

A multi-scale numerical and experimental study of permeation of polymer fluids in soils (PoPFS)

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ABSTRACT: Support fluids maintain excavations open until they are replaced with structural elements, e.g. piles, and diaphragm walls. Synthetic polymer fluids have a competitive advantage over bentonite slurries in many cases as they have a simpler site footprint, involve less material haulage and management of excavated soil is more straightforward. They may also lead to an improved pile performance. The barriers to widespread use of polymer fluids in geotechnical engineering are the incomplete understanding of the underlying mechanics and the lack of a framework for design analysis. These issues arise as polymer fluids have a strongly non-Newtonian rheology; their viscosity varies with shear rate and so Darcy's law cannot be directly applied. This paper presents highlights from the PoPFS study (Permeation of Polymer Fluids in Soils) using computational fluid dynamics (CFD), microfluidics experiments, pore network modelling (PNM), and permeameter testing to improve understanding of polymer support fluids. The mesh adopted in the CFD simulations is significantly smaller than the particles / voids, particle surfaces give boundaries to the flow and the Carreau fluid model is adopted. Data from these simulations include the fluid-particle interaction forces. Microfluidics enables direct, quasi-2-D, sub-pore scale observation of fluid flow and provide crucial data to establish the limitations of the numerical models. Computational cost limits the domain size considered in the CFD models, but PNM allows upscaling to larger systems and development of continuum models. Upscaling of the results to physically meaningful materials is achieved through permeameter testing adapted to monitor the progression of a polymer front in soil. Polymer support fluids have the potential to transform how we design and build underground structures. PoPFS will achieve a step-change in understanding the behaviour of polymer support fluids that will ultimately reduce the cost and environmental impact of many underground construction projects.

KEYWORDS: Excavations, support fluids, microfluidics, computational fluid dynamics, pore network modelling, fluid conductivity.

1 INTRODUCTION

The primary requirement of a support fluid is to maintain excavation stability. The use of bentonite fluids is well established; more recently polymer support fluids have emerged as an alternative (EFFC/DFI Support Fluids Task Force, 2019). The advantages of polymer fluids include significant reductions in the volumes of soil excavated and concrete used (in the case of piles if a smaller or shorter pile could be used due to a possible improvement in pile shaft capacity), a reduced site footprint, and the flexibility to design the chemistry and rheology of the polymer fluid for optimal performance (e.g. Lam & Jefferis 2018). An incomplete understanding of how polymer support fluids function inhibits their broad uptake, limits guidance available to engineers to develop robust designs, and limits the design of new polymer systems with enhanced properties.

This paper documents findings from an ongoing research collaboration that has adopted a multi-scale approach to address these gaps in understanding (see Figure 1). Highlights from each of the four strands adopted in the research are presented, i.e. computational fluid dynamics, microfluidics, pore network modelling, and permeameter testing. The most significant overarching observations are given in the conclusions.

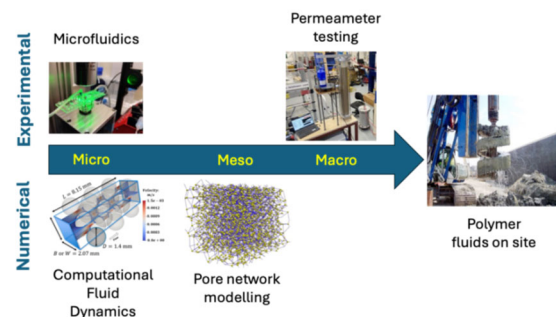


Figure 1. Illustration of multi-scale nature of research strands

2 HIGH-RESOLUTION COMPUTATIONAL FLUID DYNAMICS

High-resolution computational fluid dynamics simulations were carried out to observe the fluid flow in the void space in detail and determine the fluid-particle interaction forces. The numerical model took advantage of the symmetry of a lattice packing of uniform spheres to simulate an infinite domain of particles (see Figure 1). The key technical issues to consider were the fluid rheology and linking the intrinsic permeability of the lattice packings to real sands that had been tested in the laboratory.

2.1 Polymer fluid rheology

The polymer fluids currently used in excavation support are typically solutions of hydrolysed polyacrylamide or HPAM

(also known as PHPA). These fluids are shear-thinning so that their apparent viscosity reduces as the applied shear rate increases. The Carreau rheological model is often used to describe this relationship between viscosity (η) and shear rate; and the relationship can be divided into three regions: the upper and lower Newtonian plateaus ($\eta = \eta_0$ and $\eta = \eta_\infty$ respectively) and the shear-thinning (power-law) region. Figure 2 illustrates the relationship between apparent viscosity and fluid shear rate for a polymer concentration of 1.0 kg/m³ fitted using the Carreau model to experimental data presented in Ejezie et al. (2021). The Carreau model was already implemented in the OpenFOAM computational fluid dynamics (CFD) software (Greenshields, 2020) which was used in this research.

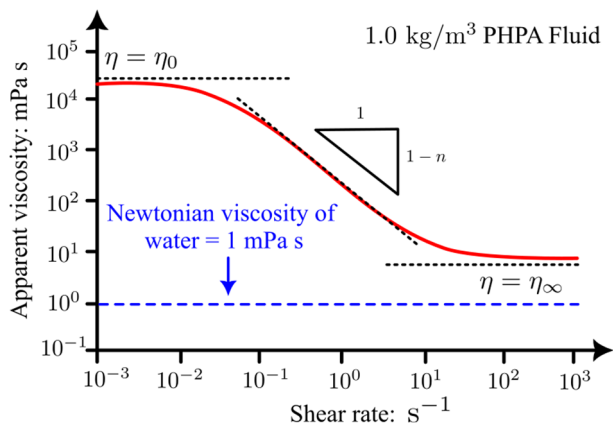


Figure 2. Illustration of Carreau rheological model adopted in the current study, fitted to experimental permeameter data in Ejezie et al. (2021) for PHPA/HPAM polymer fluid with a concentration of 1.0 kg/m³.

2.2 Selecting model geometry to match intrinsic permeabilities

The key challenge to address in using the lattice packing of uniform spheres as a model soil to inform understanding of permeation of polymer fluids in sand is selecting a realistic intrinsic permeability. Expressions for the intrinsic permeabilities of various lattice packings of uniform spheres are given in Zick & Homsy (1982). Wang et al. (2025) back-calculated suitable sphere radii values using the Zick and Homsy expressions and intrinsic permeability and void ratio data presented in Ejezie et al. (2021). This enabled development of a model geometry that was equivalent to the sand samples Ejezie et al. (2021) used in permeability tests using polymer fluids. This system geometry was used in the OpenFOAM simulations with about 1.6 million simulation cells. A no-slip fluid flow boundary condition was assumed along the sphere surfaces.

2.3 Key insight from CFD simulations

Wang et al. (2025) verified that the polymer conductivities obtained from the OpenFOAM simulation workflow agree with the experimental data in Ejezie et al. (2021). They then used the simulations to determine the fluid-particle interaction forces (F_{f-p}) acting on individual model soil grains. Figure 3 presents simulation data for a lattice packing whose geometry was selected to be representative of Sand B in Ejezie et al. (2021), i.e. D_{50} of 1.37 mm, coefficient of uniformity of 1.361, and void ratio of 0.54. As illustrated in Figure 3, the CFD simulation data indicate that the fluid-particle interaction forces at low discharge velocities are up to 10⁴ times that imposed by water. These data are significant as they demonstrate that polymer fluids can provide significant support force even without the formation of a filter cake (which is fundamental for bentonite

fluids) or the imposition of any restraint on the particles by the polymer chains in the solution.

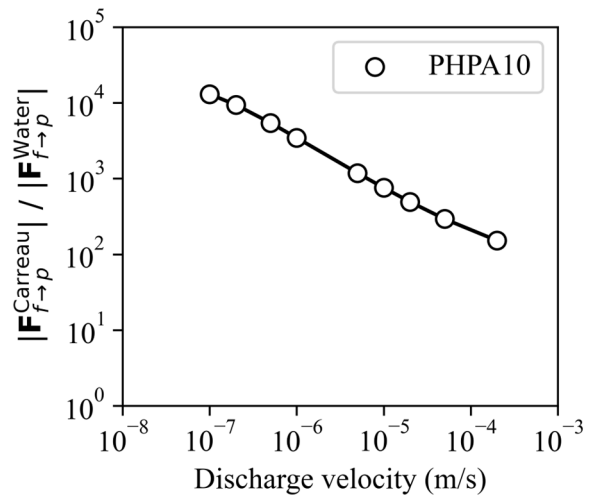


Figure 3. Fluid particle interaction force predicted for polymer fluids in high resolution CFD simulations for model equivalent to Sand B in Ejezie et al. (2021) and a PHPA/HPAM concentration of 1.0 kg/m³. Values are normalized by forces experienced for water permeation at the same discharge velocity.

3 MICROFLUIDICS

While the CFD simulations enable fluid-particle interaction forces to be measured, they suffer from the key limitation that the fluid rheology is assumed to conform to the idealized Carreau model. Microfluidics experiments in quasi-2-D flow cells have enabled direct observation of the polymer fluid behavior in physical models of soil pores. Figure 4 schematically illustrates the experimental apparatus for the microfluidics experiments. The microfluidics channel is 40 mm in total length, and the flow channel is 300 μm wide. Various pore space configurations were studied; the geometry illustrated in Figure 4Figure 5 comprises 4 pores with maximum width of 300 μm and throat widths of 25 μm. The tracer particles used to visualize the flow were 0.87 μm polystyrene beads.

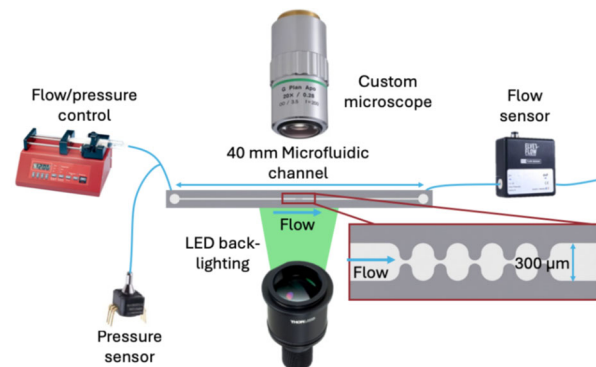


Figure 4. Schematic diagram of the microfluidics apparatus.

To advance understanding of the rheology of polymer fluids the behaviour of HPAM with a concentration of 1,000 ppm (~1.0 kg/m³) was contrasted with that of glycerol, a low-viscosity Newtonian fluid. Representative results are presented in Figure 5. The flow streamlines, picked up by imaging the tracer particles, are illustrated as points coloured so that the highest velocities are yellow and the lowest velocities are dark blue. There are key differences in the flow patterns, so that there is recirculation in the voids where HPAM is used. This recirculation is not evident in the experiment with glycerol and

is attributed to visco-elastic effects. This visco-elasticity cannot be captured by the Carreau rheological model and so ongoing research is using the more general FENE-P model in CFD simulations to better understand the implications of this visco-elasticity on the overall behaviour of polymer support fluids.

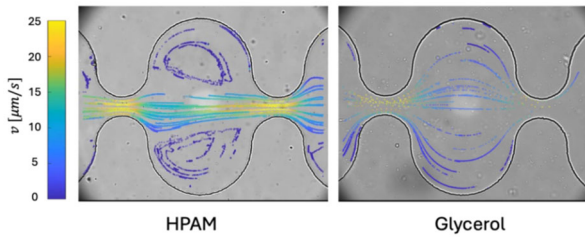


Figure 5. Representative results from microfluidics experiments: contrasting HPAM with a concentration of 1,000 ppm and glycerol.

4 PORE NETWORK MODELLING

The computational cost of the high resolution CFD simulations discussed in Section 2 necessitates a small computational domain size. Pore network models (PNMs) allow consideration of a slightly larger scale while still enabling flow in individual pores and pore throats to be simulated. In a PNM, the pore space is idealized as pores (nodes) connected by restrictions (throats). Each throat is assigned a conductance which depends on the throat geometry and the fluid properties. Flow along each throat is simulated using Darcy's law where the pressure gradient is determined considering the pressures at each of two connected pores. Mass conservation is used to generate a system of simultaneous equations which can be solved to determine the pressure at each node and the flow between them. The key challenge in the current project is to link the apparent velocity to the pressure gradient to capture the non-Newtonian rheology. Suo et al. (2025) used a Carreau-type rheological model with an effective viscosity: shear rate relationship similar to that presented in Figure 2 to develop expressions relating the fluid shear rate to the pressure gradient, and then, link the effective viscosity and the fluid shear rate. Sphere packings were generated using the discrete element method (DEM) to provide void space topologies for a range of specified particle size distributions (PSDs). As in the case of the CFD simulations in Section 2, the PNM simulations were verified by comparison with data for Sand B in Ejezie et al. (2021), as shown in Figure 6.

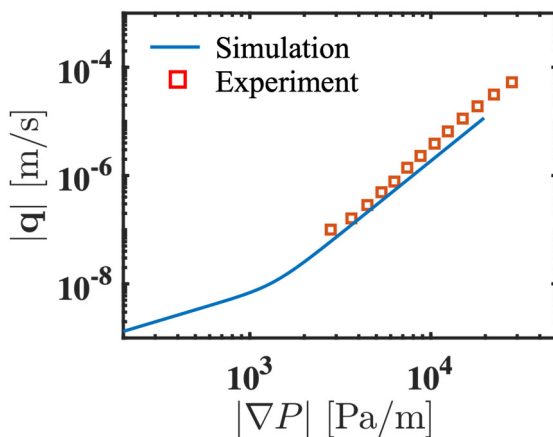


Figure 6. Variation in Darcy velocity with pressure gradient: Comparison of PNM data with experimental data for Sand B and

HPAM/PHPA concentration of 1.0 kg /m³ represented in Ejezie et al. (2021)

Data from the validated PNM applied void space topologies for a range of PSDs revealed that the flow of polymer fluids in soil can be categorized into three regimes. Referring to Figure 2, at low flow rates / pressure gradients, the flow rheology is within upper Newtonian plateau with $\eta = \eta_0$ and so Darcy's law governs the system response. As the pressure gradient increases there is a transitional regime where the viscosity in some of the throats is at the upper Newtonian plateau, while in other throats shear thinning occurs and the rheology is described by the power law illustrated on Figure 2. Finally, at higher pressure gradients, the rheology of the fluid in all of the throats is within the power law region. The shear thinning effect leads to the development of preferential flow pathways within the granular packing. The PNM data were used in upscaling to develop an expression for the effective viscosity that can be used to quantify the polymer conductivity for application in continuum models of flow which is detailed in Suo et al. (2025).

5 PERMEAMETER TESTING

While very useful permeameter test data were provided in Ejezie (2021), these tests did not consider propagation of the polymer front into water-saturated soil. Understanding the dynamics of this penetration is very important as the head gradient which provides stability to the excavation face depends on the polymer conductivity (which is a function of the viscosity) and also the penetration distance. Understanding of permeation was advanced using a custom-built 1 m long permeameter. A photo of the permeameter is given in Figure 1, while Figure 7 illustrates the experimental configuration schematically. As illustrated in Figure 7 a key feature of the permeameter is the series of tappings fitted with threaded and sealed steel fittings along the side of the column which are connected to pore pressure transducers via flexible tubing. Wall effects are mitigated as the steel fittings penetrate 20mm beyond the Perspex cylinder wall into the soil.

A range of sand and polymer combinations were investigated in the permeameter. Data from the experiments are presented in terms of the volume of fluid entering the permeameter normalized by the total pore volume within the permeameter (PVI). When PVI=1, sufficient polymer fluid has entered the sample to completely fill the pore space. As illustrated in Figure 8(a) the pressure drop across the volume of soil penetrated by fluid is almost linear and it has a significantly higher gradient than the pressure drop in the water-saturated soil. As the polymer fluid penetrates down the column, the pressure gradient across the polymer fluid decreases because there is a fixed head and the polymer path is increasing. The data can also be considered in terms of the flow rate against the quantity of polymer that has permeated into the column; a non-linear relationship is observed so that the flow rate reduces as the volume of polymer in the column increases. A 1-D continuum flow model was developed using the polymer permeability expressions derived in Suo et al. (2025) and assuming a sharp interface between the polymer-saturated soil and the water-saturated soil. A reasonably good match is achieved between this relatively simple model and the experimental data; giving confidence that the developed expressions for polymer fluid conductivity can be implemented in more sophisticated two- and three-dimensional models that can better capture the in-situ excavation geometries.

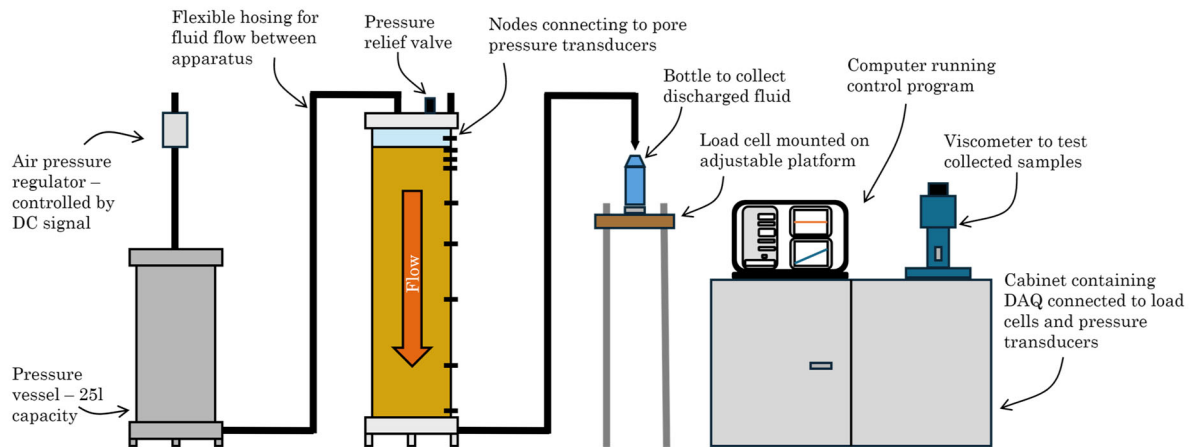


Figure 7. Schematic representation of the custom-built permeameter.

6 CONCLUSIONS

This paper has given a high-level overview of an ongoing multi-scale research project that aims to advance understanding of the permeation of polymer fluids in soils. The research tools adopted included computational fluid dynamics, microfluidics, pore network modelling, and permeameter testing. Key observations from each research strand are:

1. The high resolution computational fluid dynamics simulations showed that in the absence of any filter-cake formation or interaction between soil grains and the polymer chains, the high levels of viscosity achieved by the polymer fluids at low flow rates impart fluid-particle interaction forces that, for the fluids investigated, are up to four orders of magnitude higher than can be achieved using water alone.
2. The microfluidics experiments showed that the polymer fluid rheology is more complex than had hitherto been appreciated in the geotechnical engineering community. Flow recirculation in the voids is indicative of a visco-elastic rheology, which may give added benefits to the use of these fluids in excavation support.
3. Pore network model simulations revealed that the fluid flow can be categorized into three regimes and that preferential flow can develop along pathways where there is shear thinning. Data from the pore network model simulations were used to develop a general expression for polymer fluid conductivity in soil that can be used in continuum models.
4. A 1m tall custom-built permeameter has provided data to verify a simple 1-D continuum model that can be applied to describe the permeation of fluid into soil adjacent to an excavation.

Ongoing research aims to advance understanding of the implications of viscoelasticity for application of polymer fluids in the field and to extend the continuum models to two and three dimensions.

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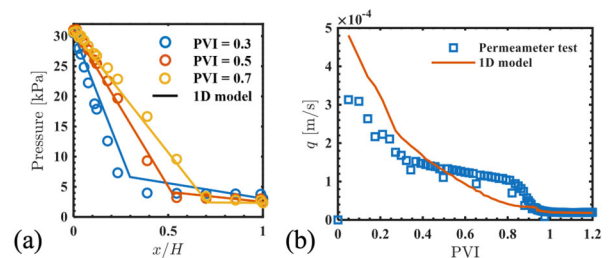


Figure 8. Data from permeameter experiments (point data) compared with 1-D continuum model of flow penetration (solid lines) (a) Variation in pressure with position (x) along permeameter column height (H is total height of permeameter column) (b) Variation in Darcy velocity with volume of polymer penetrated, quantified using PVI.

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