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(Research Article)

The influence of mixing technology on the flow properties of bulk materials

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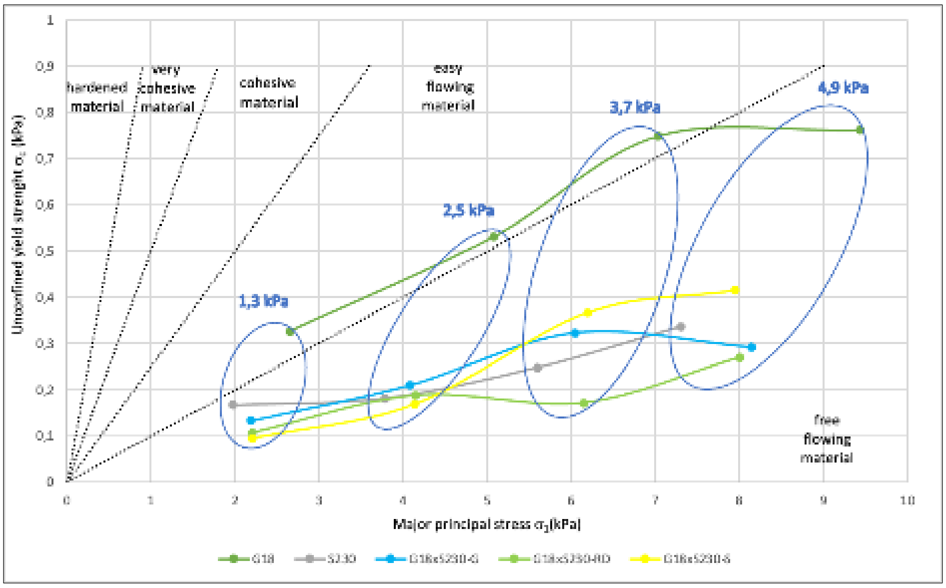
Abstract

This work focuses on whether the used mixing technology can affect the flow properties of the created mixture. For these purposes, 3 test mixtures were created from the same materials only with a different mixing technology. Their flow properties were subsequently measured on these mixtures in the laboratory. These properties were compared with each other. The influence of the mixing technology on the flow properties was demonstrated. Differences were mainly shown by the flow function and the values of the angle of external friction. For internal friction, the influence of mixing technology was not significant.

Keywords: Mixing technology; Flow properties; Bulk solids; Mixtures

Graphical abstract



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1. Introduction

Nowadays, particulate matter is part of a large number of production processes, e.g. in the construction industry [1], food industry [2], pharmacy [3], etc. Understanding and accurate description of mechanical-physical properties is the basis for achieving today's required efficiency and the highest technical standards in industry. This is the only way to achieve progress in the design of equipment that transports, processes or stores these materials. A large part of the production processes requires the material to be in motion (e.g. discharging from a hopper, etc.).

The purpose of this work is to try to provide an initial insight into whether we can influence the flow properties of the mixture of materials by the variously chosen technology of mixing particulate matter. This dependence could bring a deeper understanding of the behavior of bulk mixtures in subsequent processes after mixing. This would also open up the possibility of influencing a correctly set mixing technology on the resulting behavior of the mixture towards the desired properties.

The field of use of bulk materials is wide and there are a number of representatives from this group of materials (building bulk materials, food mixtures, etc.). For this research, the article will work with materials that are from the group of abrasive materials used, for example, in blasting equipment.

Bulk mixing technology is still a largely understudied chapter in the field of processes involving bulk materials. Nowadays, however, this topic is very actual and is often discussed in the scientific community, as can be seen from a number of publications (e.g. [4][5][6]).

In this study, flow properties affecting the behavior of the material in motion, such as the effective angle of internal and external friction, will be observed. However, the main parameter for the flow comparison will be the flow function ffc. Jennike introduced this for a better assessment of the flow properties of the material, e.g. in the design of reservoirs. He defined it generally as the ratio between the principal stress in the bulk material σ_1 and the compressive strength σ_c. [7]

$$ff_c = \frac{\sigma_1}{\sigma_c} \tag{1}$$

This relationship generally tells us that the lower the compressive strength of the bulk material, the better the material flows. Based on this relationship, the classification of bulk materials was developed by other scientists. According to [8], bulk materials according to ffc are divided into:

- ffc < 1 – hardened material
- 1 < ffc < 2 – very cohesive material
- 2 < ffc < 4 – cohesive material
- 4 < ffc < 10 – easily flowing material
- 10 < ffc. – free-flowing material

If we plot these values on a graph, we get a graphic representation of the individual flow bands separated by straight lines, the so-called flow lines, which determine the boundaries of the behavior of the bulk material flow. For specific materials, we can determine their own flow curves by measuring their flow parameters, and after entering them into the above-mentioned graph, we can observe whether they stay in one flow zone throughout the entire flow line. If the flow curve of the material extends to multiple strips, we can predict how its flowability will change depending on the applied stress and adapt the material handling processes accordingly.

2. Materials

This paper deals with determining whether the chosen mixing technology can affect the flow properties of the resulting mixtures. However, for the initial research of this issue, it was advisable to choose materials that have similar properties in terms of mechanical-physical parameters such as bulk density or granulometry, but more pronounced differences in flowability. Due to the difference in the flow rate of the input components of the mixtures, it can be assumed that the resulting flow curves of the individual mixtures will be further from the original curves of the pure input materials, and therefore the sought phenomenon could then be more visible.

The reasons mentioned above led to the decision to work with abrasive materials. The range of these materials used in practice makes it possible to use both materials resembling in their shape and size distribution loose matter found in nature (e.g. steel scrap) and also precise, identically shaped particles (e.g. balls).

Steel grit named G18 was chosen as the material for the creation of test mixtures. Sharp-edged steel grit is a very effective abrasive material. It is produced by crushing heat-treated granulate of larger diameters. The shape of the grain is irregular and sharp-edged.

Figure 1 Steel grit G18

G18 material will be mixed with S230 steel granulate. Steel granulate is one of the most widely used abrasive materials for blasting. It is made of eutectoid alloy steel. Steel granules are characterized by a relatively long service life, lower dustiness and a round grain shape.

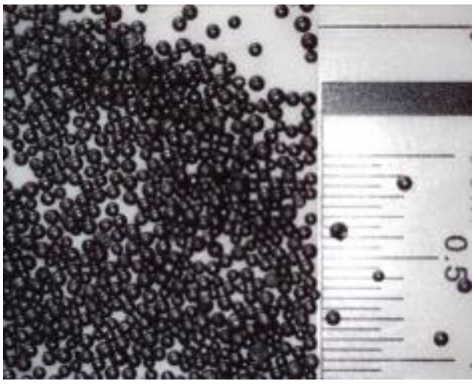

Figure 2 Steel granules S230

It was decided that for the needs of this work, the mixtures will be mixed in a volume ratio of 50:50, so that a total of 1 dm3 of the test mixture is created. This volume was chosen in such a way that it completely satisfied the volumes for which the individual test mixers were designed and provided a sufficient amount to carry out individual tests and measurements, without unnecessary wastage of input materials. An overview of the created mixtures can be seen in Table 1.

Table 1 Mixture overview

Name	**1st Component**	**2nd Component**	**Mixing technology**
G18xS230-G	G18	S230	Gravity mixing
G18xS230-RD	G18	S230	Rotary drum
G18xS230-S	G18	S230	Stirrer mixing

2.1. Measurement methods

This chapter describes the instruments that were used to measure the observed properties both for pure materials and subsequently for created mixtures.

2.1.1. External friction angle measurement

Jennike's linear shear machine was chosen to measure external friction. The angle of external friction was measured for two contact materials, namely plexiglass and PLA plastic from a 3D printer.

The principle of the test consists in measuring the shear force S_w, which is needed to move the bulk material inside the ring along the selected contact material. The material inside the ring is loaded with a normal force N_w against the contact surface. The contact material (9) is placed on the base of the machine (2). A ring (3) is then placed on it, filled with loose material and covered with a lid (4), which is weighted at point (5). The shear force is created by a drive with a constant speed, which it transmits through the stem (8) to the bracket (6,7) moving with the ring.

By performing the test, we obtain a diagram showing the shear force S_w as a function of the normal force N_w. Since we also know the area of the test ring, in addition to the function S_w (N_w), we can also determine the functional dependence τ_w (σ_w) of the normal stress σ_w and the shear stress τ_w. The resulting curve is called the wall yield locus. The shape of the curve affects the type of bulk material and contact material used for the reservoir.

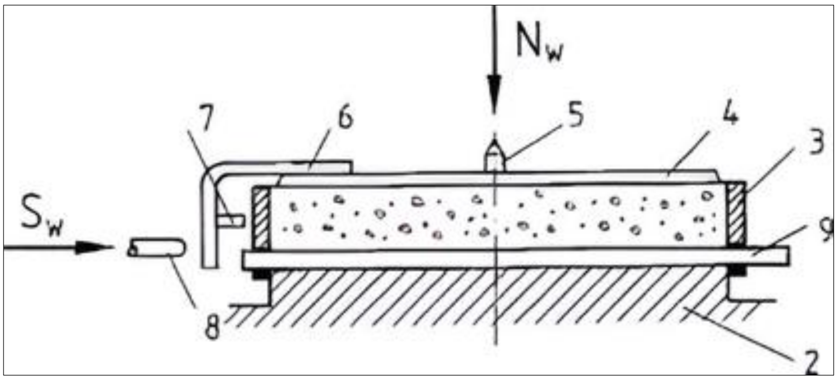

Figure 3 Scheme of a shear test to determine external friction angle [9]

2.1.2. Measurement of the angle of internal friction and flow function

The internal friction angle was measured on a Brookfield Powder Flow Tester (PFT). It is a device from the group of rotary shear machines.

A sample of particulate material has a volume defined by the dimension of the test cell. Before starting the measurement, the entire sample is weighed to determine its weight. The principle of operation of the PFT is to push the finned lid vertically into the ring of the shear cell. A calibrated load cell inside the device is used to check the control of the compaction tension. The annular shear cell is then rotated at a defined speed and the torque resistance of the powder in the shear cell moving against the powder in the stationary lid is measured by a calibrated reaction torque sensor. The results processed by the software of the device then depend on a number of parameters, such as the geometry of the lid, the size of the cell, the speed of rotation of the cell, the pressure load acting on the sample. All these parameters affect the calculation of the resulting flow rate of particulate matter.

PFT measures the following parameters on the basis of which it then evaluates the flow properties of materials:

- Compressive strength of the material
- Main consolidation stress
- Time consolidation
- Angle of internal friction
- Angle of external friction
- Strength cohesion of the material
- Density

2.2. Mixing equipment

In order to assess whether the mixing technology can affect the flow characteristics of the materials, it is necessary to select suitable equipment in which the mixing of the test materials will take place. Based on the conducted research among the methods of mixing particulate matter currently used in practice, three mixers were chosen. Each of the mixing devices represents one of the three mixing principles suitable for this type of material.

The following devices are installed:

- Drum mixer
- Gravity mixer
- Convection mixer

2.2.1. Drum mixer

A drum mixer was chosen as a representative of mixers with a rotating chamber. It is a simple mixing method that is popular in practice for its low operating costs, easy handling, and low energy consumption. For the reasons mentioned above, this type of mixer is also often used in laboratory conditions, as it is easy to monitor the homogenization process. Thanks to this, the description of this mixing method has already become the subject of many scientific works, and the process of mixing in this way is relatively well understood (e.g. [10], [11], [12], [13]).

We used a device previously constructed for the purpose of studying the mixing process of particulate matter using DEM [14], which is available in the VŠB-TUO laboratory.

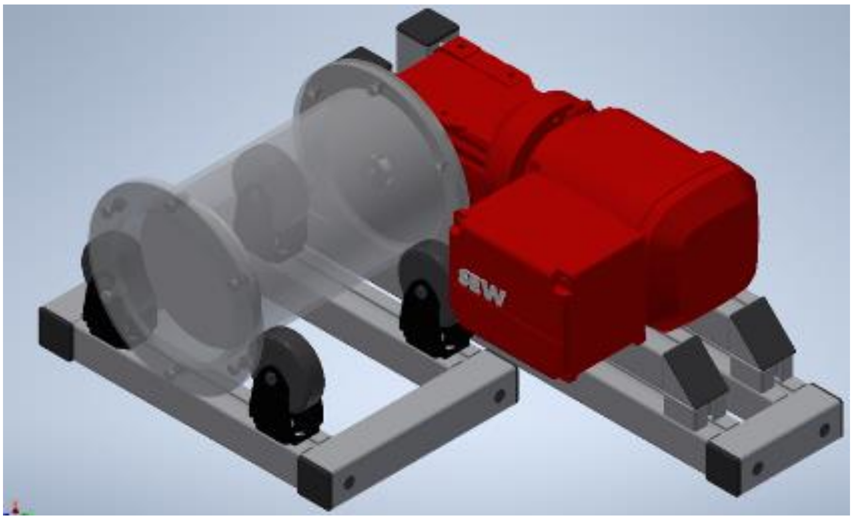

Figure 4 Rotary drum model [14]

This rotary drum model consists of a construction made of aluminum structural profiles. They are equipped with a motor with a SEW Eurodrive gearbox, which takes care of turning the mixing chamber through a tongue and groove located in the drum flange. The drum itself is then placed on 4 wheels that are attached to the frame in such a way as to allow the drum to rotate. The drum is made of plexiglass and has a diameter of 140 mm. The length of the drum is 245 mm. This material was chosen so that it was possible to visually observe the entire mixing process and its typical phenomena.

The power input and regulation of the electrical energy flowing into the motor is taken care of by a frequency converter, which can be used to regulate the speed of the drum. The nominal revolutions on the transmission shaft are 60 min^{-1}.

Before actual mixing in the rotary drum, a calibration experiment was first performed with a small mixing chamber to determine the correct rotation speed (a speed of 36 rpm was chosen). The speed at which the drum rotates directly affects the mechanisms of material movement in the drum. From the literature dealing with the mechanisms of movement of particles in a drum mixer [15], we know that the so-called avalanche movement of the material is optimal for mixing in a drum mixer, when the material is carried along the wall of the drum to a certain height, where it is then separated and rolled over the upper layer material. In this way, optimal mixing of the mixture is achieved after a certain time. Another factor affecting the proper functioning of the mixer is the filling of the mixing chamber. From a study dealing with mixing in this type of equipment, it is evident that for most materials, around 50% filling of the mixing chamber is ideal. There must be a sufficient amount of material for all the mixing mechanisms to work properly, and at the same time, enough space is ensured for moving the layers of material between each other.

Measured portions of the mixture were always poured into the volume drum, using a measuring cylinder. The drum was then sealed with the face using screws and attached to the drive. Subsequently, mixing was started at the optimal speed for the given material. Mixing time was set to 10 minutes for all mixtures.

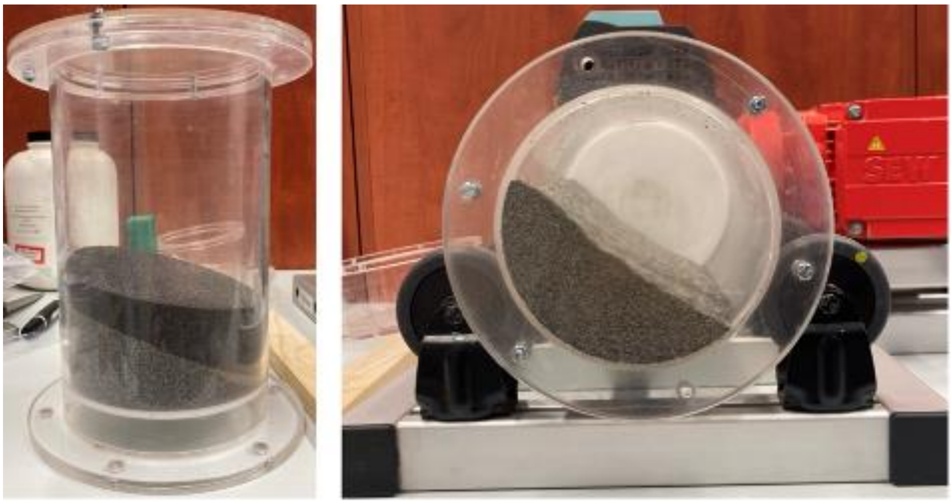

Figure 5 Drum with material (left), mixing process (right)

2.2.2. Gravity mixing

For the gravity mixing method, instead of a classic silo with a specially adapted internal geometry, the principle of mixing along the conveyor path was chosen. In this type of gravity mixing, the material is conveyed through a differently inclined pipe, which has differently shaped partitions in it, which the material hits, the individual grains change their trajectory and thus mixing occurs. Examples of constructions of these devices can be seen in Figure 6.

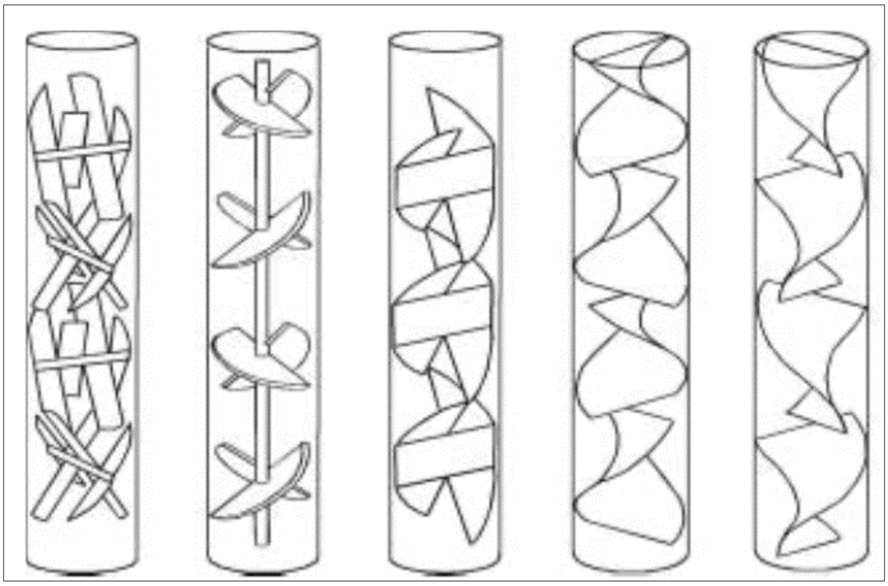

Figure 1 Examples of internal geometry for gravity mixing along transport route [16]

This mixing method is widely used for mixing gases, liquids or suspensions. In the field of bulk materials, this is still a less common option. Nevertheless, today it is receiving more and more attention because it brings great benefits. In particular, it is about mechanical simplicity, there is no need for a drive or moving parts. Another advantage is the practically zero space requirements, there is no need to reserve a special space for the mixer, it can simply be replaced for part of the transport route along which the material travels. The material is set in motion only by its own weight or by the pressure difference in the device. The aforementioned can thus bring considerable economic savings, also considering that the equipment requires almost no regular maintenance. The disadvantage is that the mixing may not be as good as with other mixing methods, and for some groups of materials this method may be completely unsuitable (e.g. cohesive materials).

For the needs of this research work, a construction variant using internal helical structures was chosen. The mixer is made up of several segments. The initial part consists of a container divided into two parts for individual input materials. Each half of this segment has a volume of 0.5 dm3 and in the lower part the part ends with a slide. Pulling out the slide allows the materials to enter the parts responsible for their mutual mixing. The mixing itself is handled by a set of 4 parts. In each part of the mixer, one helix thread is formed inside the tube. Two parts have a right-hand helix and two have a left-hand helix. The parts are assembled one behind the other in such a way that the direction of rotation of the helix alternates and at the same time the helices are always turned by 90° relative to each other, thus the flow streams of the individual materials are separated and their gradual mixing occurs.

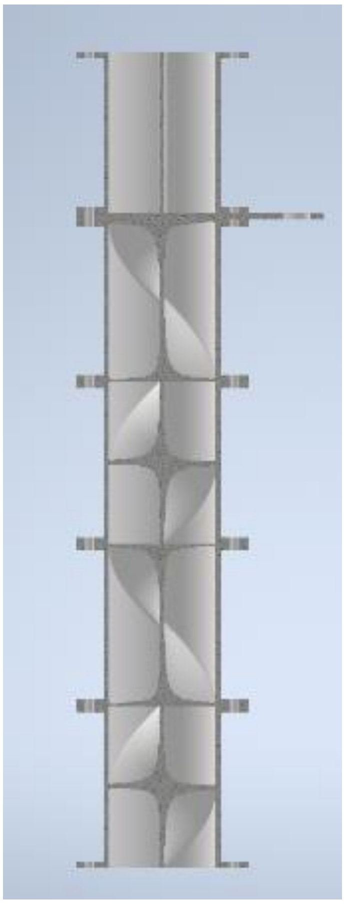

Figure 2 A view of the internal geometry of the gravity mixer

The entire assembly is designed in a modular way so that the number of mixing parts can be further increased in case of insufficient mixing.

The individual parts of the mixer were created using a Prusa i3 MK3S+ 3D printer. PLA filament (Polylactic acid) was chosen as the material, which stands out for its easy processability and low price. For these reasons, it is recommended by the manufacturer for the production of device concepts or prototypes.

This mixing method is the easiest and fastest of the three proposed. The appropriate material was poured into the designed reservoir divided by a partition into two parts, each of which has a volume of 0.5 dm3. By quickly pulling out the slide that separates the container with the material from the body of the mixer itself, it is possible to enter the components of the mixture into the device. The components of the mixture passed through the mixer by their own weight and, thanks to its geometry, they were mixed and then poured into the holding container. The entire mixing process takes a few seconds.

Figure 3 Gravity mixer (left), container with material (right)

2.2.3. Convection mixer

The third device, used for the production of mixtures needed for research works, is from the field of convection mixers. In convection mixers, mixing is handled by an active element in the form of a stirrer, which sets the material in motion and enables quick and efficient mixing in a relatively short time.

A simple tool, widely used in the construction industry for mixing dry and wet mixtures of building materials, was chosen as a mixer, see figure 9.

Figure 9 Used stirrer (Hornbach, https://www.hornbach.cz/p/michadlo-stavebnich-smesi-100-x-600-mm-uchyceni-sds/5908971/, Last accessed on 28/03/2024)

The stirrer was attached to a Hilti TE-2 multifunctional drill, which served as a drive. The mixer has dimensions of 100 mm x 600 mm, mixing took place in a container with a diameter of 130 mm and a height of 300 mm. The mixing process itself is carried out by an operator holding the equipment in the correct position to mix the components of the mixture. The entire assembly of the device can be seen in Figure 10.

Figure 10 Convection mixing

The individual components of the mixture were measured in a measuring cylinder and placed in a mixing container. The stirrer was then inserted into the container and kept in a constant position. The duration of the mixing process was set at 2 minutes. After mixing, the material was subsequently moved to a container from which samples were taken and tests of the material's properties were carried out.

3. Measurement results

3.1. External friction angle

Table 2 shows the resulting values of the angle of external friction for mixtures of steel grit G18 and granulate S230. It can be seen from the results that the values of the external friction angle differ depending on the chosen mixing technology. For both contact materials, the values range in approx. 2°. However, which technology showed the lowest and highest external friction values varies depending on the contact material. While the stirrer mixing method achieved the lowest friction values for PLA plastic, on the contrary, in the case of Plexiglass, this method showed the highest friction values.

Table 2 External friction angle results

Name	**Plastic PLA**		**Plexiglass**	
	External friction angle φ_x	Coefficient of external friction μ	External friction angle φ_x	Coefficient of external friction μ
G18xS230-G	24.29°	0.45	17.67°	0.32
G18xS230-RD	23.10°	0.43	17.00°	0.31
G18xS230-S	22.17°	0.41	18.82°	0.34
G18	31.67°	0.62	25.06°	0.47
S230	17.28°	0.31	14.80°	0.26

3.2. Angle of internal friction

The effective angle of internal friction was measured using a rotary shear machine. Furthermore, the device measured how the value of the effective angle of internal friction changes depending on the main consolidation stress exerted on the sample.

For the mixture of steel grit G18 and granulate S230, the mixture prepared by the gravity method reached the highest angle of internal friction (32°). Mixtures prepared by mechanical mixing methods (rotary drum, stirrer) showed lower values with a difference in the order of tenths. The lowest internal friction angle was 31.4° for the rotary drum mixing method. The results can be seen in the table below.

Table 3 Effective angle of internal friction results

Name	Effective angle of internal friction φ_e
G18xS230-G	32°
G18xS230-RD	31.4°
G18xS230-S	31.7°
G18	39.2°
S230	27.4°

From the point of view of the variability of the effective angle of internal friction depending on the stress created on the sample, a slight decrease in the effective angle of internal friction can be observed for all samples with increasing consolidation stress. A graph showing the change in the effective angle of internal friction can be seen in the figure below.

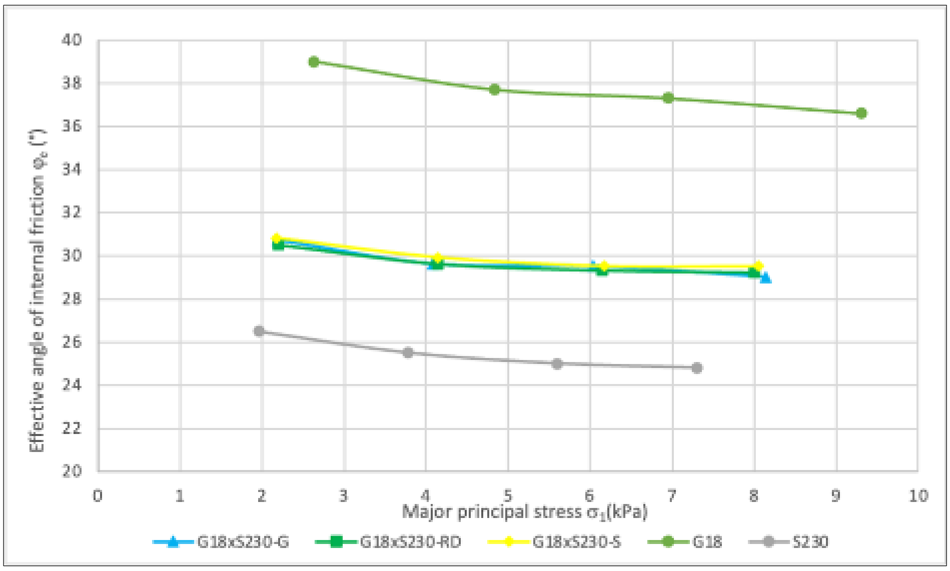

Figure 11 Effective angle of internal friction as a function of stress

3.3. Flow function

As one of the key properties for assessing the influence of mixing technology on the flow characteristics of particulate matter, the ffc flow function was chosen for this study. Its course, like the input materials, was measured on a PFT rotary shear machine.

G18 steel grit showed a flowability outside the range of free-flowing materials during the measurements. The G18xS230 mixture then showed significantly better flowability compared to the mentioned G18 grit. All 3 mixtures are in the area of free-flowing materials in the entire measurement range. Their fluidity is very similar to the character of pure granulate. At certain stresses, even the created mixtures show better flowability compared to pure S230 granulate. The mixture created by mixing in a rotary drum achieved the best result, especially in the area of higher stresses. At a lower stresses, the flow rate of the mixture is similar to that of granulate S230. Bigger differences then occur at higher stress. The variability of the flowability based on the consolidation stress can be clearly seen in the result of mixing with a stirrer, where the mixture created in this way shows the best flowability in the area of lower stresses, compared to other methods. However, as the stress increases, the flowability worsens to such an extent that in the region of higher stress, the sample created by mixing with a stirrer becomes the worst flowing of all 3 mixtures.

Table 4 Principal consolidation stress, compressive strength and flow function of G18xS230 mixtures

Normal stress (kPa)	G18xS230-G			G18xS230-RD			G18xS230-S		
	σ_c (kPa)	σ_1 (kPa)	ff_c (-)	σ_c (kPa)	σ_1 (kPa)	ff_c (-)	σ_c (kPa)	σ_1 (kPa)	ff_c (-)
1,3	0.13	2.19	16.46	0.11	2.20	20.56	0.10	2.21	23.21
2,5	0.21	4.08	19.44	0.19	4.15	22.07	0.17	4.14	24.50
3,7	0.32	6.04	18.71	0.17	6.15	35.76	0.37	6.19	16.87
4,9	0.29	8.15	27.90	0.27	8.01	29.65	0.42	7.95	19.16

Table 5 Principal consolidation stress, compressive strength and flow function of pure materials

	G18			S230		
Normal stress (kPa)	σ_c (kPa)	σ_1 (kPa)	ff_c (-)	σ_c (kPa)	σ_1 (kPa)	ff_c (-)
1,3	0.33	2.65	8.13	0.17	1.97	11.81
2,5	0.53	5.08	9.56	0.18	3.79	20.80
3,7	0.75	7.04	9.39	0.25	5.60	22.57
4,9	0.76	9.43	12.38	0.34	7.30	21.74

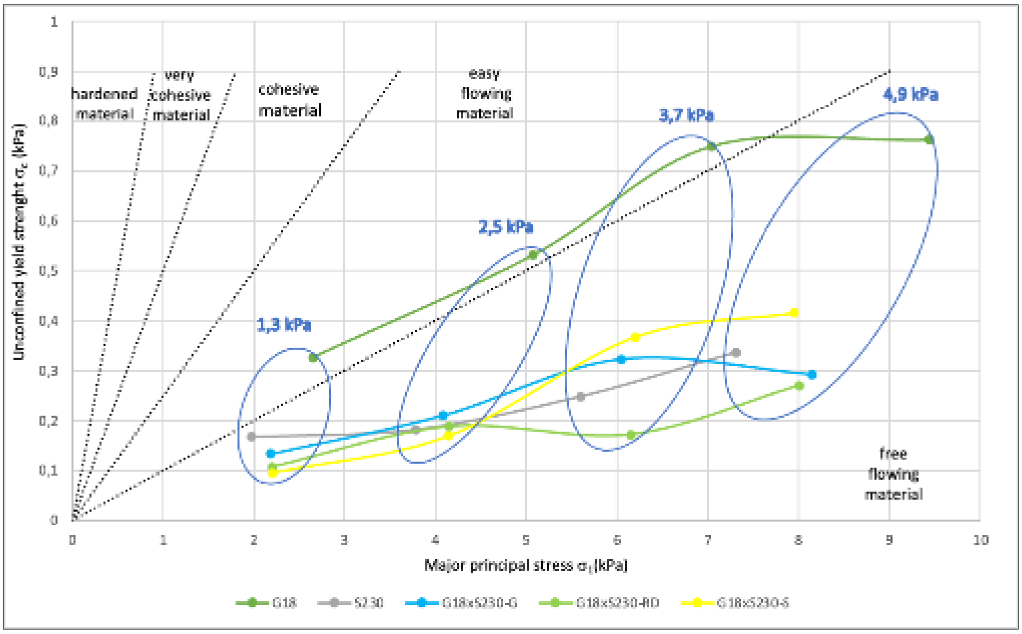

Figure 4 Flow function of examined materials

4. Discussion

It follows from the measurement results presented above that the mixing technology used to create the mixtures really affects the individual flow properties of these mixtures. However, it is also evident from the measured data that some mechanical-physical properties of materials are more sensitive to the influence of technology than others and show greater differences between samples of the same mixtures created by different methods. This is visible in the case of the external and internal friction angle values. In the case of the external friction angle, there are clear differences between the different mixing methods. On the contrary, for the effective angle of internal friction, larger differences in the measured values did not appear.

An interesting finding in the area of the angle of external friction is that for the same material, which was applied to different contact materials, the best and worst mixing methods often turned out to be different technologies. This is visible, for example, on the G18xS230 mixture. For PLA contact material, the sample prepared by gravity mixing had the highest external friction, but for Plexiglass, it was the sample prepared by stirrer mixing. An explanation may be that when a sample of materials is sheared over a rougher surface, its particles tend to stick together more and move relative to each other, which may be more advantageous for the arrangement of particles produced by one mixing method than another. This phenomenon will also need to be further investigated in follow-up research works to confirm whether it is a really existing dependence and how it is related to the size of the particles in the mixture.

From the measurements, the effective angle of internal friction was shown to be one of the properties less sensitive to the chosen mixing technology. For the G18xS230 mixtures, the differences in the measured values ranged only in tenths of degrees. For the G18xS230 mixture, the sample prepared by the gravity method showed the highest value, and the rotary drum mixing method showed the lowest value.

In the ffc flow function plotted for individual mixture samples, we can observe fairly significant differences between the curves of individual mixing methods. An interesting aspect deserving more attention in further research is the change in ffc function when the stress is increased. This can be observed, for example, on the material G18xS230-S, which appears to be the best-flowing of the three mixtures in lower areas of consolidation stress load, but with increasing stress, the compressive strength increases more than the other two mixtures and thus becomes the most difficult-to-flow mixture.

5. Conclusion

From the results presented above, it can be seen that for these specific mixtures, differences in flow properties can be observed depending on the mixing technology used. It was evident from the measurements that the influence of the mixing technology is more pronounced on some of the measured parameters than on others. While for the values of the effective angle of external friction, the values between the individual methods differ only slightly, for the angle of external friction and the flow function ffc, the differences were larger.

The angle of internal friction for the mixtures created by different methods differed only in the order of lower tenths of a degree. Also, on the graphical representation of the dependence of the effective angle of internal friction on the main consolidation stress, it was visible that all mixtures move almost at the same level and react almost identically to the change in stress.

The influence of mixing technology on the resulting values of external friction was more pronounced than that of the angle of internal friction. The mixing technology used influenced the values of the angle of external friction in orders of degrees. Furthermore, it was found that for the same material applied to different contact materials, different mixing technologies come out as the best and worst methods. This finding needs to be further developed in follow-up research. The influence of technology on the angle of internal friction could thus be used to improve flow properties, e.g. at the discharge from the reservoir.

From the point of view of the flow function, the differences between the individual mixtures were most pronounced. By creating mixtures, the flowability of all samples was improved compared to pure materials. Differences between individual mixtures can be observed both in the values of the flow function and in its course depending on the normal stress. For different normal stress loads of the samples can be observed as the best flowing mixtures are created by different methods. In this case, it is therefore not possible to say which mixing method produces the best flowing mixtures. It is necessary to take into account the stress states in which the resulting mixtures will be.

In the follow-up research, a greater number of materials should be included in the measurement and it should be observed whether this phenomenon manifests itself in them as well. There will be an opportunity to adjust the flow properties of mixtures only by using appropriate technology, which can be advantage in practice.

Nomenclature

Symbols

σ_1	Major principal stress	[kPa]
σ_c	Unconfined yield strenght	[kPa]
ff_c	Flow function	[-]
N_w	Normal force	[N]
S_w	Shear force	[N]
σ_w	Shear stress	[kPa]
τ_w	Normal stress	[kPa]
μ	Coefficient of external friction	[-]
φ_e	Effective angle of internal friction	[°]
φ_x	External friction angle	[°]

Abbreviations

PLA	polylactide fibres
VŠB TU-Ostrava	VSB - Technical University of Ostrava

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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