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ORIGINAL PAPER

Physico-mechanical parameters of rock materials used in open pit reclamation – a case study of CTL Maczki-Bór S.A. mine in Poland

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Abstract
The aim of the research was to assess the variability of selected physical and mechanical properties of Carboniferous barren rocks in the Upper Silesian Coal Basin and to analyze the impact of time and increasing vertical pressure on the mechanical parameters of the mixture of these rocks used in the reclamation of the open pit. Both type of tests were conducted in a strength press. For lithologically and stratigraphically differentiated rock samples, strength parameters in various states of humidity (air-dried and capillary saturation state) were determined, including compressive strength, cohesion and the angle of internal friction. It was found that the strength of all types of rock increases with geological age, however saturation of these rocks with water causes their structural weakening, which is especially noticeable in the case of sandstone and claystone. In the case of mudstone, due to their structure, the reduction of strength after saturation with water is not so significantly noticeable. In the second part of the laboratory tests, 5 samples of Carboniferous post-mining waste with different storage times in the open pit were subjected to the assessment of changes in density and compressibility in relation to increasing values of vertical pressure. It was found that the long-term depositing of waste in the excavation is conducive to the intensive development of hypergenic processes. This contributes to the disintegration of sedimentary rocks, which causes changes in their physical and mechanical parameters. This phenomenon is additionally intensified by the increasing vertical pressure with thickness of waste layers.

Keywords Waste rock · Rock debris · Physico-mechanical properties · Open pit reclamation

Introduction

The primary purpose of open pit reclamation by filling it with rock material is to restore the usefulness of post-mining areas. The selected direction of reclamation, method of open pit backfilling, and type of filling material determine the possibility of safe future economic use of a site, particularly the prospects of establishing surface and underground infrastructure in the area. Most frequently, open pits are reclaimed using rock material (wastes) originating from the extraction and processing of deposits of different geological, mineralogical, petrographic, and age characteristics, compared to those of the deposit mined in a given open pit. Such reclamation is commonly practiced for mines containing nearly all types of deposits, including raw clastic materials (Sołtysiak et al. 2019), energy resources (Ardejani 2003), and non-ferrous and precious metal ores. Mining waste suppliers are obliged to perform preliminary testing of rock material within the scope of its physico-mechanical properties and chemical composition prior to delivery for recultivation purposes. Depending on the final function of the reclaimed site, the waste must be tested in terms of its granulometric composition, specific gravity, water retention, filtration coefficient (Newman et al. 1997), plasticity, degree of compaction, compressive strength (Agarwal 2009), load capacity (Naderian and Williams 1997), cohesion, and angle of internal friction (Filipowicz and Borys 2007). Information on the granulometric composition of mining wastes is important due to the need to assess the impact of grain size

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on the rate of pollutant release, porosity and permeability of wastes, humidity, and the characteristics of pollutant transport mechanisms (Report 1995).

An example application of rock material originating from various lithologies for open pit reclamation is the CTL Maczki-Bór S.A. filling sand mine, where Carboniferous waste rock originating from hard coal mines in the Upper Silesian Coal Basin (USCB) has been used as a backfilling material since the 1970s. The waste rock assessed in this study was obtained from preparatory, development, extraction, and processing work related to hard coal mining in the USCB (Probierz et al. 2017). The waste rock in the sublevel dump is in the form of rock debris with various grain size distributions, primarily with predominant stone and gravel fractions and local sand fractions. Its properties depend on numerous factors, including the type of sedimentary waste rock (clastic or argillaceous) and its percentage content, as well as the exposure time to weathering conditions, that is, the storage time for waste extracted from hard coal mines.

Rock material stored in a post-mining waste dump undergoes structural and textural transformations. These result from the progression of physical and chemical weathering processes and depend on technical factors, such as the method of deposition, compaction, and consolidation of the waste. The high stored rock material disintegration rate and weak mechanical parameters, particularly the very low (under 20 MPa) and low (20–40 MPa) uniaxial compressive strengths (UCSs) determined for USCB waste rock (Bukowska 2012), are significant in terms of numerous parameter changes within the waste dump over time compared to the properties of "fresh" stored rock (clastic and argillaceous). Literature sources state that the greater argillaceous rock content in the waste dump vertical profile and disintegration processes both influence the reduction of hydrogeological parameters (Gwoździewicz and Bukowska 2012).

The slope stability of a sublevel post-mining waste dump is an important scientific and technical issue that determines safe recultivation and reclamation. This problem is highly complex, and to date, researchers have failed to develop a theory concerning natural and anthropogenic rock medium degradation mechanisms that would ultimately solve issues related to the stability of such sites. The primary reason is the large number of factors that influence the stress, strain, and displacement distributions within the forming waste dump, particularly within areas modified by the mechanical influence of technical compaction processes. Generally, causes of the loss of slope stability are gravity and the resulting stresses in the soil medium (Duncan and Wright 2005). The site is also characterized by the internal dump structure, but only up to the original terrain elevation level. This leads to a predominant impact of gravity and vertical influence on the material stored below, which limits the risk of slipping.

Some researchers attribute the loss of slope stability to excessive exposure to maximal unbalanced forces, displacement velocities of up to 10^{-6} m/s, large displacements (Coetze et al. 1998; Dawson and Roth 1999), tangential strain distribution (Regueiro and Borja 1997; Zettler et al. 1999), and the degradation mechanism of shearing, by which the propagation of the degradation zone – from the bottom up – does not reach the overburden, wherein the degradation zone is subjected to tensile stresses. The primary determinant of slope stability is the stability index. Its value is determined using various strength parameters, including the shear and tensile strength, angle of internal friction, and cohesion of the material forming the slope. The heterogeneity of this rock medium makes it challenging to describe it and classify its geotechnical parameters in detail. Generally, the accuracy of ground data descriptions is considered to be low (Wysokiński 2004).

Geotechnical or geomechanical hazards may occur in areas of post-mining waste dump and heaps. Examples include waste dump foundation deformations and general dump deformations that may lead to reduction of dump stability and occurrence of deformations in the vicinity of this object. One of the factors influencing the level of these hazards are physical properties, including rock and soil mechanical properties, as evident from the weak parameters of the ground beneath the dump (Yin et al. 2009).

Considering the above factors, in this study, we analyzed certain properties of mining waste stored in the sublevel dump at the CTL Maczki-Bór S.A. filling sand mine. The purpose was to document the variability of the maximum stress equal to the compressive strength, cohesion and angle of internal friction, as well as compressibility, compaction, and grain size distribution variations depending on the mining waste storage time in the sublevel dump; moreover, we aimed to explore the possibility of applying this knowledge to forecast the strength of the reconsolidated dump, its resistance to the influence of water, and consequently, the stability of the slopes generated by the continuous dump formation process. The geomechanical parameter variability of the waste rock originating from the USCB mines was investigated from a chronostratigraphic perspective (including two states of humidity), while simultaneously factoring in its storage time in the dump within the open pit.

Area of study

The CTL Maczki-Bór S.A. open pit has two types of slopes: external slopes formed from typically fine- and medium-grained subsoils, i.e., quaternary sand, and internal slopes formed from loose clastic material, such as hard coal mine waste rock. The force distribution in bulk state soils that are systematically compacted (elastoplastic medium), as is the case in the study area, is complex and poses great difficulties to researchers in terms of determining the state of stress, strain, and displacement within a waste dump. The configuration of slopes formed in the continuing process of sublevel post-mining waste dump formation at the CTL Maczki-Bór S.A. open pit is variable, and the slope face undergoes dynamic changes over time with simultaneous compaction of the material stored at the top of the dump. As a result, the dump slopes are typically in a permanently loose state and made up of a coarse-grained clastic medium formed from strong cohesive rocks with a layered structure, which aids in maintaining slope stability.

The authors of the Ecological Review for Maczki-Bór S.A. mine adopting assumptions made by Kidybiński (Kidybiński 1982), defined the optimal conditions and factors leading to the natural reconsolidation of the sublevel post-mining waste dump at the CTL Maczki-Bór S.A. filling sand mine as follows:

- Water flows toward the dump to ensure an average rock debris humidity of 4.0–4.5%.
- Occurrence of a clay or claystone stratum with the appropriate slakeability in the upper layer, wherein as a worst-case scenario, the samples crack because of the influence of water along the lamination (this may affect sorted rock material, the content of which includes mudstone and claystone).
- Loading of reconsolidated rock debris (rubble) resulting from the post-mining waste dump height and a minimum reconsolidation time of three years.

In the case of a sublevel dump with a thickness of up to approximately 30 m that has been filled to the original terrain elevation level in the open pit, the predicted vertical stress at this depth can reach a maximum of approximately 0.6 MPa. Vertical stress corresponds to the pressure of the rock stored on the earliest deposited material that forms the bottom layer of the dump.

In the case of the CTL Maczki-Bór S.A., the mining waste dump is currently being drained by a system of drainage ditches within the open pit and a main mine water drainage system pumping station located in the center of the excavation. As a result, the water table within the open pit is maintained at a constant level, with minor seasonal variations in elevation. The rock material deposited within the mine is currently filled with water in the bottom part of the dump and occasionally in its peripheral fragments. The dump was subjected to water accumulation within the limits of the cone of depression related only to periodic precipitation and water infiltration into the spoil bank. Ceasing water drainage will fill the interclastic spaces up to the natural water table stabilization level or the maintained water table level. The rock material below the water table would be flooded and saturated, tightly filling free spaces, which on one hand, will be a rock-weakening factor, but on the other hand, given the change in the effective stress state, will be a factor contributing to maintaining material stability. Additionally, the increase in groundwater table may contribute to an upward displacement of the rock material grain framework in the saturation zone, resulting in an increased waste dump volume. However, the scale and consequences of this phenomenon are extraordinarily difficult to predict. The material layer subjected to the influence of atmospheric factors will be limited to the narrow aeration zone after stabilization of the water table within the spoil bank. Therefore, future planning of spoil bank top layer repurposing will depend on the top morphology and will require a separate geotechnical test program based on field testing methods and current laboratory analysis results.

Samples

Geomechanical property laboratory tests were conducted on two types of mining waste samples:

- We tested fresh rock debris constituting caved roof rock from hard coal longwall mining. Analysis was performed on a regular laboratory samples cut from waste rock (Fig. 1). Areas of coal mines and coal that appear within the USCB, allowing for the broadest possible reflection

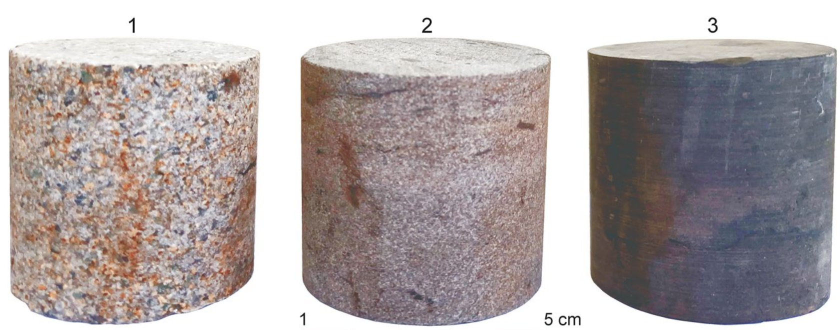


Fig. 1 Carobniferous rocks sampled from mines in USCB: 1. sandstone, 2. mudstone, 3. claystone

of the geomechanical rock property variation considering the lithological and stratigraphic formations (Fig. 2), were selected.

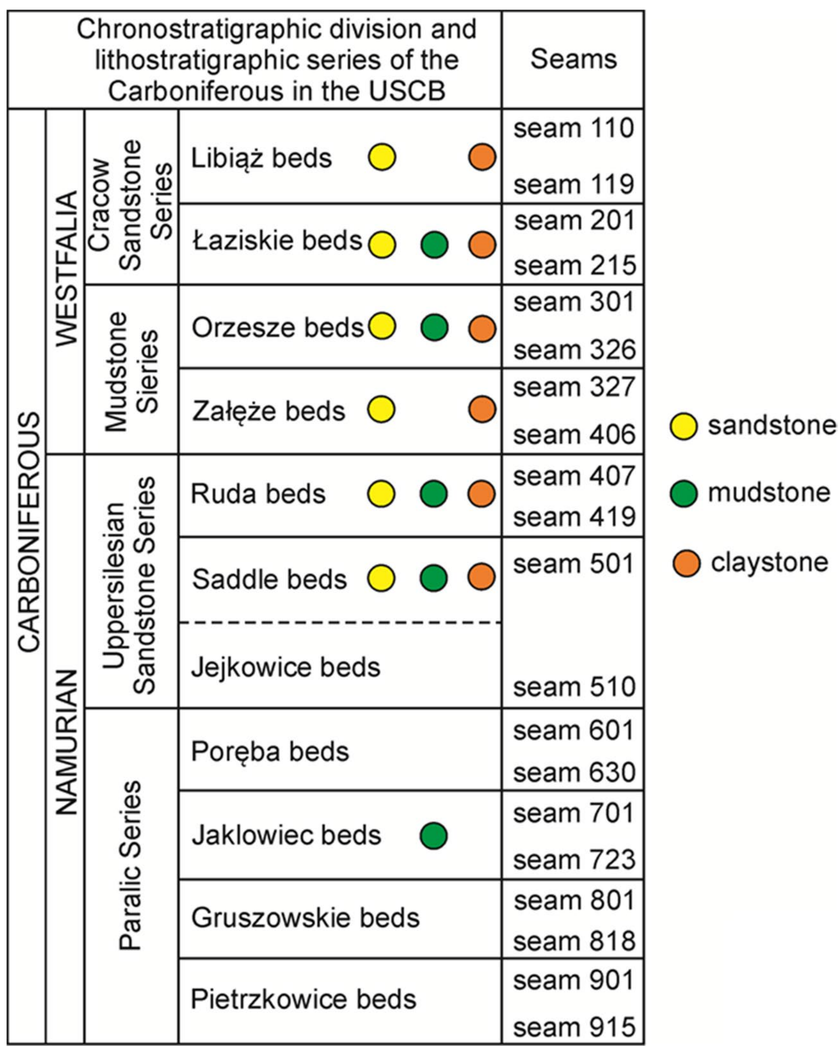
- We tested rock material used for excavation backfilling, characterized by various storage times in the filling sand open pit. Five samples of unsorted rock material with various storage times were collected. These included fresh (stored for up to six months), weathered (3–15 years), and strongly weathered waste (stored for more than 15 years) (classification per Skarżyńska (Skarżyńska 1997), Mirkowski and Badera (Mirkowski and Badera 2015). The samples, each with a mass of 110 ± 5 kg, were collected after removing approximately half a meter of soil and weathered rock, or directly from the dump slopes (Fig. 3, Fig. 4). They were used to prepare five samples with a mass of approximately 12 kg each and a grain size composition equal to the large samples collected from the dump, which were subsequently tested under laboratory conditions according to the designed testing scope.

Fig. 3 Sampling of backfilling material (post-mining waste) from Maczki-Bór open pit

Methodology

The aim of this study was the assessment of selected geomechanical parameter values (Bukowska 2012; Gwoździewicz and Bukowska 2012; Kidybiński 1985; Wiłun 1987) of fresh mining waste originating from various Upper Carboniferous

Fig. 2 Lithostratigraphic series of the USCB Carboniferous sediments with locations of sampling areas (seams/beds) for laboratory testing



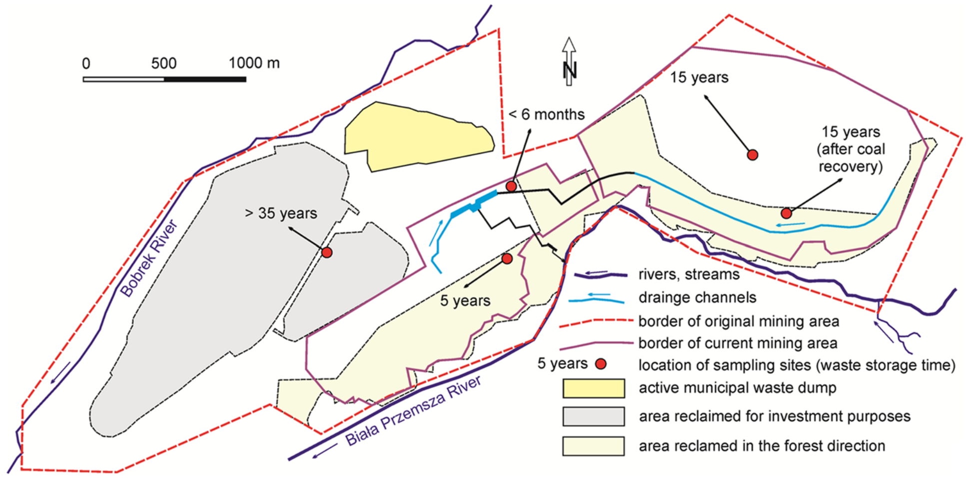


Fig. 4 Sampling location map for post-mining waste deposited in the Maczki-Bór open pit

lithostratigraphic series of the USCB, as well as the analysis of rock material with various storage times collected from the top layer of the post-mining waste dump at the CTL Maczki-Bór S.A. filling sand mine.

The fresh rock material constituting caved roof rock from hard coal mining was subjected to analysis of UCS, cohesion, and angle of internal friction. In contrast, the waste samples collected from the spoil bank were subjected to variation assessments of the volume density at the adopted levels of loading, compression modulus, granulometric composition, and uniformity coefficient, based on grain classes as per Wiłun (Wiłun 1987). The methodological scheme of laboratory tests is shown in Fig. 5.

Fresh rock material

Tests of the rocks collected from various Upper Carboniferous lithostratigraphic series of the USCB were conducted

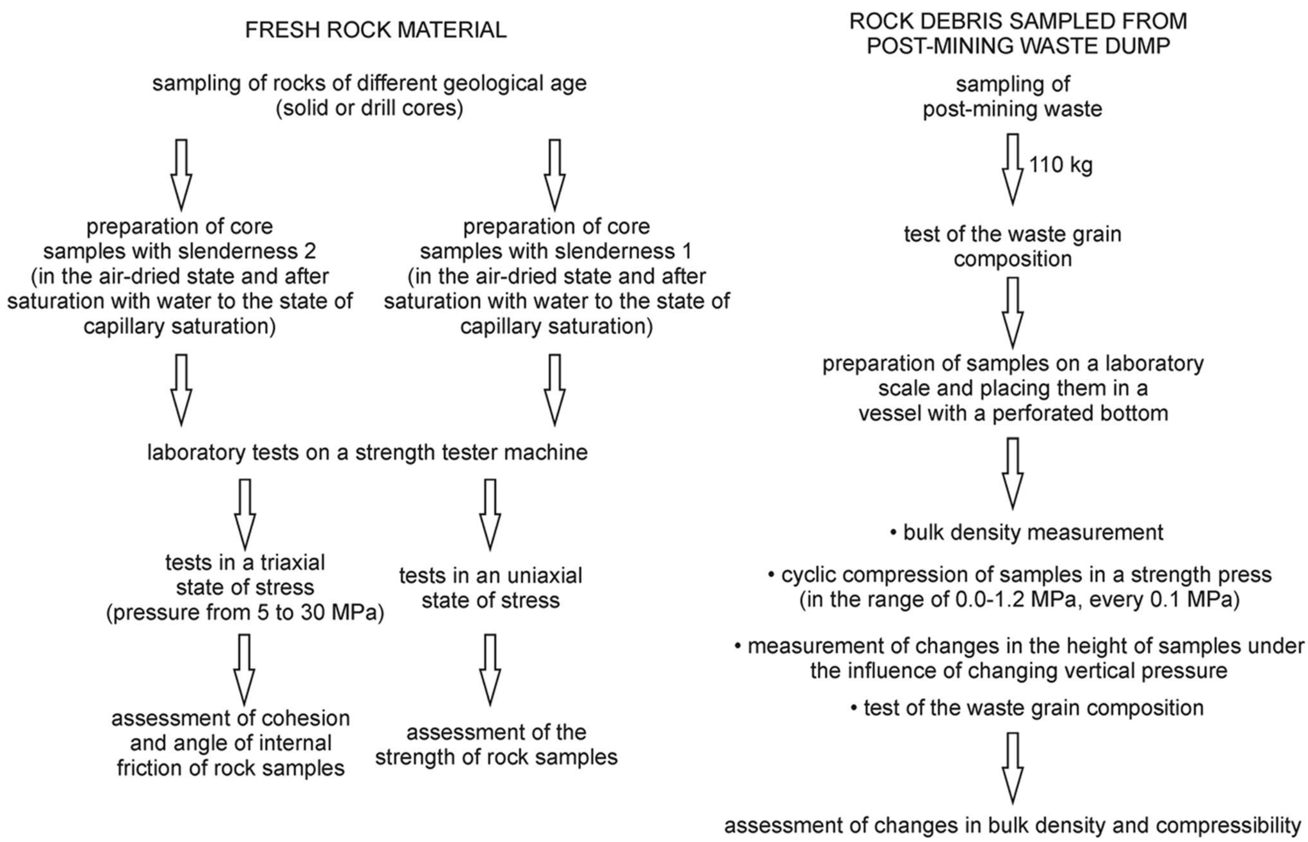


Fig. 5 The methodological scheme of laboratory tests

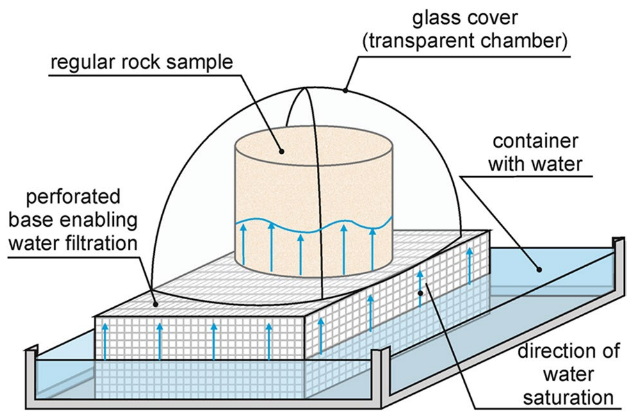


Fig. 6 Device for gravity drainage capacity determination by capillary saturation: analysis of a regular solid rock sample (according to Bukowski (Bukowski 2007), modified)

under complex stress, including uniaxial compression (stress condition $\sigma_1 > 0$, $\sigma_2 = \sigma_3 = 0$) and conventional triaxial compression (stress condition $\sigma_1 > 0$, $\sigma_2 = \sigma_3 = p$). The mechanical properties of the rock were determined using samples in two states of humidity: an air-dried stste and stste of capillary saturation (Bukowski 2007). Saturation of rock samples was carried out in a closed container, placing the cores on a tray lined with a filter material immersed in water. The process of moisture infiltration and saturation of samples with water was each time controlled by recording the weight increase of the sample. The achivement of the total capillary humidity of the sample was assumed after stabilizing the weight of the cores in the water saturation process (Fig. 6, Fig. 7). The samples were compressed using an MTS testing machine with a deformation velocity of approximately 0.008 mm/s. The loading direction was perpendicular to the lamination (Fig. 8).

The UCS was determined using cubic or cylindrical samples with a slenderness ratio of 1. An empirical calculation coefficient of 0.89 was applied to relate the UCS to the slenderness recommended by the International Society for Rock Mechanics (ISRM) (Ulusay and Hudson 2007). The cohesion and angle of internal friction were evaluated using cylindrical samples with a slenderness of 2 by applying confining pressures ranging from 5 to 30 MPa. The values of these parameters were determined based on the parabolic envelope of the Mohr circles in a coordinate system of shear stress–normal stress.

The course of the exemplary stress–strain curve is shown in Fig. 9

Rock debris sampled from the post-mining waste dump

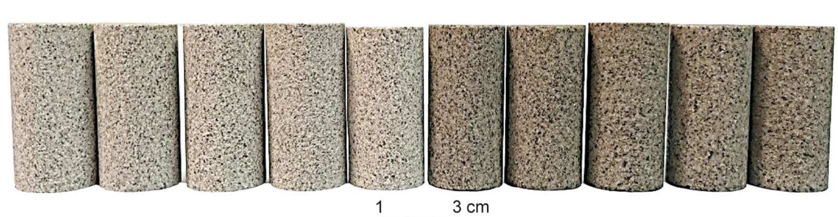
Assessing the selected physical parameters of the rock debris collected from the waste dump required appropriate sample preparation for laboratory testing. Samples of mixed rock material, approximately 12 kg each, with grain composition equal to that of the samples collected directly from the dump, were prepared. The study of the grain composition was carried out with a set of sieves from 0.063 mm to 120 mm using a laboratory shaker. The shaking process lasted at least 10 min, and if necessary, the test time was extended. The tests were carried out in accordance with the dry method, because the material sampled for testing did not show any tendency to caking.

An initial compaction of the rock material placed in an oedometer was performed to evaluate the compressibility and volume density by exerting minimum pressure against the sample using testing machine plates. The samples were loaded in an MTS 810 NEW testing machine until the adopted maximum stress of 1.2 MPa was reached, with the intent to achieve maximum sample compaction – Fig. 10. The experimental recording made it possible to determine the changes in rock material density and compressibility during individual stages of loading (every 4 kN). After the loading test, a sieve analysis was performed and used as the basis for determining the uniformity coefficient of the tested rock material.

The compressibility of a tested material or rock is its ability to reduce its volume under the influence of an exerted load. This characteristic is defined by the compression modulus, which was determined during gradual vertical loading of the sample under conditions that prevented its horizontal deformation. The change in the sample compression modulus from the sample height in a loose state $h = h_o$ at $\sigma = \sigma_0 = 0$ MPa to the sample height $h = h_{12,}$ at $\sigma = \sigma_{12} = 1.2$ MPa was determined using an interval of $\Delta\sigma_i = \sigma_i\text{-}\sigma_{i-1} = 0.1$ MPa. The sample height variations during the individual loading stages were calculated as $\Delta h_i = h_i\text{-}h_{i-1}$.

The volume density of the stored mining waste for individual vertical sample loading levels was determined based on the mass of a rock material unit of volume, including pores. The sample density variability was determined from the

Fig. 7 Changes in the moisture content of exemplary sandstone samples during capillary saturation - before and after soaking with water



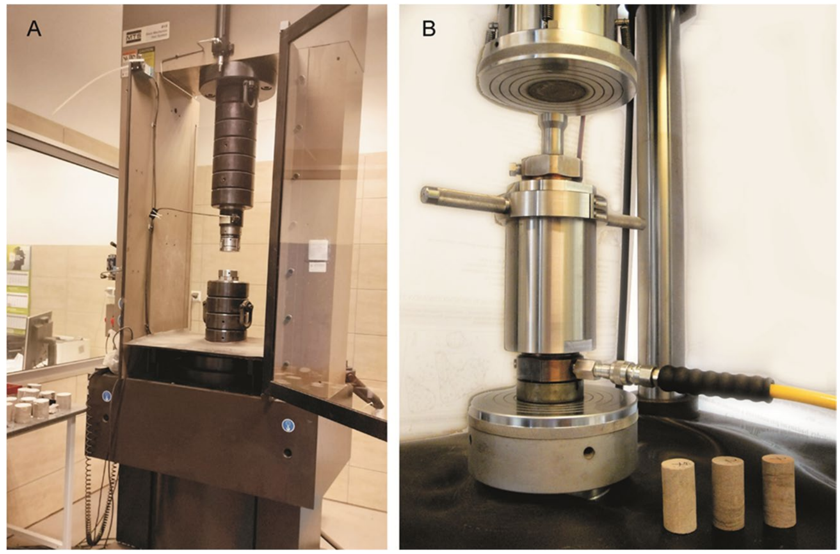


Fig. 8 Device for testing rocks under stress conditions: A- uniaxial, B - triaxial

density ρ_0 defined at a sample height $h = h_0$ ($\sigma = \sigma_0 = 0$ MPa), indicating a loose state, to the density ρ_{12} defined at a sample height $h = h_{12}$ ($\sigma = \sigma_{12} = 1.2$ MPa) using a frequency increment of 0.1 MPa.

Results and discussion

Fresh rock material

The mixture of waste rock collected during hard coal mining, which was stored in the sublevel post-mining dump, consisted of clastic rock (sandstone with various grain size distributions and mudstone), as well as argillaceous rock (primarily claystone). The rock originated from various

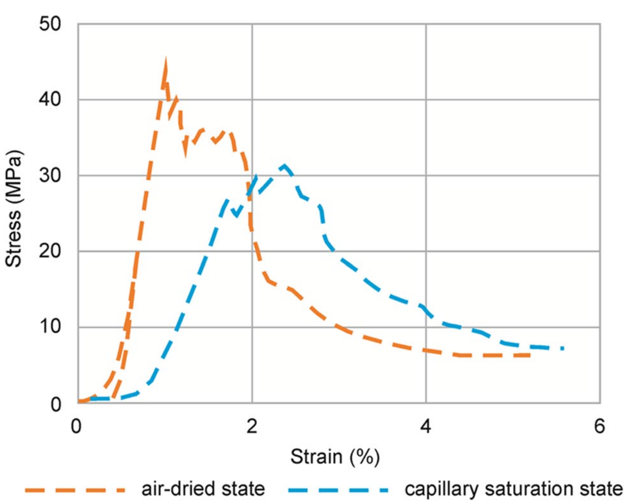


Fig. 9 Course of an exemplary stress–strain curve for claystone of the saddle layer

Upper Carboniferous lithostratigraphic series of the USCB (Fig. 2). The determined values of the UCS, cohesion, and angle of internal friction for barren rock of various geological ages, from the youngest beds of the Cracow Sandstone Series to the oldest currently extracted beds of the Paralic Series, are presented in Fig. 11. The mechanical parameter values of 2100 samples were determined in an air-dried state and in a state of capillary saturation. Based on these results the average values of individual geomechanical parameters were calculated.

The UCS values the individual geological beds (layers) in the USCB were determined through experiments conducted on fresh waste (Table 1).

In the case of the investigated Carboniferous sandstone, the UCS determined in the air-dried state increased with geological age. A significant influence of water on sandstone strength was also identified, and the determined structural weakening coefficients resulting from the water activity ranged between 0.6–0.8, irrespective of rock age. Further, the tests demonstrated that the sandstone compressive strength decreased by approximately 20–40% under capillary saturation with water compared to the values in the air-dried state. The tested Carboniferous mudstone, owing to its structure and texture, lost less strength (2–22%) than sandstone as a result of the influence of water, with structural weakening coefficients ranging from 0.78 to 0.98.

Similar to sandstone, claystone achieved a stronger structure with age, which was reflected by an increase in compressive strength. The influence of water on the claystone structure was evident, and the determined structural weakening coefficients were generally at 0.5.

The results obtained for the Upper Carboniferous sedimentary rock collected from various lithostratigraphic series of the USCB confirmed prior test results, whereas the determined coefficient

Fig. 10 Measuring set for testing the compressibility of samples: **A**—cylinder with a perforated bottom with a sample, **B**—compressibility testing on a strength testing machine

values were within the compressive strength ranges defined for this type of rock (Bukowska 2012). It should be noted that these tests were conducted in a state of capillary saturation, which was hypothesized to offer a good approximation of the natural humidity conditions found in a mined Carboniferous rock mass that was drained of free water (Bukowska and Bukowski 2012).

The parameters that, apart from the UCS, also belong to the group of strength parameters are cohesion and the angle of internal friction. The values of these parameters were determined in an air-dried state and in a state of capillary saturation (Table 2).

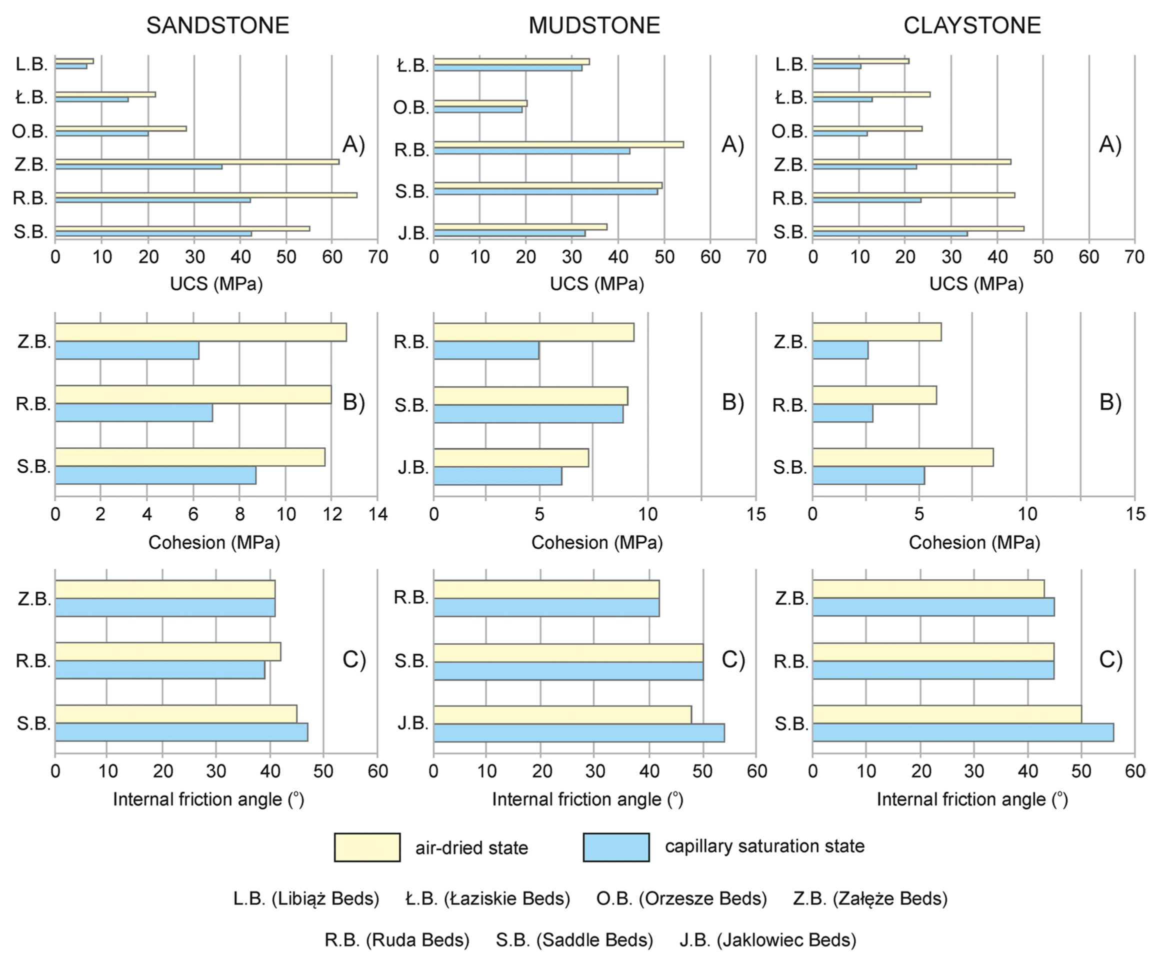


Fig. 11 Variation charts of strength (**A**), cohesion (**B**), and angle of internal friction (**C**) for sandstone, mudstone, and claystone of various Upper Carboniferous lithostratigraphic series of the USCB in various states of saturation

Table 1 UCS variability intervals for Carboniferous clastic and argillaceous rocks of various geological ages in the USCB

Lithostratigraphic series	Geological age	Saturation state	UCS (MPa)		
			Sandstone	Mudstone	Claystone
Cracow Sandstone Series	Libiąż Beds, Łaziskie Beds	air-dried	8.1–21.7	33.8	20.8–25.5
		capillary saturated	6.6–15.6	32.1	10.4–12.8
Mudstone Series	Orzesze Beds, Załęże Beds	air-dried	28.3–61.5	20.2	23.8–43.0
		capillary saturated	20.0–36.1	19.2	11.9–22.5
Upper Silesian Sandstone Series	Ruda Beds, Saddle Beds	air-dried	55.1–65.4	49.5–58.1	43.8–45.8
		capillary saturated	42.4–42.2	48.4–42.5	22.3–33.6
Paralic Series	Jaklowiec Beds	air-dried	–	37.7	–
		capillary saturated	–	32.7	–

The cohesion values determined in the air-dried state exhibited little differences between the Carboniferous sedimentary rocks found in the USCB, with greater cohesion for clastic rock than for argillaceous rock, represented by claystone.

The cohesion values determined for sandstone, mudstone, and claystone under conventional triaxial compression in two states of humidity demonstrated that the values decreased in the water-saturated state compared to the air-dried state. The determined structural weakening coefficients, reflecting the influence of water on rock cohesion, generally ranged from 0.43 to 0.75, which corresponded to a cohesion loss of 25–57%. It was also observed that the greater the geological age of the rock, the lower the difference between the cohesion determined in the two states.

For all lithostratigraphic series and rock types (sandstone, mudstone, and claystone), the angle of internal friction in the air-dried state ranged from 41° to 50° and remained at a constant level or exhibited minor variations after water saturation.

There are no scientific publications presenting information on the influence of water on rock cohesion and the angle of internal friction via capillary saturation. Therefore, this study presents novel results important for engineering practice since they include the rock mass water content, which has a significant influence on the mechanical parameters of rock in the natural environment. However, that is not to say that the influence of water on the mechanical properties of sedimentary rock has not been studied by other researchers. Information regarding the influence of water on uniaxial, triaxial, and tensile strengths is described in publications by Masuda (Masuda 2001), Hale and Shakoor (Hale and Shakoor 2003), Li and Reddish (Li and Reddish 2004), Vásárhelyi and Ván (Vásárhelyi and Ván 2006), Cherblanc et al. (Cherblanc et al. 2016), Wong et al. (Wong et al. 2016), Shi et al. (Shi et al. 2016), Petrov et al. (Petrov et al. 2017), Özdemir and Sarici (Özdemir and Sarici 2018) and Majeed and Abu Bakar (Majeed and Abu Bakar 2018). The most important findings exclusively concerning the influence of water on the UCS and Young's modulus of sedimentary rock were described by Kijewski and Lis (Kijewski and Lis 2009), Yilmaz (Yilmaz 2010), Małkowski et al. (Małkowski et al. 2014), and Yao et al. (Yao et al. 2015). Numerous researchers have reported a linear relationship between the UCS in an air-dry state and the UCS after water saturation, as well as almost full or at least a high or very high correlation between these variables (Hawkins and McConnell 1992). However, some researchers did not confirm this linear relationship, as their experiments demonstrated that the studied sandstone did not exhibit a significant UCS reduction under the influence of water (Hale and Shakoor 2003). Our tests also confirmed the relationship between the UCS and rock humidity imposed by capillary ascent or the gradual immersion of the sample in water.

Table 2 Rock geomechanical parameter values determined in two states of humidity

Rock type	Geological age	Saturation state	Cohesion (MPa)	Angle of internal friction (°)
Sandstone	Załęże, Ruda, Saddle Beds	air-dried	11.7–12.7	41–45
		capillary saturated	6.2–8.7	39–47
Mudstone	Ruda, Saddle, Jaklowiec Beds	air-dried	9.0–9.3	42–50
		capillary saturated	4.9–8.8	42–50
Claystone	Załęże, Ruda, Saddle Beds	air-dried	5.8–8.4	43–50
		capillary saturated	2.6–5.2	45–54

Table 3 Sample compression modulus and volume density values at adopted loading stages rising by 0.1 kN

Stress (MPa)	Waste storage time in the post-mining waste dump									
	< 0.5 years		5 years		15 years (after coal recovery)		15 years		> 35 years	
	ρ (kg/m^3)	M (MPa)	ρ (kg/m^3)	M (MPa)	ρ (kg/m^3)	M (MPa)	ρ (kg/m^3)	M (MPa)	ρ (kg/m^3)	M (MPa)
0.0	1531	0	1485	0	1439	0	1286	0	1271	0
0.1	1577	3.458	1528	3.595	1479	3.781	1347	2.247	1337	2.050
0.2	1607	5.267	1557	5.374	1512	4.505	1391	3.112	1381	3.104
0.3	1627	7.805	1582	6.275	1540	5.460	1419	4.993	1419	3.754
0.4	1646	9.063	1602	7.857	1565	6.360	1445	5.603	1448	4.990
0.5	1662	10.433	1619	9.687	1589	6.628	1467	6.605	1473	5.928
0.6	1680	9.261	1638	8.802	1607	9.041	1486	7.652	1493	7.470
0.7	1690	16.109	1654	10.175	1631	6.810	1502	9.996	1511	8.221
0.8	1703	13.504	1667	13.133	1645	11.572	1516	10.517	1527	9.499
0.9	1719	10.517	1677	16.046	1658	12.339	1529	12.424	1542	10.407
1.0	1730	16.364	1687	16.327	1670	13.732	1540	13.261	1556	11.433
1.1	1742	14.189	1697	16.483	1682	14.433	1551	14.108	1568	12.649
1.2	1750	22.308	1706	20.186	1694	14.685	1562	14.910	1580	14.463

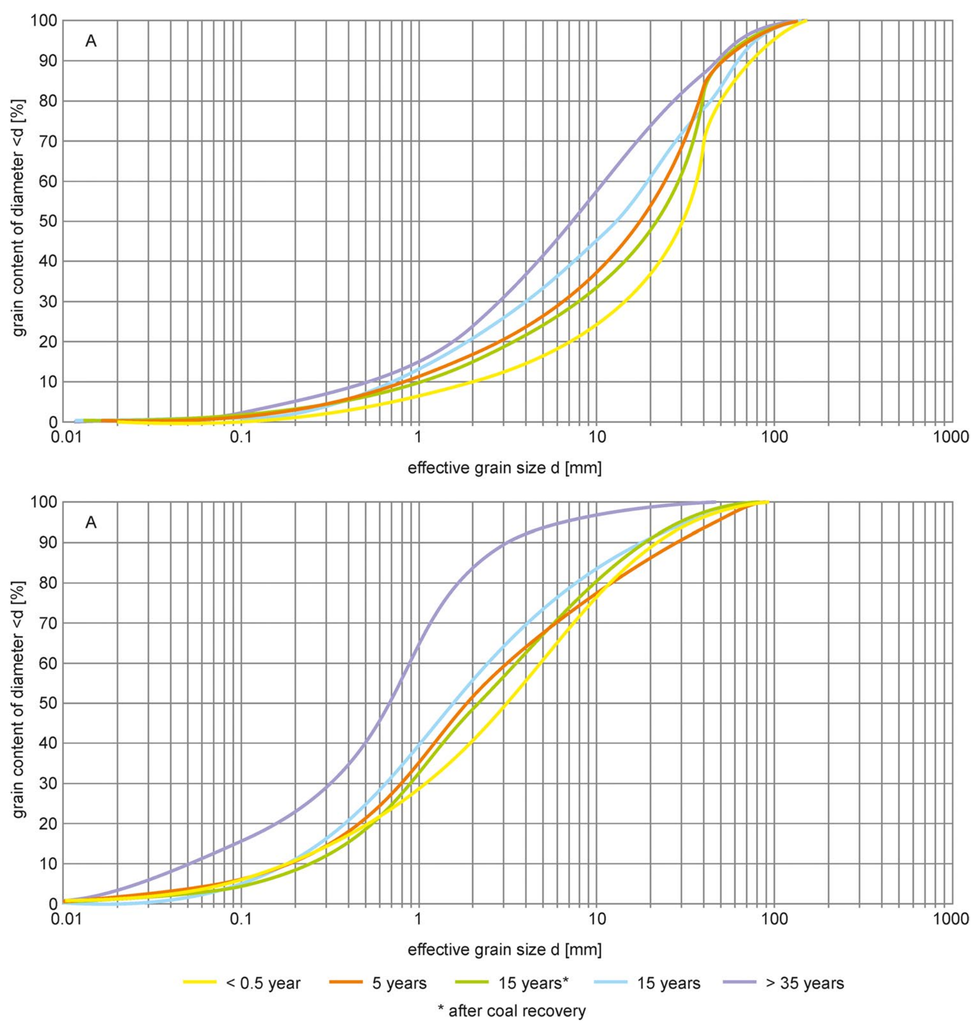


Fig. 12 Grain fraction contents in the mining waste collected from the dump: **A** - before uniaxial compression; **B** - after compression

Rock debris sampled from the post-mining waste dump

A sieve analysis was performed on the rock material collected from five spots on the top of the post-mining waste, both before and after the compressibility tests conducted in the oedometer (Table 3). The result was the identification of the grain fraction contents in the samples characterized by various storage times on the CTL Maczki-Bór S.A. spoil bank (Fig. 12). The physico-mechanical parameters of the prepared samples are presented in Table 3.

The geotechnical characteristics of the Carboniferous rock in the CTL Maczki-Bór S.A. excavation largely depend on the content of individual waste rock types (clastic rock, argillaceous rock, and coal residues), the proportions of individual rock types in layers successively stored in the dump, and the storage time. The two-stage laboratory tests provided information on the selected physico-mechanical parameters of the fresh material transferred for open pit reclamation, as well as on the influence of time, vertical pressure, and water on the physical parameter variability of rock debris already deposited in the working environment.

Sieve analysis of the waste collected from the post-mining waste dump prior to compression in the testing machine demonstrated that the gravel fraction exhibited the greatest contribution by mass, with an average content between 57% (15-year-old waste) and 66% (15-year-old waste after coal recovery). The stone fraction was represented by single large rock fragments that constituted from 12% (oldest waste) to 31% (youngest waste) of the content by mass. The highest sand fraction contents were found in the oldest and 15-year-old waste (approximately 21%), and its contribution was more than twice as great as that of fresh (youngest) waste. These results confirm the hypothesis that rock degradation through weathering processes (together with the age of the waste stored in the open pit excavation) causes a reduction in coarse particle content to the benefit of finer fractions, whose content ranged from 0.5% to 2.5% in the longest-stored waste of the CTL Maczki-Bór S.A. dump.

The sieve analysis subsequently performed on the samples compressed in the testing machine indicated a significant influence of pressure on the grain composition and disintegration of rock fragments. After laboratory testing, the waste primarily exhibited gravel and sand fraction contents, which had the greatest percentage contributions in all samples, ranging within 15.0–52.3% and 35.2–69.3%, respectively. However, the gravel fraction content decreased with rock storage time in the spoil bank to the benefit of finer fractions (primarily sand). The samples' silt fraction content (by mass) increased to over 10% in the oldest waste, whereas the clay fraction content was negligible (largely below 1%).

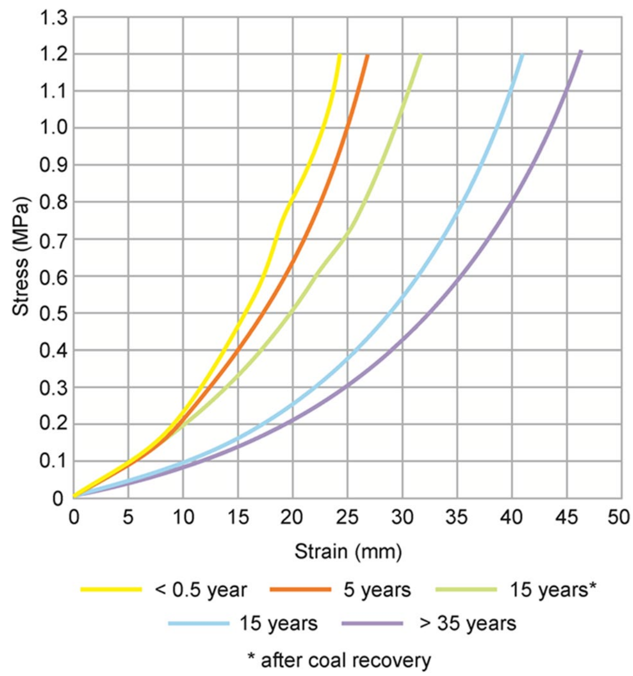


Fig. 13 Stress–strain curves of compressed mining waste samples

Analysis of geomechanical property of the mixture of Upper Carboniferous rock stored in the dump was conducted based on the variability of selected parameters as a result of loading in the testing machine, constituting a simulation (prediction) of rock material behavior at greater depths, as reflected in the stress–strain curves (Fig. 13).

Mining waste originating from hard coal extraction processes in Poland used for the reclamation of the CTL Maczki-Bór S.A. open pit is characterized by a general growing tendency of the uniformity coefficient (grain size distribution) and an increasing trend in waste storage time in the dump. The oldest waste, stored for over 35 years and for over 15 years, can be classified as strongly weathered, taking into account the influence of physical and chemical weathering processes (Mirkowski and Badera 2015; Skarżyńska 1997). The remaining samples were classified as weathered, partially weathered, and fresh mining waste.

After the compressibility tests, grain composition tests and a uniformity coefficient assessment were carried out again, and the results were used to classify the oldest and strongly weathered waste as multi-grained and the younger waste as very multi-grained. After characterizing these two groups, it was assumed that the oldest sediments' bulk density and porosity would differ from those of the sediments stored for shorter periods, which may explain the courses of the stress–strain curves. The stress–strain curves can also be used to formulate

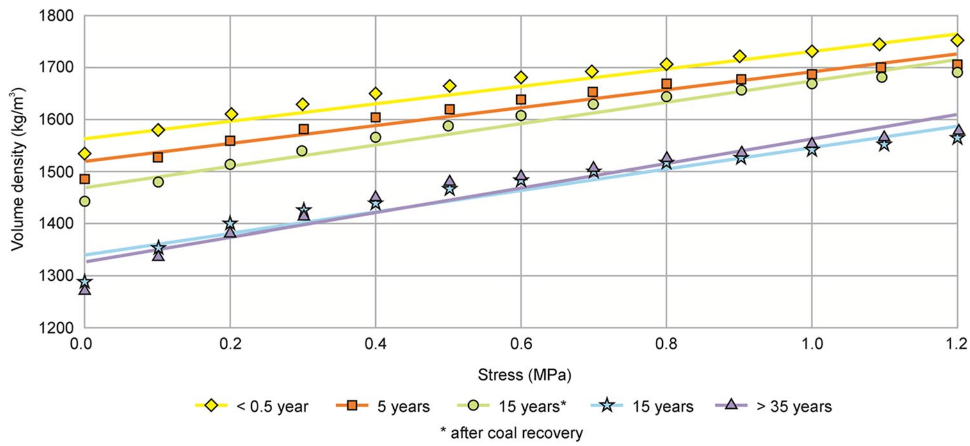


Fig. 14 Volume density as a function of stress during individual stages of sample loading

a conclusion regarding the increase in strain within the adopted stress values of up to approximately 1.2 MPa together with the increase in waste storage time in the CTL Maczki-Bór S.A. dump. However, time was not the dominant factor in terms of its influence on the physico-mechanical parameter values, which were primarily determined by the geological age, origin, formation, structure, and texture.

The results of the sample loading experiments conducted using the strength-testing machine indicated a relationship between the volume density during individual stages and the storage time in the dump (Fig. 14). An increase in volume density was observed each time after sample compression, relative to the (initial) bulk density, i.e., directly after placing the loose, sieved material in the testing cylinder. The tests demonstrated that longer storage time led to greater differences between the bulk density values determined for a load of 0.0 kN and the density observed for the maximum load applied during the experiments. The increase in these values ranged from 13% for fresh waste to 20% for sediments stored for more than 35 years. This can be attributed to numerous factors including the varied waste grain size distribution and variability of uniformity coefficient. The lack of information regarding the proportions of individual sedimentary waste rock contents (sandstone, mudstone, and claystone) deposited in the CTL Maczki-Bór S.A. dump should be highlighted. Further, the mining waste deposited in the spoil bank also contained coal, but the coal content, originating from preparatory, development, and extraction work and/or coal enrichment processes (wash dirt) and flotation (the finest grain sizes), is also unknown. Its amount in the waste deposited in the dump, which primarily depends on the processing efficiency, has a significant influence on the tested parameter results. The presence of an increased amount of coal in the waste mass deposited in the spoil bank could also explain the lower volume (bulk) density of the prepared laboratory samples of the oldest waste. Additionally, the mining waste grain framework density plays an important role in explaining the above, and it depends on factors such as the mineral composition and the degree and manner of individual mineral grain cementation. However, these issues were not the subject of this study.

Analysis of the results made it possible to develop functional relationships between the stress values at individual loading levels and the volume density of the prepared samples, with reference to the bulk density determined for the studied sediments (Fig. 14). This relationship, within a stress range of up to 1.2 MPa, is well described by the linear function presented in Table 4. The coefficients of correlation *r* ranged from 0.962 to 0.981, indicating a very strong Pearson linear correlation between the variables.

Based on the sample loading tests conducted in the strength testing machine within the adopted stress range of up to 1.2 MPa (in increments of 0.1 MPa), a linear relationship was found between the stress and the compression

Table 4 Regression analysis results $\rho = f(\sigma_1)$ for rock material with various storage periods in the dump

Period of waste storage (age of wastes)	Relation	Coefficient of determination R^2	Standard estimation error
<0.5 year	$\rho = 167.571 \cdot \sigma_1 + 1565.901$	0.956	14.685
5 years	$\rho = 173.101 \cdot \sigma_1 + 1519.201$	0.951	15.947
15 years (after coal recovery)	$\rho = 205.112 \cdot \sigma_1 + 1470.011$	0.963	16.301
15 years	$\rho = 207.581 \cdot \sigma_1 + 1340.017$	0.925	24.138
>35 years	$\rho = 234.582 \cdot \sigma_1 + 1328.701$	0.929	26.490

Table 5 Regression analysis results $M = f(\sigma_1)$ for rock material with various storage periods in the dump

Period of waste storage (age of wastes)	Relation	Coefficient of determination R^2	Standard estimation error
< 0.5 year	$M = 12.986 \cdot \sigma_1 + 3.084$	0.795	2.495
5 years	$M = 14.217 \cdot \sigma_1 + 1.921$	0.963	1.053
15 years (after coal recovery)	$M = 10.828 \cdot \sigma_1 + 2.071$	0.936	1.075
15 years	$M = 12.039 \cdot \sigma_1 + 0.951$	0.992	0.415
> 35 years	$M = 10.999 \cdot \sigma_1 + 0.671$	0.996	0.261

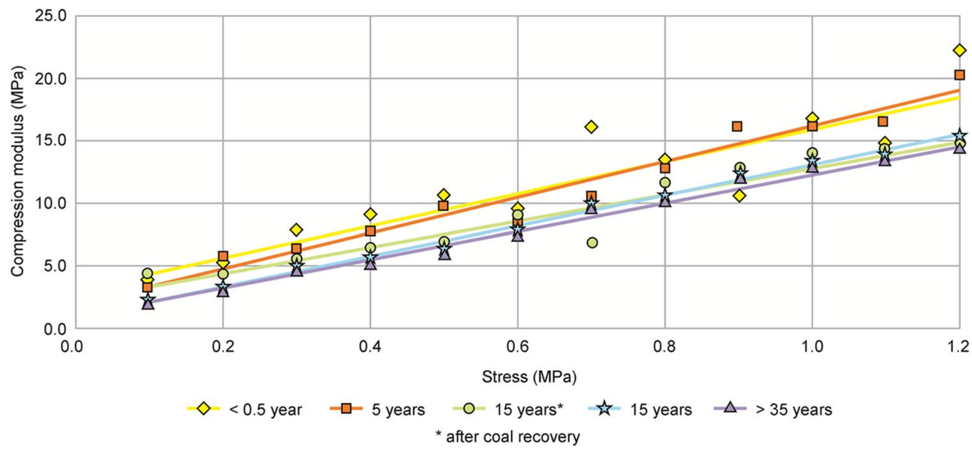


Fig. 15 Compression modulus as a function of stress during individual stages of sample loading

modulus. The obtained correlation coefficients indicated a strong correlation (r = 0.892) between the stress and compression modulus variables for fresh waste. The correlation coefficients of the stress and compression modulus variables for the older waste demonstrated a very strong correlation (r = 0.967–0.998) (Table 5, Fig. 15).

The compressibility curves for mining waste with various storage times in the dump were described with a power function (Fig. 16, Table 6), whereas the coefficients of correlation r = 0.950–0.994 indicated a very strong correlation between the load and height reduction variables during successive stages of loading (Δh). In contrast, the compressibility curve demonstrated that the height reduction Δh within the stress range of 0.8–1.2 MPa, corresponding to a load of 40–44 kN, stabilizes at a level of about 1 mm, regardless of the waste storage time, which corresponds with the stabilization of the sample pore space and grain framework.

The bulk density/compression modulus relationship (Fig. 17) was described using the linear function presented in Table 7. The bulk density/compression modulus relationship had correlation coefficients of r = 0.878–0.973, which indicated a strong correlation between the x and y variables for fresh waste and a very strong correlation for samples prepared from mining waste stored longer periods in the dump.

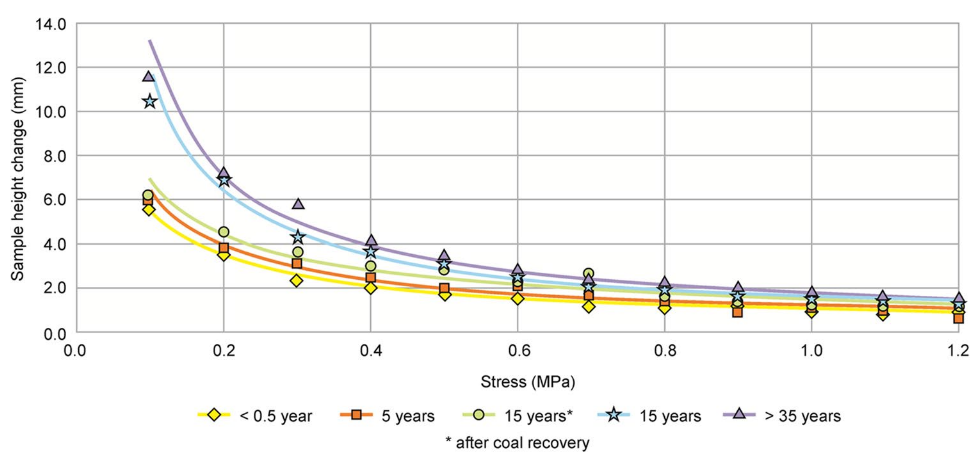


Fig. 16 Rock material compressibility curves

Table 6 Regression analysis results $\Delta h = f(\sigma_1)$ for rock material with various storage periods in the dump

Period of waste storage (age of wastes)	Relation	Coefficient of determination R^2	Standard estimation error
< 0.5 year	$\Delta h = 1.125 \cdot \sigma_1^{-0.696}$	0.918	0.834
5 years	$\Delta h = 1.193 \cdot \sigma_1^{-0.738}$	0.960	0.686
15 years (after coal recovery)	$\Delta h = 1.533 \cdot \sigma_1^{-0.658}$	0.903	0.508
15 years	$\Delta h = 1.548 \cdot \sigma_1^{-0.886}$	0.989	1.530
> 35 years	$\Delta h = 1.757 \cdot \sigma_1^{-0.884}$	0.988	1.612

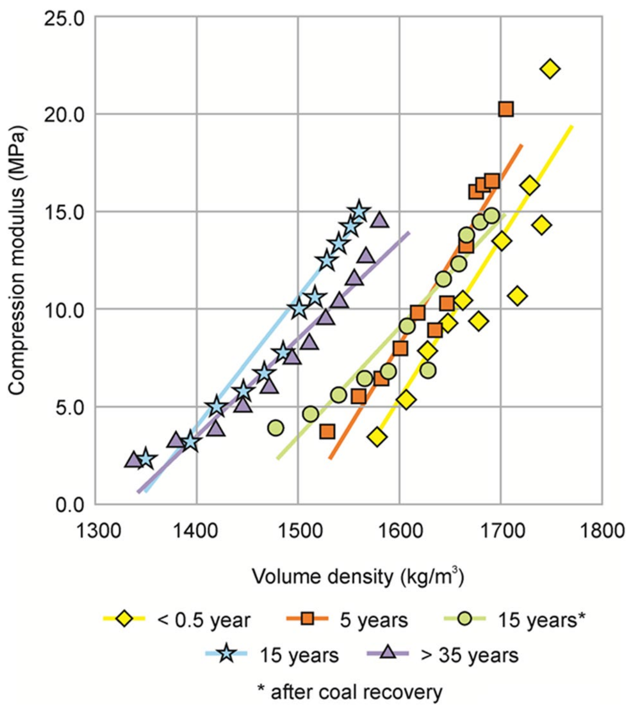


Fig. 17 Sample volume density and corresponding compression modulus determined at various sample loading levels

The issue of the most accurate identification of the physico-mechanical parameters of non-cohesive antopogenic soils used in the reclamation of the excavation is particularly important in terms of the general safety of the reclaimed areas and those designed for development. In the conditions of parallel: residual exploitation of the sand deposit, reclamation of the excavation and development of the top of the heap with surface infrastructure, the design of slopes made of post-mining waste should absolutely be carried out in accordance with the accepted rules and standards. Internal and external slopes should be constructed using material whose properties will not change under the influence of external factors (e.g. physical weathering, water impact) to the extent enabling the loss of their stability.

Conclusions

Based on laboratory tests of fresh clastic and clayey rocks belonging to various lithostratigraphic layers of the USCB and weathered and fresh post-mining waste, which was a mixture of sandstone, mudstone, claystone and coal stored in the Maczki-Bór open pit in unknown proportions, the following was shown:

a) Clear influence of geological age and humidity of the studied sedimentary rocks on the UCS:
b) the geologically older rocks, the higher the UCS in the air-dry state,
c) UCS reduction as a result of capillary saturation of rocks is varied, which is indicated by the calculated values of structural weakening coefficients, which are in the following ranges: 0.2—0.4 for sandstone, 0.02—0.22 for mudstone and 0.5 for claystone.
d) Small variation of cohesion values in the air-dried state for Carboniferous sedimentary rocks of the USCB due to the geological age and rock moisture:
e) the calculated values of structural weakening coefficients as a result of capillary saturation of rocks range from 0.25 to 0.57,

Table 7 Regression analysis results $M = f(\rho)$ for rock material with various storage periods in the dump

Period of waste storage	Relation	Coefficient of determination R^2	Standard estimation error
< 0.5 year	$M = 0.084 \cdot \rho — 128.\ 56$	0.772	2.631
5 years	$M = 0.086 \cdot \rho — 129.440$	0.904	1.694
15 years (after coal recovery)	$M = 0.054 \cdot \rho — 77.608$	0.875	1.499
15 years	$M = 0.063 \cdot \rho — 84.002$	0.946	1.059
> 35 years	$M = 0.050 \cdot \rho — 66.257$	0.933	1.083

f) the geologically older rocks, the smaller the difference between the cohesion determined in the air-dried state and the state of capillary saturation.
g) There is no clear influence of geological age and humidity on the angle of internal friction of each of the three types of rocks, which varies from 41° to 50° and generally remained constant or slightly changed after the rocks saturation with water.
h) In all prepared samples, which are a mixture of rocks from coal mining and coal processing, before compression in the testing machine the gravel fraction dominated. The largest amount of sand fraction was found in the oldest waste, and the share of dust and clay fraction did not exceed a few percent. In the samples after compression in the testing machine, the gravel and sand fractions had the largest percentage share.
i) The course of the stress–strain curves of the samples taken from the post-mining waste dump shows that:
j) the oldest, very weathered sediments classified as multi-grained may differ in bulk density from younger wastes (very multi-grained), due to the proportions of individual rock types, including the presence of coal,
k) the increase of the deformation value also depends on the waste storage time. However, the time factor does not have a dominant influence on the values of mechanical parameters, which are determined primarily by the geological age of the rocks, their origin and structure,
l) the storage time of post-mining waste affects the difference between the values of bulk density and density determined for the maximum load used in the experiments—from 13% for fresh waste to 20% for waste stored over 35 years.
m) The course of the compressibility curves shows stabilization Δh of about 1 mm in the range of the designed stress values, regardless of the waste storage time. This indicates that the rock debris loaded with a vertical force (without the possibility of transverse deformation) has reached the maximum compaction for the given pressures. For waste stored for about 15 years and more, the compressibility modulus obtained for stresses of approximately over 1.1 MPa stabilizes at a constant level, which also indicates a significant advancement of the sample consolidation process.
n) The rectilinear function with correlation coefficients indicating a very strong correlation between the variables ($r > 0.9$) described the relationships $M = f(\sigma_1)$ and $M = f(\rho)$. Exceptions were the relationships $M = f(\rho)$ and $M = f\ (\sigma_1)$ for fresh waste, which were characterized by a strong correlation between variables. The relationship $\Delta h = f(\sigma_1)$ was described by a power function with correlation above 0.9.
o) The authors believe that the designed and performed scope of research and the adopted methodology are sufficient to implement the results in the design of technological processes of storage, formation and subsequent management of heaps, using the rock material as described in the article.
p) The entrepreneur's experience shows that in an area that has already been reclaimed and directed for development (large-area halls, warehouses), mechanical compaction of anthropogenic soil to a compaction index > 0.95 is a safe geotechnical criteria. Despite the rising water table, compacted mechanical areas reach the state of maximum reconsolidation.
q) The laboratory test results obtained for the Carboniferous waste rock and waste deposited in the dump may constitute a valuable and irreplaceable set of input data for numerical models of geotechnical and hydrogeological conditions. These models may enable the long-term prediction of the influence of open pit closure and reclamation on environmental and general safety, as well as aid the planning of protecting the open pit area from negative consequences constituting the repercussions of the adopted mine reclamation direction.

Author contributions Conceptualization: (Mirosława Bukowska, Przemysław Bukowski); Methodology: (Mirosława Bukowska, Przemysław Bukowski, Anna Smolorz, Katarzyna Niedbalska); Investigation: (Mirosława Bukowska, Anna Smolorz, Katarzyna Niedbalska); Results interpretation (Mirosława Bukowska, Katarzyna Niedbalska, Przemysław Bukowski); Graphics: (Mirosława Bukowska, Katarzyna Niedbalska); Writing—original draft (Mirosława Bukowska); Writing—review and editing: (Mirosława Bukowska, Katarzyna Niedbalska, Przemysław Bukowski); Supervision: (Mirosława Bukowska, Katarzyna Niedbalska). All authors read and approved the final manuscript.

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Data availability All available data generated during this study are presented in this article. The remaining data are in the archives of the Central Mining Institute in the form of a digital record of the course of rock sample destruction in the stress–strain conditions.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Funding sources had no involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

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