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CERTAIN PROPERTIES OF HUMID GRANULAR MATERIALS

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This study deals with the properties of humid granular materials. The processes involving these materials are very frequently encountered under industrial conditions because in fact the processing of completely dry materials does not exist. Water vapour is present in the air under any conditions which means a certain amount of moisture in the granular bed. A general friction coefficient of granular materials has been proposed as contributing to a moisture influence on processing. The friction coefficient constitutes a basic independent variable encompassing an impact of moisture on the behaviour of a humid granular material in the mechanical process. Furthermore, the function of outflow has been proposed as an important analytical-empirical parameter to describe the processing of solids.

key words: screening, friction in granular material, granular material, humidity, water capacity

INTRODUCTION

It must be mentioned that dry granular materials do not exist. A certain portion of a granular material even after its removal from a drier constitutes a two-phase solid-liquid system because it is exposed to water vapour present in the air. Hence, analysing a mechanical (dry) process with a granular material, e.g. screening, we deal with such a small amount of moisture that the granular material behaves as if it were dry though actually it contains some moisture. It is an appropriate increase in a moisture content in the granular material that influences its behaviour in the mechanical process.

Thus it is crucial to consider a moisture content in a granular material, in particular in the case of such mechanical processes as screening or proportioning. This study

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describes certain notions whereby one may take into consideration an impact of humidity on the behaviour of grain layers in industrial and laboratory technological processes.

CHARACTERISTICS OF HUMID GRANULAR MATERIALS

The basic characteristic of a humid granular material is its moisture content, i.e. humidity:

$$W = \frac{g_w}{g_s} 100\% \quad (1)$$

where: g_w – mass of water in the material portion examined, kg
 g_s – mass of a dry material portion, kg

In the real granular materials one distinguishes two types of moisture:

W_{pr} – passing moisture, defined by an amount of water which is removed during air drying, reaching an equilibrium state with the atmospheric humidity

W_h – air-dry material moisture comprising water remaining in the material after air drying, evaporated after drying at the temperature 105 - 110°C.

We may consider the total humidity W_c which is the total of two previously mentioned types of moisture. The extent of a humid process is illustrated in the form of a numerical – humid curve in Fig.1. In Figure 1 three critical humidity coefficients are presented (a moisture content):

W_p – transient coefficient

W_d – dynamic humidity coefficient

W_s – static humidity coefficient

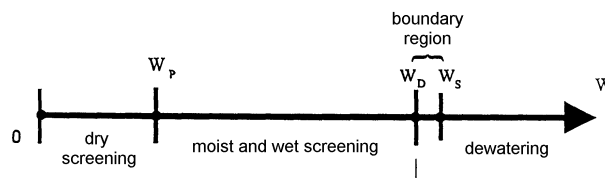


Fig. 1. Humidity axis

The transient coefficient W_p is defined in the following way: it is such humidity of granular material that causes the elongation of the time of a process. To exemplify, in the case of screening the time indispensable to screen the same mass of a humid material is elongated. It is not possible to establish one universal value of the transient humidity for all the materials screened. For one type of materials the moisture content 1–2% brings about a double elongation of the screening time. For other types the screening time is established on the level of 10–12%.

A granular bed at the lag time may be defined using the static humidity coefficient W_s . This is an amount of moisture (water) which may be contained in a granular bed (a granular layer) in the lag time. Nevertheless, when a granular bed is placed onto a vibrating screen, one may observe a quick removal of a certain amount of water from this bed and, thus, obtain the so-called dynamic humidity coefficient W_d . The dynamic humidity coefficient is always smaller than the static one. That is why the dynamic humidity coefficient of a granular bed may be defined as a moisture content in a material in spite of its exposure to the action of the inertial forces (the driving forces of the process).

Above the boundary $W_d - W_s$, defined by the dynamic and static humidity coefficient, one may notice the dehydration and washing zone of granular materials. In the case of certain granular materials one may observe such a considerable influence of moisture that a humid screening zone is not present. The separation of the upper and bottom class is possible under the exposure of excess water and it occurs in the dehydration or washing zone.

The subsequent essential parameter determining the mechanical processes, the process of humid screening in particular, is a shape of grains which constitute a granular bed. It is until recently that in the calculations concerning granular materials processing as well as in other processes one has applied a surface factor of a grain shape. The factor is defined as a quotient of the surface area of a grain to the surface area of a sphere, being of the same volume as the grain. Due to the fact that in the mechanical processes, including the process of screening, the application of this factor is seemingly unjustified, a spherical factor of a grain shape has been proposed. In a mineral grain we may distinguish the so-called main dimensions of a grain (Fig. 2) including the length, width and thickness of a grain (a , b , c respectively). Furthermore, having $a > b > c$, the spherical factor of a grain is given by the formula:

$$\varepsilon_k = \frac{b \cdot c}{a^2} \quad 0 < \varepsilon_k \leq 1 \quad (2)$$

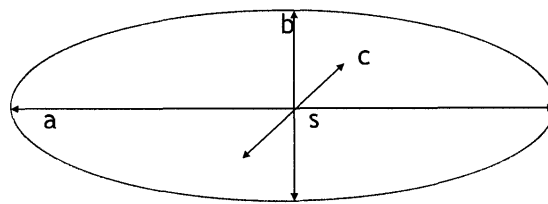


Fig. 2. Spherical factor of a grain shape

It is worth mentioning that for a cube and a sphere the factor reaches value 1. The more isometric a grain is, the more the value of ε_k approaches 1. The more anisometric

the grain is (e.g. the predominance of one dimension – a needle shape), the more ε_k approaches 0 but it never reaches this value.

The author of this paper proposes a different, simple method taking into account the grains of the materials which are subjected to different processing operations. Three basic shapes of grains are distinguished (Fig. 3):

- spherical grains (Fig. 3a)
- sharp-edge grains (Fig. 3b)
- irregular grains (Fig. 3c)

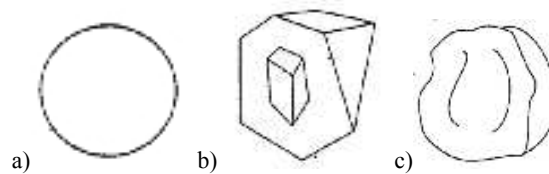


Fig. 3. Models of grain shape

The previous papers concerning the topic proposed 9 different grain shapes. Nonetheless, the results of the research of, for instance, the screening of one of the separated mixtures were similar and, thus, applying the method of the subsequent reductions of particular groups, the three aforementioned shapes have been proposed. It has been demonstrated that a great number of real grain materials, being screened and processed in different branches of the national economy, may bear a strong resemblance to one of the aforementioned groups. This way of describing a grain shape is based on attributing a concrete material to one model mixture and, next, on using the appropriate project correlations required for a given model mixture. The whole research carried out by the author of this study is done independently for three model materials which are as follows: spherical grains – agalite (ceramic material, siliceous, being, for example, waste in various chemical processes); sharp-edge grains – aggregate of rock materials; irregular grains – natural mining sands. The method which takes into consideration the shape of a grain is a very primitive one but for many materials it gives good practical results.

The last parameters extremely important in the processes of the granular material processing are an internal and external friction coefficient of those materials. Determination of those coefficients is done using the method of direct shearing, which is known in the literature as the Jenike method. To carry out such examination spherical boxes and a special research stand are used. In the investigation of direct shearing the idea of inducing such deformation of a sample (Fig. 4) is applied in order to have make it occur along the plane required. Next, a horizontal slip of one box with regard to another one – immovable – is forced with a simultaneous measurement of the shearing force. However, to determine the external friction coefficient of a given

grain medium on a given surface (a sieve, for instance) – one measures the force being needed to move the spherical box on this surface.

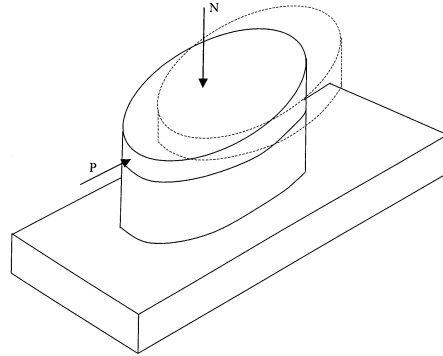


Fig. 4. Shearing boxes of linear motion (Jenike, 1964)

Another shearing box known apart from the Jenike box is a shearing box invented by Schulze (1996). The method is based on the rotating shearing motion of the box as in contrast with the previously analysed method of linear motion (Fig. 5). It must be underlined that applying the methods positive results may be gained which will characterise a humid grain material. Nevertheless, it is the Jenike method which has become more widespread nowadays. The shearing boxes of the device in a cross-section are demonstrated in Figure 6.

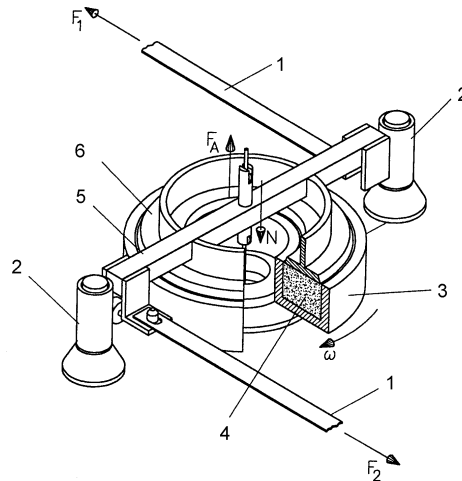


Fig. 5. Rotating shearing box (Schulze, 1996) 1 – pulling slat; 2 – guide roll; 3 – shearing box; 4 – granular material; 5 – support beam; 6 – cover

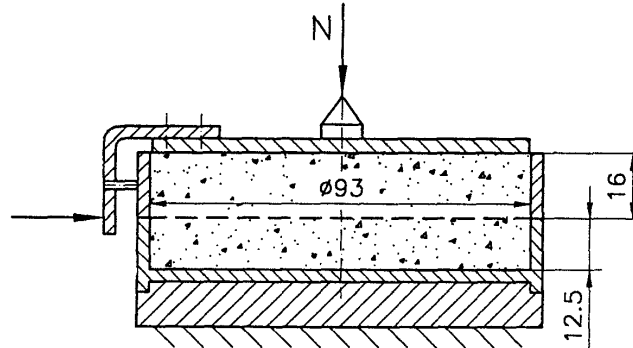


Fig. 6. Box of linear motion used for direct shearing of granular materials (Jenike, 1964)

To characterise the fluidity of a granular material one may use the factor ff_c [5]. It is a quotient of the tension of a material σ_l to its resistance σ_c :

$$ff_c = \frac{\sigma_l}{\sigma_c} \quad (3)$$

According to Jenike [1964], the following ranges of the parameter may be distinguished:

- $ff_c < 1$ a non-flowing material
- $1 < ff_c < 2$ a very cohesive material
- $2 < ff_c < 4$ a cohesive material
- $4 < ff_c < 10$ a slowly flowing material
- $10 < ff_c$ solely flowing

The dependencies (the extents of flowing) have been graphically demonstrated in Figure 7.

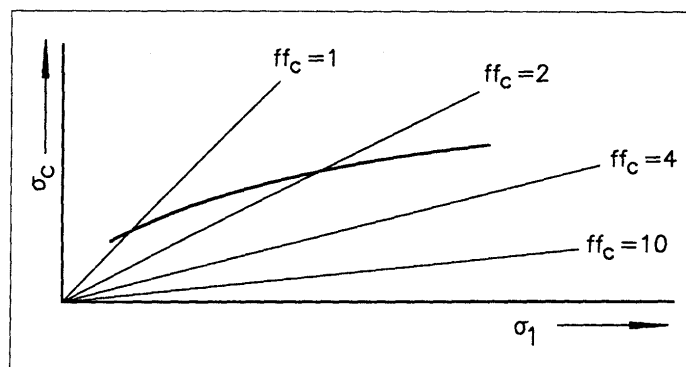


Fig. 7. Flowing zones of granular materials

RESULTS OF EXAMINATION OF GRANULAR MATERIALS MODEL PROPERTIES

MATERIALS AND METHODS

An important quality of a granular material, which is subjected to mechanical processing is a coefficient of internal friction. In Poland the research is in compliance with the standard requirements PN-88/B-04481. To carry out the examinations properly it is important to select an appropriate normal thrust which is reflected in the dependence of a shearing force upon the way of shearing. The curves obtained as a result of the test are of a shape demonstrated in Figure 8. The normal thrust is to be obtained by the method of the force N alteration in the shearing boxes (Fig. 6). The curve illustrates the state of the material consolidation surplus which may occur in the case of humid materials. Then, it is essential to decrease the load N . When we deal with the curve in the form 8b, then it means that the material is too loose and it becomes necessary to increase the load N (Fig. 9). On the examination of the shearing coefficient, which is to be applied to the characteristics of a granular material during screening, the normal thrust of a minimum value must be considered. Nonetheless, this minimum value of the normal thrust should enable to reach the curve demonstrated in Fig. 8c.

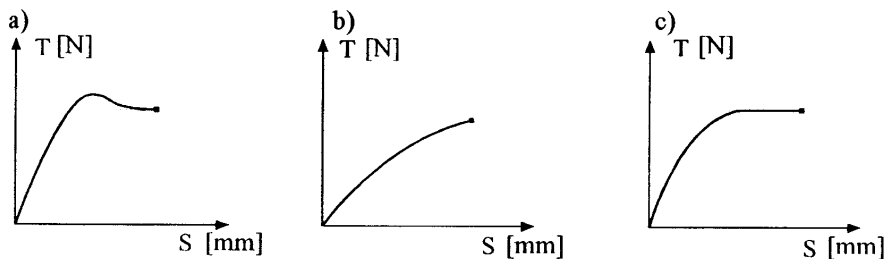


Fig. 8. Curves of shearing

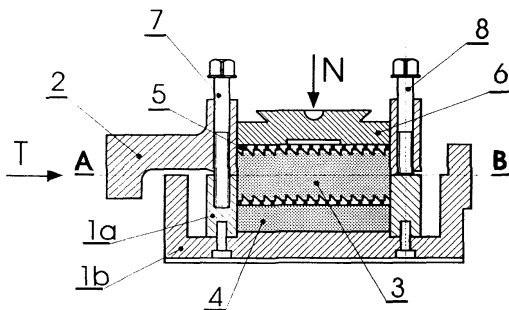


Fig. 9. Shearing box

Another very important feature of the granular materials screening process, including loose media, is a function of outflow [Schmidt, 1984; Schulze, 1996]. The function of outflow is the relation of the length of a sieve or the screening time to the height (thickness) of a layer on a sieve or the mass of a material remaining in the screening layer on the sieve. It may be noted that this is a kinetics curve of screening, the physical reflection of which is the line of an upper layer on a sieve during screening (Figure 10). A dumping curve starts at the point A and up to the point B we have gravitational dumping. Then we can observe screening up to the end point which is the length of the sieve L_{opt} or the time of screening t_{opt} . The curve constitutes an outline of the upper layer surface. According to the ease or difficulty of screening (this depends on the material humidity), the function of outflow, being an exponential function of a base e, acquires different forms (Fig.10). At the end of screening, in the end cross-section of the layer we have a thick grain bed (an over-screen product) of the thickness H_{KG} and a fine grain bed (an under-screen product) of the thickness H_{KD} . The whole thickness of the layer comprises two thicknesses. The effectiveness of screening is determined by a share of H_{KD} in the whole H_K . In Figure 10 one may also observe a dumping layer of the thickness H_W . It may be defined as such a close-to-a sieve layer of the thickness H_W from which, during one cycle of the work of a screening machine, the whole bottom class, contained in the layer, outflows. Hence, one of the aims of this study is the empirical determination of the function of outflow for the aforementioned model materials. To perform the experiment, the laboratory shakers of a vertical sieve motion and the dynamic coefficient $K=3:6$ were used.

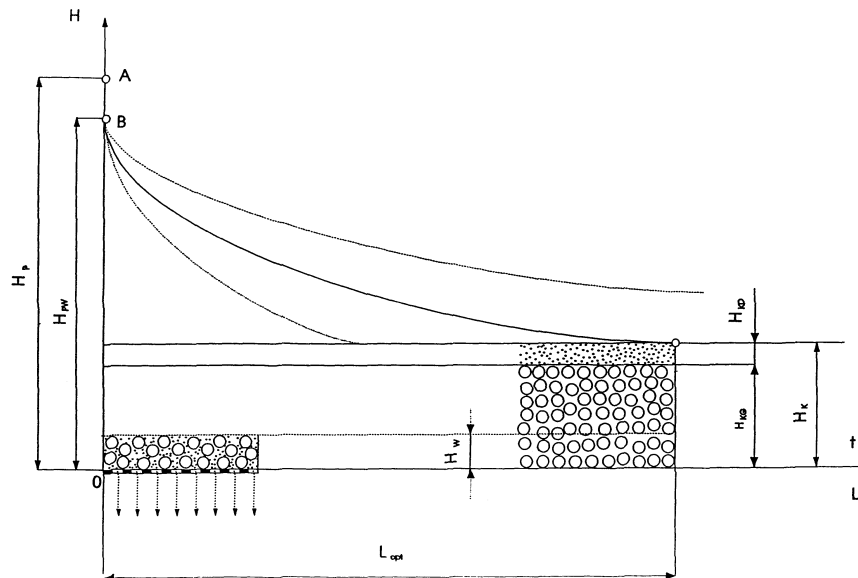


Fig. 10. Function of outflow

RESULTS OF MODEL GRANULAR MATERIALS' SHEARING INVESTIGATION

As a consequence of the model granular materials' shearing examination the tangent of the friction angle (the internal friction coefficient) of those materials was calculated. The value of the normal thrust $N=347.92\text{N}$ was taken in accordance with the previously analysed conditions. The parameter μ_0 (the internal friction coefficient) replaces the humidity of the material and other parameters being characteristic of a granular bed. It must be underlined that the parameter μ_0 defines more accurately the ability of the granular material to move and behave in various mechanical processes.

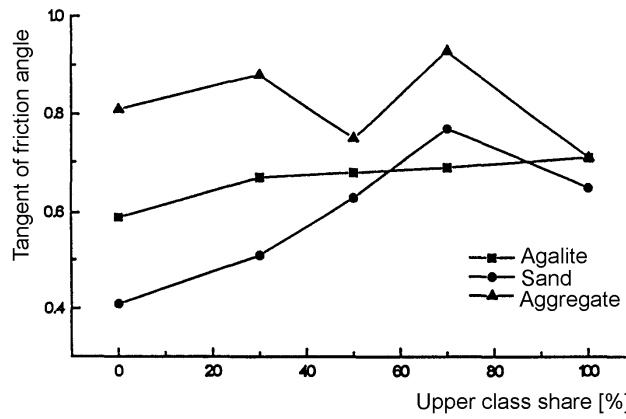


Fig. 11. Dependence of the upper class upon the tangent of friction angle ($W=0\%$)

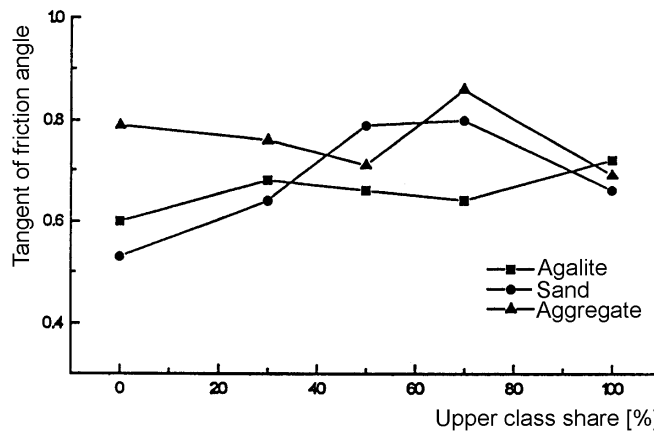


Fig. 12. Dependence of the upper class upon the tangent of friction angle ($W=4\%$)

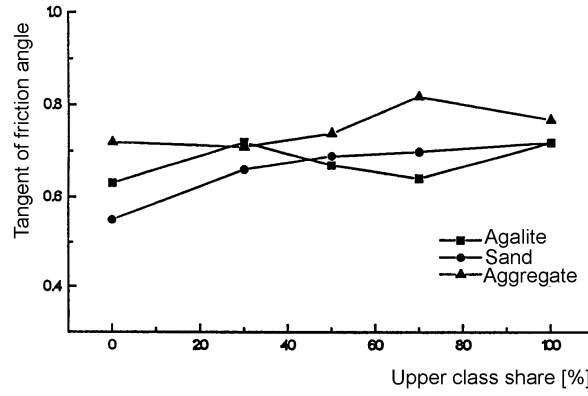


Fig. 13. Dependence of the upper class upon the tangent of friction angle ($W=8\%$)

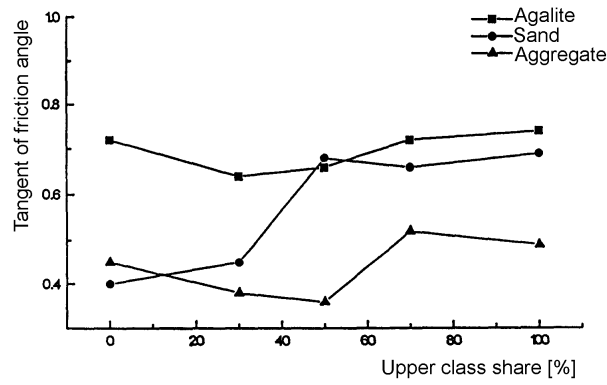


Fig. 14. Dependence of the upper class upon the tangent of friction angle ($W=12\%$)

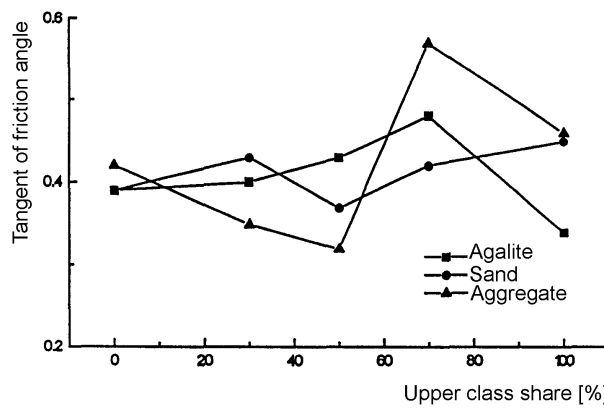


Fig. 15. Dependence of the upper class upon the tangent of friction angle ($W=W_s$)

In Fig. 11 – 15 the dependence of the upper class in a screening bed upon the friction coefficient (the tangent of the friction angle), for the three model granular materials is demonstrated. Each diagram is applicable to a different level of moisture in the material. The values of the humidity are as follows: $W=0\%$, 4% , 8% , 12% and W_s (the static humidity on the humidity axis).

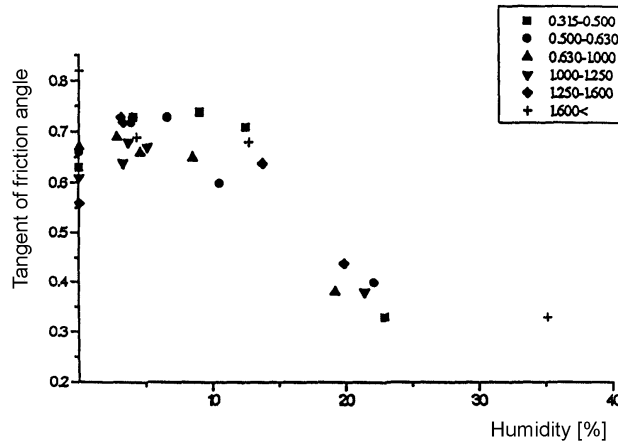


Fig. 16. Dependence $\mu=\mu(W)$ for agalite

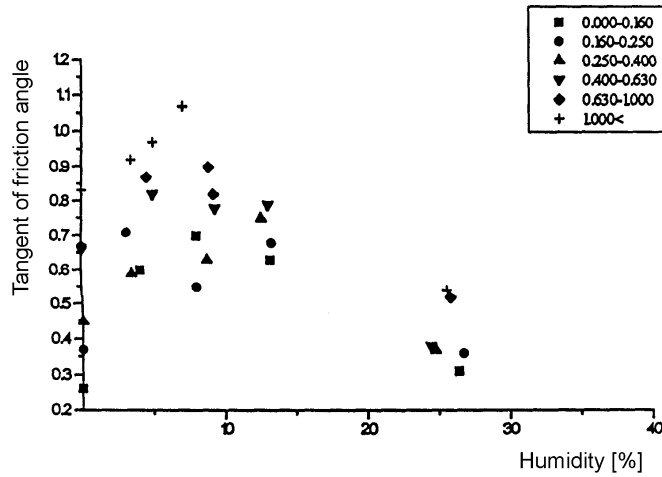


Fig. 17. Dependence $\mu=\mu(W)$ for sand

In Fig. 16 – 18 the dependence of the model material humidity on the tangent of the friction angle for particular grain classes is demonstrated (the size ranges of the classes are provided in mm). The diagrams present agalite, sand and aggregate.

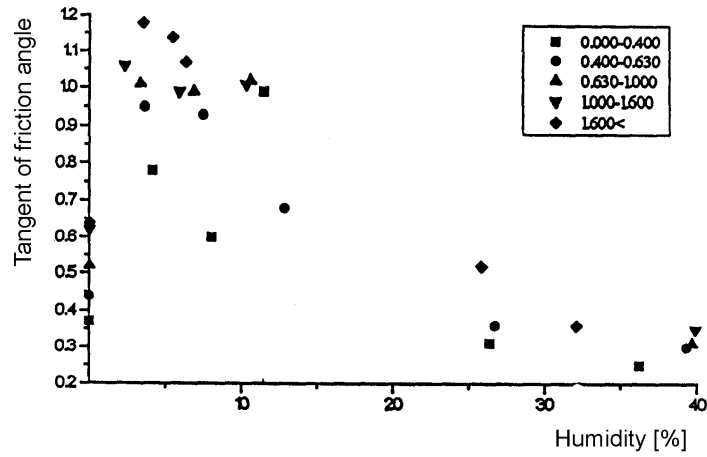


Fig. 18. Dependence $\mu=\mu(W)$ for marble aggregate

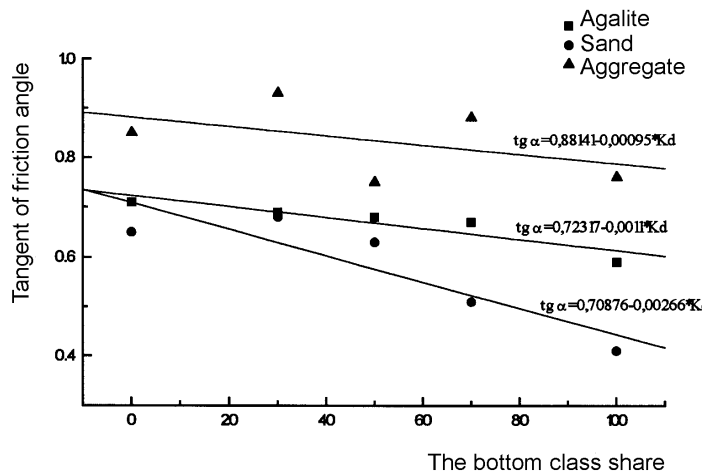


Fig. 19. Coefficient of internal friction for dry materials ($W=0\%$).

In Fig. 19 the coefficient of internal friction (the tangent of the friction angle) for the model materials (agalite, sand, marble aggregate), being dry $W=0\%$ and depending on the bottom class in %, is presented. The dependence was correlated in the form of the linear function as follows:

$$\mu_0 = f(K_d) = A+BK_d \tag{4}$$

The results of the examination allow to estimate the coefficient of internal friction for granular materials. The coefficient encompasses the physical properties of a given

material, the humidity and its influence on various mechanical processes, including screening. The parameter plays a role of an independent variable.

RESULTS OF THE EXAMINATION OF MODEL GRANULAR MATERIALS WATER CAPACITY

Two coefficients of water capacity of the model granular materials (static and dynamic) were determined. The results of the examination are presented in Figs 20-22. Considering the process of graining of the model materials, the boundaries between the upper and bottom classes are as follows:

- for agalite -1 = 1.0 mm
- for sand -1 = 0.4 mm
- for aggregate -1 = 1.0 mm.

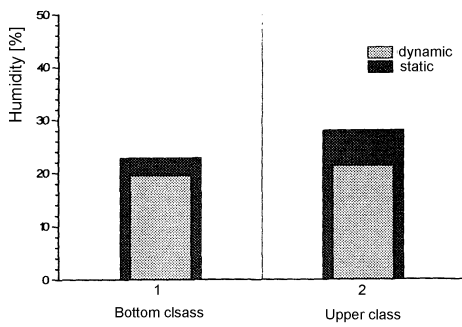


Fig. 20. Bar chart showing static and dynamic humidity for agalite

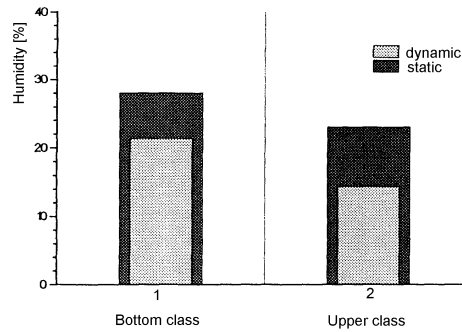


Fig. 21. Bar chart showing static and dynamic humidity for sand

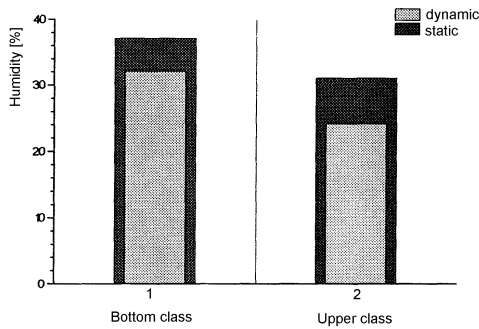


Fig. 22. Bar chart showing static and dynamic humidity for aggregate

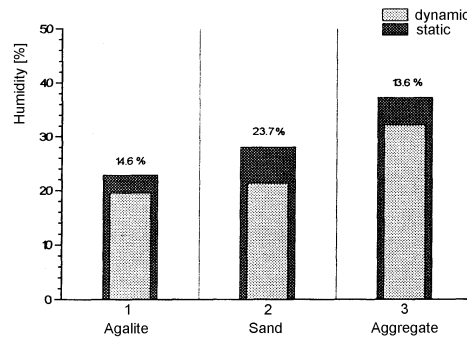


Fig. 23. Collective bar graph showing the bottom class static and dynamic humidity

In Figs 23 and 24 the moisture content in the bottom and upper classes is demonstrated. Furthermore, for each of the material the percentage decrease of the dynamic water capacity relative to the static one was calculated. A decrease in the dynamic water capacity regardless of the grain composition of the material may be noticed.

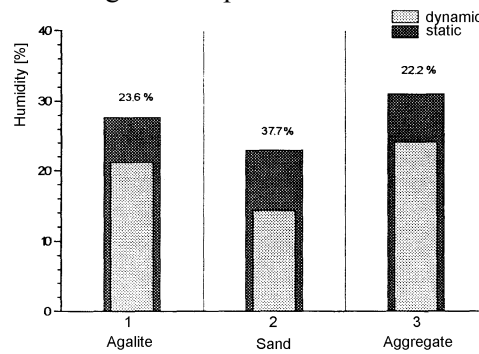


Fig. 24. Collective bar graph showing the upper class static and dynamic humidity

CONCLUSIONS

In this paper a relative humidity axis of the granular material has been introduced. The axis defines the influence of the humidity on the behaviour of the granular material during screening or another mechanical process. As a result of the research the boundary zone on the axis was determined, depicting the processes of dehydration and screening. It contributed to the determination of the static and dynamic water capacities of the granular material.

The subsequent element of this paper is an introduction of the spherical factor of a grain shape as a new characteristic defining a shape of grains in a loose material. The factor describes an external form of a grain. To the second way of determining a grain shape one may account the application of the three grain materials: spherical, irregular and sharp-edge grains. The whole research and correlations obtained were carried out for the three aforementioned model media.

The following stage of the study was the application of the general friction coefficient of a grain material which defines the aptitude of the material to screen. The coefficient may be successfully applied to other mechanical processes involving grain materials. It is advocated to replace the coefficient in the research concerning humid materials, taking into consideration the fact that various materials respond differently to their moisture content. The standardized methods of the coefficient determination exist and, thus, the possibility of easy and simple determination of the parameter has appeared.

In the mining industry the process of dehydration on sieves is applied, being one of the unit operations with humid (two-phase) granular materials. To accomplish this aim, it is the most convenient to use a wave sieve (Fig. 25) which is more efficient than a screening table.

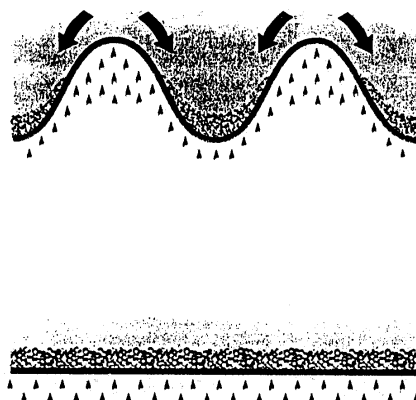


Fig. 25. Wave sieve and screening table

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REFERENCES

- JANIKE A. W., Storage and Flour of Solids; Bull. No. 123, Engng. Exp. Station, Uniw. Utah, 1964
 SCHMIDT P., Das Siebklassieren, Chem. Ing. Tech. 56 (12), 897-907, 1984
 SCHULZE D., Vergleich das Fliessverhateno leicht fliestender Schuttguter, Schuttgut 2. Nr 3, 347-356, 1996
 WODZIŃSKI P., Screening and Screens, Łódź Technical University Publishers, Łódź, 1997 (in Polish).
 WODZIŃSKI P., Screening of Fine Granular Material Coal Prep. 23 (4), 185-213, 2003

LIST OF SYMBOLS

- K – dynamic indicator of a screen [-]
 α - inclination angle of a screen [1°]
 n – frequency of a screen [Hz], [min^{-1}]
 B – width of a screen [m]

L – length of a screen [m]

H – length (thickness) of a layer on a screen [m]

t – time [s]

W – humidity [-], [%]

ε_K – spherical factor of a grain shape [-]

μ – friction coefficient

σ_f – operating shear [Pa]

σ_C – shearing resistance of a granular material (bed) [Pa]

P. Wodziński, *O pewnych właściwościach wilgotnych materiałów ziarnistych*, Physicochemical Problems of Mineral Processing, 42 (2008), 195-210 (w jęz. ang)

Niniejsza praca dotyczy właściwości wilgotnych materiałów ziarnistych. Procesy z udziałem tych materiałów występują bardzo często w warunkach przemysłowych, bo tak naprawdę przeróbka całkowicie suchych materiałów nie istnieje. W każdym warunkach mamy do czynienia z parą wodną w powietrzu, a to oznacza zawsze pewną ilość wilgoci w medium ziarnistym. Jako miernik wpływu wilgoci na przebieg procesów przeróbczych zaproponowano nie zawartość wilgoci w materiale (jak dotychczas), ale uogólniony współczynnik tarcia materiału ziarnistego. Stanowi on podstawową zmienną niezależną, uwzględniającą wpływ wilgoci na zachowanie się wilgotnego materiału ziarnistego w procesie mechanicznym. Podano ponadto funkcję wypływu będącą ważnym, parametrem analityczno-empirycznym dla opisu różnych procesów przeróbczych ciał stałych

słowa kluczowe: przesiewanie, tarcie ziarnistego materiału, ziarnisty materiał, wilgotność, przepuszczalność wodna