Flow of foamed grout in granular soils

L'’Ecoulement du Couli Mousse dans le Terrain Granuleux

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ABSTRACT
In traditional method of chemical grouting, the soil voids are almost 100% filled with the grout. However, experience has shown that only minor deposition of the grout at the inter-particle contact may be sufficient to achieve the desired improvement of the soil. Minor deposition of the grout is possible by the foaming process in which liquid chemical grout is converted into foamed grout. The flow of chemical grout has been studied by many, but flow of foamed sodium silicate grout has not been investigated since it is a new process. A comprehensive experimental lab study was therefore conducted to study the flow of foamed chemical grout in one-dimensional and two-dimensional models. Experiments were designed to simulate a variety of soil types, moisture conditions, foam injection patterns, etc. Qualitative and quantitative experiments were conducted to assess the efficacy of foam displacement.

RÉSUMÉ
Dans la mcthode traditionnelle du couli chimique, les vides du terrain sont presque 100% remplis du couli. Pourtant, il a ele constate que seul un petit depot au contact inter-particle pourrait suffire pour arriver au niveau voulu d'amélioration du terrain. Un petit depot du couli est possible par le processus de moussage dans lequel le couli chimique liquide se convertait en couli mousse. L'écoulement du couli chimique est largement rccherchee, mais l'écoulement du couli sodium silicate reste encore un domaine peut et die car c'est un nouveau processus. Done, une étude compréhensive expérimentale etatit conduite au laboratoire pour étudier l'écoulement du couli mousse chimique dans des modèles unidimensionnel et bi-dimensienel. Les experiments etaicnt désignes pour simuler une variété de types de terrain, des conditions d'humidité, la façon d'injection de la mousse, etc. Les experiments qualitatifs et quantitatifs ont été conduits pour déterminer l'efficacité du déplacement de la mousse.

Keywords : Chemical grouting, foamed grout, soil improvement, flow of foamed grout.

1 INTRODUCTION

The petro-chemical industry has been studying use of aqueous foam to enhance oil recovery (EOR) since the fifties; considerable research has been done since then to explore various properties of the foam. Use of foam for grouting granular soils to varying degree of cementation is a newly developed technique called foamed grouting process (Ali and Woods, 2009). Liquid chemical grout is converted into foam either before injecting or after injecting it into the soil strata. The flow of liquid chemical grout has been studied by many researchers (Karol 1983), but flow of foamed chemical grout hitherto has not been investigated. Therefore a comprehensive lab research was undertaken to study the flow of foamed grout in different types of soils and its interaction with pore water to facilitate future studies aimed at modeling it. This paper presents experimental results of the flow of foamed grout in one-dimensional (1-D) and two-dimensional (2-D) models. It also presents the results of a microscopic study of the flow of the foamed grout in homogeneous and stratified granular soil.

2 EXPERIMENTAL DESIGN AND PHYSICAL MODEL

Experiments were designed to simulate a variety of soil types, foam injection patterns, and to explore the displacement capabilities of the foamed grout. The materials and equipment used in this study are shown in Table 1. The 1-D models were made of cylindrical plexiglass tube with appropriate fittings at both ends and the 2-D model was fabricated from half inch thick plexiglass sheets. Mainly Ottawa 20-30 sand was packed in the 1-D and the 2-D models, but a few tests were conducted by packing different portions of 1-D model with glass beads and Mortar sand as shown in Figure 1b. In all the experiments an internal foaming process was used for the foam generation (Ali and Woods, 2009). The liquid was injected with a constant flow rate pump and the flow of air was controlled by a pressure regulator. Qualitative and quantitative experiments were conducted to assess the efficacy of foamed grout displacement. For qualitative experiments, video camera and still photographs were used to record the displacement of water by the foam. To quantify these data, sand from the model was removed after the experiments and soaked in clean water to see the color of the water in addition to microscopic observations of the sand.

3 SELECTION OF THE SURFACTANTS

3.1 Selection Criteria

A surfactant (abbreviation of surface-active agent) is a new component, which hitherto has not been added to sodium silicate grout. There is no standard procedure for the selection of surfactants for engineering use. For foam chemical grouting, the surfactant was selected based on the following criteria:

Table 1. Materials used in the Experiments

Material	Types	Name
Sands	3	a. Ottawa 20-30 b. Mortar c Glass beads
Surfactants	2	a. Bio Terge AS40
Models	3	a. 1-D (13 in. long) b. 1- D (45 in.
Chemical grout		Sodium silicate +

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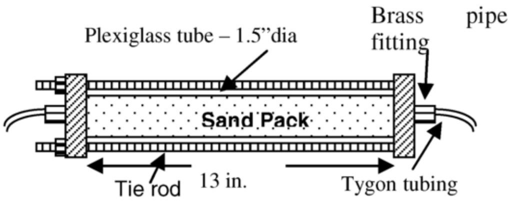
- Good foaming agent for the sodium silicate grout system
- Easy availability
- Moderate or low cost
- Low toxicity
- Biodegradability

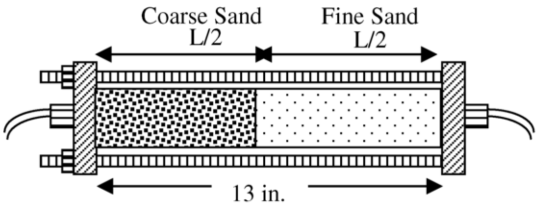
3.2 Screening Process

A screening procedure similar to others (Bernard, Holm, and Jacobs, 1965) was devised and implemented. Figure 2 shows the flow chart of the overall screening process. Numerous promising surfactants with desirable characteristics were collected from different manufacturers. Most of the surfactants performed well in sodium silicate solution, but only few of them generated foamed when ethyl acetate was added to the sodium silicate. Two surfactants which proved to be most suitable and used for the foamed grouting were:

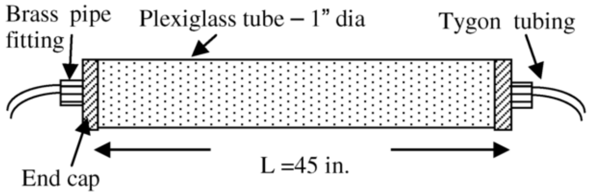
- Bio Terge AS-40
- DowFax 2AO



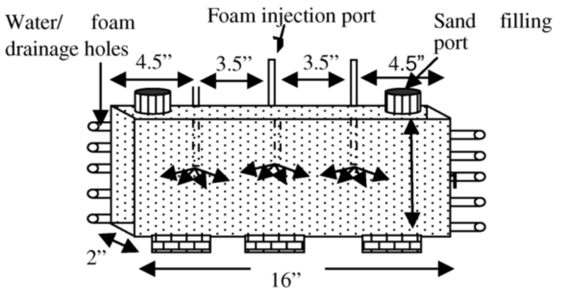
a. 13" 1-D plexiglass model.



b. 13" 1-D plexiglass



c. 45" 1-D plexiglass model.



d. 2-D model filled with sand.

Figure 1. Components and dimensions of 1-D and 2-D Models.

4 FOAM CHARACTERISTICS

Critical Micelle Concentration (CMC), foam quality, and foam stability are the most important properties of the foam. Micelle formation is the property of surface-active solutes to form colloidal sized clusters in solution; foam quality is the abilities of different liquids and surfactants to produce foam; foam stability relates to the persistence or the life of foam. The selected surfactant should not only be able to generate ample foam in a given chemical environment, but the foam should also be stable. The CMC of the surfactants was determined by measuring surface tension using the ring method (Milton, 1987). Contrary to the traditional Ross-Miles method, a foam generator was used to generate foam from the sodium silicate grout to study its quality. Measured volumes of foam at different air-liquid ratios were collected in a graduated glass cylinders and the corresponding flow times were recorded. The quality of foam was calculated from these volumes using equation given by Darsh et al, (1988). In this study, the stability of the foam was determined by two methods: 1) generate a column of foam in a glass cylinder and measure the height of the column after some time intervals; and 2) generate a column of foam in a glass cylinder and measure the rate of drainage of the liquid film at bottom of the cylinder. The stability decreases as the quality of the foam decreases.

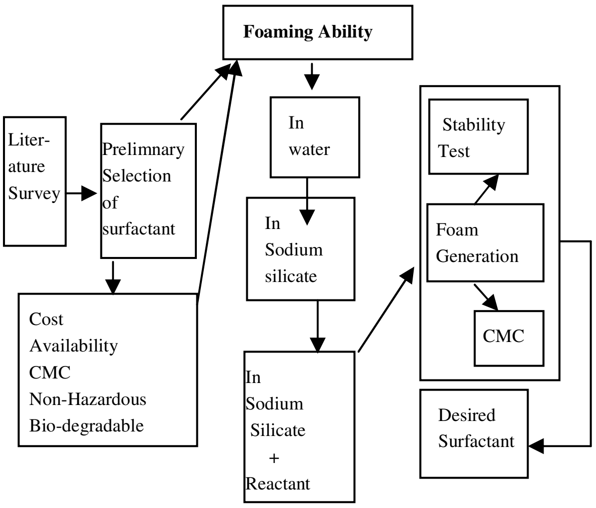


Figure 2. Flow chart for screening and selection of surfactants.

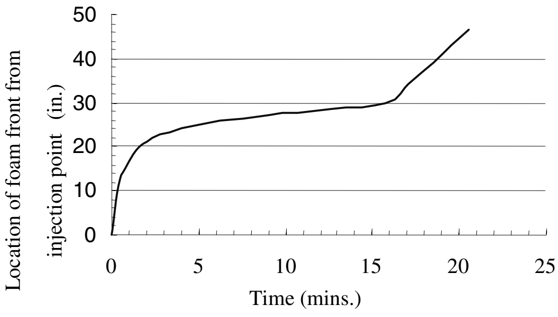


Figure 3. Location of foam front versus time in 45 in. model.

5 FOAM-WATER DISPLACEMENT

This section presents the results of the foamed grout-water displacement experiments in the 1-D and 2-D models. The experimental procedure was as follows:

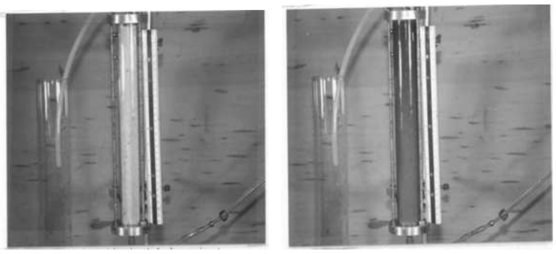
1) pack the model with sand to the desired density;
2) saturate the model with red colored water to facilitate observation of the foam front;
3) connect the model to the foam generation/ injection apparatus;
4) generate/ inject foam in the model until all the colored water is expelled from the model;
5) remove the sand from the model in a white clean ceramic container, and fill the container with clean water and

observe the color of the water (hereafter referred to as wash water).

5.1 *1-D Experiments*

The 13 in. 1-D model was held vertical and the foam was injected from the bottom of the model whereas the 45 in. 1-D model was held horizontal and the foam was injected from one end. All the experiments were performed by packing the 1-D models with Ottawa 20-30 sand. Figure 3 shows the location of the foam front at different times in the 45 in. model. It can be noted from the figure that the foam front advances fast in the first 20 in. of the model, and then the advance rate decreases in the next 10 in. because of the pressure head losses, and large length of the foam column and greater volume of pore liquid to be pushed. In the last quarter of the model, the foam front again advances slightly faster because the volume of the pore fluid has decreased.

Figure 4 show various stages of the 1-D experiments; Figures 4c and 4d explicitly show that the foamed grout advances with a very clear and distinct front; no fingering phenomenon was observed. A mass balance of the liquid grout in the model was performed and at the end of the test, only 20 ml. of the liquid grout in the form of foam occupied the entire pore volume (PV=206 ml). Also the wash water was clean and showed no trace of red color.



a. Clean sand packed in the model and ready for experiment.

b. Sand saturated with red colored water.

c. Interface of the foam-water in 13 in. model.

d. Interface of foam-water in 45 in. model.

Figure 4. Various stages of the foam-water displacement experiment in 1-D models.

5.2 *2-D Experiments*

All the experiments were conducted by packing the 2-D model with 20-30 Ottawa sand. Three injection ports were installed at the top of the model for injection of foam. Five holes were drilled on each short side to simulate pervious boundaries on the sides. No drainage was allowed from the top and bottom to simulate impervious boundaries.

5.2.1 *1-Point Injection*

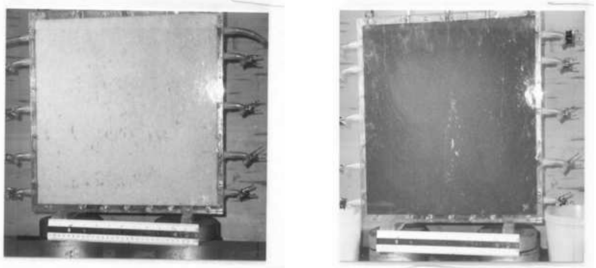
Various stages of this 2-D experiment are shown in Figure 5. After saturating the model with red colored water, the side drains were opened to reach residual saturation under the influence of gravity. The foam was injected from the center port only, and the two side injection ports were closed. The foam expanded in the form of a circular bulb, as shown in Figure 5c, with a clear sharp foam front expelling all the colored water from of the bulb. The foam was injected until the color of the foam draining out of the model was absolutely clear as shown in Figure 5d. The liquid drained out of the model was collected for the mass balance calculations; 117 ml. of liquid grout in the form of foam occupied the entire pore volume (1075 ml.) of the model at the end of the test; this volume of liquid grout can be further reduced by injecting air (only) for a longer time. The wash water was absolutely clear with no traces of red colour.

5.2.2 *Two Point - Simultaneous Injection*

The aim of this experiment was to observe the behavior of the foam fronts when they come in contact, to simulate field condition where foamed grout is simultaneously injected through numerous adjacent holes. It was observed from the experiment (Figure 6) that the foam fronts expanded all around in a circular fashion like the previous experiments and purged all water from the bulb. The water pushed by one foam front did not enter into the other bulb but instead moved along the boundaries of the bulb, and out of the model through the drain holes. The wash water was clear and showed no sign of the red color.

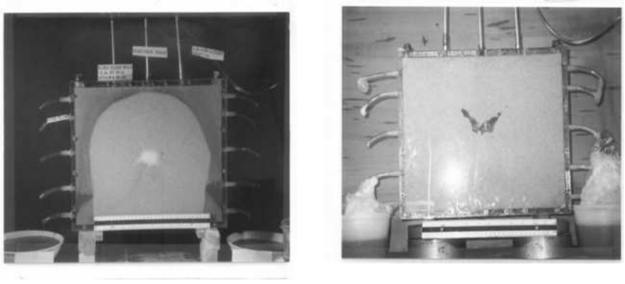
5.2.3 *Sequential Injection from Two Points*

This experiment simulated the field conditions where foam is injected through one set of holes, and then through an adjacent set of holes. In this experiment the foam was first injected from the right port only, and when the foam front reached the center of the model, as shown in Figure 7a, foam injection was stopped from right port, and then the injection started from the left port only, and continued till all the model was purged of the colored water. It was observed that the water pushed by the second foam front did not enter the area cleared by the first foam front, but instead moved around edges of the first bulb and eventually out of the model. This behavior may be explained by the fact that the foam in the first bulb had enough pressure to resist the penetration of foam and water pushed by the second foam front.



a. 2-D model packed with Ottawa 20-30 sand.

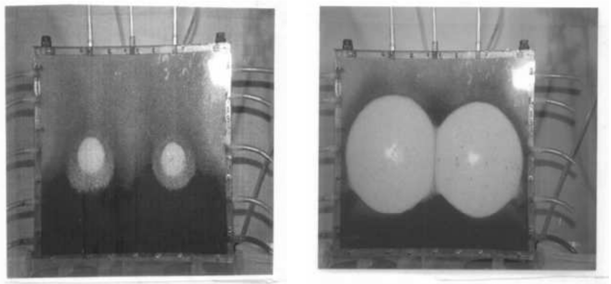
b. 2-D model saturated with colored water.



c. The foam bulb.

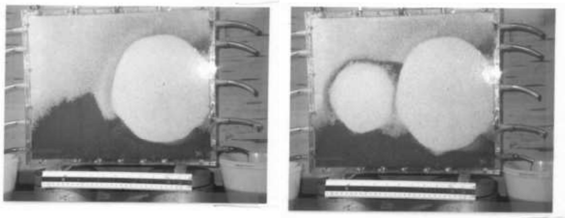
d. Model after completion of the experiment.

Figure 5. Various stages of 2-D experiment (one point injection).



a. Formation of the two bulbs. b. Foam fronts in contact..

Figure 6. Simultaneous injection of foam from two ports.

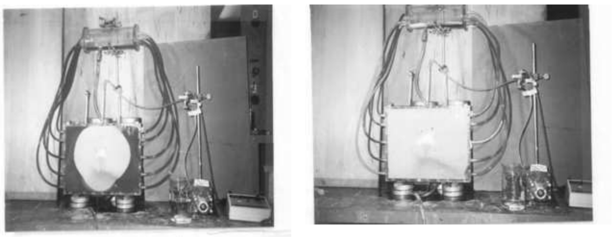


a. Injection of foam from the right port only. b. Injection of foam from the left port only.

Figure 7. Sequential injection of foam from two ports.

5.2.4 One Point Injection in Saturated Soil

This experiment was designed to assess the ability of the foamed grout to expel pore fluid from some depth below the ground water table. The apparatus setup is shown in Figure 8; the model was saturated with colored water flowing under gravity from the overhead reservoir as shown. Foam was injected from the middle injection port only and it was observed that the foam cleared the area in the shape of a bulb as before, and pushed the water from the model back into the overhead reservoir as shown in Figure 8a and b. There was no trace of the red color in the wash water.



a. The colored water being pushed out the model and into the reservior.

b. The model cleared of the dyed water.

Figure 8. Dyed water pushed out of the model and into the reservoir located at some height above the model.

6 MICROSCOPIC STUDY

Several studies (Owete, 1987; Raza, 1970; etc.) have been carried out to investigate the macroscopic/ microscopic flow of foam in homogeneous or heterogeneous porous media in the laboratory, but there is hardly any study on the flow of foam in a stratified soil zone. This experiment was designed to simulate stratified soil conditions in the field. The direction of the flow of foam was perpendicular to the stratification. The 13 in. model was filled with glass beads in one half and Mortar 6-10 sand in the other half to simulate a coarse and fine sand layer, respectively. A CCTV system alongwith stereo-zoom microscope, allows collection of real-time images for analysis at a latter stage. The stereo-zoom microscope can magnify the image by a factor of 10X to 70X.

6.1 *Flow in Homogeneous Material*

Foam flows through the soil matrix by occasional merging and splitting of adjacent bubbles or by a "break-reform process";as observed by Owete (1982).

6.2 *Flow from Fine to Coarse Sand*

When the foam flowed from the finer sand to the coarser sand, or in other words, when the foam was generated in the fine soil, the size of the bubbles was very small, moved through the coarser size and their size remained almost unchanged except for a very few which grew in size.

6.3 *Flow from Coarse to Fine Sand*

The size of the foam bubbles generated by the coarse sand was larger than those generated by the finer sand. It was observed that, when foam moved from coarse to fine sand, the larger foam bubbles separated themselves into smaller bubbles, depending on the size of the pore throat and the pore space. Contrary to the previous case, where a number of small bubbles could be accommodated in the pore space of coarse sand pores, in this case it was found that at times only one foam bubble occupied the whole pore space in the finer sand.

7 CONCLUSION

The findings of this research agree fairly well with the previous studies performed by researchers in the petro-chemical field. The foam moves with a clear/ distinct front and purges all the pore fluid in the soil mass. Therefore foam grouting may not be used only for contact grouting of soil but it may also be an efficient and cost-effective means of decontamination of subsurface formations. The mass balance calculations show that a small volume of surfactant solution in the form of foam can occupy a large pore space. It was observed in this study that foam is much more stable in the porous media than in the glass cylinder as the foam bubbles were observed in sand samples even after 2 to 3 days when they were removed from the models.

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