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Journal of Hazardous Materials 62 (1998) 265–280

JOURNAL OF HAZARDOUS MATERIALS

Foam propagation through soils for enhanced in-situ remediation

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Received 11 July 1997; revised 20 July 1998; accepted 22 July 1998

Abstract

The use of gas–liquid foams as a means of delivering chemicals to the subsurface is being considered as an aid to in-situ soil remediation schemes involving bioremediation, chemical oxidation and soil washing. Experiments were conducted to investigate the physics of foam flow in soils and to identify parameters that are important to allow foam injection at low pressures so as to avoid problems due to channelling and soil heaving. Gas–liquid foams of quality (gas-content) ranging from 87 to 99% were flowed through soils of permeability ranging from 0.09 to 900 darcy (0.09 to 900 μm^2) in vertical columns 3 in. (7.6 cm) in diameter. Surfactant solutions used for foam generation included an aqueous anionic surfactant Standapol ES-2 and two ethanol-based surfactants developed for in-situ soil flushing. These foams behaved as highly viscous fluids in flowing through soils; the apparent viscosity increased with increasing soil permeability. Foams seem to break and regenerate. At steady state, there was a net accumulation of liquid in the pore space. Based on material balance calculations, liquid content in the soil ranged from 7 to 59%. This is much higher than the liquid content of the injected or produced foam. It was observed that pressure gradients for downflow were only a fraction of that for upflow. The results also suggest that low pressure gradients can be obtained by using foams of higher quality (gas content) and a foaming agent that provides good foamability but low foam stability.

Keywords: Soil remediation; In-situ remediation; Foam; Surfactant; Soil-flushing; Polyaromatic hydrocarbons; PAH; MGP sites

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PII: S0304-3894(98)00191-5

1. Introduction

Foams are being developed as a promising new medium to carry amendments for in-situ remediation of sites contaminated with chlorinated and non-chlorinated organic compounds including polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) [1,2]. Foams display properties that are vastly different from the fluids that constitute the foam. They have been used by the oil industry for enhanced oil recovery (EOR) processes, primarily as a mobility control agent to help prevent channelling of injected fluids into high permeability zones of an oil bearing formation [3–5]. There are, however, several differences between the use of foams in oil recovery and their intended use in soil remediation. Oil recovery operations generally occur deep underground, in consolidated rocks where high injection pressures are permissible. Soil remediation is conducted in unconsolidated soils generally at 10 to 30 ft (3 to 9 m) depth, where high injection pressures can cause soil heaving and fracturing. While displacement of mobile oil is the primary purpose of EOR processes, the use of foams in vadose zone soil remediation schemes would be to either deliver nutrients and render contaminants more available for bioremediation, or to dissolve/emulsify the soil contaminants in a soil flushing process.

While bioremediation is the most widely applied approach to the in-situ remediation of non-volatile organic waste contaminated soils, the use of chemical oxidation and solvent flushing have also been investigated [1,6], either as independent processes or in combination with biological degradation. The latter have particular applicability to the treatment of soils contaminated with recalcitrant compounds such as 4–6 ring PAHs. Efficient operation of an in-situ bioremediation process depends on the efficient delivery of oxygen, moisture and nutrients to the subsurface, good soil/liquid contact and good transfer of contaminants to the liquid phase. The use of foams is being considered for delivering the necessary amendments for this process. Potential advantages are reduced effects of soil heterogeneity and the fact that surfactants used to generate the foam can also improve soil wettability and contaminant desorption. Another advantage of using a foam is the large surface area of the liquid in the foam compared to the air–liquid interface without foam. Gaseous nutrients, which have been used in some remediation tests [7], can also be incorporated into the foam formulation.

In-situ soil flushing involves the use of an appropriate surfactant solution or solvent and can be used to dissolve or emulsify the contaminants and bring them to the surface for disposal/destruction or above the ground bioremediation. Ethanol based surfactant systems have been developed for this treatment scheme [1]. In soil flushing, a major concern is the need to contain treatment fluids to the remediation zone. Migration of fluids containing dissolved contaminants away from the treatment zone can lead to spreading of the contaminated zone, and is of particular concern if the fluids migrate down to the groundwater [8,9]. Potential advantages that the use of foams in this treatment scheme can provide are better control on the volume of fluids injected, uniformity of contact, and the ability to contain the migration of contaminant laden liquids.

The selection of a foam formulation depends on several factors which are often site-specific. These include the potential loss of surfactant by adsorption on soil [10], the loss of foamability due to contaminant dissolution [11], and the pressure required to inject the foam [1,2]. From a physical perspective, to prevent problems due to channelling or soil heaving it is necessary to restrict injection pressure to about 1 psi/ft (22.6 kPa/m) of depth, corresponding to the weight of the soil overburden. The objective of the work reported here was to investigate the pressure gradients during the flow of foam through soils with the intention of identifying factors that are important to the propagation of foam at low pressure gradients.

2. Characteristic properties of foams

The foams considered here may be defined as relatively stable and homogeneous dispersions of gas in a foaming-agent solution containing a surfactant. The physical structure of the foam, and many of the properties depend on the relative proportion of gas and liquid constituting the foam. The *Quality* of a foam is a term used to specify the gas content of a foam. It is defined as

$$\text{Foam Quality} = \frac{\text{Gas Volume}}{\text{Total Foam Volume}}$$

Expansion Factor is a parameter used to describe the foamability of a solution. It is defined as

$$\text{Expansion Factor} = \frac{\text{Foam Volume}}{\text{Liquid Volume}}$$

The presence of a gas phase in foams makes foams compressible. Foams can undergo compression and decompression cycles; however, their number is limited by the degradation of the foam [11]. Because of its compressibility, both foam quality and expansion factor depend on the pressure. It is important, therefore to define a reference pressure for the quality. In this paper, *Foam Quality* at atmospheric pressure has been used to define the gas content of the foams.

Another characteristic important to the performance of foams is the stability. Stability of a foam refers to the ability of the foam to resist bubble breakdown. Foam stability in static foam is sometimes quantified by the time required for the drainage of half of the liquid volume (time of half-drainage).

3. Experimental

Initial studies on the nature of foam flow through soils were conducted using the equipment illustrated schematically in Fig. 1. Foam was generated by flowing surfactant solution and air simultaneously through a porous disc. The flow rates of surfactant solution and air could be varied independently in order to control the foam quality and generation rate. The foam was flowed through sand or soil packed in an acrylic cylinder

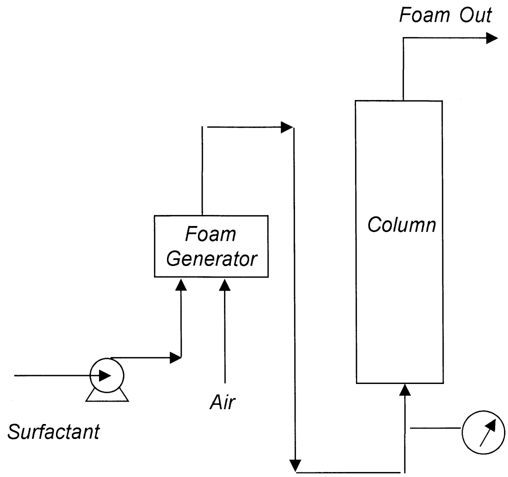

Fig. 1. Schematic of apparatus for foam flow experiments.

1 ft (30.5 cm) long and 3 in. (7.6 cm) in diameter. Foams of quality ranging from 87 to 99% were generated for the experiments and flowed at rates ranging from 10 to 30 cm^3/min. A pressure gauge at the upstream end of the sand pack measured the inlet pressure. The foam always exited the column at atmospheric pressure. The column was held in a vertical position and the foam could be made to flow either up or down by reversing the inlet and outlet connections.

The experiments where foam characteristics were being investigated were conducted using a silica sand of permeability 14 darcy (μm^2), and porosity 39% while experiments designed to include the variation in soil properties included other sand columns of permeability ranging from 0.09 to 900 darcy (μm^2). The soils used included a PAH contaminated silty sand from a former Manufactured Gas Plant (MGP) site. An aqueous foam generated using a 1% solution of an anionic surfactant, Standapol ES-2 (Henkel, Hoboken, NJ), was used in the majority of experiments conducted. This surfactant provided a stable foam that was good for investigating the nature of foam propagation in soils. In addition, two other proprietary surfactant formulations [1] developed at the Institute of Gas Technology (IGT) specifically for use in in-situ soil flushing of PAH contaminated soils were also used in some experiments. These were a solution of IGT FF-13 in 100% ethanol, and a solution of IGT FF-52 in an ethanol–water mixture containing 30 to 40% (v/v) ethanol.

In all the experiments foam was flowed through the sand or soil pack till near steady conditions were achieved in terms of the pressure drop and the texture of the exiting foam, before the pressure gradient data reported here were recorded. This often took several hours, during which period the pressure gradient increased with time. The exact behavior during this transient phase depends on several factors, including whether the soil pack was initially wet or dry, and whether there is a significant adsorption of surfactant from the foam onto the sand or soil.

4. Results

4.1. Effect of foam quality and flow rate on injection pressure

Since the pressure gradient developed during foam flow is one of the key considerations in the use of foams for soil remediation, the effect of injected foam quality on the pressure gradient at various foam flow rates was investigated. Fig. 2 shows the variation of observed pressure drop with foam quality for foam generated using a 1% aqueous solution of Standapol ES-2. The flow rates reported were measured at atmospheric pressure, and correspond to the sum of the volumetric rates of injection of liquid and gas. A significant observation in Fig. 2 is that at qualities greater than around 90% the observed pressure gradient decreased sharply with increasing quality. This decrease is indicative of a possible change in the structure of the foam. It has been observed that the structure of foam is dependent on the quality [11]; higher quality foams consist of larger bubbles with thinner liquid films. It can be expected that the variation of pressure drop

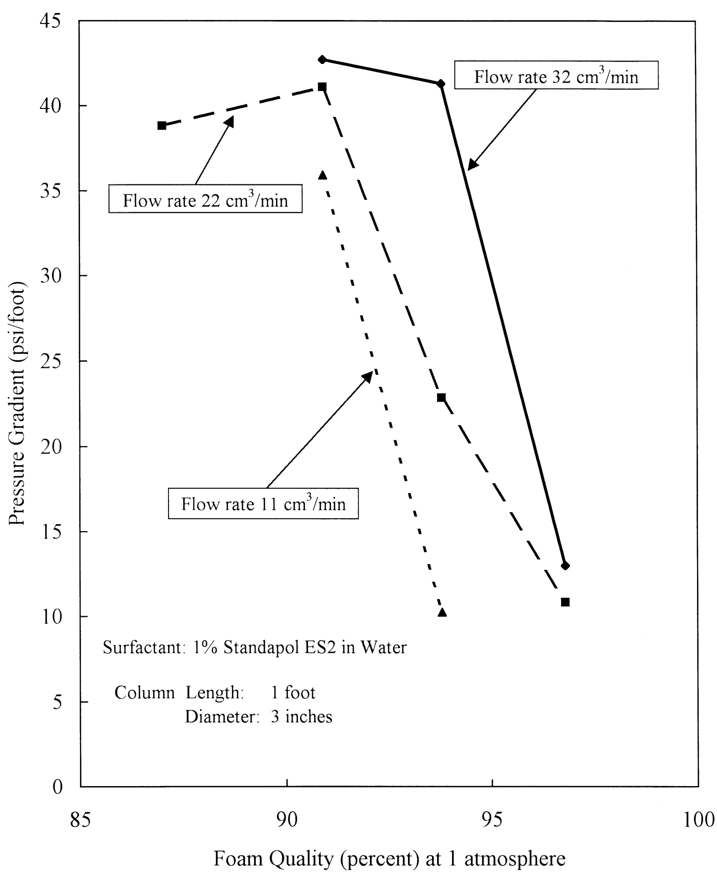

Fig. 2. Effect of foam quality on pressure gradient.

with quality for any foaming agent that gives a stable foam will display a behavior qualitatively similar to that in Fig. 2.

The data in Fig. 2 suggest that for a stable foam such as that generated by the surfactant Standapol ES-2, it may be necessary to operate at a quality of around 99% if the pressure gradient has to be restricted to less than 1 psi/ft as dictated by the need to prevent soil heaving. The injection of foam at very high quality means, however, that the rate at which surfactant solution is injected is considerably lower. For example, increasing the foam quality from 95 to 99% at the same foam injection rate means a factor of five reduction in the rate at which the liquid enters the soil. If the intended use of foams is for an in-situ soil flushing process, this could translate to a five-fold increase in the time scale for remediation.

Fig. 3 is a plot of foam pressure drop across the column vs. flow rate for the aqueous foam generated using a 1% solution of Standapol ES-2. On such a plot a Newtonian fluid would yield a straight line through the origin. There appears to be significant differences in the behavior of the foam at different gas contents. The 91% quality foam

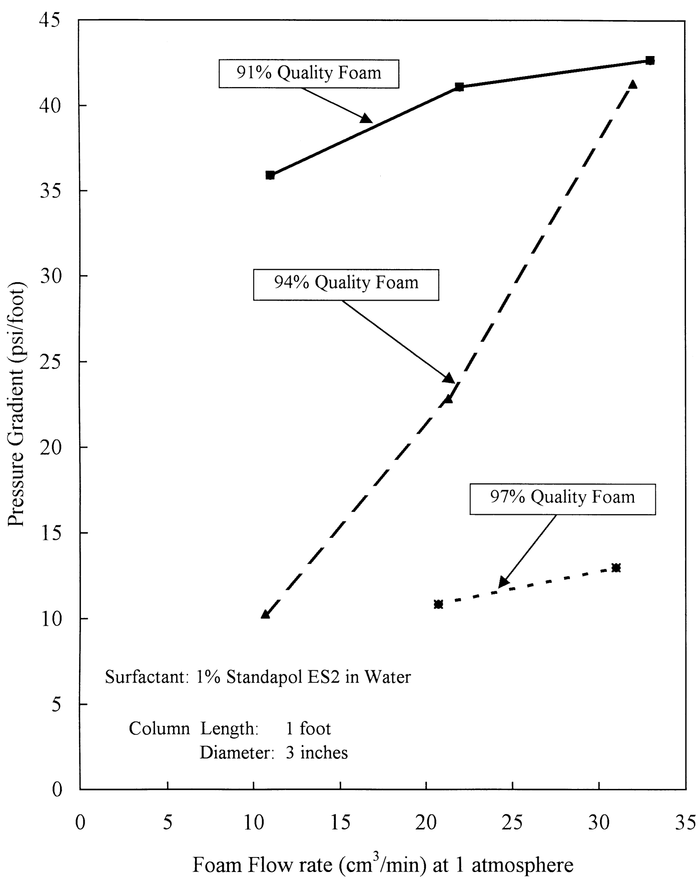

Fig. 3. Effect of foam flow rate on pressure gradient.

shows a non-Newtonian behavior, unlike that at the other two gas contents. While no concrete explanation is possible for the behavior observed in Fig. 3, there were significant differences observed in the texture of the foam exiting the column. The texture depended on both the injected foam quality and the flow rate. In general, the bubble size of the foam was larger at higher quality. The 91% quality foam consisted of very fine, nearly spherical bubbles, while the 97% quality foam often had slugs of gas mixed in. The texture of the foam exiting the column was generally coarser (larger bubble size) than that entering, and also tended to be coarser at lower flow rates. The data for 91% quality foam in Fig. 3 suggest the possibility that under conditions that are conducive to this kind of non-Newtonian behavior, there may exist a threshold injection pressure that needs to be exceeded in order to initiate foam flow. It also appears from the data in Figs. 2 and 3 that foam quality has a more dramatic impact than flow rate on injection pressure.

4.2. Effect of foam formulation

Pressure drops in the 14-darcy (μm^2) permeability silica sand column using the stable aqueous foam from a 1% Standapol ES-2 solution are compared in Fig. 4 with pressure drops obtained with a less stable, ethanol-based foam. IGT FF-13 is a proprietary surfactant formulation used in 100% ethanol. The ethanol based foam formulation displayed much lower pressure drops than the aqueous Standapol ES-2 foam. Visual observation of the fluids exiting the column showed that the Standapol ES-2 was exiting as a foam, whereas the IGT FF13 was exiting more as two separate phases. IGT FF13 foam entering the column also had a much coarser texture than the Standapol ES-2 foam, and had occasional slugs of gas mixed in with the foam. It appears that the greater foam stability obtained with aqueous Standapol ES-2 results in a larger pressure drop through the column. This suggests that from the perspective of reducing resistance to foam propagation, a less stable foam is desirable, though the surfactant solution should have enough foamability to regenerate the foam in the soil.

4.3. Liquid hold-up during foam flow

Data obtained on the movement of the foam front through the column and the variation of pressure gradient across the column with time were analyzed to obtain information pertaining to the amount of liquid held in the column during foam flow. These experiments were conducted starting with a dry sand column (14 darcy) so that the movement of foam up the column could be visually observed through the transparent walls of the column. Fig. 5 shows foam propagation data obtained using an aqueous foam generated from a solution of 1% Standapol ES-2. Data based on visual observation of the movement of the foam front from bottom to top of the sand column have been plotted for two experiments with input foam qualities of 87 and 99%, respectively. The location of the front has been plotted as a function of the pore volumes of foam injected. The pore volume of the sand column was 510 cm^3.

If the gas to liquid ratio throughout the column was the same as in the injected foam, foam should exit the column after injection of only one pore volume. It is obvious from

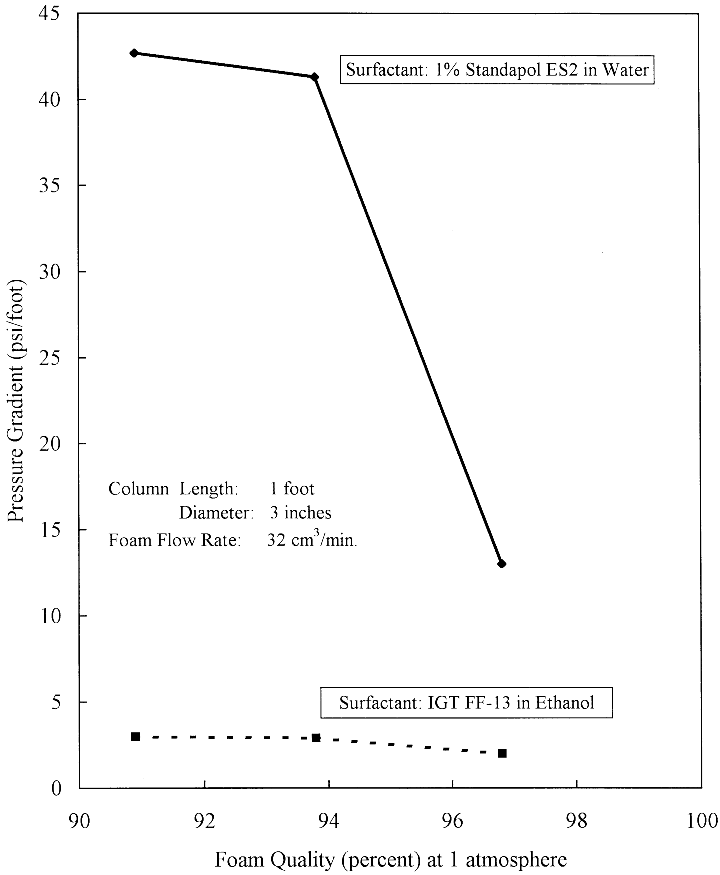

Fig. 4. Effect of foaming agent on pressure gradient for foam flow.

the data in Fig. 5 that significantly more than one pore volume of the foam needs to be injected before it exits the column. The average gas to liquid ratio in the column at any time is therefore lower than that in the injected foam. Based on the pore volumes of foam injected it can be calculated that 34% of the column pore volume was occupied by surfactant solution for the case when 87% quality foam was injected. Similarly, for the injection of 99% quality foam, approximately 7% of the pore volume was occupied by liquid The foam fronts progressed at a constant velocity through the column, as evidenced by the linearity of the plots in Fig. 5. This suggests that the gas and liquid contents of the column were uniform along the column length for each experiment.

Data during injection of foam into a dry sand column were also obtained with foams generated using surfactant IGT FF13 in 100% ethanol, and the surfactant IGT FF52 in a 40% (v/v) ethanol–60% water mixture. Data on liquid hold-up and pressure gradient for these two systems are summarized in Table 1 along with data for the aqueous foam. The liquid content in the pore space was 59% for the foam formulated with 100%

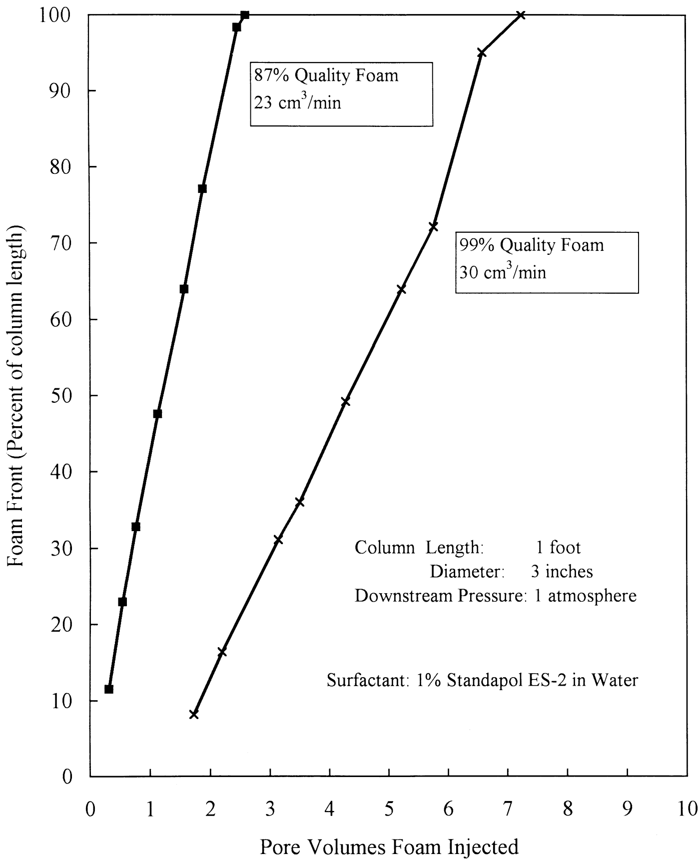

Fig. 5. Foam propagation profile during upflow of an aqueous foam.

ethanol, while the somewhat more stable foam generated by the ethanol–water mixture flowed with a liquid content of 40% of the pore space. It is clear from the data in Table 1 that the liquid content in the soil pores was significantly higher than in the injected foam. This lends support to the idea that even the relatively stable foam (from surfactant Standapol ES-2) propagates through the sand by a process that involves breakage of the foam, and regeneration, till it eventually takes on characteristics dictated by the sand-pack. Thus, the texture (bubble size) of the injected foam is probably not as critical to the foam propagation process as the surfactant formulation and the quality of the foam. The relatively large proportion of liquid held in the soil pores during foam flow means that allowance has to be made for this excess liquid in the design of a field system.

Surfactant adsorption onto soil can also influence foam propagation and liquid hold-up. While no quantitative measurements of surfactant adsorption in the sand column were carried out, two qualitative observations pointed to an initial loss of surfactant due to adsorption: foamability of the exiting fluid, and change in color of the

Table 1
Summary of liquid hold-up and pressure drop data

Surfactant	Foam quality (%)	Foam flow rate (cm^3/min)	Pressure gradient (psi/ft)[a]	Liquid saturation in column (% pore volume)
Aqueous (1% Standapol ES-2)	87	23	38	34
	94	21	22	–
	99	30	5	7
Ethanol (IGT-FF13)	91	33	2	59
Ethanol–water (IGT-FF52)	87	23	1.5	40

[a] 1 psi/ft = 22.62 kPa/m.

exiting solution for the ethanol-based foam. The exiting foam initially consisted of separate slugs of gas and liquid, and gradually changed to a continuous foam stream. The data reported in Table 1 correspond to conditions where the texture of the exiting foam had ceased to change. In the case of the ethanol-based foam, the loss of surfactant was also evident from the initial lack of coloration in the exiting liquid, since the surfactant used imparted a color to the solution.

A detailed investigation of the effect of foam flow rate and quality on liquid hold-up was not conducted. Nevertheless, the data in Table 1 suggest that higher quality of injected foam results in smaller liquid content in the pore space during flow in columns. Also, the ethanol based foams propagated with a higher liquid content in the column than the aqueous foam, probably due to the lower stability of the ethanol foams.

4.4. Upflow vs. downflow

Experiments were conducted in the vertical 3-in. (7.6 cm) diameter column to determine pressure gradients for foam-flow in both upward and downward direction in several soils in the permeability range of 0.09 to 900 darcy (μm^2). The soils used included clean sands of permeability 900 darcy and 8 darcy, a contaminated MGP site soil of permeability 4 darcy, and a low-permeability (0.09 darcy) soil which consisted of an artificial blend of a silty-clay and the 8 darcy sand in the ratio of 1:3 respectively by weight. The permeability of each soil to water was measured after it was packed into the column. Thereafter the water was drained out of the column, with the aid of a vacuum if necessary, before foam was injected into the column. Foam injection rates of 10 to 30 cm^3/min were used, corresponding to superficial velocities of 10 to 30 ft/day (3 to 9 m/day) for this column. The foam was ethanol-based and of quality 95%, generated using a surfactant solution containing the surfactant IGT FF-52 in a matrix of 30% (v/v) ethanol and 70% water.

Fig. 6 shows a plot of measured pressure gradient across the column in psi/ft vs. foam flow rate for the soils tested. The upflow data are shown with solid lines and the downflow data with dashed lines on this plot. In all cases the data reported in Fig. 6 correspond to pressure readings obtained several hours after starting the foam flow, presumably at or close to steady state when surfactant adsorption effects had become

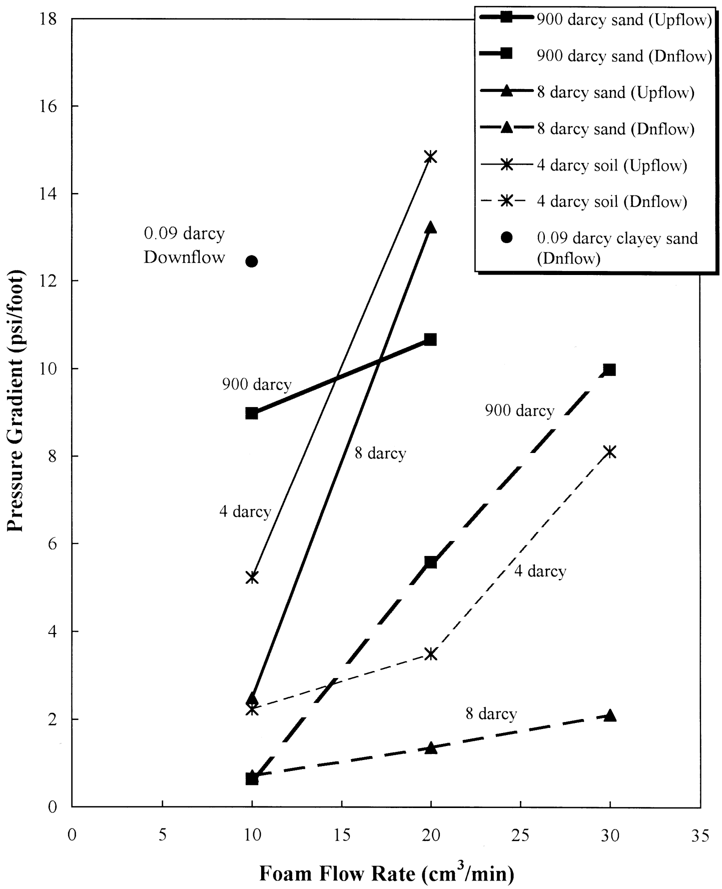

Fig. 6. Pressure gradient for upward and downward flow of an ethanol-based foam through various soils.

negligible. The data clearly show that the pressure gradient for downflow of foam was only a fraction of that during upflow for all the soils tested. This strong gravitational effect is further indirect evidence of the presence of separate gas and liquid phases in the pore space during foam flow. If the foam moved like a homogeneous single-phase fluid, the direction of flow would not affect the pressure gradient significantly, owing to the low density of the foam as compared to the liquid.

As expected, the soil having a permeability of 4 darcy offered greater resistance to the passage of foam than did the sand of permeability 8 darcy. However, a surprisingly high pressure drop was observed for the flow of foam through the coarse sand of permeability 900 darcy. The pressure gradient through this sand was higher than that through soils whose permeability is lower by two orders of magnitude. Some visual observations made during the transient part of the experiments may provide a physical explanation for this apparent anomaly. It was observed that the time period over which the column conditions became favorable to the movement of foam in a stable manner through the sand was less than 90 min for the high permeability (900 darcy) sand, in contrast to as long as 6 to 7 h for the finer (range 1–10 darcy) sands. The behavior of foam in the 900 darcy sand can be attributed to the larger pore size in this sand pack being more conducive to movement of foam without significant breakage. Furthermore, the small surface area of the large sand grains constituting the 900 darcy sand pack results in significantly less surfactant adsorption (and hence better foam stability) than in the other soils. Apparently the breakage of foam in moving through the soil pore space is a key factor in its propagation at low pressure gradients. The variation of foam pressure gradient as a function of soil permeability is further addressed in Section 4.5 where the concept of effective viscosity of foams has been used to analyze the data.

4.5. *Effective viscosity of foam*

The foam flow data obtained were analyzed using the single-phase Darcy's equation to calculate an effective viscosity for the foams. Though the mechanism for foam movement actually involves a process of foam breakdown and regeneration throughout the porous medium [12], the effective viscosity is a useful parameter for characterizing foam flow under different conditions. The effective viscosity concept has been used in earlier studies to characterize foam flow and to compare viscosity estimated from flow through porous media with that measured in conventional fluid viscometers [11,13]. In general, the viscosity of foams measured in a viscometer may not correlate with the effective viscosity in a porous medium due to the difference in mechanism for these two processes.

The effective viscosity was calculated as:

$$\mu_{(\mathrm{foam})} = \frac{kA}{q_{(\mathrm{foam})}} \frac{\Delta P}{\Delta L}$$

where μ = viscosity, cp; k = permeability, darcy; q = flow rate, cm^3/s; A = column cross-section, cm^2; ΔL = column length, cm; ΔP = pressure drop, atm.

The data for flow of an ethanol–water based foam (Fig. 6) were used to calculate effective viscosity for flow through soils of different permeability in up- as well as down-flow. The results are shown in Fig. 7 as a plot of effective viscosity vs. soil permeability. The upflow data are shown by solid lines and the downflow data by dashed lines. The calculated effective viscosity is seen to vary from as low as less than 1 cp to greater than 1000 cp depending on the permeability of the soil. Effective viscosity for the flow of aqueous Standapol ES-2 foam in upflow through 14 darcy sand ranged from 50 to 250 cp, based on the data in Fig. 2. As expected from the higher pressure gradients observed with the aqueous foams, this effective viscosity is slightly higher than that for the ethanol based foam at the same permeability.

An important observation in Fig. 7 is that the effective viscosity of the foam increases with increasing soil permeability. In other words, this foam behaves like a more viscous fluid in high-permeability soils than in low-permeability soils. The mobility of such a foam, defined by the ratio of soil permeability to effective viscosity, varies very little over a wide range of soil permeabilities. The fact that foam mobility is relatively

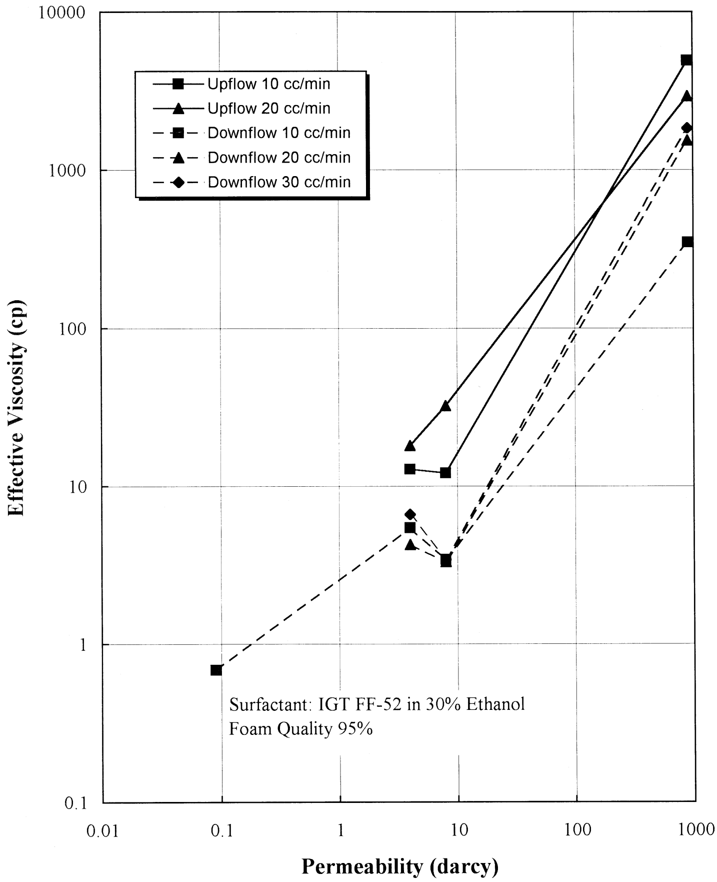

Fig. 7. Effective viscosity of an ethanol-based foam as a function of soil permeability.

independent of soil permeability can be useful in preventing fluid leak-off into high permeability channels [14–16].

5. Discussion

While providing some insight into the mechanism of, and the parameters controlling foam flow in soils, the results of this study highlight the extremely complex nature of the interaction between foams and soil. It is evident that the flow characteristics of foam in a porous medium are not easily predictable without experimentation involving the foam and the soil under consideration. This is because of the transient (unstable) nature of foams, their non-Newtonian behavior, and the fact that flow characteristics are determined by the properties of the foam *as it exists in the porous medium*.

However, despite the seemingly unpredictable nature of foam flow, the results of this study point to some general considerations that are important to the use of foams for chemical delivery and/or soil flushing during in-situ soil remediation. Surfactant type and foam quality (gas content) appear to have considerably more influence than other factors on foam flow, as evident from the summary of liquid hold-up and pressure drop data in Table 1. The flow mechanism is one involving breakage of the foam in the soil pores, and subsequent regeneration. A surfactant that provides a foam that breaks easily (relatively low stability) in the soil, but also has good foamability (so the foam regenerates easily) would be preferable from the perspective of low resistance to foam flow. Based on the data obtained in this study, the ethanol-based foams came closer to meeting this criterion than the aqueous Standapol ES-2 foams. The foams generated using the anionic surfactant Standapol ES-2 experienced high pressure gradients, except at very high qualities close to 99%. For aqueous foams, investigation of other surfactants is necessary to arrive at one that provides lower pressure gradients during foam-flow.

Another significant observation is that the soil pore space during foam propagation held anywhere from 7 to 60% liquid whereas the foam injected contained from 3 to 13% liquid. Besides reinforcing the idea that foams propagate by a process of breakage and regeneration, this result is important from the perspective of calculating surfactant inventories required in the field. Another implication of this result is that one can expect increased tendency for downward migration of liquid due to the high liquid content in the soil. The problem could be even more challenging in field applications than in the homogeneous laboratory columns due to soil heterogeneity, which provides increased possibility for segregation and channelling of air and liquid phases after the foam breaks in the soil. The above concerns are probably more significant in the case of soil flushing using ethanol based foams. Another result that points to the possibility of downward migration of surfactant solution is the fact that significantly lower pressure gradients were observed for downflow of foam as compared to upflow (Fig. 6). Several preventive measures can be considered for field application to control downward migration. These include injection of air from below the foam injection zone to help regenerate foam and keep it moving up, and the location of some withdrawal wells below the foam injection wells to collect any fugitive liquids.

6. Conclusions

Some specific conclusions from the work performed are listed below.

- Pressure gradients obtained for the flow of different foams through a medium grained sand of permeability 14 darcy (μm^2) varied from about 40 psi/ft (905 kPa/m) for an aqueous foam to about 2 psi/ft (45 kPa/m) for ethanol based foams. The lower pressure gradients observed in ethanol based foams appear to be a result of their lower stability. In general, the results indicate the need for a foam that has relatively low stability but high foamability in order to achieve acceptably low pressure gradients of the order of 1 psi/ft (22.6 kPa/m).
- Foam flow can exhibit a non-Newtonian, pseudoplastic behavior depending on the characteristics of the foam and the soil. This suggests the possibility that under some conditions there may exist a ‘threshold injection pressure’ that needs to be exceeded before foam will begin to flow into the soil.

· Foams exhibited a high apparent viscosity in flowing through soils. Furthermore, foam-flow pressure gradient varied only by about one order of magnitude for soils whose permeability spanned four orders of magnitude. This implies that delivery of chemicals by foam injection can help reduce leak-off into naturally occurring high-permeability zones.

· The texture (bubble size) of externally generated foam does not appear to be critical to the propagation of foam through soils. Experimental observations in soil columns showed that the texture of exiting foam differed from that of the inlet foam, indicating that the mechanism of foam propagation involved breaking of the foam after it entered the column, with subsequent re-formation within the sand pack.

· During foam flow the soil held significantly more liquid than would be expected from the gas to liquid ratio in the injected foam. The gas to liquid ratio in the sand pack varied with the foam formulation and the gas content of the injected foam. It was calculated that the percent pore volume occupied by surfactant solution in the 14-darcy sand pack was as low as 7% for the injection of aqueous foam of 99% gas content, and as high as 59% for a 91% quality ethanol foam.

· Higher quality foams exhibited lower pressure gradients during flow, and also lower liquid hold-up in the soil. The trend was most significant at qualities above 90%, and more dramatic for the stable aqueous foam used.

· Data showed that the pressure gradient for downflow of foams was only a fraction of that for upflow. This suggests that downward migration of liquid may be a problem that will need to be addressed during foam injection in the field.

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