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THE EVALUATION OF THE PHYSICO-MECHANICAL PROPERTIES OF SELECTED CARPATHIAN SANDSTONES IN TERMS OF THEIR USE AS A ARMOURSTONE

OCENA WŁAŚCIWOŚCI FIZYKO-MECHANICZNYCH WYBRANYCH PIASKOWCÓW KARPACKICH W ASPEKCIE ICH WYKORZYSTANIA JAKO KAMIENIA DO ROBÓT HYDROTECHNICZNYCH

This article presents the results of laboratory tests of the physical and mechanical properties of various types of sandstone selected from ten quarries from Carpathian flysch. The parameters were used to evaluate the quality of the sandstone and its suitability for use as armourstone in accordance with applicable standards and quality guidelines. The requirements of the BN-79/8952-31, EN 13383-1:2003 and the CIRIA, CUR, CETMEF (2007) standards were compared. Sandstone can display a large variability of parameters depending on its origin. This, in turn, results in a varying degree of its susceptibility to the destructive effects of water and climate

Keywords: armourstone, hydraulic engineering, properties of carpathian sandstones

W artykule zestawiono wyniki przeprowadzonych badań laboratoryjnych właściwości fizyko-mechanicznych wybranych rodzajów piaskowców fliszu karpackiego: krośnieńskich, magurskich, cergowskich oraz godulskich eksploatowanych w dziesięciu kamieniołomach. Przedstawione parametry wykorzystano do oceny jakości kamienia stosowanego przy wznoszeniu budowli hydrotechnicznych, takich jak ostrogi, progi, jazy czy zabezpieczenia brzegów, itp. Piaskowce te oceniono na podstawie wymagań jakości materiału skalnego wg różnych klasyfikacji (CIRIA, CUR oraz normowych). Przebadane piaskowce charakteryzują się całkiem dobrymi parametrami, jeśli chodzi o gęstość objętościową, nasiąkliwość, mrozoodporność. Również wytrzymałość na ściskanie oraz odporność na ścieranie (tarcza Boehmego) i odporność na rozdrabnianie (Los Angeles), badane na próbkach suchych wskazują, iż jest to materiał o dość dobrej jakości oraz odporności na działanie czynników mechanicznych. Jednak wykonanie badań wytrzymałościowych oraz odporności na ścieranie (micro-Deval) próbek wcześniej nasyconych wodą powoduje obniżenie jakości materiału skalnego, mimo, że wartość nasiąkliwości jest na dość niskim poziomie. Co w przypadku zastosowania takiego materiału jako kamienia do robót hydrotechnicznych

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w miejscach stałego dynamicznego oddziaływania wody może poważnie zagrozić trwałości konstrukcji.

Trudności w ocenie jakości materiału skalnego przeznaczonego na konstrukcje hydrotechniczne upatrywać należy również w współistnieniu różnych klasyfikacji. Najbardziej rozbudowana jest klasyfikacja CIRIA, CUR, CETMEF (2007). Według tych kryteriów badane piaskowce zakwalifikowałyby się co najwyżej jako marginalne a nawet złe. Wskazywałoby, że co najwyżej mogą zostać zabudowane w konstrukcjach o niewielkim obciążeniu warunkami wodnymi. Całkiem inny obraz jakości badanych piaskowców daje ocena wg BN-79/8952-31. Prawie wszystkie uzyskałyby klasę I, co oznaczałoby, że mogą zostać zastosowane w każdych warunkach wodnych, nawet w konstrukcjach morskich czy oceanicznych. Analizując badany materiał skalny wg wytycznych PN-EN 13383-1:2003, szczególnie ze względu na wartość wytrzymałości na ściskanie w stanie nasycenia wodą, to ogólnie uplasowują się na pograniczu kategorii CS80 oraz CS60. Niestety brak odporności na ścieranie dyskwalifikuje zastosowanie tych piaskowców nawet w środowisku o umiarkowanym oddziaływaniu fal czy zawiesiny mułu.

Słowa kluczowe: kamień do robót hydrotechnicznych, budowle hydrotechniczne, właściwości piaskowców karpackich

1. Introduction

In order to prevent water erosion, protect human habitats against flooding, and improve navigability, water regulation works are undertaken in rivers and water bodies. Regulation and reinforcement works constitute a branch of hydraulic engineering and mainly involve the regulation of rivers and streams, the construction of dams and retaining walls, the erection of banks for canals and reservoirs as well as the reinforcement of flood embankments, earth dams, bridge abutments, etc. Sometimes, excessive human interference in nature leads to changes in the environment which have an adverse impact on both humans and the ecosystem. All work which affects hydraulic conditions must, therefore, be carried out in accordance with rules of sustainable development in order to minimize the impact of such structures on the environment. One such principle consists of refraining from applying typical technical solutions such as constructing concrete or reinforced concrete hydraulic structures or reinforcing slopes with concrete. Instead, preference is given to more environmentally friendly solutions which make use of natural rock material.

The aim of the study was to evaluate the quality of selected sandstones of the Carpathian Flysch Belt as material for use in hydrotechnical works. These sandstones were evaluated on the basis of the requirements of stone material quality according to various classifications (CIRIA, CUR, and CETMEF standards). Furthermore, the problems that may arise when using various guidelines have also been pointed out.

2. Armourstone in Regulation and Reinforcement Structures

All regulation works in rivers and streams should aim at preserving the natural conditions prevailing in the bed of the watercourse, without changing hydrological characteristics. Hydraulic regulation structures which use armourstone include spurs, dams, weirs, sills, and gabion baskets (Duszyński, 2007). A groyne (Fig. 1) is a structure composed of stone or stone-and-earth dykes arranged crosswise to the direction of the water flow and which partially cuts into the bank of the river and the river bed. These structures are mostly used in shallow and wide rivers in order

Fig. 1. Groyne on the Vistula River. Photography by the Regional Water Management Board in Gdańsk (http://rzgw.gda.pl)

Fig. 2. The use of gabion baskets and mattresses (http://www.ogradzamy.pl)

to limit the transport of bedload carried by the stream and are also used in river bed regulation and shore protection.

Dams also play a similar role. Threshold dams are erected across a watercourse and can also be made of riprap. They differ from standard dams by having a flat surface which is completely submerged underwater. The purpose of thresholds is the damming of water to prevent erosion of the river bed and to favour the natural formation of pools which form an ideal environment for river fauna and flora. Another example is structures formed by gabions filled with rock material. The most commonly used gabions in hydraulic structures are rectangular baskets with dimensions ranging from 0.5 m to several meters, mattresses with a surface area of up to several square meters, and cylinders with a length of several meters. Such gabions are made with wire resistant to corrosion and are filled with crushed rock material or river rocks with similar shape and dimensions. Structures made from gabions (Fig. 2) are ideally suited for reinforcing slopes or the bed of a watercourse in parts where water flow is fast or turbulent. Very often, entire hydraulic structures such as dams, thresholds or barrages or their parts are constructed with gabion elements. Such structures are readily used because they blend easily into the environment, they are permeable to water, resistant to wave action, and their erection, modernization or disassembly are very simple (Jędryka & Kaminska, 2004).

Structures of stone are environmentally friendly because they do not create barriers between the aquatic and terrestrial environments and allow free migration of fauna as well as the spread of vegetation. The greatest challenge in natural stone constructing is, therefore, access to a suitable rock material which is resistant to environmental and climatic effects.

3. Quality Requirements for a Rock Material

Armourstone consists of coarsely graded aggregates and is used in structures which are subjected to the continuous impact of water flowing at different speeds, wave action or currents. Armourstone can weigh from several kilograms to several tonnes. However, the suitability of armourstone for use in hydraulic construction projects is not only considered from the perspective of size and weight. In order to withstand operating conditions, an appropriate rock material must be selected.

In hydraulic construction, the assessment of material quality is often based on standards which were developed by an international team of experts in 1991 and updated in 2007 (CIRIA, CUR, CETMEF, 2007; Topal & Acir, 2004; Latham et al., 2006; Pilarczyk, 2010). Armourstone quality assessment according to this classification is based on an extensive set of laboratory and field tests (Table 1). Based on these guidelines, PN-EN 13383-1:2003 was developed.

TABLE 1

A guide to the quality and durability of the stone for hydrotechnical works based on field and laboratory tests (CIRIA, CUR, CETMEF, 2007)

Test properties	Reference	CIRIA / CUR Criteria			
		Excellent	Good	Marginal	Poor
Mass density, Mg / m^3	BS EN 13383-2: 2003	>2.7	2.5-2.7	2,3-2,5	<2.3
Water absorption,%	BS EN 13383-2: 2003	<0.5	0.2-2.0	2.0-6.0	>6.0
Microporosity / total porosity,%	Lienhart (2003)	<2	2-6	6-20	> 20
Methylene blue adsorption, g / 100g	Verhoef (1992)	<0.4	0.4-0.7	0.7-1.0	> 1.0
Compressive strength, MPa	BS EN 1926: 2001	>120	120-80	80-60	<60
Schmidt impact index, % rebound	ISRM (1988)	>60	50-60	40-50	<40
Sonic velocity, km/s	BS EN 14579: 2005	>6	4.5-6	3-4.5	<3
Point load strength index, MPa	ISRM (1985)	>8	4-8	1.5-4	≤1,5
Fracture toughness, MPa m$^{1/2}$	ISRM (1988)	>1.7	10-1.7	0.6-1.0	≤0,6
Indirect tensile (the Brazilian) strength, MPa	D3967-95a ASTM, ISRM (1978)	>10	5-10	2-5	<2
Los Angeles % loss	BS EN 1097-2: 2000	<15	15-25	25-35	>35
Micro-Deval % loss	BS EN 1097-1: 2000	<10	10-20	20-30	>30
$MgSO_4$ soundness, % loss	BS EN 1367: 2000	<2	2-10	10-30	>30
Freeze-thaw, % loss	BS EN 13383-2: 2003	<0.5	0.5-1	1-2	>2.0
Wet-dry, % loss	ASTM D5313-04	<0.5	0.5-1	1-2	>2.0

Each property of armourstone is rated for quality and durability on a four-level scale ranging from poor, marginal, good to excellent, irrespective of the type and place of use. This is very helpful in interpreting the individual characteristics of armourstone and makes it easier to select the right material for a particular hydraulic structure. CIRIA, CUR, CETMEF (2007) recommends the following interpretation of the individual ratings:

- Excellent – the material is almost ideal but may not always be available. It can be used in all conditions without risk of failure.
- Good – the material properties are better than average. The use of such a material should not result in major degradation although it may show signs of damage if it is misused or is used beyond the lifetime for which the structure was designed.
- Marginal – the material properties are worse than average. There is a high risk of damage in case the stone is used in structures which are overloaded with water action. Enhanced quality control at each stage of production, design, and construction of hydraulic struc-

tures is necessary. The use of such armourstone may lead to a shortened lifespan of the structure and increased expenditure on repair and modernization.
– Poor – the material properties are much worse than average. The material should not be used in hydraulic structures as it can be easily damaged.

Current specifications regarding armourstone quality are provided in standards EN 13383-1 and EN 13383-2. For applications in hydraulic engineering, natural, artificial or recycled stone may be used. The scope of testing depends on the origin of the rock material and its application. The basic properties which are determined from irregular rock material are the mass density, water absorption, and freezing and thawing resistance. These tests are carried out in accordance with PN-EN 13383-2:2003. Another parameter is failure resistance which is determined from the compressive strength of water-saturated samples and resistance to abrasion measured through the abrasion test for aggregate grades of 10/14 mm using the micro-Deval drum. The minimum densities of rock material used for armourstone construction should be 2.30 Mg/m^3. Absorption tests allow the assessing of whether the material is completely resistant to freezing and thawing. The upper limit for the absorption coefficient is 0.5%. Above this value, a freezing and thawing resistance test must be conducted and consists of submitting water-saturated samples, which are additionally protected against evaporation by foil wrapping, to cycles of freezing in air and thawing in water. After 25 cycles, the weight loss is measured, and a visual assessment is carried out in order to assess the presence of cracks. The FTA category includes materials for which a weight loss exceeding 0.5% or open cracks were found in at most one sample after performing the test. The remaining samples should not have cracks or incur weight loss greater than 0.5%. In the opposite case, the rock may obtain a rating declared by the producer. Compressive strength tests in full saturation are performed in accordance with PN-EN 1926:2001 on different samples of rock. The strength requirements are listed in Table 2.

TABLE 2

Classification of armourstone with respect to strength requirements provided in PN-EN 13383-1: 2003

The average compressive strength of 9 samples by discarding the smallest value out of 10 samples, [MPa]	**The compressive strength of 2 samples out of 10 at most, [MPa]**	**Category** CS
≥80	<60	CS_{80}
≥60	<40	CS_{60}
Other value declared by the stone producer		$CS_{Declared}$
No requirement		CS_{NR}

An important feature of the rock material is also its abrasion resistance which is determined in accordance with PN-EN 1097-1:2000. At least six pieces of aggregates of 10/14 size which are obtained by armourstone fragmentation are tested. Abrasion resistance classes are shown in Table 3.

For coastlines where sea action results in impacts with thick gravel, in mountain streams or in environments where dynamic action of water occurs, it is recommended to use a material of class MDE10. Armourstone category M_{DE20} is recommended for high-wear environments, for example, in places where occasional sea storms occur while the M_{DE30} armourstone class can be used in an environment which is characterized by constant wave action or the presence of suspended silt.

TABLE 3

Abrasion resistance classification according to PN-EN 13383-1:2003

Micro-Deval	Category
≤10	M_{DE10}
≤20	M_{DE20}
≤30	M_{DE30}
Other value declared by the stone producer	$M_{DEDeklarowana}$
No requirement	M_{DENR}

It so happens that the rock material intended for armourstone is assessed on the basis of outdated standard BN-79/8952-31. This standard very carefully specified the requirements regarding the type of rock material, its shape, dimensions as well as its physical and mechanical properties. Armourstone was also categorized based on its properties, into four classes (Table 4).

TABLE 4

Physical and mechanical properties of armourstone according to BN-79/8952-31

Properties	Unit	Class of Natural Rock			
		AND	II	III	IV
Compressive strength in the air-dry state	MPa	80	60	20	5
Freezing and thawing resistance	cycles	25	25	21	10
Abrasion resistance in Boehme's abrasion tester	mm	2.5-5	5-7	7-10	—
The mass density – igneous and metamorphic rocks – sedimentary rocks	g/cm^3	2.45-2.85 1.90-3.00		2.50-2.75 1.70-2.60	— 1.35-1.80
Water absorption – igneous and metamorphic rocks – sedimentary rocks	%	0.5 2.5	1.5 4.0	— 12.0	— 30

A fundamental mechanical criterion is the compressive strength in a dry state in conditions where the majority of the structure is constantly exposed to water. In addition, water absorption of a few percent may result in material softening and in the rinsing of the binder which may dramatically decrease the compressive strength, especially in sedimentary rocks.

4. Quality evaluation of selected types of sandstone

4.1. Petrography characteristics

Carpathian Sandstone is one of the most popular rock materials, used as aggregates, cladding material, and armourstone. It was formed as a result of deep-sea flysch sedimentation, diagenetic processes, and significant tectonic disturbances. A characteristic feature of the sandstone is its grey colour with blue, greenish or yellow hues depending on the origin. It is characterized by different mineral compositions of both the aggregates and the binder. The mineral composition is dominated by quartz (30%-50%) and includes secondary components such as feldspar, plagioclase, mica, and lithoclasts, glauconite and others which represent a few to a dozen percent of the total volume. The cement of the sandstone consists primarily of silica and different proportions of clay and carbonate substances, even for a material from the same deposit. Sandstone is usually found in the vicinity of slate, has a very large range of shoals, and displays characteristic lamination or fractional layering (Bromowicz & Figarska-Warchoł, 2012).

In the presented work, sediments represented by lithofacial varieties of sandstones: Godula, Cergowa, Magura, and Krosno were the subject of research (Fig. 3). The Krosno Sandstone represents rock samples from the Barwałd, Górka-Mucharz, and Porąbka quarries, while the Magura Sandstone represents samples from Klęczany, Dąbrowa, Osielec, and Męcina. The Cergowa and Godula Sandstones represent rock samples from the Komańcza-Jawornik and Lipowica quarries and Głębiec quarry, respectively.

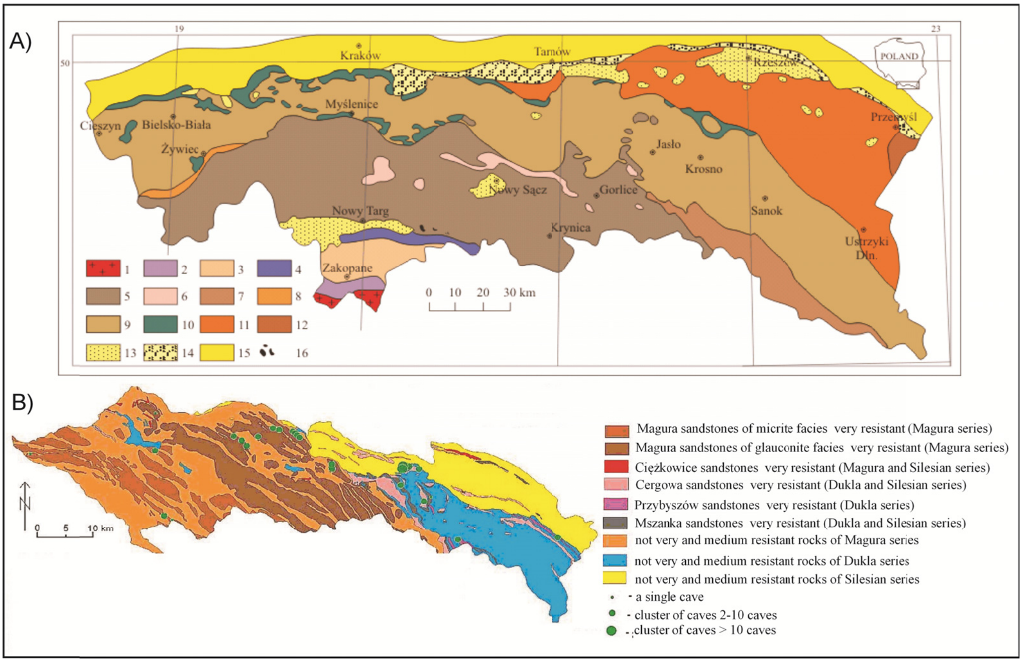

Fig. 3. A) Geological sketch–map of the Polish Carpathians (http://ing.uj.edu.pl), Legend: 1 – crystalline core of the Tatra Mts., 2 – High Tatra and sub-Tatra units, 3 – Podhale flysch, 4 – Pieniny Klippen Belt, 5 – Magura nappe, 6 – Grybów unit, 7 – Dukla unit, 8 – Fore-Magura unit, 9 – Silesian unit, 10 – Sub – Silesian unit, 11 – Skole unit, 12 – Sambor-Rożniatov unit, 13 – Miocene deposits upon the Carpathians, 14 – Zgłobice unit, 15 – Miocene deposits of the Carpathian Foredeep, 16 – andesites; B) Carpathian sandstones (http://beskid-niski.pl)

The Godula sandstones are usually found as medium and coarse varieties, with an addition of glauconite. This type occurs mainly in the vicinity of the Silesian and Little Beskids. On the western side of the Carpathians, three levels can be distinguished: lower, middle and upper, and upper level are not composed it’s application. The predominant types of sandstone are greywacke and oligomyctic sandstones, rarely do we meet arkose and quartz sandstones with the tendency for more quartz rocks to occur in the lower level and greywacke sandstones in the middle level. In the vicinity of the Little Beskids, the thickness of these sandstones reaches a value of up to 1500 m, which gives a greater prospect of obtaining and developing extraction of these raw materials (Radwanek-Bąk, 2005). Sandstones from the Głębiec deposit consist mainly of quartz (an average of 57.9%) and a large number of rock crumbs (average 13.3%). The remaining components are found in a smaller share: feldspar (on average 8.0%), micas (on average 2.3%), and glauconite (on average 2.7%). Regarding the binder of the sandstones, on average 15.8%, is made of silica, predominantly over clayey and carbonaceous matter (Rębiś & Smoleńska, 2010).

The Cergowa sandstones are found in two tectonic varieties of the flysch Carpathians. Near Dukla, lie the south-western part of these rocks, while the vicinity of Silesia is distinguished by sandstone in its north-eastern part. They occur in layers forming deposits above the horn layers of the menilite series, their thickness reaching 300 meters. They are hard rocks, resistant to crumbling and weathering. The binder of the Cergowa sandstones is usually calcareous and rarely clayey. The sandstones of Cergowa also contain a significant amount of carbonates.

The Magura sandstones occupy large areas of the Magura unit (Fig. 3). These sandstones form very thick beds and build the high peaks of the middle part of the Carpathians: Babia Góra, Pilsko, Turbacz. They are usually grey in colour and their binder is clayey-calcareous or siliceous-clayey, a limestone-siliceous binder is less common. The most prevalent of these sandstones are fine and medium-grained deposits. Within them, there are assorted larger grains of quartz, muscovite plaques, fragments of shales, and grains of glauconite. The thickness of the beds may reach up to several metres, although they usually occur in layers with a thickness of 1-5 m. The morphological elevations are formed by varieties that do not show crusted separateness and this type of studied sandstone is also resistant to weathering (Radwanek-Bąk, 2005).

The Krosno sandstones occupy quite large areas of the flysch formations of the Silesian, Skole, and Magura units and also occur in the central part of the Carpathian depression and Dukla folded sediments (Fig. 3). In the Krosno sandstones, three levels are marked: lower, middle, and upper. In the lower level, there are visible block sandstones which occur in the form of the thick beds. These rocks easily undergo weathering and disintegration, there are no clayey interbeds within them. In contrast, sandstones from the middle level form thin layers of fine-grained, very compact sandstones with a lot of shale inserts. Upper-level rocks have a shale character and are not of major operational importance. The studied Krosno sandstones represent deposits from Górka-Mucharz, Barwałd, and Porąbka. They are built by thick-bedded sandstones with a thickness of up to 5.4 m in the Barwałd quarry and up to 6 m in the Górka-Mucharz excavation. These sandstones are characterized by a greyish-blue colour, a fine-grained texture and a disordered structure. They are composed mainly of quartz grains in the proportion of 36.8% (Barwałd deposit) and 35.2% (Górka-Mucharz deposit), and lithoclasts in the amount of 13.5% (Barwałd deposit) and 14.7% (Górka-Mucharz deposit). Feldspars and micromicas occur in minor, several percent shares. Glauconite, organic substance, and pyrite are sporadically found. The binder present in the amount of 37.5% (Barwałd deposit) and 42.7% (Górka-Mucharz deposit) is carbonate-siliceous with a small amount of clayey material. Among the carbonate components, sparite prevails over micrite (Rębiś & Smoleńska, 2010).

4.2. Physical and mechanical properties

The properties of Carpathian flysch sandstones are very well known. There is a lot of literature concerning the evaluation of the geotechnical and resistance parameters of sandstones in relation to weathering and even deterioration (Pinińska, 2003; Rębiś & Smoleńska, 2010; Łukasiak, 2013). Carpathian flysch sandstones are characterized by high internal changeability of the stone material, expressed by the presence of laminates, pores, fissures, the direction of mineral grain arrangement etc., all of which have a direct influence on the significant spread of property values, especially the mechanical values of these stones (Kłopotowska & Łukasiak, 2017; Figarska-Warchoł & Stańczak, 2016; Łukaszewski, 2007; Tajduś & Tajduś, 2017; Niedbalski et al., 2018).

All the results presented in tabs 5-7 come from studies of material acquired from resource areas designated for the use of stones in hydrotechnical works. All tests were performed at the Rock and Stone Property Research Laboratory (LBWSiWK AGH Krakow) accredited by the Polish Centre for Accreditation (PCA). The test results were divided into three groups, namely physical properties (Table 5), strength requirements (Table 6), and resistance to abrasion and fragmentation (Table 7).

TABLE 5

The physical properties of sandstone (based on LBWSiWK reports)

Type	Quarry	Mass density, Mg / m^3		Absorption, %		Freeze-thaw,, % loss	
		According to PN-EN 13383-2: 2003					
		min-max	Medium	min-max	medium	min-max	medium
Krosno Sandstone	Barwałd	2.31-2.71	2.55	0.25-3.70	1.75	0.02-1.85	0.26
	Górka-Mucharz	2.60-2.65	2.63	0.94-1.52	1.17	0.01-0.21	0.12
	Porąbka	2.64-2.68	2.67	0.39-0.78	0.60	0.06-0.24	0.12
Magura Sandstone	Klęczany	2.56-2.69	2.65	0.30-1.80	0.73	0.00-0.20	0.03
	Dąbrowa	2.60-2.66	2.64	0.90-1.50	1.10	0.07-0.52	0.20
	Osielec	2.54-2.69	2.59	0.13-1.86	0.53	0.02-1.93	0.18
	Męcina	2.50-2.59	2.54	1.26-2.47	1.86	0.09-1.03	0.21
Cergowa Sandstone	Komańcza	0.58-2.66	2.63	0.86-1.96	1.25	0.05-0.66	0.34
	Lipowica	2.48-2.77	2.62	0.52-2.94	1.34	0.05-1.62	0.22
Godula Sandstone	Głębiec	2.40-2.51	2.44	1.14-3.71	2.91	0.09-0.35	0.19

Every sandstone satisfies the minimum mass density requirement of 2.30 Mg/m^3. The absorption coefficient values indicate fairly significant variations (0.13% to 3.71%). Due to the high value of the coefficient of water absorption, additional frost resistance tests were required for all of the sandstones. The average weight loss after 25 cycles of freezing and thawing did not exceed the threshold value of 0.5% for sandstone from only four quarries; Górka-Mucharz, Porąbka, Klęczany, and Głębiec. However, the weight loss incurred by the remaining sandstones indicates that only a small decrease in durability is possible due to frost action. Submitting the water-saturated test samples to freezing and thawing cycles caused a decrease in the average strength and an increase in its disparity. In the dry air state, the compressive strength is a rather high value and remains above 100 MPa. By saturating the samples with water, the Rc value is usually reduced by 20% (Klęczany) to 40% (Głębiec) compared to the dry samples. Sandstone

TABLE 6

Compressive Strength (based on LBWSiWK reports)

Type	Quarry	Compressive strength, MPa					
		According to PN-EN 1926:2001					
		Air-dry state		After water saturation		After the frost resistance test	
		min-max	medium	min-max	medium	min-max	medium
Krosno Sandstone	Barwałd	57-178	122	40-153	86	63-111	81
	Górka-Mucharz	105-138	121	73-115	88	21-102	80
	Porąbka	—	—	77-124	94	—	—
Magura Sandstone	Klęczany	91-207	164	66-161	131	—	—
	Dąbrowa	—	—	63-170	89	—	—
	Osielec	—	—	63-194	114	—	—
	Męcina	—	—	59-123	91	—	—
Cergowa Sandstone	Komańcza	115-207	170	94-161	133	108-149	133
	Lipowica			94-173	134	75-142	110
Godula Sandstone	Głębiec	125-157	146	55-117	85	—	—

TABLE 7

Resistance to abrasion and fragmentation (based on LBWSiWK reports)

Type	Quarry	Abrasion on the Boehme disk in the air-dry state, mm		Abrasion resistance in the micro-Deval drum, %		Resistance to fragmentation in the Los Angeles drum, %	
		According to PN-B-04111:1984		According to PN-EN 1097-1:2000		According to PN-EN 1097-2:2000	
		min-max	medium	min-max	medium	min-max	medium
Krosno Sandstone	Barwałd	2.3-5.8	4.1	60.9-74.0	69.2	49.1-51.4	50.3
	Górka-Mucharz	3.8-4.9	4.6	—	—	—	—
	Porąbka	—	—	35.2-36.8	35.7	24.3-29.5	26.0
Magura Sandstone	Klęczany	3.2-3.9	3.5	22.1-40.3	28.5	17.7-25.8	20.2
	Dąbrowa			37.6-38.1	37.9	26.7-28.2	27.5
	Osielec	2.8-6.7	4.8	31.7-51.1	41.6	21.5-42.0	31.3
	Męcina			43.1-59.0	46.7	28.7-37.3	33.4
Cergowa Sandstone	Komańcza	3.7-4.5	4.0	30.9-40.9	36.7	27.7-31.5	28.8
	Lipowica			39.1-47.1	37.4	20.1-27.4	23.3
Godula Sandstone	Głębiec	—	—	45.0-46.2	45.6	50.7-51.7	51.2

subjected to freezing and thawing cycles causes the compressive strength to decrease by at most a few percent with respect to the saturated sample. The decrease of the resistance to squeezing after water saturation is very high and may be a result of the quantitative and qualitative diversity in the petrographic composition of the studied stones. The changeability of technical qualities of sandstones is largely a result of the influence of the type and amount of adhesive.

The magurskie sandstones (Klęczany) are poor in limestone, and the dominating element of the adhesive is a loamy-silicate substance. The adhesive in godulskie sandstones (Głębiec) consists of silica with the addition of carbonates and loamy minerals. However, among those, there are petrographic types whose dominating constituents are loamy minerals. The presence of loamy minerals, mainly smectites, has an influence on the absorption and accumulation of water. This phenomenon causes a rise in the absorptivity of stone materials, which is confirmed by the achieved absorption results. The study shows that godulskie sandstones are characterized by a significantly higher absorption capability, i.e. an average of 2.91% in comparison to magurskie sandstones whose average value was 0.73%. The enormous influence of water on the results is also visible in the analysis of the resistance to abrasion in the micro-Deval apparatus using water. The average sandstone weight loss values in the micro-Deval abrasion test show variable results ranging from less than 30% for the Klęczany quarry to even 69% for Barwałd. These values are very high, and in most cases cause this material to be unsuitable as armourstone even in an environment with still water. Such material may only be used in parts of the structure which do not have permanent contact with water. This is also confirmed in the CIRIA, CUR, CETMEF (2007) guidelines according to which almost all sandstones except for those from the Klęczany deposit are classified as poor. On the other hand, an analysis of weight loss incurred during the Los Angeles resistance to fragmentation tests (test in dry conditions) indicates that the sandstones can be classified in a variety of ways ranging from good (Klęczany, Lipowica) to bad (Barwałd and Głębiec). The remaining sandstones are classified as marginal. Abrasion on the Boehme disk reduces the height of the sample by up to 5 mm (except for samples from Osielec). This fact, along with its high compressive strength in the dry air state, categorizes the rock material as class I armourstone according to BN-79/8952-31.

5. Conclusions

The study reviewed the results of the analysis of physical and mechanical properties of the selected Carpathian flysch sandstones, Krosno, Magura, Cergowa, and Godula. The analyzed sandstones are characterized by quite good parameters in terms of bulk density, absorption, and frost resistance. The resistance to abrasiveness (Boehme test) and fragmentation (Los Angeles test) tested on dry samples show that the material is of quite good quality and is resistant to the effects of mechanical factors. However, compressive strength tests and the analysis of resistance to abrasion (micro-Deval) of the samples previously saturated with water lead to deterioration of the quality of the stone material despite the quite low value of absorption. This fact makes the use of this material as armourstone dangerous in terms of the durability of the construction, especially as these areas are constantly exposed to the dynamic influence of water.

The difficulties in the evaluation of the stone material for hydrotechnical constructions should also be considered in the light of various classifications. The most extensive classifications are CIRIA, CUR, and CETMEF (2007). According to these criteria, the studied sandstones would qualify as marginal or bad at best. This would imply that they might be used in built-up constructions with low water load. The use of this stone can be connected to the short exploitation time of the structure and would be necessary to maintain full control over the quality of the stone material. A completely different image of the quality of the studied sandstones is provided by the evaluation using BN-79/8952-31. Nearly all of them would achieve class I, which would mean that they could be used in any water conditions, even in marine or oceanic constructions.

Unfortunately, due to the low resistance to abrasion in the presence of water, they would be quickly destroyed. While analyzing the studied material in accordance with the standard PN-EN 13383-1:2003, particularly in terms of the resistance to abrasion when saturated with water, they generally achieve the borderline values of categories CS_{80} and CS_{60}. Unfortunately, the lack of resistance to abrasion disqualifies the use of these sandstones even in an environment with a moderate influence of waves or silt.

The requirements included in the norm PN-EN 13383-1:2003 are sufficient for the basic evaluation of the quality of the stone for hydrotechnical works. However, in order to fully evaluate the usefulness of the stone, one can refer to the classifications CIRIA, CUR, and CETMEF (2007), whereas it is unacceptable to refer to BN-79/8952-31 requirements because they use the results of the analysis of dry materials. In summary, Carpathian Sandstone can be used in the construction of small local hydraulic structures using gabions, loose boulders or in strengthening shores and slopes. However, due to the large variability of sandstone parameters, a quality assessment of the rock material is necessary prior to every use.

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