

Article

Assessment of Selected Characteristics of Enrichment Products for Regular and Irregular Aggregates Beneficiation in Pulsating Jig

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Abstract: Article concerns problem of jig beneficiation of mineral aggregates and focuses especially on problem of separation of hard-enrichable materials. Investigative programme covered tests in laboratory and semi-plant scale and material with different content of regular and irregular particles, along with various particle size fractions, was under analysis. Two patented solutions were utilized as methodological approach and densities and absorbabilities of individual products were determined and major novelty of approach consist in separate beneficiation of regular and irregular particles. Results of laboratory investigations showed that more favorable separation effectiveness was observed for the narrow particle size fractions of feed material. In terms of absorbability difference between separation products from I and IV layer was 0.4–0.5% higher for regular particles, and up to 0.5% higher for irregular grains. Differences in densities of respective products were 0.1% higher for regular particles. Results of semi-plant tests confirmed the outcomes achieved in laboratory scale. The qualitative characteristics of separation products in terms of micro-Deval and LA comminution resistance indices were one category higher for regular particles, and two categories higher for irregular grains, comparing to the raw material.

Keywords: aggregates; jig beneficiation; mineral processing; raw materials; separation



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1. Introduction

Jig beneficiation is a simple and economical method of raw materials enrichment. It is especially efficient for separation of minerals with relatively high differences of their densities. The environmental footprint of jig beneficiation is also low, especially in terms of dust and noise pollution but also due to relatively low water and energy consumption, comparing to flotational separation or chemical beneficiation, and also selected operations of mechanical enrichment [1–3].

An up to date review of the jiggging operation fundamentals and outlines of directions for future research and developments were presented in [4]. The configuration, operational principles, and main applications of different jig types have been comprehensively reviewed. A description of the main theoretical approaches was also presented, with highlighting of strengths and weaknesses of operations. Gravity separation is, in general, quite simple method of raw material beneficiation and quite well documented in literature. This method is economically efficient and does not require an intensive consumption of energy and other media [5,6].

Jig beneficiation is most commonly used for coal preparation, where the difference in densities of coal and the waste rock are high [7,8]. In rock materials processing, the effectiveness of separation process might be lower, but it greatly depends on the degree of

useful mineral liberation and the difference in densities of the material being separated. However it appears that apart from density several other features of the feed material are influential, like particle size and the shape of individual particles [9,10]. Results of various investigation show that after suitable preparation of the feed material i.e., separation of entire feed into narrow particle size fractions, together with distinction of regular and irregular particles, may significantly increase the effect of jig process beneficiation. The jig enrichment technology can also be used in the processing of other mineral resources, especially in removing of impurities at initial stages of aggregates, sand or gravel treatment [11]. It is also possible to recover in jigs building materials from demolition debris and road materials [12], electronic waste or plastic [13,14].

Industrial practice shows that jigs are common in plant operation, however not in all sectors of mining and mineral processing industry. Beneficiation of raw materials with relatively high differences of densities are not problematic, but in some aspects, especially when the difference between the density of useful mineral (i.e., than can be used effectively in further production) and the gangue, or between the two product to be separated, is lower, application of jigs is an issue [4].

There are relatively low number of publications concerning applications of jiggling processes into aggregate enrichment. More results can be found in concrete separation especially the materials from demolition of building constructions [15,16]. Despite of that the problem of aggregate segregation is significant, because it influences improvement of qualitative characteristics of final products, through elimination of weaker and partially damaged particles, as well as weathered grains [17,18].

2. Materials and Methods

2.1. Research Significance

There has been done a significant development in the design of settling machines in recent years, resulted from a high demand for good quality aggregates [4,19,20]. An application of density separation methods into aggregate production can be used more effectively in industry due to the different lithological and physical properties of the separation products and variations in values of strength and absorbability parameters [21,22]. These applications are suitable for natural, recycled and anthropogenic aggregates [15,16]. The article presents results of tests on a prototype and unique *SET* device (a separator for hard-enrichable particles), constructed especially for research purposes according to the patented concept (Patent PL 233318B1). The main and innovative idea presented in the paper concerns running the jig beneficiation process in more narrow particle size fraction, and separately for regular and irregular particles. Such an approach was not presented in literature.

2.2. Methodology

The enrichment process in a jig takes place as a result of the separation of the feed into fractions according to the selected physical feature, i.e., the density [23]. It can be effective in the air, water or other liquid medium lighter than the components of the enriched material. Rock materials with different densities can be characterized by different settling velocities when they are subjected to a vertical pulsating motion in a specific medium (i.e., water). The theoretical bases of separation in jigs have been described by Newton-Rittinger law. According to this law, the description of particle movement in a liquid under the influence of pulsation takes into account the limiting settling velocity in a situation in which the geometric sum of gravity and hydrostatic buoyancy forces, as well as the medium resistance that act on a single particle, equals zero. It is assumed that when the material layer in the jig loosens, each particle moves freely, regardless the presence of surrounding particles. The free settling ratio (Equation (1)) can be helpful in assessing the separability of the material under treatment.

$$e = \frac{d_1}{d_2} = \frac{\rho_2 - \rho_0}{\rho_1 - \rho_0} \quad (1)$$

where: index 1—particles of lower density; index 2—particles of higher density; d —particle diameter, [mm]; e —free settling ratio; ρ_1, ρ_2 —particle densities, [g/cm³]; ρ_0 —liquid density, [g/cm³].

The free settling ratio, e , gives an indication of the scope of the feed material preparation needed for enrichment in jigs and defines the following natural limitations for the process, which, if not taken into account, can significantly reduce the efficiency of separation:

- feed should contain a minimum of equally settling particles i.e., differentiated in terms of densimetric and granulometric properties,
- the material must be homogeneous in terms of density distribution,
- the feed material should be proceeded into narrow granular classes.

Two most common efficiency indicators used in assessment of jigs performance are the probable error (Ep) and imperfection (I) [24]. The regularity and irregularity of particles can be measured by means of the Schultz caliper or on a bar slotted screen. The obtained values of shape and flatness coefficients indicate whether the particle can be regarded as a regularly shaped or not. The general principle is that if the shortest dimension of a particle is more than two time smaller than its longest dimension, the particle is regarded as irregular in shape. Also, particles that are porous have a natural ability to absorb a significant amount of water. Porosity was determined indirectly by determining the volume of water retained within an individual particle. The effectiveness of jig beneficiation was also analyzed in terms of a particle's water absorption properties or 'absorbability'—an index determined by measuring the amount of water absorbed by the particle immersed in water.

Primary aim of application of jigs in raw materials enrichment is a feed separation into products according to density of individual particles, but the material can be also separated according to the shape. Particle settling velocity is determined by density, size and shape of a particle and can be calculated on the bases of Formula (2), derived from heuristic considerations [25]:

$$v = 5.33\sqrt{x}\sqrt{d_p}\sqrt{\left(\frac{k_1}{k_2}\right)} \quad (2)$$

where: $x = (\rho - \rho_0)/\rho$ —density of reduced particle, ρ —density of particle, ρ_0 —density of the liquid, d_p —projection diameter of particle, k_1 —volumetric shape coefficient, k_2 —dynamic shape coefficient.

On the basis of work [18,26] there can be noticed differences in settling velocities of regular and irregular particles (Table 1), while the greatest variations can be observed in upper product (layer IV).

Table 1. Settling velocities for regular and irregular particles in individual layers (jig products).

Number of Layer (Product) in the Jig	Settling Velocity, [m/s]		
	For Regular Particles	For Irregular Particles	Difference
I	0.21	0.18	0.03
II	0.20	0.16	0.04
III	0.19	0.14	0.05
IV	0.22	0.16	0.06

It can be also noticed that regular particles have higher values of settling velocities, due to lower resistance of their round edges. It is then possible to obtain a more effective separation process of regular and irregular particles in enrichment of a materials with narrow particle size fraction. This has been investigated in a semi-plant tests within the paper. The entire research program includes laboratory and semi-plant tests and in semi-plant scale the jig constructed especially for purposes of investigations, according to the concept of a patented invention (PL 233318B1), was used. Variables in laboratory tests were selected considering qualitative criteria (content of regular or irregular particles),

and technological aspects of aggregate production (fine or coarse products). These variables entirely determine value of obtained products, thus control of these parameters may influence the economic effectiveness of a mineral aggregate production plant. Different levels of variables in experiments, in turn, were adopted on the bases of characteristics of typical commercial aggregate products.

3. Experimental

3.1. Characteristics of Testing Device

An innovative approach presented in the paper consists in a separate enrichment of regular and irregular particles. Narrow particle size fractions were divided from the material prior to the jigging process. The reason of applying the above procedure was that properties of particles in specific size fractions are more homogenous, and variations in values of individual features (i.e., density, absorbability, porosity) could be more visible. In the first stage of investigations laboratory scale experiments were performed, and then semi-plant tests were carried out. Preparation of feed for laboratory tests was possible thanks to the application of a patented solution (Figure 1) for production of regular and irregular aggregates (Patent PL233689). The solution has not been used in aggregate production so far, and the findings of the paper show that its application is justified and may give measurable effects.

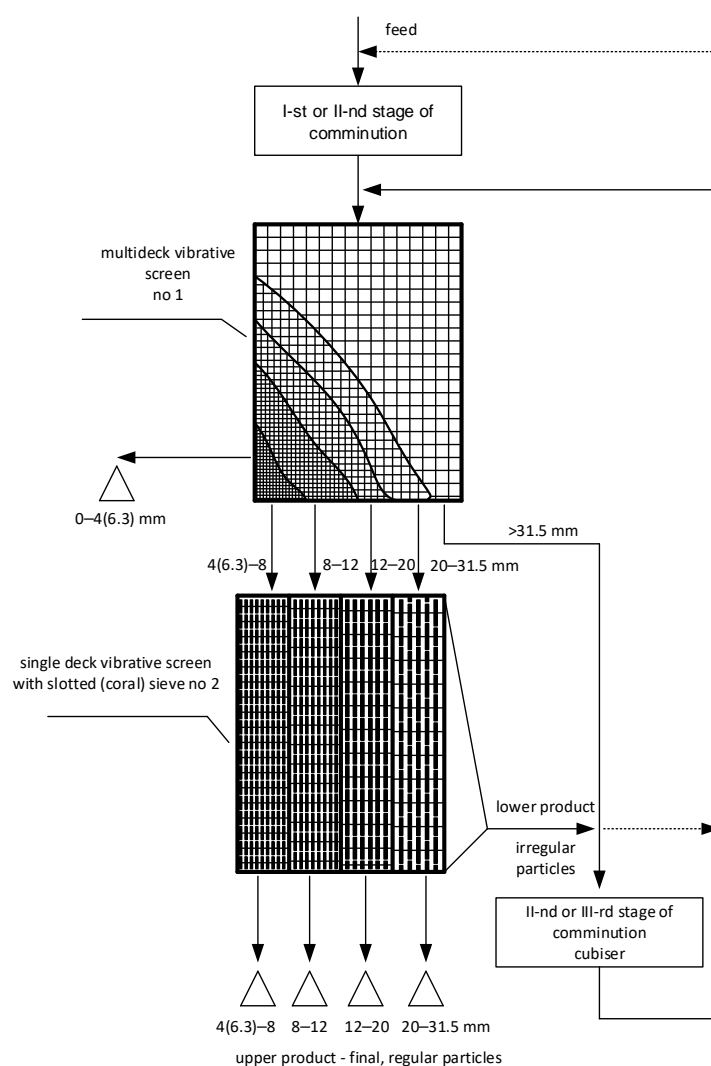


Figure 1. Idea of the aggregate production circuit with a closed recirculation for selective screening and crushing operations (Patent PL233689).

The circuit designed according to the innovative idea, can produce a final aggregate product with irregular particle contents as low as 2–3%. It requires only the application of quadratic and slotted mesh sieves, cooperating with the crusher working in a closed circuit, either operating on a first or second stage. The obtained irregular particles can be comminuted in the same crusher or in a secondary stage of crushing, for example in an impact crusher (cubiser) what can additionally improve the quality of the product. The contents of irregular particles in final products depends on capacity of the screen with slotted sieve and especially on the relation between the narrow particle fraction range and size of the slot in sieve. This sieve should be selected according to " $d_{\max}/2$ " principle, i.e., half of the maximum size of the particle fraction. For the reason that content of irregular particles is lower for coarser particle fractions and the screening efficiency for coarser particles is better, screening of irregular particles in coarser fractions will be easier and more efficient.

Laboratory scale tests were carried out in a jig, in which the regular and irregular particles were enriched separately. The height of the working chamber of the device was 400 mm, the inner diameter of the rings: 100 mm, the height of the ring: 25 mm. The pulse frequency was 90 cycles per minute. Each product layer consisted of two rings: the two lowest rings constituted layer I (the bottom one), while the seventh and eighth rings were layer IV (the upper layer). Additionally, for comparison, enrichment tests were carried out for the material with natural content of regular and irregular particles. Experiments were carried out for various particle size fraction of material and various content of regular and irregular particles.

The second stage of experiments—semi-plant tests—were conducted for the feed prepared according to the patented technology for production of aggregates based on separation of narrow particle size fractions according to size and shape, and downstream densimetric enrichment of particles. The hard-enrichable particles separator (*SET*) is a device that utilizes water as a working medium for separation of the aggregate feed into two fractions differing from each other in terms of density and other physical and mechanical properties (Figure 2). The degree of aggregate separation is variable and depends on the amount of water used and an amount of individual size fractions of the aggregate. Primary operational characteristics of the separator parameters are presented in Table 2. Operational throughput of device was 2500 kg/h, and tests were conducted at high (serie I) and low (serie II) height of the separation threshold. In the serie I the position of the threshold in separator allowed for obtaining 75% of lower (heavier) and 25% of upper product. In the serie II of semi-plant investigations the share in separation products was reverse, i.e., 25% of lower product and 75% of upper one.

3.2. Research Programme and Scope of Analyses

The scheme of research programmes both in laboratory and in semi-plant scale is presented in Figure 3. The regular and irregular particles in each narrow size fraction were separated by classifying on a screen with slotted apertures, according to the standard PN-EN 933-3:2012. The prepared narrow size fractions were enriched in a jig and the idea of operation of such circuit was to eliminate equally settling particles prior to the gravitational separation process, which would have a negative effect on the separation sharpness in the jig. Detailed characteristics of the feed material for laboratory tests is presented in Table 3. Separation products were subjected to density, absorbability and porosity analyses. Density was determined with using of Archimedes law, while absorbability was established by weighing of wet and dry product and performing suitable calculations.

Separation products were subjected to density, absorbability and porosity analyses. Density was determined with using of Archimedes law, while absorbability was established by weighing of wet and dry product and performing suitable calculations. It is worth to mention here, that obtained absorbability values do not determine the real absorbability indices that can be determined according to relevant standards. In this case we rather mean the "processing" or "operational" absorbability, that is an amount of water that individual

particle can absorb while it is in the jig during the process. The porosity, in turn, was determined manually, i.e., each particle was inspected and it was classified as a “porous particle” when pores and irregularities covered more than 50% of its surface. This porosity determined in this way can be rather understood as an external one, because this technique does not allow for determination of internal structure of individual particle.

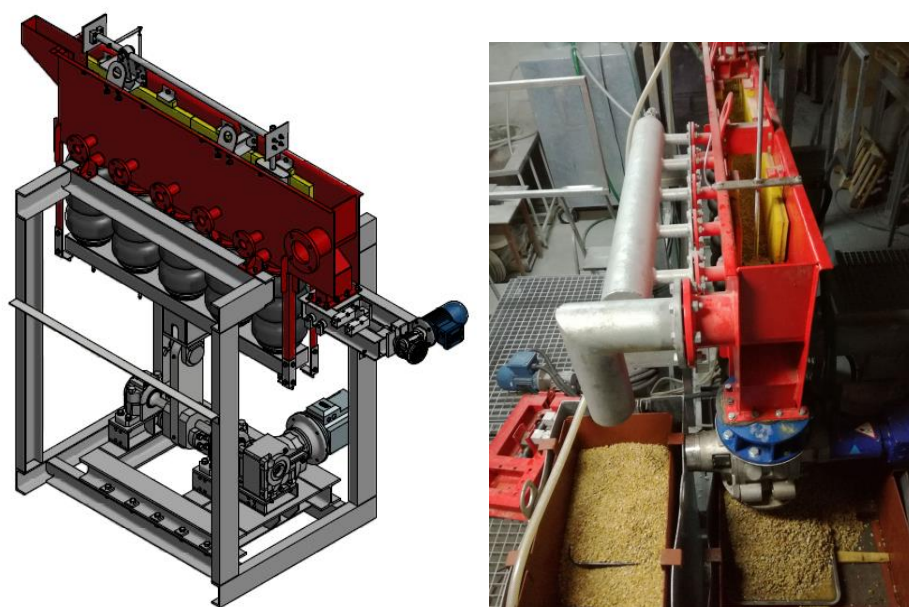


Figure 2. Model of the SET separator (left), device in plant conditions (right).

Table 2. Characteristics of operational parameters of SET device.

Parameter	Unit	Value
Maximum throughput	[kg/h]	2750
Maximum water flow	[dm ³ /h]	5500
Frequency of bellows pulsation	[1/s]	0.8–1.2
Jump of bellows	[mm]	50–140
Nominal power	[kW]	4
Dimensions of sieves	[mm]	150 × 2900

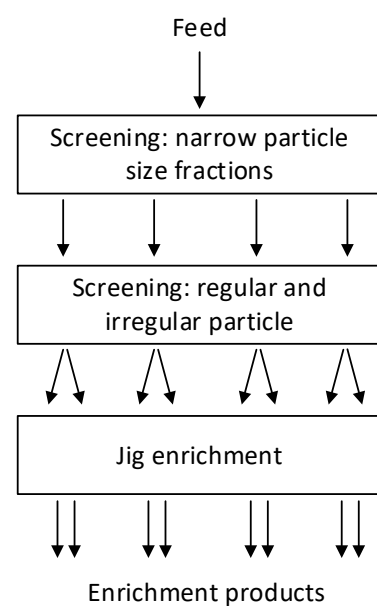


Figure 3. The screening and beneficiation scheme.

Table 3. Summary characteristics of individual tests.

Test Number	Type of Material	Particle Size, [mm]	Regular Particles Content in Feed, [%]	Irregular Particles Content in Feed, [%]
I	gravel	8–16	89	11
II	gravel	8–16	100	0
III	gravel	8–10	0	100
IV	gravel	8–10	100	0
V	gravel	6.3–8	0	100
VI	gravel	6.3–8	100	0

4. Results and Discussion

4.1. Laboratory Scale Tests

Each jig enrichment product in laboratory scale was assessed in terms of its water absorption and density and results are presented in Tables 4 and 5.

Table 4. Summary results of separation achieved in laboratory tests-density.

Test Number	Density, [g/cm ³]			
	Number of Layer in the Jig			
	I	II	III	IV
I	2.67	2.66	2.66	2.63
II	2.66	2.67	2.69	2.68
III	2.64	2.64	2.63	2.61
IV	2.74	2.66	2.65	2.62
V	2.64	2.62	2.60	2.60
VI	2.73	2.66	2.66	2.61

Table 5. Summary results of separation achieved in laboratory tests-absorbability.

Test Number	Absorbability, [%]			
	Number of Layer in the Jig			
	I	II	III	IV
I	1.03	1.52	1.54	2.08
II	1.27	1.71	1.74	1.91
III	2.95	4.09	4.46	4.75
IV	2.55	3.34	3.54	3.96
V	2.97	3.21	3.47	4.05
VI	0.97	1.85	2.22	2.51

Analysis of results obtained for tests I and II (coarse aggregate in wide particle size fraction 8–16 mm) shows that absorbability achieved for the bottom layer I was the lowest. For consecutive higher layers it was increased; in total the difference between layers I and IV was over 1% for natural feed (containing 11% of irregular particles). For feed with regular particles, the respective difference was smaller, achieving approximately 0.8%. It is evident that the properties of individual layers are different when the feeds have 0 or 11% irregular particles, but the differences are relatively low, and don't exceed 0.5%. The values of densities in individual enrichment products are relatively small, however the upper layer (IV) demonstrates the highest difference between regular and irregular products of jig enrichment.

Analysis of specific enrichment products in narrow particle size fractions show that the achieved values of densities are much higher, both for coarse and fine particles, than in tests on a feed with a natural particle size composition. Differences in absorbability for two upper layer exceeds 1.5% which is approximately 5 to 6 times higher, comparing the

results obtained for wide particle size fraction 8–16 mm. Differences in absorbability for the two upper layer exceeds 1.5% which is approximately 5 to 6 times higher, compared to the results obtained for a wide particle size fraction 8–16 mm. Differences in densities are also higher in enrichment products treated in narrow particle size fractions. The highest difference, as high as 0.1%, was observed for the lowest layer I. The differences in densities for products from layers 2 to 4 from tests III and IV were as much as two times greater compared to analogous products from a feed with a particle size range of 8–16 mm.

Results of tests V and VI show that processing absorbability of regular particles was significantly lower than for irregular particles. In the case of density it can be observed that lower products contain the highest number of particles with highest density value. Together with increasing the number of separation product its density decreases. This phenomenon of density segregation is presented in Figure 4. Product from layer I with regular particles (left) had the highest content of quartz particles comparing to the other products, especially to irregular particles (test V), where a sandstone predominated.

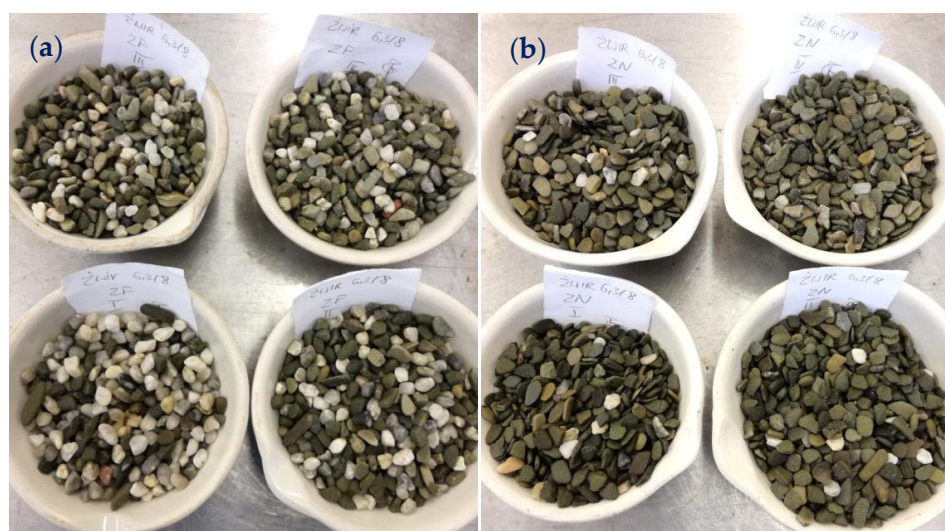


Figure 4. Separation products: regular particles (a) (Test VI), irregular particles (b) (Test V).

Calculated averaged values of absorbability and density are presented in Table 6. Inspecting the table it can be seen that there is little difference between the values for irregular and regular products (tests I and II) when the material has a natural particle size composition. However, for material with a narrow particle size range (tests III and IV) the absorbability is much greater in material consisting of irregular particles than it is in material consisting of regular particles. This indicates that the application of the patented solution for improving the quality of beneficiated material—by splitting the feed into narrow size classes—is justified. No significant improvement in variation of density was observed. Summary of percentage contents of porous particles in each layer of enrichment were presented in Figure 5.

Table 6. Average values of absorbability and density for individual tests.

Test Number	Average Absorbability, [%]	Average Density, [g/cm ³]
I	1.54	2.64
II	1.65	2.68
III	3.09	2.63
IV	1.38	2.67
V	3.38	2.61
VI	1.80	2.67

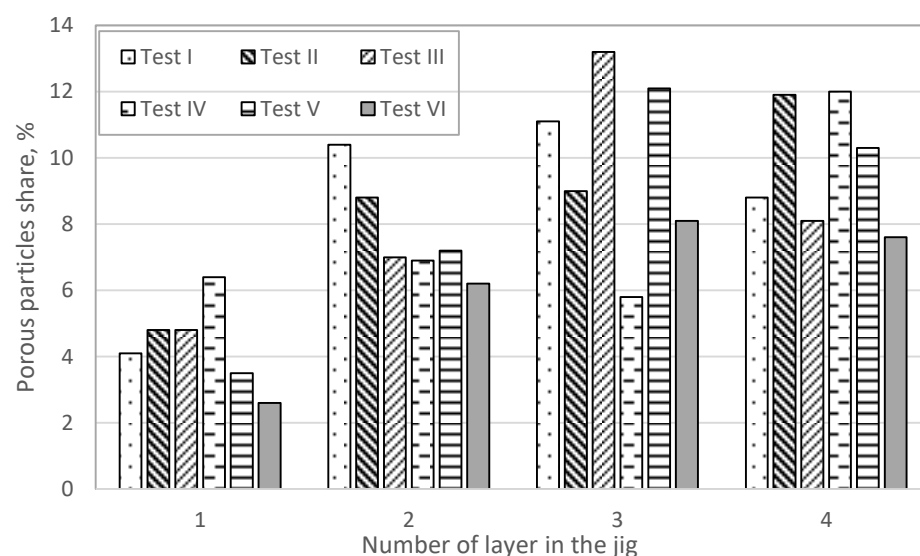


Figure 5. Characteristics of porosity of individual enrichment products for all laboratory tests.

The obtained results show that for tests I, III and V the highest percentage content of porous particles was observed in layer 2 and 3. It appears that this is valid for irregular particles products, regardless of the size range of the material. For tests V and VI, in turn, the content of irregular particle is the lowest for the bottom layer 1. It was caused through accumulation of the highest number of quartz particles with low porosity. It is also worth to mention that accumulation of porous particles in layer I was the lowest in all tests I–VI. It is also correlated with their density and absorbability. In layers 3 and 4, in turn, the highest content of porous particles can be observed.

Comparing the obtained results it can be concluded that the classification of the feed material into narrow particle size fractions and dividing them according to the shape brings better results in the jig enrichment process, due to the narrowing of the parameters of the aggregates and the elimination of equally settling particles.

Modeling results show that relationships between the number of separation product and its selected feature is in correlation, to some extent. Relationships between density/absorbability and number of the separation product (specific layer in the jig) do not show significant correlation for the entire set of data. There can be observed hyperbolic relationship, indeed, but statistical significance of this model is rather low (Figure 6).

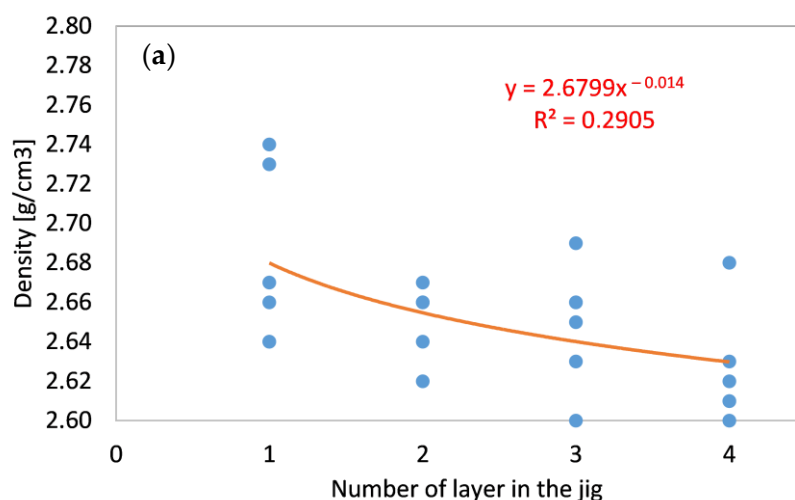


Figure 6. Cont.

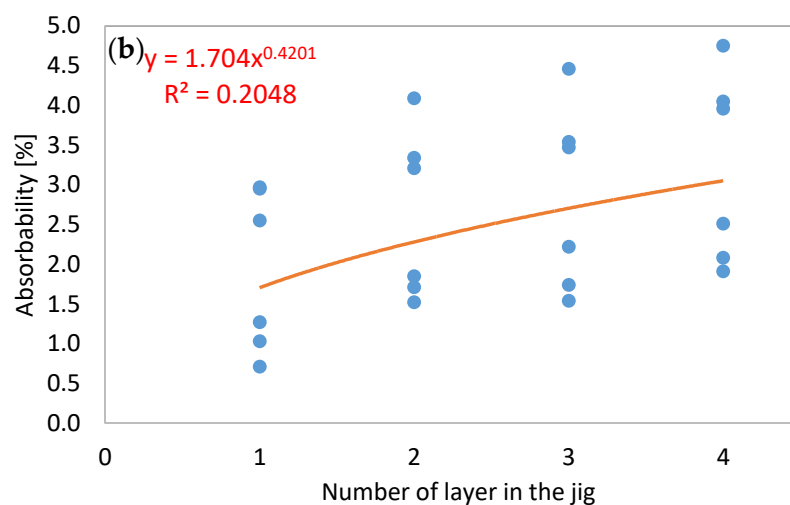


Figure 6. Model of separation for density (a) and absorbability (b).

More precise modeling results can be obtained when enrichment products obtained from regular and irregular feed material will be analyzed separately. Results for density was presented in Figure 7, while models for absorbability in Figure 8. Relationship between density and number of enrichment product for regular particles shows high level of accuracy ($R^2 = 0.935$) and is statistically significant. Lower statistical significance shows model for irregular particles but it is also significant on the probability level 95%. In the case of absorbability (Figure 6b) the model is statistically significant only for irregular particles. However both models show the similar type of relationship. Tendency in density decreasing together with increasing the number of layer describes well a hyperbola, while absorbability can be characterized through exponential model, with the power at x less than one.

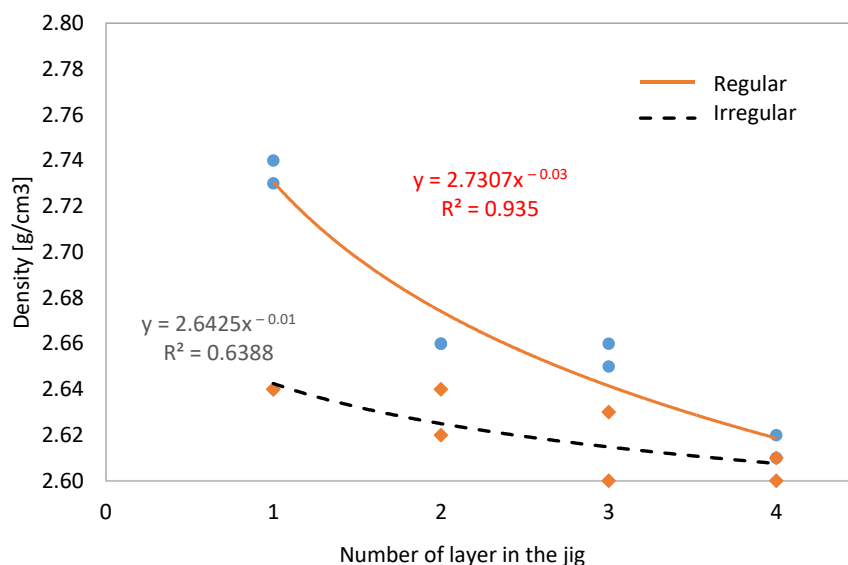


Figure 7. Model of separation density calculated separately for regular and irregular particles.

Density models show that for regular particles the power at x is greater in absolute numbers, but the second coefficient shows no impact on the shape of particles. Models of absorbability show that power at x is also greater for regular particles. In this case this value is greater than zero. Higher impact of the second coefficient can be observed, and it is higher for irregular particles (2.9632) than for regular ones (1.4325). In general, the modeling results justify the approach consisting in run of jig beneficiation process separately for

regular and irregular particles. Achieved accuracies of fitting to operational data were higher both for density and absorbability. It could be then easier to predict the outcomes for such processes, not to mention the main achievement—improvement of qualitative characteristics for products enriched in such a manner.

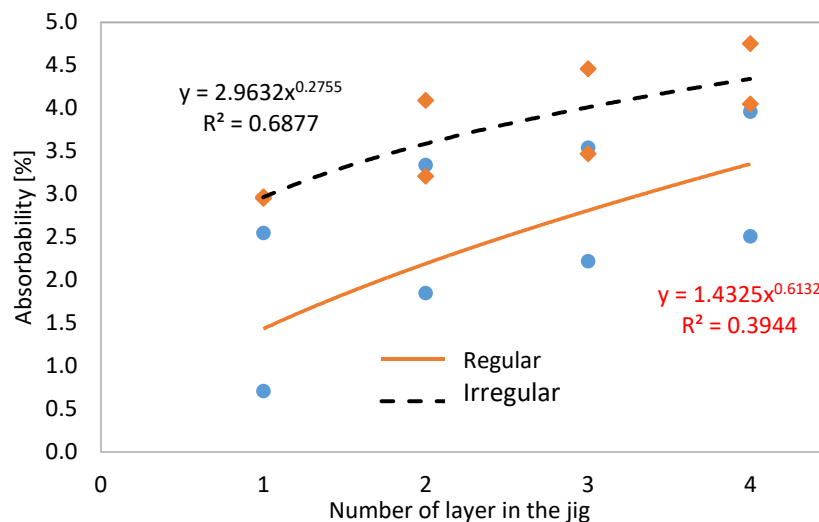


Figure 8. Model of separation density calculated separately for regular and irregular particles.

4.2. Semi-Plant Scale Tests

Results of tests conducted in semi-plant scale are presented in Tables 7 and 8. The test series with a high threshold level shows that differentiation of products both in terms of absorbability and density is not very significant. It is probably due to relatively wide range of particle size (10–16 mm) of the feed material.

It has turned out that preparation of the aggregate for narrower particle size fractions by screening and size separating gave more favorable enrichment results. It was confirmed in results of tests III–VI, especially for aggregates with irregular particles (tests III and V). Enrichment products, depending the number of a layer, were also differentiated in terms of density.

Table 7. Summary characteristics of individual tests in separator SET (high threshold).

Test Number	Layer of Product	Absorbability, [%]	Density, [g/cm ³]
I	lower	1.32	2.66
	upper	1.71	2.63
II	lower	1.49	2.69
	upper	1.83	2.68
III	lower	3.58	2.64
	upper	4.51	2.61
IV	lower	3.18	2.68
	upper	3.81	2.62
	lower	2.26	2.63
V	upper	3.67	2.61
VI	lower	1.26	2.70
	upper	2.20	2.61

Results of experiments conducted at low threshold also showed no significant differences in terms of density. There were observable significant variations in enrichment of narrow particle size fractions, especially for regular particles (test IV and VI), in turn. These results confirm the purposefulness of suitable preparation of the feed material for enrichment process, it is expected to obtain an appropriate differentiation of products in terms of water absorption and density. On the example of test I (Table 7) it can be noticed

that about 65% of flat particles were accumulated on the surface (Figure 9), while the remaining of irregular particles were allocated deeper in both layers. The height of the upper layer was 20 mm.

Table 8. Summary characteristics of individual tests in separator SET (low threshold).

Test Number	Layer of Product	Absorbability, [%]	Density, [g/cm ³]
I	lower	1.11	2.67
	upper	1.93	2.65
II	lower	1.29	2.66
	upper	1.91	2.68
III	lower	3.05	2.65
	upper	4.66	2.62
IV	lower	2.49	2.75
	upper	3.88	2.66
V	lower	2.89	2.66
	upper	3.49	2.60
VI	lower	0.68	2.73
	upper	2.12	2.65

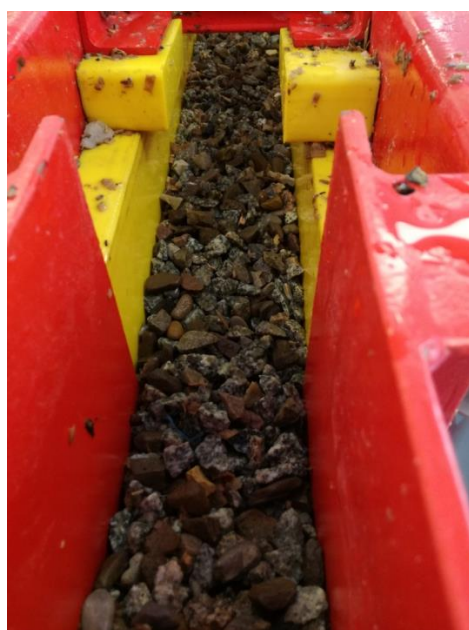


Figure 9. Upper layer in the SET separator for the test with irregular particles.

Shape investigations of separation products were carried out by means of 3D Keyence VHX-7000 microscope. The figures map the profiles of the projection surface (base of particle) in space after transformation of an image into 3D by the computer (Figure 10). A particle is considered irregular if a profile of the length of its base is three times larger than the profile of its width or height. The analysis proves that more flat particles accumulate in the top layer.

Further investigations included comparative analysis of enrichment products obtained in the serie II (low threshold) with typical aggregates before enrichment process in SET device. Grinding resistance (Los Angeles) according to the standard PN-EN 1097-2, as well as micro-Deval (PN-EN 1097-1), were determined. Results are presented in Table 9.

Analysis of results presented in Table 9 indicates that the raw aggregate with 11% of irregular particles is characterized by the least favorable parameters (LA = 40, MDE = 30). The most favorable parameters, in turn, were obtained for enrichment product of the SET device, achieving LA = 30 and MDE = 10. Application of enrichment process makes

it possible to increase significantly quality of physical and mechanical parameters of products, and at the same time increases potential commercial and industrial utilization of such products. It is especially significant in exploitation of poor or lower quality deposits or utilization of aggregates from recycling or tailings.

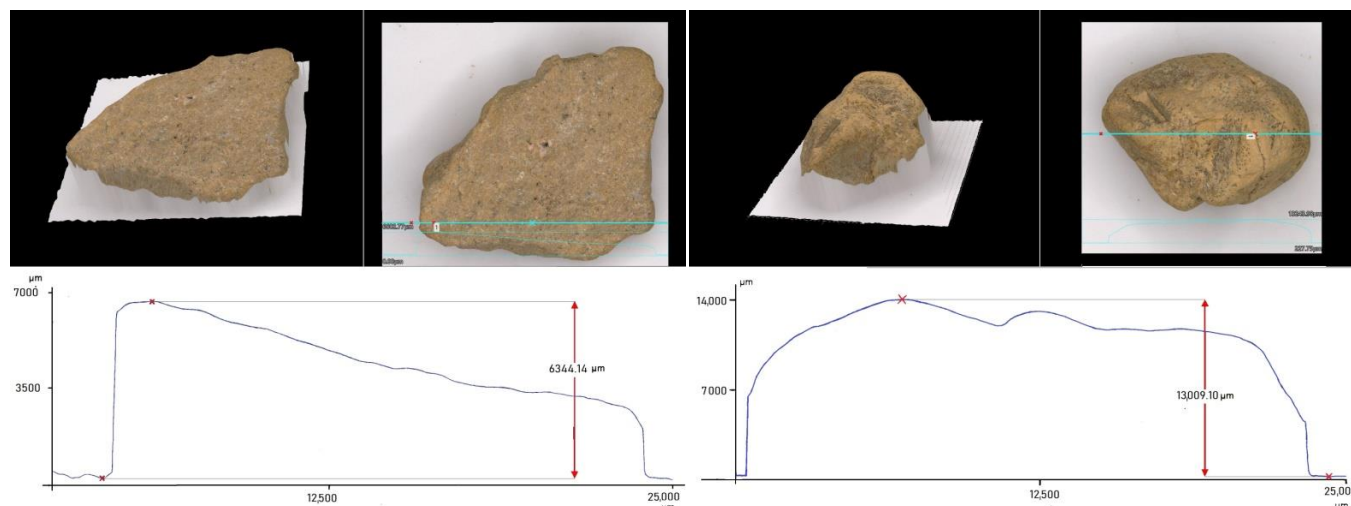


Figure 10. Exemplary analysis of irregular (**left**) and regular (**right**) particle in 3D Keyence VHX-7000 microscope.

Table 9. Results of Los Angeles and micro-Deval indices for a gravel aggregate in particle size fraction 10–14 mm at different stages of enrichment.

Gravel Aggregate 10–14 mm	Los Angeles Index, LA [%]	Micro-Devala Index, M_{DE} [%]
Raw material (typical) with 11% of irregular particles content	36.7 category LA40	29.8 category M_{DE} 30
Raw material without irregular particles	31.9 category LA35	17.6 category M_{DE} 20
Product enriched in SET device, without regular particles (low threshold)	29.5 category LA30	9.8 category M_{DE} 10

5. Conclusions

The aim of the paper was to demonstrate how the efficiency of a jig separation process for aggregate minerals could be improved. Thanks to the application of a patented classification circuit prior to jiggling, the absorbability and density of individual products in specific layers in the jig were diverse on average for 0.8 and 0.5% respectively, comparing to values achieved for material without prior pretreatment.

In terms of water absorption, very favorable results (significant diversification of results) were obtained especially for narrow particle size fractions of separation products, where the difference between individual layers was greater than 2% (laboratory tests V and VI). Similar differences were observed for the density. The particles with the highest density have accumulated in the lower layers, which was due to the fact that in this layer the majority of quartz particles of low porosity was also present. It is also worth noting that in all tests, the least porous particles accumulated in layer 1, which also correlates with the density of these grains and their water absorption.

It should be noted, however, that greater differentiation between the enrichment products was obtained for using of a laboratory ring jig in comparison with the semi-plant SET device. This difference mainly results from the number of layers and the longer duration of enrichment process (5 min) in laboratory jig. In the SET device, in turn, the material has been enriching for several dozen seconds. It should be also taken into account that the SET device is a prototype that operates together with a set of screens

separating the aggregates into narrow particle fractions according to size and shape, constituting the patented invention number PL 233318B1.

Considering the obtained results, it can be concluded that screening of feed material into narrow particle size fractions and the separation of these fractions also in terms of shape brings more favorable results of jig aggregate enrichment, due to the narrowing of the parameters of the aggregates and the elimination of equally settling particles.

The obtained results of the investigations show that jig beneficiation of aggregates in the proposed circuit may result in more efficient process performance, and also leads to more efficient use of raw materials and less waste production. It needs to be pointed out that the obtained differences in density and absorbability are not very large. However, a suitable design of the circuit and process operation may be effective in producing a more homogenous aggregate product in terms of their physical and mechanical properties. An application of jig beneficiation in the mineral aggregates production industry may help both in efficient separation of the final products and in elimination of fractions of particles with an abnormal density and/or absorbability from the final products, as well as decreasing the content of irregular particles. An overarching aim of the approach is increasing the strength properties of aggregate products, which attracts a higher value in many sectors of the building industry. A good example can be results of comminution resistance (Los Angeles index) and micro-Deval abrasion resistance. The raw aggregate with natural content of irregular particles (app. 11%) was accounted to lower categories according to LA and MDE. After enrichment process the product was characterized by higher categories, at the same time gaining the higher quality.

Patents: Two patents granted in Poland were utilized in the paper:

Author: Gawenda T. Title: Układ urządzeń do produkcji kruszyw foremnych, AGH w Krakowie.

Patent No. PL233689 granted on 8.07.2019.

Authors: Gawenda T., Saramak D., Naziemiec Z. Title: *Układ urządzeń do produkcji kruszyw oraz sposób produkcji kruszyw*. AGH w Krakowie, Patent No. PL 233318B1 granted on 7. 06. 2019.

Norms and standards: PN-EN 933-3:2012. *Badania geometrycznych właściwości kruszyw—część 3: Oznaczanie kształtu ziaren za pomocą wskaźnika płaskości*.

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