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Hydrogeological and physico-mechanical responses of physically heterogeneous waste rock to storage time and vertical pressure

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The variability of the selected properties of mining waste under the influence of its long-term storage and increasing vertical pressure is assessed, through tests conducted on five samples of waste rock used in the reclamation of an open-pit mine. It was found that the considerable variability in the mining waste grain size, exhibiting extreme strength and slakeability parameter values, influences the filtration properties of the rock material. Increasing vertical pressure exerted under laboratory conditions resulted in significant grain degradation, material consolidation and permeability reduction. Exponential functions are the most accurate way of characterising the correlations between the rock sample volume density and the filtration coefficient. The test results demonstrated that the oldest waste was characterised by the lowest permeability and highest compressibility. The material with half a year storage time exhibited the highest filtration properties. Waste stored for 15 years and subjected to coal recovery was also characterised by high permeability. The mining waste filtration coefficients obtained for each vertical pressure value were referenced to values characteristic for soil and rock at a water temperature of 10°C (the average annual temperature of shallow groundwater in the area of waste sampling for laboratory testing).

Key words: reclamation, mining waste, rock properties, compressibility, volume density, porosity, permeability.

INTRODUCTION

The global extraction of mineral raw materials as well as fossil fuels and metal ores generates enormous quantities of waste, which is commonly stored on the surface in the form of waste dumps, resulting in permanent alterations to the landscape and to changing forms of land use. For many years, researchers worldwide have been investigating critical and innovative technologies for mining waste management, while implementing the results of their work (BRGM, 2001; Lebre et al., 2017). The recovery of mining waste and tailings with their subsequent use in mining, building engineering and geoengineering is considered good practice around the world. The social, economic and practical success of an investment depends on the ability to select the type and properties of the waste appropriate for the purpose of a project as well as for local conditions and needs. The ultimate purpose of an infrastructural element built in whole or in part using waste from the mining sector poses a number of requirements in terms of the physico-mechanical, hydrogeological, geotechnical and chemical properties of the waste (Adamczyk, 2012; Vo et al., 2021; Segiu et al., 2023).

In railway and highway engineering, such waste finds application as subcrust, aggregate for road paving and for constructing fills and embankments. In hydrotechnical engineering, waste finds common application e.g. in the construction of levees, dams and the modification of river beds, whereas in mining areas it can be used for the reclamation of open-pit mines and for levelling deformed post-mining surfaces (Bian et al., 2012; Galis and Szlugaj, 2014; Shengo, 2021). These products must fulfil the appropriate technical criteria for their quality parameters. To guarantee the stability and durability of the buildings being erected, the aggregate prepared using mining waste must be characterised by the appropriate soil bearing capacity, strength parameters, cohesion, compressibility (Agarwal, 2009; Lamani et al., 2016), gradation, volume and actual density, resistance to abrasion (Alinabiwe et al., 2021), maximum resistance to frost impact, porosity (Skarżyńska, 1995), as well as the humidity, water retention and permeability of the waste (Newman et al., 1997; Ferdos et al., 2015).

Almost all these physico-mechanical and hydrogeological parameters show variability in terms of their values relative to the time-varying processes of weathering, water accumulation, disintegration, and compaction as these affect the rock material. The variable properties of the mining waste result from its nature and origin, as well as the scope and manner of its use.

The testing of selected physico-mechanical and hydrogeological properties of mining waste has been much studied in recent years, both *in situ* at the waste dumps using radar,

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geoelectrical (Villain et al., 2011, 2015) and radioactive methods (Diodato and Parizek, 1994) and under laboratory conditions. This made it possible to better understand the behaviour of various types of the rock materials involved under different conditions and states of stress and humidity. The laboratory tests conducted by Alonso et al. (2016) confirmed the influence of water on the degradation of the mining waste rock structure and demonstrated a strong relationship between the propagation of rock grain fractures and the water energy expressed in relative humidity and suction pressure. These tests revealed the collapse of the granular skeleton of rock under conditions of constantly rising stress and relative humidity. In the case of mining waste structurally similar to granular soils, a loss of permeability can also be observed together with rising suction pressure (Azam et al., 2020). Increasing the mining waste humidity results in a decrease in suction pressure, and consequently in a reduction in strength parameters (Zawadzki and Bursa, 2018). The assessment of these parameters, specifically the rock material permeability and humidity, is particularly important in the design of levees, including when using mining waste.

In a triaxial state of stress, mining waste generally exhibits a strain hardening characteristic with the simultaneous loss of volume under the influence of loading (Xiao et al., 2014; Huang et al., 2019). These phenomena are observed in all types of sites formed from mining waste. They particularly concern areas of subsurface waste deposition, e.g., within the boundaries of open-pit mines totally reclaimed by backfilling using waste rock, or subsidence troughs levelled using waste. In such areas, the resistance of the external slopes limits the lateral displacement of the material (e.g., creeping, flowing, sliding) or even makes it impossible. In such conditions, the vertical stress $_1$ ($_1$>0 and $_1$> $_2$, $_3$) leads to terrain subsidence as a result of material compaction, increasing the density of the waste and decreasing its porosity and permeability. The processes taking place within the mass of the waste deposited in an open-pit excavation are similar to those observed in backfilled shallow mine workings. Guo et al. (2022) indicated that together with the increase in axial stress, mining waste used as backfilling material shows a logarithmic increase in axial strain. At low stress (<5 MPa), the greater coarse grain (>20 mm) content contributes to a greater soil bearing capacity of the waste. On the other hand, Wickland et al. (2010) indicated that the presence of fine-grain flotation tailing additions in the structure of mining waste formed from homogeneous rock is a factor beneficial to the improvement of the mining waste soil bearing capacity, as it results in the simultaneous reduction of filtration coefficients by over one order of magnitude.

The high pressure exerted on the mining waste dumps by the mass of the deposited materials results in considerable disintegration of the rock particles, modifying the initial grain and pore distribution of their rock structure and influencing their permeability (Valenzuela et al., 2008). The experiments conducted by Tovele et al. (2021) on samples of mining waste with various proportions of stone, sand and dust indicate significant differences in the filtration coefficients and porosity for various vertical pressure values (ranging from 100 to 1600 kPa). The adopted consolidation pressure values, at a level of 100 kPa, roughly correspond to an overburden with a thickness of 5 to 10 m (Klojzy-Kaczmarczyk et al., 2016). The authors of these studies observed that, generally, the greater the coarse grain content in the waste mixture, the higher the porosity and permeability obtained during laboratory testing. However, the process also depends on the mineral content of the mining waste mixture. Chen et al. (2019) confirmed in their studies that the presence of a high quantity of detrital quartz with high maturity and strong compaction resistance in the rock samples results in an increased significance of the rock material grain size distribution in the forming of the waste pore space, which influences the actual porosity and permeability.

In terms of the hydrogeological and geotechnical parameters, variability can be observed with regard to the age of the waste. Depending on the mineral and petrographic composition of the waste, the manner of its storage, its purpose, method of processing for specific uses etc., these changes can occur with different intensity and rate of propagation over time. In the case of Carboniferous waste rock from a mine in the Lower Silesian Coal Basin in Poland (Filipowicz and Borys, 2004), storing the waste in dumps for seven years results in a significant reduction of the gravel content with respect to the sand and dust content, an increase in optimal moisture from 13% to 19%, a decrease in dry density by nearly 10% and a reduction of this rock medium's permeability by over two orders of magnitude. The reduction in the filtration parameters of waste stored for seven years follows primarily from the changes in grain size. Long-term mining waste weathering leads to rock particle disintegration and displacement, resulting in a change in the hydrogeological conditions within the waste dump. Due to its small pore sizes, fine-grained waste (matrix-supported structure) is strongly responsible for the general humidity of a waste dump. Coarse-grained waste usually constitutes a drainage layer (Herasymuik et al., 1995, 2006).

Considering the current state of knowledge regarding the hydrogeological properties of mining waste used in land and environmental engineering as well as their variability under different states of stress and humidity, this paper attempts to complement the gaps in the assessment of the influence exerted by interdependent water interactions, the age of the mining waste and increasing vertical pressures on the waste grain structure and intergranular space. Tests of hydrogeological and selected physico-mechanical properties were made on mining waste used in the reclamation of an open-pit. The analysis encompassed material characterised by various storage times (from half a year to over 35 years). The tests involved the assessment of parameters such as the rock material grain size distribution, porosity, filtration coefficient, volume density and compressibility. The responses of these selected parameters to variable consolidation pressures were determined and their mutual correlations identified. The assessment also included the influence of water on the rock material compaction, and changes in selected hydrogeological and physico-mechanical parameters as a result of mining waste relocation within the spoil bank/waste dump together with coal recovery from the rock debris. The aim of the proposed and verified laboratory test series was to provide information on the potential ranges of variability for the selected parameters of mining waste characterised by different storage times, and subjected to various states of vertical stress and water accumulation. The information obtained on the effects of the natural and/or technical rock material reconsolidation for various states of humidity can be applied to predict the behaviour of structures formed from mining waste, as well as to assess the environmental impact of waste use and storage.

TEST METHODOLOGY

The laboratory tests were conducted on samples of mining waste originating from hard coal extraction and used as backfilling material in the reclamation of an open-pit mine. Five samples of mining waste were collected, with a mass of about 120–150 kg each, characterised by various storage times in the excavation, i.e. from half a year to over 35 years. The laboratory

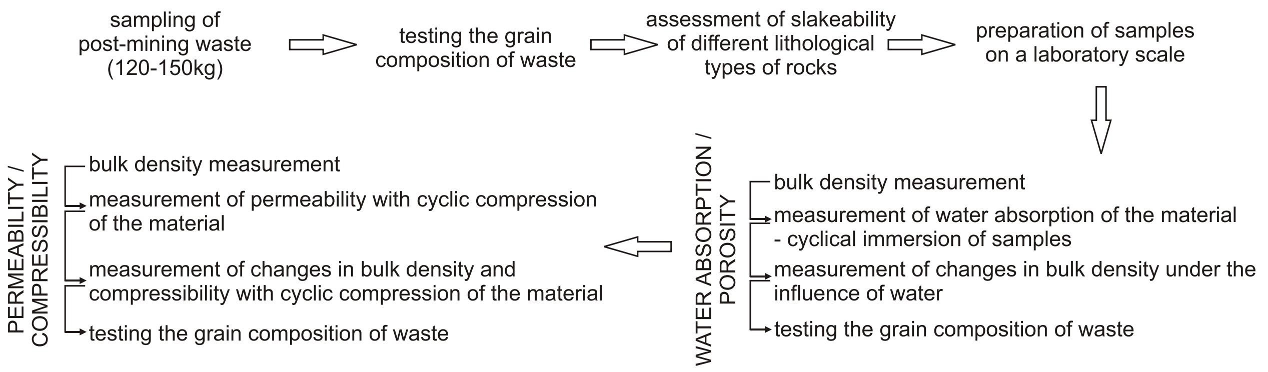


Fig. 1. Laboratory test methodology for selected hydrogeological and physico-mechanical parameters of mining waste

tests were aimed at assessing the waste gradation, slakeability, porosity and permeability, as well as density and compressibility under various states of vertical stress. The tests were performed according to the test methodology shown in Figure 1. The entire research methodology, from sampling, through laboratory tests to the development of results and conclusions, was carried out by the author of this article.

MINING WASTE GRAIN COMPOSITION TESTING

The grain size analysis was performed in three stages for each waste sample:

- the first stage involved a grain size assessment of waste sampled directly from the top layer of the spoil bank, i.e. from the aeration zone,
- the second stage provided information exclusively on the influence of groundwater on the degree of grain degradation. The test was performed on model samples after water absorption determination,
- the third stage encompassed grain size analyses of waste samples of different ages, after prior assessment of the filtration properties of materials subjected to cyclic compression.

The results obtained served as the basis for assessing the range of grain size of the mining waste and of its variations under the influence of water and vertical pressure.

MINING WASTE SLAKEABILITY ASSESSMENT

The slakeability test results were used to assess the influence of water on the integrity of the rock forming the material used in the open-pit reclamation. The tests were conducted using two methods: Skutta's (Skutta, 1962) and GIG's (Central Mining Institute) according to Kidybiński (1982) for sandstones and mudstones collected from each waste sample. The test samples were collected at random, as in the methodological recommendations of the methods applied.

Skutta's method consists in soaking the sample once in water then observing and noting the variation of its state after $^{1}/_{2}$h, 4h and 48h. The forms of rock disintegration are evaluated according to a scale ranging from *A* to *H*, where: *A* means no changes within the sample, and *H* means total disintegration into grit and/or mud.

The GIG three-day test consists in determining the degree of degradation for rock samples subjected to a cycle of submerging (24h), draining (24h) and repeated submerging (24h) in water. The impact of the water on the sample condition is assessed according to a scale of 0.1 to 1.0, where 1.0 means no changes to the sample's form and consistency, and 0.1 means the disintegration of the sample into sludge.

WATER ABSORPTION DETERMINATION

The test was performed using a method developed at the Central Mining Institute (GIG), entailing the cyclic flooding and draining of rock debris samples (Bukowski, 2004, 2010). For the purposes of determining the mining waste water absorption, the test setup was modified relative to its original shape, into the form of a vessel with a double bottom, where the upper one was perforated and the lower one had a valve for filling and draining the vessel of water (Fig. 2).

Laboratory samples with a mass of ~12 kg were prepared, with each having the same grain size distribution as in the original sample. The determination was conducted in five cycles of sample flooding and draining (saturating the samples with water from below in order to deaerate the material). Each sample was flooded for a total of 37 days. The time during which the flooded samples remained in the test stands varied from 2 to 12 days depending on the stage of testing. The water absorption tests were concluded after the stabilisation of the water volume used to saturate the samples in the final stages of the determination, and after the stabilisation of the water volume following the sample draining. Balancing the water volume used for the total flooding of the waste, and factoring in the volume and mass of the sample before and after testing, yielded information necessary to assess the volume of free spaces in the rock material. Following the conclusion of all the cycles, the material was dried at room temperature and the grain size distribution was determined.

MINING WASTE PERMEABILITY AND COMPRESSIBILITY TESTING

These tests were conducted using a device constructed at the Central Mining Institute (Bromek and Bukowski, 2002; Prusek et al., 2014). It is a test stand operating on the principle of an oedometer-type apparatus, where the analysis is based on Kamieński's tube method (gradient-varying method of filtration coefficient determination). For the purposes of mining waste parameter testing in this study, the test methodology was modified relative to its original design (the flooding of samples from below was introduced).

The test entailed cyclic compression in a testing press of mining waste samples (12 kg each) placed in a cylindrical vessel with a perforated bottom that prevented the lateral expansion of the rock material. Following each compression stage,

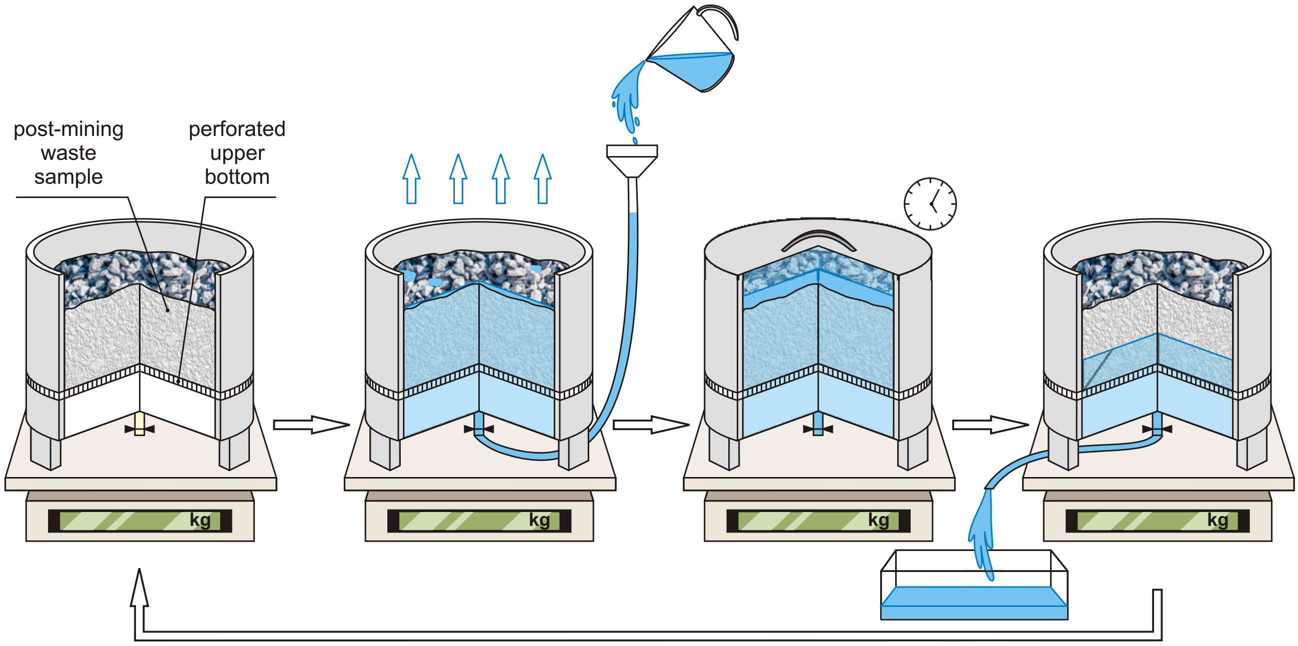


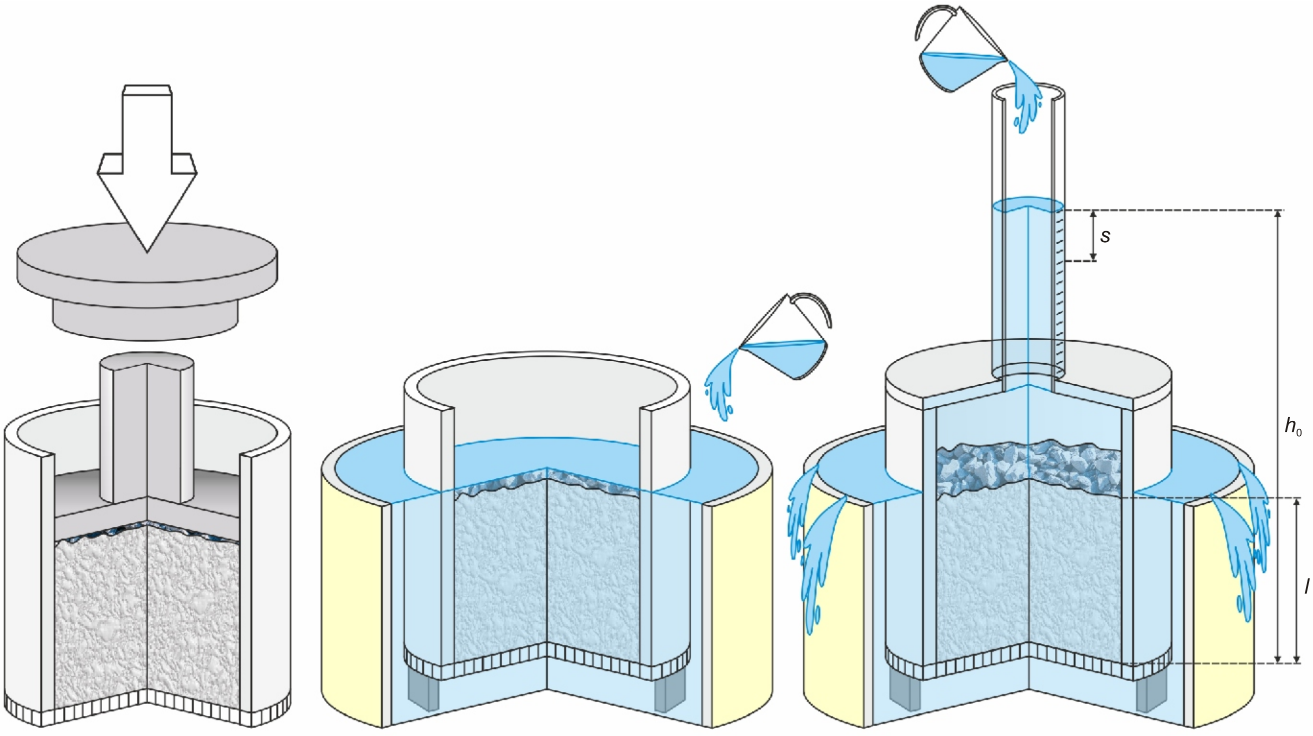
Fig. 2. Course diagram of mining waste water absorption determination

the volume density of the samples was determined, after which the filtration coefficients were measured (test course according to the diagram shown in Fig. 3).

The loads exerted on each sample were selected so as to reflect the pressure within the spoil bank structure at various depths. 7 measurement cycles were performed for each sample (with 5 measurement cycles for the oldest sample) at vertical pressures ranging from 0.0 MPa to 1.0 MPa. The filtration coefficients were calculated according to the following formula (Rogoż, 1987):

$$k \quad \frac{a}{A}\;\frac{l}{t} \quad \ln 1 \quad \frac{s}{h_0} \tag{1}$$

where: a – internal area of the scaled tube cross-section [m^2], A – area of the sample cross-section [m^2], l – filtration path length (sample height) [m], t – time of water table decrease by a value of s [s], s – value of water table decrease over a time t [m], h_0 – primary pressure [m].



s – interval of lowering the water table [cm] h_0 – original water pressure [cm] l – filtration path length (sample height) [cm]

Fig. 3. Course diagram of mining waste permeability and compressibility testing

The test was conducted using water at a temperature of 20 ± 3°C. The actual average annual temperature of the water flowing through the waste spoil bank is lower. Therefore, the filtration coefficients obtained were recalculated to a value characteristic of a temperature of 10°C, using the following formula (Turek, 1971):

$$k_{10} \quad \frac{k_t}{0.7 \quad 0.03t} \qquad [2]$$

where: k_t – filtration coefficient obtained during testing at a water temperature t [m/s].

TEST RESULTS, ANALYSIS AND DISCUSSION

MINING WASTE GRADATION

The laboratory analyses of grain size distribution were conducted on waste samples in a state of natural humidity. The mining waste collected for the laboratory testing was characterised by considerable variation in grain size distribution. Variations could be observed both with reference to the time of exposure to external factors (stage I) as well as the influence of water (stage II) and vertical pressure (stage III; Fig. 4).

In all the samples, the gravel fraction made the greatest contribution by mass, with an average content ranging from 57% in the case of waste stored for 15 years to 68% for waste stored for 15 years after coal recovery – stage I. The stone fraction was typically represented by single large chunks of rock, whose contribution by mass ranged from 12% (longest storage time) to 30% (shortest storage time). The contribution of coarse particles decreased with the simultaneous increase in finer fractions together with the rising age of the waste, as a consequence of material degradation resulting primarily from weathering processes. The highest sand fraction content was found in the oldest waste (20%), and its contribution was over twice as great as in fresh waste.

Grain size is one of the basic classification criteria for clastic deposits, including subsoils and anthropogenic soils. The results for mining waste showing a lithological character different from the original allow conclusions to be drawn about the manner of material heaping and consolidation, as well as about the degree of re-sedimentation and degradation of the waste. The granulometric diversity can be assessed e.g. on the basis of the uniformity coefficient C_U and the coefficient of grain size distribution curvature C_C:

$$C_U \quad \frac{d_{60}}{d_{10}} \qquad [3]$$

$$C_C \quad \frac{d_{30}^{\ 2}}{d_{10} \quad d_{60}} \qquad [4]$$

where: d_{10}, d_{30}, d_{60} – diameters of grains that, together with smaller ones, constitute 10%, 30% and 60% respectively of the soil sample mass tested [in mm].

In international literature and practice, it is typically assumed that C_U values greater than 4 classify soils as non-uniform for gravel, whereas values greater than 6 indicate soils non-uniform for sand (Keaton, 2018). If C_C also ranges from 1 to 3, then such cohesionless soils are easily consolidated, and thereby useful for embankment construction due to their good grading characteristics.

As revealed by the sieve analysis results, the mining waste constitutes non-uniform, poorly sorted (multimodal) soil with a constant granulometric pattern (Table 1). In geotechnical practice, separate categories of multi-fraction (C_U 15) and very multi-fraction (C_U 15) materials are defined for such soils (Wiłun, 1987).

Overall, the waste samples collected for testing were characterised by a general growing tendency of the uniformity coefficient together with the age of the waste (stage I). The oldest waste showed the highest gradation uniformity coefficient values (C_U = 26), and the fresh wastes the lowest gradation uniformity coefficient (C_U = 15.6). According to the classification, these are very poorly sorted anthropogenic soils, i.e. they are characterised by good propensity for consolidation during the formation of the spoil bank structure. This is also corroborated by the C_C coefficient values in the recommended range of 1 to 3.

During laboratory testing, the rock material degradation process as a result of water (stage II) and vertical pressure (stage III) influence showed a clear trend for each of the mining waste samples analysed. Regardless of the age of the waste and the type of rock forming the material, the stone fraction (angular fragments of the original solid rock mass with dimension 70 mm < d < 200 mm) decreased with a corresponding increasein the gravel and sand fractions (Fig. 4). In the overall balance, the increase in the mudstone fraction content was particularly clear, as its contribution after laboratory testing increased by a factor ranging from 3.5 to nearly 9 relative to the state before testing. A considerably lower fraction increase (by a maximum factor of 3) was noted for the sand fraction. The disintegration of large

Table 1

Uniformity coefficients C_U and coefficients of grain size distribution curvature C_C for mining waste of various ages, sampled from the spoil bank (stage I), after water absorption testing (stage II) as well as after compressibility and filtration coefficient testing (stage III)

Waste sample	Stage I			Stage II			Stage III		
	C_U	C_C	type**	C_U	C_C	type**	C_U	C_C	type**
>35 years	26.0	2.0	very poorly sorted	17.4	3.8	very poorly sorted	24.7	3.5	very poorly sorted
15 years*	18.7	1.6	very poorly sorted	11.5	0.9	poorly sorted	20.0	1.3	very poorly sorted
15 years	20.0	1.7	very poorly sorted	51.0	4.4	very poorly sorted	35.0	2.7	very poorly sorted
5 years	16.4	2.2	very poorly sorted	10.4	2.6	poorly sorted	16.6	2.5	very poorly sorted
<1/2year	15.6	2.4	very poorly sorted	8.4	0.7	poorly sorted	10.2	1.2	poorly sorted

* – sample after coal recovery; ** – according to the classification of Wiłun (1987)

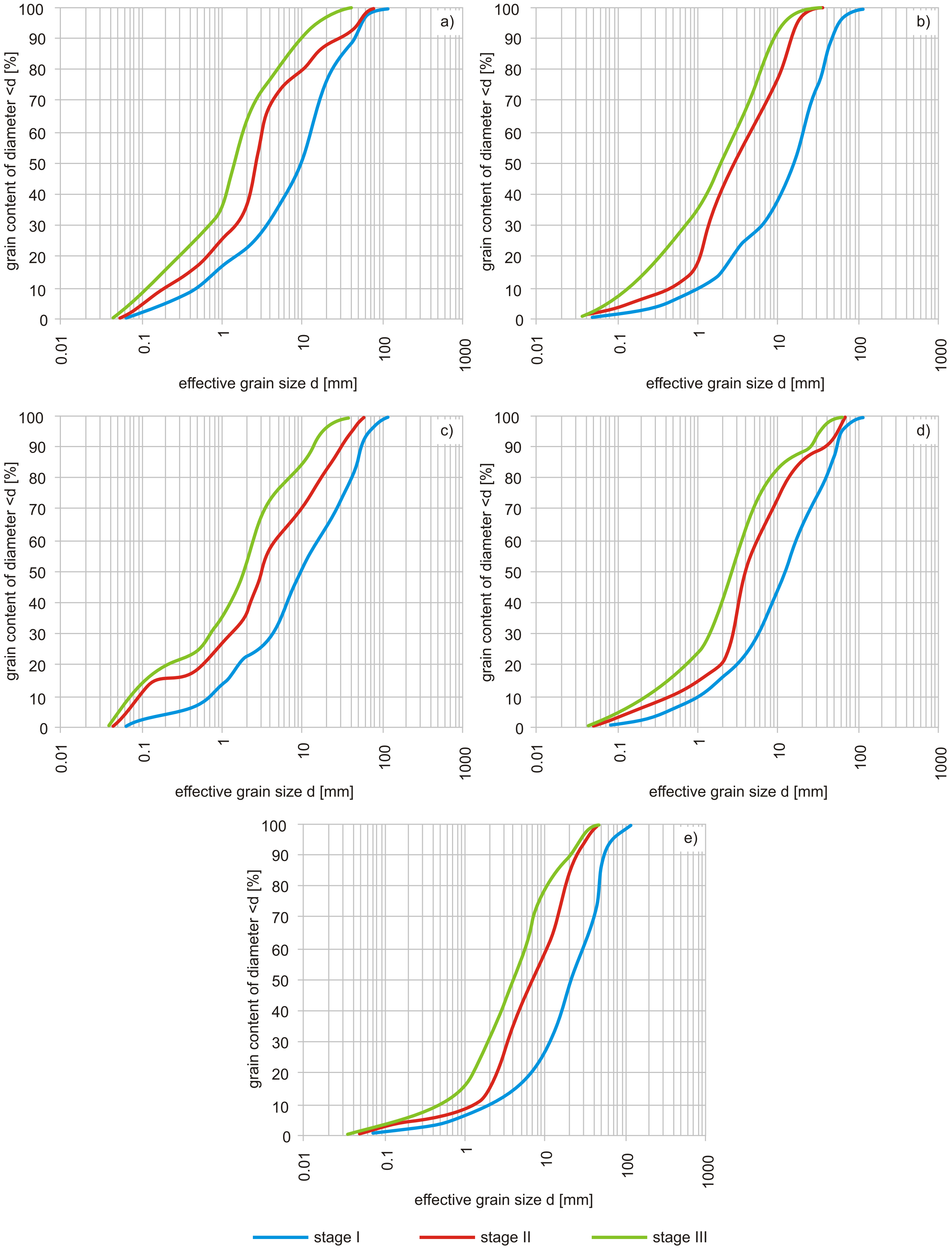


Fig. 4. Mining waste granulometric curve charts: (A) storage time over 35 years, (B) storage time of 15 years, after coal recovery, (C) storage time of 15 years, (D) storage time of 5 years, (E) storage time under half a year, sampled from the spoil bank (stage I), after water absorption testing (stage II) as well as after compressibility and filtration coefficient testing (stage III)

Table 2

Slakeability determination results by Skutta's method (Skutta, 1962) and the GIG three-day test (Kidybiński, 1982)

Sample		Skutta's method				Kidybiński's method
		$^1/_2$ h	4 h	48 h	total	
> 35 years	sandstone	A	A	A	AAA	1.0
	mudstone	A	A	A	AAA	0.6
15 years*	sandstone	A	A	A	AAA	1.0
	mudstone	A	A	A	AAA	1.0
15 years	sandstone	A	A	A	AAA	1.0
	mudstone	A	A	A	AAA	0.8
5 years	sandstone	A	A	B	AAB	1.0
	mudstone	A	A	A	AAA	1.0
< half year	mudstone	B	D	F	BDF	0.6

* – after coal recovery

stone chunks led to changes in the uniformity coefficient values for the soils. Following water absorption testing, the C_U coefficient generally showed a decrease in the samples, except for waste stored for 15 years. In that case, a significant increase of this coefficient was a result of the 8-fold decrease in the effective grain size d_{10} after stage II of testing, which indicated a considerable increase in the smallest fraction, disproportional to the changes of the remaining size fractions in the sample. After this stage of testing was concluded, the samples of waste stored for 35 and 15 years were very non-uniform, while the remaining samples constituted poorly sorted waste.

Following the compressibility and filtration coefficient testing (stage III), another increase in the C_U coefficient was observed relative to stage II in samples stored for 35 years, 15 years after coal recovery, 5 years, and half a year. The sample of waste stored for 15 years exhibited a decrease in C_U relative to stage II and an increase relative to stage I. After this stage of testing was concluded, the sample with the lowest storage time constituted a poorly sorted soil, whereas the remaining waste samples were very non-uniform. Such a pattern of C_U coefficient changes indicates a very regular variation in the individual size fraction proportions in the samples under the influence of vertical pressure. On the other hand, the influence of water by itself results in more variable degradation of the clastic material.

MINING WASTE SLAKEABILITY

The slakeability determination results for the selected types of rock sampled from the mining waste, as obtained using Skutta's and Kidybiński's methods, are compiled in Table 2.

Among all the rock samples collected from the mining waste, the mudstones sampled from the material with the shortest storage time were characterised by the greatest susceptibility to the influence of water. The prolonged reclamation of the site, from which the samples were collected, conducted using materials from numerous suppliers, made it impossible to determine the lithostratigraphic origin of the waste sampled for laboratory testing. The sample with the shortest storage time was the exception, as the entrepreneur's records confirmed its origin. Waste rock from hard coal mines extracting coal from the Łaziska and Orzesze units was deposited in the location of its sampling. According to published values, waste rock from this region is typically characterised by low strength parameters (Bukowska, 2009). This was corroborated by the slakeability testing, where the mudstone samples from the waste with the shortest storage time underwent significant fracturing (Kidybiński's method) and fragmentation (Skutta's method) (Fig. 5).

In the remaining cases, the sandstone and mudstone samples generally showed no significant changes to their forms during the tests using Skutta's method. On the other hand, during

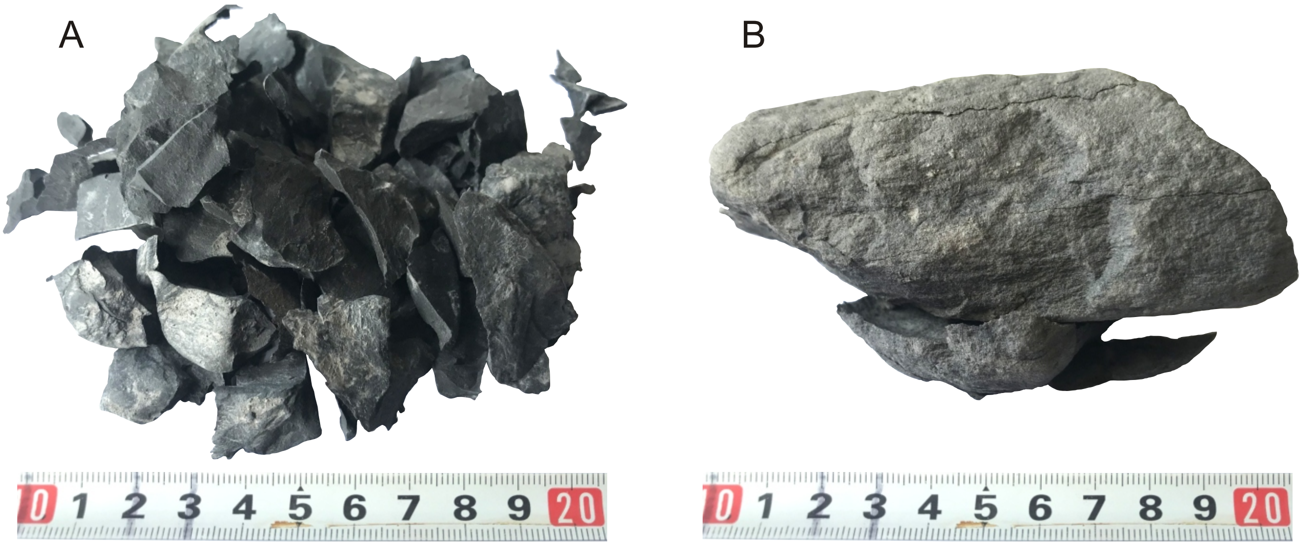


Fig. 5. Disintegration of mudstone samples collected from waste with the lowest storage time as part of slakeability testing using (A) Skutta's method, (B) Kidybiński's method

the GIG's three-day tests, only the mudstones sampled from waste older than 35 years fractured along the bedding planes (similar to the waste with the shortest storage time).

WASTE WATER ABSORPTION

The cyclic water absorption testing results for mining waste of various ages are compiled in Table 3, presenting data concerning the variation of water masses absorbed by each sample over time. Water absorption (*W*) can be expressed as a percentage relationship between the mass of water absorbed by each sample in all five stages of the test and the mass of the sample before laboratory testing, from the following formula:

$$W\ \frac{M_W}{M_S}100\% \qquad [5]$$

where: M_W – absorbed water mass [kg], M_S – sample mass in an air-dry state [kg].

The water absorption calculated from the above formula can be equated to the effective porosity of rock and soil.

Based on the test results, it was concluded that the waste sample water absorption varied depending on the stage of testing (it decreased over time; Fig. 6). As a result of the water's influence (including the fragmentation and displacement of various grain size fractions), the pore space in the waste decreased, leading to a reduction in the void volumes available for water saturation. Fresh waste and waste stored for 5 years (from ~16–16.5% in the first stage of testing to ~12–13% after its conclusion) were characterised by the lowest water absorption ranges (similar to each other). Mining waste with a storage time of 15 years showed a decrease in water absorption ranging from nearly 25.5 to 20% during the tests. After the recovery of coal from this type of waste, its water absorption decreased from over 19% to nearly 16%. In the case of the oldest waste, the reduction in pore space ranged from nearly 18% to ~15%.

Based on these tests and calculations, it was observed that the quantity of water absorbed by each waste sample was the greatest during the first stage of material saturation. Over time, the process became much less rapid. The greatest change in water absorption (decrease) between stage I and II was found for samples stored for 15 and 5 years (by ~15.7% each), whereas in the remaining waste samples the variations ranged from 9.2 to 9.6%. In the entire test cycle, the mining waste sample water absorption decreased by ~17–25% relative to the first stage of water saturation, with the lowest variation for the oldest sample, and the greatest for the waste stored for 5 years. These phenomena are a consequence of the observed compaction of the material, as well as the decrease in its volume and increase in volume density under the influence of water (Table 3 and Fig. 7A).

A logarithmic growth of the volume density of all the samples occurred during the laboratory tests, depending on the total observation time and showing a very strong correlation between the variables (R^2 ranging from 0.982 to 0.996). The greatest change in volume density over the entire water absorption testing cycle was found for samples of waste stored for 5 years (~25%), whereas the lowest change was observed for the oldest waste samples (~13%). Furthermore, an analysis of the laboratory test data revealed a correlation between the waste volume density variation and the water absorption variation, which also showed very good fit (R^2 from 0.936 to 0.997; Fig. 7B).

Table 3

Mining waste water absorption determination results

Sample	Stage / days / total days	Sample mass [kg]	Absorbed water mass [kg]	Water absorption / porosity [%]	Volume density [g/cm^3]
>35 years	I / 2 / 2	11.758	2.094	17.809	1.211
	II / 6 / 8		1.902	16.176	1.273
	III / 12 / 20		1.850	15.734	1.316
	IV / 9 / 29		1.785	15.181	1.344
	V / 8 / 37		1.741	14.807	1.365
15 years*	I / 2 / 2	11.446	2.214	19.343	1.474
	II / 6 / 8		2.010	17.561	1.584
	III / 12 / 20		1.924	16.809	1.647
	IV / 9 / 29		1.860	16.250	1.688
	V / 8 / 37		1.806	15.778	1.713
15 years	I / 2 / 2	11.406	2.894	25.373	1.214
	II / 6 / 8		2.440	21.392	1.328
	III / 12 / 20		2.396	21.006	1.377
	IV / 9 / 29		2.322	20.358	1.412
	V / 8 / 37		2.286	20.042	1.443
5 years	I / 2 / 2	11.564	1.860	16.084	1.236
	II / 6 / 8		1.568	13.559	1.362
	III / 12 / 20		1.480	12.798	1.443
	IV / 9 / 29		1.448	12.522	1.487
	V / 8 / 37		1.396	12.072	1.545
<$^1/_2$ year	I / 2 / 2	11.382	1.864	16.377	1.413
	II / 6 / 8		1.684	14.795	1.557
	III / 12 / 20		1.570	13.794	1.626
	IV / 9 / 29		1.488	13.073	1.694
	V / 8 / 37		1.466	12.880	1.721

* – after coal recovery

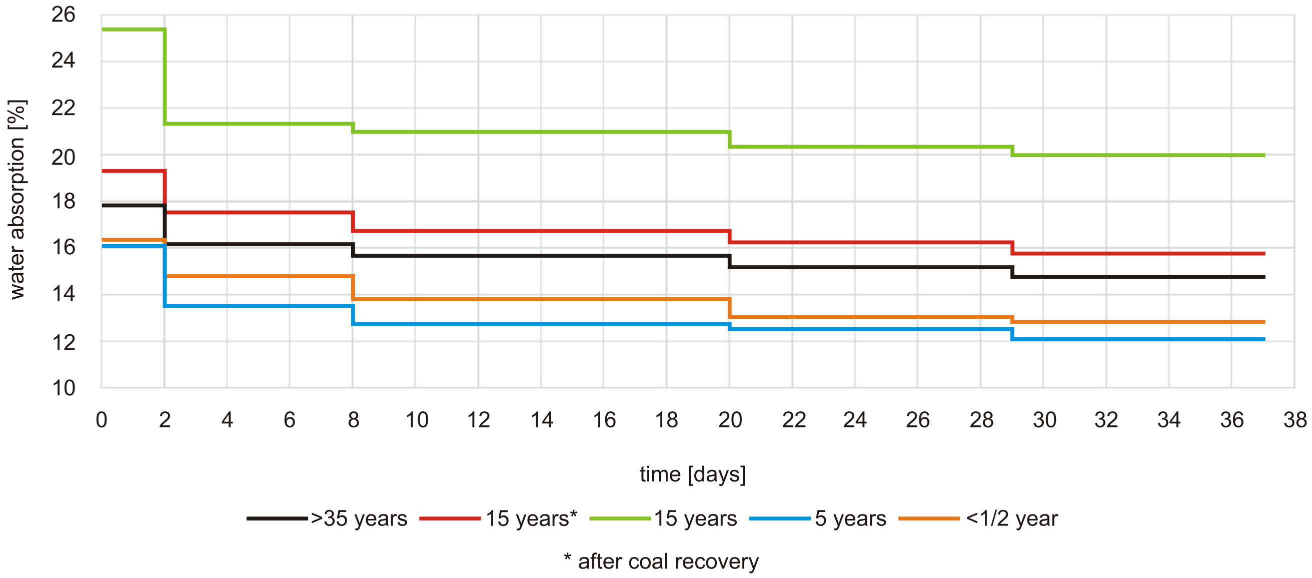


Fig. 6. Water absorption variation chart for mining waste of various ages

The rock material density and water absorption variability was the result of degradation of the waste grain structure, which contributed to the partial disintegration of the waste and the filling of its larger intergranular pores with finer material (Fig. 4, stage II). Therefore, the porosity of the rock material forming the waste decreased, though primarily at the expense of the biggest voids, which in turn led to a decrease in the sample permeability. Such a trend in the processes occurring in the rock material was also indicated by the progressively decreasing water volumes obtained during the tests, both in terms of those drained from, and those additionally absorbed by, the waste.

WASTE PERMEABILITY AND COMPRESSIBILITY

For each waste sample, filtration coefficient testing was performed several times after each compression cycle, i.e. for different intervals of water table decrease in the scaled tube [parameter *s* in formula (1)], as well as in a number of repeating test cycles. The selection of intervals and the number of cycles depended on the waste permeability and changed together with the value of the adopted vertical pressure. Average test results are compiled in Table 4.

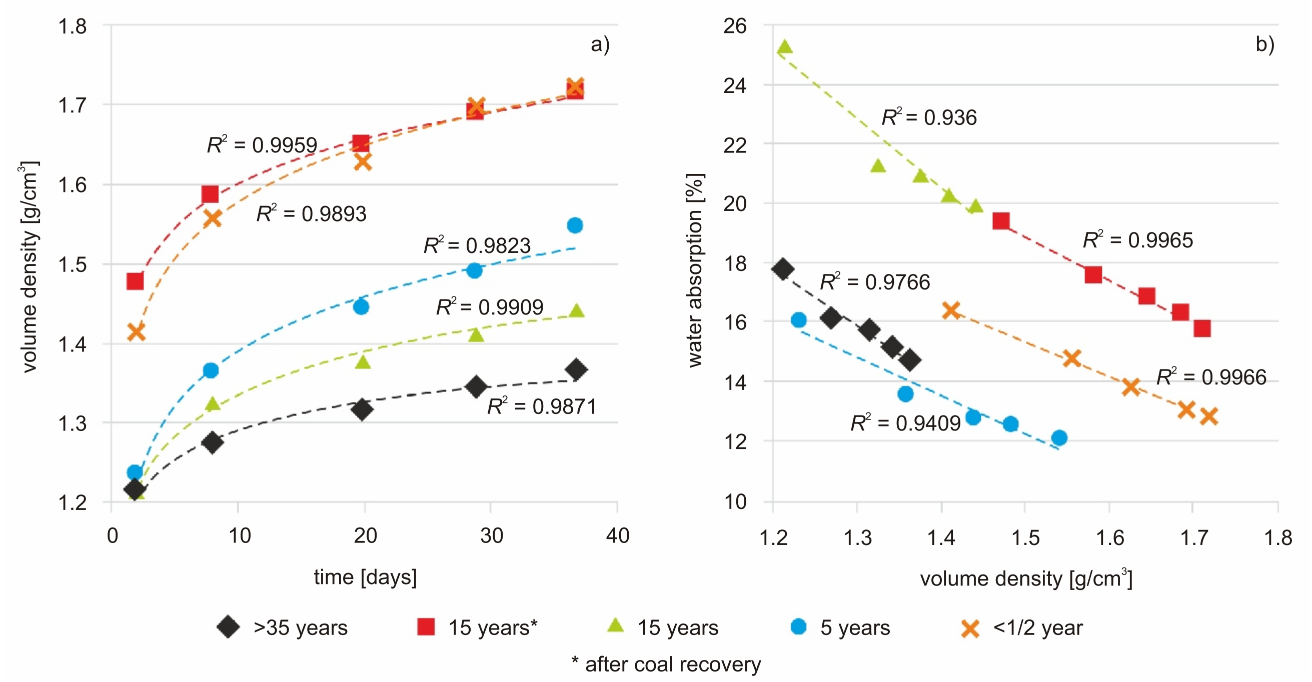


Fig. 7. Variation charts (A) sample volume density depending on saturation time, (B) water absorption relative to the volume density variation of mining waste of various ages

Table 4

Mining waste filtration coefficient and volume density test results at various (increasing) vertical pressures

Sample	Vertical pressure [MPa]	Volume density [g/cm^3]	Filtration coefficient obtained during testing [m/d]	Filtration coefficient after temperature correction [m/d]
>35 years	0.00	1.260	8.830	7.970
	0.09	1.543	0.598	0.471
	0.18	1.630	0.138	0.108
	0.36	1.761	0.034	0.027
	0.54	1.828	0.019	0.015
15 years*	0.00	1.546	350.471	272.740
	0.09	1.691	142.590	110.965
	0.18	1.712	131.025	101.197
	0.36	1.828	51.233	39.870
	0.54	1.866	34.216	26.320
	0.72	1.932	13.875	10.673
	1.00	2.019	7.162	5.509
15 years	0.00	1.326	77.533	59.641
	0.09	1.398	47.749	36.730
	0.18	1.420	34.471	26.516
	0.36	1.499	11.804	9.080
	0.54	1.524	9.217	7.090
	0.72	1.559	4.681	3.601
	1.00	1.596	2.218	1.706
5 years	0.00	1.318	166.129	126.334
	0.09	1.491	46.615	35.449
	0.18	1.557	26.977	20.515
	0.36	1.692	7.528	5.725
	0.54	1.770	3.245	2.468
	0.72	1.832	1.231	0.936
	1.00	1.867	0.768	0.584
$^1/_2$ year	0.00	1.648	875.182	629.627
	0.09	1.700	429.700	309.137
	0.18	1.732	256.746	184.709
	0.36	1.813	105.550	75.935
	0.54	1.876	41.801	30.073
	0.72	1.943	18.648	13.416
	1.00	1.985	5.645	4.061

* – after coal recovery

The tests conducted revealed a significant variation in the waste filtration and density parameters depending on the time of waste storage and at different values of vertical pressure (simulation of vertical pressures at various mining waste dump depths under laboratory conditions; Fig. 8). The oldest waste, with a storage time of over 35 years, was characterised by the lowest permeability. The material with the shortest storage time (up to half a year) showed the best filtration properties. Waste stored for 15 years and subjected to coal recovery was also characterised by high permeability.

Generally, as from common observations, the intense rock chunk disintegration processes, which occur inside and on the surface of the waste bulk, result primarily from weathering in the aeration zone and from the influence of water and the mass of the overburden in the saturation zone (in the case of subsurface mining waste storage, e.g. in open-pit mines). The filtration coefficients in the vertical pressure profiles for samples selected for laboratory testing decreased from 7.97 to 0.015 m/d in the case of the oldest waste, and from 629.627 to 4.061 m/d for fresh waste. A significant filtration coefficient variation, particularly in the first two measurement cycles, was observed in the case of waste stored for 15 years before and after coal recovery. Both samples were characterised by the same time and manner of storage as well as a similar geological age of the rock forming the waste. The repeated loosening and relocation of waste combined with hard coal recovery by flotation resulted in an increase of the filtration coefficients for waste in a loose state by a factor of nearly 4.5. Before coal recovery, the waste stored for 15 years was characterised by a decrease in filtration coefficients ranging from 59.641 to 1.706 m/d, whereas after coal recovery the values were higher and ranged from 272.740 to 5.509 m/d.

The groundwater in the aeration zone is subject to flow under the influence of gravity, i.e. it flows down under the influence of the liquid's own mass and the soil suction forces, which decrease together with proximity to the groundwater table. This phenomenon concerns infiltration water originating from precipitation. As in the current classification of loose formations by

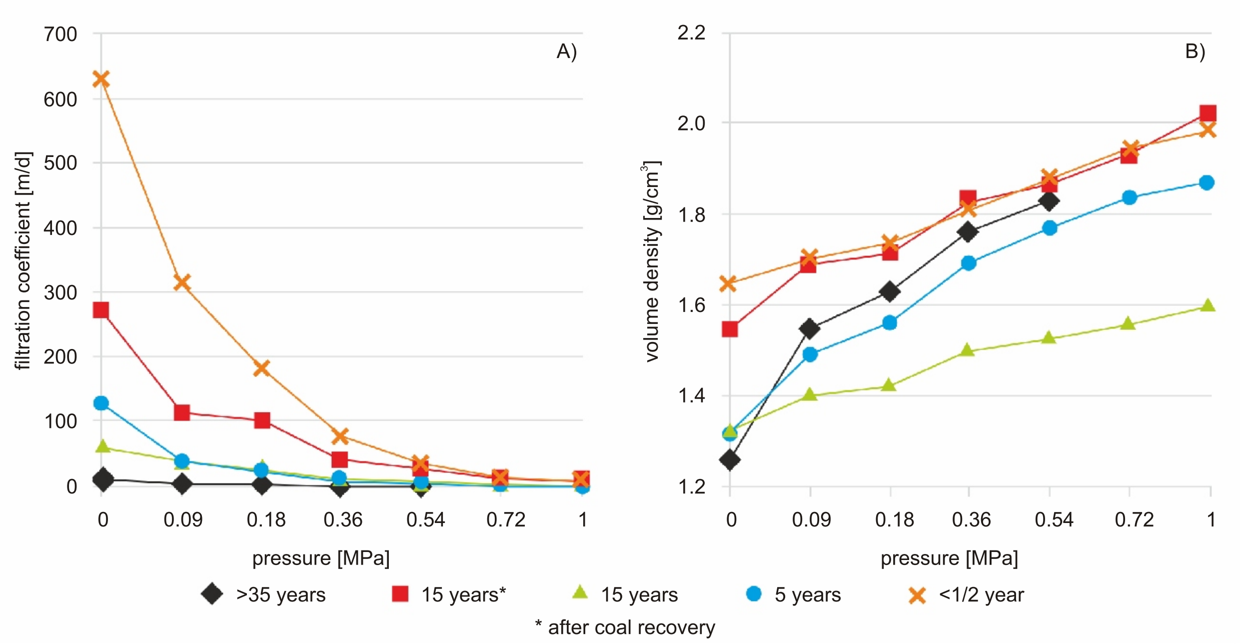


Fig. 8. Variation charts of (A) filtration coefficients, (B) volume density for mining waste of various ages at increasing vertical pressure

vertical permeability (Gawicz, 1983; Table 5), each of the waste samples in the aeration zone was characterised by high and/or very high permeability, despite the decrease in the filtration properties together with the increasing pressure. As indicated by published data, the average filtration coefficients in saturation zones are characterised by significant anisotropy (Chief et al., 2008), which decreases together with depth as a result of soil pore space compression.

In the saturation zone, the groundwater flow proceeds according to Darcy's law, and in a porous soil and rock medium such as the bulk mining waste serving as the source of the waste samples, this depends on the forces exerted on the water, including gravity, pressure, inertia, friction and surface forces. Under conditions of equal resistance, all the forces determining the groundwater movement are distributed evenly over the entire course of the flow. In such cases, the water movement (the direction and velocity of the flow) depends on the hydraulic gradient and the filtration coefficient. The laboratory testing results indicate that for horizontal water filtration, according to the classification of Pazdro and Kozerski (1990; Table 6), the waste in loose state was characterised by high (samples of >35 years and 15 years) and very high (remaining samples) permeability. With increasing vertical pressure, its filtration properties decreased considerably. After the conclusion of testing, it constituted semi-permeable waste (sample of >35 years), as well as waste with low (sample of 5 years), and medium (remaining waste samples) permeability. On the other hand, according to the classification of Hölting (1989), all the waste samples before the compression cycle showed very high permeability, whereas after testing they were poorly permeable (sample of >35 years) and permeable (remaining waste samples). The waste permeability reduction was a resultant of the rock material fragmentation degree and the pore space compression.

Many years of experiments conducted in different international research institutions concerning the hydrogeological properties of loose rock, particularly medium-grained rock, have revealed a correlation between the filtration coefficient and soil grain size distribution. These observations made it possible to develop empirical formulas for determining filtration coefficients depending on the equivalent diameters selected. The most commonly employed and verified formulas (Dananaj and Frankovska, 2004) include:

a. Hazen's equation, whose application is limited to soils with an equivalent diameter d_{10} within 0.1-3.0 mm and C_U coefficient values within 1 and 5:

$$k_{10} \quad c \quad d_{10}^{2} [\mathrm{m/d}] \qquad [6]$$

Table 5

Vertical permeability classification for rock (per Gawicz, 1983)

Rock permeability classes	Filtration coefficient	
	[m/s]	[m/d]
very well permeable	$>1.1 \cdot 10^{-6}$	$>10^{-1}$
well permeable	$1.1 \cdot 10^{-6} \div 1.1 \cdot 10^{-8}$	$10^{-1} \div 10^{-3}$
average permeable	$1.1 \cdot 10^{-8} \div 1.1 \cdot 10^{-10}$	$10^{-3} \div 10^{-5}$
poorly permeable	$1.1 \cdot 10^{-10} \div 1.1 \cdot 10^{-11}$	$10^{-5} \div 10^{-6}$
very poorly permeable	$1.1 \cdot 10^{-11} \div 1.1 \cdot 10^{-12}$	$10^{-6} \div 10^{-7}$
practically impermeable	$<1.1 \cdot 10^{-12}$	$<10^{-7}$

Table 6

Horizontal permeability classification for rock (after Hölting, 1989 and Pazdro and Kozerski, 1990)

Classification according to Hölting (1989)			Classification according to Pazdro and Kozerski (1990)		
Filtration coefficient [m/s]	Filtration coefficient [m/d]	Permeability	Permeability	Filtration coefficient [m/s]	Filtration coefficient [m/d]
$>10^{-4}$	>8.64	very high permeable	very high permeable	$>10^{-3}$	>86.4
			high permeable	$10^{-4} \div 10^{-3}$	$8.64 \div 86.4$
$10^{-6} \div 10^{-4}$	$8.64 \cdot 10^{-2} \div 8.64$	permeable	average permeable	$10^{-5} \div 10^{-4}$	$8.64 \cdot 10^{-1} \div 8.64$
			poorly permeable	$10^{-6} \div 10^{-5}$	$8.64 \cdot 10^{-2} \div 8.64 \cdot 10^{-1}$
$10^{-8} \div 10^{-6}$	$8.64 \cdot 10^{-4} \div 8.64 \cdot 10^{-2}$	low permeable	semipermeable rocks	$10^{-8} \div 10^{-6}$	$8.64 \cdot 10^{-4} \div 8.64 \cdot 10^{-2}$
$<10^{-8}$	$<8.64 \cdot 10^{-4}$	very low permeable	impermeable rocks	$<10^{-8}$	$<8.64 \cdot 10^{-4}$

b. the "American" USBSC formula, developed by Yugoslavian and Polish hydrogeologists based on American studies of the relationship between the filtration coefficient and the effective grain size d_{20}, whose application is limited to soils with an equivalent diameter d_{20} within 0.01–2.0 mm:

$$k_{10} \quad 0.36 \quad d_{20}^{2,3} [\mathrm{cm/s}] \tag{7}$$

c. Seelheim's equation, whose application is limited to loose soils of high uniformity:

$$k_{10} \quad 0.357 \quad d_{50}^{2} [\mathrm{cm/s}] \tag{8}$$

where: k_{10} – filtration coefficient at a water temperature of 10°C, c – coefficient depending on the uniformity coefficient, d_{10}, d_{20}, d_{50} – effective grain size corresponding to a content of 10, 20 and 50% of grains on the grain size curve, respectively [mm].

In terms of tests performed on mining waste samples, an analysis was conducted concerning the correlation between the filtration coefficients obtained [calculated from formula (1)] and selected effective soil grain sizes (Table 7). The compilation below encompasses the results of tests performed for the stage before determining the compressibility and permeability of waste of various ages (stage II) and after the tests were concluded (stage III).

The results determined indicate a polynomial (second degree) relationship between the filtration coefficients obtained (in both stages of the tests and for all the waste samples of various ages in total) and the effective grain sizes d_{10}, d_{20} and d_{50} (Fig. 9A). A statistical analysis reveals that the regressions explain between ~82.5% (for effective grain size d_{50}) and 86.5% (for effective grain size d_{20}) of the data variability, therefore the fitting of all the models can be considered good. At the same time, the highest obtained correlation between filtration coefficients and the effective grain size d_{20} is reflected in the indicated application criteria of formula (7). Among the empirical equations adopted for the assessment of filtration coefficients for mining waste of various ages, only the "American" USBSC formula can provide the most reliable results. In the cases analysed, Hazen's and Seelheim's equations are not applicable, given the large range in grain sizes of the waste.

A slightly higher correlation of linear character was observed between the effective grain sizes and the filtration coefficients obtained for samples before compression, i.e. for a quasi-loose state (Fig. 9B). For this stage of testing, the regressions explain between ~86.3% (for effective grain size d_{20}) and 89.5% (for effective grain size d_{10}) of the data variability, therefore the fitting of all the models can also be considered good. No correlation, or weak correlation, was found between effective grain sizes and filtration coefficients obtained for the mining waste after the conclusion of testing (stage III).

Table 7

Filtration coefficients and selected effective grain sizes for mining waste of various ages at different states of stress and vertical pressure determined by laboratory testing

Sample		$<^1/_2$ year		5 years		15 years		15 years*		> 35 years	
Stage of testing		II	III	II	III	II	III	II	III	II	III
Pressure	[MPa]	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0	0.54
d_{10}	[mm]	1.05	0.58	0.51	0.27	0.085	0.072	0.48	0.16	0.19	0.15
d_{20}	[mm]	2.40	1.20	1.40	0.66	0.60	0.20	1.10	0.37	0.64	0.32
d_{50}	[mm]	7.10	4.00	3.40	2.20	3.00	1.80	3.10	2.05	2.70	1.60
k	[m/d]	629.63	4.06	126.33	0.58	59.64	1.71	272.74	5.51	7.97	0.015

* – after coal recovery

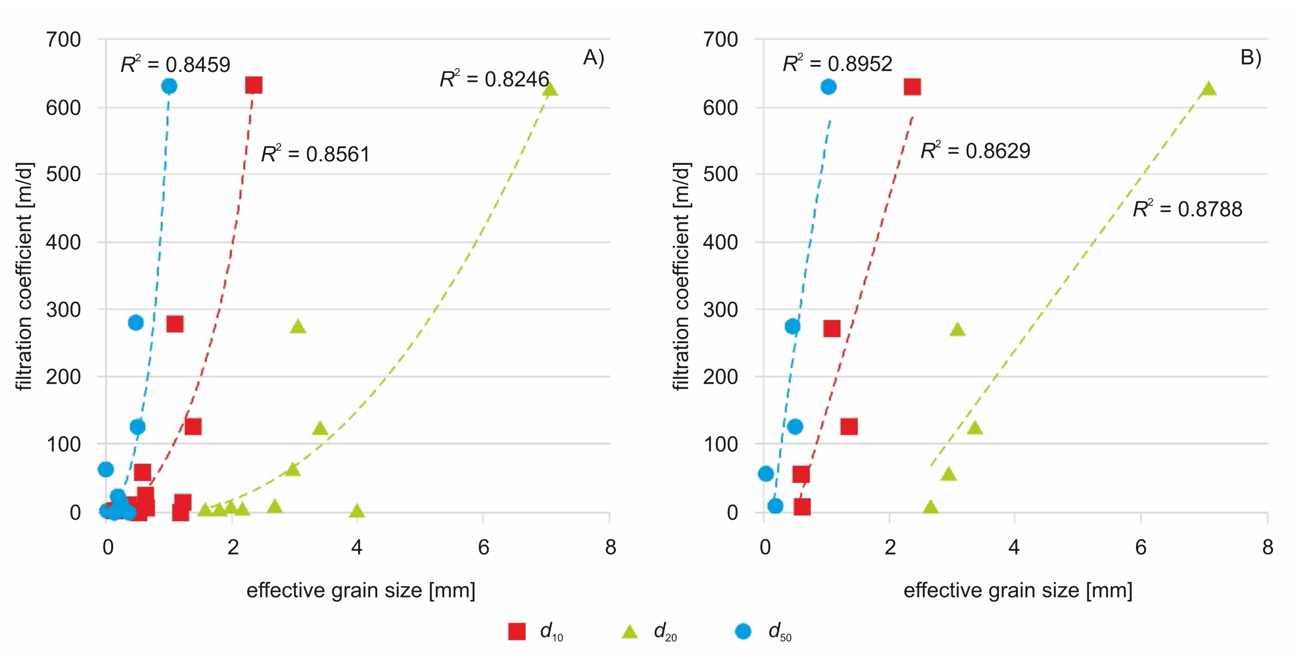


Fig. 9. Correlation charts for effective grain sizes d_{10}, d_{20} and d_{50} and filtration coefficients obtained by laboratory testing (A) for two test stages before and after sample compression, (B) for samples before compression, i.e. for a quasi-loose state

The laboratory tests also revealed that a cyclic change to the analysed sample volume density (Fig. 8B) occurred as a result of large rock chunk fragmentation and waste pore space compression due to the influence of vertical pressure. An increase in mining waste density occurred within the range of the adopted loads. The greatest variations were noted for waste stored for the longest time (from 1.26 to 1.83 g/cm^3, i.e. an increase by ~45%) and for 5 years (from 1.32 to 1.87 g/cm^3, i.e. an increase by ~41.6%), but the testing of the oldest waste sample was concluded at a pressure of 0.54 MPa due to the considerable reduction in filtration coefficients and the silt clogging of its surface during compression. The lowest density increase was observed in the case of waste stored for 15 years and half a year (up to 20.4% for both samples).

The laboratory test results indicated a very strong correlation between the volume densities and filtration coefficients obtained at the given degrees of loading (Fig. 10). The relationships between these variables are characterised best by an exponential function. The regressions explain between 97.4% and 99.4% of the data variability for each of the waste samples analysed, therefore the fitting of all the models can be deemed very good.

Waste sample height variations were observed on the basis of the tests conducted at the adopted vertical pressure range, which can be described by means of power functions (Fig. 11). The coefficients of determination R^2 indicate a very good fitting of the models, and the regressions obtained explain between 94.3% (waste stored for 15 years after coal recovery) and 99.5% (waste stored for 35 years) of the data variability.

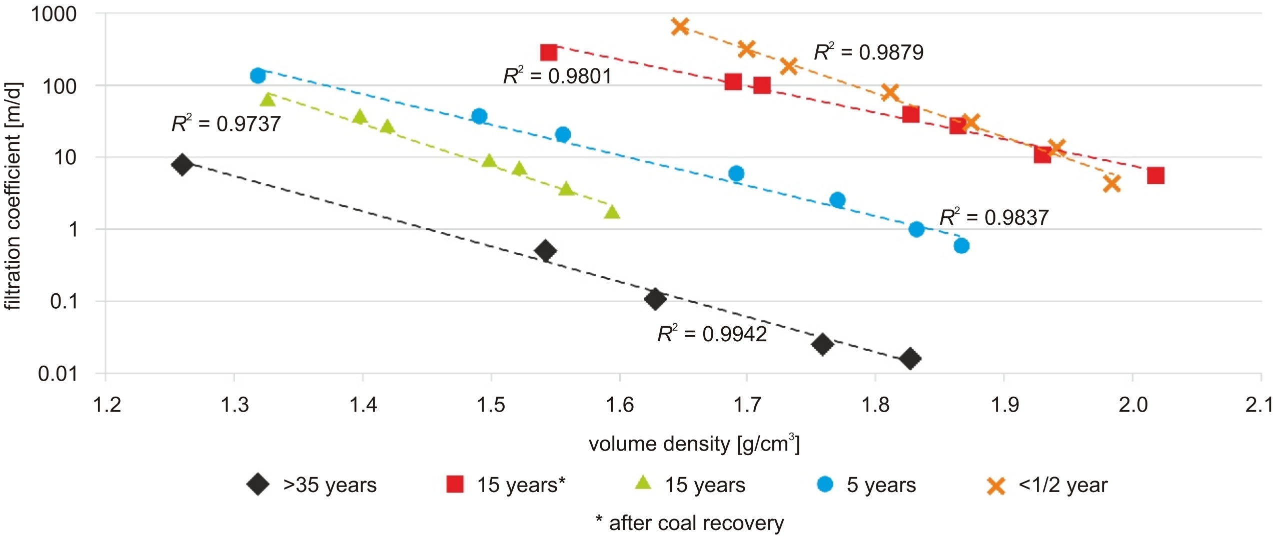


Fig. 10. Correlation charts for mining waste volume densities and filtration coefficients obtained by laboratory testing

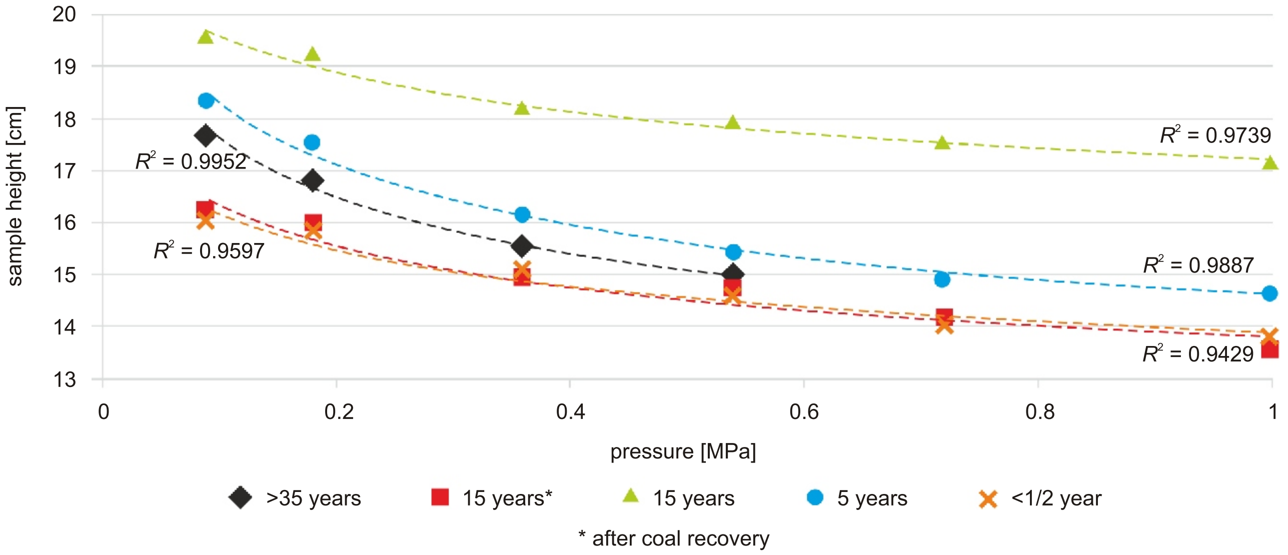


Fig. 11. Correlation charts for mining waste sample height at different degrees of loading (vertical pressure)

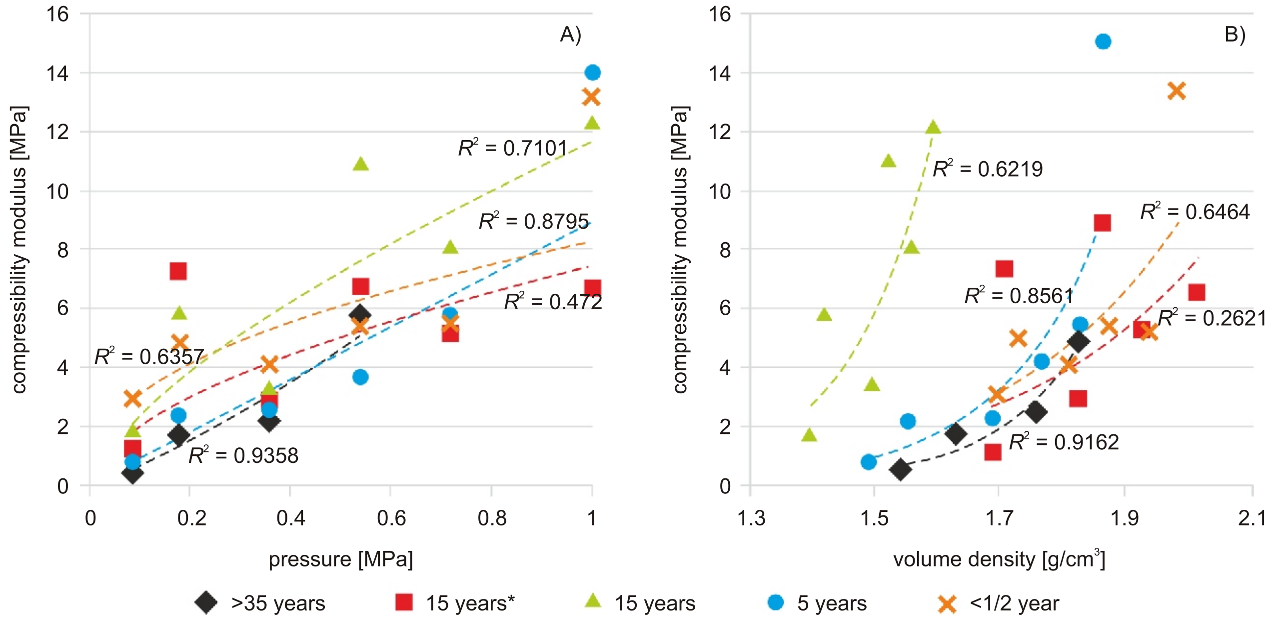
The compressibility of soils is a phenomenon consisting of the change in soil density under external loads. The laboratory testing conditions assumed the cyclic compression of the waste samples each time after concluding the filtration coefficient testing, at a given degree of loading. Given the destructive influence of water on the granular skeleton and the intergranular space, observations of the full destressing of soil as a result of unloading were not conducted. Correlations were found after analysing the course of the sample height variations with regard to the number of loading cycles (Table 8), which are most accu-

Table 8

Cyclic loading test results for mining waste of various ages

Sample	Cycle	Pressure [MPa]	Pressure increment p [MPa]	Sample height [cm]		Sample height change *h* [cm]	Compressibility modulus M [MPa]
				h_0	h_k		
>35 years	I	0.09	0.09	21.7	17.7	4.0	0.49
	II	0.18	0.09	17.7	16.8	0.9	1.77
	III	0.36	0.18	16.8	15.5	1.3	2.33
	IV	0.54	0.18	15.5	15.0	0.5	5.58
15 years*	I	0.09	0.09	17.7	16.2	1.5	1.06
	II	0.18	0.09	16.2	16.0	0.2	7.29
	III	0.36	0.18	16.0	15.0	1.0	2.88
	IV	0.54	0.18	15.0	14.6	0.4	6.75
	V	0.72	0.18	14.6	14.1	0.5	5.26
	VI	1.00	0.28	14.1	13.5	0.6	6.58
15 years	I	0.09	0.09	20.6	19.6	1.0	1.85
	II	0.18	0.09	19.6	19.3	0.3	5.88
	III	0.36	0.18	19.3	18.2	1.1	3.16
	IV	0.54	0.18	18.2	17.9	0.3	10.92
	V	0.72	0.18	17.9	17.5	0.4	8.06
	VI	1.00	0.28	17.5	17.1	0.4	12.25
5 years	I	0.09	0.09	20.7	18.3	2.4	0.78
	II	0.18	0.09	18.3	17.6	0.7	2.35
	III	0.36	0.18	17.6	16.2	1.4	2.26
	IV	0.54	0.18	16.2	15.4	0.8	3.65
	V	0.72	0.18	15.4	14.9	0.5	5.54
	VI	1.00	0.28	14.9	14.6	0.3	13.91
$^1/_2$ year	I	0.09	0.09	16.6	16.1	0.5	2.99
	II	0.18	0.09	16.1	15.8	0.3	4.83
	III	0.36	0.18	15.8	15.1	0.7	4.06
	IV	0.54	0.18	15.1	14.6	0.5	5.44
	V	0.72	0.18	14.6	14.1	0.5	5.26
	VI	1.00	0.28	14.1	13.8	0.3	13.16

* – after coal recovery



* after coal recovery

Fig. 12. Correlation charts for mining waste compressibility modulus in relation to (A) the vertical pressure adopted during testing, (B) soil volume densities at given degrees of loading

rately described by exponential functions (coefficients of determination R^2 from 0.9592 to 0.9892). Observations indicated that for maximum vertical pressures of 1.0 MPa (0.54 MPa for the oldest waste sample), no waste sample showed a stabilisation of the height variation, which means that the soils had not yet reached a density close to the maximum, at which state they would undergo only elastic deformation.

The test results (Table 8) revealed that the correlations between the calculated compressibility modulus for the waste samples analysed and the vertical pressures adopted during testing can be described to various degrees of accuracy by power functions (Fig. 12A). According to the classification adopted (Buda and Jarynowski, 2010), the model fitting ranges from low for waste stored for 15 years after coal recovery (R^2 = 0.4577), through satisfactory for waste stored for half a year and 15 years (R^2 of 0.6280 and 0.7398 respectively), to high for waste stored for 5 years (R^2 = 0.8950) and very high for waste stored for 35 years (R^2 = 0.9540). Low and satisfactory correlations indicate more irregular sample height variations during compression. The courses of compressibility determinations for the samples of waste stored for 15 years and half a year clearly showed stepwise height changes for the vertical pressure increments adopted. This was particularly well seen in the second compression cycle, where the samples showed a height decrease by only 2–3 mm. This phenomenon was also the cause of the low and satisfactory correlations of these samples' compressibility modulus with the volume densities obtained during testing (Fig. 12B) – R^2 from 0.2621 to 0.6464. At the same time, exponential functions describe the relations of these variables with high (R^2 = 0.8561) and very high (R^2 = 0.9162) fit for the samples of waste stored for 5 and 35 years.

SUMMARY AND CONCLUSIONS

Selected hydrogeological and physico-mechanical properties are analysed, of Carboniferous mining waste used for 35 years in the reclamation of an open-pit. The years of waste deposition in the excavation create favourable conditions for the intense development of hypergenic processes resulting in the disintegration and fragmentation of sedimentary rocks (sandstones, mudstones and claystones), leading to changes in their parameters that affect the recharge, accumulation and flow of water. This phenomenon is further enhanced by the rising vertical pressure following the heaping of additional layers of waste as well as the destructive influence of water on rock debris and the time of the waste's exposure to these factors. The laboratory tests conducted on the samples of mining waste characterised by various ages (with a storage time of half a year to over 35 years) made it possible to formulate the following observations and conclusions:

a. The mudstones originating from fresh waste are the most susceptible to the disintegration and deterioration of their structure under the influence of water. The mudstones from the oldest waste also show a tendency to fracture along bedding planes during slakeability tests.
b. The mining waste water absorption, which corresponds to the effective porosity, varies over time and decreases together with subsequent cycles of sample saturation. This is related to the reduction in pore space as a result of the waste grain structure degradation. The waste stored for the shortest time and for 5 years is characterised by the lowest water absorption range, while the waste stored for 15 years shows the highest range.
c. The cyclic saturation and draining of waste samples result in a logarithmic increase of mining waste volume density over time. The rock material water absorption variations show a strong negative correlation with the values of volume density.
d. The waste with the longest storage time in the excavation is characterised by the lowest filtration properties, which is the result of its degradation due to the co-occurrence of multiple factors leading to its weathering and disintegration. The highest permeability was determined in the case of the fresh waste sample with the

highest content of grains and rock chunks with diameters >20 mm (nearly 52%) and the highest gradation uniformity.

e. Pore space compression and waste permeability reduction occur together with rising vertical pressure. The highest absolute filtration coefficient variations at a pressure range of 0.0 to 1.0 MPa (up to 0.54 MPa for the oldest waste) were found for fresh waste, the result of its very high initial permeability in a loose state as well as the low strength parameters of the rock forming the waste, which facilitate its degradation. The highest relative filtration coefficient variations (difference in the values of coefficient *k* relative to the values determined for the waste in a loose state) were found for the oldest waste sample.

f. In terms of horizontal filtration, in the loose state the waste analysed is characterised by high and very high permeability, whereas following testing the waste ranges from semi-permeable to possessing low and medium permeability. As regards vertical filtration, across the entire adopted pressure profile the mining waste analysed is characterised by high and/or very high permeability.

g. An increase in the waste volume density occurred together with an increase in vertical pressure. The greatest changes were observed for the oldest waste samples, whereas the lowest density increase could be seen for the waste with a storage time of 15 years, and half a year.

h. In the initial state (before the laboratory testing), the gravel fraction showed the greatest contribution by mass in all the waste samples. The coarse grain content decreased with the simultaneous increase in finer fractions together with the rising age of the waste. All the waste constituted very poorly sorted soils with a tendency for increases in the uniformity coefficient with the storage time. After the laboratory testing of the waste was concluded, the stone fraction underwent total reduction in all the waste samples, leading to an increase in the gravel and sand fractions.

i. After mine closure and completion of pit reclamation the compacted waste mass will cause a change in the local conditions of groundwater circulation around the excavation. Due to the much lower values of porosity and filtration coefficients of wastes than native sediments around the excavation, groundwater table may accumulate in the direction of their flow and cause flooded areas on the ground surface.

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