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BASIC GEOTECHNICAL PROPERTIES OF MINING AND PROCESSING WASTE — A STATE OF THE ART ANALYSIS

1. Introduction

Coal mining waste is a material which is composed of rock fragments coming from pre--mining operations such as preparatory or enabling works. These colliery spoils are mostly deposited on the surface in heaps which has an impact on the environment due to air and water pollution and also by occupying place and causing area degradation. Other serious problems connected with these objects are related to issues with their stability. Processing waste is mineral rejected material which is a by-product of the coal enrichment separation processes such as washery, gravity separation, sedimentation and flotation. Waste disposal of this kind of material takes place in heaps as well as in sludge ponds.

Knowledge about the geotechnical properties of mining and processing waste is needed for minestone utilization as well as for the safe storage thereof in stable heaps. The geotechnical properties of fresh minestone differ from its properties and behavior after longer storage. Transport, handling, compaction and weathering cause changes in the physical and mechanical parameters of mining waste. Moreover, minestone from the same coal level may have a different petrographic and mineral composition, which will be reflected in the geotechnical parameter values.

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2. Petrographical characteristics

The determination of the petrographic composition of minestone is one of the most important studies needed to specify the potential use of mining waste in the construction industry. Table 1 shows a comparison in the petrographic composition of mining waste in Poland and selected countries.

TABLE 1
Petrographic composition of minestone — comparison between Poland and other countries

Rock	Content [%]			
	Poland		Germany (1995)[2]	Spain (1995)[2]
	LCB (1980–2000)[1]	USCB (1997–2003)[1]		
Claystones	31.3–70.0	73.0–98.0	47.0–66.0	10.0–70.0
Mudstones	20.0–46.7	2.0–40.0	8.0–36.0	5.0–40.0
Sandstones	9.0–18.0	2.0–33.0	0.0–4.0	10.0–80.0

1 [5]
2 [8]
LCB — Lublin Coal Basin, USCB — Upper Silesian Coal Basin

Petrographical composition of minestone was presented by Skarżyńska [8]. Table 2 contains a short description of these rocks. Figure 1 shows the percentage of mineral composition in minestone.

TABLE 2
Minestone rock content (made on the basis of [8])

Name of the rock	Main mineral composition	Characteristic properties
Claystones Clay shales	kaolinite, illite, quartz, ferrous minerals, dolomite, pyrite	— low plasticity — susceptible to erosion
Mudstones	fine-grained sandstone joined by clay binder, dolomite, ankerite, siderite	— not eroded by water — substantial mechanical resistance — easily disintegrate into small slabs
Coal shales	coal, pyrite, clay minerals	— combustible (with content in coal > 30%)
Sandstones	quartz, feldspar, mica,	— high mechanical resistance — rarely occur in minestone

3. Basic geotechnical properties of coal mining and processing waste

3.1. Grain size composition

The principal classification of minestone is connected with specific coal production operation and divides mining waste into two groups:

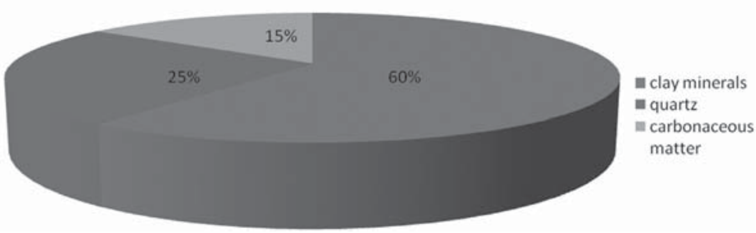

Fig. 1. Typical minestone composition (made on the basis of [8])

1) minestone derived directly from first development mining as well as from exploitation works, these wastes have a grain size up to 500 mm;
2) minestone formed during enrichment processing, such as:
   - coarse-grained washery wastes from gravity separation (grain size: 10–250 mm);
   - fine-grained washery wastes from jigging process (grain size: 0.5–30 mm);
   - tailings — from flotation (grain size < 1 mm).

Figure 2 shows the range estimated by the size distribution curves for mining waste in various stages of storage. In fresh minestone, gravel and cobble fractions predominate. In mining waste stored in landfills there is more fine grained material — this caused by the weathering processes.

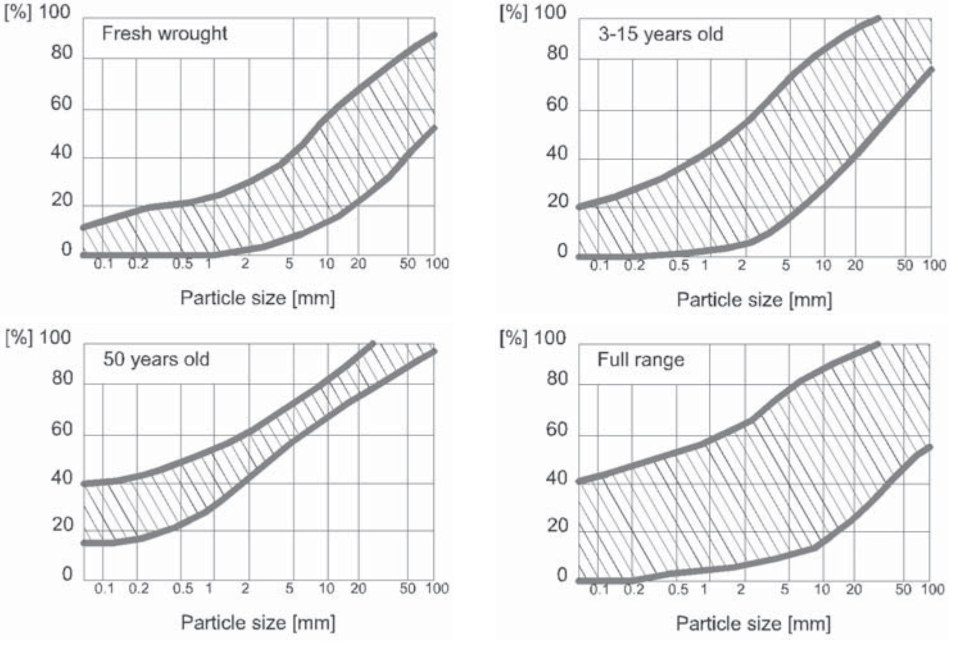

Fig. 2. Effect of time on particle size distribution range of minestone (Upper Silesia Coalfield, Poland) [8]

The particle shape and structure of mining waste indicate that the material has higher shear strength in consolidated form. Table 3 compares the content of the fraction with duration of storage and thus indicates that the grain size of the minestone changes with time.

TABLE 3
Grain size distribution of coal mining wastes from mine in Lublin Coal Basin (LCB) and Upper Silesian Coal Basin (USCB) [5]

	Content of the fraction [%]			
	Cobbles > 40 mm	**Gravel 2–40 mm**	**Sand 0.063–2 mm**	**Silt and clay < 0.063 mm**
LCB Coal Mine "Bogdanka"				
fresh waste	0–12	70–75	6–10	8–19
5 year old waste	0–5	58–74	13–23	12–19
7 year old waste	0–8	45–67	14–19	19–34
10 year old waste	0–13	70–80	6–12	8–21
USCB from dumping sites				
new	30–38	43–54	10–15	3–8
old	4–18	38–61	9–21	2–30

3.2. Moisture content

Fresh wrought minestone has 4–7% moisture [8, 2], but due to storage this rises up to about 20%. The higher absorption of water is conditioned by grain size distribution of coal mining waste as well as by atmospheric conditions. The table below gives a comparison of moisture values for coal mining waste from Germany, Poland and Spain (Table 4). It can be seen that moisture depends on the enrichment method and grain size of the minestone.

TABLE 4
The moisture value for minestone from different countries [8]

Country	**Moisture content [%]**		
	Average	**Minestone from washery plants**	
		ϕ 10–150 mm	**ϕ 1–10 mm**
Poland	4–18	4	10
Germany	5–8	4–5	7–10
Spain	2–14	5	9–10

3.3. Density

Table 5 shows a comparison between bulk density and specific gravity values for coal mining waste from different countries.

TABLE 5
Density parameters for coal mining waste [8]

Country	Unit Weight [kN/m³]	Specific Gravity [-]
Poland	13–19	1.86–2.55
Germany	14–19	1.86–2.38
United Kingdom	8–21	1.66–2.84

The bulk density of minestone is a function caused by its porosity and particularly due to the bulk density of the rock particles. The porosity of fresh wrought material may reach 30% due to the dominance of coarse fractions and a shortage of fine fractions. Weathering does not, however, significantly affect bulk density [8]. Bulk density of minestone depends upon moisture and coal content as well as type and size of petrographical composition of the waste.

The specific gravity of minestone is conditional on coal content and particle size. The lower the coal content, the higher the value of specific gravity that coal mining waste can reach. The specific density of coal is between 1300–1500 kg/m^3.

The relationship between bulk and dry density as well as the age of minestone in Poland is presented in Table 6. It can be seen that mining waste density rises with time. This is due, inter alia, to the fact that mining wastes stored at the landfill have direct contact with the elements.

TABLE 6
Basic physical parameters values for minestone in Poland [2, 8]

Minestone	Unit Weight [kN/m³]	Dry Density [kN/m³]
Fresh wrought	13–16	12–15
From new heaps	17–18	16–17
From old heaps	15–19	12–17

3.4. Compaction

Optimum moisture content and maximum dry density of minestone basically depends on grain size distribution, strength of rock fragments, time of storage and applied compactive effort [2, 8]. In order to estimate the optimum moisture content as well as the maximum dry density, Standard and Modified Proctor Tests Methods are implemented. The results obtained from the former method for the minestone in Poland are included in Table 7.

Mining waste compaction by the Modified Proctor Method gives about 2–6% higher values of maximum dry density than those obtained in the standard method, while the optimum moisture value is about 6–26% lower than that received in the standard one [2].

TABLE 7

Maximum Dry Density and Optimum Moisture Content of Minestone According to the Standard Proctor Test (Poland)

Minestone	MaximumDry Density [kN/m^3]		Optimum Moisture content [%]	
Fresh wrought	17.0–19.0[1]	16.2–19.0[2]	6.0–12.0[1]	7.0–14.5[2]
From new heaps	15.0–19.0[1]	16.0–19.0[2]	10.0–14.0[1]	9.0–16.0[2]
From old heaps	14.0–20.0[1]	12.0–20.0[2]	11.0–18.0[1]	11.0–19.0[2]

1 [8]
2 [2]

3.5. Shear strength

The shear box test and the triaxial compression apparatus test (300×300×300 mm for minestone with diameter < 40 mm and 150×150×150 mm for mining waste with size less than 10 mm) are the most common methods for analyzing the shear strength of coal waste parameters.

Table 8 contains a comparison between the shear strength parameters for fresh and stored minestone which clearly shows that weathering has an influence on cohesion growth.

TABLE 8

Shear Strength parameters of Minestone in Poland [8]

Minestone	Angle of Internal Friction [°]	Cohesion [kPa]
Fresh wrought	26–42	5–35
From old tips	30–47	34–35

Under drained conditions, minestone behaves essentially as a granular material, which means that cohesion passes to zero. The effective internal friction angle is in the range of 22.5° to 50° [8].

Shear strength testing for minestone from a waste dump of the "Wesoła" Hard Coal Mine in Mysłowice was conducted by Gruchot A., Zawisza E., Gubała S. (2009) [6] using a middle-sized triaxial compression apparatus test. Research was carried out on mining waste samples with varying density but constant dimensions: height and diameter of 30 cm and 15 cm, respectively. The conclusion from that investigation was that both burnt and non-burnt mining waste have high shear strength parameter values. Consolidation does not have significant influence on internal friction angle values, but it does have an impact on the cohesion level. The table below shows the results of the mentioned analysis (Table 9).

Similar conclusions were reached by Skarżyńska [8], on the basis of data given in her publication for minestone in Poland, which states that — depending on the type of material used — the cohesion value changes with compaction from a range of 2–22 kPa to 2–80 kPa.

TABLE 9
Angle of Internal Friction and cohesion values for minestone from "Wesoła" Hard Coal Mine [6]

Compression index	Minestone	Minestone	
		Burned	**Non-burned**
0.90	φ [°]	41.30	43.40
	c [kPa]	40.90	7.90
1.00	φ [°]	41.20	49.30
	c [kPa]	76.40	0

The shear strength research conducted by Zawisza [10] using the standard apparatus of direct shearing with box dimensions of 12×12×7.8 cm and a middle size apparatus with box dimensions of 30×30×20 cm gave the following value for the strength parameters: φ = 33°, c = 28 kPa for I_S = 0.90, which were increasing up to values φ = 41°, c = 49 kPa for I_S = 1.00. The Table 10 presents the results of this study.

TABLE 10
Shear strength parameters values for mining waste [10]

Minestone	Moisture [%]	I_S = 0.90	I_S = 0.95	I_S = 1.00	Cohesion [kPa]		
					I_S = 0.90	I_S = 0.95	I_S = 1.00
"Makoszowy" Hard Coal Mine	8.70	33.00	34.40	41.40	28.40	43.40	49.00
"Sośnica" Hard Coal Mine	8.10	32.60	-	38.00	18.50	-	46.00

3.6. Permeability

Minestone permeability depends on several factors such as grain size distribution, compression index, age of the heap on which the mining waste is stored and weathering process.

Cholewa [4] analyzed changes in the filtration processes in two models of embankments which had been formed from un-burnt coal refuse shown in figure 3. The results of this investigation in provided in table 11. The difference between these two models was the slope angle. An inclination of 1:0.75 in the first model caused damage in the slope bottom, moreover crevices and leaching a small fraction of waste material as well as the settling process in the

TABLE 11
Shear strength parameters values for mining waste [10]

	Model 1	Model 2
Compression index I_S	0.97	
Hydraulic gradient	0.58	0.50
Test duration	11	42
Reason for end of the study	piping	flow stabilization
Filtration ratio [m/s]	$2.02\ 10^{-4}$	

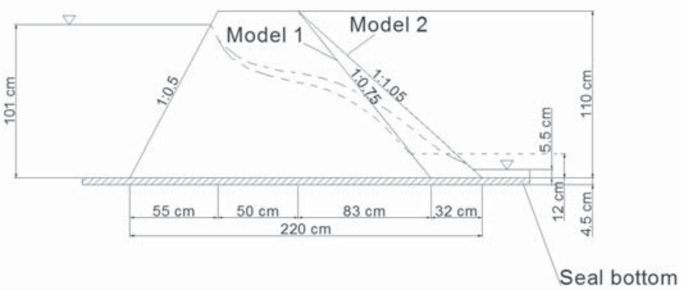

Fig. 3. Mining waste embankment models — cross-section [4]

lower part of the object which appeared on the surface. In the second model, where the slope was 1:1.05, no failure was observed.

The filtration path extension in the second model, which was the result of the slope changing, caused a decrease in the hydraulic gradient.

3.7. Consolidation settlement

The settlement of minestone depends on its consolidation properties, which are defined by the modulus of compressibility. The consolidation of mining waste is connected with grain size distribution, petrographic composition and also moisture content. Minestone is composed of different materials, which have a varying potential to compact as well as permeability. According to Skarżyńska's investigations [8], due to these reasons, low loading — under 50 kPa, gives a compressibility modulus value in the narrow range of 6–8 MPa but with a rising load — up to 300 kPa, the compressibility modulus results in higher values between 17–75 MPa.

Long-term compressibility tests show that 50–70% of settlement occurs within 10 days, and the remaining 30–50% within 70–340 days after loading. Furthermore, the modules of compressibility are higher for fresh wrought materials than for weathered material deposited in old tips [8].

3.8. Mechanical crushing

In fresh wrought minestone, where coarse fractions usually predominate, there are higher values of strength parameters such as cohesion or internal friction angle than in comparison with fine grained minestone obtained in mechanical crushing. Table 12 shows a comparison between these parameters. It obviously can be seen that the strength properties of this material decrease after crushing.

3.9. Swelling

Swelling is one of the most important parameters for minestone, especially when talking about its behavior during storing in comparison with the influence of atmospheric conditions.

TABLE 12
Changes of some properties of minestone after crushing [8]

Minestone	Moisture Content	Dry Density	Angle of Internal Friction	Cohesion
	[%]	[kN/m^3]	[º]	[kPa]
Original	2	15	25	800
After crushing, < 0.06 mm	17	14	18	47

Swelling causes lower values for shear strength. The swelling of minestone depends on the water absorption, which is characteristic for clays, marls, shales and mudstones. This process is directly connected with the high soaking occurring in this kind of waste. Unburnt mining waste, due to its coarse grain size usually has a low value of swelling — within its porosity. The values of swelling indicators depend on the primary moisture of the sample as well as its consolidation (swelling increases as the consolidation increases and falls as the moisture increases). For minestone from the "Janina" Hard Coal Mine the result of the free swelling test conducted by T. Zydroń [11] gave indicators between 4,7% to 12%. This means that mining waste can be classified as a swelling soil.

3.10. Spontaneous self-ignition

Anthropogenic soil — a name which is very often used for mining waste is a specific type of raw material which has a characteristic behavior. One aspect of this behavior is the possibility of self-ignition due to the presence of small coal particles.

In spite of the fact that the main components of minestone are noncombustible, it can still contain up to 20% of coal and 1% of piryte, which can trigger the self-ignition process on the dumping ground. With this process underway, the temperature rises rapidly and can even reach 1200ºC. As a result, the mechanical properties of minestone change.

It is worth noting that another reason which causes the self ignition of coal particles is contamination caused by the pouring out of boiler ashes onto the heap.

Table 13 contains a summary of important minestone properties in the Upper Silesia Region.

4. Summary

The first step in specifying the utility of minestone is to identify its main physical, chemical and mechanical properties. In Poland, mining wastes are applied in engineering construction (high values of their strength parameters confirm their common usefulness as construction materials). A second common way in which they are used is for building materials production, because of the huge amount of illite they contain. Another possibility of their development is in the mining management area, for example in reclamation works.

In spite of the fact that in line with modern waste management principles, current trends in the mining industry all seek to minimize the amount of mining and processing waste

TABLE 13

Properties of Rocks Associated with Coal Seams in an Upper Silesia Coalfield (Poland) [8]

Properties	Units	Claystone and Clay Shales	Mudstones	Coal Shales	Sandstones
Unit Weight	[kN/m^3]	21.0–27.0	21.0–26.0	14.0–22.0	20.0–27.0
Specific gravity	[—]	2.4–2.8	2.3–2.8	1.6–2.8	2.5–2.8
Porosity	[%]	2.6–14.0	4.0–10.0	—	0.6–19.0
Porosity index	[—]	0.04	0.01–0.03	—	0.01–0.2
Absorption	[%]	0.07–7.0	0.1–4.0	0.2–3.0	0.3–8.0
Unconfined compression strength	[MPa]	8.0–62.0	9.0–107.0	10.0–58.0	6.0–166.0
Tensile strength	[MPa]	2.0–6.0	2.0–8.0	—	3.0–11.0
Angle of internal friction	[º]	23.0–27.0	26.0–29.0	—	30.0–35.0
Cohesion	[MPa]	1.0–15.0	1.0–15.0	—	3.0–20.0
Modulus of deformation	[MPa]	73.0–177.0	96.0–177.0	—	68.0–296.0

generated, minestone is still inherently a by-product of hard coal mining. Moreover, a lot of this kind of waste is still stored in heaps. This is the reason why there is a huge need for finding new ways of utilizing minestone and its effective disposing of it in order to minimize mining's impact on environment.

Min-novation is a transnational project, one of the principal aims of which is to find new technologies and innovative solutions in the mining and mineral waste management sector. Among the main outputs of the project will be a compendium of knowledge, which will cover state of the art as well as innovative and commercially available technologies in the mining and processing waste management field.

This paper is an input to the compendium and its objective was to present basic information about the geotechnical properties of minestone and give an introduction to the in-depth analysis connected with mining waste landfill and stability issues.

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