CHARACTERISATION OF SPOIL MATERIALS TO DEVELOP AN EQUIVALENT SPOIL MATERIAL FOR PHYSICAL MODEL TESTS

CHARAKTERYSTYKA ODPADÓW POGÓRNICZYCH W CELU OPRACOWANIA MATERIAŁU RÓWNOWAŻNEGO DO MODELOWANIA FIZYCZNEGO

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The engineering behaviour of spoil (overburden) needs to be explored either to understand the stability of reservoir slopes under various geological and climatic conditions or for the effective utilisation of reclaimed mines for sustainable infrastructure (e.g., onshore wind turbines). The spoil material is usually considered as highly heterogeneous, and samples collected from the same site can exhibit widely varying characteristics. In this study, spoil material from a mine site in the Czech Republic is characterised using in-situ field tests and laboratory tests. Cone penetration tests were performed in the field and sample cores were collected for laboratory testing. In the laboratory, the index and engineering characteristics of the spoil were evaluated. Given the measured characteristics and behaviour of the field spoil, an equivalent spoil is proposed to perform physical modelling tests using geotechnical centrifuge. This enables simulation of the field spoil behaviour in controlled centrifuge testing, from which other aspects of spoil (e.g. stability of spoil slopes, spoil-structure interaction) can be investigated.

Keywords: *cone penetration testing, laboratory testing, shear strength, soil water characteristics curve, spoil*

Zachowanie zwałowisk pogórniczych (nadkładu) pod względem inżynieryjnym powinno zostać zbadane w celu określenia stabilności zboczy zbiorników poeksploatacyjnych w różnych warunkach geologicznych i klimatycznych lub w celu efektywnego wykorzystania rekultywowanych kopalń do budowy zrównoważonej infrastruktury (np. lądowych turbin wiatrowych). Materiał zwałowisk pogórniczych jest zwykle uważany za wysoce niejednorodny, a próbki pobrane z tego samego miejsca mogą wykazywać bardzo różne właściwości. W niniejszej pracy, materiał odpadowy z czeskiej kopalni został scharakteryzowany przy użyciu badań terenowych i laboratoryjnych in-situ. W terenie przeprowadzono sondowania CPT, a do badań laboratoryjnych pobrano próbki rdzeniowe. W laboratorium oceniono właściwości indeksowe i inżynieryjne materiału. Biorąc pod uwagę zmierzone cechy i zachowanie się materiału pogórniczego, zaproponowano materiał równoważny do wykonania modelowania fizycznego z wykorzystaniem wirówki geotechnicznej. Umożliwia to symulację zachowania się materiału w kontrolowanych badaniach wirówkowych, na podstawie których można badać inne cechy materiałów pogórniczych (np. stabilność skarp zwałowiska, interakcje zwałowisko-konstrukcja budowlana).

Słowa kluczowe: *sondowanie CPT, badania laboratoryjne, wytrzymałość na ścinanie, krzywe retencji wodnej gruntu, zwałowisko*

Introduction

In general, most post exploitation open pit voids are turned into water reservoirs, mostly dedicated to recreational purposes. Most of the surface mining sites that have now been abandoned have been restored for similar applications (Rainbow, 1990; Grimshaw, 1992). The stability of pit lake slopes after flooding remains an area of uncertainty. Further, it is far more unusual to find construction of any kind being built on reclaimed mining spoil, unless it is of a low-rise industrial format. As a sustainable measure, many researchers have proposed the use of these reclaimed mining sites for renewable energy generation (e.g., installation of wind turbines). Either to understand the stability of pit lake slopes under varying climatic conditions or for the effective utilization of mining spoil tips to build infrastructure, it is essential to understand the physical and mechanical characteristics of field spoil materials. Spoil (over-burden) is usually considered highly heterogeneous, either between sites or even locally within a single location. The spoil from open cast coal-mining sites ranges from cohesionless sandy material to very fine-grained cohesive material. A small amount of organic matter has also been reported in spoils of different areas, such as Poland and Turkey (Kasiński and Piwocki, 2002).

Stability of mine pits or spoil-structure interaction analyses cannot be easily explored in the field as it is impossible to vary the water conditions as required or to test structures under different loading conditions. Therefore, physical modelling using a geotechnical centrifuge is widely used for such investigations as centrifuge testing simulates the field stress-strain conditions in a small scaled model. However, a large amount of spoil is required for centrifuge experiments. Further, for a fair comparison of results from different centrifuge tests, the characteristics of the laboratory spoil between tests should be controlled. Either obtaining large quantities of spoil from the field or expecting similar field spoil behaviour during different tests (as spoil is highly heterogeneous) is practically impossible. Therefore, an equivalent spoil that can exhibit similar engineering behaviour as field spoil needs to be developed from commercially available soil materials for performing centrifuge experiments.

Problem statement

An extensive programme of field and laboratory tests were performed to characterize the spoil material from two sites in the Czech Republic. Cone penetration tests (CPTs) were performed on the spoil around Lake Most and laboratory tests were conducted on core samples collected from the Czechoslovak Army Mine (ČSA) open pit mine, Czech Republic. This characterization was predominately done to evaluate the influence of material properties and geological features on short- and long-term stability of reservoir slopes and to investigate the feasibility of using reclaimed mine sites for onshore wind turbines. Further, for performing centrifuge experiments to study these specific applications, an equivalent spoil was needed that could exhibit similar engineering behaviour as the field spoil from the Czech Republic.

Characterisation of field spoil

Field characterisation using CPT

CPTs were performed along Lake Most, the Czech Republic. Lake Most is situated in the central part of the Most Basin, approximately 2 km to the north from the city Most. 21 cone penetration tests (CPT) were performed, at depths ranging from 5.4 m to 117.6 m and with a total length of 1017.40 m of penetration. The rate of CPT penetration is 2 cm/s. The diameter of the CPT cone was 35.7 mm, with a cross-section area of 10 cm^2 and tip angle of 60°. The frictional resistance as the CPT penetrates through the soil can be measured through a sleeve friction sensor of surface area 150 cm^2, which is part of the CPT device. In addition, the CPT device had a pore pressure sensor behind the tip to measure the pore pressures during the penetration of the cone through the soil. From CPT data, cone resistance (q_c), sleeve friction (F_s) and soil pore pressure (u) were recorded. Knowing q_c, F_s, and u from the CPT data, many index and engineering properties of spoil material can be interpreted from well-established correlations available in the literature. However, the correlations available in the literature are developed or proposed for specific soil types and hence engineering judgement is required before interpreting the CPT data using any existing correlations. In this analysis, CPT data is mainly used for soil classification of spoil material. Figure 1 shows a typical CPT outcome and Figure 2 shows the soil classification from Jefferies and Davies (1993) using the measured CPT data. As Figure 2 shows, the spoil at the site is mainly made up of fine-grained material (clay or clayey silt or silty sand). Data from the other 20 CPTs also indicated that the site is predominantly constituted of fine-grained material. CPT data has been used to interpret other geotechnical parameters of spoil (such as friction angle, permeability, undrained shear strength) which are not discussed here as they are beyond the scope of this paper.

Laboratory characterization of spoil

It was not possible to collect sample cores or perform any in-situ tests other than CPTs along lake Most as the whole area has been biologically reclaimed. Therefore, soil sample cores were collected from ČSA open pit mine, the Czech Republic. The ČSA is an open-cast brown coal mine located in the North Bohemian Basin of the Czech Republic. In Czech, the area is locally referred to as Mostecko and it lies in between the city of Most and the town of Litvínov. Based on extensive studies, it is believed that the lake that will be created in the ČSA open pit mine will have similar geotechnical parameters as the final slopes of Lake Most. Seven spoil samples from depths of 6.2 m to 131.7 m were collected for the geotechnical characterisation (Tab. 1).

Extensive soil characterisation tests to evaluate the index (Atterberg limits, particle size distribution analyses, specific gravity tests) and engineering properties (oedometer tests, triaxial tests and simple shear tests) were performed on the spoil samples cored from ČSA open pit mine. To determine the particle size distribution, wet sieve analysis and hydrometer analysis with Sodium Hexametaphosphate as a dispersant were performed on the seven spoil samples obtained from ČSA open pit mine. Figure 3 shows the particle size distribution curves of the seven spoil samples. As Figure 3 shows, the spoil is predominantly fine-grained with clay content ranging from 20% to 60%. Atterberg limits and specific gravity of spoil samples were also determined and listed in Table 2. The plasticity index of samples from CSA mine indicate that the samples at deeper depths have low to medium plasticity silt, but the plasticity index increases as the sample depth approaches the surface. It is possible that weathering action near the surface is the reason for the clay dominated material at the shallower depths. The specific gravity of the tested spoil samples is in the range of 2.67 to 2.71; samples with larger percentage of clay relate to the peak values (Tab. 2).

Equivalent spoil for centrifuge experiments

As mentioned earlier, commercially available soil minerals (e.g., silica sand for liquefication based studies, kaolin powder for clay experiments) are used in the centrifuge experiments to maintain homogeneity in a single experiment or consistency between the centrifuge experiments. For performing any centrifuge experiments to investigate the influence of spoil properties and geological features on short- and long-term stability of reservoir slopes and to investigate the feasibility of using reclaimed mine sites for onshore wind turbines, it is essential to develop an equivalent spoil for the centrifuge experiments

Tab. 1. Details of sample cores collected from ČSA open pit mine
Tab. 1. Szczegóły dotyczące rdzeni pobranych z kopalni odkrywkowej ČSA

Sample	Depth (m)
CSA01	6.2 - 6.6
CSA02	14.5 - 15.0
CSA03	28.2 - 28.6
CSA04	51.3 - 51.6
CSA05	71.0 - 71.4
CSA06	91.0 - 91.3
CSA07	131.2 - 131.7

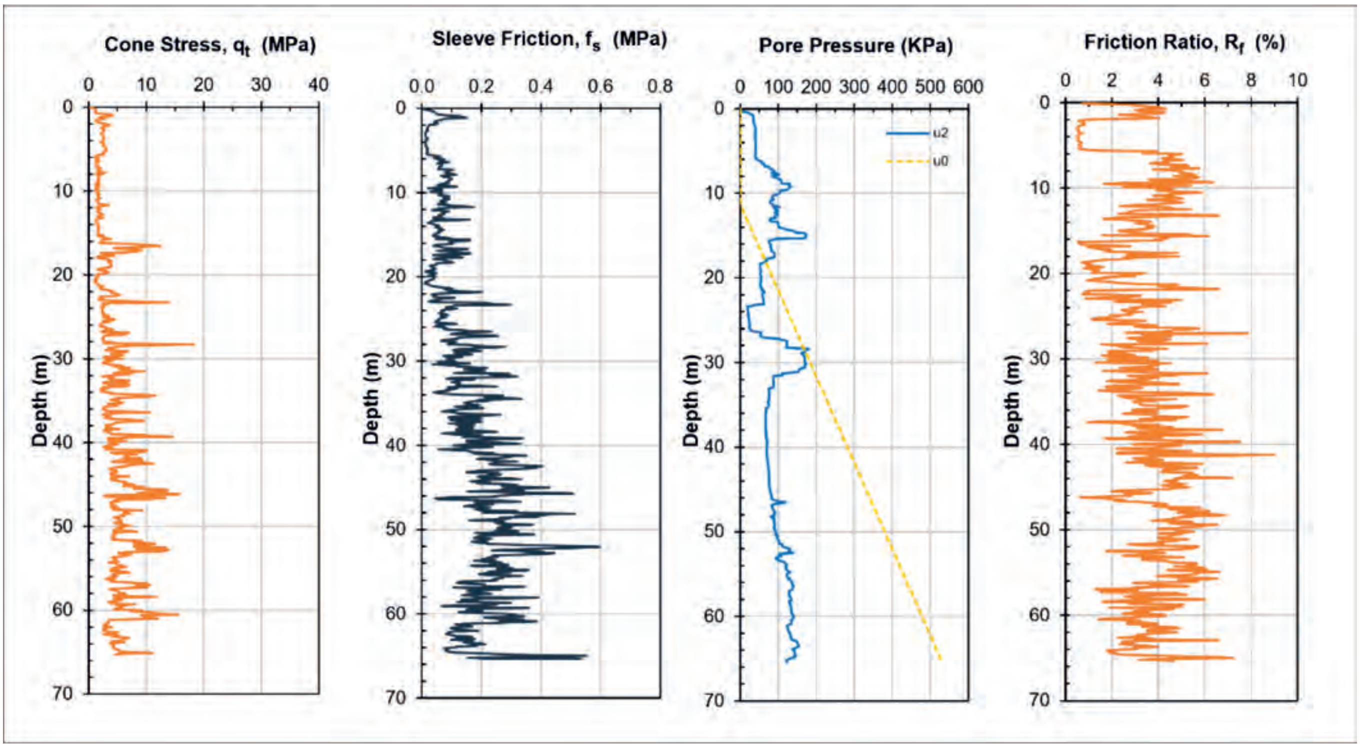

Fig. 1. Example of data obtained from CPTs performed at Lake Most.
Rys. 1. Przykład danych uzyskanych z sondowań CPT wykonanych przy jeziorze Most.

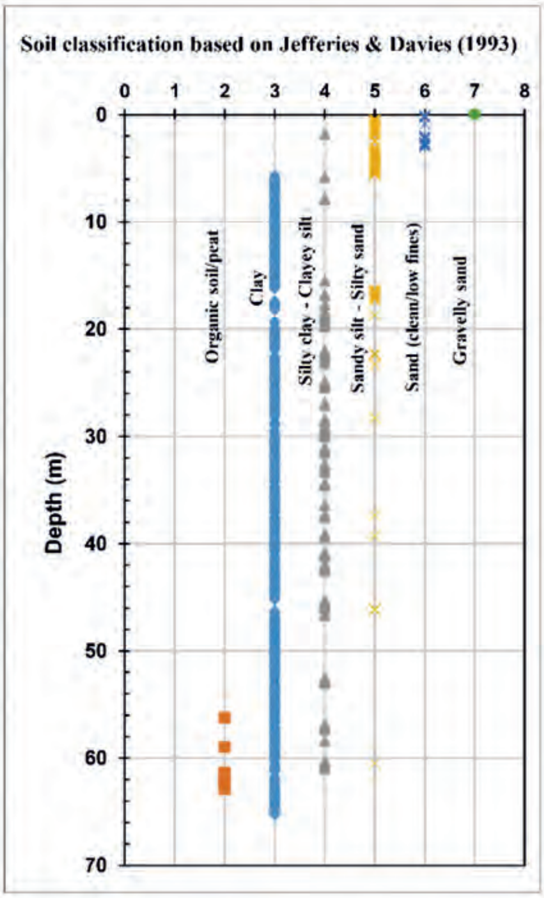

Fig. 2. Classification of spoil from CPT data using Jefferies and Davies (1993)
Rys. 2. Klasyfikacja materiału pogórniczego na podstawie danych CPT wg Jefferiesa i Daviesa (1993)

from commercially available soil minerals. For developing the equivalent spoil, resemblance of particle size distribution and Atterberg limits between equivalent spoil and field spoil are considered as the criteria.

The field spoil has silt content in the range of 30% to 70% and clay content in the range of 20% to 60%. Due to the presence of a large portion of cohesive fine grained particles, the field spoil samples have plasticity index in the range of 18% to 29% (Tab. 2). Cohesive (or plastic) silt is not commercially available. Instead, sand particles crushed to a silt size are generally used in centrifuge or large-scale modelling experiments (e.g., Apostolou et al. 2016). For developing the equivalent spoil material, a commercially available A50 silica flour was adopted for the silt. These crushed silt size particles may not exhibit any cohesive nature. Further, instead of adopting kaolin alone for the clay particles, a mixture of bentonite and kaolin was considered to achieve the plasticity characteristics listed in Table 2. This is due to the higher plasticity characteristics of bentonite compared to kaolin; this mixture can compensate for the non-plastic nature of the adopted silt particles. Different proportions of silt, bentonite and kaolin clay were mixed together and the Atterberg limits were determined. Eventually, a 50% silt + 30% bentonite + 20% Kaolin was found to give a plasticity index close to that of the samples from the ČSA open pit mine spoil material. Figure 3 shows the particle size distribution of the proposed equivalent spoil in comparison to field spoil samples. Table 2 shows the comparison of Atterberg limits between proposed equivalent spoil and field spoil samples.

The following section covers the comparison of other engineering characteristics between the field spoil and proposed equivalent spoil.

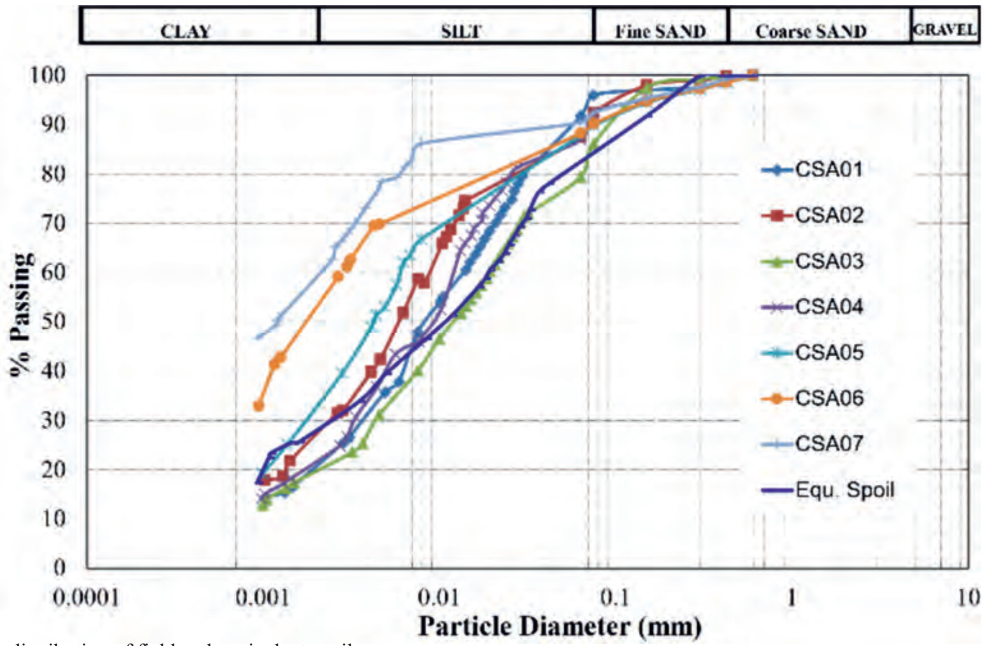

Fig. 3. Particle size distribution of field and equivalent spoil
Rys. 3. Rozkład uziarnienia materiału pobranego w terenie i równoważnego

Tab. 2. Atterberg limits and specific gravity of field spoil samples and proposed equivalent spoil
Tab.2. Granice Atterberga i ciężar właściwy próbek materiału pobranego w terenie i proponowanego materiału równoważnego

Sample	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Specific gravity *(G_s)*
CSA01	58.3	31.3	27	2.706
CSA02	60.4	31.6	28.8	2.686
CSA03	63.2	36.76	26.44	2.698
CSA04	55.13	27	28.13	2.703
CSA05	52.14	31.36	20.78	2.697
CSA06	51.84	28.55	23.29	2.691
CSA07	51.93	33.95	17.98	2.675
Equ. spoil	45.85	20.22	25.63	2.518

Tab.3. Consolidation characteristics of field and equivalent spoil
Tab. 3. Charakterystyka konsolidacji materiału pobranego w terenie i równoważnego

Sample ID	C_c	C_r	σ'_{vc} (kPa)	Permeability (m/s)
CSA01	0.24	0.14	-	-
CSA02	0.32	0.12	400	0.72E-11
CSA03	0.15	0.09	330	1.21E-11
CSA04	0.29	0.14	310	0.54E-11
CSA05	0.20	0.11	150	0.43E-11
CSA06	0.20	0.12	90	1.28E-11
CSA07	0.21	0.11	30	1.01E-11
Equ. spoil	0.52	0.05	-	1.30E-11

Comparison of consolidation characteristics

Figure 4 shows the response of field spoil samples and equivalent spoil sample in oedometer tests. Table 3 summarises the results (compression index C_c, recompression index C_r, pre-consolidation stress σ'_{vc}, and vertical permeability) from oedometer tests.

In Figure 4 and Table 3, the samples for oedometer tests were obtained by careful trimming of cores without disturbing the structure of the field samples (and thus maintaining the 'undisturbed' characteristics). However, for equivalent spoil, the oedometer samples were prepared by mixing dry soil with water at a water content equivalent to twice the liquid limit of the equivalent spoil (~46%). Therefore, due to significant moisture content in the equivalent spoil slurry at the beginning of the consolidation process, the compressibility characteristics of the equivalent spoil were significantly larger than the field samples, as shown in Figure 4 and Table 3. However, the permeability of equivalent spoil is close to that of the field samples (Tab. 3), indicating the suitability of the proposed equivalent spoil to simulate the field spoil behaviour.

Comparison of shear strength characteristics

Consolidated Isotropic Undrained (CIU) triaxial tests were performed on the field and equivalent spoil materials to

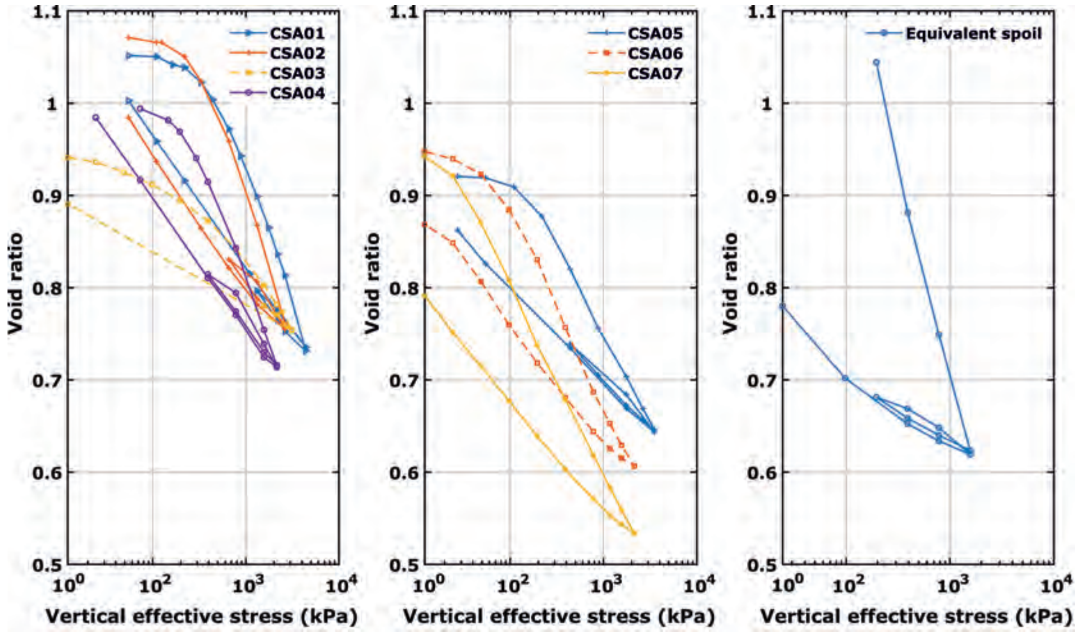

Fig. 4. Consolidation curves of field spoil and equivalent spoil
Rys. 4. Krzywe konsolidacji materiału pobranego w terenie i równoważnego

determine the shear strength characteristics. CIU triaxial tests were carried out on two field spoil samples and three equivalent spoil samples under different confining stresses. Samples of 50 mm diameter and 100 mm length were considered for the CIU triaxial tests. The field spoil samples were obtained by trimming the undisturbed sample cores, whereas the equivalent spoil samples were prepared by consolidating the spoil slurry under a vertical stress of 180 kPa. To perform triaxial experiments, the spoil specimens were placed in the triaxial cell and saturated through water flushing and back pressure saturation. The saturation process took a significant amount of time to achieve Skempton's pore pressure parameter 'B value' greater than 0.95 due to the very low permeability of the spoil materials. The specimens were then consolidated to the desired effective confining pressure. The applied deviator stress against axial strain data from triaxial tests are presented in Figure 5a. The over consolidation ratio (OCR) in Figure 5a represents the ratio of maximum past consolidation pressure to the pre-shear consolidation pressure (σ_c). The shearing of all the specimens was done at a very slow strain rate of 0.003 mm/min in order to allow for uniform pore water pressure equalisation throughout the specimen. The excess pore water pressure response is shown in Figure 5b. The critical state friction angles obtained from the above experiments are presented in Table 4.

Based on the test data, it was found that the field spoil exhibited very low critical state friction angles (around 20°). A significant difference in critical state friction angle between the field spoil and equivalent spoil is demonstrated in Table 4. However, simple shear tests on 70 mm diameter and 25 mm thick spoil samples indicated that the equivalent spoil exhibits stress hardening behaviour upon shearing, as shown in Figure 6a. The friction angle of equivalent spoil from simple shear tests is strongly influenced by the shear strain magnitude (Fig. 6b). The simple shear test results indicate that the friction angle of equivalent spoil could be anywhere in between 20° to 25°. Therefore, the proposed equivalent spoil exhibits satisfactory agreement of the shear strength characteristics compared to the field spoil. Due to the highly heterogeneous nature of field spoil samples, any small deviation in shear strength characteristics

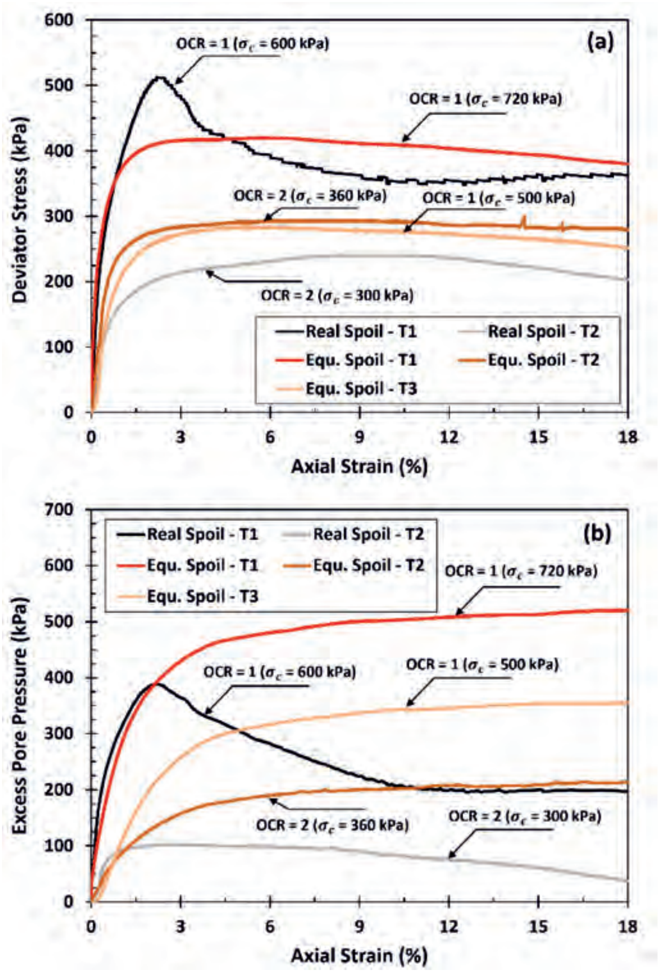

Fig. 5. Shear behaviour of real and equivalent spoil material in CIU triaxial tests (a) deviator stress-axial strain response, and (b) excess pore-water pressure response
Rys. 5. Ścinanie materiału rzeczywistego i równoważnego w badaniach trójosiowych CIU (a) odpowiedź "dewiator naprężenia - odkształcenie osiowe", oraz (b) odpowiedź na nadmierne ciśnienie wody porowej

can be considered as negligible. Therefore, by considering particle size, plasticity characteristics and shear strength parameters, the 50% silt + 30% bentonite + 20% kaolin mixture was chosen as a suitable equivalent spoil material that can be used in centrifuge experiments.

Comparison of soil water characteristics curve

A soil water characteristics curve (SWCC) represents the relationship between soil moisture and suction. The SWCC for field spoil and equivalent spoil was generated using the chilled mirror hygrometer technique as per the specifications of ASTM D6836 (2016). The experiments were conducted using a WP4C Dew Point Potentiometer device. The specimens for these experiments were extracted from the slurry consolidated spoil samples, which were prepared by consolidating spoil slurry under 180 kPa normal stress.

The extracted specimen was placed in the retaining dish and the whole assembly then placed inside the sealed chamber of a potentiometer to equilibrate the water vapour between the spoil specimen and air phase inside the chamber. The relative humidity was measured by detecting the first occurrence of condensation of water on the mirror present inside the chamber (Leong et al., 2003). The total suction was then determined through the measured relative humidity using Kelvin's equation. (ASTM D6836, 2016). Figure 7 shows the SWCC of field and equivalent spoil. The total suction (ψ_t) values were obtained in both the wetting and drying paths to evaluate the hysteretic response of soil suction.

The distinct difference between wetting and drying path can be observed for both real and equivalent spoil. The total suction value in the drying path was higher than the wetting path at the same degree of saturation. To fit the curve in the entire suction range, the mathematical fit (Equation 1) developed by van Genuchten (1980) was used. The parameters for the mathematical fit were obtained through the experimental results and are presented in Table 6 along with corresponding air-entry values (AEV) of wetting-drying SWCCs.

$$S_e = \left(\frac{1}{1+(\alpha\psi)^n}\right)^m \quad (1)$$

$$S_e = \frac{S-S^r}{1-S^r} \quad (2)$$

where, α and n are fitting parameters, m = 1-(1/n); ψ = suction; S = degree of saturation, and S^r = residual degree of saturation.

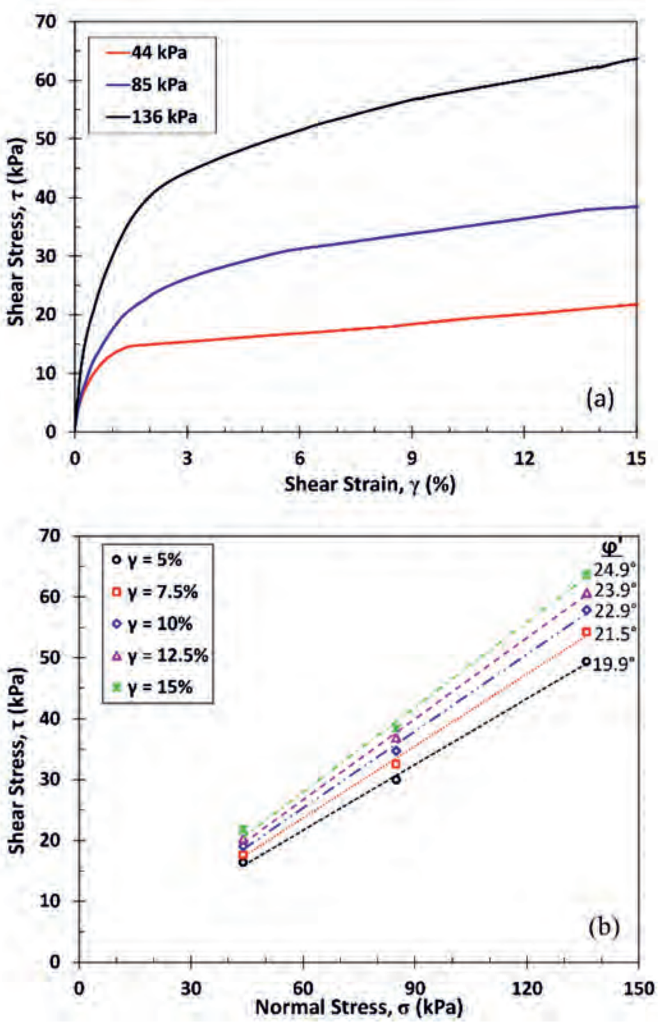

Fig. 6. Simple shear response of equivalent spoil (a) stress-strain behaviour, and (b) variation of shear stress against normal stress
Rys. 6. Ścinanie proste materiału równoważnego (a) zależność naprężenie-odkształcenie oraz (b) zmiana naprężeń ścinających w stosunku do naprężeń normalnych

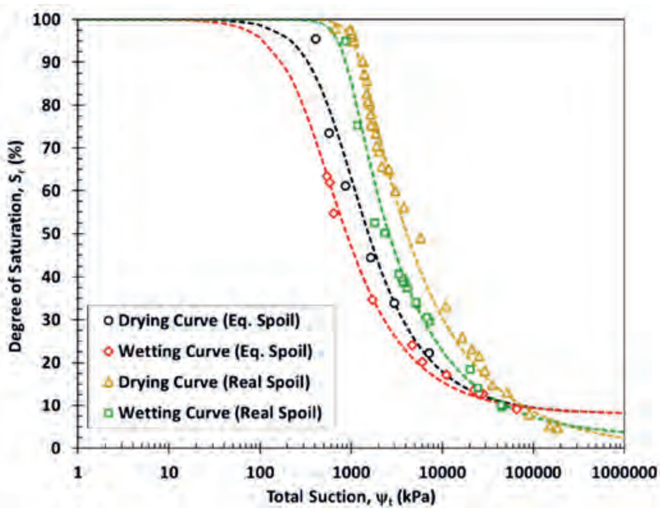

Fig. 7. Soil water characteristics curves of field spoil and equivalent spoil
Fig. 7. Krzywe retencji wodnej gruntu dla materiału pobranego w terenie i równoważnego

Tab. 4. Critical state friction angle determined from CIU triaxial tests.
Tab. 4. Kąt tarcia w stanie krytycznym wyznaczony z badań trójosiowych CIU

Soil	Critical state friction angle, φ' (degrees)
Field spoil	20.6
Field spoil	19
Equivalent spoil	28.2
Equivalent spoil	29.2
Equivalent spoil	28.5

Conclusions

Spoil materials from the Czech Republic were characterised using in-situ and laboratory tests to investigate engineering behaviour. Based on results, an equivalent spoil was proposed that aligns well with the field spoil in terms of particle size distribution, plasticity characteristics and shear strength characteristics. A noticeable difference in SWCC was found between the field and equivalent spoil, nevertheless the difference can be minimized with further testing of equivalent spoil at higher degrees of saturation levels. The equivalent spoil can subsequently be used within physical modelling (geotechnical centrifuge) experiments to study engineering applications that include real spoil materials.

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Heap of the Lubelski Węgiel Bogdanka coal mine, Poland