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Structure and properties of expanding polyurethane foam in the context of foundation remediation in expansive soil

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Abstract

Polyurethane foams have many applications and their fundamental properties have been widely investigated, mostly in relation to specific applications. In manufacturing, the need to produce homogeneous materials has led to the optimization of the formation processes and the understanding of the foam behaviour actually applies to homogeneous material. When applied to foundation remediation, expanding polyurethane foam is formed in the ground under conditions which are less controlled than in manufacturing processes or in the laboratory. Consequently, macrovoids and interfaces are created which result in a heterogeneous foam material. This paper investigates the microstructure and physical properties of expanded polyurethane foam injected in the ground using Scanning Electron Microscopy and physical testing. It is shown that the compressive strength is reduced by the resulting structural heterogeneity and the hydraulic conductivity is increased, but only to a value equivalent to that of a typical clay soil.

Key words: Polyurethane foam, foundation remediation, expansive soil, compression, permeability, microstructure

1 Introduction

Polyurethane foams are commonly used in many applications including packaging, cushioning, space filling and insulation but more rarely in geotechnical engineering. Various features of polyurethane foam behaviour have been investigated since they were first developed in the 1960s. According to the application of the foams in manufacturing and industry, attention is usually focused on one or more specific fundamental properties. From these studies, knowledge has been acquired on mechanical behaviour of foams subjected to dynamic and quasi-static compression (Zhang et al., 1998; Ford and Gibson, 1998; Mills and Zhu, 1999), on the insulation properties (Nikitina et al., 1982) or on long term behaviours such as creep (Nolte and Finley, 1970). Several studies have been performed on the water transfer properties of open cell polyurethane foams (Gent and Rusch, 1966; Dawson et al., 2007) but little data is actually available on water transfer in closed cell poyurethane foams (Mondal and Khakhar, 2006; Sabbahi and Vergnaud, 1993). The foam formation process has also received much attention (Artavia and Macosko, 1994; Mitani and Hamada, 2003; Seo and Youn, 2005; Schwartz and Roy, 2002). For many applications homogeneous materials are required. Consequently, molding processes have been optimized (e.g. in Yacoub and MacGregor, 2003) in order to produce material with good homogeneity. Consequently, most existing knowledge about the fundamental properties of foam or about its mechanical behaviour is only strictly applicable to homogeneous material.

It is now commonly acknowledged that the unconfined uniaxial compression behaviour of polyurethane foams displays an elastic-perfectly plastic behaviour

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followed by a densification phase when compressed along the rising direction (Youssef et al., 2005). The foam response is slightly different when compressed perpendicular to the rising direction; namely, in the transverse direction. In this situation, a hardening phase replaces the plastic plateau (Tu et al., 2001; Zhang et al., 1998). The behaviour of a foam is linked to its microstructure as noted by Barma et al. (1978). Several behaviour models have been developed which focus on the shape of the basic cell to reproduce the mechanical response, its dependency on density and anisotropy (Ford and Gibson, 1998; Mills and Zhu, 1999; Barma et al., 1978). Moreover, a detailed study of the evolution of microstructure during compression shows that the struts and walls progressively bend causing irreversible deformation (Youssef et al., 2005; Hamza et al., 1997).

Foundation remediation techniques using polyurethane foams have only appeared in the last 25 years and a "deep lifting" process has been patented more recently (Canteri, 1998), which from a geotechnical perspective is at the border between underpinning and grouting. The polyurethane foam is injected in the ground at discrete locations under an existing structure to correct differential settlements and to apply compactive forces to the foundation soils. The two components of the foam, which mix as they are injected through a tube into the ground, react to produce the polyurethane foam which expands in the ground. The expansion pressure it exerts is used to lift the structure, remediating a differential settlement problem without excavation or the installation of additional foundation elements (see case history in Favaretti et al. (2004)). This technique can provide an effective and efficient solution for many differential settlements problems (e.g. erosion of the soil, settlement of poorly compacted soil, settlement due to adjacent work site, consolidating/collapsing soil) and it has even been used in cracked expansive clay soils. It also limits further settlements.

For geotechnical engineering purposes, it is of prime importance to understand the hydro-mechanical behaviour of the composite material that results from the in situ injection of foam into an expansive clay. Obviously, this requires characterization the behaviour of each component i.e. foam and expansive clays. In particular, the water permeability and the behaviour of the foam in compression are of interest. When remediating a sunken structure, the foam is injected in several shots. Each of these is allowed to expand before the next is delivered. As a consequence, later shots interact with earlier shots as they expand. The formation of the foam can not be controlled and the resulting hardened product is found to be far from homogeneous, affecting the applicability of test results obtained from homogeneous foams formed in the laboratory. This study has been undertaken in order to assess the difference in the hydraulic and mechanical properties, between foams formed in the ground and foams produced in the laboratory.

This paper first shows that the microstructure of the foam injected in a cracked dry soil is different from that of an homogeneous foam formed in the laboratory. The heterogeneity of the foam is investigated using Scanning Electron Microscope images. Then, the consequence of the foam heterogeneity on its hydraulic and mechanical properties is evaluated from a series of uniaxial unconfined compression tests and permeability tests. The results show that tests performed on homogeneous material formed in the laboratory are not representative of the foam which is produced in the ground.

2 Test material

A polyurethane foam formed with densities ranging from around 37 kg/m^3 to 145 kg/m^3 is studied. The material tested herein is the one used by Uretek for the deep lifting application. It is formed from an exothermic reaction between a polyol and an isocyanate, mixed in specific volumetric proportions, as recommended by Uretek. Reaction times depend on the temperature of the components and, for the foundation remediation application, the foam hardens within a few minutes. The foam used in this research, when reacted without confinement (free expansion), reaches a volume thirty times greater than that of the initial components with a density of about 37 kg/m^3. When injected into a soil, the final volume of the foam depends on the volume of voids available and the level of confinement. Expansion pressures of up to 10 MPa have been reached (Favaretti et al., 2004). Once injected and expanded under a foundation, the foam is considered to be stable since it is only degraded by UV radiation and some volatile solvents (e.g. acetone) that normally should not be found under a building. The closed cell structure of a 37 kg/m^3 foam is shown in Figure 1. From Scanning Electron Microscope images, it appears that the basic cell size ranges from 0.1 mm to 0.4 mm and that the cells have the form of irregular polyhedrons. Due to the closed porosity, the polyurethane foam is relatively resistant to water absorption and it can be used to displace and exclude water in some geotechnical applications (Tourcher, 1989). The same raw materials, mixed always in the same proportions, as recommended by Uretek for this application, were used for all the tests described in this study, on specimens formed in the laboratory and on specimens formed in the ground.

3 Tests methods

The expansion of the foam has to be relatively fast for the efficiency of the remediation process, since the need for further lifting can only be assessed after the lifting due to resins already injected has been evaluated. Moreover, the injection process is incremental at many points beneath the foundation, and the levels are monitored. The fast expansion of the foam combined with multiple injection points results in subsequent "shots" of resin affecting foam formed by earlier "shots".

The objective of this study is to investigate how such an injection process affects the structure of the foam in foundation remediation applications and therefore its mechanical and hydraulic properties. As mentioned previously, two types of samples are considered. First, are foam samples formed by injection into a dessicated expansive clay soil (specimens labeled G for ground), in which the foam forms into narrow irregular veins. Second, are samples formed by injection into closed high pressure PVC tubes to make both homogeneous specimens and heterogeneous specimens incorporating contact planes between early and later shots of resin (see Figure 2). These specimens are labeled H (for homogeneous) and C (for contact), respectively. By knowing the internal volume of the PVC tube and monitoring the mass of the injected foam, a range of different target values of bulk density were achieved for these samples. The density of the foam formed in situ is difficult to monitor and control. For specimens formed at about one meter deep, foam density naturally fluctuates between 85 and 145 kg/m^3. This point is discussed in section 4. As shown by Favaretti et al. (2004), the density increases with the level of confinement so that the deeper the resin is injected, the denser it shoud be. In the following, the subscripts "c" and "k" added to the specimen label indicate samples tested to measure either compressive strength or permeability, respectively.

The international standard for testing polymers in compression (ISO 844:2001(E), 2001) recommends the use of square prism specimens of 100 (L) $\times$ 100 (W) $\times$ 50 (H) mm. Because the study deals with foam formed in situ in the cracks of the soil, the tests had to be performed on smaller specimens. However, the sample aspect ratio of 2 is considered to remain appropriate and so a standard specimen size of 20 $\times$ 20 $\times$ 10 mm was adopted. H_c and C_c specimens of this size were compressed only in the rising direction.

All G_c specimens came from veins of foam formed in the ground (as in Figure 3) and they were tested either parallel to the rising direction or perpendicular to the rising direction, namely transverse direction, (labeled G_c^R and G_c^T, respectively), as highlighted in Figure 3. The widest foam vein is approximately 10 mm thick so that specimens G_c^T of approximately 20 $\times$ 20 $\times$ 10 mm could be prepared. As trimming of the end surfaces of G_c^T specimens would cause excessive shortening of the samples, a cap of mortar was used to obtain flat and parallel surfaces. Specimens G_c^R were only 10 $\times$ 10 $\times$ 5 mm due to the limited width of the recovered foam veins. However, using such small specimens does not compromise the validity of the results, since no major defects were visible in the prepared samples and a length of 10 mm is still representative when the size of the basic cells in the G foam is around 0.1 mm. All of the specimens were compressed at a strain rate of 0.0016 s^{-1} or 0.1 min^{-1}. The experimental details are summarized in Table 1. Note that smaller veins have not been considered because of the difficulty to obtain representative samples. Consequently, the possible dependance of foam yield stress on its thickness has not been assessed. This point will be discussed in section 5.

Specimen	H_c	C_c	G_c^R	G_c^T
Foam	Lab formed Homogeneous	Lab formed Including contact	Injected in situ	Injected in situ
Dimensions	20 × 20 × 10	20 × 20 × 10	10 × 10 × 5	20 × 20 × 10
Loading dir.	Rising	Rising	Rising	Transverse

Table 1

Detail of the specimens tested in compression

The permeability tests were performed in Rowe Cells using GDS pressure controllers. An pressure difference of 25 kPa between the inlet and the outlet of the cell was applied and the outlet flow rate was monitored. Standard Rowe cells were used for testing homogeneous foam (diameter 74 mm, height 20 mm) and a modified Rowe cell arrangement was used for the foam formed by injection in the ground. The modification consisted of the use of a higher external ring which was combined with an additional internal ring to avoid water leakage at the ring/foam interface (see Figure 4). The G_k foam was mounted in the Rowe cell, still in contact with the original soil it was injected into. This allowed the cell to be filled completely to prevent any deflection of the foam due to the applied water pressure and possible consequent leakage. The permeability of the clay has been previously measured, allowing back calculation of the foam permeability. This was done using a serial material model, for which the following relationship prevails:

$$\frac{h_f}{k_f} = \frac{h_{cs}}{k_{cs}} - \frac{h_s}{k_s} \tag{1}$$

with k_s, k_{cs} and k_f the permeability of the soil, of the composite specimen and of the foam, respectively, and h refers to the height of each material, with the same subscript meaning. Note that the Darcy permeability is intrinsic to the material and does not depend on its thickness.

4 Results

4.1 Foam formation in the ground

When injecting the foam into a desiccated clay, it is observed that it can either propagate through existing cracks or it can create new fractures in the soil. With the foam following the weakest path, its propagation is a somewhat random phenomenon. In any case, the foam hardens in veins, which can be of various morphology and dimensions as shown in Figure 5. Figure 5 (a) shows a relatively wide vein of foam, formed in a 20 mm crack whereas Figure 5 (b) shows that the foam can fill much smaller cracks (down to 0.5 mm). In general, the wider the cracks, the further the foam is able to propagate. One consequence is the development of foam dendrites at the soil/foam interface (Figure 5 (a)) to a depth of about 3 mm. The foam/soil interface at the scale of the basic cell can be seen in Figure 6. At this scale, it appears that there is a layer of cells which are simply in contact with the soil without being bonded to it. In the light of this image, it can be deduced that a dendrite is likely to form if a void larger than the size of the basic cell exists in the soil at the crack interface. Some soil particles can be found within the foam in the vicinity of the soil/foam interface. However, very few soil particles are found in the bulk of the foam i.e. in the middle of the vein. In case of propagation in open cracks, the resin mixes with the soil only at the interface and if the resin fractures the soil, it is still believed that the resin mixes mainly at the interface.

During a foundation remediation process, the foam is injected in successive "shots" so that the lift occurs incrementally and can be monitored. One direct consequence of this is the interaction between successive shots of foam, as is visible in Figure 5 (a) where a subsequent shot has cracked the previous one. As a result, macrovoids and contact planes are formed in the foam, that results in a structure which is actually made of several sub layers. The formation of macrovoids such as those observed in Figure 5 (a) is allowed by the significant width of the crack (20 mm) and they are not so obvious in foams formed in smaller cracks (e.g. in Figure 7 (a)). However, when looking closer using the SEM, it appears that the foam in smaller cracks is still heterogeneous (see Figures 7 and 8). Figure 7 (a) is a view of foam filling a 10 mm wide crack, in which a darker stripe of foam is visible (view of the R-T plane). The circled region has been magnified in Figure 7 (b) and it appears that the foam microstructure is highly heterogeneous: the intersected cells are either almost circular or very elongated and the sizes range from 30 μm to 300 μm. The distribution of the cell sizes is the result of the propagation and hardening of the foam and it does not appear to be uniform or gradual, although there is some suggestion of gradual changes in orientation.

Figure 8 shows the structure of the foam in the rising direction (R-T plane). Points A and B on Figures 8 (a) and (b) correspond to points A and B in Figure 7 (a). The point C is common to Figures 7 (a) and 7 (b). The darker stripe visible in Figure 7 (a) is denoted as zone 2. It can be seen that the micro structure of zone 2 is different from that of zone 1: the cells are bigger and more elongated, with their longer axes aligning with the rising direction, denoting a possible flow. The heterogeneity of the foam appears quite clearly in this image.

Several previous works have shown that the response of the foam in compression is governed by the size and shape of the elementary cells. The analysis of these SEM images raises the issue of the relevance of the tests performed in the laboratory on homogeneous specimens when they are extrapolated to the foam injected in the ground. This is considered in the next sections.

4.2 Influence on the mechanical properties

As noted previously, the behaviour of polyurethane foams in unconfined uniaxial compression is well known. A typical evolution of nominal stress versus nominal strain is shown in Figure 9 (a) for a homogeneous foam having a density of 52 kg/m^3. Three phases are identified: an elastic phase, a plastic plateau and finally, a densification phase. This result is entirely consistent with the behaviour described by Tu et al. (2001).

The measure density of foam injected in the ground varies significantly (from 85 to 145 kg/m^3). This is mainly due to the manner in which the foam is injected i.e. as multiple "shots" but also to the method of specimen preparation. Indeed, specimens G_c^T are made of the entire foam vein including the foam/soil interface and their measured density ranges from 110 to 140 kg/m^3. Specimens G_c^R have been formed by grinding to remove the soil/foam interface so that they only incorporate the central part of the foam. From the SEM image in Figure 8 it can be assumed that the foam close to the interface is slightly denser than the foam in the middle of the crack. Indeed, the cells are smaller and more numerous, meaning that there are more walls or solid material in a given volume. This observation suggests that the soil moisture does not act as a blowing agent. This localized increase of density explains why the average density of specimens G_c^R is generally lower than that of specimens G_c^T.

Because most properties of polyurethane foams are density dependant (e.g. as noted in Saha et al. (2005)), attention has been focused on the value of the elastic yield stress as a function of density as displayed in Figure 9 (b). As expected for the homogeneous material (H_c specimens), the yield stress increases consistently with the density. A unique linear trend can be reasonably defined for the homogeneous material compressed in the rising direction ($R^2 = 0.93$, 24 points).

The effect of heterogeneities within the foam specimens on their yield stress was investigated. It was observed that when a contact plane occurs within homogeneous specimen (sample series C_c), its yield stress is significantly reduced. However, none of the specimens appeared to be physically broken along the contact plane. It was also found that for foams of similar density, the yield stress of the heterogeneous foam formed in the ground was lower than that of the homogeneous material. This difference is consistent with a heterogeneous microstructure and the occurrence of occasional larger voids.

The yield stress is generally found to be lower in the transverse direction (Tu et al., 2001). However, in this research, this trend could not be verified. Indeed, the yield stresses in both rising and transverse directions are very similar and seemingly limited to values between 250 kPa and 500 kPa. Obviously the density of G_c^R specimens is, on average, lower than that of G_c^T and this should be appreciated when considering the anisotropy of the specimens. However, the difference in density between G_c^R and G_c^T specimens comes from the difference in the preparation protocol, i.e specimens including the soil/foam interface versus trimmed specimens without soil/foam interface. Preparing the specimens in the same manner should lead to similar values of density. The reduction in yield stress, compared to the best-fit trend for homogeneous samples, is given in Figure 10. It can be seen that the yield stress is reduced by an average of 62% with a maximum reduction of 80 % for only 3 specimens. Considering that specimens C_c, formed in the laboratory and incorporating contact planes, display a lower compressive strength compared to homogeneous material, it can be concluded that the reduction in yield stress for specimens G_c^R and G_c^T is only due to the heterogeneous micro structure (Barma et al., 1978) and not to any soil particles in the foam. Even though the actual yield stress is lower than the expected value for an equivalent homogeneous material, the yield stress for the majority of specimens is still more than 250 kPa. Note that the reduction of mechanical strength could be compensated, if required, using less blowing agent, which would increase the density and consequently, the compressive strength. However, this would be detrimental to the technique as the production of carbon dioxide generates the swelling pressure used to lift up the structure.

The difference in behaviour, in response to compression in the rising direction and compression in the transverse direction, should be readily apparent (Tu et al., 2001) and, as noted before, explained by the shape of the basic cell. Some complementary Scanning Electron Microscope images have been obtained to study the microstructure of the foam injected in the ground, in the direction transverse to injection (see Figure 11, viewed in the R-R plane). The foam appears to be heterogeneous, similar to its appearance in the R-T plane. No significant difference can be observed in the cellular structures viewed in the rising and the transverse directions. Consistently, the mechanical responses are also very similar , with neither the rising direction nor the transverse direction compression curves displaying a plastic plateau. On the contrary, a strain hardening process is visible in both situations, with the form shown in Figure 12. Indeed, the only small differences between the compression behaviour in the rising and transverse directions is that a slightly higher compressive strength is measured in the rising direction and a slightly reduced strain to the onset of densification is observed for compression in the transverse direction.

4.3 Influence on the hydraulic properties

Attention was paid, when preparing the specimens for the permeability tests, not to tear the foam in order to prevent any flow through micro cracks that might be inherent to the preparation procedure. As for the study of compression properties, the permeability was also studied as a possible function of density (see Figure 13 (a)).

For the homogenous foam (specimens H_k), a steady state flow could only be obtained for the lightest foam, which formed by expanding freely to a density of 37 kg/m^3. The corresponding permeabilities range from 10^{-8} m/s to 10^{-9} m/s. The homogeneous materials of greater density would not allow water to flow due to the closed cell structure of the material. The permeability of the impermeable samples has been arbitrarilty set at 10^{-18} m/s in order to indicate them on a logarithmic scale on the same figure. The foam was shown to resist flow for applied water pressures up to 200 kPa. Beyond these pressures, water was able to permeate at the foam/ring interface, but still the closed cells did not rupture.

Due to the heterogeneity and the interconnected macrovoids they incorporate, the G_k specimens were found to be slightly permeable. Only three specimens could be tested from the veins exhumed from the ground with their adjacent soil (with a density around 140 kg/m^3). As noted before, the foam permeability has been back-calculated from the tests on the foam/soil composite, using a serial material model and knowing the permeability of the silty clay (around 3×10^{-7} m/s). Despite the in situ foam being denser than the specimens formed in the laboratory, the determined permeability of specimens G_k is around 10^{-10} m/s. The structure of the foam is still predominantly closed cells but the existence of connected macrovoids in the deformed structure allows some water flow through the foam.

5 Significance for the foundation behaviour

The compressive strength of the heterogeneous foam formed in the ground was found to be on average 62% lower than that of the homogeneous foams of the same type and density formed in the laboratory. However, the unconfined yield stress is still around 300 to 400 kPa. Once injected, the foam could be compressed vertically by the overburden load (overlying soil plus structural loading) and/or horizontally, in the situation of a dry expansive soil which swells in response to wetting. In either case, the stresses exerted on the foam in the foundation are unlikely to exceed its yield stress. The typical foundation loading for residential houses in Australia is usually much lower than 50 kPa (Walsh and Cameron, 1997) and with foam injection at a depth of around 2 m, the in situ soil load is around 40 kPa.

Natural expansive soils can display high swelling pressures (e.g. 1300 kPa in the study by Williams (1992)), however, such swelling pressures are determined in the laboratory under total confinement. This is unlikely to occur due to the numerous open cracks of the soil., many of which a re too small to accommodate significant resin propagation. Uppal and Palit (1969) have shown that the swelling pressure drops significantly if there is even a small volume of unfilled macrovoids in which the soil can swell freely. A reduction of 68 % of the peak swelling pressure of an unvoided clay soil, has been recorded for a soil with as little as 1% macrovoids in its total volume. Further, as shown in Figure 12, no plastic plateau is observed when compressing the foams formed in situ. On the contrary, a hardening process takes place leading to a progressive increase of the strength. Consequently, the loss of mechanical strength arising from heterogeneity does not jeopardize the mechanical stability of the resin in the specific context of an injected clay soil.

The reduction in mechanical strength, measured at 62%, could only be measured for the thickest resin veins (10 mm thick). No quantification of the reduction in mechanical strength has been made on smaller veins of resin due to the difficulty to prepare and test the specimens (see Figure 5 (b)). However, the thickest veins (10 mm thick) provide the most significant contribution to the mechanical behaviour of the composite soil mass, and the smaller veins regardless of their behaviour, are considered unlikely to significantly reduce the mechanical behaviour of the treated soil foundation.

With a hydraulic conductivity of around 10^{-10} m/s, the heterogeneous foam is found to have a similar permeability to an intact clay for which typical values of hydraulic conductivity range from 10^{-10} m/s to 10^{-12} m/s. However, the cracked soil mass is a dual permeability system where advective flow through open cracks is a dominant component of the water movement (Chertkov and Ravina, 2000). Therefore, in a clay foundation soil, the relevant permeability to consider is not that of the bulk clay but that of the cracks. When the foam fills the cracks, it prevents water from penetrating rapidly deeply in the soil mass. Even if the foam is not totally impervious to water, it significantly reduces the water transfer in the cracked soil mass.

This is of particular importance for the soil swelling issue related to the application of this technique in expansive soils (Buzzi et al., 2007). Indeed, with reduced water transfer in the soil mass due to the presence of foam in the cracks, soil swelling is delayed, which is desirable to reduce the risk of overlifting of the remediated infrastructure, should post-remediation foundation wetting occur.

6 Conclusions

Polyurethane foams have been widely studied since their invention in the 1960s. Most features of their behaviour are now well understood. However, because many applications require homogeneous material, the acquired knowledge has been focused on homogeneous specimens. A foundation remediation technique using expanding polyurethane foams has been developed quite recently. In this application, the foam is injected into the ground in an incremental manner and its expansion is used to lift settled structures and to prevent further settlements. It has been observed however, that expansion and propagation of the polyurethane foam in the cracks of a dessicated clay soil results in a foam material that is heterogeneous at a macro scale with obvious features that result from the interaction of the successive injections and flow through narrow fissures and sharp corners. This structural heterogeneity has been confirmed at the micro scale using a Scaning Electron Microscope : the size and shape of the cells vary significantly across the specimen and some larger voids are visible. Moreover, the cell size is not distributed uniformly in the foam. This obvious heterogeneity compromises the relevance of results obtained in the laboratory on free-rise, homogeneous specimens.

A series of 40 compression tests have been performed on homogeneous and heterogeneous foam. Because the foam in the ground could be compressed either vertically and horizontally, compressions in both rising and transverse directions have been applied on the samples coming from the ground. The results of compression tests on homogeneous and heterogeneous foams clearly show that the foam injected in the ground has a yield stress ranging from 250 kPa to 500 kPa, which is from 40 to 80 % lower than that of the homogeneous material.

The homogeneous foam is a closed cell structure and the permeability tests have proved that it is almost impermeable. The foam injected in the ground is still a closed cell structure but because of localized damage to the cell structure resulting from multiple episodes of injection and expansion, small amounts of water are able to flow. A permeability of around 10^{-10} m/s has been determined for this material.

The study undertaken herein has enabled the effect of heterogeneity on the relevant mechanical and hydraulic properties of the polyurethane foam used in a foundation remediation technique to be evaluated. This is of particular relevance for accurate geotechnical assessment of the composite soil mass made of foam and clay. Even though an obvious reduction in yield stress and an increase in permeability have been noticed, their effect are not considered to compromise the validity of the expanding polyurethane foam injection as a foundation remediation technique. This is because the yield stress of the foam is still several times greater than the typical foundation pressures beneath lightly loaded structures, and the permeability of the injected foam is lower than, or similar to, that of the uncracked clay soil. This means that foam injection will effectively and significantly reduce the bulk permeability of a cracked clay soil, impeding sudden wetting of remediated foundation soils.

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7 Acknowledgments

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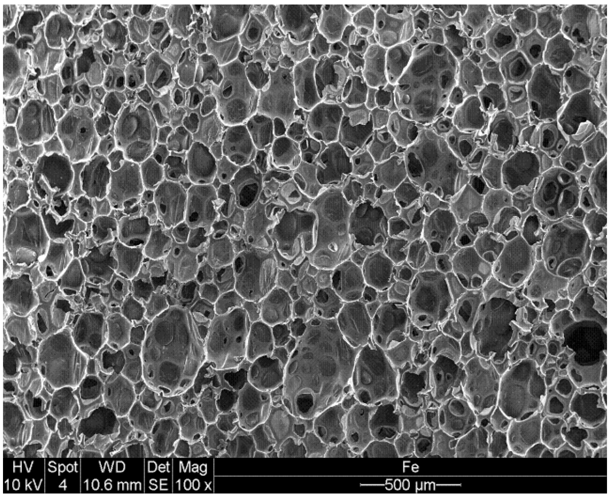
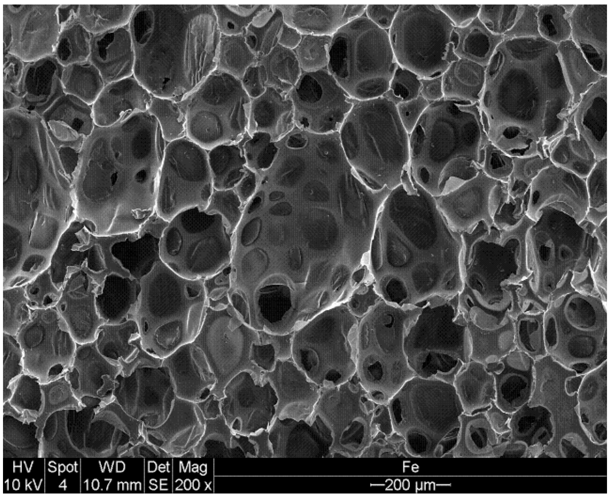


(a)



(b)

Fig. 1. Image of the free expanded polyurethane foam (density of 37 kg/m^3) obtained by Scanning Electron Microscope. (a) Magnification $\times$ 100. (b) Magnification $\times$ 200.

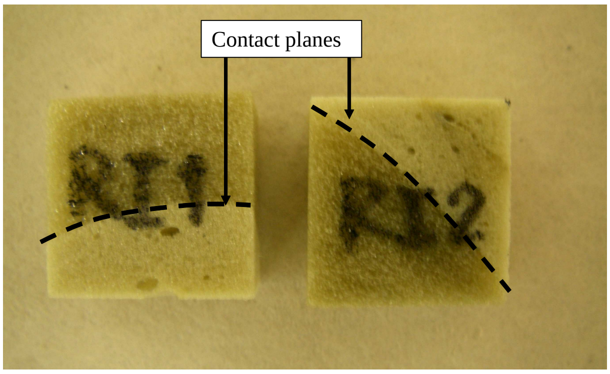


Fig. 2. View of two C_c specimens: foam formed by multiple injections in PVC tubes, showing consequent internal contact planes. Dimensions: 20 mm $\times$ 20 mm $\times$ 10 mm.

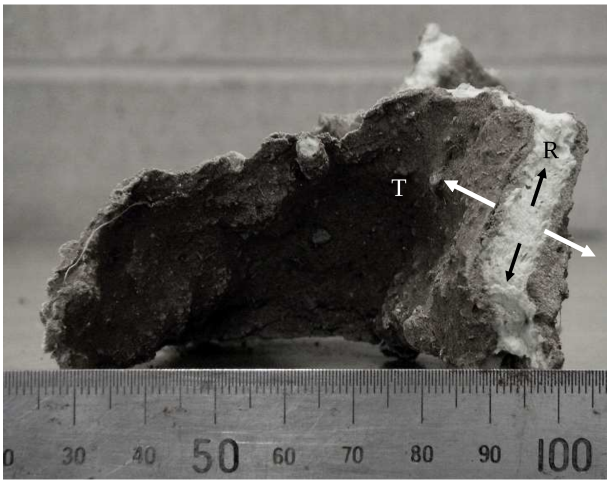


Fig. 3. View of a vein of foam formed in a cracked clay soil. T and R correspond to the transverse and rising directions, respectively.

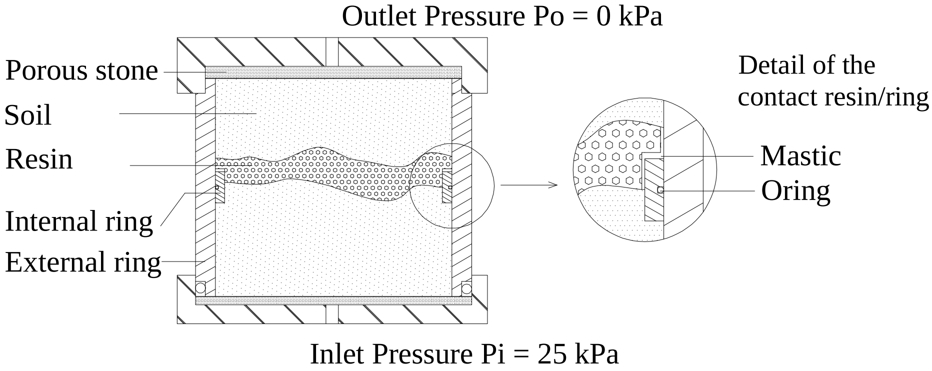
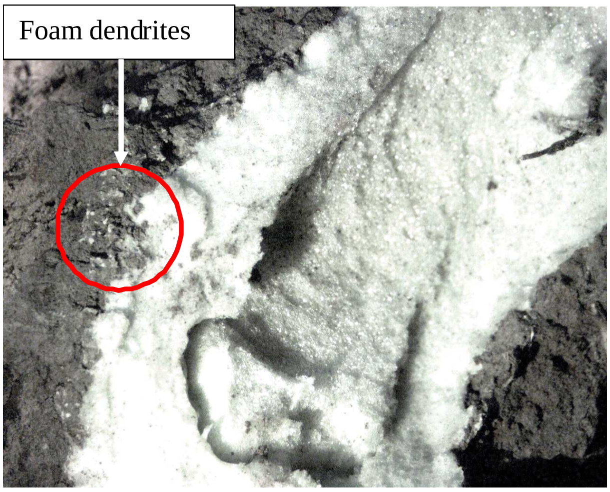


Fig. 4. Schematic representation of the modified Rowe Cell used for the composite soil. Total height of permeability tests on composite soil-foam specimen : $h_{cs} = 70$ mm. Thickness of the foam vein : $h_f \approx 10$ mm.



(a)

(b)

Fig. 5. (a) View of foam formed in the ground, showing dendrites. Width of the crack: 20 mm. (b) View of foam injected soil specimen of 100 mm diameter.

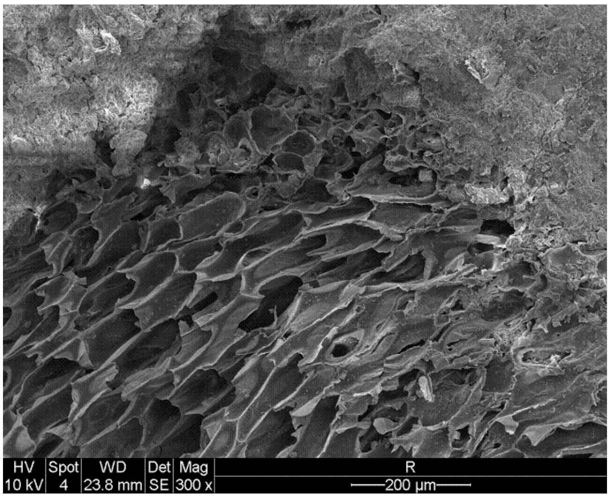
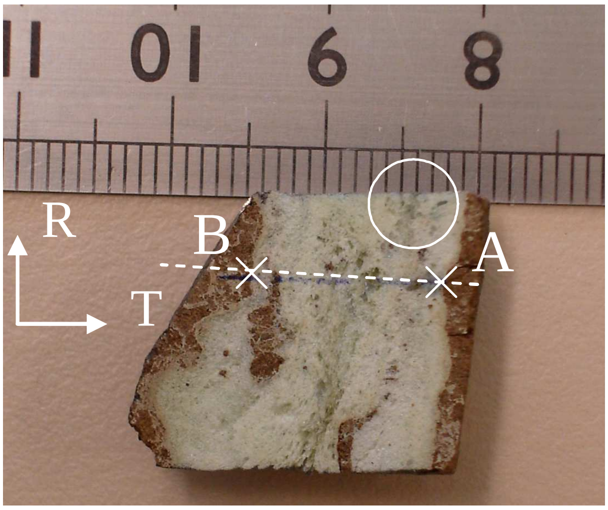
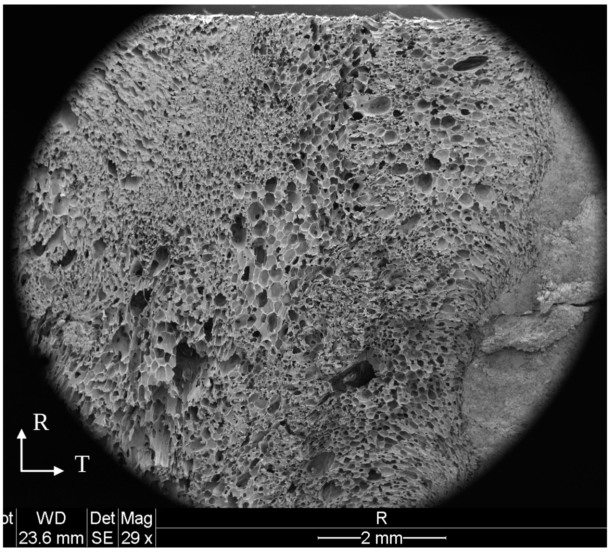


Fig. 6. Soil-foam interface. Image obtained by Scanning Electron Microscope. Magnification × 300.



(a)



(b)

Fig. 7. (a) View of foam having formed in a crack. (b) Magnification of the circled zone with the Scanning Electron Microscope. R and T refer to the rising and transverse directions, as defined in Figure 3.

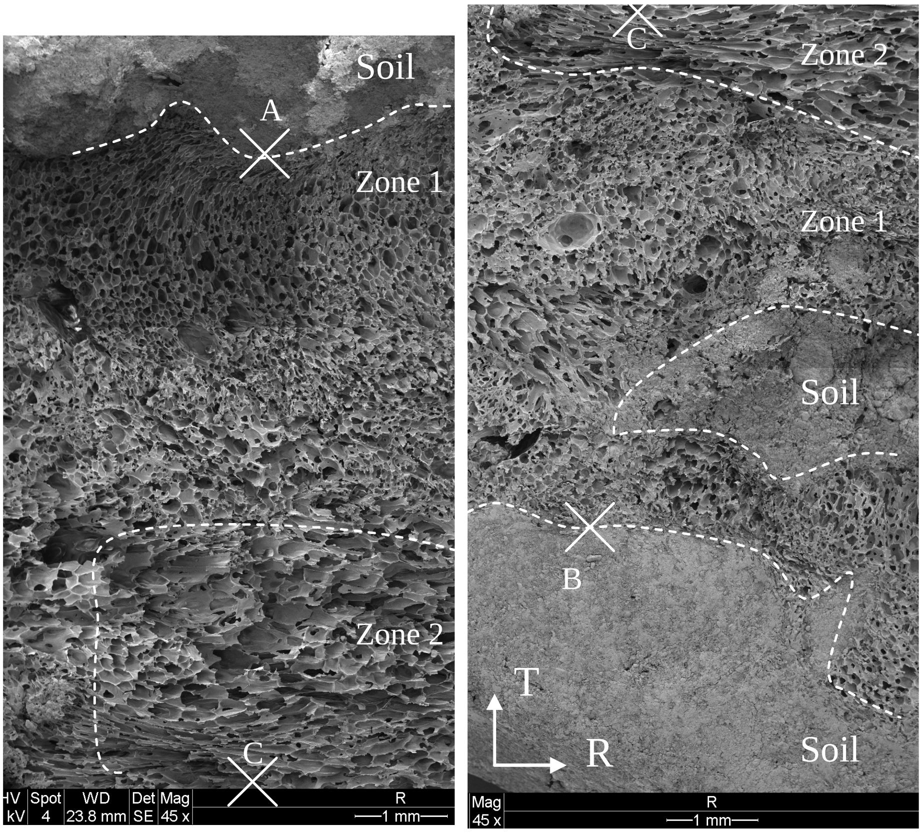


Fig. 8. Magnification of the foam specimen shown in Figure 7 (a). Points A and B correspond to points A and B in Figure 7 (a). Both figures match in point C. Magnification $\times$ 45.

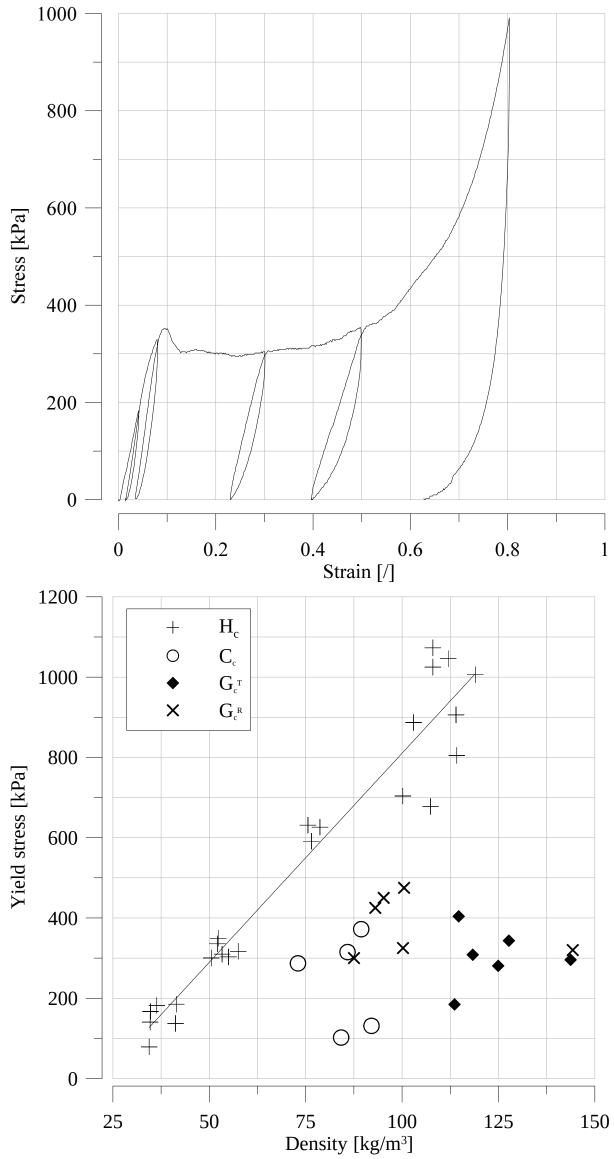


Fig. 9. (a) Evolution of nominal stress versus nominal strain during an unconfined uniaxial compression in the rising direction on homogeneous polyurethane foam (density 52 kg/m^3). (b) Results of all compression tests: yield stress versus density.

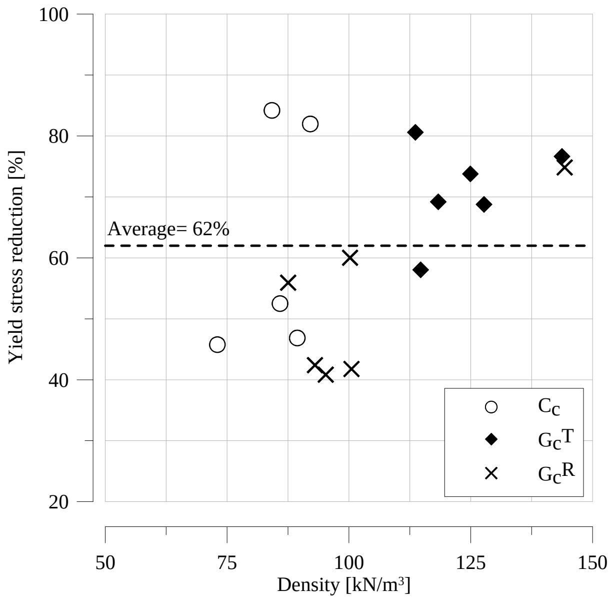
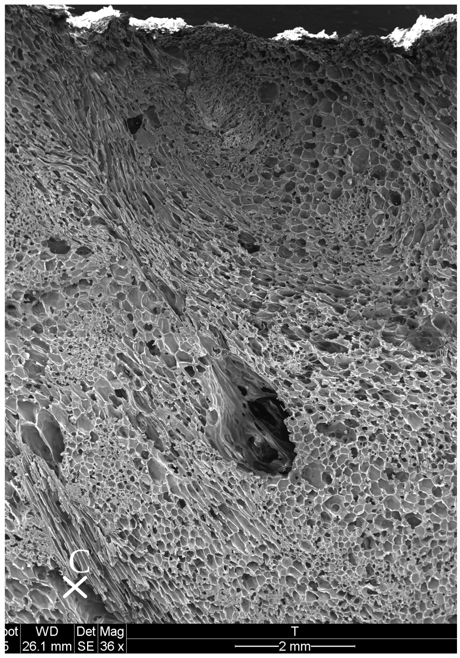
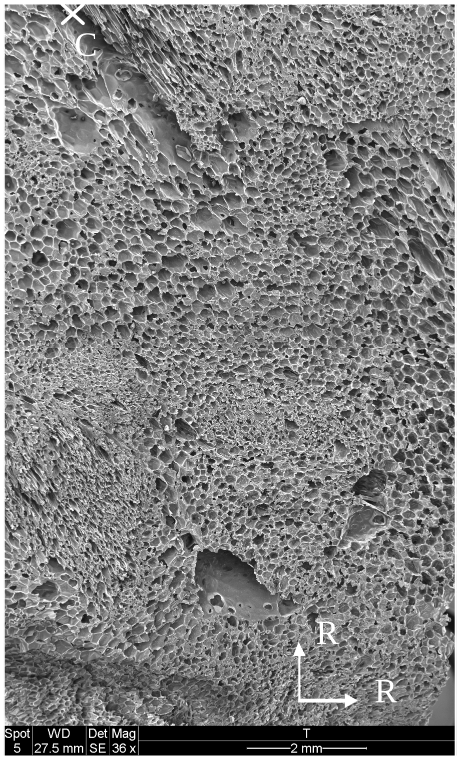


Fig. 10. Value of the yield stress reduction versus density for heterogeneous specimens. The yield stress loss is defined as $\frac{\sigma_{pr}-\sigma_{exp}}{\sigma_{pr}}$ where σ_{pr} is the value of predicted yield stress given by the linear fitting obtained on homogeneous specimens and σ_{exp} is the experimental value measured.



(a)



(b)

Fig. 11. Scaning Electron Microscope image of the foam injected in the ground. View in the transverse direction in the R-R plane. Magnification × 36. Figures (a) and (b) join together at point C.

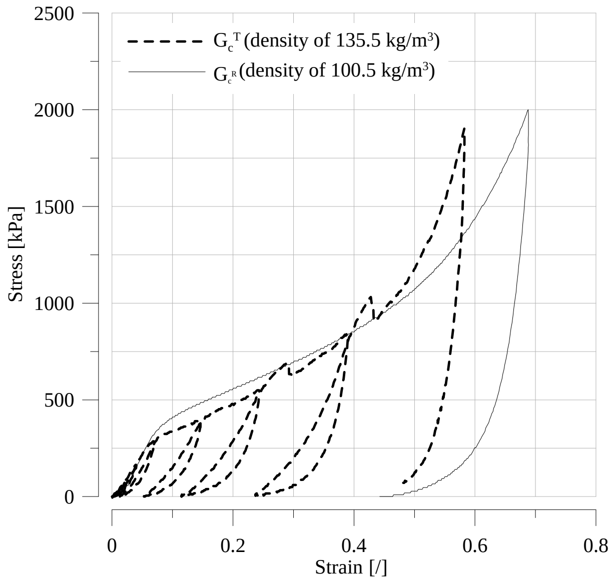


Fig. 12. Evolution of nominal stress versus nominal strain during an unconfined uniaxial compression test for the foam injected in situ. The dotted line corresponds to a compression in the transverse direction and the full line in the rising direction.

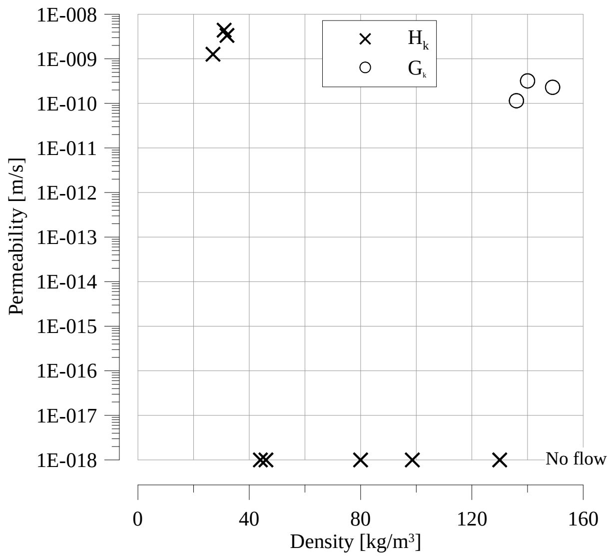


Fig. 13. Results of permeability tests on foam injected in the ground (G_k) and homogeneous material (H_k). The results correspond to an applied water pressure of 25 kPa.