X-RAY COMPUTED TOMOGRAPHY STUDY OF FOAM INJECTION FOR THE ENHANCED RECOVERY OF DIESEL FUEL IN CONTAMINATED SOILS

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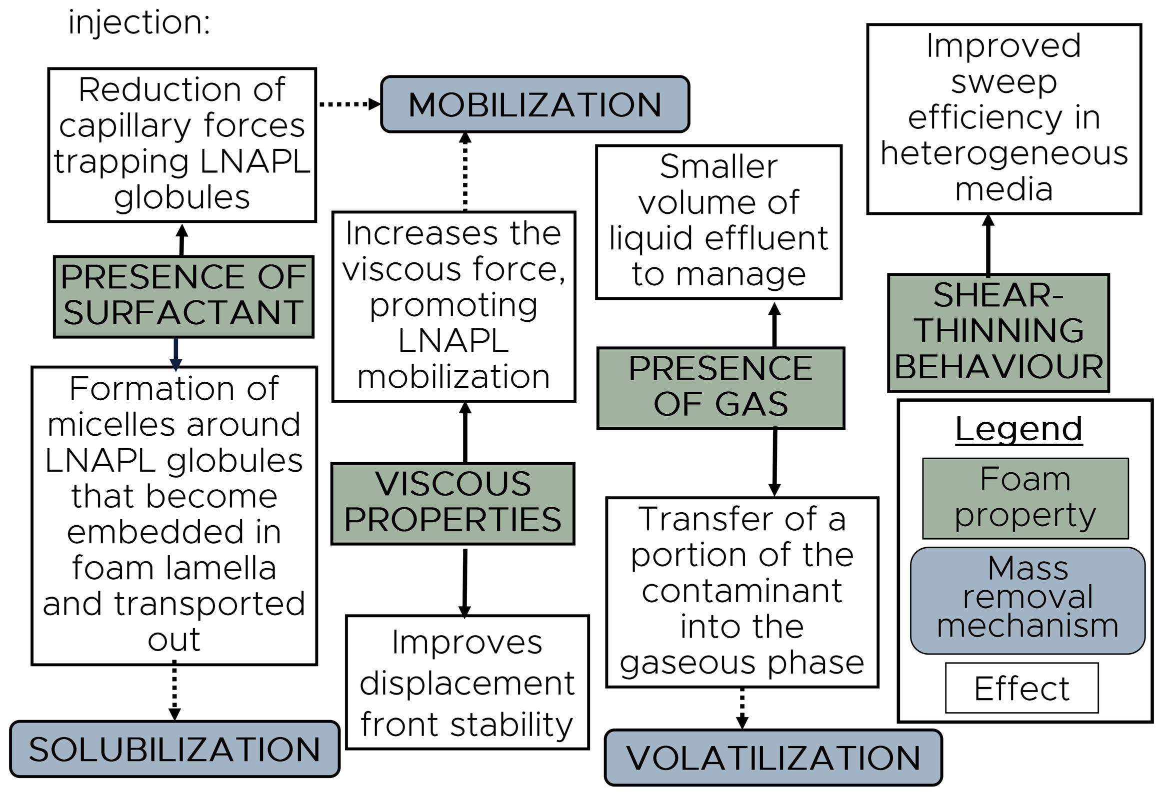
Context

- This project focuses on optimization of the surfactant foam injection technology for the recovery of Light Non-Aqueous Phase Liquids (LNAPL) from soil via mobilisation, as it is the most efficient mass removal mechanism (compared to volatilization and solubilization).
- Experiments were designed around a hypothetical scenario: meet remedial objectives in soil at an operating industrial site with a relatively deep groundwater table (≥ 7 mbgs).
- We envision that foam injection would be applied as part of a treatment train: following an initial contaminant mass reduction step in the source zone via multiphase vacuum extraction of the LNAPL lens, surfactant foam generated *in situ* would be used to recover the trapped residual saturation.

Theory

Foams present many advantages over surfactant solution injection:



Challenges

- Foam injection proven to improve Enhanced Oil Recovery gas-flooding processes plagued by channeling and gravity override
- Injection pressures in shallow, unconfined aquifers are limited by soil fracturing concerns → foam injection technology not optimized for environmental remediation (ER) applications.
- Ideal operating parameters for foam injection in ER are not well understood, difficult to study:
  - When column experiments rely on effluent sample analysis, information is lost due to the time delay between the occurrence of displacement mechanisms in the medium, and production of the associated effluent fluids.
  - Organic dyes are used to study NAPL displacement by foam in micromodels: parameters quantified visually in these tightly-controlled experiments (bubble density, NAPL saturation) are not easily measured in experiments where soil constitutes the porous medium.

Hypothesis

By fine-tuning foam injection operating parameters, it is possible to achieve immiscible displacement of an organic contaminant (resulting in significant mass recovery) while maintaining low injection pressures that are feasible to implement at the field scale.

Project Objectives

1. Optimize the medical CT-scanner at INRS-ETE for imaging three-phase (diesel fuel, water, air) flow experiments in sand columns; develop an algorithm capable of extracting saturation profiles for each fluid from CT images, and test accuracy of the results.
2. Evaluate whether the information extracted from CT images can improve our understanding of the complex interdependence between foam morphology, LNAPL saturation distribution, pressure gradient, and contaminant removal efficiency.
3. Using the lab experiment results, evaluate the field-scale applicability range (initial contaminant concentrations, depths to source zone, soil permeabilities, injection-recovery well spacings) of the foam injection protocols tested.

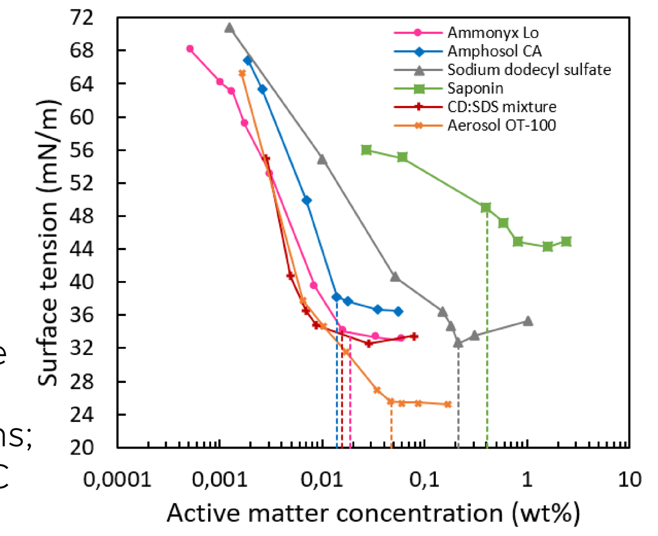
Surfactant Screening

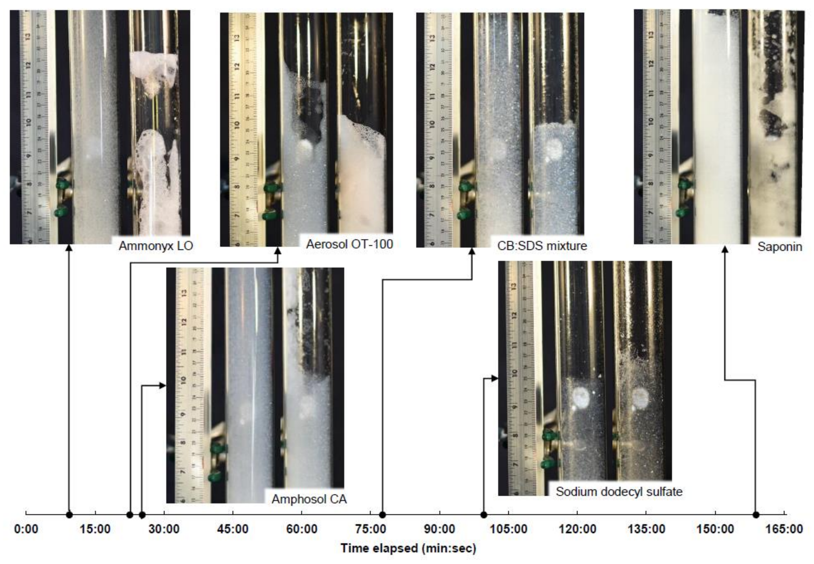
6 surfactant candidates were screened for their ability to generate and propagate strong foam inside the contaminated sand column.

a) Characterization of physical properties

- Critical micelle concentration (CMC) of each surfactant determined experimentally using surface tension–active matter concentration isotherms;
- Measuring density and viscosity of 20 CMC solutions;
- Measuring interfacial tension (IFT) between 20 CMC solutions and diesel
- **Key result:** IFT values rank as follows

Aerosol OT-100 < CB-SDS mixture < Ammonyx Lo < Amphosol CA < Sodium dodecyl sulfate < Saponin



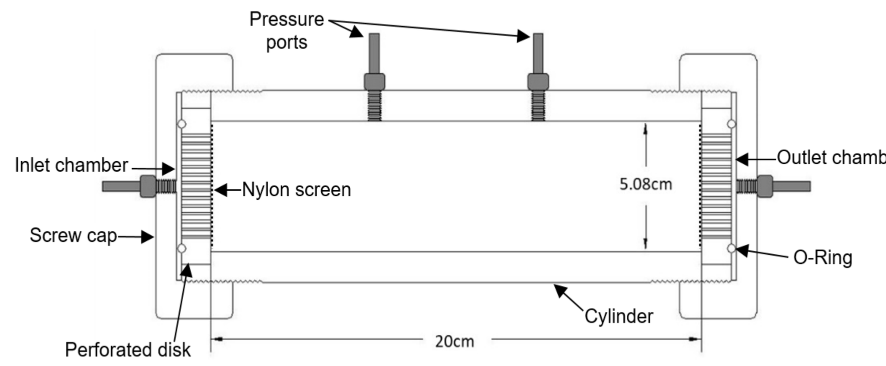


b) Bulk foam stability tests

- Using a glass column into which fixed quantities of surfactant solution and diesel were placed, air was bubbled through a sintered glass disk at the bottom of the column via a pressurized air line. Once the resulting foam column reached a given height, the air was shut off and foam height reduction was monitored over time to estimate the foam's half-life.
- **Key result**: The results suggested that Saponin might be the best candidate for displacing an organic phase using foam

c) Preliminary foam flow-rate tests

- Co-injection foam tests were carried out for each surfactant solution in Teflon columns packed with silica sand contaminated with diesel at residual saturation. The gas fractional flow rate was set at 0.85. The total foam flow rate (Q_{foam}), initially fixed at 10 mL/min, was increased stepwise in 5 mL/min increments, until a continuously increasing pressure gradient was induced along the column (signifying that generation and propagation of foam is occurring).
- The idea behind this approach was to determine the minimal Q_{foam} required to initiate strong foam generation in the presence of a residual organic phase, while minimizing pressure gradients.
- **Key result**: none of the surfactant candidates were able to induce a measureable increase in pressure gradient in the column, except for the CB:SDS mixture.



CT Scan parameters and algorithm used

- Optimized imaging protocol used:
  - Doping agent (1-iododecane) added to LNAPL @ 20 wt%;
  - Slice thickness of 0.4 mm;
  - Medium-resolution (U40u) kernel;
  - Tube voltages of 140 kVp (high-Σ level) and 80 kVp (low-Σ level).
- A three-part algorithm was developed and applied:
  1. Multiple scan averaging to reduce image noise;
  2. An image realignment code;
  3. Matrix operations to calculate fluid saturations (S_{oil}, S_{gas}, S_{water}):

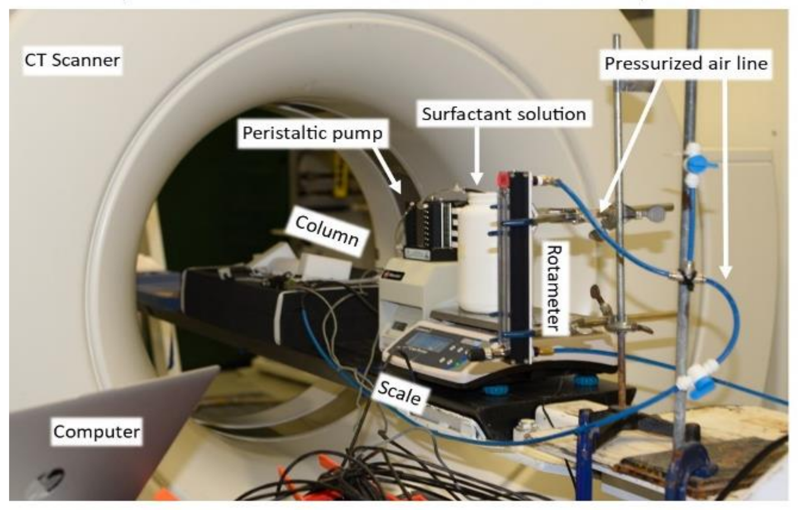
$$S_{oil} = \frac{[(CT_{wet})_1-(CT_{dry})_1][(CT_{wog})_2-(CT_{dry})_2]-[(CT_{wet})_2-(CT_{dry})_2][(CT_{wog})_1-(CT_{dry})_1]}{[(CT_{oil})_2-(CT_{dry})_2][(CT_{wet})_1-(CT_{dry})_1]-[(CT_{oil})_1-(CT_{dry})_1][(CT_{wet})_2-(CT_{dry})_2]}$$

$$S_{gas} = 1 - \left[\frac{(CT_{wog})_1 - (CT_{dry})_1}{(CT_{Sor})_1 - (CT_{dry})_1}\right]$$

$$S_{water} = 1 - S_{oil} - S_{gas}$$

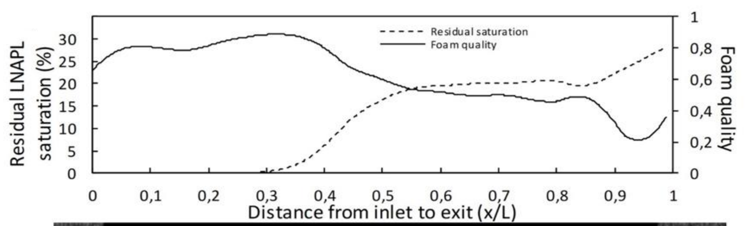
CT-Scan Study of Foam Injection

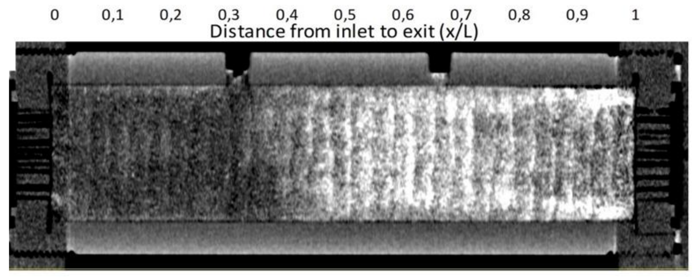
- The surfactant candidate that presented the most promising results in the screening process (CB:SDS mixture) was selected for further testing in 2 final foam injection experiments with CT imaging, performed respectively at high and low pressure for comparison purposes.
- The column was imaged 11 times during each test.
- The optimized Q_{foam} value determined from the preliminary foam flow-rate test was used.

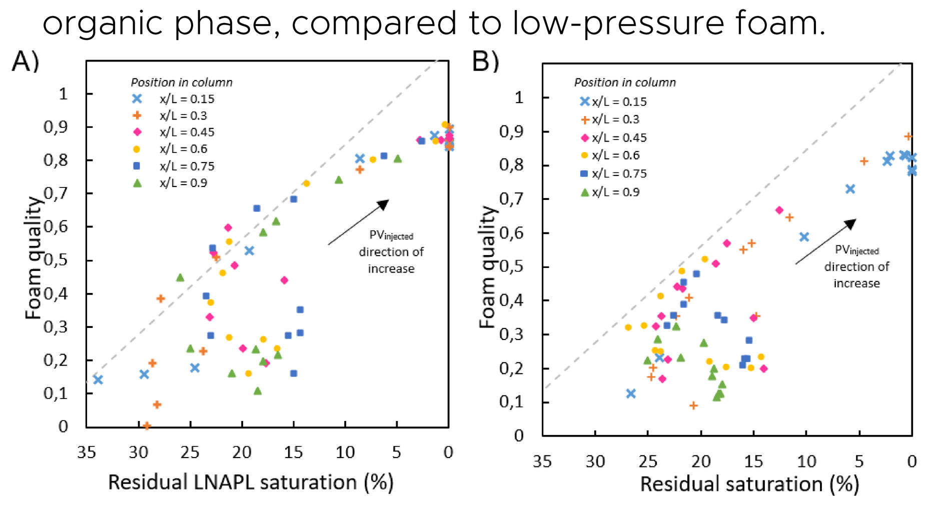


LNAPL desaturation dynamics

- In the high-pressure test (A), high foam qualities were observed to coexist with high LNAPL saturations at given positions within the porous medium. This was not observed for the low-pressure test (B).
- Suggests that high-pressure foam may be more resistant to collapse when it enters into contact with an organic phase, compared to low-pressure foam.

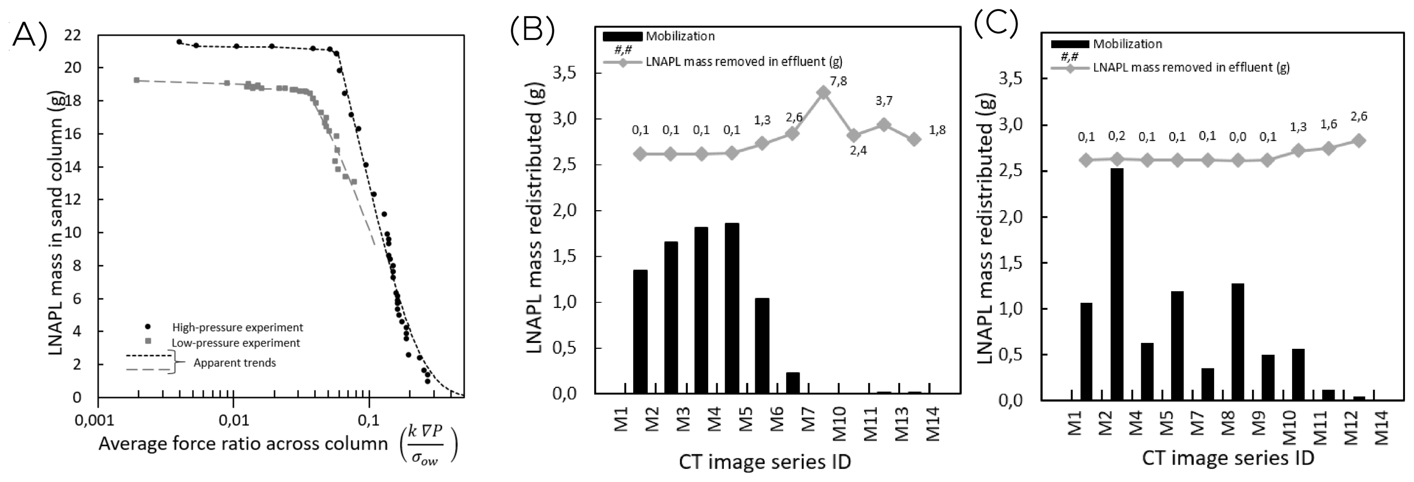






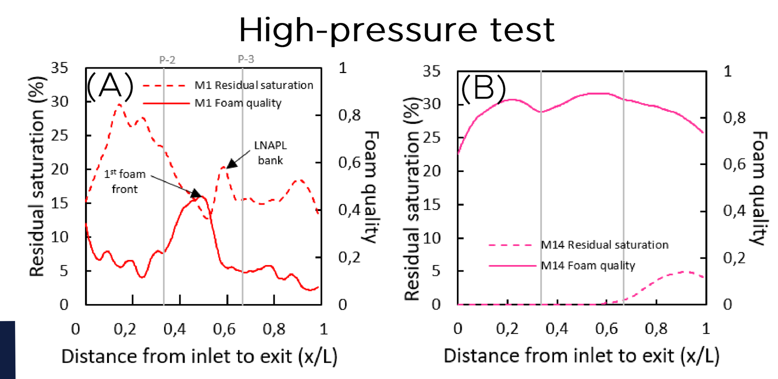
Mass balance and Investigation of recovery mechanisms

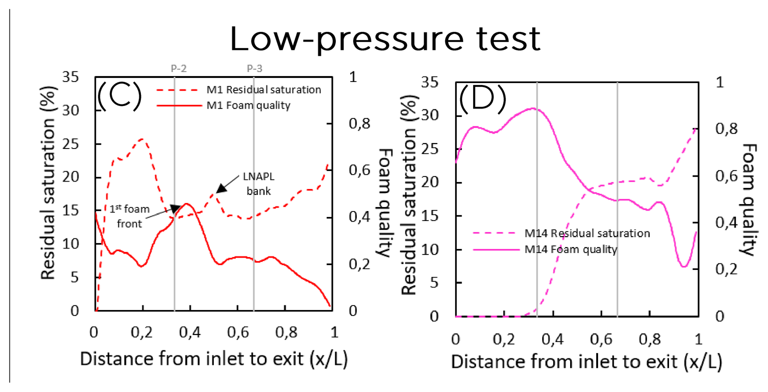
- Column effluents were collected, C_{10}-C_{50} analyzed to quantify diesel recovery.
- Together with the reduced capillary force, the strong viscous forces involved in the high-pressure test enabled complete capillary desaturation (96% removal), while the low-pressure experiment resulted in low LNAPL mass removal (32%) (A).
- Mobilization was the dominant removal mechanism for both the high- and low-pressure experiments, though the contribution of solubilization to overall mass recovery was slightly higher in the low-pressure experiment.
- For both the high-pressure (B) and low-pressure (C) experiments, the fluid saturation profiles indicate that redistribution of LNAPL mass within the column by mobilization began in the early stages of injection (i.e. before M1).



Evolution of foam morphology

- *In situ* foam quality was independent of injected foam quality early in both experiments (A and C). Morphology of the foam was dictated by the conditions inside the porous medium, including LNAPL saturation and distribution, and uneven pressure profiles in the column.
- The foam quality profiles obtained showed that within the sand column sections where significant desaturation was achieved (B and D), *in situ* foam qualities were similar in both experiments, regardless of the magnitude of the pressure gradient across the column.





Conclusion and Future Work

- The types of analyses presented in this study, made possible through CT imaging techniques, can be of valuable use to future laboratory-scale studies focused on optimizing the foam injection technology for low-pressure scenarios without compromising LNAPL mass recovery.
- Future efforts should be focused on optimizing the surfactant solution formulation to achieve ultra-low IFT values, and on developing an injection strategy that limits pore plugging by viscous foam.

References

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INRS Institut national de la recherche scientifique

Université du Québec

Lab CT Scan
Laboratoire multidisciplinaire de tomodensitométrie pour les ressources naturelles et le génie civil

NSERC CRSNG

Acknowledgements

We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC).