; 2) a foam front more viscous

For a stable front: surfactant solution pre-flush is needed

Foam Injection Pressures

210 cm H_2O

- At 00:35 (min:sec)→ Stable Front
- At 01:30 (min:sec)→ Unstable Front

The unstable front indicates a viscosity lowering that decreases the sweep efficiency and increases foam's velocity

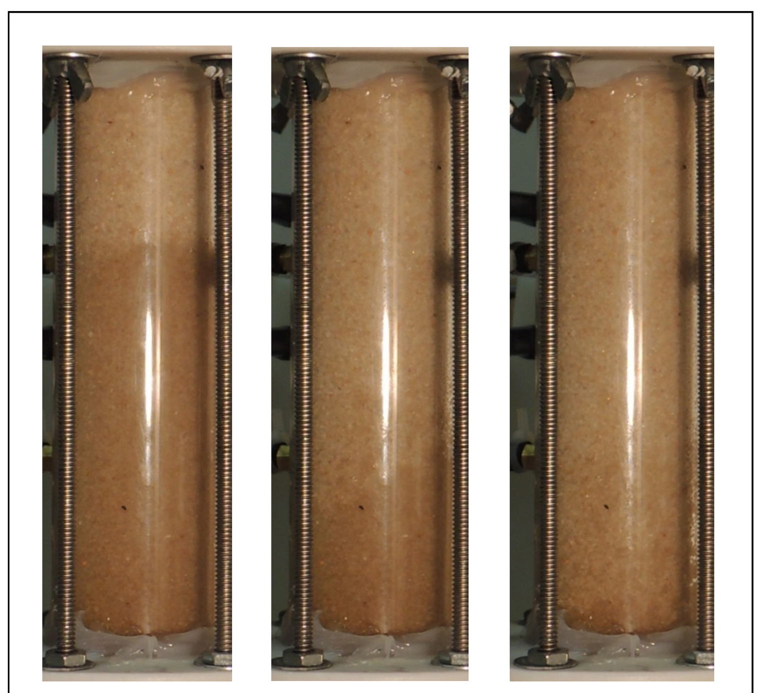


Figure 8 - 210 cm Foam Injection time (min:sec)
00:35 01:30 01:55

350 cm H_2O

Foam front is stable through out the experiment at this pressure.

For a stable front: high injection pressure is needed

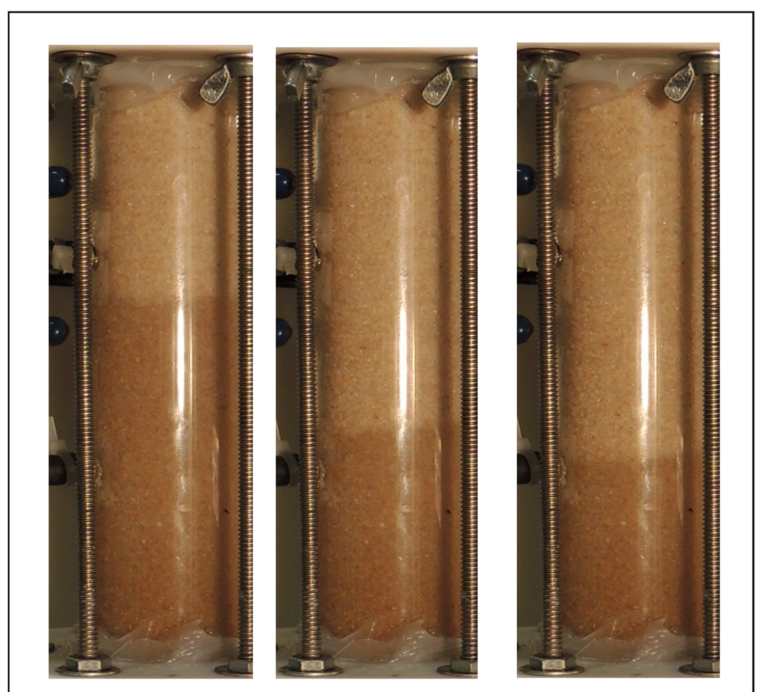
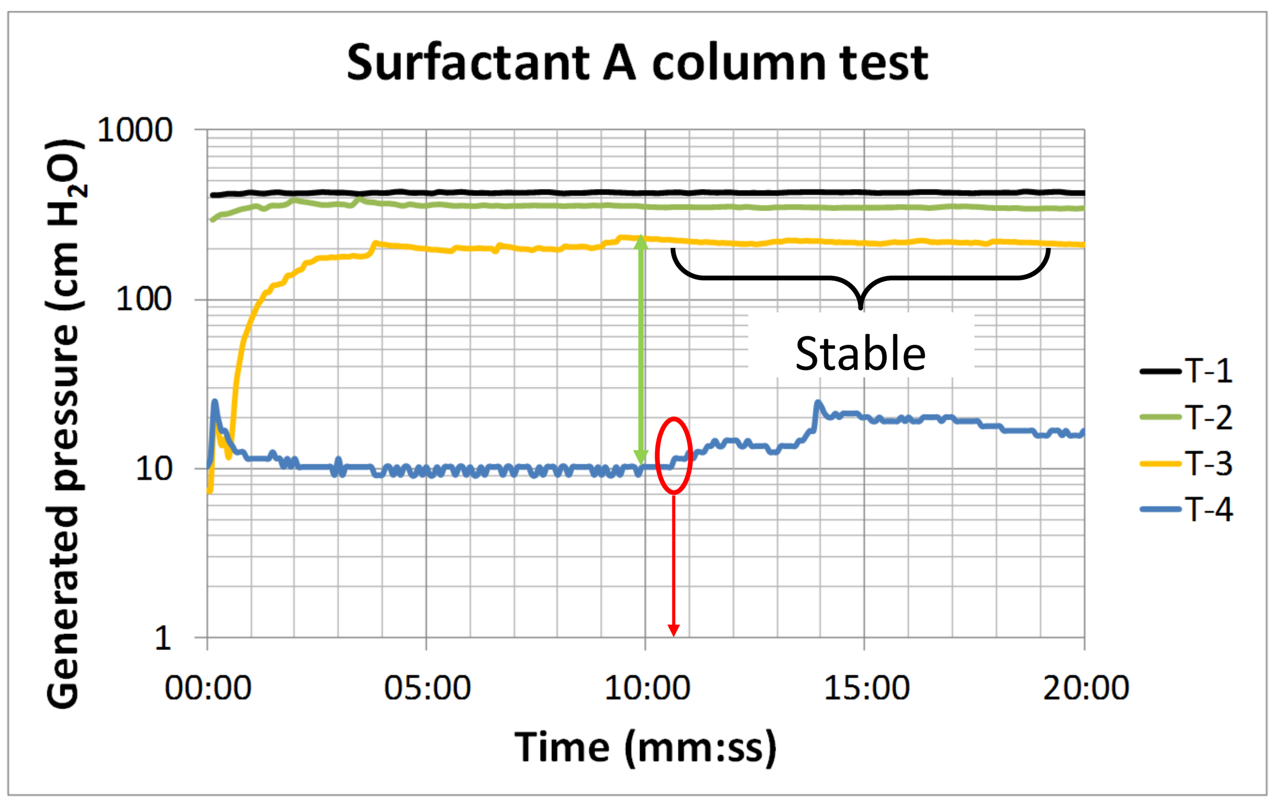
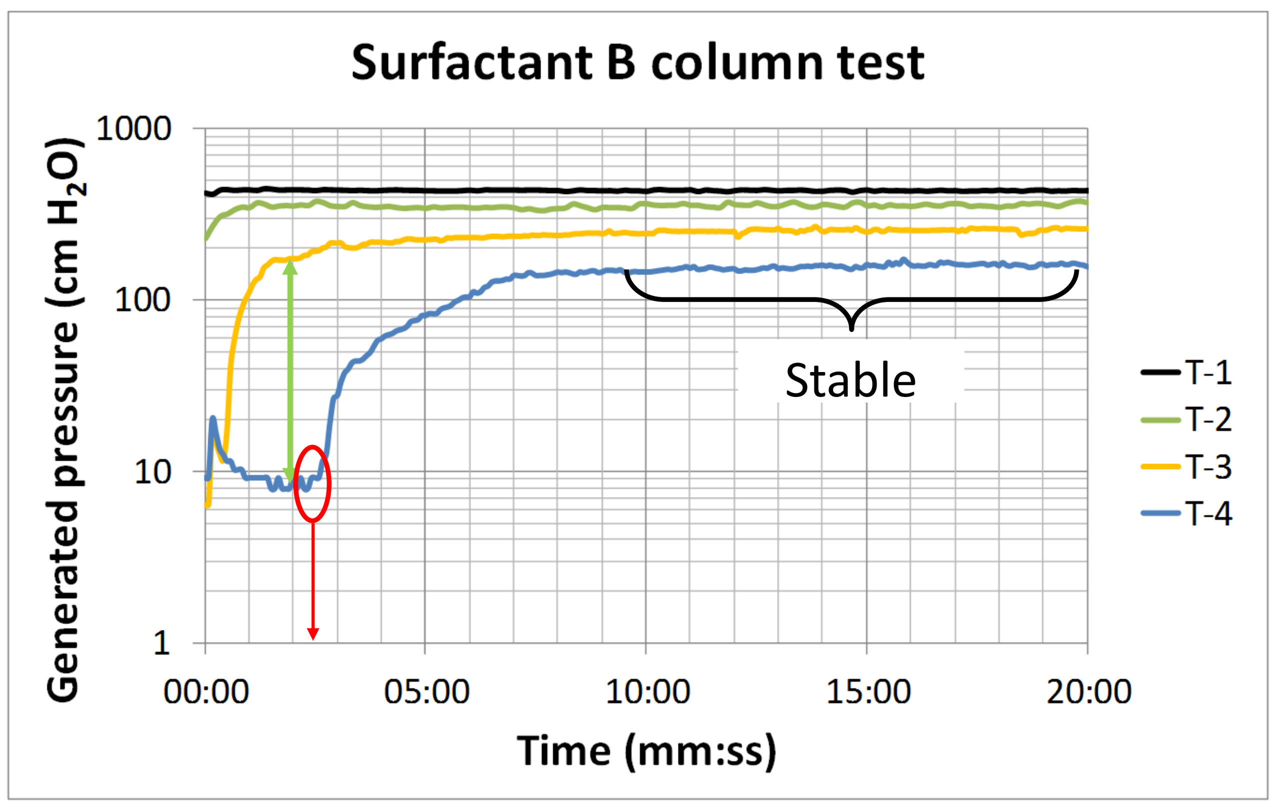
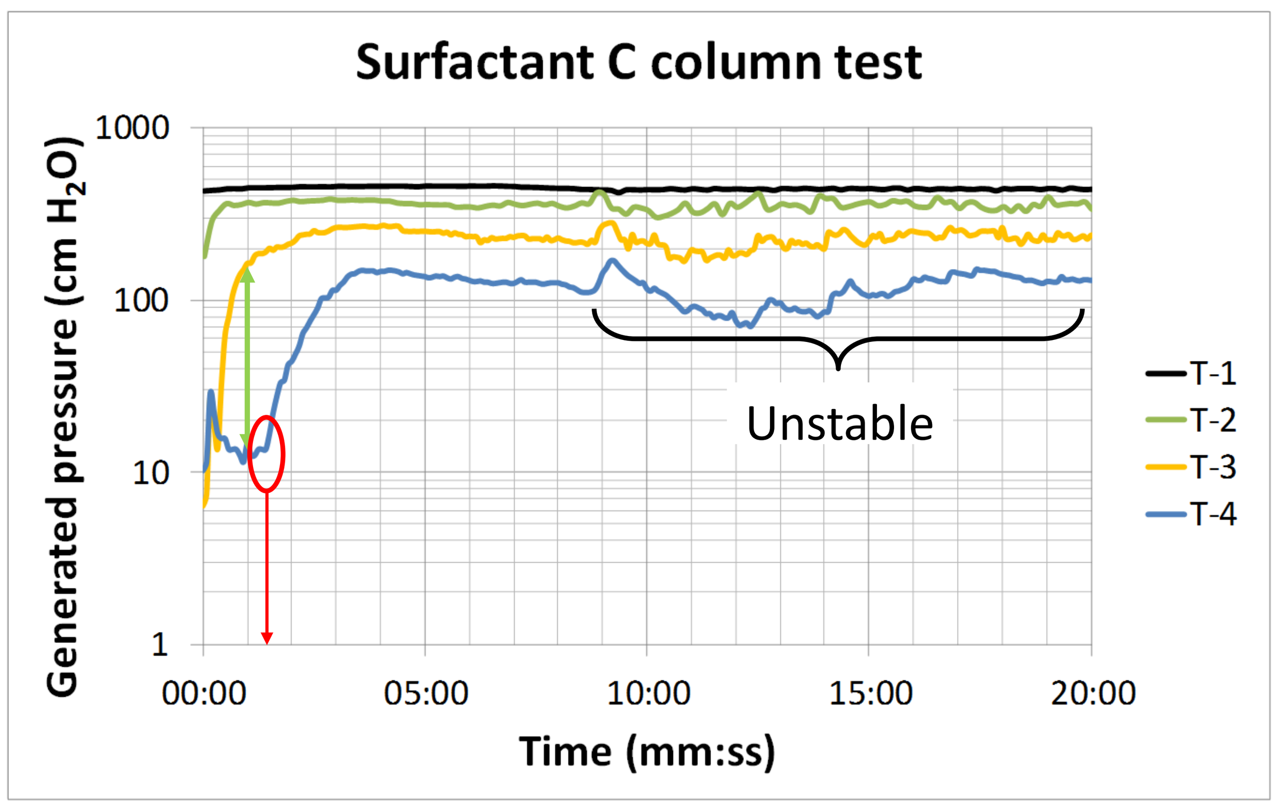


Figure 9 - 350 cm Foam injection time (min:sec)
00:35 01:30 01:55

Foam Behavior in Sand Column







Those graphs are the raw measures of pressure transducers throughout column tests.

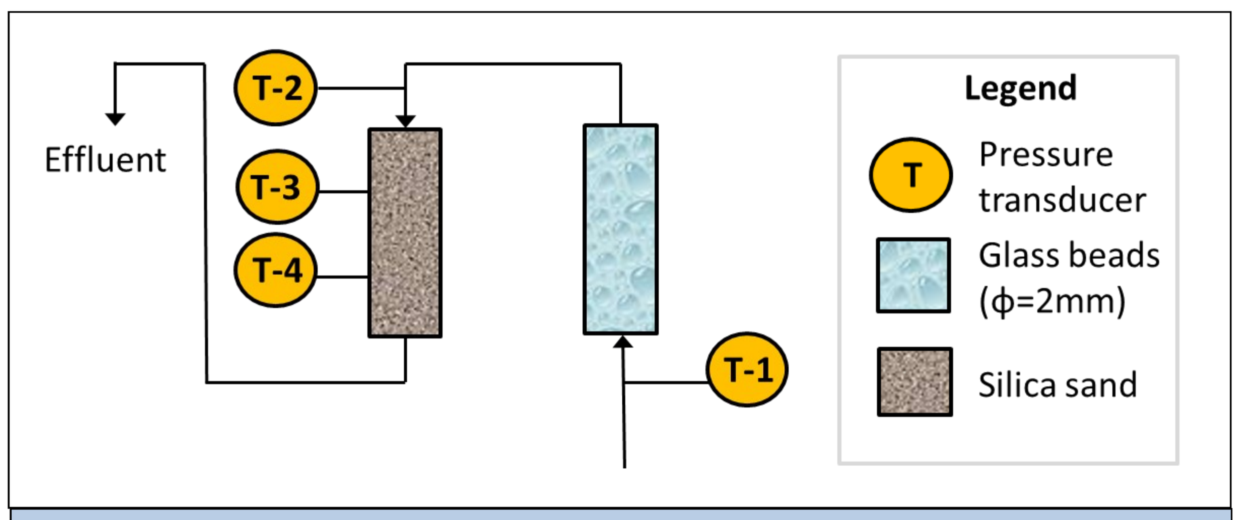


Figure 10 - Pressure transducers positions

: Time at which the front passes the transducer T-4

- Surfactant A → 10:30
- Surfactant B → 02:30
- Surfactant C → 01:00

The more viscous foam is, the longer time it takes for the front to reach T-4. So, surfactant A is the most viscous and C the least.

: Pressure drop between T-3 and T-4 before the front passes T-4

- Surfactant A → 214 cm H_2O
- Surfactant B → 182 cm H_2O
- Surfactant C → 152 cm H_2O

The more viscous foam is, the bigger is the pressure drop between T-3 and T-4. Surfactant A is therefore the most viscous and C the least. Those results fit with the Ross Miles tests; Surfactant A has the best foamability and has the greatest viscosity while B is second and C is last.

It is possible to predict foam behavior during column tests with Ross Miles Test.

Key Findings

Conditions to keep a foam front stable: - surfactant pre-flush

- high foam injection pressure

Surfactants foamability can be compared with Ross Miles test to predict their behavior during silica sand column tests

Future Works

- Column tests with other foam production methods
- Column tests with other media (different grain size)
- Column tests with LNAPL
- 2D Sandbox tests with heterogeneous soils

Figure 11 - 2D Sandbox filled with silica sand

Aknowledgements

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References

Pankow, J.F. and Cherry, J.A., ed., 1996: Dense chlorinated solvents and other DNAPLs in ground water. Waterloo Press, Portland, Or., 522 p.