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Analysis of sieve holes blocking in a vibrating screen and a rotary and drum screen

Katarzyna Lawinska[*], **Remigiusz Modrzewski**[**]

[*] Institute of Leather Industry Lodz, Zgierska 73, 91-462 Lodz, Poland
Corresponding author: k.lawinska@ips.lodz.pl (Katarzyna Lawinska)
[**] Faculty of Process and Environmental Engineering, Department of Process Equipment, Lodz University of Technology, Wolczanska 175, 90-924 Lodz, Poland

Abstract: Main objective of screening is to separate a group of grains, which dimensions fall within the specified limits, from the given feed. A large number of sieve and screening machines designs is available. During screening of granular materials in industry, sieve holes are often blocked. The phenomenon of screen blocking involves grains of varying sizes and geometries being clogged in sieve holes. This significantly decreases the screening efficiency. The mechanism of sieve holes blocking is largely random. A dry and contamination-free granular material with 0.1-2.5 mm size was screened in this study. The grains with spherical (agalite and chromium stainless shot), sharp-edged (aggregate) and irregular (quartz sand) were used in screen tests under various conditions. Screening tests included both intermittent, as well as continuous screening. Identification on blocking of sieve holes was conducted using vibrating devices and a rotary and drum screen with a cone-shaped sieve. This paper specifies the main operational parameters of these machines that had remarkable influence on the blocking of sieve holes.

Keywords: *sieve, screen blocking, screening machines*

Introduction

Screening is a random process that takes place as a result of the effect of gravitational forces, which is why its intensity is usually insufficient. The aim of mechanical classification (screening) is to divide particulate material into groups of grains according to their sizes. For this purpose, screens equipped with either one or several sieves are used. Therefore, sieves are essential elements of the screening process. The selection of a correct sieve for a given particulate material determines the course of screening. The scale of the process is quite large because millions of tons of products are being screened every single day. The size distribution of particulate matter is very important for determining its physicochemical properties for a large number of

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processes in various industries. During screening a number of parameters have to be dealt with, and these parameters need close monitoring and control (Pocwiardowski et al., 2014). Many factors have been identified that affect this unit operation, including the size and shape of particles relative to the aperture of the sieve, the mesh size of the sieve itself, the amount of material on the sieve surface, the direction of movement of the sieve, the rate of movement of the material relative to the sieve surface (Allen, 2003; Liu, 2009). In these studies it was demonstrated how factors, such as flour type, milling method, moisture content, tapping, sieving method, sieving duration, and their interactions can affect sieving efficiency and performance. Factors affecting the accuracy of separation of the feed into different products make the grain of a specific density report to a product stream different than identified with the laboratory tests (Baic and Blaschke, 2011). There are many models describing the screening process. The probability of screening in a cell, shape and size of the holes and particle sieve material shared with the influence of the relative speed of their movement was determined (Akhmadiev and Gizzjatov, 2013). The flow behavior of granular materials is generally described by using a continuum mechanics approach (Chirone et al., 2016). The well-known discrete element method (DEM), involving the integration of ordinary differential equations describing the motion of a free arrangement of material solids in the Cartesian space was used by Li et al. (2003), treating the sieve as an immobile sieve. The DEM method enables, above all, modelling of forces occurring when individual grains come into contact with each other and observing the impact of those forces on macroscopic properties of the fragmented material (Jafari and Saljooghinezhad, 2016). Delaney et al. (2012) performed a direct quantitative comparison, across a range of operating conditions, between laboratory scale experiments and simulations using the discrete element method (DEM). The work of Ivanov and Vaisberg (2015) revealed their experience in developing a fast-acting computational modelling algorithm and calculation of devices for vibrational size classification of ores, solid waste and other bulk materials. Alkhaldi and Eberhard, (2007) presented a numerical model for studying the particle screening process using the discrete element method that considers the motion of each particle individually. Vibrating screening is still one of the main operations in solid–solid and solid–liquid separation processes (Standish et al., 1986; Guerreiro et al., 2016).

The process of particulate materials screening is stochastic, therefore, the probability of an event occurrence plays a significant role. It is a random process that is mostly attributed to the gravitational force. That is why most quantitative considerations regarding this process are approximate. There are also many articles describing the impact of the shape and size of grains on the course of processes and operations (Fitzpatrick, 2007; Rhodes, 2008; Igathinathane et al., 2012; Liu et al., 2015), as well as concerning the optimization of the separation process and screening machines (Hong, 1999; Felix et al., 2002; Baragetti et al., 2015; Zhou, 2015).

Sieve holes blocking

During the screening of granular materials under industrial conditions, significant blocking of sieve holes usually occur (sometimes even more than half of the holes become blocked). Blocking is an unfavorable phenomenon, since it reduces the surface area of the lower size fraction flow through the analyzed screen. When sieve holes are blocked by grains they are excluded from the active surface of the sieve, reducing the effective screening area. The significant reduction of the active surface of a sieve cannot be disregarded when designing and selecting a proper screen. Some equipment is recommended for removing the effect of blocking. This equipment, however, puts an additional load on the screening machine. Some devices are equipped with an autonomous drive that makes the screen design even more complicated.

Literature on this subject provides only a few examples of sieve holes blocking during the screening of particulate materials. It was reported by Feller (1980) that both partial passage and clogging of the screen should be considered in order to evaluate the screen performance.

The screen blocking coefficient, f, is applied for the quantitative description of screen blocking. It is defined as the ratio of the number of free holes (n_{free}) to the total number of holes in the sieve (n_{total}):

$$f = \frac{n_{free}}{n_{total}} \quad . \tag{1}$$

The value of the screen blocking coefficient varies in time. It changes from the value of $f = f_0$ (for time $t = 0$, prior to the start-up of the screening machine, this means that the screen has not performed a vibration yet, however, there are already sieve holes that are blocked) to the value of $f = f_\infty$ (for time $t = t_\infty$ the dynamic equilibrium of sieve holes blocking and unblocking processes is set; from that moment on the value of the screen blocking coefficient does not change any more). An exponential (Lawinska et al., 2015):

$$f = f_\infty + (f_0 - f_\infty)e^{-k_0 \cdot t} \tag{2}$$

or logistic function (Lawinska et al., 2014):

$$f = \frac{f_0}{1 + (f_0 - f_\infty)e^{-c \cdot t}} \tag{3}$$

model may be used for describing sieve holes blocking. In Eq. 2, k_0 is the blocking constant. The phenomenon of blocking the holes of the sieve is a process resulting from two processes occurring simultaneously at the time of clogging and declogging of sieves $k_0 = k_1 + k_2$, where k_1 is the screen blocking constant and k_2 is the screen unblocking coefficient. In Eq. 3 c is a constant. Properties of particles may be divided into chemical, energy-related and physical ones. The latter, which include particle shape, particle surface toughness, abrasion susceptibility and hardness, determine the sieve holes blocking probability (Baic, 2013). A reliable and an accurate measurement of the particle size and the particle size distribution (PSD) is central to characterization of particulate material (Rhodes, 2008). Research results confirmed the effect of particle size unequivocally. As the particle size decreases the bulk density of pulverized coal also decreases. Moreover, the decrease of the particle size causes an increase of the cohesiveness and wall adhesion (Fitzpatrick, 2007).

Vibrating, rotary drum screens

Screens are used for segregation and classification of particulate materials. Screening machines may be classified based on the direction of the particulate material flow through a screen. Thus, this equipment would be classified into two main groups: screens with linear material flow through the machine, and screens with either radial or spiral flow of the segregated material through the machine. The second class is based on the design configuration, i.e. circulating and rotary screens, screens with vibrating sieves, circulating screens with vibrating sieves, screens with spatial sieves motion and fluid-flow screening machines. The principal element of a screening machine is the vibrator, i.e. a device that provides the vibrations to the sieve.

Screening of particulate materials using vibration takes place in two ways: periodically (using a laboratory vibrator and control sieves), and continuously (a single-plane circulating screen). The main parameter of vibrating devices that affects sieve holes blocking is the toss indicator K. The value of K is the ratio of the normal screen acceleration amplitude component to the normal gravitational acceleration component (Fig. 1) and is defined as:

$$K = \frac{4\pi^2 n^2 A \sin\beta}{g \cdot \cos\alpha} \tag{4}$$

where n is the sieve vibration frequency, A is the vibration amplitude, β is the angle of vibrations direction inclination to the sieve surface, α is the angle of the sieve inclination to the horizontal line. Parameters in Eq. (4) are constant and stem from the design of a vibrating screening machine.

In rotary screens, cone sieves with the spiral motion of the material layer on the sieve are used. Those sieves may be either horizontal, vertical or slightly deflected from the vertical rotation axis. The screens of such a type basically use two operation principles, i.e. the centripetal motion of the grain, where the loose material is fed to the outer rim of the sieve and moves spirally on the surface of the sieve cone in the direction of its axis, or the centrifugal variant in which the grain is fed axially and as a result of the centrifugal force it moves to the rim of the cone sieve (the grain moves in the direction from the axis to the outer rim of the sieve).

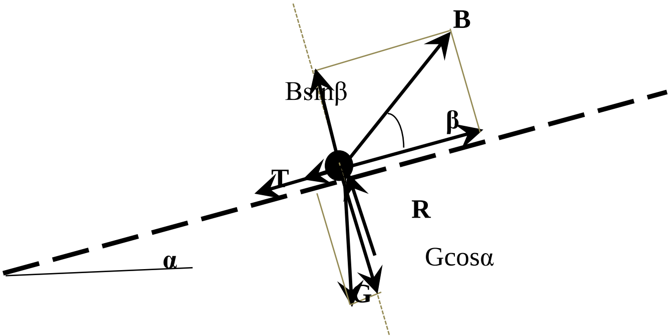

Fig. 1. Forces affecting the grain during a toss on a sieve: *G* – gravity force, *T* – friction force, *B* – inertial force, *R* – ground reactive force

A prototype of a rotary and drum screen was built as a part of this research. In comparison to the common drum screens, this design is equipped with a characteristic cone-shaped sieve that results in changes in the value of specific speed. The advantage of such screen lays in its simple design and a low cost of both the equipment itself and its operation when compared to other models.

Figure 2 shows the distribution of forces affecting a single grain on a cone-shaped sieve that makes a circular motion. It involves a centrifugal variant in which the grain moves in the direction from the axis to the outer edge of the sieve, while the friction force, *T*, is oppositely directed. In a centripetal variant, the sense of the friction force will be directed oppositely to that shown in Fig. 2.

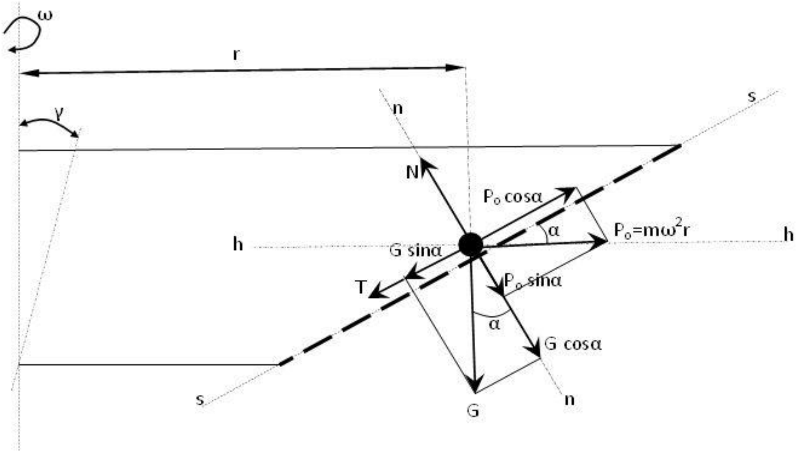

Fig. 2. Forces acting on the seed on the surface of the conical sieve: *G* – gravity force, *T* – friction force, P_0 – centrifugal force, *N* – sieve pressure on the grain

Horizontally (*h-h* direction), the centrifugal force P_0 (its relevant components in the direction are tangent to the sieve surface *s-s*, and in the direction perpendicular to the sieve, *n-n*), as well as the gravity force *G* (and its components) affect the grain. The sieve pressure on the grain, *N*, is acting in a normal direction (to the sieve). In a limit state of equilibrium, when the grain on the sieve is immobile in relation to the sieve (does not move up nor down the sieve), the friction force *T* = is equal to zero (at the first stage of the grain motion). In such a case, components of forces affecting the grain are equal:

$$G \sin \alpha = P_0 \cos \alpha \tag{5}$$

$$mg \sin \alpha = m\omega^2 r \cos \alpha \; . \tag{6}$$

The boundary, critical rotational speed of a cone-shape sieve motion may be determined using Eq. 5 and 6. Over this rotations value the grains move up the sieve, while below this value they move down the sieve:

$$\omega = \sqrt{\frac{g}{r} tg\alpha} \;\; \text{(Rad/s)}. \tag{7}$$

Materials and methods

The principal tests were preceded with the division of material into fractions. The division was made in such a manner that the widest possible size range of grains occurring in the actual deposit could be used. The granular material of the fraction of 0.1-2.5 mm was screened for the purpose of this study. The materials tested were dry, free of moisture. Spherical grains (agalite and chromium stainless shot), sharp-edged grains (aggregate) and irregular grains (quartz sand) were used as experimental media. In total, over 100 mixtures varying in their grain-size composition were tested. An example of grain-size composition of grain mixtures used for testing is shown in Fig. 3.

Two basic processes of mechanical classification are discussed in particulate materials screening theory: The transient process (laboratory, periodic screening) and the fixed process (industrial, continuous screening). The tests were performed on three test stations, i.e. using a laboratory vibrator and control sieves, a single-plane circulating screen and a rotary and drum screen with a cone-shaped sieve.

A series of tests for three test stations were conducted for the following process parameters:

1. For a laboratory vibrator and control sieves (Fig. 4): sieve hole size *l* = 0.5, 0.63, 0.8, 1, 1.2 mm, toss indicator: *K* = 1.5, 1.98, 3.5, 4.9; linear and flexural vibrations. Regulation of the toss indicator is characteristic of a laboratory vibrator.

2. For a single-plane circulating screen (Fig. 4): sieve hole size: l = 0.63 mm, toss indicator: K = 1.5, efficiency: Q = 240kg/h, riddle inclination angle to the horizontal surface 15°, an electric vibrator with the speed 1400 rpm used for the screen drive.
3. For a rotary and drum screen with a cone-shaped sieve (a centripetal variant): sieve hole size l = 0.63 mm, efficiency Q = 98, 135, 182 kg/h, the drum (sieve) rotational speed: 0.46, 0.70, 0.93, 1.12RPM, the sieve inclination angle: 0, 5, 10, 20 and 28°. A screen (Fig. 5) comprises a sieve fitted onto a rotating shaft driven by a motor reducer, which the rotational frequency is regulated by an inverter. The motor reducer is fitted onto the base using a joint, and through this it was made possible to deflect the rotation axis within 30° from the vertical (Fig. 5).

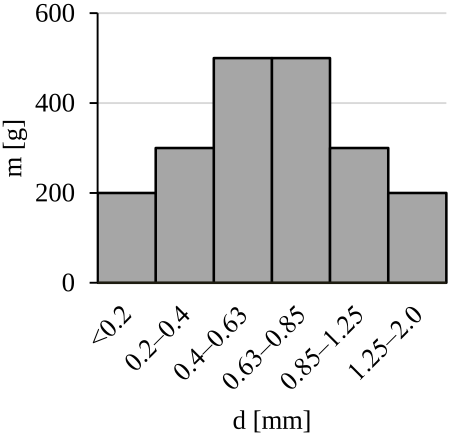

Fig. 3. A particulate composition for mixtures (the rotary and drum screen with a cone-shaped sieve): m – mass of individual fractions of grains, d – grain size in a fraction

The mixtures were screened using a set of screens with square holes made of metal wire (PN-ISO 2395:2000, PN-ISO 565:2000, PN-ISO 2591-1:2000 ISO3310-1, ISO3310-2, ASTM-E11). The main part of the tests involved the screening of each mixture, one by one, through the tested sieve (Figs .4 and 5). A control sieve with the mixture was placed in the vibrator. Prior to the start-up of the vibrator the blocking coefficient f_0 (for time t = 0) was calculated in relation to the given particulate material at the moment it was fed onto the screen. After the vibrator was started, the material was screened through the sieve in time t. The sieve surface was divided into smaller areas on which the number of blocked sieve holes were counted. After the mixture was screened, the number of free sieve holes was counted (manually) at spots on the screen. A template with cut-out frames, each covering 100 sieve holes, was used (Figs. 4-6). The blocking coefficient was calculated using Eq. 1. The values of coefficient f obtained from different spots on the screen were averaged and treated as the blocking coefficient for the given sieve in the given time. Screening continued until steady state t_∞ was reached (the number of blocked holes in the sieve was constant, f_∞). The measurement cycle for one screen comprised $n + 1$ measurements that differed in screening time $t_,$ t_n, t_{n+1}, ... t_∞. At the final stage of the test, the sieve was cleaned of blocked grains and the removed grains were added to the tested mixture.

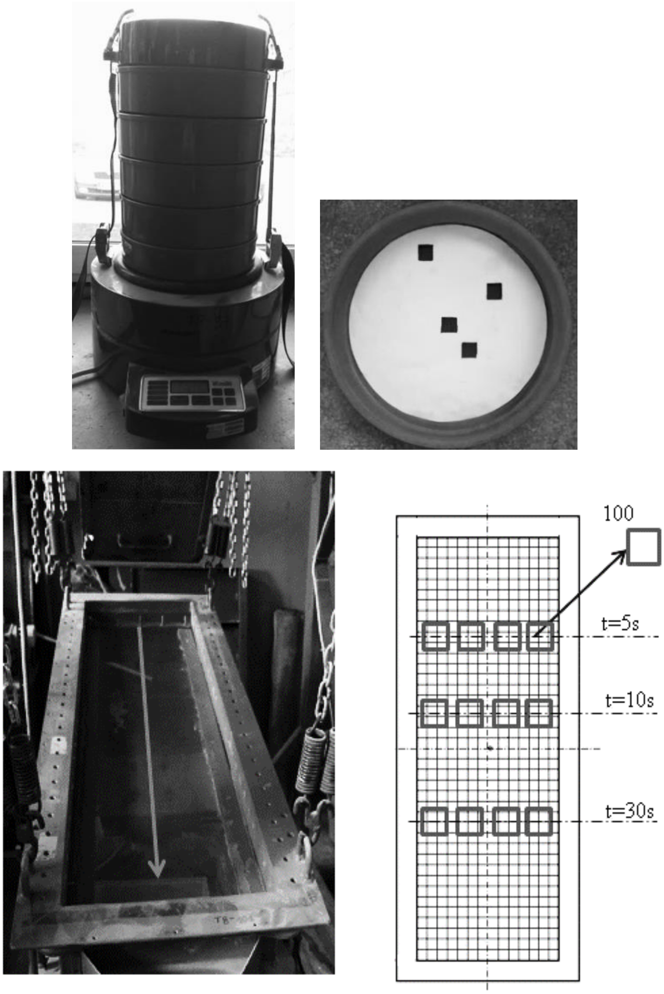

Fig. 4. Test stations with templates with cut-out frames.
A laboratory vibrator and control sieves (upper), and a single-plane circulating screen (lower)

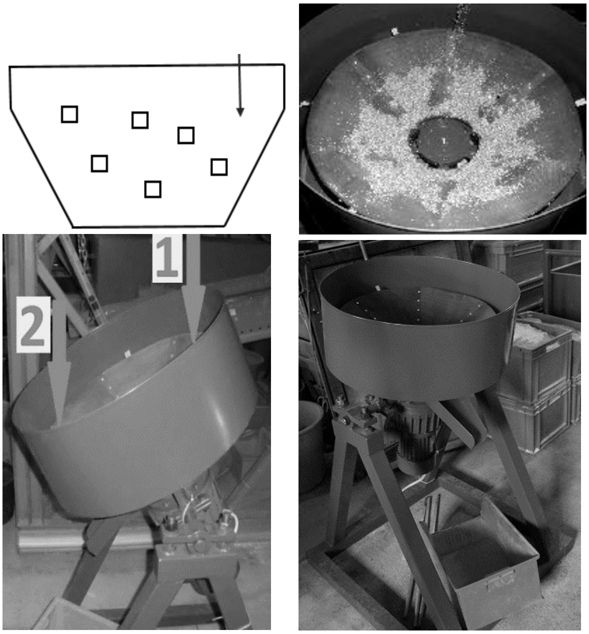

Fig. 5. Rotary and drum screen with a cone-shaped sieve
with templates with cut-out frames

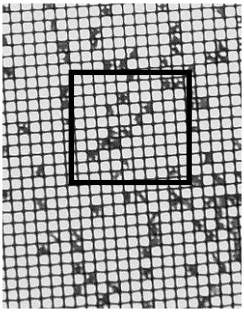

Fig. 6. Blocked sieve holes

Results and discussion

The results show that both shape and size of grains have a significant impact on blocking of sieve holes. Three model shapes of particulate materials are known: round-like particles (spherical particles), particles with sharp edges (sharp-edged particles) and particles with an irregular geometry. Particulate materials that are used in industry may be divided between the model groups according to their shape. Tests show that sharp-edged grains block sieve holes with the greatest degree. For this grain shape, the screen blocking coefficient is the lowest (Fig. 7). The highest number of free holes were observed for screening spherical materials, that is when the screen blocking process was the least (a laboratory vibrator and control sieves, l = 1 mm, K = 1.5, and the same conclusion for a single-plane circulating screen l = 0.63 mm, K = 1.5, Q = 240 kg/h).

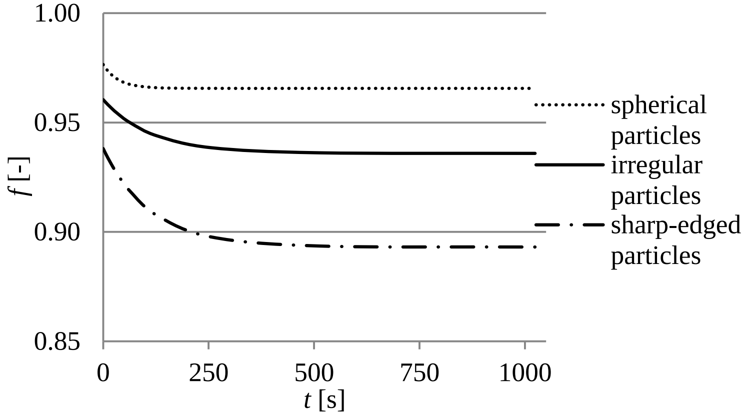

Fig. 7. Impact of grain shape on sieve holes blocking (a laboratory vibrator and control sieves, l = 1 mm, K = 1.5)

An important factor that affects the intensity of sieve holes blocking is the content of hard-to-screen grains in the feed. Hard-to-screen grains are such grains which dimensions are similar to the sieve holes and these particles are the most difficult to screen. There is a small probability for such grains to pass through the sieve holes and a large amount of these grains remain over the screen. The hard-to-screen grains assumed in this research have the following dimensions: $0.8l \le \bar{d} \le 1.2l$ ($\bar{d}$ – average particle size, l – sieve hole size). The results show (Fig. 8) that the number of blocked sieve holes increases with the increase in the content of hard-to-screen grains in the feed for a laboratory vibrator and control sieves and for a single-plane circulating screen.

The obtained results are represented graphically using diagrams of screen blocking coefficient over time. The rate of sieve holes blocking is proportional to the number of free holes. The higher number of free holes correspond to greater tendency for getting clogged. Furthermore, it may be assumed that the greater the blocked surface fraction, $(1 - f)$ the higher the tendency for sieve holes unblocking is, since the probability of screen holes unblocking is greater. The coefficient f reaches its lowest values for the greatest number of blocked sieve holes. The coefficient value increases, aiming for the value of ≈ 1 in these cases, the sieve hole blocking process was less considerable.

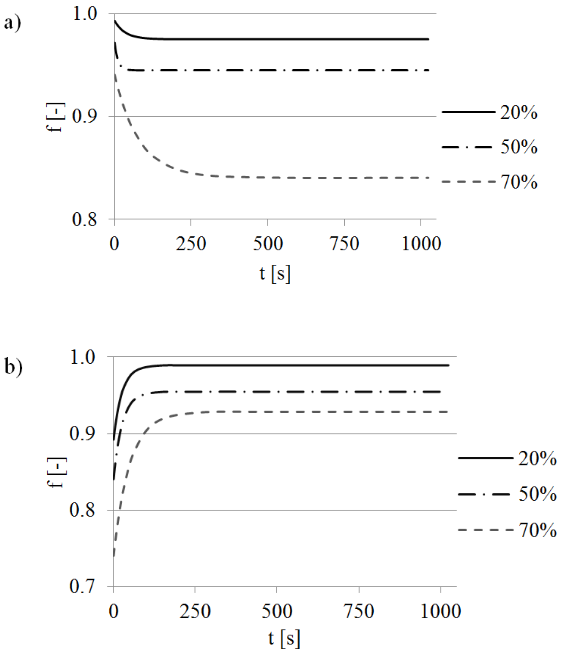

Fig. 8. Impact of the amount of hard-to-screen grains in the feed on screen blocking coefficient (a laboratory vibrator and control sieves): a) when $f_0 > f_\infty$ (spherical grains, $l = 0.63$ mm, $K = 3.5$), b) when $f_0 < f_\infty$ (irregular grains, $l = 0.63$ mm, $K = 35$)

The variability of the blocking coefficient in time was determined on the basis of the obtained values. Figure 8 shows that two characteristic runs functions decrease and increase in the volume of screen blocking coefficient. The balance is reached as seen in Fig. 8. The curves in Fig. 8a show a case when the number of blocked sieve holes increases during screening ($f_0 > f_\infty$), while in Fig. 8b show that the number of blocked sieve holes drops, the number of free holes increases as a consequence ($f_0 < f_\infty$). The value of coefficient f_0 determines the degree of sieve holes blocking at the moment that the material is fed onto an immobile screen, which is why it depends on the type of material and grain size composition of the feed. The coefficient f_∞ describes screen blocking at the final stage of the screening process (i.e. in steady time). The value of f_∞ depends, above all, on the toss indicator (the amplitude of the vibration and the vibrations frequency). In practice, a case when $f_0 > f_\infty$ is usually encountered.

Sieve holes blocking in vibrating screens

A proper selection of Sieve holes blocking is of great importance for screening (Lawinska and Wodzinski, 2012; Lawinska et al., 2016; Lawinska and Modrzewski, 2016). The course of the curve depends on $f_0 - f_\infty$ (Eqs. 2 and 3). One may notice that for all values of the toss coefficient K, the coefficient f_0 (f for time $t = 0$) is the same.

Figure 8 shows the impact of the value of the vibrating device toss indicator on sieve holes blocking.

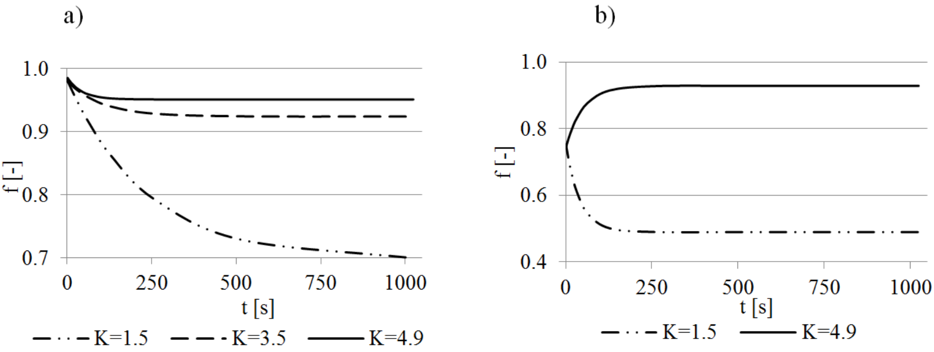

Fig. 9. Impact of the value of the vibrating device toss indicator on sieve holes blocking (laboratory vibrator and control sieves), a) spherical grains, l = 1 mm, b) irregular grains, l = 0.5 mm

Figure 9a shows the change in screen blocking coefficient with time for one mixture for intermittent screening (spherical grains). In this case f_0 does not change, f_∞ is variable due to the variable value of toss indicator K. Figure 9b shows the results for a mixture of a different grain-size composition (irregular grains). Therefore, the parameter f_∞ has a decisive influence on the course of the f = f (t) function. The lowest values of f_∞ occur when the toss indicator is equal to K = 1.5 (Fig. 9a). Based on the plots shown, it can be stated that the course of the f = f(t) curve depends first and foremost on the value of the toss coefficient K. Values of the blocking coefficients for different toss coefficients K are shown in Table 1. It may be concluded that sieve holes blocking is less significant for higher values of the toss indicator K. Figure 9b proves that the value of the toss indicator also affects the monotonicity of the f coefficient function course in time. A low value of toss indicator K = 1.5 results in a significant increase in the number of blocked sieve holes when the screening time is exceeded (f≈0.5). Higher values of K = 4.9, for the same mixture, result in the unblocking of blocked sieve holes when the screening time is exceeded.

Table 1. Screen blocking coefficients for varying values of the toss indicator

Screen blocking coefficient	K = 1.5	K = 3.5	K = 4.9	K = 1.5	K = 4.9
	Fig. 7a			Fig. 7b	
f_0	0.982	0.98	0.984	0.744	0.741
f_∞	0.700	0.924	0.951	0.490	0.928
$f_0 - f_\infty$	0.282	0.056	0.033	0.254	-0.187

Sieve holes blocking in a rotary and drum screen with a cone-shaped sieve

Considering the design features of a rotary and drum apparatus, the impact of the drum inclination and the disk rotational speed on sieve holes blocking were determined (Fig’s. 10 &11).

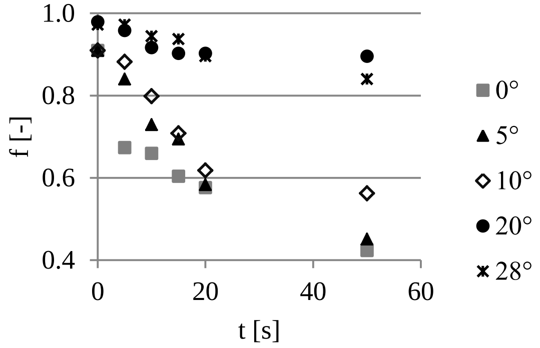

Fig. 10. Impact of the angle of inclination of a drum in a rotary and drum device on screen blocking coefficient (irregular grains, *l* = 0.6 3mm, drum (sieve) rotational speed 0.7 rpm, efficiency *Q* = 135 kg/h)

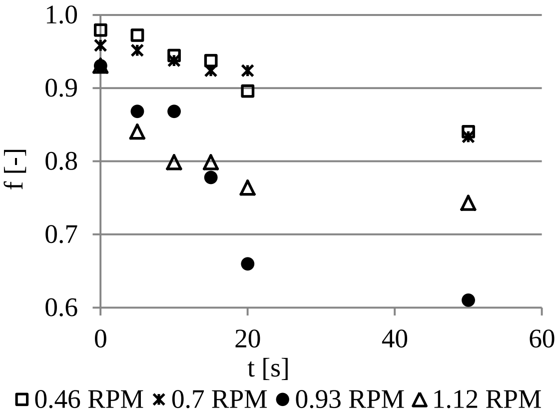

Fig. 11. Impact of the disk rotational speed in a rotary and drum device on the screen blocking coefficient (irregular grains, *l* = 0.63 mm, sieve inclination angle 20°, efficiency *Q* = 182 kg/h)

From the diagrams above, it may be concluded that the inclination angle of a drum and the disk rotational speed in a rotary and drum device with a cone-shaped sieve significantly affects sieve holes blocking. The number of blocked holes in a cone-shaped sieve is smaller for larger angles of the drum inclination, i.e. 20° and 28°. Higher values of the disk rotational speed in a rotary and drum device with a cone-shaped sieve intensify sieve holes blocking.

Comparative analysis of sieve holes blocking for vibrating, rotary and drum screen with a cone-shaped sieve

Drum screens are characterized by a low efficiency in materials separation. It is mostly due to the poor dynamics of the particulate layer movement inside the screen drum and blocking of the sieve holes. Blocking of sieve holes occurs in all types and designs of the screens. However, it proves to be a significant problem in drum screens, as once a hole is blocked, it cannot be easily unblocked. In the case of vibrating screens the movement dynamics is completely different. Vibrating screens are usually equipped with flat sieves installed in a rectangular riddle. Their vibrations are induced by electrical vibrators. As a result of the vibrations, the blocked sieve holes become unblocked after some time, and consequently, the overall number of blocked sieve holes becomes comparable to those in screens with no vibrations (in drum screens). In rotary and drum screens, at the first stage, there is a rapid fall and a quick screening process on a cone-shaped sieve. With the increase in the sieve diameter, the nature of movement changes into turning and screening of the remaining lower fraction.

In order to compare sieve holes blocking on vibrating screens (laboratory vibrator and single-plane circulating screen) and a drum screen (rotary and drum screen with a cone-shaped sieve) optimum working conditions of the devices and mixtures of uniform grain-size composition were selected.

Figure 12 shows that sieve holes blocking is more significant in a rotary and drum device with a cone-shaped sieve than in a vibrating screen, the value of blocking coefficient, f, is lower. Consequently, the number of blocked holes in a cone-shaped sieve of a rotary and drum screen is higher, which results in a smaller active surface area of the screen and decreased screening performance.

It may be concluded from the charts that the individual parameters of screening machines and their values affect sieve holes blocking and, consequently, the process of particulate materials screening. A proper selection of the process parameters provides for a reduction in the number of blocked sieve holes in screens in which a given sieve is installed. The main factors affecting sieve holes blocking include:

a) the shape of screened material and the content of hard-to-screen grains in the mixture,
b) the device toss indicator (vibrating screen),
c) the drum (sieve) rotational speed and sieve inclination angle (rotary and drum screen).

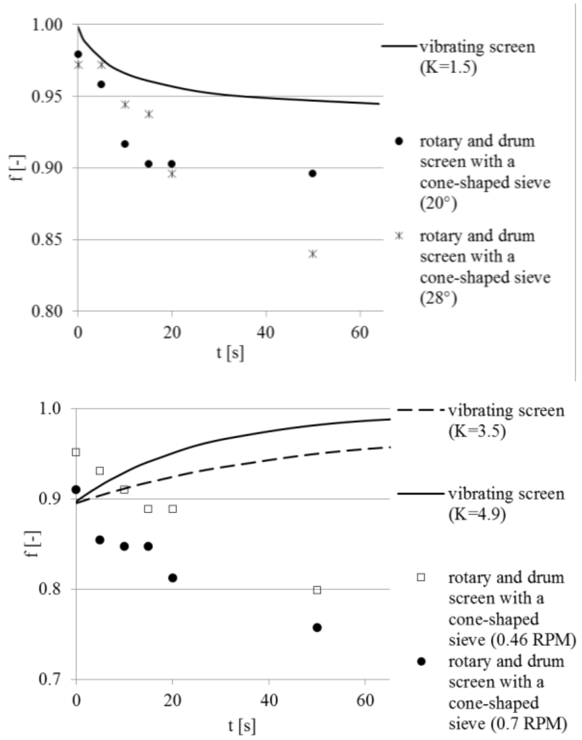

Fig. 12. Comparison of sieve holes blocking for vibrating devices and rotary and drum devices of different parameters (irregular grains)

Conclusions

Screening is the most common type of mechanical classification. Scale of the process and the large variety of sieve types and screen designs prove that the described research is legitimate. The phenomenon of screen blocking involves grains of varying size being blocked in sieve holes. This is a phenomenon that significantly decreases the screening efficiency. Disregarding the screen blocking coefficient may lead to remarkable inaccuracies in design. Sharp-edged grains block sieve holes to the greatest degree (*f* coefficient reaches its lowest value). The number of blocked sieve holes increases with increase in the content of hard-to-screen grains in the feed. Sieve holes blocking is less significant for higher values of the toss indicator ($K>3$). The optimum working conditions for rotational devices are 20° and 28° (the sieve inclination angle), as well as 0.46 and 0.7 rpm of the drum (sieve) rotational speed. For these values the number of blocked sieve holes is lower as compared to other operating parameter levels. When screen designs are compared, it was seen that the number of blocked sieve holes for vibrating devices is lower than rotary and drum screen. In conclusion, the design of a screening machine also affects blocking of sieve holes.

Currently, studies on defining a new screen blocking coefficient are in progress. It is proposed that the $F_{blocking}$ coefficient specifies the % number of blocked sieve holes in relation to the total number of sieve holes. The assumption of the $F_{blocking}$ coefficient facilitates the analysis of blocked sieve holes and is a reliable value.

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