Geotechnical Aspects of Underground Construction in Soft Ground, Kastner, Emeriault, Dias, Guilloux (eds)
 ISBN 2-9510416-3-2

Soil conditioning for EPBM tunnelling: compressibility behaviour of foam/sand mixtures

S. Psomas
FaberMaunsell, Beckenham, Kent, UK

G.T. Houlsby
Oxford University, Oxford, UK

ABSTRACT: Soil conditioning improves the performance of earth pressure balance tunnelling machines by modifying the properties of the excavated soil. Foams are used as soil conditioning agents with EPBMs, because they offer some significant benefits over other conditioning agents, and also widen the range of application of EPBMs. In this paper the compressibility behaviour of foam/sand mixtures is examined. Compression tests were carried out in a conventional Rowe cell. The test results revealed that foam/sand mixtures can remain stable at significant stress levels.

1. SOIL CONDITIONING IN EPBMs

1.1 Background

The term *soil conditioning* refers to the use of suitable additives (conditioning agents) in various proportions to alter the soil properties of the excavated spoil. Soil conditioning agents used in EPBM (Earth Pressure Balance Machine) tunnelling are site and project specific, and are typically foams, bentonite slurries and/or polymer suspensions. The range of soils, which can be excavated using an EPBM, can be extended to include coarse-grained soils by using soil conditioning. Soil conditioning agents improve the performance of several of the EPBM parts and may be introduced at various points such as the tunnel face, machine head and screw conveyor (Milligan 2000). The improvement comes about by reducing permeability and by controlling the shear strength and the compressibility of the spoil. The aim of this paper is to examine the compressibility behaviour of foam/sand mixtures, similar to those in an EPB machine.

The increase of the compressibility of the soil in the pressure chamber through the addition and mixing of conditioning agents improves the workability and the homogeneity of the spoil. A more compressible and 'plastic' material in the pressure chamber behaves as a high viscosity fluid and, as a result, better control of the fluctuations of the pressure distribution at the face can be attained. This, in turn, appears to improve the stability of the tunnel face and provides better control of ground movements, thereby contributing to safer working conditions for the personnel in the tunnel.

As a result of the above, higher advance rates can be achieved due to the improved flow characteristics of the conditioned spoil through the cutter head and the lubrication of the moving parts. Because in EPB shields, screw conveyors transport the excavated material from the pressurised excavation chamber to the tunnel exit under atmospheric pressure, the removal rate and the rate of advance must be compatible, otherwise loss of the support pressure at the tunnel face occurs. Using soil conditioning agents, the extrusion through the screw conveyor can be controlled without causing excessive wear or consumption of power (Milligan, 2000).

The major advantage of using foam instead of bentonite-based conditioning agents is that a significantly smaller volume of extra liquid is added to the natural water content of the soil. This, in turn, results in a smaller volume of excavated material and can eliminate the need to process the slurry in a surface plant. As 90% of foam consists of air, which will escape entirely after only a few days, the original consistency of the soil can be restored very quickly. The remaining 10% of the foam is a water based solution.

1.2 Objective of the research

The objective of this paper is to present part of the preliminary research work carried out at Oxford University on the effectiveness of foaming agents when mixed with coarse-grained soils. To investigate the basic behaviour of foamed soil, tests on the fundamental soil properties – compressibility, permeability and shear strength of soil – were carried out. Testing included mixing, compression, permeability and shear-box tests. In this paper only the compressibility tests results of foam/sand mixtures are examined.

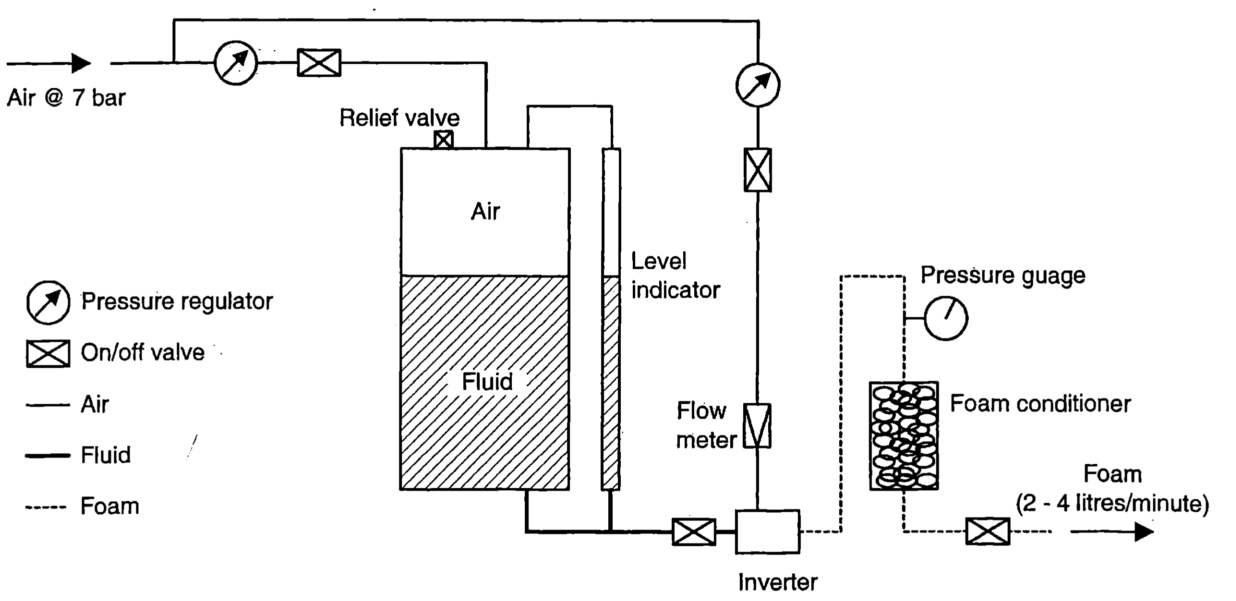

Figure 1: Foam generator

2. MATERIALS AND EQUIPMENT

Laboratory testing was carried out by employing standard and non-standard equipment

2.1 Foam Generator

To produce foam of the prescribed quality a foam generator was designed and built in-house. The main systems and components are shown in Figure 1. The liquid consisted of water and the foaming agent (concentrate). The foam generator operates by mixing solution (liquid) with compressed air at a proportion approximately 10:90. The solution consists of water (over 90%), the foaming agent (concentrate dissolved in water) and a small amount of polymer. Foam concentrate and water were mixed and placed the pressure tank. The solution was then pressurised through the inlet valve on the top of the tank with compressed air. The fluid and the compressed air had to be mixed before reaching the mechanical conditioner. This was achieved in a 'Venturi' Inverter. The foam was then conditioned in the mechanical conditioner, filled with perforated tubes (15 mm in diameter) to produce relatively stable foam with approximately a single bubble size. The maximum pressure of the air system was 7 bar and the operating pressure was 1.8 bar. The generator delivered foam at a rate of 2-4 litres per minute at atmospheric pressure.

After each test the ER (Expansion Ratio: the ratio of a measured volume of foam over the volume of the liquid required for its production) was measured in a drainage pan of 2242 ml capacity. The ER ranged between 9 and 40. The elapsed time between production and testing was kept to a minimum. Another measure of the foam quality is the drainage time *i.e.* the time required to drain out a certain quantity of liquid from the drainage pan. The drainage time for half-life of the foam (i.e. drainage of 50% of the liquid forming the foam) varied between 15 and 25 minutes.

2.2 Materials

The sand used was uniform, so that when it was mixed with foam, it produced a homogenous mixture. The sand was Leighton Buzzard silica type DA 81DF. It is a very uniform material (CU = 1.4) with G_s = 2.65 and mean particle diameter d_{50} = 0.165 mm. Minimum and maximum void ratios for fine sand were calculated as 0.61 and 0.91 respectively. In each test, the quantity of dry sand used was between 1500 and 2000 *g*.

Different types of foaming agent (protein based and synthetic) were tested. The foams tested included foaming agents from Angus Fire (P90 and PP90 protein based foaming agents) and from CETCO (SC200, DrillTerge and Versa VSX synthetic polymeric foaming agents). However, after carrying out some preliminary compression tests where all foaming agents showed evidence of similar behaviour, only one type of foaming agent, based on the CETCO Versa foam, was used in the remaining compression tests. After some trials, the final foam solution consisted of VSX 'Versa' foaming agent 3% per volume and a polymer mixture consisting of VCP oil, Instapac425 (PHPA – Partially Hydrolised PolyAcrylamide) and SC200. This polymer mixture was conventionally named as 'FOP' and was used at a dosage of 0.7% per volume. The role of 'FOP' is to act as a 'booster' enhancing the bubble production. The total quantity used was 210 ml of foaming agent and 50 ml of 'FOP'. This mixture appeared to produce foam with a stable bubble size. From a first microscopic inspection, the size of the foam bubbles produced was in the range of 0.1 to 1 mm.

The bentonite used was the CETCO Hydraul-EZ type bentonite at approximately 5% per weight (mixture of bentonite powder to water at a proportion 5:95). The dosage in this case was between 0.03 and 0.04 by mass of dry sand used. However, better mixing was achieved when the water had a pH between 7 and 8. The water was treated with caustic soda (NaOH) or soda ash (Na_2SO_4) so that the pH reached 8.

In some cases, a small proportion (25-40 ml) of a polymer mixture 'WOP' (Water : VCP Oil : Polymer) was added. In the case of coarse sands, the addition of 'WOP' helped to produce a more homogenous foamed soil by creating a high viscosity fluid matrix. 'WOP' was added during mixing in the soil mixer bowl as a 'pre-conditioner', prior to the addition of foam. The best performance of the 'WOP' mixture was achieved with the proportion of oil:polymer of 2:3. The final 'WOP' dosages used were 0.0125 ml per gram of dry sand. However, when bentonite slurry was added, the effectiveness of the 'WOP' mixture decreased.

It must be mentioned that PHPA polymer and oil were not volatile; after putting a specimen of predetermined quantity in the oven at 120°C for 24 hours, the mass remaining was 97 and 98% respectively. Thus the presence of these materials affects the apparent water content of the soil as measured by conventional oven-drying methods.

For foam/sand mixtures, the bulk density varied between 1.05 and 1.65 kg/l depending on the foam quantity and the presence of bentonite.

Samples were prepared following the same procedure for each of test. The soil mixer bowl was filled with sand in a dry state. Afterwards, water was added in a proportion that gave a mixture of prescribed water content. For the mixing a small robust single-phase soil mixer of 4.56 litre capacity was used. In the case of bentonite mixtures, the prescribed quantity of bentonite powder was mixed with water (pH 7.5) in a separate pan. Then the polymer mixture was added and mixed with the bentonite slurry until visual uniformity was achieved. This sequence was important in preserving the effectiveness of the polymer in retaining water. Afterwards, the mixture was poured over the saturated sand into the soil mixer bowl. Where foamed soil was tested in combination with bentonite and polymer, the bentonite slurry was mixed with saturated sand first and then foam was added. Mixing was considered as complete when the mix appeared to be homogenous.

2.3 Rowe Cell

Compressibility tests were performed in a 75 mm diameter Rowe cell. The maximum allowable vertical pressure was 240 kPa. The pressure and the displacement of the diaphragm were measured electronically through a Data Acquisition Unit (DAU). The Signal Conditioning Units (SCU) provided power to the transducers, amplified the return signal and stored it in memory. The unit was controlled by a PC which enabled access to the data at any time during the test. Measurements were taken at a rate of one per second. The type of test conducted was with 'equal strain' loading and single drainage at the bottom, using a pair of sintered bronze porous discs on the top and bottom of the sample. These discs were placed beneath the diaphragm to collect water draining vertically from the sample and also to provide 'rigidity' allowing a uniform displacement to be applied to the whole top surface of the specimen. Eight different loading stages (from 20 to 226 kPa) were carried out in each test and four unloading stages, with each load increment representing a factor of load of $\sqrt{2}$.

3. COMPRESSION TESTS RESULTS

The tests on fine sand are listed in Table 1. Test f04 represents the average results of compression tests in saturated fine sand respectively. FIR stands for foam injection ratio, which was defined as the ratio of the foam volume used in the mixture over the volume of the mixture.

Table 1 also presents the initial and the final values of voids ratios. Most of the reduction in volume was due to gas compression in the undrained stage.

Test name	Foamer type, quantity, Expansion Ratio (ER)	Foam Injection Ratio (FIR)	Voids Ratio initial	Voids Ratio final
f04	N/A	N/A	0.92	0.64
f05	P90, 400 ml-10%, ER: 12	27.2	1.41	1.06
f06	P90, 500 ml-10%, ER: 9	31.9	1.65	1.14
f07	P90, 750 ml-10%,ER:14.8	40.7	1.68	1.20
f08	PP90, 500 ml-5%, ER: 22.4	31.9	1.43	1.06
f09	PP90, 500 ml-5%, ER: 10	31.9	1.40	1.19
f10	PP90, 750 ml-5%, ER: 27.1	41.2	1.77	1.10
f11	PP90, 1000 ml-5%, ER: 12.4	47.6	1.63	1.21
f12	SC200, 500 ml-5%, ER:16.9	31.9	1.55	1.12
f13	SC200, 750 ml-5%, ER:13	41.2	1.78	1.19
f14	Versa,400 ml-5%, ER:11.2	27.2	1.47	1.21
f15	Versa, 600 ml-5%, ER:11	34.7	1.71	1.17
f16	Versa, 500 ml-7%, ER:12	34.1	1.53	1.11
f17	Versa, 800 ml-7%, ER:40	44.3	2.16	1.22
f18	Versa, 800 ml-7%, ER:14	44.5	2.13	1.19
f19	Versa, 800ml-7%, ER:15.7	45.3	2.21	1.18
f22	Versa, 900 ml-7%, ER:14.8	47.0	2.40	1.13
f25	Versa, 600 ml-3%, ER:15	35.9	1.72	1.20
f26	Versa, 1000 ml-3%, ER:15	36.9	1.78	1.31
f30	N/A	N/A	1.06	1.01
f31	N/A	N/A	2.18	1.03
f36	Versa, 400 ml-3%, ER:20	21.9	1.14	1.09
f38	Versa, 500ml-3%, ER:15	25.3	1.40	1.16
f39*	N/A	N/A	1.72	0.75
f40*	Versa, 1000ml-3%, ER:21	N/A	2.69	1.16
f41*	Versa, 1000ml-3%, ER:20	39.0	1.88	0.83
f43*	Versa, 700ml-3%, ER:20	37.0	1.97	0.93
f45*	Versa, 1000ml-3%, ER:18	39.0	2.10	0.82
f46*	Versa, 1100 ml-3%, ER:20	41.0	2.73	0.86
f47*	Versa, 1100 ml-3%, ER:20	41.0	2.78	0.74

*All tests from f39 to f47 included 'WOP'. Tests f39 and f40 used bentonite

Before and after each test, the sample was weighed and the water content and dry density and were determined so that the voids ratio could be calculated. The measurements taken in the tests included an element of redundancy which allowed certain cross-checks to be made. The critical parameter in determining the initial or final voids ratio was the water content, which is defined as the ratio of water mass over the solids mass. The mass of solids included the non-volatile component of the additives (polymer and oil) as described earlier. The water content in the mixer bowl, as calculated based on the proportion of the mixed materials, was slightly different from the measured water content of the sample. However, these discrepancies, expressed as loss or gain of water were quite small (on average 1% per test).

The tests were carried out in two stages: undrained and drained. In the former, the bottom outlet was closed and the load was applied. During the unloading stage, the bottom outlet was left open. The undrained stage usually lasted some seconds; this time was enough to compress the gas phase at the particular pressure. After the immediate settlement was completed, the outlet was opened and the consolidation was recorded. The vertical pressure was increased to the next increment as soon as the LVDT measurements reached a steady value. Although there was no provision to measure the gas expelled at each stage, it appeared that the final proportion of gas to water voids ratio was higher than the initial one in most cases, demonstrating that at the end of the test the soil was drier than before the test.

As can be seen in a typical example in Figure 2, the most significant compression took place in the range of low vertical stresses (20-40 kPa) for a typical foam/fine sand test (f22). It is interesting to note that for foam/sand tests (without polymer or bentonite), after the increment of 56.6 kPa, the settlement was almost exclusively during the undrained stage. This type of behaviour can be attributed to the fact that in the undrained stage volume change is due to foam bubble compression. The amount of gas, which went into solution, was assumed negligible. At the drained stage the water was expelled with some of the gas, the pore water pressures dropped to zero and consolidation took place. In the unloading stage, some bubbles once more expanded, increasing the voids ratio slightly.

Volume change behaviour can be quantified by plotting the void ratio against the applied total vertical stress. In figures, only the compression stage is shown for illustration purpose since the unloading stage did not significantly change the final value of voids ratio. In each plot, a typical saturated sand compression test (f04) is included for comparison purposes. Also, in each plot the maximum and the minimum voids ratio lines for the dry sand are included. These values are referred to as a relative density of 0 and 100% respectively.

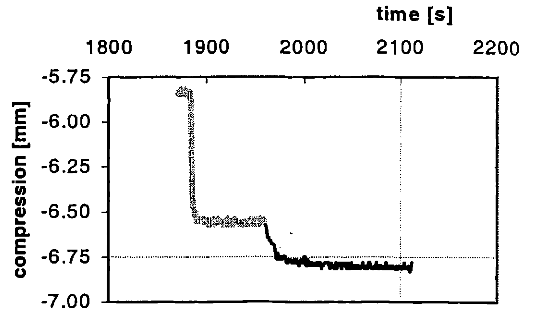

Figure 2. Compression variation with time for foam/sand test at 28.3 kPa. The undrained stage is depicted in grey colour, the drained in black.

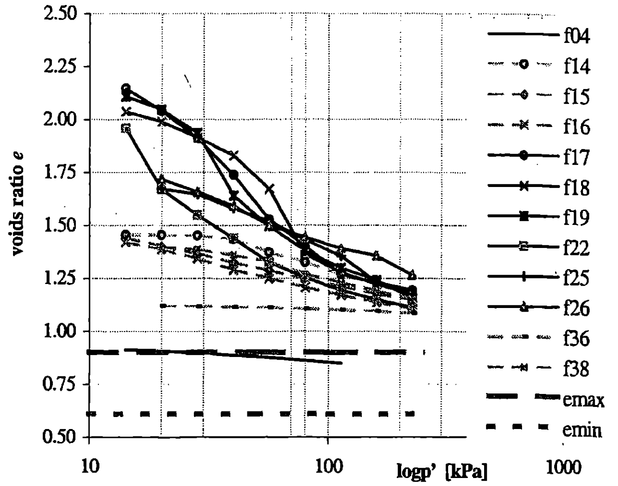

Figure 3: Foam/sand compression tests with 'Versa' foam

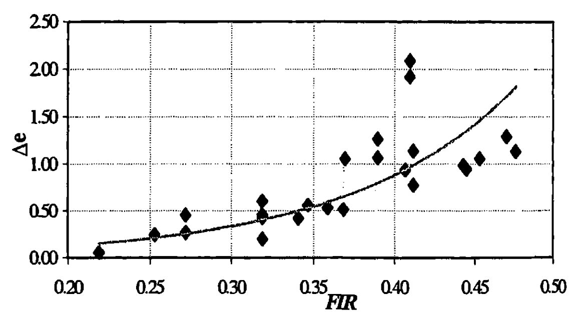

Figure 4: The effect of FIR on volume change behaviour for all foam/sand compression tests

Figure 3 depicts foam/fine sand tests with different FIR but using the same foaming agent (Versa foam). For the purposes of enhancing illustration, the low FIR (less than 35%) tests are depicted with dotted lines whereas the high FIR tests (more than 35%) with continuous lines. Tests reached a stress level of 226 kPa. The curves of the foam/sand mixtures lie above the loosest dry sand curve (corresponding to negative values of relative density). The results also clearly showed that the higher the FIR used, the larger the difference in voids ratio for samples tested under the same loading conditions. This is clearly illustrated in Figure 4, where volume changes are plotted against FIR.

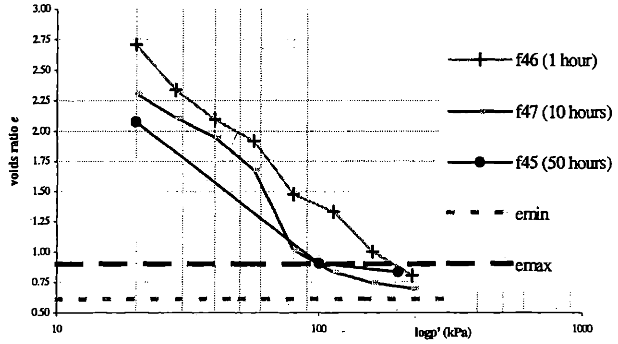

Figure 5: Time effects on foam/sand mixtures.

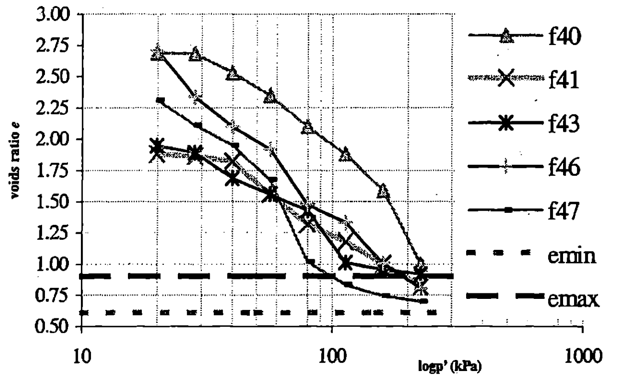

Figure 6: Foam/sand compression tests with bentonite and polymer

Clearly the degradation of foam with time is an important feature, and the relative performance in tests with different loading rates was studied. Tests f45, f46 and f47 were almost identical and the sole difference was the time intervals at each loading stage: for f46 the duration of the test was 1 hour whereas for the f47 it was 10 hours. For f45 the duration was 50 hours but there were only three loading stages. The results are shown in Figure 5, showing that the slower tests involved lower voids ratios.

For comparison reasons some tests were carried out with other conditioning agents, some of them in combination with foam. For instance test f40 (see figure 6) exhibited reduced compressibility due to the presence of bentonite. The compressibility of the mixtures with other conditioning agents but without foam (sand with bentonite and/or polymer) was much lower than for the foam tests. Initial voids ratios were high in the case of tests with bentonite due to the addition of a considerable quantity of water (Table 1).

4. DISCUSSION

4.1 Principal conclusion

The work centred on establishing an initial assessment of compressibility behaviour of foam/sand mixtures. The most important finding is that foam/sand mixtures of high FIR, when tested in Rowe cell, exhibit high volume changes and can sustain high vertical pressure whilst retaining high final voids ratio (higher than the loosest dry state). It appeared that the foam/sand mixture has a composite action: the sand itself would have been compacted to a much lower density and the foam would have been crushed at such stress levels. This was an interesting finding since it was unexpected that such high ratios could be sustained at that stress level. The high compressibility of the sand/foam mixture demonstrates that foam integrates well with sand and is able to retain gas bubbles at pressure over 200 kPa. It is an encouraging finding for tunnelling applications because such high pressures are likely to occur in the pressure chamber of an EPB machine.

This outcome coupled with the fact that sand/foam mixtures at moderate/high FIR when sheared exhibit very low values of shear strength (Houlsby & Psomas, 2001), is very promising for EPB tunnelling.

The test results presented in this paper are for fine sand only. Tests were, however, also carried out on coarse sand, and these are detailed in Psomas (2001). Broadly the same conclusions were drawn for the coarse sand as for the fine sand.

4.2 Other observations

It appeared that the quality of the foam was dependent on the quality of the foaming agent, the proportion of the air:liquid mixture and the pressure under which the air and the fluid is delivered. It is of prime importance to note that these observations are related to the particular foam generator used.

For the compression tests in Rowe cell, the most important variables were the proportion of the foaming agent and the volume of foam produced (for example FIR) and less significant was foaming agent type, at least for the tested range of ER

Foam and fine sand seemed to integrate well, when the water content before the addition of foam in the mixing bowl corresponded to 100% saturation of the sand. Above that quantity, the surplus water in the mixer bowl degraded the added foam very quickly. The addition of bentonite altered the behaviour of foamed soil, but before further conclusions can be drawn, further testing is required. Polymer with excessive water, when added to foamed fine sands, had a negative effect on foam, facilitating its degradation. It was evident that the choice of time scale for each test was of prime importance in the cases where bentonite slurry mixtures were tested.

5. ACKNOWLEDGEMENTS

The research work presented here was funded by Pipe Jacking Research Group, a consortium consisting of Pipe Jacking Association (PJA), three Water Service companies and industrial partners, and is part of a research program focusing on soil conditioning and lubrication in tunnelling and pipe jacking.

6. REFERENCES

Milligan GWE, 2000: "Lubrication and Soil Conditioning in Tunnelling, Pipe Jacking and Micro-tunnelling; A state-of-the art review". Pipe Jacking Research Group, http://www-civil.eng.ox.ac.uk.

Houlsby GT & Psomas S, 2001: "Soil conditioning for Pipe Jacking and Tunnelling: Properties of Foam/Sand mixtures." Conference & Exhibition 'Underground Construction 2001, Excel, London, 18-20 September, pp128-138

Psomas, S. (2001) "Properties of foam/sand mixtures for tunnelling applications", MSc Thesis, Oxford University