GOSPODARKA SUROWCAMI MINERALNYMI

Tom 27 2011 Zeszyt 1

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Laboratory test for EPB tunnelling assessment: results of test campaign on two different granular soils

Introduction

Earth Pressure Balanced (EPB) shields, starting from their first applications in Japan in the 70s, are currently the most used tunnelling machines around the world. The possibility of using conditioning agents that change the mechanical and hydraulic behaviour of a soil, changing it into a plastic paste and thus permitting soil pressure applications at the tunnel face, is the key point to explain the increasing utilization of this technology. Consequently, thanks to conditioning agents, face stability can be controlled (Anagnostou, Kovari 1996), the machine head torque can be reduced and tools wear can be minimized.

Despite its great importance, not much laboratory research have been registered on soil conditioning, particularly for cohesionless soils. The conditioning set is usually defined on the basis of a trial-and-error procedure developed directly at the job sites.

Among the studies concerning ground conditioning, the following should be mentioned: Kuribashi et al. (1993), Maidl (1995) Herrenknecht and Maidl (1995) and Quebaud (1998), who offered the first qualitative quantification of the effect of foam, and Milligan (2001), who developed a state-of-the-art procedure with specific reference to microtunelling applications while the EFNARC (2005) guidelines provide useful indications on the use of conditioned products. The simple slump cone test was used by Peron and Marcheselli (1994), Quebaud et al. (1998), Bordachar and Nicolas (1998), Jancsecz et al. (1999), Williamson et al. (1999), Peña (2003), Boone et al. (2005), Vinai et al. (2006) and Peila et al. (2009) to provide a procedure for the definition of soil plasticity, finally Borio and Peila (2010)

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developed tests to evaluate the permeability of the conditioned soil. Tests able to simulate large scale tests, using screw conveyor devices have been carried out by Bezuijen and Schaminée (2001), who studied the behavior of conditioned sand soils with both a full-scale and a laboratory model screw conveyor, Yoshikawa (1996), who performed a number of tests using a full-scale EPB screw conveyor with plastic soil and with different screw speeds and Merritt and Mair (2006), who used a laboratory screw conveyor device to test the extraction of soil from a tank with a sub-horizontal screw and carried out 16 tests on clay samples. This laboratory device was made up of a pressurized tank which was connected to a 1m long and 0.1m diameter horizontal screw conveyor which was instrumented in four sections to measure the torque and the total stress, the soil-casing shear stress and the pore water pressure, Peila et al. (2007) who developed a laboratory device made up of a 1500 mm long screw conveyor with an upward inclination of 30° connected to a 800 mm high pressurized tank with a inner diameter of 600 mm. The device was instrumented to measure torque, tank and screw conveyor loads, plate displacement and the weight of the extracted material.

From the above analysis of the described studies, it appears that only a test that is able to simulate the extraction of soil from the bulk chamber with the screw conveyor inclined upwards, as in real machines, can offer a quantitative indication of the conditioned soil behavior for EPB use. Thus, it appears relevant to develop a standard laboratory device that would allow the positive effect of soil conditioning to be quantified and to permit an easy comparison of various conditioning products.

The characteristics of the device developed by Peila et al. (2007) and the results obtained on many different types of soil where EPB tunnelling was carried out are discussed in order to point out the great quality and feasibility of the results that can be achieved using the proposed test device.

1. Description of the experimental apparatus

Normal EBP machines, with a diameter of between 5 m and 10 m, have a screw conveyor with a 0.6 m to 1.2 m diameter and a length/diameter ratio of between 13 and 5, even though the length of the screw can be longer when it is necessary to deal with high water pressure.

The used laboratory device prototype (Peila et al. 2007; Vinai et al. 2008), is a 1:10 screw conveyor scale model of a standard metro tunnel machine. It was designed to allow an index laboratory test which could handle a limited ground volume to be performed but also soils with relatively large particles (up to 20 mm) to be tested. The device is made of an 800 mm high tank with a 600 mm nominal internal diameter filled with soil. An aluminium plate, connected to a hydraulic jack, with a stroke of 500 mm, applies a nominal pressure to the tank of up to 2 MPa, which is the value that can be encountered in a number of urban tunnels at a depth of 10–20 m. A 1500 mm long screw conveyor is coupled to the tank with an upward inclination of 30°. The diameter of the screw case is 168 mm, the flights have a pitch of 100 mm and the screw shaft has a diameter of 60 mm.

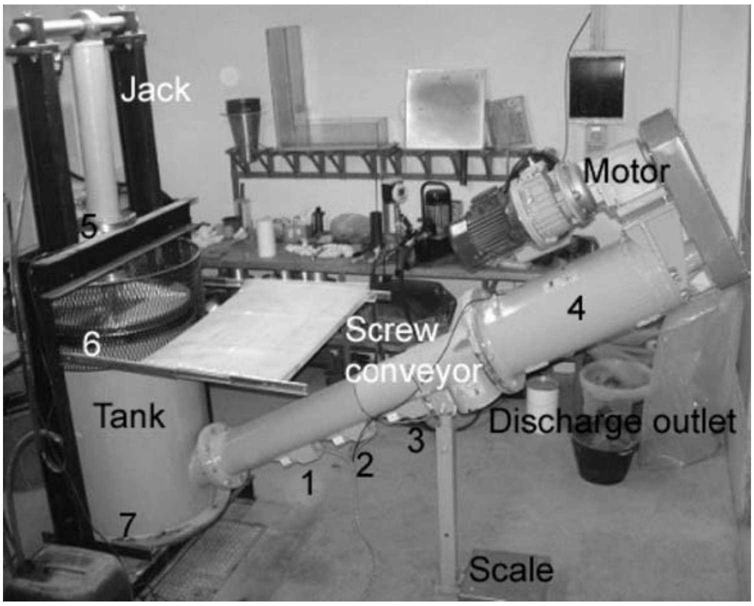


Fig. 1. Sensors installed on the screw conveyor laboratory device (Peila et al. 2007)
1, 2, 3 – total pressure cells; 4 – torquemeter; 5 – displacement wire transducer;
6, 7 – total pressure cells in the tank

Rys. 1. Czujniki zainstalowane na laboratoryjnym przenośniku ślimakowym (Peila i in. 2007)
1, 2, 3 – czujniki parcia całkowitego; 4 – momentometr; 5 – przetwornik przemieszczenia;
6, 7 – czujniki parcia całkowitego w zbiorniku

The device was instrumented with the following sensors, as shown in Fig. 1: three total pressure cells (numbers 1, 2 and 3) to measure the total normal stress applied along the screw conveyor case. The cells are spaced 250 mm apart and the first cell has a distance of 430 mm from the tank; a torque meter, in line with the screw shaft, to measure the torque transferred from the motor (number 4); a displacement wire transducer to control the upper plate movement (number 5); two total pressure cells, to measure the load under the upper plate and on the bottom of the tank (numbers 6 and 7).

The foam used for the soil conditioning is obtained from an industrial foam generator adapted for laboratory purposes.

1.1. Test procedure

The soil sample for the tests is prepared by mixing a soil with a known moisture in a concrete mixer with the required amount of foam (Fig. 2). The conditioned soil is then poured into the tank. This operation is repeated until the tank is full (about 350 kg of conditioned soil). The upper plate is then positioned and pushed down by the jack to reach the test pressure. The screw conveyor is then started and the material is collected and weighed at the discharge outlet. During the extraction of the material, the upper plate is moved

Fig. 2. Soil conditioning in the mixer bowl

Rys. 2. Modyfikowanie gruntu w pojemniku miksera

downwards to keep the pressure in the tank constant. During the test, the pressure in the tank and along the screw device and the torque are monitored continuously.

The described device was calibrated through series of tests on a reference monogranular sand with different conditioning amounts. These results were reported in Vinai et al. (2008) but many other tests were carried out on different soils where EPB tunneling was used and the results are summarized in Table 1 to provide a basis for comparison of the effect of soil conditioning.

2. Extraction tests on soil from the Turin metro excavation

Tests were carried out on a Turin alluvional soil, obtained from an area where a new stretch of the existing metro line is being excavated. The soil was sieved with a 20 mm mesh to avoid that large cobbles can damage the testing device screw conveyor and the grain size distribution utilized for the research is reported in Fig. 3. The natural water content of the soil was 7% and this value was used in the tests.

A preliminary slump tests campaign conducted on the conditioned soil allowed us to ascertain that a foam with a FER of 16 and FIR of 30% permitted to obtain a good soil conditioning. The screw conveyor speed was kept constant at 6 rpm during the tests.

Only the data from the test on the conditioned soil are presented and discussed in the following graphs, since the test on the saturated soil (not conditioned) was interrupted after a few minutes to prevent damaging the apparatus, since the value of torque on the screw conveyor was too high for the device. Table 2 reports the measured data for the tests on the Turin soil compared to those obtained for the reference sand (Vinai et al. 2008).

TABLE 1

Results of the carried out tests using the screw conveyor device

TABELA 1

Wyniki testów przeprowadzonych na przenośniku ślimakowym

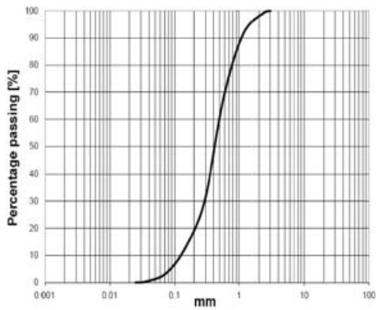
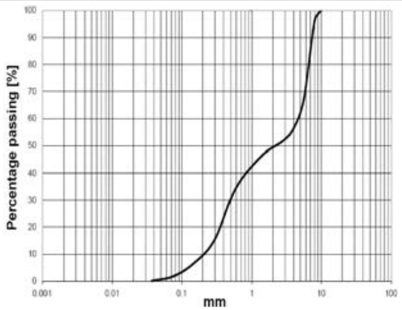
Soil	Conditioning agent	Test parameters	Pressure in the tank [kPa]	Torque during regular extraction [Nm]	Pressure along the screw [kPa]	Extraction speed [kg/s]
1	2	3	4	5	6	7
 Sand	Foam A c = 2%	FIR = 40% FER = 17 w = 10% Screw speed: 6 rpm	Theoretical top pressure: 90 Measured top: 80/95 Measured bottom: 90/100 Good transmission of the pressure	6–10	Cell 1: 20-23 Cell 2: 12-14 Cell 3: 4-6	0,183
			Theoretical top pressure: 90 Measured top: 60/80 Measured bottom: 60/80 Average transmission of the pressure	8–10	Cell 1: 23-28 Cell 2: 12-17 Cell 3: 4-7	0,193
	No conditioning	Saturated sand Screw speed: 6 rpm	Theoretical top pressure: 90 Measured top: 90/150 Measured bottom: 75/85 Poor transmission of the pressure	35–40	Cell 1: 4-6 Cell 2: 7-9 Cell 3: 2-4	0,145
 Sand and Gravel	Foam A c = 2%	FIR = 40% FER = 17 w = 8% Screw speed: 6 rpm	Theoretical top pressure: 90 Measured top: 75/80 Measured bottom: 70/75 Average transmission of the pressure	8–10	Cell 1: 35-30 Cell 2: 22-18 Cell 3: 8-5	0,210
	No conditioning	Saturated soil Screw speed: 6 rpm	Theoretical top pressure: 90 Measured top: 50/60 Measured bottom: 50/60 Poor transmission of the pressure	25–30	Cell 1: 6-8 Cell 2: 4-6 Cell 3: 2-4	0,137

TABLE 1. cont.

TABELA 1. cd.

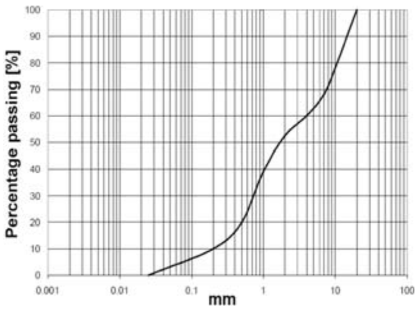
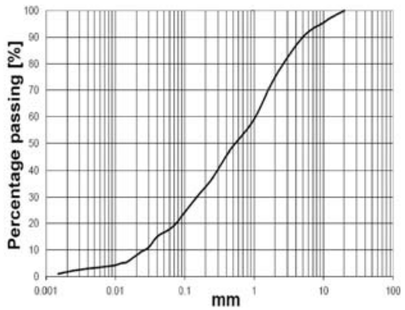
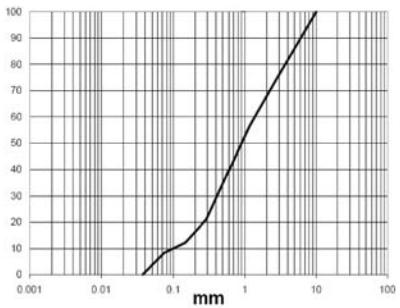
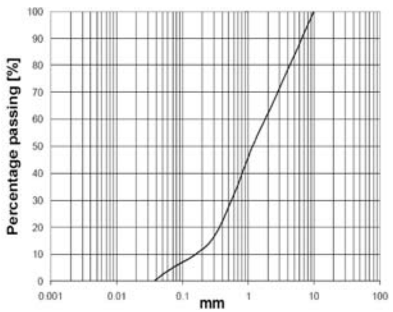
1	2	3	4	5	6	7
 Turin Metro – Lot 2 Alluvional soil	Foam A c=2%	FIR = 25% FER = 18 w = 7% Screw speed: 6 rpm Cut off value of the grain size: 20mm	Theoretical top pressure: 90 Measured top: 45/55 Measured bottom: 65/75 Good transmission of the pressure	40-50	Cell 1: 9-12 Cell 2: 8-10 Cell 3: 3-5	0,136
	No condi-tioning	Saturated soil w =12% Screw speed: 6 rpm Cut off value of the grain size: 20mm	Theoretical top pressure:60 Measured top: 25 Measured bottom: 25 Poor transmission of the pressure	It was not possible to extract the material from the tank.		
 Rome Metro – Metro C jobsite Pozzolanic soil	Foam A c=2,5%	FIR = 20% FER = 16 w = 30% Screw speed: 6 rpm	Theoretical top pressure: 120 Measured top: 115 Measured bottom: 100 Average transmission of the pressure	10-12	Cell 1: 25-15 Cell 2: 20-10 Cell 3: 15-8	0,178
	No condi-tioning	w =30% Screw speed: 6 rpm	Theoretical top pressure: 120 Measured top: 150 Measured bottom: 75 Bad transmission of the pressure	It was not possible to extract the material from the tank.		

TABLE 1. cont.

TABELA 1. cd.

1	2	3	4	5	6	7
 Brescia Metro Alluvional soil	Foam A c=2%	FIR = 30% FER = 10 w = 11% Screw speed: 6 rpm Cut off value of the grain size: 20mm	Theoretical top pressure: 90 Measured top: 50/75 Measured Bottom: 65/90 Good transmission of the pressure	50-60	Cell 1: 27-33 Cell 2: 16-19 Cell 3: 9-11	0,233
 Milan Metro – Castellanza jobsite Alluvional soil	Foam A c=2%	FIR = 25% FER = 16 w = 10% Screw speed: 6 rpm Cut off value of the grain size: 20mm	Theoretical top pressure: 90 Measured top: 55/80 Measured Bottom: 65/80 Average transmission of the pressure	20-40	Cell 1: 20-25 Cell 2: 17-20 Cell 3: 6-8	0,246

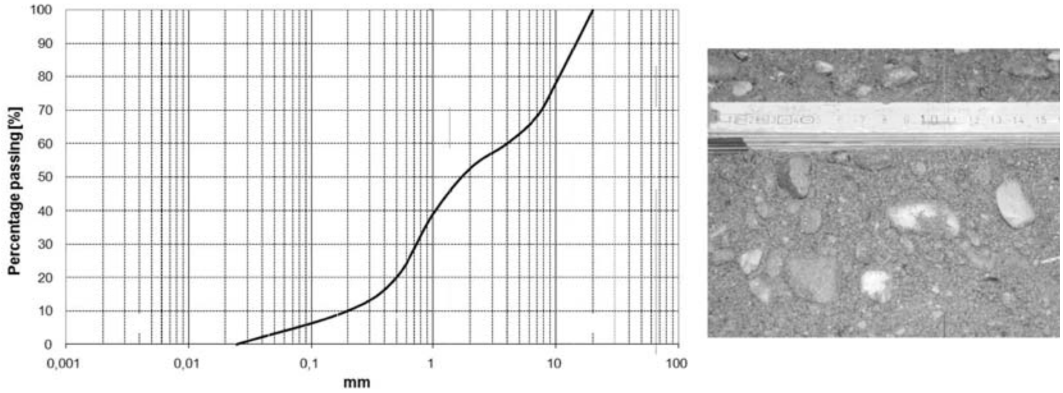


Fig. 3. Grain size distribution of the Turin soil and photograph of the soil

Rys. 3. Rozkład wielkości ziaren gruntu turyńskiego i zdjęcie gruntu

TABLE 2

Results of tests on the reference sand and the Turin soil

TABELA 2

Wyniki testów piasku porównawczego i gruntu turyńskiego

Test	Theoretical pressure [kPa]		Measured pressure [kPa]		Torque [Nm]	∂ disp. [mm/s]	Cell 1 [kPa]	Cell 2 [kPa]	Cell 3 [kPa]
	top	bot.	top	bot.					
Saturated refer. sand	90	105	~150	~100	30–40	0.3	4–8	4–6	2–4
Conditioned refer. sand	90	105	~80	~95	6–10	0.5	20–28	12–17	4–6
Saturated Turin soil	60	75	~25	~25	50	–	–	–	–
Conditioned Turin soil	60/90	75	~45/60	~65/90	50	0.6	9–12	8–10	3–5

The test data show that it is difficult for the pressure to be transmitted in the unconditioned saturated soil since the torque reaches high peaks, mainly because of the large grains, while the conditioned soil shows good behavior compared to the reference sand.

During the test, the theoretical pressure inside the tank was set at 60 kPa and then increased to 90 kPa to study its behavior at two different pressure levels (Fig. 4); the medium value of torque required for the extraction of the conditioned Turin soil was about 50 Nm for the diagram reported in Fig. 5. This is due to the internal friction of the gravel, which represents a 20% percentage of grains, for a larger diameter than 10 mm.

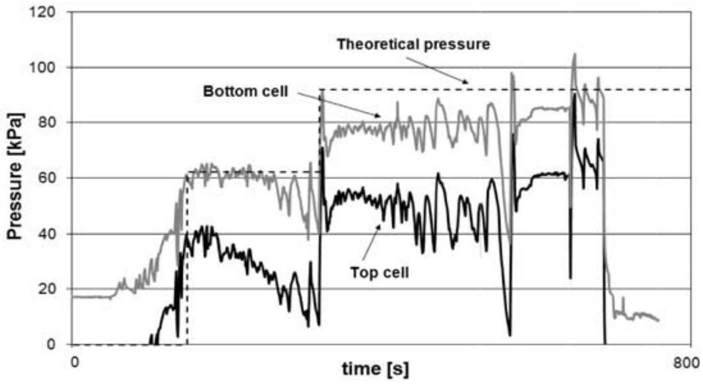


Fig. 4. Conditioned Turin soil. Pressure recorded by the sensors installed in the tank

Rys. 4. Zmodyfikowany grunt z Turynu. Ciśnienie zarejestrowane przez czujniki zainstalowane w zbiorniku

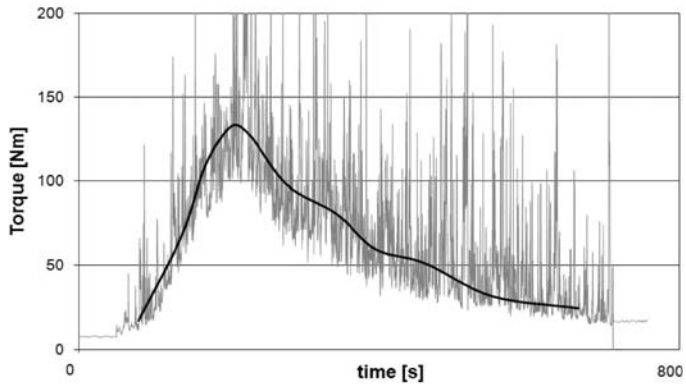


Fig. 5. Obtained diagrams of the recorded torque for the conditioned Turin soil

Rys. 5. Otrzymane wykresy przedstawiające zarejestrowany moment obrotowy dla modyfikowanego gruntu z Turynu

The pressure values registered by the pressure cells along the screw conveyor were disturbed by the larger fractions of the soil and these generated the peaks which can clearly be seen in Fig. 6. Despite this, the medium values registered by the three cells were quite constant and with a drop along the screw conveyor.

On the basis of the results of the tests, the following comments can be made:

— the conditioned material permits an almost regular transmission of the pressure inside the tank. This effect indicates that the conditioned material transmits the pressures in a proper way and it is therefore able to support the front during EPB applications;
— the pressure measured in the cells along the screw conveyor shows homogeneous values in time, but lower values compared to the pressure applied in the tank. The drop in pressure experienced during the passage from the tank to the screw is probably induced by the larger soil fractions, which are not able to maintain a perfect "plastic" behavior;

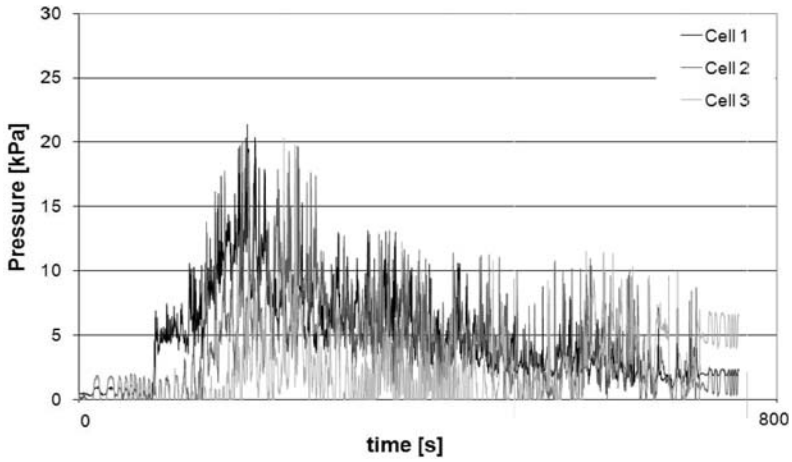


Fig. 6. Conditioned Turin soil. Pressures recorded by the sensors installed along the screw conveyor

Rys. 6. Zmodyfikowany grunt z Turynu. Ciśnienia zarejestrowane przez czujniki zainstalowane wzdłuż przenośnika ślimakowego

— the pressure applied inside the screw is regularly dissipated during the extraction;
— the torque applied to extract the material is almost regular and high punctual values are induced by the larger grains inside the material itself. The medium value is close to that registered for the reference saturated sand;
— the displacement of the upper plate is regular and this suggests that the extraction of the conditioned material could easily be controlled also at the machine scale;
— extraction with the screw conveyor determines a reduction in plasticity of the conditioned soil. The chaotic movement of the material inside the screw conveyor probably increase the separation between the soil and water and damages the conditioning bubbles. The soil at the screw outlet results to be dry, compared to the conditioned soil at the beginning of the test (Fig. 7).

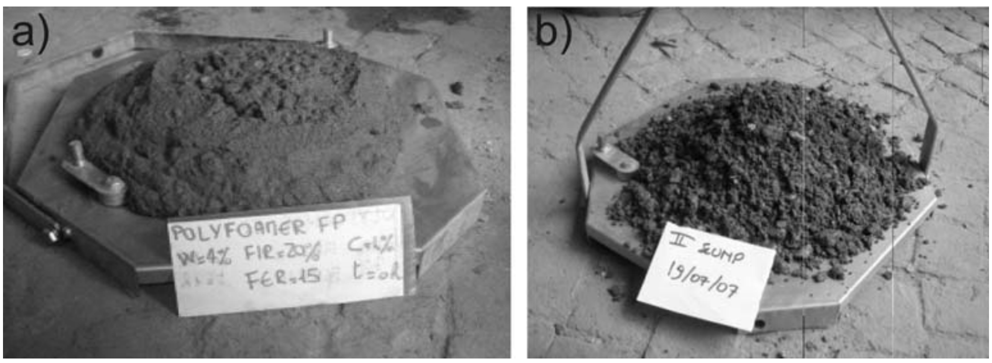


Fig. 7. Conditioned soil before (a) and after (b) the extraction from the tank

Rys. 7. Zmodyfikowany grunt przed (a) i po (b) wydobyciu ze zbiornika

3. Extraction tests on Rome metro C soil

The tests on the Rome metro C soil were carried out on the pozzolanic soil, a volcanic sand which grain size distribution is presented in Fig. 8. The natural water content of the soil was 30% and this value was used in the tests.

A preliminary slump tests campaign on conditioned soil permitted us to ascertain that using a foam with a FER of 16 and a FIR of 30% led to an optimal soil conditioning. During the tests the speed of the screw conveyor was kept constant at 6 rpm.

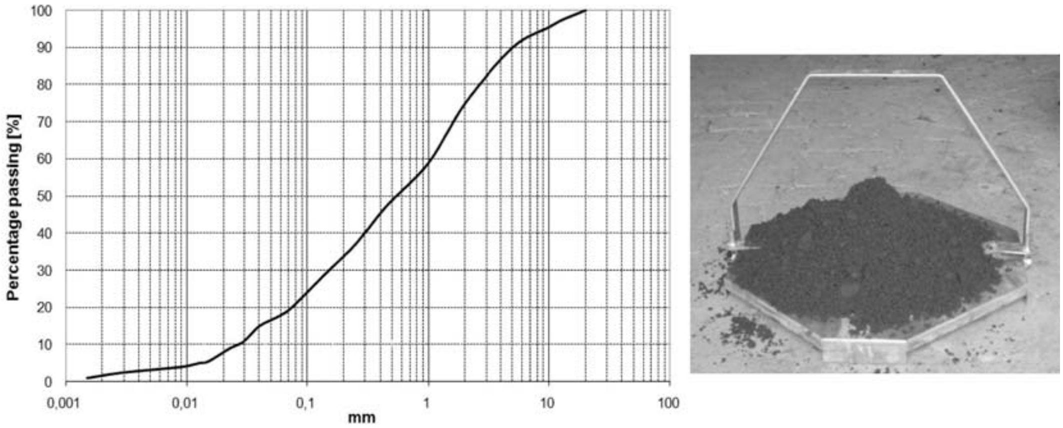


Fig. 8. Grain size distribution of the Roman soil and photograph of the soil

Rys. 8. Rozkład wielkości ziaren gruntu rzymskiego i zdjęcie gruntu

TABLE 3

Results of the tests on the reference sand and the Roman soil

TABELA 3

Wyniki testów piasku porównawczego i gruntu rzymskiego

Test	Theoretical pressure [kPa]		Measured pressure [kPa]		Torque [Nm]	∂ disp. [mm/s]	Cell 1 [kPa]	Cell 2 [kPa]	Cell 3 [kPa]
	top	bot.	top	bot.					
Saturated refer. sand	90	105	~150	~100	30–40	0.3	4–8	4–6	2–4
Conditioned refer. sand	90	105	~80	~95	6–10	0.5	20–28	12–17	4–6
Roman unconditioned soil	90/120	~120	~135	60/75	–	–	–	–	–
Roman conditioned soil	90	105	~70	~80	11	0.55	20–30	13–23	10–15

In the following graphs, only the data from the test on the conditioned soil are presented and discussed, since the test on the non conditioned soil was interrupted after a few minutes because it was not possible to extract the material from the tank. Table 3 reports the measured data compared with those obtained for the reference sand.

3.1. Test on the unconditioned pozzolanic soil

The test on the unconditioned pozzolana soil was carried out in order to evaluate the behavior of the natural soil when being extracted by an EPB machine.

The test clearly shows that it is not possible to extract this soil from the apparatus without conditioning, since the screw creates a hole in the material itself that is then stable and no material flow is induced in the machine.

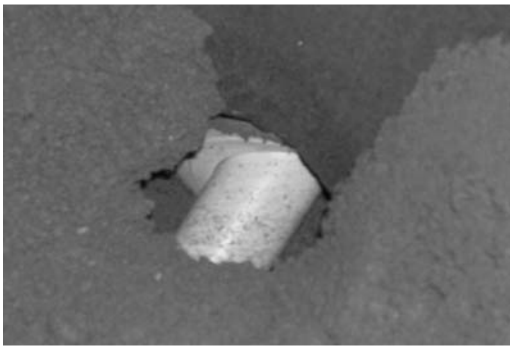


Fig. 9. Stabil void in the pozzolana induced by the screw and that prevent any flow of the material

Rys. 9. Stabilna próżnia w pucolanie wywołana przez śrubę, która zapobiega przepływowi materiału

3.2. Test on the conditioned pozzolanic soil

The theoretical pressure of the tank was set at 90 kPa but at the beginning of the test it was difficult to control the pressure with the jack, probably because of local compaction of the soil inside the tank, but after some displacement the conditioned soil was able to transmit the applied pressures inside the tank without any problems as clearly shown in Fig. 10.

The screw torque value during the extraction when the pressure was stabilized is stable and has a value of 11 Nm, very close to the value requested for the conditioned reference sand (Fig. 11).

The pressures registered along the screw conveyor are similar to those recorded for the conditioned reference sand and they show a good and regular decay along the screw itself (Fig. 12).

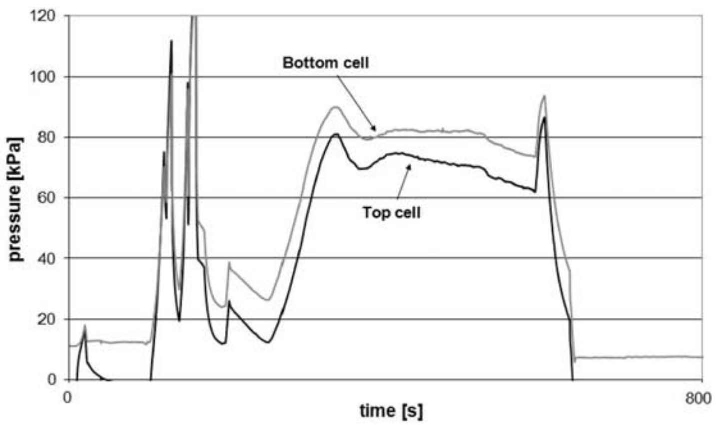


Fig. 10. Conditioned pozzolanic soil. Pressure recorded by the sensors installed in the tank

Rys. 10. Zmodyfikowany grunt pucolanowy.
Ciśnienie zarejestrowane przez czujniki zainstalowane w zbiorniku

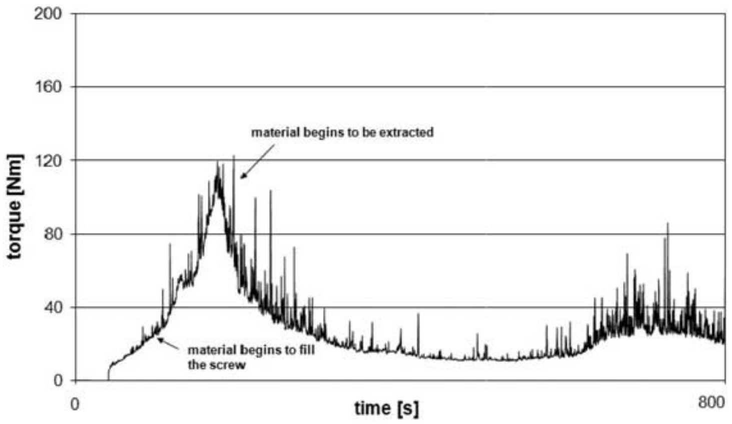


Fig. 11. Value of the torque for the conditioned pozzolanic soil

Rys. 11. Wartość momentu obrotowego dla zmodyfikowanego gruntu pucolanowego

On the basis of the tests carried out on pozzolanic soil some general considerations can be made:

— the natural soil cannot be extracted from the tank, by a screw conveyor, with its natural water content;
— the natural water content in the soil is important since it directly influences the amount of foam required to achieve an optimum conditioning;
— a FIR of 30% has given a good quality to the soil-foam mix after time zero and at an environmental temperature of about 20°C for all the tested foams (Fig. 13).

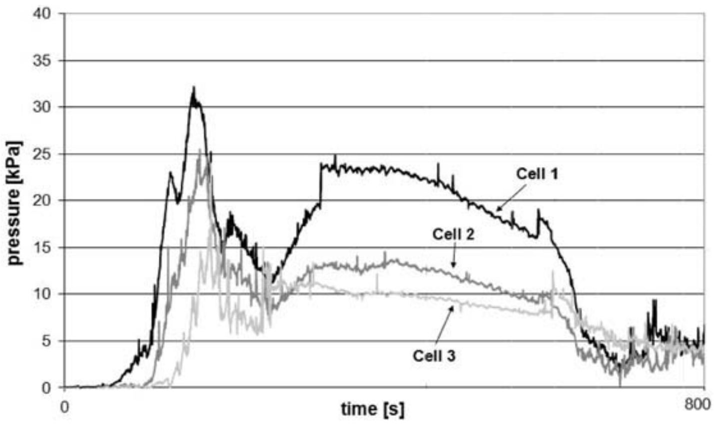


Fig. 12. Pressures recorded by the sensors installed along the screw conveyor for the pozzolanic soil

Rys. 12. Ciśnienia zarejestrowane przez czujniki zainstalowane wzdłuż przenośnika ślimakowego dla gruntu pucolanowego

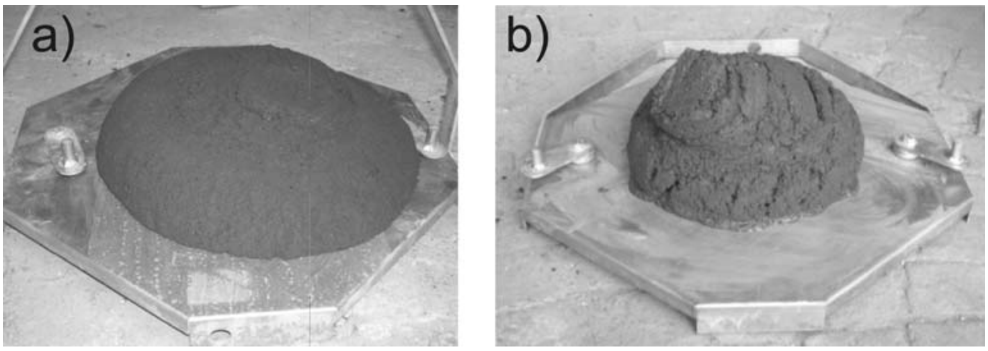


Fig. 13. Conditioned soil before (a) and after (b) extraction from the tank

Rys. 13. Zmodyfikowany grunt przed (a) i po (b) wydobyciu ze zbiornika

Conclusions

The presented research has shown how the proposed and developed screw conveyor device can offer important information on the behavior of conditioned soil for EPB machine application, not only for simple monogranular soil, tested in the preliminary researches, but also for heterogeneous material such as the soils where the metro of Turin and Rome in Italy were excavated.

The proposed device can, therefore, be considered as a feasible tool for a correct design phase when an EPB machine has to be used, particularly when complex soil conditions can be found and a preliminary knowledge of the conditioning effect has to be understood to minimize the excavation risks during tunneling.

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TEST LABORATORYJNY DLA OCENY TUNELOWANIA METODĄ EPB: WYNIKI TESTÓW DLA DWÓCH RÓŻNYCH GRUNTÓW ZIARNISTYCH

Słowa kluczowe

Wiercenie tuneli metodą EPB, zarządzanie ryzykiem, modyfikowanie gruntu

Streszczenie

Tarcze wyrównanych ciśnień gruntowych (*Earth Pressure Balance*) to obecnie najczęściej stosowane maszyny do tunelowania na świecie. Możliwość zastosowania środków do modyfikowania gruntu, które zmieniają jego mechaniczne i hydrauliczne właściwości, zmieniając go w plastyczną masę i pozwalając tym samym na wykorzystanie parcia gruntu na przodku, jest kluczowa dla wyjaśnienia rosnącego wykorzystania tej technologii. Mimo wielkiego znaczenia modyfikowania gruntu nie zanotowano zbyt wielu badań laboratoryjnych na ten temat, szczególnie jeśli chodzi o grunty niespoiste. Sposoby modyfikacji definiuje się zwykle metodą prób i błędów bezpośrednio na miejscu wykonywania pracy. Test, który potrafi symulować wydobywanie gruntu z komory roboczej za pomocą skierowanego w górę przenośnika ślimakowego, tak jak w prawdziwych maszynach, może dostarczyć informacji dotyczących zachowania się gruntów modyfikowanych podczas stosowania technik EPB. W artykule przedstawiono cechy charakterystyczne urządzenia i wyniki otrzymane dla różnych rodzajów gruntów. Podkreślono ważność i wysoką jakość wyników otrzymanych przy zastosowaniu proponowanego urządzenia badawczego.

LABORATORY TEST FOR EPB TUNNELLING ASSESSMENT: RESULTS OF TEST CAMPAIGN ON TWO DIFFERENT GRANULAR SOILS

Key words

EPB tunnelling, risk management, soil conditioning

Abstract

Earth Pressure Balanced shields are currently the most utilized tunnelling machines throughout around the world. The possibility of using conditioning agents that change the mechanical and hydraulic behaviour of a soil, changing it into a plastic paste and thus permitting soil pressure applications at the tunnel face, is the key point to explain the increasing utilization of this technology. Despite its great importance, not much laboratory researches can be registered on soil conditioning, particularly for cohesionless soils. The conditioning criterion is usually defined on the basis of a trial-and-error procedure developed directly at the job sites. A test that is able to simulate the extraction of soil from the bulk chamber with the screw conveyor inclined upwards, as in real machines, can offer a quantitative indication of the conditioned soil behavior for EPB use. The characteristics of the device and the results obtained on many different types of soil are discussed in order to point out the great importance and quality of results that can be achieved using the proposed test device.