Innovative technological circuits for regular aggregates production

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Abstract. The aim of the article is to discuss possibilities of production of aggregates with increased content of regular particles, on some well-known examples, as well as presentation of methods of aggregate production, which was not previously present in the industry. Traditional aggregate production circuits require application of three or four grinding stages (depending on the particle size of the feed), but for fine particle fractions of aggregates irregular grains occur on average approximate content of 10%. The innovative technological circuit can produce the aggregates with the content below 3% irregular grains, even in a single- or two-stage crushing circuit.

1. Introduction
The processing of rock materials is currently more and more challenging in aspect of final products quality. The specific market requires big amounts of products of narrow particle size distribution and specified shapes (cubic ones) by possibly low permitted share of elongated or flat particles. The physicochemical properties of the material depend on location of exploitation and because of that they are unchangeable while desired size and shape of particles or surface’s texture are possible to achieve dependably on applied processing methods during their production (especially comminution) and can directly influence on other features.

The most important rock materials for road and civil engineering are aggregates being produced from magmatic rocks. The basalt and melaphyre aggregates find wide applications in construction of upper layers of road surface. These layers, transferring huge dynamic loads and being directly abrading and under influence of disadvantageous atmospheric conditions should be constructed of aggregates of low abrasion, highly durable and resistant to water and frost [1]. Besides, these aggregates should characterize with particles shape being closed to spherical or cubic ones, have sharp edges and coarse fracture planes.

In civil engineering most of aggregates built of magmatic rocks is used to produce high quality concretes and special concretes. Also here the most desired are regular particles of spherical or cubic shapes because particles of other shapes have bigger surface requiring enlarged amount of concrete and water. Furthermore, flat and elongated particles have tendency to orientate in one plane what is connected with possibility of creating air voids [2]. The growth of flat particles contents influences on growth of free spaces what causes necessity of increasing the amount of mortar in concrete and in this way influences on increased amount of consumed concrete. Their significant share in the aggregate influences badly on durability of a concrete.
The ratio of particle width and their coarseness has also very important influence on particles durability. The irregular particles, especially flat ones indicate the biggest abrasion. It was stated that especially high influence of irregular particles on aggregates durability occurs by their contents of 25-50%. For example, the durability of basalt aggregate is lower by 55% when the share of irregular particles is equal to 50% [1]. So, both the granulometric distribution and particles shape decide about the quality of the aggregate. Also physicochemical properties, like resistance to comminution determined by abrasion in ball mill Los Angeles are important. The regular particles have lower susceptibility to comminution (lower value of LA factor), lower absorbability, abrasion what is related to concrete’s or road surface’s durability [3,4].

J. Malewski noticed the problems of defining measure of shape and interpretation of particles shape factors [5]. He defined the particles shapes, like spherical, cubic, elongated or flat. To avoid discrepancies in evaluating particles shapes and interpretation of the results the following norms were used in the conducted researches: PN-EN 933-4:2008. Investigations of geometrical properties of aggregates - Part 4: Determination of particles shape – shape coefficient and PN-EN 933-3:2012. Investigations of geometrical properties of aggregates – Part 3: Determination of particles shape by means of flatness factor [6,7].

2. Possibilities of increasing share of regular particles in mineral aggregates

Undoubtedly, the appropriate choice of the crushers with exploitive parameters influence on possibilities of increase of regular particles share. Other important features are amount of comminution stages and sort of technological systems.

To produce aggregates in purpose of getting particles of beneficial shape the cone granulators and impact crushers (cubisers) are being used. Cone granulators characterize with special shape of crushing chamber ensuring multiple comminution of individual particles and usually slightly lower jump and higher rotations what ensures that particles have longer way to pass in working chamber. To produce grits in cone granulators is necessary equip the installment with buffer containers which should get feed to these crushers by covering their total working chamber. In this way the optimal comminution is achieved and inner cone is protected against abrasion caused by material’s fall from height.

The especially interesting are impact crushers with vertical shaft. The progress in material branch allows to use them also to crushing very hard materials. Furthermore, the way of feeding (system stone – stone) in such devices limits consumption of working parts of the crusher. Cubisers are more and more often used in aggregates production, especially concerning limestones and dolomites. However, products of impact crushers indicate the contents of finest fractions (like <2 mm) much higher than in case of jaw or cone crushers.

It is worthy to remember that improperly selected device parameters influence on its exploitation, like energy or working parts consumption which influence on quality of the products (shape and size of particles).

Technological systems have their task in processes of comminution and classification conducted in mineral processing plants. The quality of obtained products depends not only on appropriate selection of comminuting devices but also on cooperating ones (classifiers), dependably on sort of processed material. Assuming certain technological process we usually consider work characteristics of individual devices which depend among others on physicochemical properties of the feed and values of constructive and steerable parameters of the devices. The obtaining of good results depends also on way of process conducting (amount of comminution stages, technological cycles, steering on material flow streams to selected devices etc.).

It occurs that comminution of material in crushers with closed circuit is more beneficial because during material’s return the filling of crushing chamber is higher and flat, naturally physically weaker particles are crushed easier what influences on their better shape. The appropriately designed comminution systems with closed circuit allow to control material’s flow and also to get better quality of products. According to conducted investigations [8] the contents of flat particles in product after...
stabilization of material’s flow in closed circuit was, dependably on particle fraction, lower by 4-15% than for product being crushed in open circuit (without return).

In paper [9] the conditions and results of four-stage systems of comminution in two selected basalt aggregates production plants located in Lower Silesia were presented. Table 1 presents sorts of crushers being installed on individual comminution stages in plants A and B, their comminution degrees and shape coefficients of products particles.

**Table 1.** S80 and S50 comminution degrees and shape coefficients K, obtained on consecutive crushing stages [9].

| Type of crusher | S80 | S50 | K [%] |
|-----------------|-----|-----|-------|
| **Plant A**     |     |     |       |
| jaw JM st-1     | 4.6 | 4.2 | 21.0  |
| cone Svedala Superior S3000 st-2 | 2.5 | 3.6 | 38.0  |
| cone Svedala Hydrocon H4000 st-3 | 2.3 | 2.1 | 14.3  |
| impact Barmac MK st-4 | 1.5 | 1.8 | 6.0   |
| cone Krupp st-2 | 4.2 | 3.6 | -     |
| cone Svedala Hydrocon H4000 I st-3 | 2.3 | 2.8 | -     |
| cone Svedala Hydrocon H4000 II L1 st-3 | 1.2 | 1.6 | 13.3  |
| **Plant B**     |     |     |       |
| cone Svedala Hydrocon H4000 II L2 st-3 | 1.2 | 1.4 | 10.0  |
| cone Svedala H3000 L1 st-4 | 2.2 | 2.9 | 16.3  |
| cone Svedala H3000 L2 st-4 | 2.3 | 2.5 | 16.4  |
| cone Svedala H3000 L2 st-4 | 1.1 | 1.3 | 7.2   |

The shares of irregular particles in individual particles fractions of comminution products are shown on Figure 1 (plant A) and 2 (plant B). Figure 1 shows that there is very high content of irregular particles (>60% for particle size fractions <16 mm) after crushing conducted in cone crusher S3000 (second stage). This content significantly lowers in following comminution stages, especially after using cubiser Barmac. From the analysis of data presented on Figure 2 it occurs that the lowest contents of irregular particles are obtained for product of comminution in impact crusher Dragon (third stage) and the share of such particles in fraction >16 mm is the lowest after crushing in H3000 crusher (fourth stage).

The data presented in Table 1 allow to determine dependencies between shape coefficient and comminution degree. This relation was presented on Figure 3. As it is visible the highest comminution degrees are typical for crushers working in initial stages of the process. However, better shape coefficients can be obtained for particles of products obtained in following stages by lower comminution degrees. The very high value of $K$ for S50=3.6 occurs from the particularly high amount of irregular particles in fraction <16 mm after comminution in cone crusher S3000, what was described above

![Figure 1](image-url)
Figure 2. Share of irregular particles (shape coefficients) in individual particle size fractions of chosen comminution products – plant B, summer period [9]

Analysis of efficiency of multistage comminution on example of basalt rocks allows to make some important conclusions. The shape coefficient of particles in impact crushers products is lower than shape coefficient of the products of cone crushers. However, in cone granulators it is possible to get particles fractions of low (even lower than the one obtained in impact crushers) contents of irregular particles but under condition that the outlet gap is properly selected. The size of this gap is crucial in context of not only granulation but also of comminution products particles shape. For each fraction of the aggregate there is optimum size of outlet gap by which the most appropriate particles shape can be achieved. This value is close to the size of required fraction. The shape coefficient in comminution products lowers with lowering of comminution degree, it is possible then to ensure appropriate shape of comminution products particles through application of bigger amount of comminution stages in aggregates production technology. It can be noticed especially for final comminution. Unfortunately, it is connected with purchase of higher amount of devices and more expensive exploitation.

Figure 3. Influence of the shape coefficient on comminution level [9]

It occurs that comminution processes with return of material not only bigger than cut point but even fine one (being called also as bed) are being used in mineral aggregates production in purpose of lowering contents of irregular particles. Such investigations were carried out by Metso Minerals in cone granulators producing grits [10]. To this purpose two three-stage systems were used. In first system (Figure 4) two first stages of crushers work in open circuits. Cone granulator on third stage works in closed system with full charge. All devices are joined in the way ensuring maximization of
capacity which was equal to 262 Mg/h. As it is shown on Figure 4 fine flat particles occurring in feed will not be crushed in any crusher and we will obtain a product of low quality. The comparison of irregular particles contents for both systems is presented in Table 2.

The second system (Figure 5) presents the situation where jaw crusher works on first stage in open system. The other crushers work in closed system while cone granulator on third stage works also with full charge as it was shown on Fig. 4. However, such system characterizes with lower capacity which was equal to 171 Mg/h but maximum contents of regular particles are obtained. It is worthy to notice that lower product from second sieve deck of first screen is on this scheme joined with lower product of first deck and being directed to cone granulator.

![Figure 4. Triple-stage system with non-selective material flow [10]](image)

![Figure 5. Triple-stage system with selective material flow [10]](image)
Table 2. Irregular particles content for products after different crushing stages for different technological systems [10].

| Crushing stage | Percentage of irregular particles contents in fractions | Non selective system | Selective system |
|----------------|--------------------------------------------------------|----------------------|------------------|
|                | 5/10 [mm] | 10/20 [mm] | 5/10 [mm] | 10/20 [mm] |
| II             | 50       | 30        | n/a       | n/a          |
| III            | 20       | 15        | 15        | 10           |
| Final product  | 34       | 22        | 15        | 10           |

The process of selective comminution with return of fine material (with bed) is beneficial in production of mineral aggregates in cone granulators but it is necessary to remember that in such case the excessive comminution should be avoided (too many comminution degrees) because it may lead to creation of fine dusts in the products. Also, the rules of selection of particle size distribution of the feed must be respected for such crushers to avoid too large shares of fine particles being lower of outlet gap size. Badly selected parameters of screen working before the crusher can influence on improper particle size distribution of the granulator’s feed. This issue was discussed in the paper [11].

3. Innovative technological systems to produce aggregates of increased contents of regular particles

The most popular technological solutions in relatively small rock materials processing plants, especially ones producing recycled aggregates from wastes, are mobile and stationary installations equipped with one or two comminution stages. While stationary installations work in closed systems, mobile one work usually open systems with one crusher, preferably of jaw type, eventually cone or impact one. Such solution is caused mainly by economic reasons of small enterprise what make the quality of the product worse. Despite there are mobile installations on the market which allow material to return, like it is in SBM MP enterprise which offers device of Remax type equipped with rotary impact crusher, not many plants have this type of installments.

To make the technological process of aggregates production more efficient in simple installations is possible to equip the system with additional multi-product screen with slotted sieve and return the lower product to additional comminution process. Figure 6 presents the scheme of such innovative system designer by the Author which serves to production of aggregates of increased amount of regular particles, which idea of invention was reported to Patent Office [12].
The system was thought in the way ensuring that even with only one crusher (for example of jaw type), despite it is not beneficial concerning quality of products is possible to get final aggregates with contents of no more than 2-3% of irregular particles. Such system requires only application of vibrative screens with sieves of quadratic mesh no 1 and slotted mesh no 2 (Figure 6) cooperating in pelting way in return with crusher being located in first or second stage. The task of multideck screen is to classify aggregates into narrow particle fractions which would occur to single deck multi-product screen with slotted sieve and then the irregular particle are being sieved (lower product) and returned again to comminution. The irregular particles can be comminuted in the same crusher or on secondary stage of crushing by impact, for example in cubiser what will affect positively on quality of the product. The contents of irregular particles in final products will depend on capacity of the screen with slotted sieve and especially on relation between narrow particle fraction range and size of the slot in sieve. This sieve should be selected according to the rule $d_{\text{max}}/2$ what means half of maximum size of certain fraction’s particle. Because share of irregular particles lowers with growth of particle fraction and efficiency of screening grows for coarser particles then sieving of irregular particles in coarser fractions will be easier and more efficient. That is why in laboratory investigations conducted in KIS AGH according to the scheme presented on Figure 6, the finest particles size fraction (6.3-8 mm) was...
investigated to verify correctness of the idea and to determine the maximum contents of irregular particles which could occur in final products.

The dolomite used in tests came from the Skała I rock mine [14]. Particle size distribution of the material was within the range 0-100 mm. The material comminuted in jaw crushers of L44.41 type and Eko-Lab type was classified on vibrative two-deck screen in the way ensuring selection of narrow particle fraction 6.3-8 mm. This fraction contained about 80% of regular particles and 20% of irregular ones. In combination of the pelting system of screens with quadratic and slotted mesh, 2 types of the following slotted sieves were used in purpose of determining the efficiency of sieving of irregular particles.

- metal wire of mesh 4x20 mm shaped lengthwise (MD lengthwise),
- polyurethanic of mesh 4x20 mm shaped lengthwise (PU lengthwise).

Schemes of investigations were presented in Figures 7 and 8, while the results are shown in Table 3.

### Table 3. Distribution of regular (ZF) and irregular (ZN) particles in 6.3-8 particle size fraction in relationship to the type of the sieve [14].

| Type of sieve | Yield (%) | Yield (%) | Contents in final product (%) | Recovery (%) | Efficiency (%) |
|---------------|-----------|-----------|-------------------------------|--------------|----------------|
|               | $\gamma_g$ | $\gamma_d$ | $\gamma_g$ ZF | $\gamma_d$ ZF | $\gamma_g$ ZN | $\gamma_d$ ZN | ZF Pk | ZN Pk | $\varepsilon_{ZN}$ | $SH_{ZN}$ |
| MD lengthwise 4x20 mm | 81.8 | 18.2 | 79.8 | 0.3 | 2.0 | 17.9 | 97.5 | 2.5 | 8.3 | 91.6 |
| PU lengthwise 4x20 mm | 91.9 | 8.1 | 79.2 | 1.4 | 12.8 | 6.6 | 86.2 | 13.8 | 60.4 | 38.8 |

![Figure 7. Scheme of investigations with irregular particles screening on a slotted wire screen [14]](image-url)

![Figure 8. Scheme of investigations with irregular particles screening on a polyurethane screen [14]](image-url)
The test results show that after application of the slotted screen in the tested technological circuit it is possible to obtain mineral aggregates with irregular particles content below 3%, instead of 20%.

The most favorable slotted screen appeared to be the wire one. The above results confirm outcomes achieved in the work published by Gawenda [13], where for both tests the contents of irregular particles (ZN Pk) equaled about 3% at the Hancock's technological efficiency of 92%.

Polyurethane sieves cannot be used for such a screening process due to their low coefficient of clearance (low recovery of regular particles: 60%, high content of irregular particles in the final product: 14% and low screening effectiveness: 39%).

According to the idea of producing aggregates of increased contents of regular particles in system of closed circuit of selective pelting process of screening and comminution, it is possible to lower contents of irregular particles from several dozen % till at least 2-3% in each particle fraction. Even by enlarging slots of sieve from 50% to 60-70% of maximum particle size of certain fraction it will be possible to eliminate almost every irregular particle from the products causing increase of the returned material in the system. After joining narrow particles fractions is possible to obtain also aggregates of other granulation range, like for example 0-31.5 mm.

Comparing comminution effects which were achieved in industrial conditions in selective system of Metso Minerals with cone granulators where, according to Table 2, the contents of irregular particle was equal to 15% for related particle fraction 5-10 mm is worthy to notice that obtained results are almost five times higher. Also, in system to produce basalt aggregates (Figure 2), in cubiser Dragon on third stage of comminution 13% of ZN was achieved in fraction 5-8 mm and in cone granulators of type H3000 and H4000 Svedala on third and fourth stages even 23% of ZN. So, these values are more than 8 times higher.

An alternative solution to the presented technological concept is the AGH-patented circuit for the production of aggregates with two crushers and a multi-deck screen for the grain classification and selective separation of irregular aggregates (PL 231748B1) [15]. The idea is shown in Figure 9. The circuit consisting of crushers contains one multi-deck screen in which the feed is separated into narrow particle size classes that are further separated into regular and irregular particles on a slotted screen placed at the bottom deck of the screen.
Figure 9. Circuit for separation of regular and irregular particles according to PL 231748B1 [15]:
A, B - crushers; 1 - hopper; 2, 3a, 4a, 5a - decks of fractional sieves; 2b, 3b, 4b, 5b - decks of slotted screens; 3c, 4c, 5c - chutes of irregular particles, 6 - chute of fine particles.

The efficiency of screening depends on sort of slotted sieve and slots size in ratio to the range of granulation of sieved fraction, dynamic parameters of vibrative screen and also on sort of applied crusher. By impact crushers applications with vertical shaft and limitation of amount of comminution stages in closed circuit, for example from four to three stages, certainly less amount of irregular particles will circulate. That influences positively on screening efficiency and also on amount of produced finest fraction <4 mm and dusts. Resignation of one comminution stage would allow to lower energy consumption even till about 1 kWh/Mg of comminuted aggregate and save costs connected with crusher’s working parts consumption being equal from about 0.2-0.5 PLN/Mg. And the costs connected with exploitation of additional screen are not significant and will be equal to about 15-35 PLN/1000 Mg of sieved aggregate dependably on sort of screen and applied sieves.

It supposes to be underlined that the advantage of the discussed system, apart from energy savings, is possibility of selective division of any particles fractions as well regular and irregular particles in these fractions. This can be done without their crushing for too long time what unfortunately takes place in traditional multistage systems. That is why more technologically advanced systems are equipped with cubisers or cone granulators on final stages of comminution which purpose is to comminute fine final aggregates by small values of comminution degrees. This is done to avoid their excessive comminution.

4. Summary
Compact rock materials especially of volcanic and metamorphic origin are valuable materials to produce aggregates for road, railway and civil engineering from which gravel, arch blocks, grits (granulated aggregates). Particle size distribution and particles shape decide about aggregate’s quality which influence highly on its durability. The contents of irregular particles in mineral aggregates
depends mainly on the way of material crushing, so on sort of applied comminuting devices, their constructive and exploitive parameters, comminution degrees and amount of crushing stages. In industrial and laboratory investigations it was noticed that the harder rock material (more compact) is more difficult to obtain regular aggregates. Besides, in finer particles fraction of comminution products the biggest amount of irregular particles is obtained so the using of cubisers on final comminution stages is advisable. With growth of comminution degree the contents of irregular particles grow too so crushers should work by not too big comminution degrees. However, all of these significant factors influence on necessity of applying multistage systems which increase both investments and exploitive costs.

An alternative in this respect can be the applied inventions of AGH in the form of installations for the production of broken aggregates in a circuit with closed cycle of selective and following process of screening and comminution (P.408045), or installations with multi-deck and multi-fraction screen (PL 231748B1), which occur (depending on the particle size of feed) in a one- or two-stage circuit, eliminating at the same time one crushing stage.

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Acknowledgments
The article is the result of the National Center for Research and Development (NCBiR) project: competition No. 1 under Sub-measure 4.1.4 "Application projects" of POIR in 2017, entitled: Opracowanie i budowa zestawu prototypowych urządzeń technologicznych do budowy innowacyjnego układu technologicznego do uszlachetniania kruszyw mineralnych wraz z przeprowadzeniem ich testów w warunkach zbliżonych do rzeczywistych”. Project is co-financed by the European Union from the sources of European Regional Development Fund under Measure 4.1 of the Intelligent Development Operational Program 2014-2020.