

Properties of fine-grained rock waste from the production of granite elements in the Strzegom region, Poland – a case study

Paweł Strzałkowski ^{1*}, Magdalena Duchnowska ², Alicja Bakalarz ³, Katarzyna Guzik ⁴, Tomasz Ratajczak ⁵, Urszula Kaźmierczak ⁶, Krzysztof Galos ⁷

¹ Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, ORCID ID: 0000-0002-2920-4512.

² Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, ORCID ID: 0000-0001-5345-6042.

³ Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, ORCID ID: 0000-0003-4391-0293.

⁴ Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, Wybickiego 7A, 31-261 Kraków, Poland, ORCID ID: 0000-0002-3804-2914.

⁵ Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, ORCID ID: 0000-0001-8658-565X.

⁶ Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, ORCID ID: 0000-0003-2939-2418.

⁷ Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, Wybickiego 7A, 31-261 Kraków, Poland, ORCID ID: 0000-0001-5649-0190.

Corresponding author: pawel.strzalkowski@pwr.edu.pl (Paweł Strzałkowski)

Abstract: The processing of granitoids as part of the production of stone elements or crushed aggregates generates significant amounts of fine-grained rock wastes in the form of solids or slurries. Problems with their rational management cause processing plants to most typically store them in waste dumps. Only a small part of these wastes is used in the construction or ceramic industries. Their effective use, in line with the ideas of circular economy, has a significant influence on the natural environment, as well as on the efficiency and profitability of processing plants. This type of waste is typically treated as fine-grained waste rock material, with no attempts being made at separating its mineral components. This article presents an analysis of the properties of rock wastes from the production of granite slabs. The tests were performed on samples of fine-grained wastes from the cutting of granite dimension stones mined in the Strzegom massif (Poland). The tests included a physical and chemical analysis and a grain size analysis, as well as magnetic separation of iron-bearing minerals. The results indicate that such wastes are fine-grained, with a chemical composition similar to that of primary materials, but also with an elevated iron content. The analysis of the results of magnetic separation indicates that it is possible to reduce the content of iron in the investigated samples. The results are a basis for further research into a mineral separation technology in the processing of rock wastes from the production of granite slabs and into concepts of their economic usage.

Keywords: granite waste, physical and chemical properties, magnetic separation, mineral processing

1. Introduction

Mining industry is an important branch of economy for most countries worldwide. However, mining activity leaves behind significant amounts of post-mining and post-processing wastes. Wastes that cannot be reused for economic or technical reasons represent a particular problem. Increasingly restrictive legislation related to environmental protection, as well as the strive for profitability, necessitate the use of technically appropriate, economically viable, environmentally friendly, and

socially responsible solutions aimed at managing and limiting the amount of waste (Durucan et al., 2006; Yilmaz, 2011).

Mining activity (related also to the production of certain types of wastes) is one of the areas having a negative impact on the environment (Blight, 2011). As noted by Aznar-Sánchez et al. (2018), current waste disposal strategies concentrate on remediation and reuse, as well as on the evaluation of the mined area for potential alternative functions. The significance of aspects related to the sustained management of mining and processing wastes is evident from the growing number of publications related to this issue (Durucan et al., 2006; Aznar-Sánchez et al., 2018; Kaźmierczak et al., 2019; Qaidi et al., 2022). Many of these publications discuss the amounts and types of wastes, their characteristics and properties, their management, or their potential for being reused in the economy. However, the majority of these publications focus on large mining enterprises (e.g. those extracting metal ores: zinc, lead, copper, iron, etc.). These publications all fit within the framework of circular economy and represent a significant step towards the optimization of mining and processing operations while limiting the negative impact of industrial activity on the natural environment.

The exploitation of common rock materials is a completely different type of mining activity. The mining, and in particular the open pit mining of rock materials is an inexpensive method of providing materials for the construction industry (Jonah et al., 2015; Yardakul, 2020) and the demand for such materials is growing (Galos et al., 2021). Large-scale exploitation of rock deposits produces wastes, which should be properly managed. One of the most important steps in the reuse or disposal of wastes is to properly understand the processes behind waste production at all stages of natural stone production (Yardakul, 2020). Attempts at implementing a circular economy in the production of rock raw materials are also aimed at promoting sustained development in mining regions. Therefore, mining enterprises involved in the extraction of rock materials have started to implement technologies and initiatives related to the use of wastes to solve ecological problems caused by mining activity (Lewicka, 2020). However, according to Bai et al. (2019), current practices and solutions are insufficient, as they are not commonly implemented by rock-mining companies, particularly in developing countries.

The mining of dimension stones is one of the most important types of rock mining – it provides stone elements used e.g. in architecture, construction, and civil engineering works. Generally, the popularity of natural stone is due to its availability, performance, and decorative qualities. An accelerating trend towards the use of natural stone as dimension stone is also related to a wide variety of stones that may serve various purposes, for example as window sills, work surfaces, as well as cladding and floor tiles. As a natural material, stone has a wide range of physical and mechanical properties and therefore it is appreciated in various applications. Some construction products made of natural stone and their parameters are standardized, e.g. in EN 1341: Slabs of natural stone for external paving – Requirements and test methods, or EN 1469: Natural stone products – Slabs for cladding – Requirements. The growing interest in dimension stone and the resulting increased production of elements from this material result in an increased amount of wastes being produced in stone-processing operations (Strzałkowski, 2021).

Stone wastes are a significant problem in many countries worldwide (Karaca et al., 2012; Kaźmierczak et al., 2018; Careddu, 2019; Yurdakul, 2020; Sá Caetano et al., 2020; Strzałkowski, 2021), raising questions about their effective reuse and environment protection. Implementation of a production method that could limit or, ideally, eliminate the amount of such wastes can bring numerous benefits (Fig. 1). The volume of non-biodegradable stone wastes (Lakhani et al., 2014) largely depends on the amount of the processed material (including the efficiency of the processing plant), on the type and size of the generated waste, on the type and geological properties of the stone, on the type of machinery used for stone processing (Karaca et al., 2012), as well as on the employed technology of natural stone processing, on the degree to which the block of stone is used to produce the ready product (Careddu and Marras, 2015), and also on the needs of the clients. Consideration should be paid not only to the amount of stone wastes, but also to their characteristics, which indicate their usage potential in the economy (Yurdakul, 2020). However, this requirement is difficult to meet, in particular when the processing plant is supplied with different types of natural stone (Strzałkowski, 2021).

With a view to the need for undertaking attempts at introducing circular economy models in enterprises involved in the mining and processing of rock raw materials, it seems necessary to initiate a discussion about technologies which could be used to manage wastes from dimension stone mining.

Therefore, the first step in addressing this problem is to investigate the properties of granite wastes from the production of stone elements: a physicochemical analysis of narrow grain-size classes and an attempt to magnetically separate minerals from these classes, as presented in this article. In effect, the results here presented will serve as a basis for further research into a processing technology of effective mineral separation in rock wastes and into concepts of their economic usage.

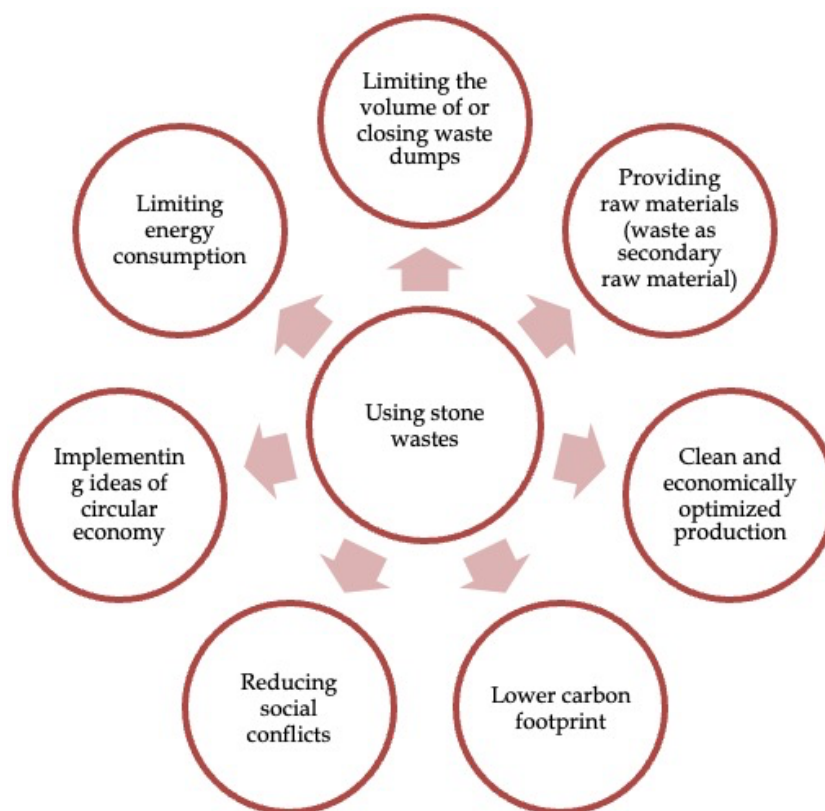


Fig. 1. Profits from the introduction of cleaner production methods in dimension stone mines (own source)

2. Characteristics of stone wastes

Stone wastes from the processing of granitoids can be in liquid or solid form (Table 1). Solid wastes, produced in the process of cutting off larger parts of natural stone or giving the texture of stone surfaces without the use of water, can have a size from several millimeters to several hundred centimeters. On the other hand, liquid waste (in the form of aqueous suspension) is composed of shredded rock masses mixed with water and a small quantity of abrasive material. This waste is produced by using water as a cooling medium and for removing fine stone particles from underneath the processing tool. On the basis of the performed analyses, Strzałkowski (2021) demonstrated that stone waste constitutes between 10% and 35% of the processed stone material, with liquid waste being more than threefold the amount of solid waste. The annual output of granite in Poland for crushed aggregate and blocks in 2023 was at the level of 11.3 million tons, assuming that the mass of fine waste from production is 10%, the annual amount of fine waste generated at processing plants would be at the level of about 1.1 million tons (Brzeziński and Miśkiewicz, 2024).

According to other sources, it is estimated that approximately 20-25% of the volume from an entire block is lost during stone cutting (Vijayalakshmi et al., 2013; Junca et al., 2015). Due to the very fine grain size and high iron content, waste from the production of granite stone blocks is classified as hazardous waste and is usually dumped in field settlements or rivers without any processing (Silva et al., 2011; Junca et al., 2015). In line with the closed-loop economy policy set by the European Commission in 2017 (Zichella et al., 2017) and with the European Commission's Thematic Strategy on Waste Prevention, it is important to carry out a proper characterization of stone-cutting sludge (Junca et al., 2015), so that it becomes possible to think of these materials not as waste, but as a sustainable resource that can be exploited and used.

Table 1. Characteristics of waste from the processing of natural stone (Strzałkowski, 2021)

Type of Waste	Definition of Waste	Description of Waste Source
<i>SOLID WASTE</i>		
Damaged stone blocks	Stone blocks that have significant defects or have been damaged and are characterized by different sizes and irregular shapes	Stone blocks that have insufficient material quality or have been damaged during transport or unsuccessfully divided into smaller parts
Damaged final stone products	Final stone products with inherent and secondary defects	During the processing operation, fractures or defects in the final stone products may occur (secondary defects) or primary defects are revealed.
Wanes / Rough edges	The first and the last slab of a stone block cut in a head saw, having one surface smooth and one surface raw/split	Wanes occur when a stone block with uneven surfaces is cut. The basic operation behind cutting a stone block is to approximate its shape to a cube. Wanes are due to the technology employed in natural stone processing.
Valvestones	Lower part of the cut stone block	Waste generated after cutting a stone block due to safety reasons and non-damage of the cut raw slabs. This waste is generated by the use of selected stone block-cutting technologies (e.g. disc saw) and is less and less frequent.
Waste from splitting	Parts of the split material outside the size standard of the product (e.g. paving stone)	When splitting natural stone into smaller-size elements (e.g. in the production of paving stone), oversize rock parts of the desired element are split off.
Waste from cutting	Parts of rock material which are smaller in volume than wanes and have a minimum of 3 smooth surfaces	Waste produced as part of the size and shape adjustment. Rock material produced as a result of cutting off the oversize parts of natural stone. The quantity of this waste depends on the volume of the cut-off stone parts and the planned cutting locations.
Dust	Fine fraction rock and abrasive material	As stone is processed, fine fractions of rock material and spalls are split/chipped off the rock. In addition, depending on the surface-treatment technology used, this type of waste may include abrasive material (e.g. sand being the product of sandblasting)
<i>LIQUID WASTE</i>		
Slurry / Cake	A mixture of water, ground fine rock, and particles of the cutting tool	This type of waste is generated at each stage of stone processing. Stone is abraded by the processing elements and subsequently mixed with water. This type of waste additionally comprises small amounts of particles from the working tools.

The situation is similar in the production of crushed stone for construction and civil engineering – the finest grain sizes are treated as post-processing waste. Such waste is typically used on a limited scale and most frequently it is deposited as useless material. This fact applies to the majority of mined rocks, magmatic, as well as metamorphic and sedimentary rocks. Waste rock materials, typically having grain sizes smaller than 2, 1, or even 0.1 mm, come from the crushing of primary stone and their usage may be due to the liberation of individual minerals present in the rock (Duchnowska et al., 2022).

In this case, the waste comminution rate obtained in the process of producing stone elements or crushed stone positively influences the profitability of the entire enrichment process of mineral raw materials. Due to their small grain size, rock wastes can be enriched in the absence of the comminution

step – the preliminary and most cost-intensive step in the processing of mineral raw materials. Therefore, the main cost involved in the potential use or processing of such wastes is related to the main operation, i.e. appropriate enrichment. Additionally, fine grain size frequently ensures a high liberation degree of individual mineral components of the rock, thus facilitating the enrichment effectiveness of the desired useful mineral.

Following the ideas of circular economy, the generated granite wastes should continue to be properly processed, if the properties of the rock allow their potential further applications. Although reusing waste in an economy is socially and environmentally important, it should also be economically profitable and technically feasible (Mitchell et al., 2004; Strzałkowski, 2021). Fine-grained granite wastes can be used among others in ceramics (Łuszczkiewicz et al., 1984; Malewski and Simiczijew 1984; Menezes et al., 2005; Panna et al., 2015), as an addition to construction materials, such as mortar, concrete, or bricks (Menezes et al., 2005; Grabiec et al., 2015; Dobiszewska et al., 2016; Singh, 2016; Dobiszewska, 2017; Gupta and Vyas 2018; Shamsabadi et al., 2018; Boadella et al., 2019), and in the production of composite materials (Karimi et al., 2020) or mineral wool (Alves et al., 2015).

Granite wastes produced in stone processing and dressing may be also a potential base of quartzofeldspathic and feldspathic raw materials (Lewicka, 2012; Panna et al., 2015; Duchnowska et al., 2022). Extensive research on the possibility of using waste granite from the Strzegom area in the feldspar industry was conducted by Ociepa (1994) and Łuszczkiewicz (2007). Similar to waste from basalt aggregate production, waste granite can also be used as an additive for concrete (Ghani et al., 2007) or mineral fertilizers (Ramos et al., 2017). In an appropriate enrichment system, their mineral components can be separated, enabling their use in various industry sectors, including in the glass, construction, ceramic, or dyeing industries.

3. Description of the study area

Rock deposits are among the key deposits in Poland, supplying various economic needs of the country. One of the most important groups of mined rock materials are various types of granitoids (plutonic igneous rocks) found in Lower Silesia and formed ca. 300 million years ago (Walendowski, 2012). In this context, the greatest economic importance is attributed to the Strzegom massif, located in the area of Strzegom, Sobótka, and Świebodzice. The massif extends over approximately 50x12 km (Puziewicz, 1990; Glapa and Sroga, 2013a, 2013b). It comprises a number of granite types, most importantly Kostrza and Chwałków types. The first type is a biotite granite with monzonite properties, found in the western part of the massif. The second type, found in the eastern and central part of the massif, is biotite granitoids having a petrographic composition from granodiorites to tonalites (Kural and Morawski, 1968). In Poland, the reserves of granite exceed 930 million metric tons, representing almost 10% of all reserves of deposits classified as crushed and dimension stone deposits (33 lithology types of igneous, metamorphic, and sedimentary rocks). Granites are the third largest group of rocks mined in Poland. The mining output has been recently relatively stable at 11.1 million metric tons per year, accounting for almost 14% of the total output of crushed and dimension stones. The Strzegom-Sobótka massif holds more than 80% of Polish resources of granitoid rocks, and the output from its deposits accounts for 80% of Polish total output of these rocks (Guzik and Figarska-Warchoń, 2023; Brzeziński and Miśkiewicz, 2024). With the assumed output of granitoids in Poland and the average share of fine-grained wastes generated due to the processing and dressing of the stone (at least several percent in the case of producing granite crushed stone and even more than 10% in the case of granite dimension stone), it is estimated that a total of more than half a million metric tons of granite waste is produced in Poland every year.

The granites of the Strzegom massif have received considerable attention from the industry mainly because of their very good physical and chemical properties, high ability to form dimension blocks, as well as the advantageous location of the deposits, detailed geological documentation and good mining accessibility (Karwacki, 1988; Glapa and Sroga, 2013a, 2013b; Guzik and Kot-Niewiadomska, 2015). Various types of granite are mined in the massif, to be used in the production of stone elements and crushed stone. The aim of this study is to present the results of an attempt at identifying the properties of granite wastes from the dressing of granite blocks in the production of stone elements. The samples

used in the tests were fine-grained granite wastes supplied by stonemasonry plants in the region of the Strzegom massif.

4. Materials and methods

The tests were performed on samples obtained from fine-grained rock wastes generated in the production of granite slabs by processing granite blocks with wire and circular saws. Three waste samples were obtained from granite mined in three deposits in the Strzegom massif. They are designated as samples A, B, and C.

The samples were obtained in the form of averaged slurries from the outlets of truncated cone-shaped settling tanks in the water-sludge systems of stone processing plants. In each of the plants, gravitational dewatering is accelerated with cation flocculating agents. The samples were collected in the form of water slurries, and the mass of solid particles in each sample was approximately 60 kg.

After the samples were delivered to the Mineral Processing Laboratory at Wrocław University of Science and Technology, the content of solid particles in the slurries was identified and subsequently each of the averaged samples served as a source of representative 1 kg samples for grain size and chemical analysis of the feed. The grain size distribution was identified in manual wet sieve analysis and with the use of the laser diffraction method (Mastersizer 3000, Malvern Panalytical, Malvern, United Kingdom). The sieve analysis in the first test stage was performed on 0.2, 0.1, 0.07, 0.04, and 0.02 mm sieves. As the fraction below 0.04 mm accounted for approximately 80% of the material, the yield of the finest grain sizes was analyzed again with the use of the laser measurement apparatus. In the case of coarse grain sizes, the results from the manual and automatic analyses were similar.

The averaged feed samples were analyzed for the content of selected chemical components. To avoid the influence of flocculant on the conducted tests, the samples after averaging were rinsed with distilled water to remove this reagent before the separation process. The feed samples were analyzed with the use of the EDXRF PANalytical Epsilon 3^X X-ray fluorescence spectrometer manufactured by Malvern Panalytical B.V. (Almelo, Netherlands). The performance characteristic of the EDXRF apparatus allowed the qualitative and quantitative elemental analysis of the tested material within the range from Al to Am. Some of the EDXRF results were recalculated into an oxide form, in accordance with the methodology of representing results for such materials.

For the separated grain size classes under 0.020 mm and 0.020–0.063 mm, an additional powder X-ray diffraction (XRD) analysis was performed in order to identify the main mineral components. For the grain sizes 0.020–0.063 mm and above 0.063 mm, the observations were performed with the use of scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM-EDS). The samples were sputter-coated with carbon and subsequently analyzed in the HITACHI S-4700 SEM provided with the EDS No-RAN Vantage microanalysis system. The observations were performed in the backscattered electron (BSE) and secondary electron (SE) beams in order to identify the main carriers of iron and other magnetic components.

In the next stage, the grain size classes were separated from the feed and magnetically enriched in order to identify the possibility of separating magnetic fractions, i.e. iron carriers, from the feed. The enrichment experiments were performed in the Frantz Isodynamic® Separator (Model L-1), supplied by Chas. W. Cook M.M. LTD. (England), type MFX. It is a laboratory device used for the precise separation of minerals having different magnetic susceptibilities (Drzymala, 2007). The electric current can be adjusted from 0 to 5 A. The relationship between the electric current flowing in the windings of the Frantz separator (in the range 0 - 0.5 A) and the magnetic field intensity (in Gauss, Gs) between the poles (L) is shown in Fig. 2. During our magnetic separation tests, the electric current in the separator coils was 0.3 A for the main operation and 0.4 A for the cleaning operation. The magnetic separation process was performed for the 0.02–0.04 mm and +0.04 mm grain size classes separated from the feed. The fraction below 0.02 mm was excessively fine to be separated, and also the enrichment of the feed across all grain sizes did not demonstrate the selectiveness of the separation. The separated products were weighed and subsequently analyzed for selected elements with the use of the EDXRF analyzer. Fig. 3 schematically shows the preparatory operations and the magnetic separation.

The magnetic separation process in the Frantz separator was performed in dry conditions. It comprised the main operation, and the resulting half-product was further cleaned from magnetic

components in the cleaning operation. This operation was performed in order to clean the tested materials from magnetic components, mainly from femic minerals present in granites and from strongly magnetic iron filings left by the steel tools used to cut the stone blocks. The purpose of this test was not to separate concentrates having the best qualitative and quantitative parameters, but to verify the general possibility of enriching the tested material.

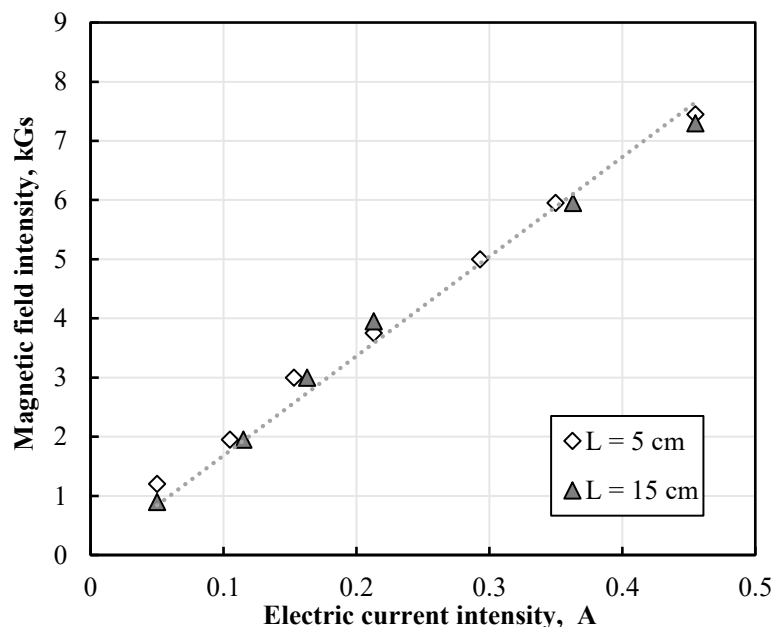


Fig. 2. Dependence of current flowing in windings of the Frantz separator and magnetic field intensity between the poles (L)

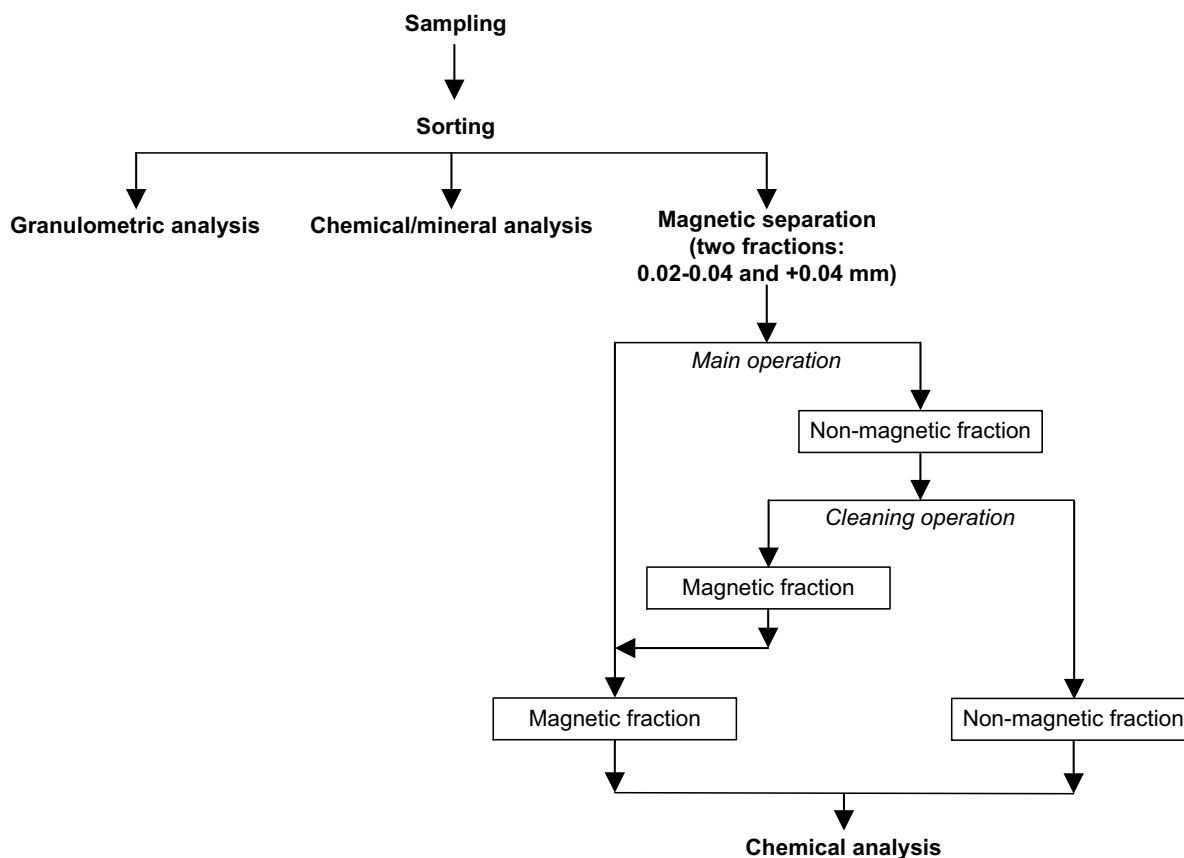


Fig. 3. Scheme of tests

After the separation process, more detailed analyses were performed for sample A. They included XRD and SEM-EDS tests for the +0.04 mm and 0.02–0.04 mm magnetic fractions and for the +0.04 mm and 0.02–0.04 mm non-magnetic fractions, as well as additionally for the -0.02 mm fraction not subjected to magnetic separation.

5. Results

The samples showed fine particles with ca. 50% content of the finest -0.02 mm fractions. The lowest content of fine fractions below 0.02 mm was found in sample C. The grain size distributions of the tested materials are shown in Table 2 and Fig. 4.

Table 2. Particle size distribution of waste samples

Particle Size (mm)	Sample A		Sample B		Sample C	
	Yield (%)	Cumulative Yield (%)	Yield (%)	Cumulative Yield (%)	Yield (%)	Cumulative Yield (%)
-0.002	2.05	2.05	3.18	3.18	1.82	1.82
0.002–0.004	5.35	7.40	7.82	10.99	4.41	6.23
0.004–0.006	5.20	12.60	7.06	18.06	4.34	10.57
0.006–0.008	5.66	18.26	6.61	24.67	5.02	15.58
0.008–0.010	5.76	24.02	5.99	30.65	5.36	20.95
0.010–0.012	5.76	29.78	5.44	36.09	5.61	26.56
0.012–0.014	5.53	35.31	4.90	40.99	5.55	32.11
0.014–0.016	5.27	40.58	4.44	45.43	5.43	37.54
0.016–0.018	4.96	45.53	4.03	49.46	5.23	42.77
0.018–0.020	4.61	50.14	3.67	53.13	4.95	47.72
0.020–0.040	29.48	79.62	23.56	76.69	32.94	80.66
0.040–0.071	14.72	94.34	14.86	91.54	15.69	96.34
0.071–0.100	3.87	98.21	5.23	96.77	3.08	99.43
+0.100	1.79	100.00	3.23	100.00	0.58	100.00

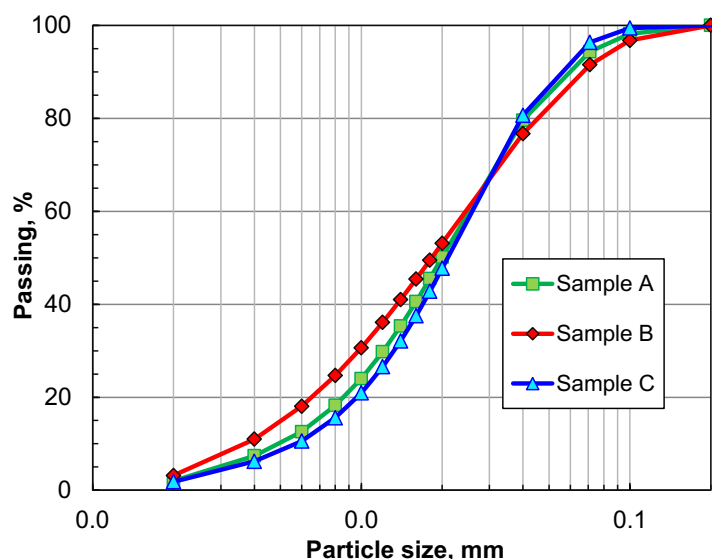


Fig. 4. Particle size distribution of waste samples in the logarithmic system

Table 3 presents the results of chemical analyses performed for the tested samples. The presented chemical composition is typical of that for granites (Al, Si, K, Ca). All of the samples have a high content of iron, particularly from the perspective of their potential application in the ceramic industry (Lewicka, 2015). This fact is attributed to the mineral composition of the granites from the Strzegom massif (except the leucogranite) and to the cutting technology of the stone blocks in the mining and processing plants

that supplied the samples. Comparing the results of the chemical composition of the tested samples with the chemical composition of the granites before their treatment (Domańska-Siuda et al., 2007, 2019), it can be concluded that the iron content of the tested samples is mainly due to the content of femic minerals. Part of the results were recalculated into an oxide form, in accordance with the nomenclature used in the literature. In the case of iron and titanium, the values are provided in both elemental and oxide forms, as necessitated by the enrichment curves used in the results description.

Table 3. Chemical composition of the studied waste samples

Element	Sample A	Sample B	Sample C
	Content of Element (%)		
SiO ₂	71.740	70.531	73.342
Al ₂ O ₃	12.601	13.324	12.304
CaO	1.560	1.556	1.429
MnO	0.044	0.062	0.044
K ₂ O	4.527	4.483	4.376
P ₂ O ₅	0.114	0.137	0.102
TiO ₂	0.321	0.429	0.280
Ti	0.192	0.257	0.168
Fe ₂ O ₃	3.632	4.482	2.847
Fe	2.540	3.135	1.991
Na ₂ O	4.309	4.259	4.243
MgO	0.330	0.431	0.221
As	0.003	0.088	0.003
Ba	0.619	0.002	0.518
Cr	0.010	0.013	0.012
Cu	0.012	0.010	0.016
Ni	0.000	0.000	0.007
Zn	0.007	0.012	0.007
Rb	0.038	0.037	0.057
Sr	0.028	0.025	0.045
Y	0.016	0.012	0.008
Zr	0.045	0.048	0.088

The feed samples were additionally subjected to XRD analysis, and the results are shown in Fig. 5. The mineral composition of the analyzed wastes is dominated by quartz, albite, biotite, and muscovite. The tests also revealed the presence, albeit in smaller quantities, of apatite and orthoclase. The 0.020–0.063 mm fraction contains limited quantities of clays, mainly represented by chlorite and illite. The content of these minerals in the <0.020 mm fraction is significantly higher, with the additional presence of smectites. The analyzed wastes may also contain small quantities of rutile and trace quantities of calcite and dolomite. The material analyzed with the use of this method does not contain (i.e. on the order of minimum 0.5%) such ore minerals as hematite, magnetite, goethite, pyrite, marcasite, siderite, and ilmenite.

SEM-EDS observations demonstrated that in the investigated wastes iron is carried mostly by natural mineral components (the so-called femic minerals), and only to a limited extent by the impurities present due to the cutting of the stone with steel tools (Fig. 6 a-l). All of the analyzed samples show relatively numerous femic minerals, represented mainly by biotite, and also by chlorite (most typically being the product of biotite transformations), as well as amphiboles and/or pyroxenes. Pyrite and iron oxides (probably hematite) are observed only occasionally. Femic minerals are found not only as independent crystals but also as inclusions in other crystals, inter alia in feldspars, quartz, and biotite. The analyzed wastes also contain insignificant quantities of Ti carriers, including its oxides. The steel filings present in the samples are alloys of iron and chromium. Their share is insignificant in relation to the mineral components of the rock (biotite and chlorite).

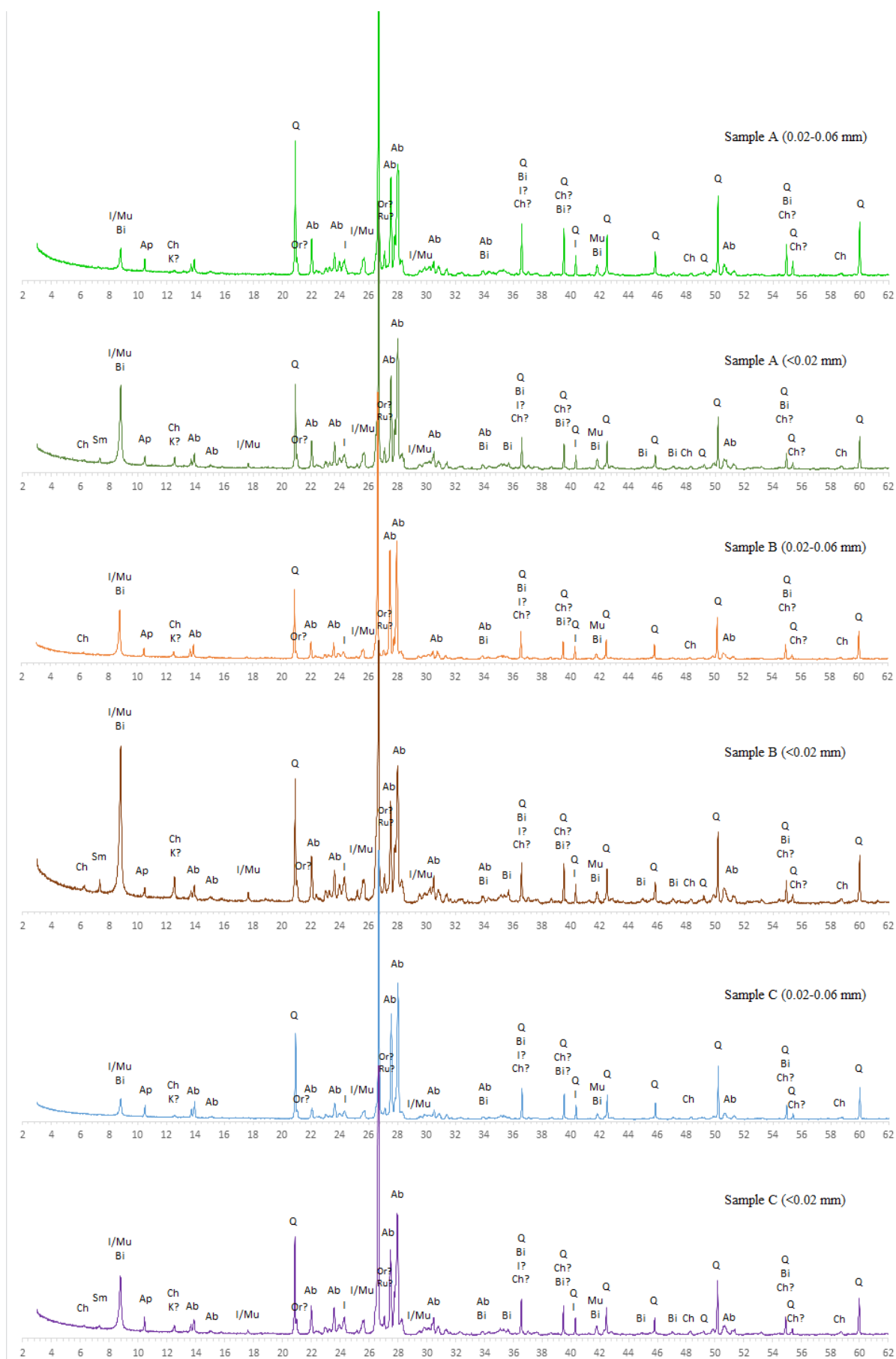


Fig. 5. X-ray patterns of the studied waste samples

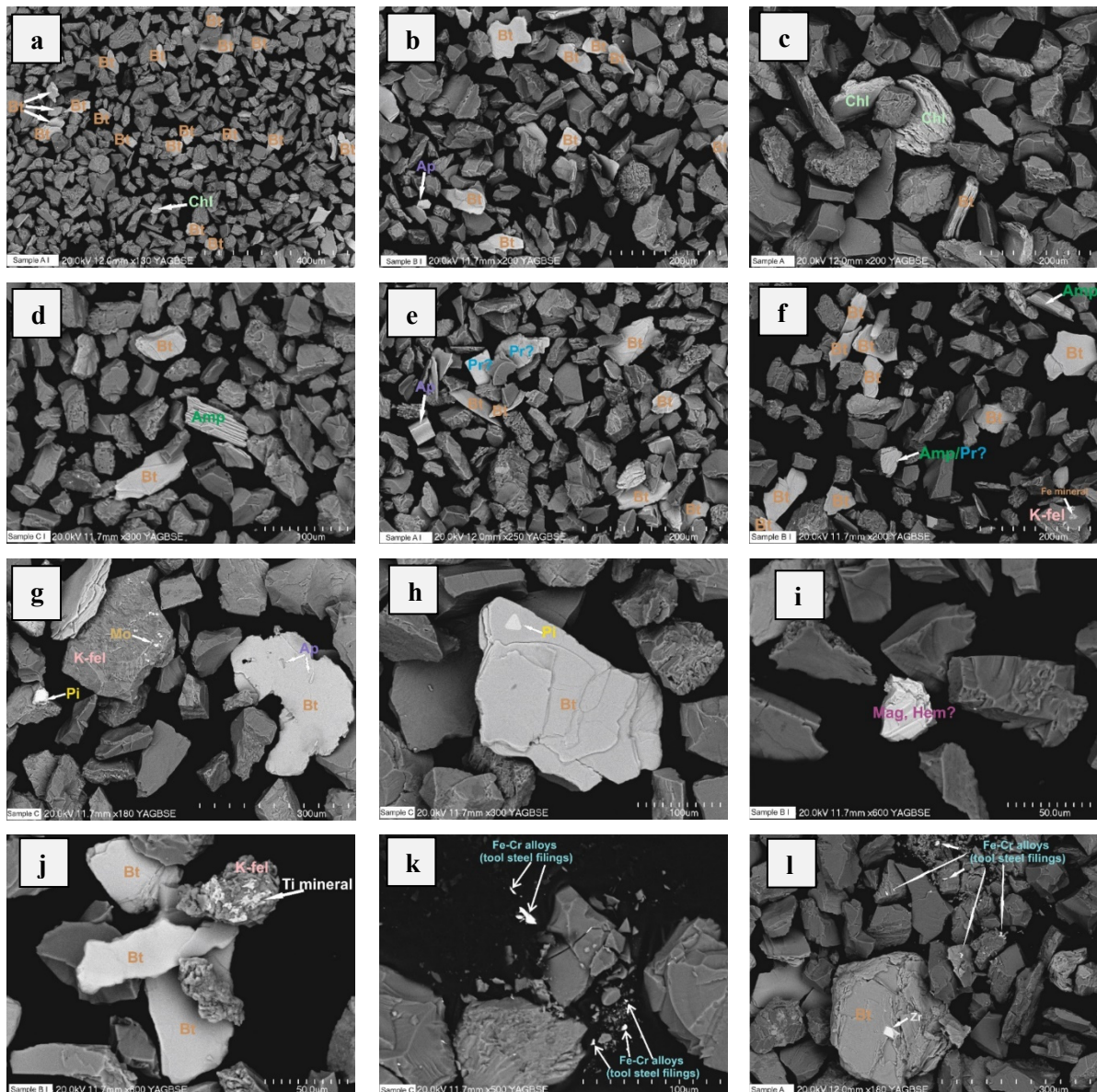


Fig. 6. a-l. Photographs of granite waste samples taken in the scanning electron microscope (SEM)
 Amp – amphibole, Ap – apatite, Bt – biotite, Chl – chlorite, Hem – hematite, K-fel – K feldspar, Mag – magnetite, Mo – monazite, Pi – pyrite, Pr – pyroxene

Tables 4–6 present the results of magnetic separation performed in the isodynamic separator. The magnetic separation was intended mainly to separate mineral components or secondary impurities, i.e. iron carriers, from the samples. In the case of the analyzed wastes, the magnetic carriers can be mainly minerals comprising iron, and to a lesser degree secondary impurities in the form of metal filings (inter alia iron and chromium alloys) from the steel tools used in the cutting of the stone. The presence of these compounds lowers the quality of the tested waste raw materials and limits their application potential e.g. quartz-feldspar powders in the ceramic industry.

Fig. 7 shows the Fuerstenau upgrading curves for the separation of iron and titanium in grain size fractions during the magnetic separation process. In the Fuerstenau curve (recovery-recovery), points closer to the top and right edge of the diagram indicate higher selectivity of the enrichment process. The enrichment parameters for individual grain size classes are balanced in the operational parameters system, i.e. in relation to the content of components in a particular grain size class. In this system, the yield of magnetic and non-magnetic fractions in the class, as well as the recoveries of the particular component in the fractions, sum up to 100%. The points in Fig. 6 indicate that in all samples, the separa-

Table 4. Magnetic separation results (Sample A)

	Particle Size (mm)													
	+0.04			0.02–0.04				–0.02		+0.04		0.02–0.04		–0.02
	Fraction													
	Feed	Magnetic	Non-Magnetic	Total	Magnetic	Non-Magnetic	Total	Total	Magnetic	Non-Magnetic	Magnetic	Non-Magnetic	Total	
	Yield of Separation Products (%)													
	100.000	0.914	9.049	9.963	1.350	19.857	21.207	68.830						
Element	Content of Element (%)							Recovery of Element in Fraction (%)						
SiO ₂	73.620	28.417	79.010	74.368	49.567	77.720	75.928	72.800	0.353	9.712	0.909	20.963	68.064	
Al ₂ O ₃	12.087	9.367	11.420	11.232	10.322	11.525	11.448	12.408	0.708	8.550	1.152	18.393	70.656	
CaO	1.521	1.192	1.040	1.054	1.461	1.231	1.246	1.673	0.716	6.185	1.296	16.075	75.728	
MnO	0.071	0.794	0.006	0.079	0.504	0.031	0.061	0.074	10.159	0.818	9.511	8.612	70.900	
K ₂ O	4.432	6.947	4.250	4.497	5.486	4.249	4.327	4.455	1.433	8.678	1.670	19.036	69.183	
P ₂ O ₅	0.297	0.284	0.234	0.238	0.247	0.257	0.256	0.318	0.874	7.115	1.123	17.143	73.746	
TiO ₂	0.318	2.980	0.101	0.365	1.689	0.215	0.309	0.313	8.575	2.887	7.176	13.452	67.910	
Ti	0.190	1.786	0.061	0.219	1.012	0.129	0.185	0.188						
Fe ₂ O ₃	3.236	40.350	0.317	3.990	23.573	1.514	2.918	3.225	11.396	0.887	9.830	9.290	68.597	
Fe	2.264	28.222	0.222	2.791	16.488	1.059	2.041	2.256						
As	0.004	0.001	0.004	0.004	0.002	0.004	0.004	0.004	0.232	9.174	0.684	20.131	69.779	
Ba	0.572	4.380	0.177	0.563	2.574	0.337	0.479	0.602	6.999	2.800	6.072	11.698	72.432	
Cr	0.013	0.067	0.006	0.012	0.048	0.013	0.015	0.013	4.594	4.072	4.859	19.362	67.114	
Cu	0.014	0.023	0.009	0.010	0.020	0.010	0.011	0.015	1.545	5.986	1.984	14.596	75.889	
Ni	0.006	0.013	0.001	0.002	0.005	0.004	0.004	0.007	2.018	1.537	1.146	13.487	81.813	
Zn	0.021	0.039	0.018	0.020	0.036	0.020	0.021	0.021	1.706	7.795	2.325	19.005	69.170	
Rb	0.053	0.133	0.065	0.071	0.102	0.063	0.066	0.046	2.299	11.100	2.609	23.769	60.223	
Sr	0.043	0.026	0.058	0.055	0.051	0.055	0.055	0.038	0.550	12.128	1.597	25.413	60.313	
Y	0.032	0.038	0.047	0.047	0.053	0.043	0.044	0.027	1.068	13.329	2.225	26.742	56.636	
Zr	0.059	0.038	0.057	0.055	0.050	0.067	0.066	0.057	0.591	8.728	1.149	22.737	66.795	

Table 5. Magnetic separation results (Sample B)

Particle Size (mm)													
Fraction													
Yield of Separation Products (%)													
Content of Element (%)													
Recovery of Element in Fraction (%)													
Element	Feed	Magnetic	Non-Magnetic	Total	Magnetic	Non-Magnetic	Total	Total	Magnetic	Non-Magnetic	Magnetic	Non-Magnetic	Total
SiO ₂	70.055	31.756	66.502	64.816	41.104	68.191	67.085	73.010	0.484	19.892	0.465	18.126	61.032
Al ₂ O ₃	12.761	10.367	11.115	11.079	10.432	11.454	11.412	13.840	0.868	18.254	0.648	16.714	63.516
CaO	1.518	1.234	1.145	1.149	1.518	1.318	1.326	1.721	0.869	15.796	0.792	16.165	66.378
MnO	0.103	0.661	0.093	0.121	0.456	0.080	0.095	0.098	6.890	19.000	3.523	14.539	56.048
K ₂ O	4.733	6.181	4.865	4.929	4.868	4.549	4.562	4.716	1.396	21.541	0.815	17.896	58.352
P ₂ O ₅	0.290	0.284	0.250	0.251	0.266	0.291	0.290	0.305	1.047	18.039	0.726	18.677	61.512
TiO ₂	0.451	2.359	0.454	0.546	1.505	0.391	0.436	0.420	5.589	21.085	2.643	16.131	54.553
Ti	0.270	1.414	0.272	0.327	0.902	0.234	0.261	0.252					
Fe ₂ O ₃	4.837	34.242	4.522	5.964	18.555	4.040	4.633	4.481	7.565	19.591	3.040	15.555	54.249
Fe	3.383	23.950	3.163	4.172	12.978	2.826	3.240	3.134					
As	0.004	0.002	0.003	0.003	0.003	0.004	0.004	0.005	0.492	14.463	0.547	17.136	67.363
Ba	0.818	3.576	0.786	0.921	2.341	0.673	0.741	0.805	4.671	20.130	2.267	15.316	57.616
Cr	0.016	0.057	0.017	0.019	0.030	0.011	0.012	0.017	3.711	21.704	1.448	12.480	60.656
Cu	0.011	0.022	0.009	0.010	0.021	0.016	0.016	0.010	2.114	16.955	1.496	26.786	52.649
Ni	0.002	0.004	0.001	0.001	0.001	0.001	0.001	0.002	2.642	12.954	0.490	11.511	72.403
Zn	0.024	0.039	0.022	0.023	0.033	0.024	0.024	0.025	1.708	18.895	1.072	18.318	60.007
Rb	0.039	0.000	0.042	0.040	0.023	0.050	0.049	0.036	0.000	22.366	0.467	23.410	53.757
Sr	0.026	0.057	0.022	0.023	0.006	0.035	0.034	0.024	2.354	17.364	0.182	25.008	55.091
Y	0.013	0.061	0.007	0.010	0.008	0.021	0.021	0.012	5.016	11.228	0.502	30.507	52.748
Zr	0.055	0.079	0.032	0.034	0.006	0.106	0.102	0.047	1.548	12.076	0.089	35.986	50.301

Table 6. Magnetic separation results (Sample C)

	Particle Size (mm)													
	+0.04			0.02-0.04				-0.02		+0.04		0.02-0.04		-0.02
	Fraction													
	Feed	Magnetic	Non-magnetic	Total	Magnetic	Non-magnetic	Total	Total	Magnetic	Non-magnetic	Magnetic	Non-magnetic	Total	
	Yield of Separation Products (%)													
	100.000	0.543	8.416	8.959	2.297	25.270	27.567	63.473						
Element	Content of Element (%)								Recovery of Element in Fraction (%)					
SiO ₂	73.185	28.271	73.485	70.745	44.922	75.983	73.395	73.439	0.210	8.451	1.410	26.236	63.694	
Al ₂ O ₃	11.678	8.438	9.574	9.505	9.092	10.637	10.509	12.493	0.392	6.900	1.789	23.018	67.902	
CaO	1.309	2.160	0.922	0.997	1.479	1.129	1.158	1.419	0.896	5.928	2.595	21.795	68.787	
MnO	0.065	0.927	0.005	0.061	0.307	0.036	0.059	0.068	7.732	0.668	10.844	14.033	66.722	
K ₂ O	4.230	5.645	3.854	3.962	4.245	4.062	4.077	4.334	0.725	7.667	2.305	24.266	65.037	
P ₂ O ₅	0.289	0.314	0.261	0.264	0.599	0.259	0.287	0.293	0.590	7.606	4.757	22.638	64.409	
TiO ₂	0.267	3.088	0.060	0.243	1.186	0.180	0.264	0.271	6.291	1.879	10.220	17.086	64.525	
Ti	0.160	1.851	0.036	0.146	0.711	0.108	0.158	0.162						
Fe ₂ O ₃	2.680	40.533	0.250	2.692	11.066	1.713	2.492	2.759	8.213	0.786	9.487	16.152	65.362	
Fe	1.874	28.350	0.175	1.883	7.740	1.198	1.743	1.930						
As	0.003	0.001	0.004	0.004	0.002	0.003	0.003	0.003	0.178	11.037	1.506	24.853	62.426	
Ba	0.482	5.115	0.142	0.443	1.645	0.327	0.437	0.507	5.763	2.480	7.841	17.145	66.771	
Cr	0.015	0.089	0.007	0.012	0.031	0.016	0.017	0.014	3.284	4.004	4.840	27.478	60.393	
Cu	0.029	0.047	0.023	0.024	0.048	0.020	0.022	0.032	0.890	6.754	3.848	17.635	70.873	
Ni	0.012	0.026	0.003	0.004	0.027	0.007	0.009	0.014	1.210	2.164	5.315	15.159	76.152	
Zn	0.023	0.043	0.021	0.022	0.028	0.022	0.023	0.023	1.024	7.751	2.821	24.381	64.023	
Rb	0.051	0.142	0.042	0.048	0.000	0.060	0.055	0.050	1.496	6.952	0.000	29.564	61.988	
Sr	0.041	0.000	0.035	0.033	0.010	0.050	0.047	0.039	0.000	7.328	0.552	31.142	60.978	
Y	0.033	0.082	0.029	0.032	0.009	0.042	0.039	0.031	1.343	7.266	0.602	31.726	59.064	
Zr	0.089	0.000	0.081	0.076	0.016	0.119	0.110	0.081	0.000	7.697	0.412	33.692	58.199	

tion causes iron to concentrate in the magnetic fraction, with the varying efficiency of this process. The point distribution shows that for samples A and C, the grain size class +0.04 mm has a significantly higher selectivity of iron enrichment in the magnetic fraction relative to the 0.02–0.04 mm grain size class. It was also observed that the enrichment selectivity is not similar for all of the samples, and that is despite the similar content of the analyzed components in the feed. As in the case of iron, titanium was also found to have a high enrichment selectivity in the magnetic fraction, with higher enrichment effectiveness for coarser grain sizes.

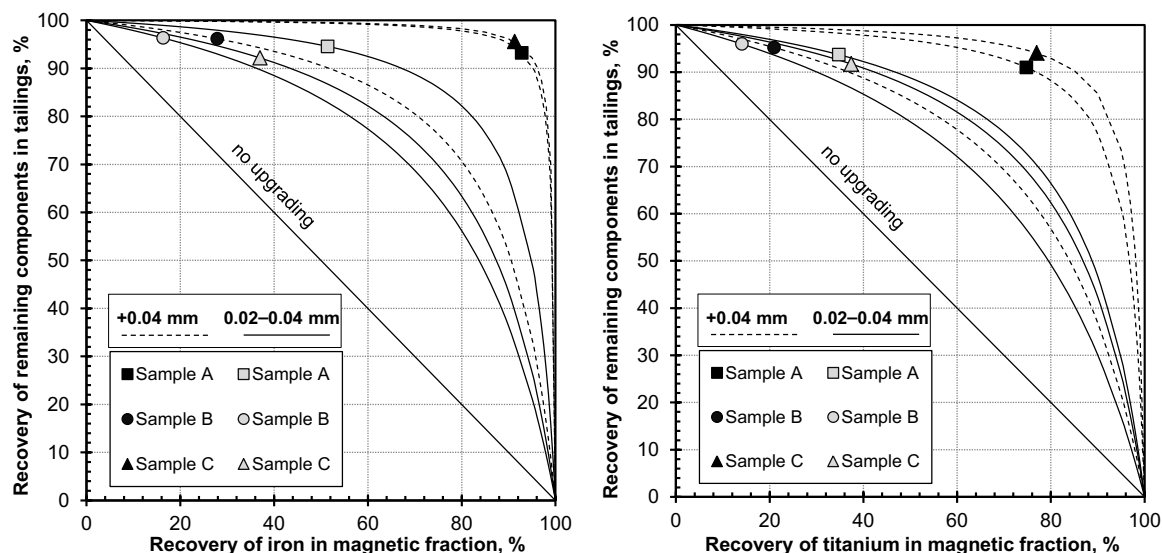


Fig. 7. Separation efficiency of iron (on the left) and titanium (on the right) in fractions from magnetic separation

Magnetic enrichment in the Frantz isodynamic separator indicates the possibility of effectively separating iron carriers present in coarser grain size classes. In the case of samples A and C, the iron content in the non-magnetic fraction decreased to a level below 0.3%, with the original content in the +0.04 mm grain size class at 2.8% and 1.9%, respectively. In the case of the 0.02–0.04 mm class, the decrease of iron content in the non-magnetic fraction was at a maximum of approximately 1%.

The tests have demonstrated that magnetic separation of the tested material is possible, albeit in narrow grain size classes. The finer the grain size of the feed to the magnetic separation process, the lower the efficiency of the iron separation process in magnetic fractions. The next step in research on this type of waste should therefore focus on the process carried out in wet magnetic separators to increase the efficiency of separating waste from valuable components, particularly in finer grain sizes. The separation process should be still preceded by the grain size classification of the tested material.

In the next stage of tests, based on the analyses of the chemical composition and magnetic enrichment efficiency across grain size classes, it was decided to perform the XRD tests on sample A (Fig. 8). The XRD analysis of the magnetic +0.04 mm fraction in sample A demonstrated the presence of biotite as the main component with additional presence of chlorite and kaolinite and with the possible presence of small quantities of muscovite, albite and apatite. In the 0.02–0.04 mm magnetic fraction, biotite was also identified as the main component, with quartz and kaolinite as other important components and with albite, chlorite, apatite, and, possibly, muscovite, rutile, and zircon as accessory components. The XRD analysis did not confirm the presence – above the detection threshold – of crystalline phases from the steel tools. In the case of the non-magnetic fraction from the separation of the +0.04 mm wastes, quartz, and albite were confirmed as the main components, with the additional presence of orthoclase and muscovite and with no confirmation in the presence of biotite and other feric minerals. In the 0.02–0.04 mm non-magnetic fraction, the main confirmed components are quartz and albite, and the accessory component is muscovite. However, the presence of orthoclase, as well as of biotite and rutile, is also possible. The XRD analysis was also performed for the -0.02 mm fraction of sample A, which was not magnetically separated. In this case, quartz, albite, muscovite, and biotite were identified as the main components, and kaolinite – as an accessory component (probably as a weathering product). The presence of orthoclase, apatite, and rutile is also possible.

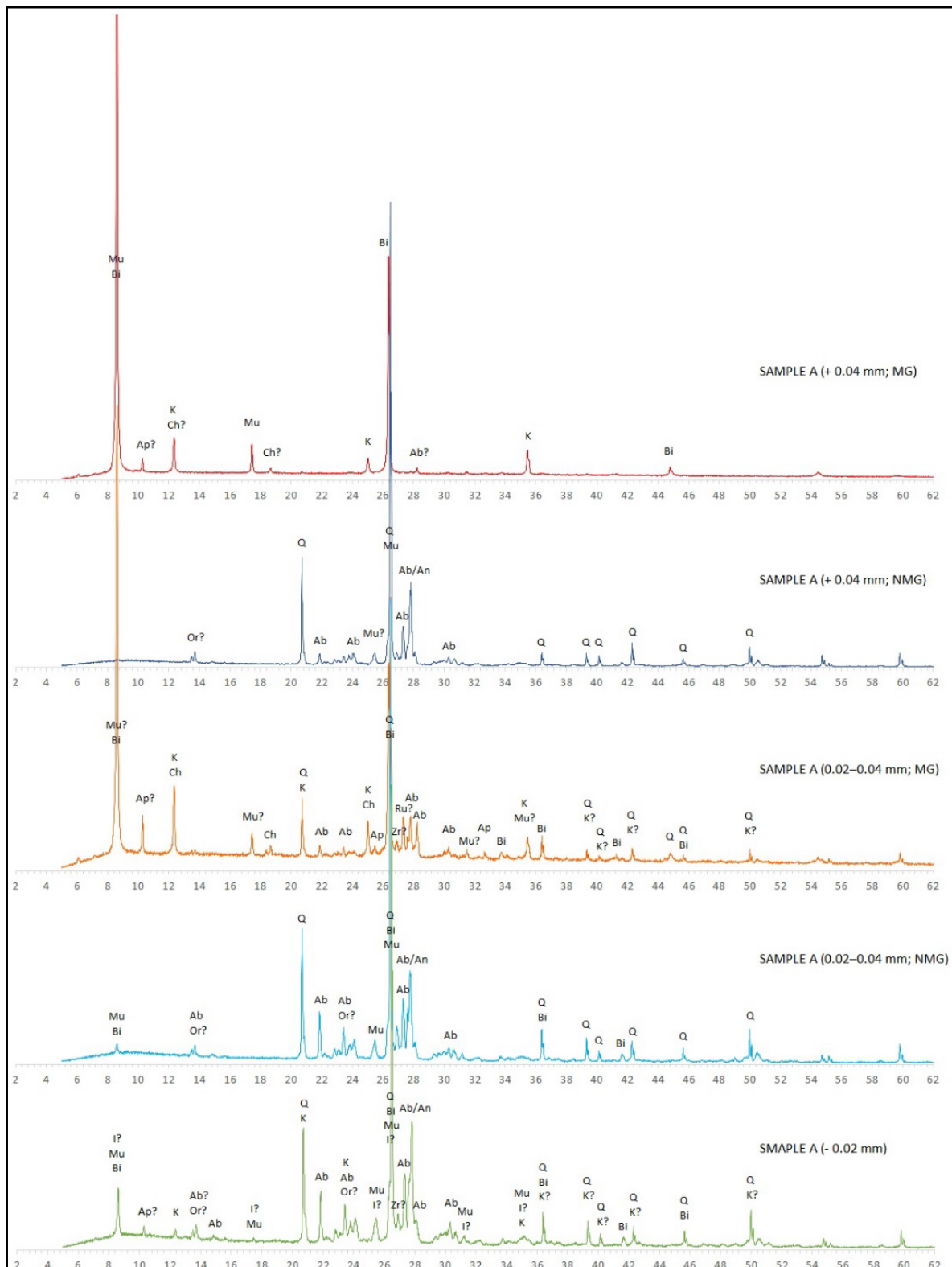


Fig. 8. X-ray patterns of waste sample A after magnetic separation

The SEM observations (Fig. 9) and the mapping of the elemental distribution in the micro area based on the SEM-EDS tests of sample A indicate that in the case of the +0.04 mm magnetic fraction (Fig. 10), the main components are minerals with scaly habit and containing Fe, K, and Si. This result confirms the results of the XRD analysis, which indicated that the sample comprises mainly biotite. Biotite was

also identified in the 0.02–0.04 mm magnetic fraction (Fig. 11). However, the sample has greater quantities of angular grains, which comprise Fe, Si, Mg, and Ca. These are probably amphiboles or piroxenes. In the case of both the +0.04 mm and the 0.02–0.04 mm magnetic fractions, the wastes also contained titanium minerals. The +0.04 mm and 0.02–0.04 mm non-magnetic fractions show the dominating presence of angular grains. It is mainly quartz, as well as Na, K, and Ca-feldspars. The analyses of the finest (–0.02 mm) fraction not separated magnetically indicated significant quantities of quartz, feldspars, and micas, as well as a content of clay minerals higher than in coarser fractions.

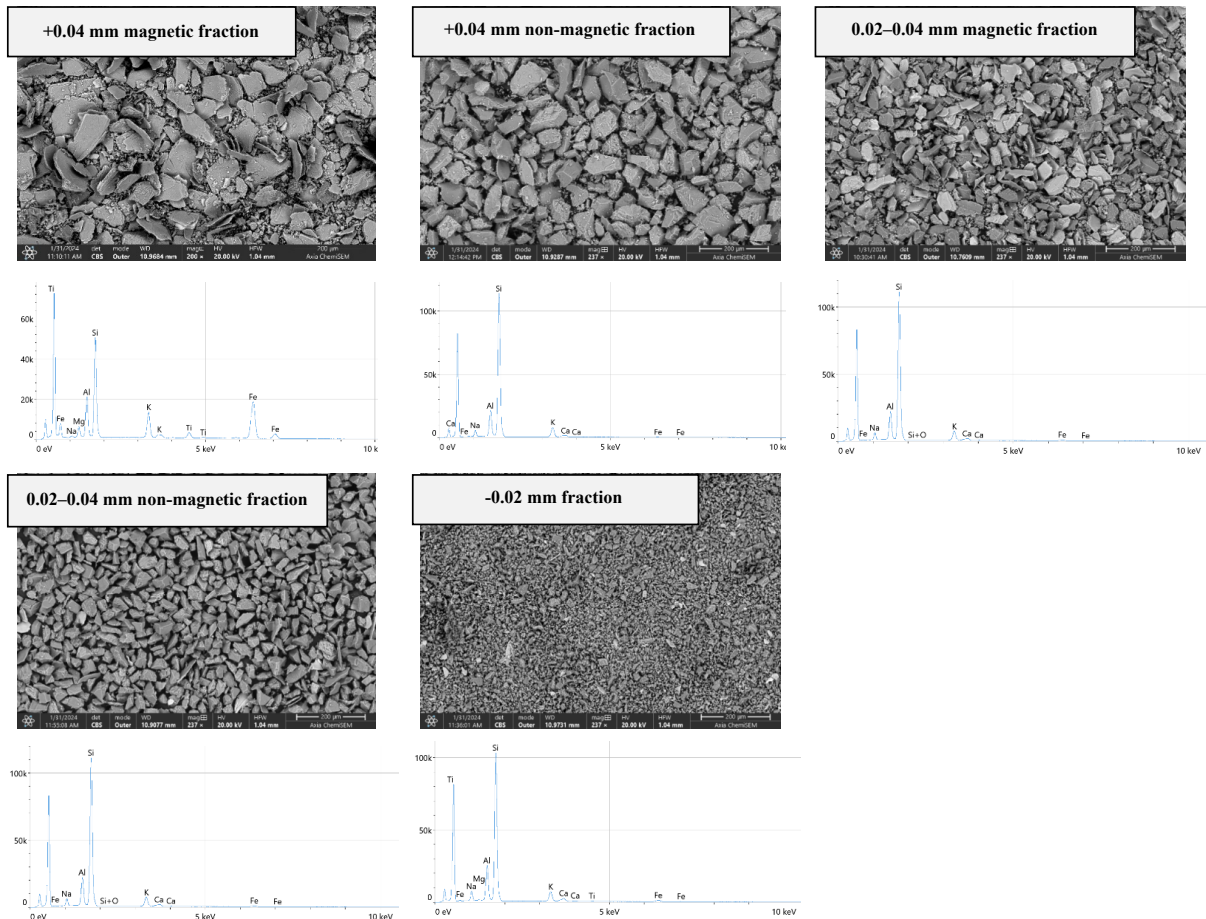


Fig. 9. SEM-EDS images of waste sample A after magnetic separation (samples of grain size +0.04 mm of magnetic and non-magnetic fraction; samples of grain size 0.02–0.04 mm of magnetic fraction and non-magnetic fraction, sample of grain size –0.02 mm – magnetic fraction not separated)

Magnetic separation is an important tool in the context of sustainable resource management, and the available research confirms its effectiveness and environmental and economic benefits. Research results show that contamination levels after magnetic separation can be significantly reduced, increasing the commercial value of the materials (Han et al., 2021; Liu et al., 2023; Herrera-Pérez et al., 2024).

As with literature data as well as studies conducted for in-house samples, it is only possible after the waste has been classified. High separation efficiency is obtained for coarser (Zichella et al., 2017), which is confirmed by our research. The observation that it is possible to magnetically separate iron carriers from the tested materials has great importance in the context of possibly using the analyzed wastes in the ceramic industry. In addition, note should be made that this separation should be performed in narrow grain size fractions. The magnetic enrichment efficiency for iron was highly selective in the case of the +0.04 mm fraction (iron carriers moved to the magnetic fraction), and not as selective in the case of the 0.02–0.04 mm fraction. It is crucial to prove that the products obtained from magnetic separation can be used as substitute materials for natural minerals, reducing pressure on natural resources.

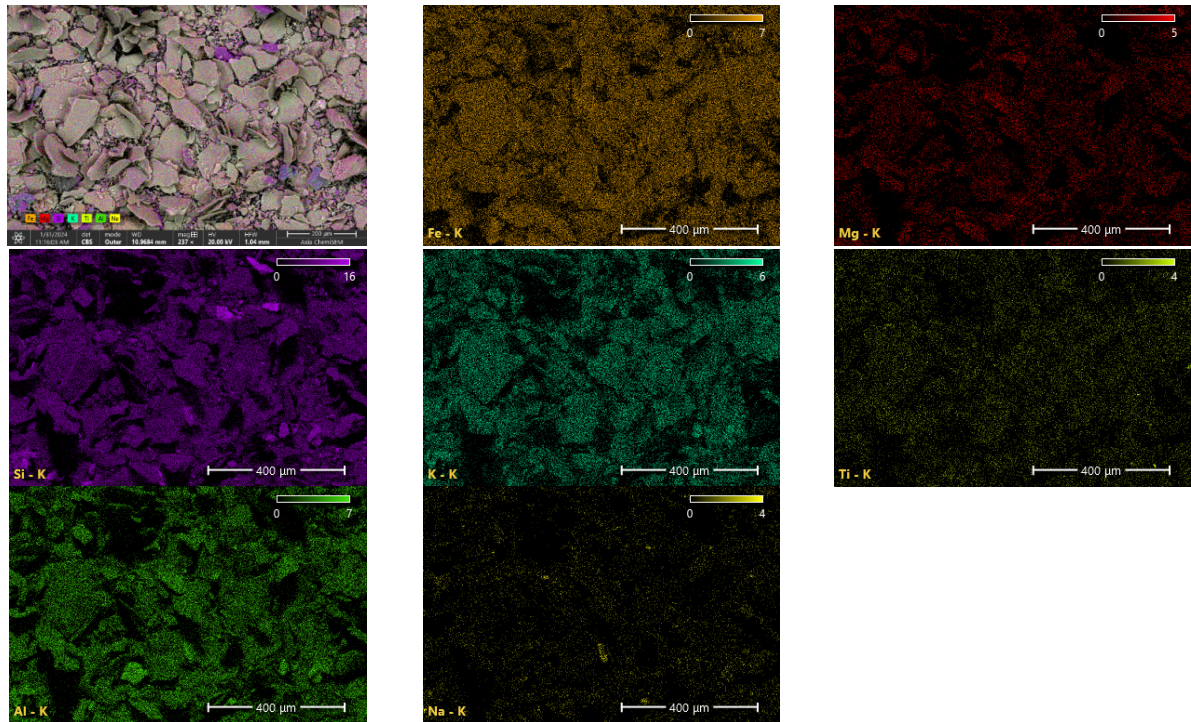


Fig. 10. SEM-EDS maps of elemental distribution in the grain size +0.04 mm magnetic fraction

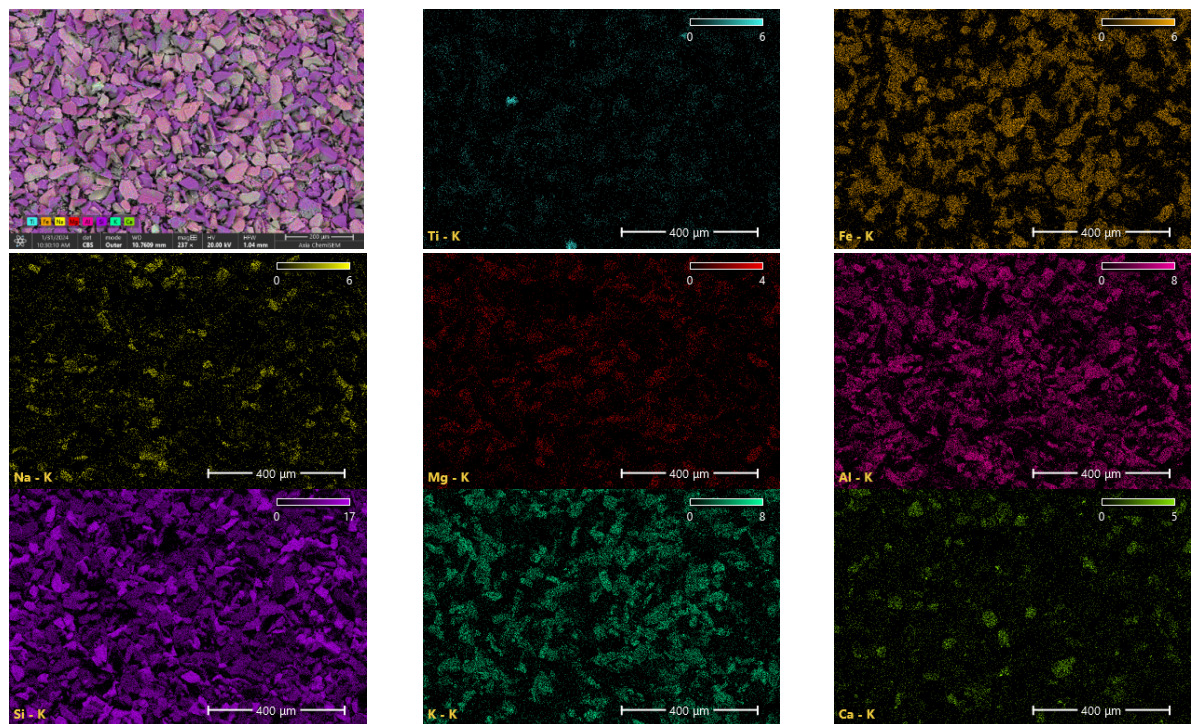


Fig. 11. SEM-EDS maps of elemental distribution in the grain size 0.02–0.04 mm magnetic fraction

6. Conclusions

Mineral waste management is a critical component of the natural stone processing industry. The main problem in recycling these wastes is their grain and mineral composition. As part of an environmental commitment, granite waste is currently being recovered worldwide to produce feldspar minerals, one of the main raw materials for ceramic products (Bailla et al., 2024). In the case of the Polish industry, these products are still mainly unrecoverable waste. In order for this waste to be used as a ceramic raw

material, it would have to be characterized by low iron density and, at the same time, a suitable grain composition (Baila et al., 2024). Our research indicates that chemical analyses demonstrate that the wastes chemically correspond to primary materials: Al_2O_3 from 12.3% to 13.32%, SiO_2 from 70.53% to 73.34%, K_2O from 4.38% to 4.53%, and CaO from 1.43% to 1.56%. Additionally, the test results show high iron content, i.e. Fe from 1.991% to 3.135%, which is mainly attributed to the high content of biotite in the feed. The studied samples were characterized by a very fine grain size similar to the majority of this type of waste, with a grade content of less than 0.04 mm at more than 80%, and the d_{50} grain is at approximately 0.02 mm.

The XRD tests indicate that the main components of the analyzed granite wastes are quartz, albite, biotite, and muscovite. The accessory components are chlorite, apatite, and orthoclase. In the 0.020–0.063 mm fraction, clay minerals (kaolinite and illite) are sporadically found, while in the <0.020 mm fraction, their content is significantly higher, and kaolinite and illite are accompanied by smectites. The SEM-EDS tests demonstrate that the main iron carrier in the analyzed wastes are ferrous minerals, represented mainly by biotite, and additionally by chlorite, amphiboles, and/or pyroxenes. The analyzed wastes also sporadically contain pyrite, iron oxides, and titanium compounds (mainly oxides). The material for the study was the sludge produced by cutting with diamond wire and disc dust, not chainsaws, hence iron contamination is mainly of natural origin, presents in small quantities relative to the mineral iron carriers and the size is significantly smaller.

For such fine waste, magnetic separation seems to be the only effective method of iron separation. It should be noted that this separation should be performed in narrow grain size fractions. The magnetic enrichment efficiency for iron was highly selective in the case of the +0.04 mm fraction (iron carriers moved to the magnetic fraction), and not as selective in the case of the 0.02–0.04 mm fraction. The observation that it is possible to magnetically separate iron carriers from the tested materials has great importance in the context of possibly using the analyzed wastes in the ceramic industry. Of course, it is crucial to prove that the products obtained from magnetic separation can be used as substitute materials for natural minerals, reducing pressure on natural resources.

The results presented here are promising and demonstrate the potential to reduce waste generation. Products characterized by a low content of magnetic fraction can be used as a feldspar raw material, while products characterized by a high content of magnetic fraction can be reused in other production sectors or disposed of in landfills, which will still bring economic benefits related to the need to landfill less waste in total. Importantly, the results indicate that efficient separation is highly probable in the case of other granite wastes which are chemically similar to primary materials. Moreover, from the perspective of the uniformity, grain size distribution, and quantity of the granite wastes generated in the production process of stone elements, the results of chemical analyses justify further research mainly comprising:

- Wet magnetic separation in HGMS separators and an optional flotation for separating quartz and feldspar powders,
- Investigations of the practical aspects/technologies of using wastes among others in the ceramic industry or building materials industry.

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