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CHARACTERISTICS OF SELECTED PHYSICAL AND MECHANICAL PROPERTIES AS WELL AS CHEMICAL COMPOSITION OF AGGREGATES BASED ON: STEEL SLAGS, PORPHYRY AND DIABASE

I. JONCZY[1], B. GRZESIK[2], M. STAWOWIAK[3], A. GERLE[4]

This paper presents the results of tests of selected physical and mechanical properties as well as the chemical composition of two types of natural aggregates: porphyry and diabase, as well as artificial aggregate based on steel slags. Based on the conducted tests, it was established that the physical and mechanical properties of the artificial aggregate exhibit slightly lower parameters as compared to the results obtained for porphyry and diabase aggregates. However, this does not limit the possibility of using the aggregate based on steel slags, as according to the applicable WT-4 and WT-5 standards, it can be used in mixtures unbound to the improved subsoil and layers of the road foundation as well as road mixtures with hydraulic binders for each category of traffic load. The chemical composition of the aggregate based on steel slags differs from the chemical composition of the tested natural aggregates. The slags contain lower amounts of SiO_2 and Al_2O_3, while the concentration of CaO and Fe_2O_3 is greater. Additionally, heavy metals have also been exhibited in the slags. However, it was established that the alkaline nature of the slags, which is affected by low sulphur content and a significant proportion of CaO, as well as the way the metals occur limit the possibility of heavy metals release and migration from slags. The tested steel slags may constitute a prospective material used in road construction.

Keywords: aggregates, steel slag, porphyry, diabase, physical and mechanical properties

[1] DSc., PhD., Eng., Silesian University of Technology, Faculty of Mining, Safety Engineering and Industrial Automation, Akademicka 2, 44-100 Gliwice, Poland, e-mail: iwona.jonczy@polsl.pl

[2] PhD., Eng., Silesian University of Technology, Faculty of Civil Engineering, Akademicka 2, 44-100 Gliwice, Poland, e-mail: bartlomiej.grzesik@polsl.pl

[3] PhD., Eng., Silesian University of Technology, Faculty of Mining, Safety Engineering and Industrial Automation, Akademicka 2, 44-100 Gliwice, Poland, e-mail: michal.stawowiak@polsl.pl

[4] PhD., Eng., Institute of Ceramics and Building Materials, Refractory Materials Division in Gliwice, Toszecka 99, 44-100 Gliwice, Poland, e-mail: a.gerle@icimb.pl

1. INTRODUCTION

Aggregates are a raw material widely used in various branches of the construction industry, as the progress in the development of urbanization causes a continuously increasing demand for this type of materials. Due to the fact that the resources of natural aggregates are starting to shrink, and the expansive mining activity leads to the degradation of subsequent natural areas, artificial aggregates are increasingly used in road construction.

By definition, aggregate is a fine-grained material used in construction that can be of natural, artificial, or recycled origin. Natural aggregate is an aggregate produced on the basis of raw rock materials obtained from natural deposits of mineral origin; the most popular include gravel aggregates (gravel-sand, sand-gravel, or generally gravels and sands), but also crushed aggregates, produced from crushed solid rocks (including basalt, granite, dolomite, sandstone). Artificial aggregate is a mineral aggregate; however, it is obtained from material resulting from an industrial process, including heat treatment or other modifications. This group is dominated by aggregates produced on the basis of smelter slags: blast furnace, steel-making, and copper production slags [16, 24].

The demand for the production of artificial aggregates, especially based on steel slags, was caused on the one hand by the need to utilise smelter waste, which arises in considerable amounts during the production process, while the other aspect was the fact that the physical and mechanical properties of these aggregates did not differ from those of natural aggregates, including those based on igneous rocks. Steel slags are increasingly used as an additive in the production of cement binders and as a substitute for natural mineral aggregates, both in unbound layers of road foundations, as well as in the production of mineral and asphalt mixtures used in road construction [30, 31, 32, 35]. In addition, the acquisition of aggregates from slags deposited in dumps results in their removal, and thus leads to the recovery and revitalization of the areas they occupy [17]. These types of activities are carried out in many countries, including Germany. Slag formed as a by-product of the electric furnace (EAF) is used as aggregates for road construction (e.g. asphaltic or unbound layers), as armour-stones for hydraulic engineering constructions (e.g. stabilisation of shores), and as fertiliser for agriculture purposes [20].

The only factor that should receive special attention when using aggregates produced from steel slags is their chemical composition. In the smelting process, some elements, including heavy metals, pass into the slag. Therefore, it is necessary to constantly monitor the chemical composition of the aggregate so as not to introduce additional pollution into the environment [1, 2, 12].

This paper presents the characteristics of selected physical and mechanical properties of three types of aggregate: artificial, made on the basis of steel slags, and two natural (crushed) aggregates – porphyry and diabase. Attention was also paid to the chemical composition of the aggregates, which may significantly affect the nature of the aggregate and the possibilities or restrictions in its use.
The purpose of the research planned and carried out in this way was to determine whether the analysed artificial aggregate, produced on the basis of steel slags, could be used interchangeably with natural aggregates.

2. RESEARCH MATERIAL

The tests included:

– about 100 kg of granular material, which was entirely a recycled aggregate produced from steel slags, with a fraction of 0÷6.3, 6.3÷2, and 25÷63 mm;
– about 200 kg of crushed porphyry and diabase aggregates. The porphyry aggregate consisted of mixes with a grain size of 0÷16, and 4÷31.5 mm, and crushed stone with a grain size of 31.5÷63.0 mm, as well as about 50 kg of grit with a grain size of 8÷16 mm. The diabase aggregate was represented by grits with a grain size of: 4÷8 mm and 8÷16 mm as well as crushed stone with a grain size of 31.5÷63 mm and unsorted crushed stone with a grain size of 0÷63 mm.

The aggregate based on steel slags was obtained with the consent of the EkoProHut Sp. z o.o. company with its headquarters in Gliwice-Łabędy. The material for the production of aggregate was steel slag, stored for several dozen years at a waste dump which is a remnant of steel smelting in open-hearth furnaces of Huta Łabędy. The slag has a grey colour, a fine-grained structure, and a porous texture. Natural porphyry and diabase aggregates were obtained from the Kopalnia Porfiru i Diabazu (Porphyry and Diabase Mine) Spółka z o.o. company [15]. The mine exploits porphyry in the town of Zalas (Lesser Poland voivodeship, Cracow administrative territory, Krzeszowice commune) and diabase in the "Niedźwiedzia Góra" deposit – the mine is located in the village of Tenczynek. The mine exploits porphyry occurring to the south of the Krzeszowice ditch. This type of porphyry is found in a compact mass near Zalas, Sanka, Frywałd, Baczyn, and Orlej. It belong to the same porphyry intrusion limited by faults on all sides and partially destroyed by erosion [5, 7, 18]. Porphyry is characterized by a grey-pink colour, a porphyry structure, and a compact, random texture. Macroscopically, one can see feldspar, quartz, and biotite phenocrysts embedded in fine-crystalline rock mass. Diabase varies in colour from black on a fresh fracture to dark grey on weathered surfaces, where one can also observe a rust-greenish coating filling small depressions in the rock. These are the spots remaining after larger olivine crystals that have been weathering (Fig. 1).

a) b) c)

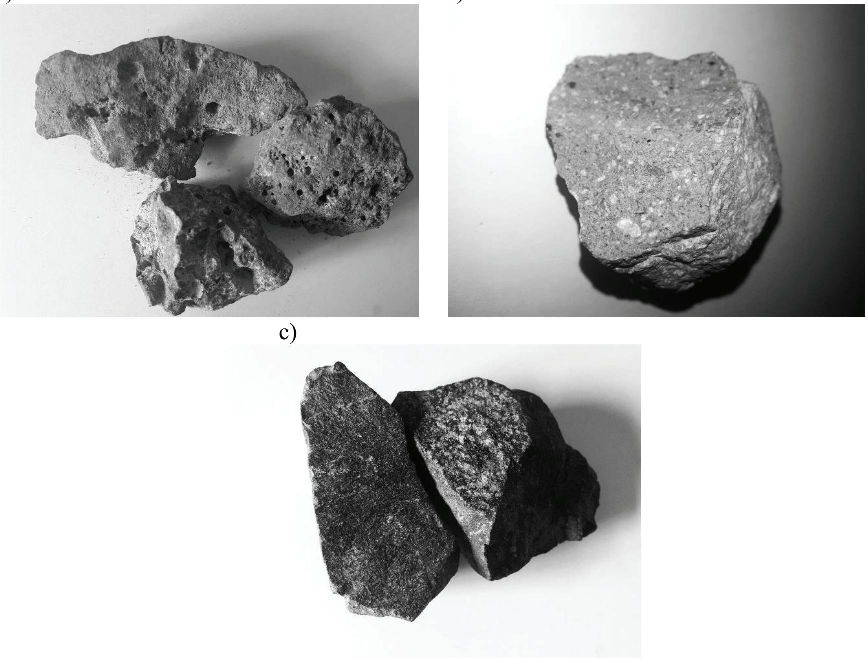

Fig. 1. Aggregate: a) based on steel slags; b) porphyry; c) diabase

3. RESEARCH METHODOLOGY

Tests of the selected physical and mechanical properties were carried out in the laboratory of the Faculty of Civil Engineering at the Silesian University of Technology in Gliwice. Properties that are important due to the nature of the current use of the tested aggregate, mainly in the construction layers of road surfaces, have been tested for. The tests determining the following properties were carried out: density, water absorption, resistance to freezing and thawing, resistance to fragmentation and crushing strength (tab. 1).

Table 1. Physical and mechanical properties according to specific basis for the implementation of research

Property	Standard	Tested fraction [mm]	Original fraction of bulk samples [mm]
Grain bulk density	PN-EN 1097-6 [26]	8/11	6.3/25 (steel slags) 8/16 (porphyry) 8/16 (diabase)
Water absorption	PN-EN 1097-6 [26]	8/11	
Resistance to freezing and thawing	PN-EN 1367-1 [28]	8/11	
Resistance to fragmentation	PN-EN 1097-2 [25]	11/16	
Crushing strength	PN-78/B-06714/40 [21]	16/31.5	6.3/25 and 25/63 (steel slags) 4/31.5 (porphyry) 0/63 (diabase)

When determining the individual properties, the most numerous fractions extracted from bulk samples were used to prepare laboratory samples. The selection of fractions is in line with standards.

The grain bulk density was expressed as a ratio of the weight of the aggregate sample dried in the dryer to the volume the sample occupies in water, together with internal, closed voids, but without the voids available to water. The test was carried out according to PN-EN 1097-6 [26], averaging the result from three determinations.

Water absorption was determined according to PN-EN 1097-6, as a percentage increase of the dry sample mass due to water penetration into the grain voids available to it after 24 hours of immersion. The result of the determination is the arithmetic mean of the absorbability of the three samples. Water absorption is declared in one of two categories, i.e. $WA_{24}1$ or $WA_{24}2$. The number after the 24 index means water absorption, respectively: not more than 1% weight and not more than 2% dry weight of the sample.

Frost resistance was determined according to PN-EN 1367-1 [28] and expressed as the average percentage weight loss of three aggregate samples, each isolated population subjected to ten twenty-four hour cycles of freezing and thawing in water. Frost resistance is declared in one of the categories: F_1, F_2, F_4, $F_{Declared}$, F_{NR}, where the number is the maximum percentage weight loss. A loss greater than 4% is declared by the $F_{Declared}$ category. The $F_{Declared}$ category means that due to the given aggregate feature, it cannot be classified into any of the aforementioned categories, while the F_{NR} category means no requirements for a given aggregate feature. The weight loss of aggregate with a grain size of *d/D* (8/11) consists of grains smaller than *d/D* 2 (passing through a 4 mm screen).

Resistance to fragmentation was determined according to PN-EN 1097-2 [25] and expressed as the Los Angeles coefficient, which is a percentage of the sample mass which passed through a 1.6 mm screen after the test, calculated according to the formula: $LA = \frac{5000-m}{50}$ where “m” is the mass remaining on the 1.6 mm screen. According to the PN-EN 13242 standard, the resistance to fragmentation designation is declared in one of the categories: LA_{20}, LA_{25}, LA_{30}, LA_{35}, LA_{50}, LA_{60}, $LA_{Declared}$, LA_{NR}. The number means the maximum percentage of the mass of the analytical sample which, after completing the test consisting of rolling the aggregate with steel balls in a rotating drum (500 revolutions at a constant speed of 31÷33 rpm), passed through a 1.6 mm screen (weight loss).

Crushing strength was determined according to PN-78/B-06714/40 [21], as a percentage loss of aggregate grain mass as a result of crushing with a force of 200 kN (with an increase of 1.25 kN/s) of the sample placed in a steel cylinder. The weight loss consisted of material passing through a 4 mm control screen.

The tests for the chemical composition of the aggregates using the X-ray fluorescence method (XRF), the determination of sulphur and heavy metal content in the slag, as well as the leaching test were carried out at the Institute of Ceramics and Building Materials, Refractory Materials Department in Gliwice. The tests were carried out on samples ground to a grain size of less than 63 μm using a grinder with a tungsten carbide lining and dried at 105°C to constant weight. In order to determine the chemical composition using X-ray fluorescence (XRF) according to PN-EN ISO 12677: 2011, the loss of ignition at 1025°C (L.O.I.) was determined. The sample, fired to constant weight, was fused with a mixture of lithium tetraborate, lithium metaborate, and lithium bromide (66.67, 32.83, and 0.5%) with a flux purity up to XRF (Spex). The weight ratio of sample to flux was 1:9. The chemical composition analysis was performed using a PANalytical MagiX PW2424 spectrometer calibrated using a series of certified reference materials JRRM 121-135, JRRM 201-210, JRRM 301-310, The Technical Association of Refractories, Japan.

The sulphur content in the slag sample was determined using a Leco SC 144 DR sulphur and carbon analyser with a resistance furnace. The sample with the addition of vanadium pentoxide was burned at 1350°C in an oxygen stream. The SO_2 content in the resulting gas was determined by measuring the absorption of infrared radiation.

In addition, heavy metal content was determined for the slags using the method of emission spectrometry with induced plasma excitation (ICP-OES). Solutions containing 0.1 g of the sample in a 100 ml flask and 0.5 g of the sample in a 50 ml flask were prepared. 0.5 or 0.1 g of the sample was weighed into a platinum bowl and moistened with a few drops of water. 1 cm^3 of a 20% sulphuric acid solution and 10 cm^3 of a 40% hydrofluoric acid solution were added. Then, the acids were evaporated to remove SiO_2 from the sample. The evaporation of acids was repeated twice. The

dry residue after the removal of SiO_2 was dissolved in 30 ml of 1:1 hydrochloric acid solution. The solution was filtered into a 50 or 100 ml flask. The filter with the residue, after washing with hot water, was incinerated and the residue was molten with 1 g of anhydrous sodium carbonate and sodium tetraborate mixture (1:1) at 1100°C for 10 min. The melt was taken up in the filtrate of the first filtration. Water was added to the resulting solution up to the volume and it was analysed. The concentrations of the elements were determined using an ICPE 9800 plasma excitation emission spectrometer from Shimadzu with a Teflon sample introduction system allowing for work with hydrofluoric acid. Operating parameters: vertical burner, side view direction, exposure time 30 s.
The leaching test was carried out in accordance with the following standards: PN-97/Z-15009 – Solid waste [22]. Preparation of the water extract and PN-98/Z150012 – Solid waste [23]. Preparation of the water extract from oily waste. In a bottle, distilled water was added to a 100 g sample in an amount ensuring a 1:10 ratio of dry waste to water. After one hour, the flask was closed and shaken in a laboratory shaker for 4 h. Then, the open bottle was left for 16 hours. After this time, the contents of the bottle were shaken for another 4, and left for 2 h. After the shaking, the contents were centrifuged in a centrifuge, filtered and collected in a labelled conical flask. Elemental concentrations were determined by atomic emission spectrometry with induced plasma excitation (ICP-OES) with parameters as above.

4. RESEARCH RESULTS

4.1. SELECTED PHYSICAL AND MECHANICAL PROPERTIES

The results of the determination of selected physical and mechanical properties are presented in Table 2.

Table 2. Test results of selected physical and mechanical properties

Property	Type of aggregate material		
	slag	porphyry	diabase
Grain bulk density [kg/m^3]	3,066	2,536	2,755
Water absorption [%]	5.6	1.7	1.5
Resistance to freezing and thawing [%]	8.0	0.6	3.6
Resistance to fragmentation LA [%]	32	16	13
Crushing strength [%]	23.5	10.7	6.3

It was established that the volume density of the artificial aggregate produced on the basis of steel slags is higher compared to the volume density of the tested natural aggregates and amounts to over

3,000 kg/m^3. The volume density values of porphyry aggregate and diabase aggregate are 2,536 and 2,755 kg/m^3, respectively. The water absorption of slag aggregate is definitely higher than that of porphyry and diabase aggregate. It amounts to 5.6%. The water absorption of the tested natural aggregate is not higher than 2%. The frost resistance of the tested aggregates, expressed as weight loss of samples subjected to ten 24-hour freezing and thawing cycles, was 8 for slag, and 0.6, and 3.6% for porphyry and diabase, respectively. Resistance to fragmentation for the analysed aggregates was as follows: slag 32%, porphyry 16%, and diabase 13%. Crushing strength, expressed as a percentage weight loss of aggregate grains as a result of crushing, definitely reached the highest value for slag (23%), 10.7 for porphyry, and 6.3% for diabase.

4.2. CHEMICAL COMPOSITION

The results of the analysis of the chemical composition of the tested aggregates are presented in Table 3.

Table 3. Chemical composition of tested aggregates

Chemical compound/element	Content in the aggregate material [wt. %]		
	slag	porphyry	diabase
L.O.I.	0.59 ± 0.06	1.19 ± 0.12	0.99 ± 0.10
SiO_2	25.37 ± 0.63	69.47 ± 1.74	53.54 ± 1.34
Al_2O_3	7.29 ± 0.36	15.04 ± 0.75	15.85 ± 0.79
Fe_2O_3	22.32 ± 1.12	2.68 ± 0.13	10.75 ± 0.54
TiO_2	0.51 ± 0.26	0.37 ± 0.19	1.77 ± 0.18
MnO	4.84 ± 0.24	0.04 ± 0.02	0.16 ± 0.08
CaO	30.06 ± 0.75	2.33 ± 0.12	6.39 ± 0.32
MgO	5.74 ± 0.29	0.91 ± 0.46	4.10 ± 0.21
Na_2O	0.18 ± 0.09	4.04 ± 0.20	3.57 ± 0.18
K_2O	0.36 ± 0.18	3.50 ± 0.18	2.00 ± 0.10
P_2O_5	1.24 ± 0.12	0.10 ± 0.05	0.89 ± 0.45
Cr_2O_3	0.64 ± 0.32	0.02 ± 0.01	0.02 ± 0.01
ZrO_2	0.04 ± 0.02	0.02 ± 0.01	0.05 ± 0.03
S (total)	0.16 ± 0.06	-	-
Elements in trace amounts, determined during qualitative analysis	V, Zn	-	-

The chemical composition tests have exhibited that in slag aggregate, the dominant components are as follows: CaO (30.06%), SiO_2 (25.37%) and Fe_2O_3 (22.32%). In addition, there is a share of: Al_2O_3 (7.29%), MgO (5.74%), MnO (4.84%) and P_2O_5 (1.24%) – however, these components occur in much smaller amounts compared to the above three major ones. The content of other oxides does not exceed 1%. In porphyry and diabase aggregates, the component with the highest concentration is SiO_2 silica, with a content of 69.47% for porphyry and 53.54% for diabase. As far as the other components in both types of aggregates tested, Al_2O_3 (over 15%), and Na_2O (about 4%) occur in similar amounts. Compared to porphyry aggregate, the share of Fe_2O_3, TiO_2, CaO, and MgO in diabase aggregate is greater: Fe_2O_3 (diabase: 10.75% Fe_2O_3, porphyry: 2.68% Fe_2O_3), TiO_2 (diabase: 1.77% TiO_2, porphyry: 0.37% TiO_2), CaO (diabase: 6.39% CaO, porphyry: 2.33% CaO) and MgO (diabase: 4.10% MgO, porphyry: 0.91% MgO). For the aggregate based on steel slags, the total sulphur content was also determined. It amounts to 0.16%. The share of selected heavy metals was determined as well. The premise for the determination of metals was the observation during the XRF analysis of the presence of trace amounts of V, Zn, and Cr_2O_3 in the amount of 0.64%. The test results are presented in Table 4.

Table 4. Content of selected heavy metals in the aggregate based on steel slag

Element	Content [mg/kg]
Cd	< 0.02
Co	7.4 ± 2.5
Cr	3,345 ± 334
Cu	211 ± 30
Pb	21.8 ± 3.6
V	884 ± 88
Zn	602 ± 60

Based on the conducted tests, it was established that the aggregate produced on the basis of slag contains elements from the group of heavy metals: chromium Cr (3,345 mg/kg), vanadium V (884 mg/kg), zinc Zn (602 mg/kg), copper Cu (211 mg/kg), and small amounts of lead Pb and cobalt Co. Due to the fact that the presence of heavy metals may be an obstacle in the economic use of slags, their leaching from the tested aggregate was measured. Based on the conducted leaching test, it was established that the signals for the measured elements in the sample of slag aggregates are comparable to those for deionised water. As the result of the analysis, only values below the limit of quantification determined as a 10-fold standard deviation from 3 measurements of the blank sample can be given (the blank sample was water).

5. DISCUSSION

This paper compares selected physical and mechanical properties as well as the chemical composition of artificial aggregate based on steel slags with two types of natural aggregates produced from igneous rocks: porphyry and diabase. The choice of the research material was not unfounded – test samples were taken from the leading producers of artificial aggregate, the EkoProHut Sp. z o.o. company, and natural aggregate – from the Kopalnia Porfiru i Diabazu Sp. z o.o. company. The use of aggregate produced on the basis of steel slags is gaining more and more popularity, which is closely linked with pro-ecological activities aimed at rational waste management. On the other hand, tests conducted in various research centres show that the quality of the produced artificial aggregate in terms of physical and mechanical parameters is comparable to the quality of aggregates produced on the basis of igneous rocks. The results of tests of selected physical and mechanical properties indicated that the artificial aggregate, compared to the tested natural aggregates, has a slightly higher bulk density, above 3,000 kg/m^3, which places it in the group of heavy aggregates. This is characteristic for smelter slags. Mikoś and Stewarski [19] report that the volume density of converter slags stored at the Huta Sendzimir dump reaches a value between 3,360 and 3,530 kg/m^3. The values of the volume density of porphyry and diabase aggregate are in the range between 2,000, and 3,000 kg/m^3, i.e. they can be assigned to the group of ordinary aggregates. It should be noted, however, that the differences in the values of the determined bulk density for individual aggregates are not too large, as they amount to 3,066 kg/m^3 for the aggregate based on slags, 2,536 kg/m^3 for the porphyry aggregate, and 2,755 kg/m^3 for the diabase aggregate.

A fairly clear difference can be seen in the water absorption values. The slag aggregate is characterised by the water absorption of 5.6%, while for porphyry and diabase aggregates the water absorption is comparable and amounts to 1.7, and 1.5%, respectively. In regard to the water absorption, the artificial aggregate can be classified as moderately absorbable, while the tested natural aggregates are not very absorbable. Such differences in the water absorption values are associated with the texture formation of the analysed materials; slags have a porous texture, while the texture of porphyry and diabase is dense. The water absorption of the tested slag aggregate is also relatively high compared to the literature data: for example, for converter slag, the water absorption determined by Mikoś and Stewarski [19] reached a value in the range of 1.5–1.7%. Compared to the tested natural aggregate, also other properties of the aggregate based on metallurgical slags, i.e. resistance to comminution, which is the leading parameter in assessing the suitability of aggregates for use in road engineering, and crushing strength, were characterised by slightly worse results [33]. The resistance to fragmentation determined for the analysed aggregates based on slags also achieved a worse result than the values reported in the literature. According to Węgliński et al. [33], resistance to fragmentation for steel slags is 27%, while tests carried out by

Góralczyk and Kukielska [10] indicate a range between 15 and 23%. The tested aggregates indicated resistance to fragmentation at the level of 32%.

However, this does not exclude the possibility of using artificial aggregate, as it has been exhibited that some of the aggregate properties, regardless of the processing method, significantly affect the properties of the product in which they were used. As an example, Góralczyk and Kukielska [10] indicate the frost resistance of the aggregate as one of the factors affecting the durability of concrete. According to the requirements of European standards, water absorption of aggregate (PN-EN 1097-6) can be assumed as an indicator of frost resistance. It is assumed that the water absorption not exceeding 1% guarantees aggregate frost resistance; in the case of slags, the water absorption value is usually higher, and yet these aggregates are frost resistant.

The chemical composition of the tested natural porphyry and diabase aggregates is quite characteristic and does not differ from the results of analyses of the material from the same deposits by other researchers – Rożen after Bolewski [4] and Wolska [34] – Table 5.

Table 5. Chemical composition of porphyry and diabase according literature

Chemical compound	Content [wt. %]	
	porphyry	diabase
	according to Rożen (1909) cited by Bolewski [4]	according to Wolska [34]
L.O.I.	-	1.31
SiO_2	69.51	50.1
Al_2O_3	12.47	15.19
Fe_2O_3	1.93	13.50
TiO_2	1.02	1.27
MnO	0,17	0.10
CaO	1.74	6.05
MgO	0.66	4.47
Na_2O	3.02	5.75
K_2O	6.29	2.40
P_2O_5	0.06	-

The above data exhibits (Table 5) a fairly high compliance of the results of research conducted in the last century with the results obtained by the authors of this paper (Table 3). It can therefore be concluded that the raw material obtained from both deposits: porphyry and diabase, is characterised by homogeneity in terms of chemical composition, which is a very favourable factor, attesting to the good quality of the produced material. The chemical composition of aggregate based on steel slags is different from that of porphyry and diabase; in the slags, a much smaller share of SiO_2 (25.37%) and Al_2O_3 (7.29%) was observed in relation to the content of these compounds in porphyry (69.47% SiO_2, 15.04%, Al_2O_3) and diabase (53.54% SiO_2, 15.85%, Al_2O_3). Slags, however, contain significantly more iron compounds – the concentration of Fe_2O_3 exceeds 22%, while in the aggregate based on igneous rock it amounts to 2.68% for porphyry and 10.75% for diabase. This is, of course, was related to the characteristics of the tested material, the origin of which is associated with the steel making process [13]. In the slags, a significant share of CaO was also observed – about 30%, while the content of calcium oxide in porphyry reaches the value of 2.33, and 6.39% in diabase. Such a significant amount of CaO in the slags positively affects their alkaline character. The previously conducted research on the slag phase composition [11, 12] showed that calcium in the slags is primarily a component of silicate phases – mainly dicalcium silicates $2CaO{\cdot}SiO_2$ as well as melilites $(Ca,Na)_2(Al,Mg)[(Si,Al)_2O_7]$ and alite $Ca_3[O|SiO_4]$. Moreover, it is included in the oxide phases of calcium ferrites CaO-FeO-Fe_2O_3 and solid solution FeO-MnO-MgO. These phases are quite resistant to weathering processes occurring under the influence of external factors. The alkaline character of the slags limits the migration of heavy metals contained in them, which was confirmed by the leaching test. The low sulphur content, which is around 0.16%, is also a favourable factor. Similar results of limited heavy metal migration from EAF (Electric Arc Furnace) slags were obtained by Gomes and Pinto [9]. The form of occurrence of the heavy metals also affects their limited migration. It has been exhibited that heavy metals do not form their own minerals in the slag. Instead, they occur either in a dispersed form in the glass or as substitutions in the internal structure of silicate phases [12]. This form of binding of heavy metals significantly hinders their release and migration from the slags. It should also be noted that, despite the decades of storage of the tested slags in a dump, and thus their exposure to external factors, in microscopic observations there were no clearly visible manifestations of weathering of the aforementioned silicate phases.

Trying to answer the question of whether it is possible to replace natural aggregates with an artificial aggregate, in this case produced on the basis of steel slags, it should be stated that there are reasons to treat these aggregates as fairly equivalent. Even though the conducted tests have shown that the physical and mechanical properties of the aggregate based on slags differ slightly from the values of these properties determined for igneous rocks, this does not disqualify them as a valuable material for aggregate production. The tested slags generally meet the requirements of the WT-4 application document to the PN-EN 13242 [27] standard for unbound aggregates for the improved subsoil and road foundation layers of each category of traffic load [36]. The increased absorbability (required less than 2.0% weight) does not exceed the level of frost resistance required for this type of material (required not more than 10% weight). In the context of using the material in road mixtures connected with hydraulic binders according to the WT-5 application document to the same standard, slag aggregate, due to its properties, is fully appropriate [37].

It should also be emphasised that the increased amounts of e.g. heavy metals in the chemical composition of slags should not always exclude the possibility of their economic use. The form of occurrence of the elements and the way they are combined with the slag building components is very important [11, 14]. It should also be remembered that steel slags are a material characterised by a very diverse chemical composition, which depends on the type of technological process carried out, i.e. the type of metallurgical charge and the additives used to improve or give the steel appropriate properties. For example, Table 6 summarises the results of the chemical composition analysis of various types of steel slag.

Table 6. Chemical composition of different types of slags

Chemical compound	Content [wt. %]				
	steel making slag BCS* [3]	electric arc furnace slag – EAFS* [29]	EAF* slag [6]	carbon steel slag – BOF* [8]	BOF* slag [38]
L.O.I.	-	-	-	1.1	1.80
SiO_2	15.10	9.36	28.92	10.80	11.97
Al_2O_3	1.69	1.93	3.72	1.90	2.16
Fe_2O_3	43.70	10.18	-	32.00	-
FeO	-	15.09	18.00	-	30.23
TiO_2	0.38	-	-	0.5	0.40
Cr_2O_3	-	-	-	-	0.20
MnO	5.70	2.99	2.23	2.6	2.74
CaO	26.40	39.42	34.09	45.00	39.40
MgO	8.80	8.61	4.15	4.5	9.69
Na_2O	0.42	-	-	-.	0.25
K_2O	-	-	-	-	0.05
P_2O_5	1.62	-	-	1.4	1.00
SO_3	0.15	-	0.13	0.4	0.12
Fe	-	18.82	-.	-	-
Free CaO	-	-	5.45	-	-
Free MgO	-	-	<1.0	-	-
Others	-	-	1.01	-	-

*Explanations:
BCS – steel making slag – BCS No., 381 BASIC SLAG (Soc std.)
EAFS – Electric Arc Furnace Slag
EAF – Electric Arc Furnace
BOF – Basic-Oxygen-Furnace

6. CONCLUSIONS

The following conclusions were reached based on the conducted research:

– Selected determined physical and mechanical properties, i.e. bulk density, water absorption, resistance to freezing and thawing, resistance to fragmentation, and crushing strength for artificial aggregate based on steel slags show slightly lower parameters compared to the results obtained for natural porphyry and diabase aggregates. However, this does not disqualify the artificial aggregate, as according to the applicable WT-4 and WT-5 standards, it can be used in unbound mixtures for the improved subsoil and layers of the road foundation as well as road mixtures bound with hydraulic binders for each category of traffic load.
– The chemical composition of porphyry and diabase aggregates is similar to that determined by other researchers in other batches of the same deposits, which indicates the homogeneity of the deposits.
– The chemical composition of aggregate based on steel slags differs from the chemical composition of the tested natural aggregates. The slags contain smaller amounts of SiO_2 and Al_2O_3, while the concentration of CaO and Fe_2O_3 is greater. Additionally, heavy metals have also been exhibited in the slags. However, it was established that the alkaline nature of the material, which is affected by low sulphur content and a significant proportion of calcium oxide, as well as the way the metals occur – primarily in the dispersed form in the glass and as substitutions in the internal structure of silicate and oxide phases – limit the possibility of release and migration of heavy metals from the slags.
– The tested steel slags may constitute a prospective material for aggregate production.

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LIST OF TABLES:

CHARAKTERYSTYKA WYBRANYCH WŁAŚCIWOŚCI FIZYKO-MECHANICZNYCH ORAZ SKŁADU CHEMICZNEGO KRUSZYW WYPRODUKOWANYCH NA BAZIE: ŻUŻLI STALOWNICZYCH, PORFIRU I DIABAZU

Słowa kluczowe: kruszywa, żużel stalowniczy, porfir, diabaz, właściwości fizyko-mechaniczne

STRESZCZENIE

W artykule przedstawiono wyniki badań wybranych właściwości fizyko-mechanicznych oraz składu chemicznego dwóch rodzajów kruszywa naturalnego: porfirowego i diabazowego oraz kruszywa sztucznego wyprodukowanego na bazie żużli stalowniczych. Na podstawie przeprowadzonych badań stwierdzono, że właściwości fizyko-mechaniczne (gęstość objętościowa, nasiąkliwość, mrozoodporność, odporność na rozdrabnianie LA, wytrzymałość na miażdżenie) kruszywa sztucznego wykazują nieco niższe parametry w odniesieniu do wyników oznaczeń uzyskanych dla kruszywa porfirowego i diabazowego. Nie ogranicza to jednak możliwości wykorzystania kruszywa na bazie żużli stalowniczych, gdyż wg obowiązujących standardów WT-4 i WT-5, może być ono stosowane w mieszankach niezwiązanych do ulepszonego podłoża i warstw podbudowy drogowej oraz drogowych mieszankach związanych spoiwami hydraulicznymi dla każdej kategorii obciążenia ruchem. Skład chemiczny kruszywa na bazie żużli stalowniczych różni się od składu chemicznego badanych kruszyw naturalnych. Żużle zawierają mniejsze ilości SiO_2 oraz Al_2O_3, wzrasta w nich natomiast koncentracja CaO oraz Fe_2O_3, w żużlach oznaczono także obecność metali ciężkich. Stwierdzono jednak, że zasadowy charakter żużli, na który wpływa niska zawartość siarki oraz znaczny udział

CaO, jak również sposób występowania metali przede wszystkim w formie rozproszonej w szkliwie oraz jako podstawienia w strukturze wewnętrznej faz krzemianowych i tlenkowych ograniczają możliwości uwalniania i migracji metali ciężkich z żużli. Badane żużle stalownicze mogą stanowić perspektywiczny materiał znajdujący zastosowanie w budownictwie drogowym.

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