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Martin Steuer (1980) studierte Maschinenbau an der TU Bergakademie Freiberg. Seit 2006 ist er am Institut für Aufbereitungsmaschinen der TU Bergakademie Freiberg als wissenschaftlicher Mitarbeiter tätig. In seiner Promotion beschäftigt er sich mit der Sortierung von Partikeln nach ihrer Form sowie Klassierprozessen auf schwingenden Klassiermaschinen.

Serial classification

A new highly efficient process for sorting particles by shape

Summary: The macroshape of particles in material mixes or fractions has considerable influence on a wide range of product properties. For this reason, in numerous industries there are potential applications for particle shape sorting methods in order to improve product properties. One of these potential applications is the production of high-grade chippings, with cubic particles complying with the technical specifications (e.g. TL Gestein-STB 04 in Germany). At the Institute of Mineral Processing Machines at Freiberg University of Mining and Technology a sorting method was developed with which it is possible to sort particles by shape.

1 Motivation for particle shape sorting

In many production processes the particle shape has a significant influence on the quality of the products produced. Many material properties, for example conveying and flow behaviour, permeability or the reactivity, depend on the particle shape [2, 4, 7, 9]. For instance, in material recycling, with the various process stages (comminution, compaction), mixes of various material groups are formed, in which the individual material groups differ significantly in their particle shape. This is the case, for example, in the shredding of various types of waste, when, for example, balls of metals or flaky, splintery plastics have to be separated from the remaining stream of materials.

In the basic industry too there exist numerous applications for particle shape sorting processes. For instance, asbestos varieties in certain deposits, in which the asbestos is found in flaky form, can be separated on the basis of their particle shape. Similar applications are known from the preparation of coal from deposits with pronounced flaky particle shape as well as from the separation of xylith (woody brown coal) from lignite [1, 3]. Another important application is the production of high-grade chippings for road and airfield construction. In the production of high-grade chippings, particle shape requirements with regard to cubicity must be met to comply with the valid technical supply specifications

Site of the development of new processes: the testing facility at the Institute of Mineral Processing Machines at Freiberg University of Mining and Technology

(e. g. TL Gestein-STB 04 Technical Terms of Delivery for Aggregates used in Road Construction). Owing to changing deposit conditions (e. g. change in the microstructural texture) or comminution technology that is not optimally adjusted to the deposit conditions (e. g. comminution based on compressive stress for an anisotropic rock structure), an unacceptably high percentage of non-cubic particles may be found in the product grades.

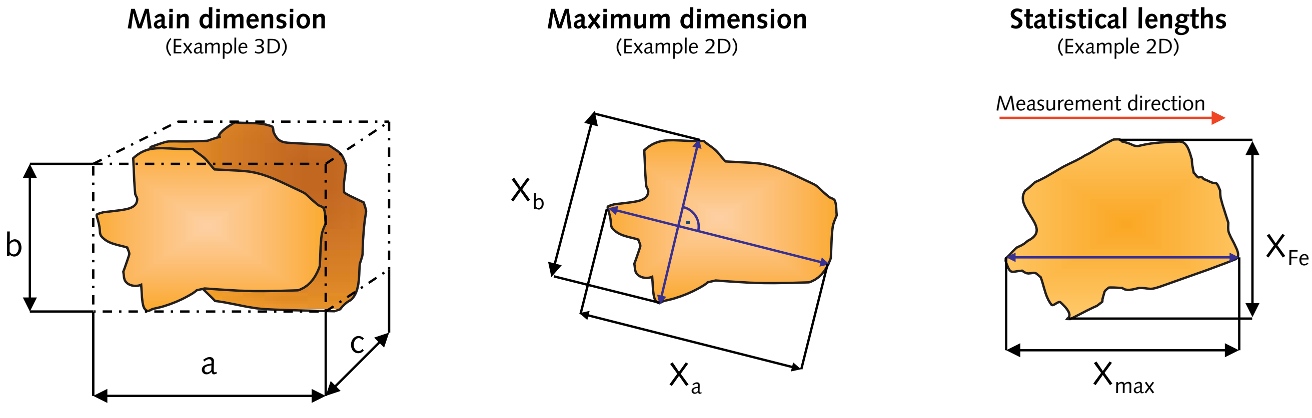
To minimize the percentage of non-cubic particles, currently multistage comminution systems are employed, in which either special short-head cone crushers, which produce cubic particles in the range of their gap width, or rotor centrifugal crushers, which operate with a size reduction ratio of $\varepsilon < 2$, resultimg in a "re-cubicizing" or crushing of non-cubic particles. At the Institute of Mineral Processing Machines at Freiberg University of Mining and Technology, a new type of process was developed in which in two spatially separated classification steps, where classification is performed based on different particle dimensions, the production of standard-compliant high-grade chippings is possible. In this process, non-cubic particles are separated from the quality fractions. The principle of the process of "double serial classification" of the high-grade chippings is explained in the following and described based on selected results. In a prepending study, particle shape is defined on basis of geometric particle dimensions.

2 Definition of the particle shape with geometric particle dimensions

In mineral processing, the group of geometric particle shape factors has proven a practicable method for the characterization of the particle shape. Geometric particle shape factors are formed with the use of defined particle dimensions **(Fig. 1)**.

These include:
- Main dimensions (2D and 3D measurement),
- Maximum dimensions (2D and 3D measurement) as well as
- Statistical lengths (only 2D measurement).

The main dimensions describe the edge lengths of a cuboid or rectangle enveloping the particle (3D) or the projected area of the particle (2D), a being the longest, b the mean and c the smallest main dimension. With use of the maximum



The following applies: $a > b > c$; $a \perp b \perp c$ The following applies: $X_a > X_b$; $X_a \perp X_b$ The following applies: $X_{max} \perp X_{Fe}$

1 Definition of the particle dimensions

dimensions, the longest chords standing vertically on top of each other of a projected area (2D) or a particle volume (3D) are used to describe the dimensions. Here X_a corresponds to the longest maximum dimension, X_b the mean maximum dimension and X_c the smallest maximum dimension. Statistical lengths, such as the maximum chord X_{max} as well as the Feret diameter X_{Fe} are used exclusively for the description of the dimensions in the 2D range. The Feret diameter defines the distance between two tangents parallel to the direction of measurement, the maximum chord the longest chord within the particle in the direction of measurement.

Depending on the method used, the particle shape is defined on the basis of the possibilities resulting in **Table 1**. A differentiation is made between elongation, cubicity and flakiness. For the production of high-grade chippings to meet the requirements of TL Gestein- STB 04, the geometric particle shape factor "cubicity" is crucial.

3 Sorting by "double serial classification" of particles based on their shape

The basic idea of the process of "double serial classification" is that with a temporally and spatially separated classification, it is possible to sort materials by particle shape on the basis of at least two different particle dimensions. For sorting by cubicity, as required for the production of standard-compliant aggregates in the non-metallic minerals industry, in a first classification step it is necessary to classify the material based on the particle length and in a second temporally and spatially classification step it is necessary to classify it based on the particle thickness. **Fig. 2** shows this principle in simplified form as a black box model.

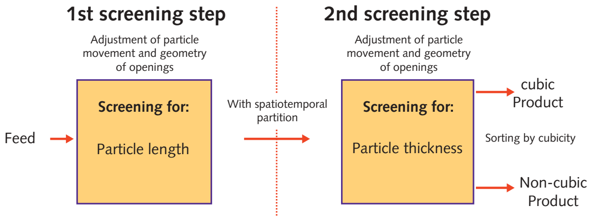
For high sorting efficiency, very sharp classification processes are necessary. With an appropriate combination of particle movement and the geometry of the classification apertures, it is possible to define according to which particle dimension classification is performed. Precise adjustment of the particle movement also guarantees optimal separation sharpness in the individual classification stages. The particle movement is determined by the screen acceleration S_V, which can be derived from the force acting on the individual particles **(Fig. 3)**.

Here:
F_a – force of acceleration in [N],
F_g – weight of the particle in [N],
a – acceleration as a result of the vibration [m/s^2],
g – gravitational acceleration in [m/s^2],

Table 1: Selected particle shape factors on the basis of the main and maximum dimensions as well as the statistical lengths

Particle shape	Definition of the particle shape from the		
	Main dimensions	Maximum dimensions	Statistical lengths
Elongation	$\Psi_L = \frac{a}{b}$	$\Psi_L = \frac{X_a}{X_b}$	$\Psi_L = \frac{X_{max}}{X_{Fe}}$
Cubicity [1]	$\Psi_K = \frac{a}{c}$	$\Psi_K = \frac{X_a}{X_c}$	–
Flakiness [1] (Flatness)	$\Psi_P = \frac{b}{c}$	$\Psi_P = \frac{X_b}{X_c}$	–

[1] Only possible with the use of three-dimensional measurement



2 Black box scheme of "double serial classification"

α – angle of incidence of the screening surface in [°] and
β – angle of incidence of the vibrating drive in [°].

As a result of the effect of the acceleration on the particle, a characteristic particle movement results, which can be described as a function of the screen acceleration S_V as a throw movement at $S_v > 1$ or as a sliding movement at $S_v < 1$. The transition from sliding to throw movement is fluent so that a differentiation can be made between very flat to very steep throws. In the selection of the classification geometry a differentiation can be made between aperture geometries with the same dimensions in the X and Y directions and classification geometries with different dimensions in the X and Y directions. **Fig. 4** shows a selection of various aperture geometries.

For sorting by cubicity with application of "double serial classification", circular apertures and rectangular geometries in the form of perforated plates and bar screens are used. If circular aperture geometries as well as a flat throw movement of the particles are used for classification, particles can be classified by their length. If classification is performed on a bar screen, with a flat throw motion, the particles orient themselves with their longest dimension (X_a) parallel to the bars of the bar screen and are classified by the particle thickness. Fig. 5 shows the movement of non-cubic particles on the described aperture geometries with a sliding motion as a single-particle model.

For the design of a machine suitable for industrial application in the non-metallic minerals industry for the production of standard-compliant high-grade chippings (in compliance with the limit values for cubicity), it is necessary for economic reasons, to perform both classification steps in one machine. For this purpose, the aperture geometries of the first and second classification steps are installed spatially separated on a single deck. For processing a wide particle size range, several combined decks are arranged on top of each other. **Fig. 5** shows the multiparticle model employed industrially for "double serial classification".

4 Selected sorting results

To evaluate the results of "double serial classification", an evaluation method adapted to the process was developed. Aim of the evaluation is to relate the results obtained in the tests to the sorting results achievable under ideal sorting conditions, i.e. to evaluate the degree to which ideal sorting is achieved. Ideal sorting is defined here as 100-% separation at a defined cut-point $\psi_{K,Tr}$ (step function as the separating function see **Fig. 6**).

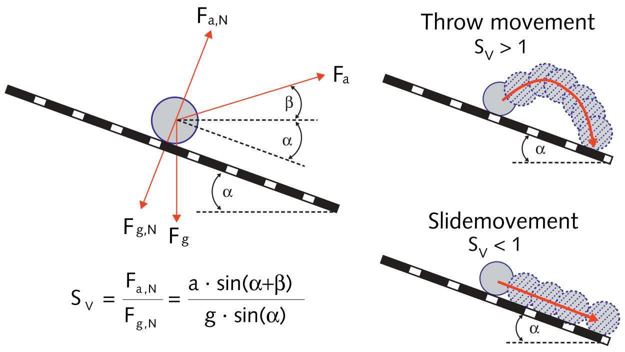
The separating criterion distribution model used for evaluation was developed on the basis of the washability curve model, which was used originally to evaluate the sortability of coal by density [8]. Using this model, it is possible to determine the particle shape factors that can be achieved under ideal sorting conditions. As a function of one fraction percentage $Q_0(\psi_K)$ e.g. of the cubic fraction, the ideal particle shape factors for the cubic and non-cubic fraction $\psi_{K,K,ideal}$ or $\psi_{K,NK,ideal}$ are determined **(Fig. 7)**.

The difference between the two values is termed the ideal particle shape difference $\Delta\psi_{ideal}$. From the particle shape factors ($\psi_{K,K,real}$ and. $\psi_{K,NK,real}$) determined in the empirical tests for the cubic and non-cubic fractions, the real particle shape difference $\Delta\psi_{real}$ is calculated. The degree to which ideal sorting is achieved is defined by the ratio of the real to the ideal particle shape difference and termed the relative sorting efficiency S_{rel}.

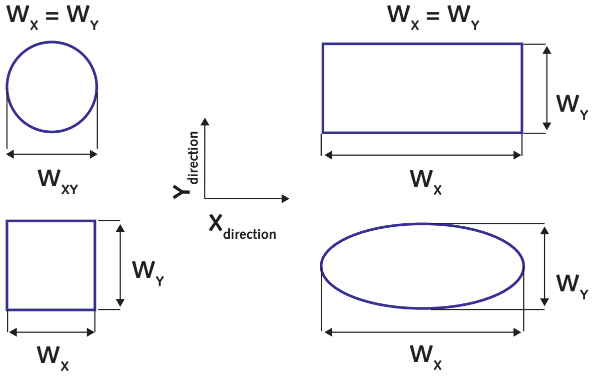
$$S_{rel} = \frac{\Delta\psi_{K,real}}{\Delta\psi_{K,ideal}} = \frac{\psi_{K,NK,real} - \psi_{K,K,real}}{\psi_{K,NK,ideal} - \psi_{K,K,ideal}} \cdot 100 \text{ in } [\%]$$

On the basis of two result presentations, the suitability of "double serial classification" is proven for use in the sorting of particles by cubicity.

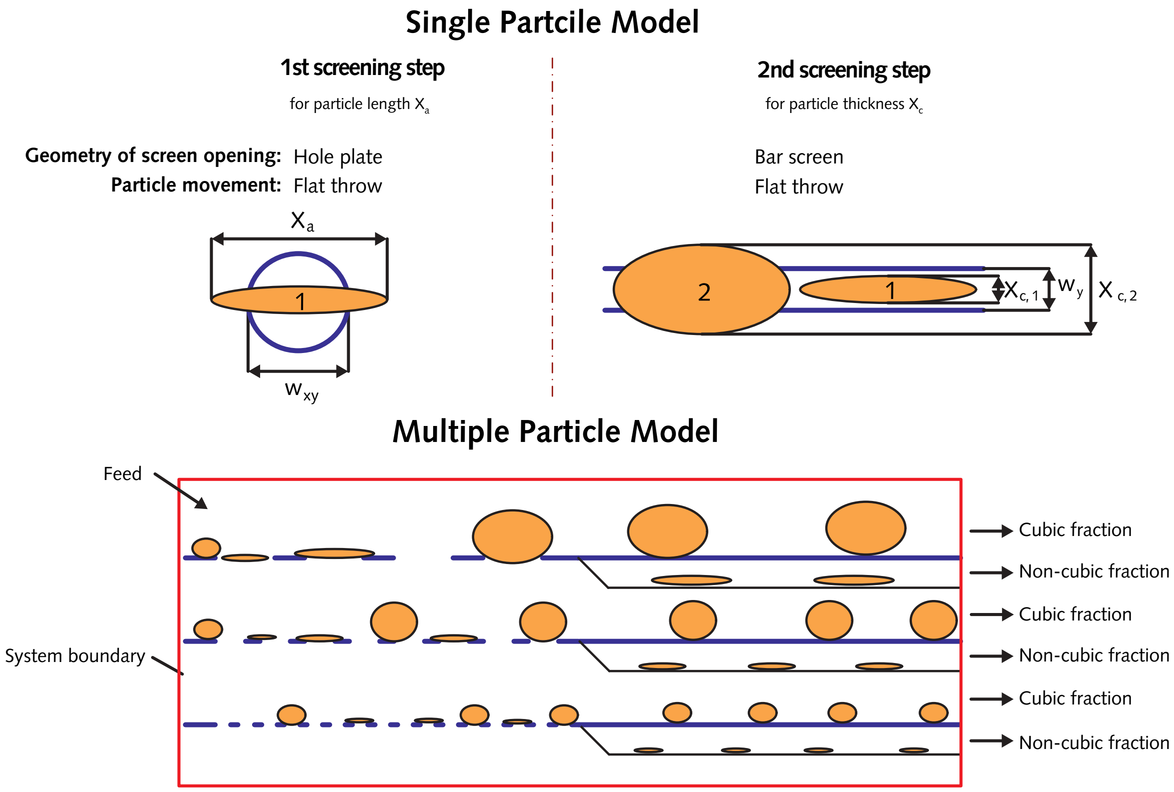
For determination of the particle shape, the method according to DIN EN 933-4 (particle shape slide gauge) and photooptical particle analysis (Haver CPA 4-2) were used. While



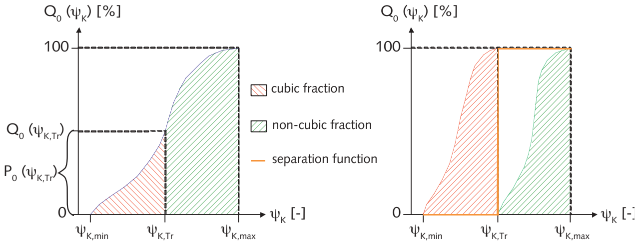
3 Forces at the single particle and the resulting particle movement



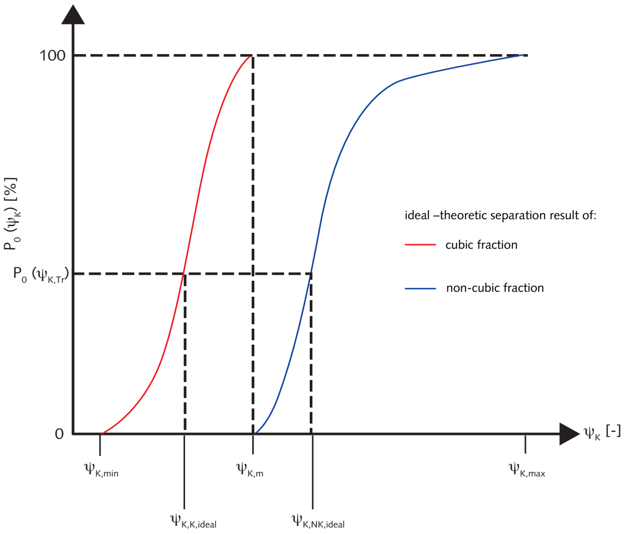
4 Possible aperture geometries for use in "serial classification"



5 Single- and multi-particle model of "double serial classification"



6 Description of an ideal sorting by particle shape cubicity

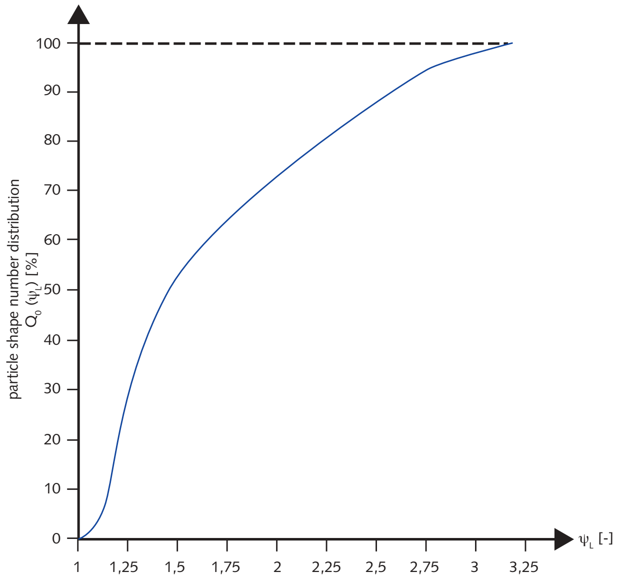


7 Separation criterion distribution model for determining the ideal particle shape characteristic values

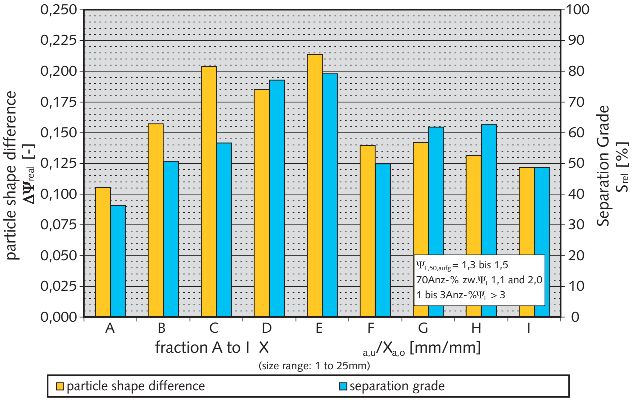
the 933-4 method for determining the particle shape determines the mass percentage SI of non-cubic particles ($\psi_K > 3$) of a fraction, the photooptical particle analysis characterizes particles according to their length/width ratio ψ_L. Stark and Müller [10] showed that for coarse aggregate grades a correlation between the mass percentage SI and the elongation ψ_L after photooptical particle analysis exists with a coefficient of determination $r^2 = 0.85$.

Fig. 9 shows the results of a sorting test in which a disperse material fraction in the size range between 1 mm and 25 mm was sorted. In a first classification step, the feed fraction is classified by length into nine sub-fractions. Granulometric analysis of the sub-fractions showed that the distribution parameter $\psi_{L,50}$ at 50 % of the particle shape number distribution $Q_0(\psi_L)$ in the nine single fractions lay in the range between 1.3 and 1.5 (elongation). Approx. 70 % by number of the particles lay in the range of an elongation of 1.1 to 2.0. Only approx. 1 to 3 % by number had an elongation higher than 3 **(Fig. 8)**. To sum up, it can therefore be formulated that this feed material consists of a very narrow particle shape number distribution $Q_0(\psi_L)$. In a second classifying step, the nine fractions are classified by particle thickness.

As a result of the second classifying step, real particle shape differences between 0.1 and 0.21 could be achieved for the various fractions. This corresponds to a relative sorting efficiency in the range between 35 % and 85 %. Using the correlation between the mass percentage SI of the non-cubic

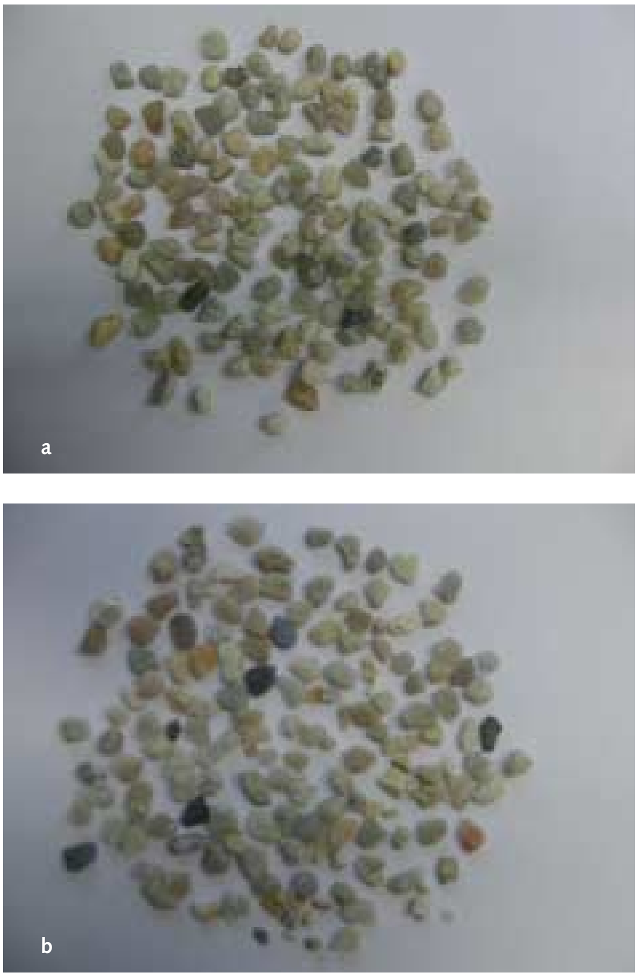


8 Example of a narrowly distributed particle shape number distribution (photooptical measurement)



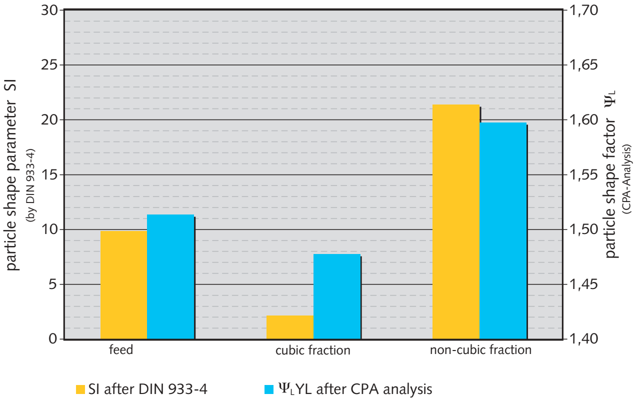
9 Results of "double serial classification" of dispersed bulk solids (1/25 mm)

particles and the length/width ratio ψ_L after CPA analysis determined by Stark and Müller, particle shape differences of 0.1 to 0.2 correspond to a difference in the mass percentage of non-cubic particles between 10 % and 20 %. From this, it can be concluded that highly efficient sorting by cubicity in the studied particle size range is possible with "double serial classification".



10 Diagram of the cubic (a) and non-cubic fraction (b) of a sorted gravel fraction 4/8 mm

In a second sorting test, the applicability of "double serial classification" by cubicity for the production of high-grade chippings in the non-metallic minerals industry was to be proven. For this purpose, a length-classified 4/8-mm gravel fraction was sorted by cubicity in a second classification step. **Fig. 10** shows the graphic diagrams for the non-cubic and cubic fractions produced. Feed material, cubic and non-cubic fraction were analysed both after DIN 933-4 as well as with photooptical particle analysis (Haver CPA4-2). **Fig. 11** shows the results obtained. In the feed fraction, a content of approx. 10 mass % non-cubic particles could be determined. According to photooptical particle analysis, this corresponds to a particle shape characteristic ψ_L of 1.51. After a second classifying step was performed, in which an approx. 75-% mass yield was obtained in the cubic fraction, there remained approx. 2 mass % of non-cubic particles with a particle shape factor ψ_L = 1.48. The non-cubic fraction had a mass percentage of non-cubic particles of approx. 21 %. This corresponds to a particle shape factor $\psi_L \approx 1.60$. Accordingly, it could be shown that the production of high-grade gravel fractions is possible.



11 Results of the sorting of a 4/8-mm gravel fraction by cubicity

With the help of "double serial classification", it is also possible to sort by elongation or flakiness. If classification is performed according to three different particle definitions, it is possible, for example, to separate particles with two characteristic particle shapes from one material stream (e. g. non-cubic, flaky from cubic, non-flaky particles).

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