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# Structure/Performance Relationships for Surfactant Stabilized Foams in Porous Media

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## ABSTRACT

*While much is known about foam performance in porous media some key knowledge-gap areas remain, one of which is the relationship between surfactant and foam performance in porous media. We compare the viscosities of two different types of polymer-thickened foams in laminar pipeline (bulk) flow versus the same foams flowing in consolidated sandstone rock. For one kind of surfactant-stabilized foam, the apparent viscosity in the rock is an order of magnitude greater than the viscosity of the "same" foam in pipeline flow. However, for another kind of surfactant, the foam apparent viscosity in the rock is very similar to the viscosity of the "same" foam in pipeline flow.*

*Using advanced imaging techniques, various core samples from each kind of experiment were examined. It was found that the morphology of the second kind of foam was consistent with an effective foam viscosity that was comparable to that experienced in laminar-flow, pipeline loop experiments. On the other hand, the morphology of the first kind of foam contained features consistent with the order of magnitude higher viscosity found for its flow in rock versus flow in the pipeline loop.*

*Our measurements show that at least part of the explanation for the observed differences among different surfactant systems with respect to bulk flow versus constrained flow is foam morphology. This work is important to the specification and formulation of the most effective surfactants for varying applications including mobility control, blocking and diverting.*

## INTRODUCTION

Stable aqueous foams are required in a variety of industrial processes, particularly in the petroleum industry's improved oil recovery (IOR) applications. A major challenge in formulating an effective foaming agent is the proper selection of surfactants. Harsh chemical environments are sometimes present in oil reservoirs and several hundred papers have been published in the past thirty five years identifying desirable foam-forming characteristics. These are reviewed elsewhere for harsh<sup>1,2</sup> and less demanding environments<sup>3</sup>.

The foaming capability of a surfactant relates to both foam formation and foam persistence, which are influenced by many bulk and interfacial physical properties<sup>4</sup>. Unfortunately, it is generally found that the performance of foams in porous media is not easily

predicted on the basis of these physical properties<sup>5</sup>, although they can be exploited to increase foamability and foam persistence. For example, water-soluble polymers can stabilize foams by increasing either the surface or bulk viscosity of the film, thereby increasing the film elasticity or decreasing the film drainage rate. They are often effective at lower concentrations than other organic additives, and more compatible with different types of foaming systems. Polymer-thickened foams have been increasingly utilized in IOR with some commercial success<sup>6</sup>.

In IOR, the unique physical structure and surface properties of foam produce a high flow impedance that improves the efficiency of crude oil production. The physical properties of the foam films likely play an important, as yet poorly defined, role in the passage of foam through porous rock. Many laboratory investigations into the generation of foam in porous media have been carried out using a variety of media. It has been noted that the nature of the medium plays an important role<sup>7,8</sup>, as does the foam texture, specifically as regards foam bubble size in comparison to the dimensions of the flow paths, in determining the rheological behaviour of the foam<sup>9</sup>. Thus, it is important that the bubble size is somehow incorporated into the rheological description of foam flow in porous media. It has been postulated that within porous media the structure of foam will bear some resemblance to bulk foam although there may simultaneously occur regions containing continuous liquid phase and continuous gas phase.

This research attempts to determine to what extent the rheological properties of the polymer-thickened foams in bulk are translated into the situation in porous media and to what extent they are determined by foam morphology.

## EXPERIMENTAL

### Materials

The two commercial surfactants used in this study were selected because they had been already shown to possess good foaming ability and stability in saline conditions<sup>1,10</sup>. The first was an anionic hydrocarbon surfactant, Dow XSS 84321.05 (Dow Chemical Co.), which is a 1:1 mixture of C10 diphenyletherdisulfonate (Dowfax 3B2) and C14 - 16 alpha olefin sulfonates (Canada Stirling AOS). The second was an amphoteric surfactant, Rewoteric AM U Varion CAS (Witco Co.), an alkylamido sulfobetaine. Table 1 provides a summary of some of their specific properties. The surfactants were used as received, without further purification, at a concentration of 0.5 % mass active in all cases.

The polyacrylamide polymer used was AC 1175a (Ciba Specialty Chemical). It was approximately 25 % hydrolysed and has an approximate molar mass of  $10 \cdot 10^6$  g/mol.

A standard, degassed, 2.1% w/w total dissolved solid (TDS) brine solution was used in all cases. It was prepared by dilution of a stock 21.0 % w/w brine solution using boiled and filtered( 0.45  $\mu\text{m}$ ) doubly deionised water. The composition of the synthetic 21.0 % w/w brine is given in Table 2. The synthetic brine was modelled on the composition of the Beaverhill Lake reservoir brine in the Western Canadian basin<sup>1</sup>. The density and viscosity of the 2.1 % w/w brine at 23° C were 1.015 g/cm<sup>3</sup> and 0.997 mPa.s, respectively. The 2.1 % brine was filtered through a 0.45  $\mu\text{m}$  filter under 10 psi pressure prior to use.

All the foams were generated with nitrogen gas (technical grade, minimum purity 99.5%).

## PROCEDURE

For foam flooding in porous media the apparatus and procedures were essentially the same as those described previous by Schramm et al.<sup>11</sup> Here the differential pressure generated across the length of the core sample is measured and the apparent viscosity is calculated using a modified version of Darcy's Law.

$$\mu_{app} = \frac{\kappa A \Delta P}{QL}$$

Brine saturated cores were flooded with foam by co-injecting the polymer-surfactant solutions and the nitrogen gas into an initial mixing chamber, then through an in-line stainless steel (0.5  $\mu\text{m}$  diameter nominal screen pores) foam generator, and then into the core. Polymer-thickened foam was injected at a rate of 2 or 4 m/day at a 95% gas-fraction foam quality. The temperature was maintained at 23° C and a back-pressure of 10 psi was set in all cases.

For the gel-foam imaging studies, the surfactant-stabilized foams were injected at a rate of 2 m/day at 80 % foam quality. The temperature was maintained at 23° C and a back pressure was set to 10 psi. The core samples were flooded with foam until steady-state flow was attained. Subsequently, the polymer was incorporated into the surfactant solution and the polymer -thickened foam was injected under similar rates. Finally, the cross-linker was incorporated into the polymer-surfactant solution and the core was shut-in for several day to allow for complete gelation. Subsequently, the core sample was sectioned into sub-samples and a suite of imaging techniques were applied. A detailed description of the foam-gelling, sectioning, and imaging techniques is given elsewhere<sup>1</sup>.

The bulk viscosities of the polymer-thickened foams were examined in a single-pass, continuous flow, pipeline viscometer. The conditions were chosen to maintain foam travel in the laminar flow region so the apparent viscosity of the polymer-thickened foams could be calculated using the Hagen Poiseuille law,

$$\mu = \frac{\pi \Delta P R^4}{8 L_1 Q}$$

Figure 1 provides a schematic of the apparatus. The pipe was 3 m long and possessed an internal diameter of 0.6 cm. Visual cells were positioned at the entrance and exit of the pipe line so that the texture of the foam could be monitored to determine whether it had significantly changed. Care was taken to ensure that the diameter of the pipe was always much greater than the bubble size so that the foam may be treated as a continuous fluid. The generally accepted minimum ratio is 10. The average bubble diameters in this work ranged from 50 to 100  $\mu\text{m}$ .

The flow rates in the pipe were chosen so that the shear rates at the wall would exactly match the wall shear rates experienced by the same foams in the core flooding experiments.

For these experiments polymer-thickened foams were generated by co-injecting the polymer-surfactant solutions and the nitrogen gas into an initial mixing chamber, then through an in-line stainless steel (0.5 and 15  $\mu\text{m}$  diameter nominal screen pores) foam generator, and then into the pipeline. Polymer-thickened foam was injected at the rate needed to achieve a shear rate of either 90 or 200  $\text{s}^{-1}$  at a 95% gas-fraction foam quality. Temperature was maintained at 23° C and back-pressure at 10 psi in all cases.

Low-energy scanning electron microscopy (SEM) was used to determine the structures of the different polymer-thickened foams in the core samples. The sample preparation and imaging techniques are described elsewhere<sup>12</sup>.

## RESULTS AND DISCUSSION

The apparent viscosities of the Varion and Dow polymer-thickened foams when flowing in porous media are shown in Figures 2 and 3. The apparent viscosities shown are specific to the shear rates experienced (90 or 200  $\text{s}^{-1}$  in this work) because these foams are shear thinning. That is, increasing the flow rate of the injected fluids decreases their apparent viscosity. It can be seen that increasing the PHPA polymer concentration also generally increased the apparent viscosity of the polymer-thickened foams, although for the Varion surfactant case we observed a reduction in viscosity at polymer concentrations above 10 g/L. This is thought to be due to a significant change in the surface elasticity of the foam lamellae at such high polymer concentrations and therefore due to a reduction in foam stability rather than to mechanical shear degradation. For each surfactant, the addition of PHPA polymer greatly increased the viscosity of the foam when flowing in porous media.

The apparent viscosities of the Varion and Dow polymer-thickened foams when flowing in the pipeline are shown in Figures 4 and 5. Again, for each surfactant,

increasing the PHPA polymer concentration generally increased the apparent viscosity of the polymer-thickened foams, although not necessarily as much as was observed for the same foams flowing in porous media. There were again cases for which we observed a reduction in viscosity at various specific polymer concentrations. The different foam generator pore sizes shown give an order of magnitude estimate of the mean bubble sizes for each series of tests reported. More detailed information on the effects of bubble size distribution will be reported in future.

## BULK VERSUS CONSTRAINED FOAM FLOW

Figures 6-9 permit comparison of the effects of adding PHPA to each kind of surfactant foam for bulk flow (pipeline) versus constrained flow (core flood) at two different shear rates. This comparison shows that the effective viscosity of polymer-thickened foams flowing in constrained media can range from about 1 to at least 25 times larger than that for the same foam in bulk flow. In this case the major difference between the conditions producing a scaling factor of 1 and that of 25 is the nature of the surfactant used. Other factors that may be important to the scaling of the foam viscosity from the bulk flow to constrained flow include the permeability, porosity, and pore size distribution of the rock.

After the flow tests were complete we carefully gelled the foams inside the rock samples, opened them and imaged them according to the special techniques developed for this purpose<sup>12</sup>. Samples from each kind of experiment were imaged using low energy SEM. Our measurements in this and previous work have clearly shown that foam lamellae in porous media can extend for considerable distances, greater than the length of individual pores, if oriented parallel to the overall direction of flow. In addition to penetrating through multiple pores, they also are able to span across multiple pores.

Figures 10 and 11 illustrate our observation that the PHPA-Dow polymer-thickened foams generally contained mostly rods and large sheet perforations. This is consistent with an effective foam viscosity that is comparable to that experienced in laminar-flow, pipeline loop experiments. On the other hand, Figures 12 and 13 illustrate our observation that the PHPA-Varion polymer-thickened foams contained mostly pore-blocking sheets. This is consistent with the 25-times higher viscosity found for its flow in rock versus flow in the pipeline loop. Therefore, at least part of the explanation for the observed differences among different surfactant systems with respect to bulk flow versus constrained flow is foam morphology. In the context of improved oil recovery from petroleum-bearing reservoirs, the latter configuration would cause blocking and diverting of injected fluids whereas the former configuration would

cause only reduced permeability of the pores to injected fluids.

In future work we plan to further investigate how surfactant structure influences foam morphology, and therefore foam performance, in porous media.

## CONCLUSIONS

We have shown that, depending upon the surfactant chosen, the apparent foam viscosity in rock can be as much as an order of magnitude greater than the viscosity of the "same" foam in pipeline flow. Our results show that the morphology of the foam in porous media, if categorized in terms of pore-blocking ability, correlates qualitatively with the rheological results. Therefore, at least part of the explanation for the observed differences among different surfactant systems with respect to bulk flow versus constrained flow is foam morphology. This is important to the specification and formulation of the most effective surfactants for varying applications and merits further investigation.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

A	Cross sectional area
L	Length
P	Pressure
R	Radius
PHPA	Partially hydrolysed polyacrylamide
PTF	Polymer-thickened foam
Q	Flow rate
	Permeability
$\mu$	Viscosity

## REFERENCES

1. Novosad, J.J. and Ionescu, E.F. In *Proceedings, Petroleum Society of CIM Annual Technical Meeting*, Calgary, AB, paper CIM 87-38-80, 1987.
2. Schramm, L.L., Mannhardt, K. and Novosad, J.J. In *Proceedings: Field Application of Foams for Oil Production Symposium*, D.K. Olsen; P.S. Sarathi (Eds.), U.S. Dept. of Energy, NIPER, Bartlesville, OK, July, 1993, NIPER-669, pp. 155-162, 1993.

3. Borchardt, J.K., In *Oil-Field Chemistry*, J.K. Borchardt. and T.F. Yen (Eds.), American Chemical Society: Washington, 3-54, 1989.
4. Schramm, L.L. and Wassmuth, F. In *Foams, Fundamentals and Applications in the Petroleum Industry*, L.L. Schramm (Ed.), American Chemical Society: Washington, 3-45, 1994.
5. Schramm, L.L. (Editor), *Foams: Fundamentals and Applications in the Petroleum Industry*, American Chemical Society, Washington, 1994.
6. Schramm, L.L. and Kutay, S. In: *Surfactants: Fundamentals and Applications in the Petroleum Industry*, Schramm, L.L. (Ed.), Cambridge University Press, Cambridge, UK, 2000.
7. Mast, Preprint, SPE Annual Technical Meeting, SPE paper 3997, 1972.
8. Farouq Ali, S.M. and Selby, R.J., *Oil and Gas Journal*, February, 57-63, 1986.
9. Nutt, C.W. and Burley, R.W., in *Foams: Physics, Chemistry and Structure*, A.J. Wilson, (Ed.) Springer-Verlag, London, 105-148, 1989.
10. Schramm, L.L. and Novosad, J.J., *J. Petrol. Sci. & Eng.*, **7**, 77-90, 1992.
11. Schramm, L.L., Turta, A. and Novosad, J.J. Preprint, SPE/DOE 7th Symp. on EOR, Tulsa, Ok., SPE/DOE paper 20197, April 22-25, 1990.
12. Schramm, L.L., Kutay, S.M., Mikula, R.J., and Munoz, V.A. *J. Petrol. Sci. Eng.*, **23**, 117-132, 1999.

**Table 1. Surfactant properties.**

Surfactant	Manufacturer	Chemical type	Average molar mass ( g/mol)	Critical micelle concentration (mg/L)
Dow XSS 84321.05	Dow Chemical	C <sub>10</sub> diphenyletherdisulfonate + C <sub>14-16</sub> alpha olefin sulfonate	440	7
Rewoteric AM CAS U	Witco	Alkylamido sulfobetaine	481	<b>19.2</b>

**Table 2 Composition of the 21.0% w/w TDS synthetic brine.**

Salt	Concentration (g/1000g)
NaCl	172.45
MgCl <sub>2</sub> :6H <sub>2</sub> O	9.4
CaCl <sub>2</sub> :2H <sub>2</sub> O	43
NaSO <sub>4</sub> :10H <sub>2</sub> O	2.15

**Table 3 Properties of the porous media and surfactants used.**

Core No.	1	2
Material	Berea Sandstone	Berea Sandstone
Dimensions (cm)	2.6 x 2.6 x 15.1	3.74 (dia.) x 9.8
Air Permeability (D)	0.439	1.003
Brine Permeability (D)	0.185	0.396
Porosity (%)	10	23
Surfactant	Dow	Varian CAS

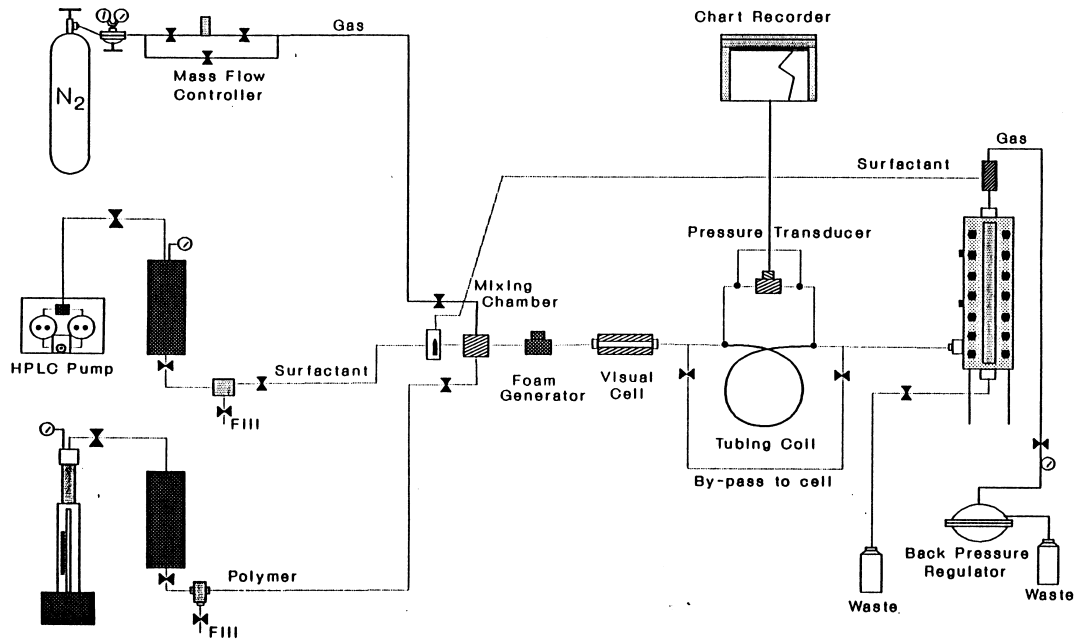


Figure 1. Schematic illustration of the pipeline viscometer.

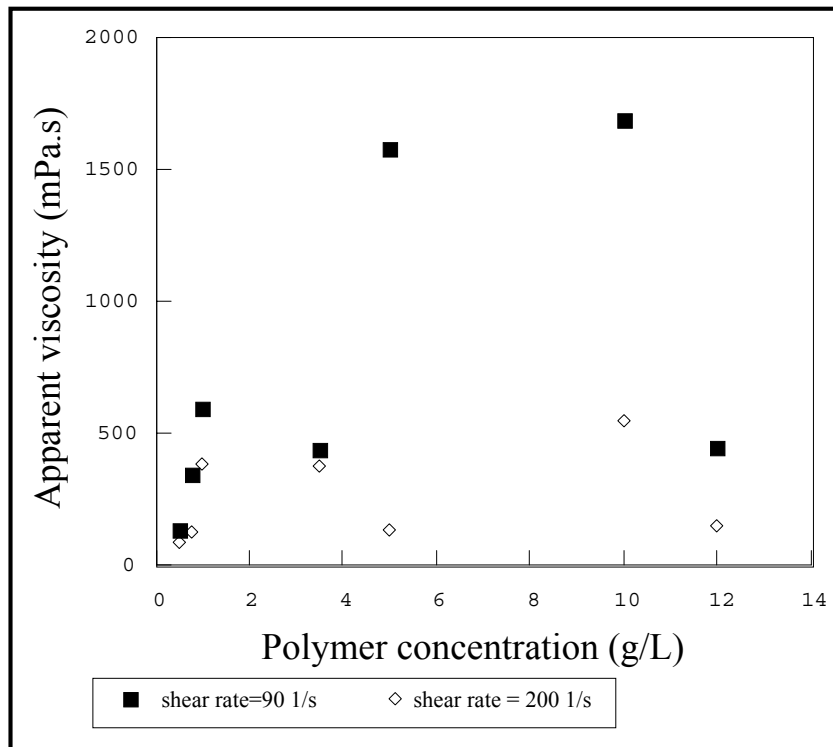


Figure 2. Core flood apparent viscosities of PHPA-Varian polymer thickened foams as a function of polymer concentration.

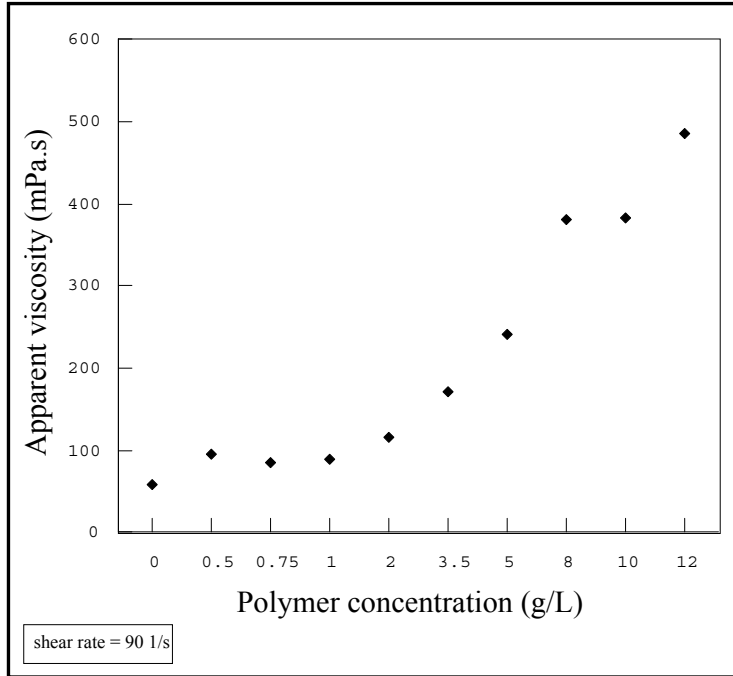


Figure 3. Core flood apparent viscosities of PHPA-Dow XSS polymer-thickened foams as a function of concentration.

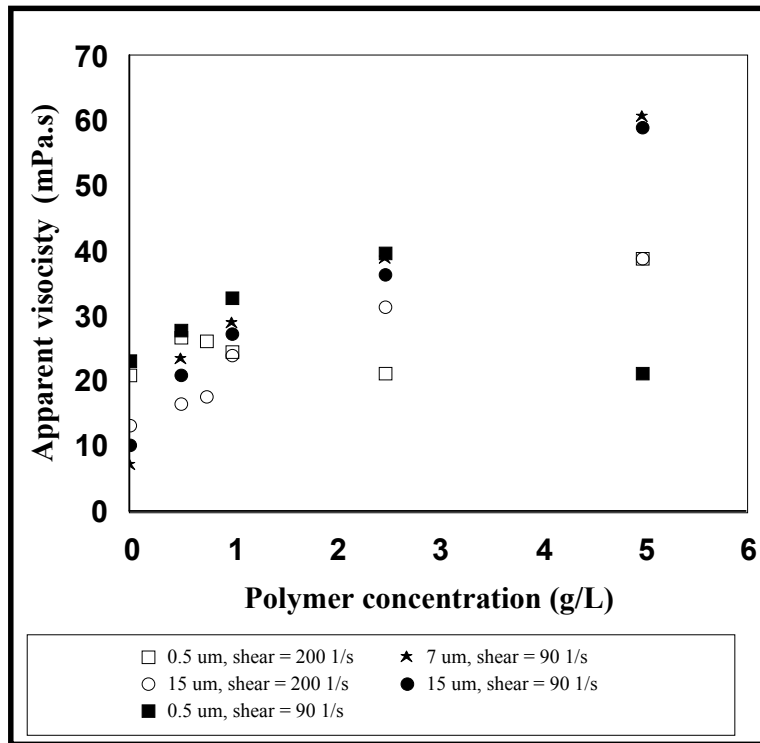


Figure 4. Pipeline (bulk) apparent viscosities of PHPA-Dow XSS polymer thickened foams.

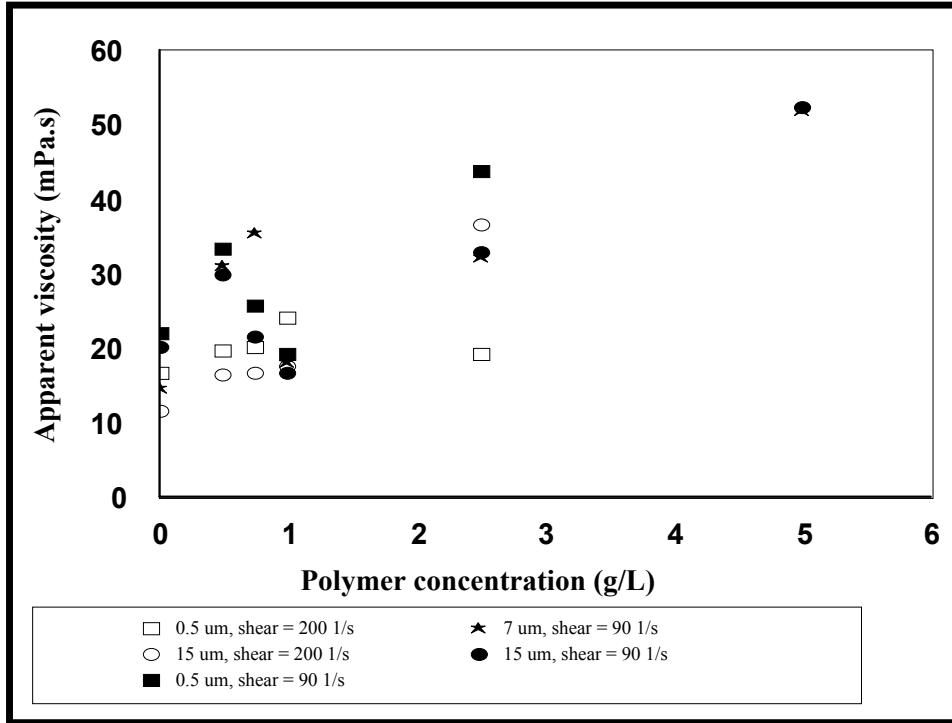


Figure5. Pipeline (bulk) apparent viscosities of PHPA-Varian polymer-thickened foams.

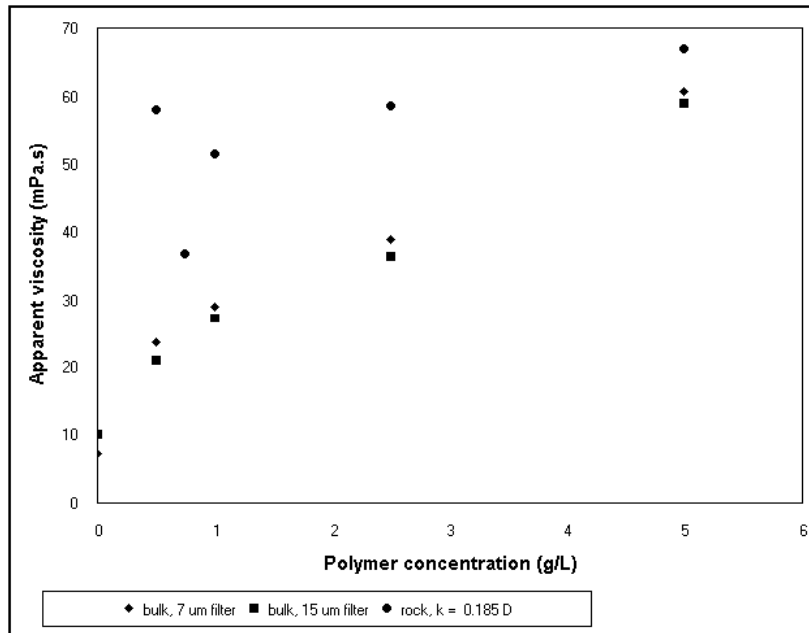


Figure 6. Comparison of PHPA-Dow polymer-thickened foam viscosities in pipeline and porous media ( $90 \text{ s}^{-1}$ )

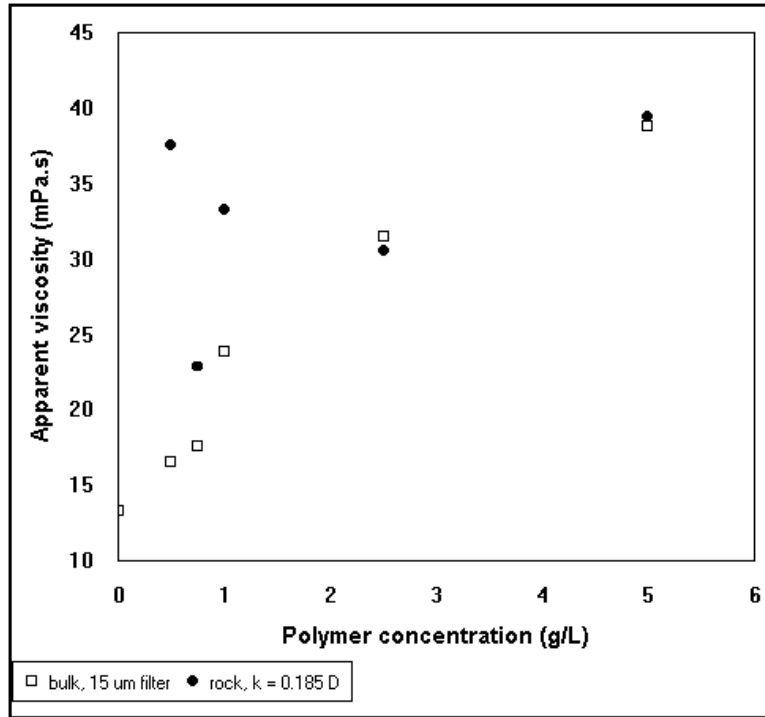


Figure 7. Comparison of PHPA-Dow polymer-thickened foam viscosities in pipeline and porous media ( $200 \text{ s}^{-1}$ ).

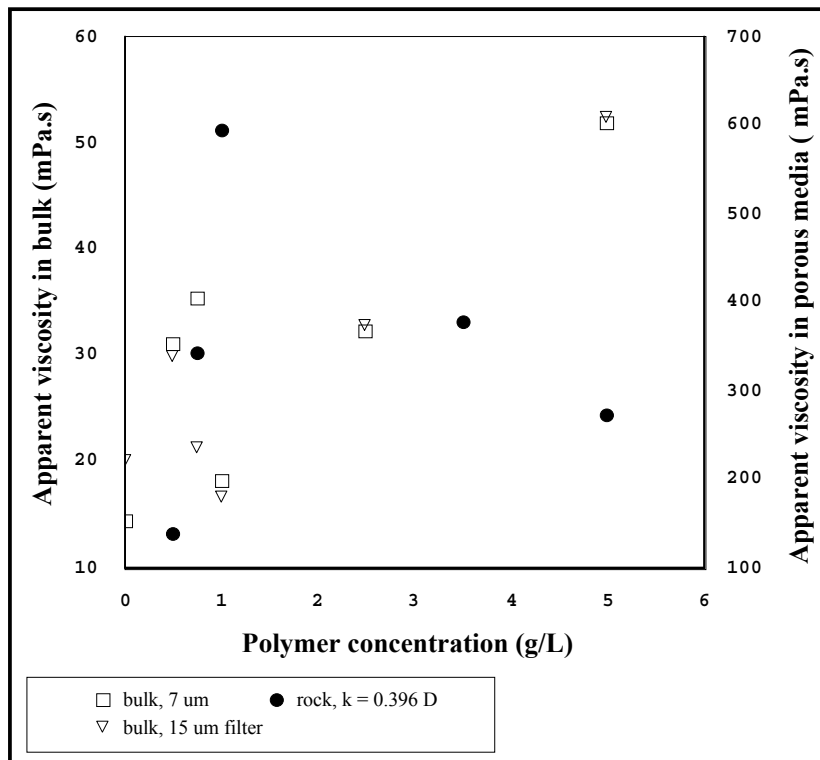


Figure 8. Comparison of PHPA-Varian polymer-thickened-foams in bulk and in porous media ( $90 \text{ s}^{-1}$ ).

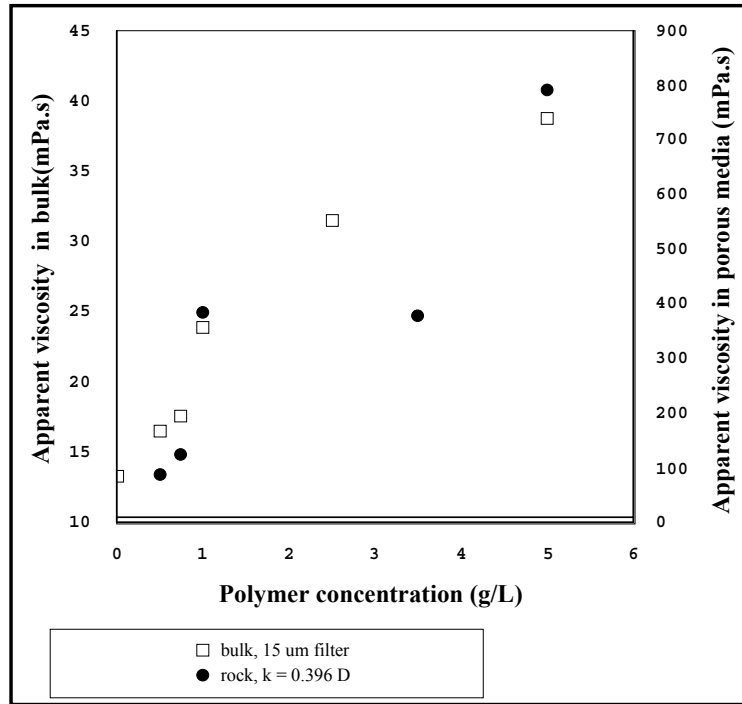


Figure 9. Comparison of PHPA-Varian polymer thickened foams in bulk and in porous media ( $200 \text{ s}^{-1}$ ).

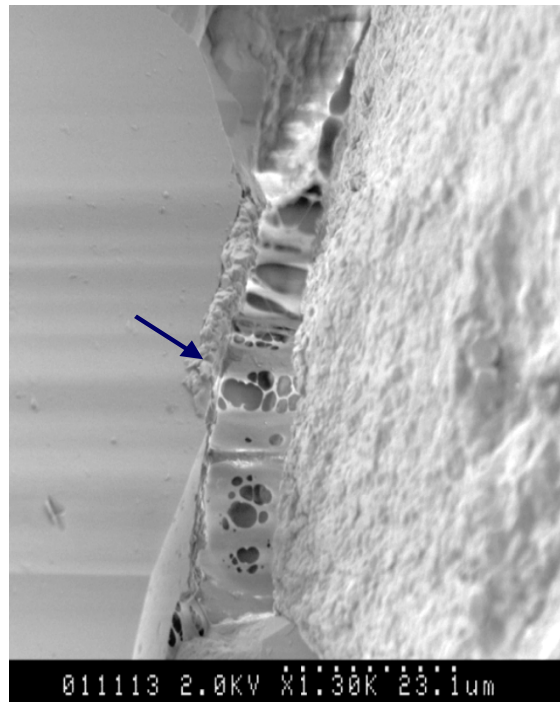


Figure 10. PHPA-Dow Foam in Berea sandstone.

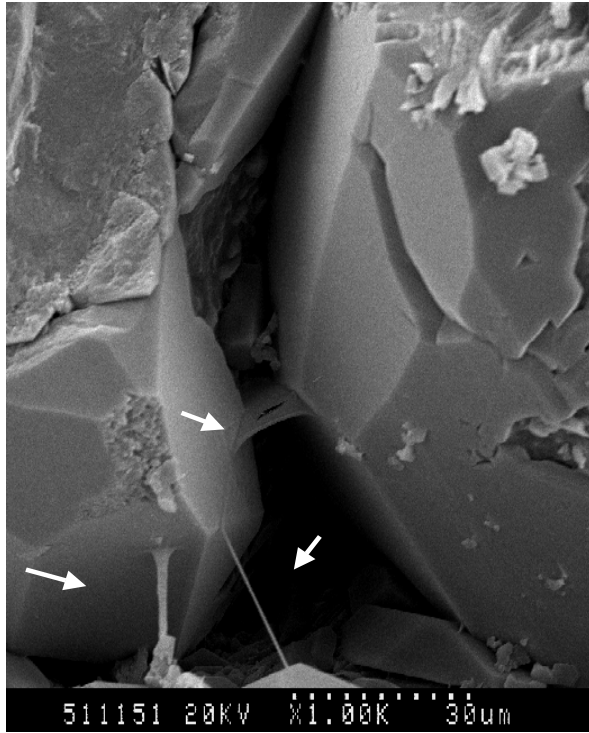


Figure 11. PHPA-Dow Foam in Berea sandstone.

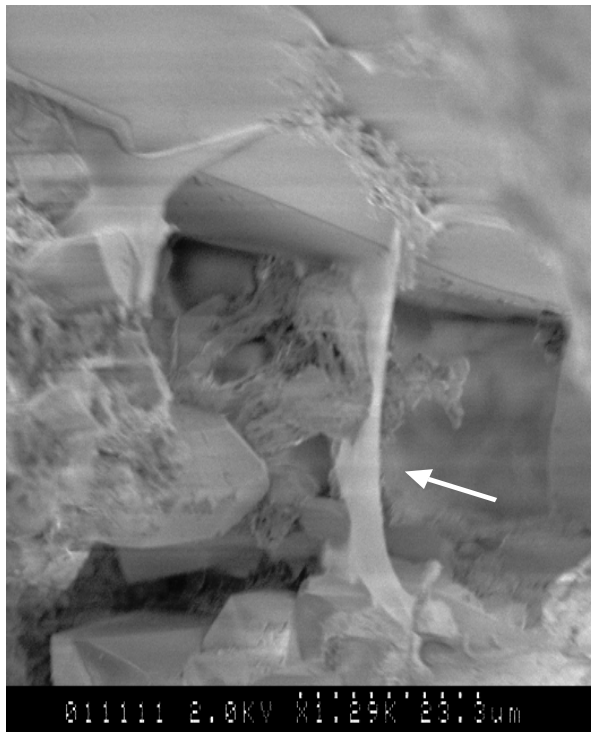


Figure 12. PHPA-Varian foam in Berea sandstone.

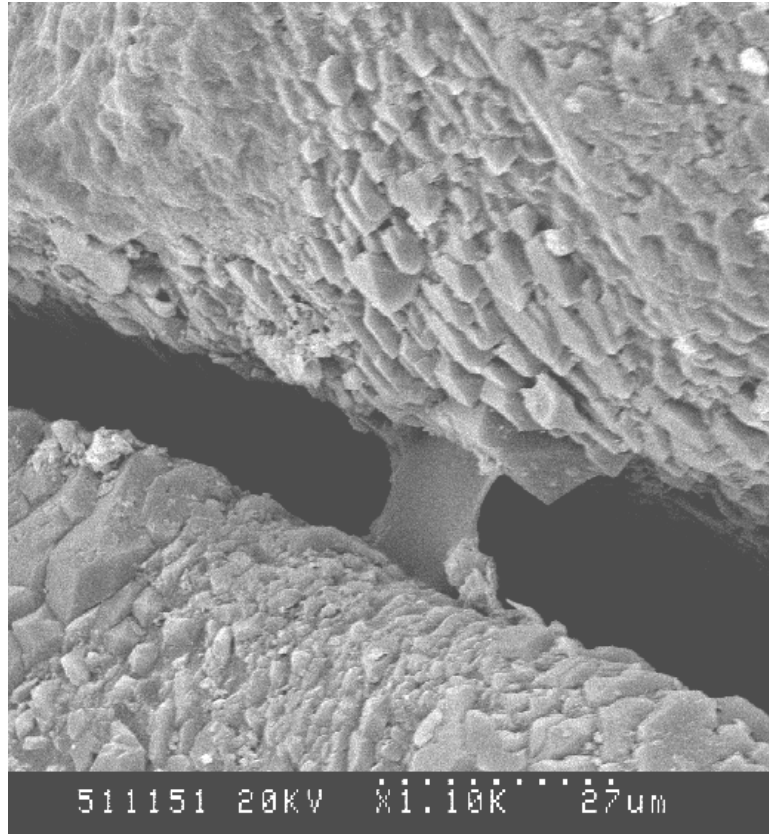


Figure 13. PHPA-Varian foam in Berea sandstone.