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RHEOLOGICAL PROPERTIES OF SLIME WASTE FROM HARD COAL PROCESSING

1. Introduction

One of the waste from coal treatment process is a slime waste. It arises in water-sludge circuit as a suspension of fine-grained coal waste with solids content of from 200 to 450 g/dm^3. It is secreted in hydrocyclones and Dorr thickeners. Depending on the feed and the treatment process, slime waste may be even more than 30% of the total waste generated [1].

For many years the main way of dealing with slime waste was it disposal in tailings ponds. Recently, through the development of methods based on the dewatering filter presses, part of the slime waste is used for engineering works or burnt in a fluidized bed boilers in addition to coal. However, due to significant amounts of the resulting slime waste, low energy parameters and the cost of dewatering, new directions of disposal are still sought. One of the most promising way is slime waste utilization as an component in fine-grained suspensions used in mining technologies, such as sealing abandoned workings caving or liquidation of dog headings [2–5].

For both the latter directions of disposal, and for other purposes where it is necessary to design parameters and infrastructure of hydraulic transport of slime waste, it is important to have information about their rheological properties. For accurate determination of them, professional equipment (viscometers) is necessary. The next step is the proper fit of rheological models to the data. Then, it is possible to calculate the flow resistance and thus requirements for the parameters necessary equipment (e.g. pumps) [3–5].

In this paper the study of the viscous behaviours of slime waste suspensions are presented with discussion of the phenomena relating to the deformation and flow of such liquids. The

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study was carried out for water suspensions with varying content of solids, prepared with slime waste from hard coal processing plant belonging to one of the Polish underground mines. The tests were done in a wide range of shear rates, with using three different measurement systems [6–9].

2. Rheological properties and models

Rheological measurement let describes deformation and flow of liquids. The complete range of shear conditions includes all possible shear rates from extremely low to extremely high values. The main rheological parameters determined on the base of the measurements are as viscosity and shear stress for different shear rates. As the results flow and viscosity curves can be obtained. Usually flow curves are illustrated as changes of sheer stress or viscosity, versus shear rate. Courses of these curves are equivalent. Viscosity curves describes suspensions tendency for thinning or thickening during shearing [10].

Rheological properties of liquids can be described and modelled with the aid of mathematical formulas. For the purpose of this study was chosen three popular rheological models: Bingham, Casson and Ostwald de Waelle (Tab. 1). Mutual correlations between the models are shown on Figure 1.

Newton's model is the simplest rheological model: the shearing stresses in here depend only on shear rate. This model describes very well the rheological properties of water, but is not suitable to describe the properties of suspensions.

Bingham model bases on two parameters: "yield point" (τ_o) and "plastic viscosity" (η_p). Analysis is very easy — because the flow curve is straight line. This model rarely allows for a precise description of liquids behaviour in a wide range of shear rates. It is used for very simple quality control tests and, thanks to its simplicity is also very useful for engineering calculations, especially for calculating the flow resistance of the liquids transported by pipeline.

TABLE 1

Typical math models used in estimation of liquids rheological properties

Rheological model	**Formula**	
Bingham	$\tau = \tau_o + \eta_p + \dot{\gamma}$	τ – shear stress τ_o – yield point η_p – plastic viscosity $\dot{\gamma}$ – shear rate k – consistency factor n – power index
Casson	$\sqrt{\tau} = \sqrt{\tau_o} + \sqrt{\eta_p \dot{\gamma}}$	
Ostwald de Waelle	$\tau = k\dot{\gamma}^n$	

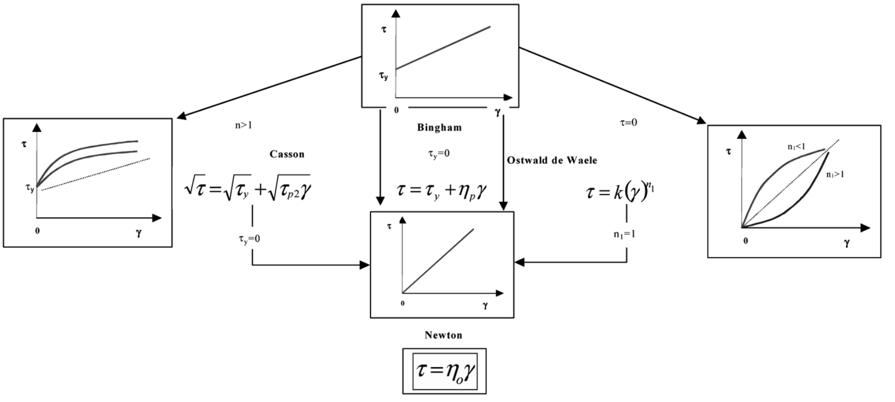

Fig. 1. Connection between typical rheological models described rheostable liquids

Casson — similarly like Bingham model is described by yield point and viscosity, but differs in course of flow curve. This model was designed for printing pastes — very high loaded suspensions.

Ostwald de Waele (or Power Low) — model for suspension without yield point included parameters such as *k* — consistency factor also called flow coefficient [Pa · s] and *n* — power index. The disadvantage of this model is that it cannot be fitted well to the course of curves at very low and very high shear rates [10, 11].

3. Materials

The subject of research was a slime waste from the processing of coal in one of the Polish mines. This waste, as mentioned in the introduction, is separated in hydrocyclones and thickeners Dorr as a suspension waste-water with solids content in the range from 200 to about 450 g/dm^3. Declared range of grain size: from 0 to 0.3 mm.

TABLE 2

Characteristic of slime waste suspensions

Slime waste (s) with water (w) dilution, s/w	Marking of the suspensions	Density, [g/cm^3]	Solid content, [%]
100s/0w	100/0	1.216	38.50
90s/10w	90/10	1.191	34.65
80s/20w	80/20	1.159	27.72
70s/30w	70/30	1.104	19.40

For the tests, slime waste was used with a water content 61.5%, which was then diluted with water in proportions by weight 90%/10%, 80%/20% and 70%/30%. In this way slime waste suspension were created with solids content from 19.4 to 38.5%. Detailed parameters of suspensions are summarized in Table 2.

4. Methods

For the proper determination of rheological parameters very important are both maintaining the same procedures for sample preparation as well as distinguish between the preconditioning step and the measure step so as to analyse samples characterized by the same previous rheological history. A well-defined sequence of actions allows one to obtain rheological results characterized by sufficient precision, repeatability and independently of the operator that will perform the measurements and/or the laboratory where they will be performed.

There are a few factor, which may significantly affected on measurements of viscosity and other rheological properties. These include primarily temperature, evaporation, sedimentation and aging of suspensions. Strict time regime was implemented. Similar were both measurement time and suspension age (period between preparation and measurement) were implemented. Moreover measurements were done in the same temperature: 25°C and vessels with the suspensions were secure for evaporation.

The study was conducted using three viscometers, working in different measuring systems. The two of them were based on a cylindrical system (spindle-container), one on the plate-plate system:

— Rheotest RN 4.1 G1-H2: a cylindrical measurement system, a cylindrical rotor (spindle) with a diameter of 27.5 mm, container (cylinder) — 38 mm, sample volume — 55 cm^3, time of one measurement: 16 minutes,

— Brookfield DV III, SC4-21: a cylindrical measurement system, the rotor (spindle) in the shape of a cylinder with conical bases, sample volume — 8 cm^3, time of one measurement: 30 minutes,

— Anton Paar Physica, PP50 d = 1mm: a plate-plate measurement system, sample volume 2 cm^3, time of one measurement: 6.5 minutes,

Principle of the measurement — a spindle or a plate, immersed in the fluid system, is rotated at different speed, and the reaction on this speed — stress caused by the resistance exerted by the fluid on the spindle is measured.

Because of appearing single grains with a diameter up to 1 mm, more than the small size gaps between moving parts in Brookfield and Anton Paar viscometer, grains with diameter more than 0.5 mm were removal from slime waste suspensions intended for these devices.

5. Measurements and results

For each of the studied suspensions shear stress was measured for different shear rate, both during its rise, and in the second stage — during deceleration. Measurement results are presented in the form of flow curves in Figure 2–4 and viscosity curves (Figs. 5–7). Table 3 contain lists of the rheological models calculated for the analysed suspensions with the determination coefficient (R^2), which indicate matching of the models to the actual curves.

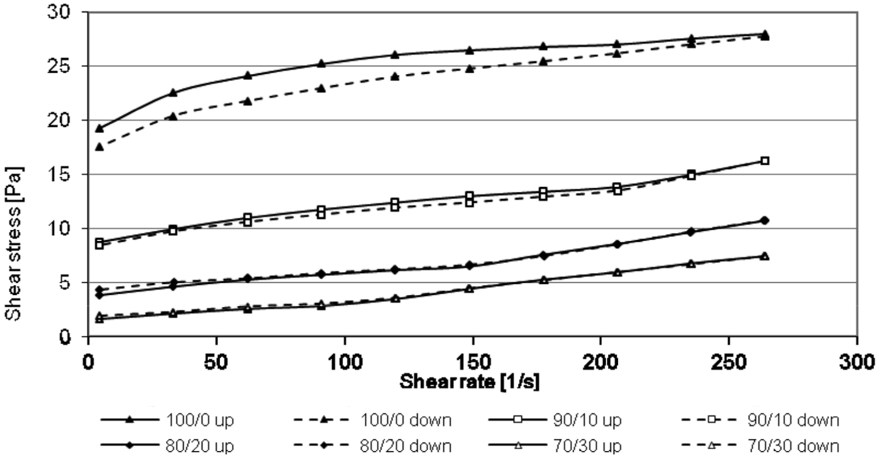

Fig. 2. Flow curve of slime waste, measured with Rheotest 4.1 G1-H2 viscometer

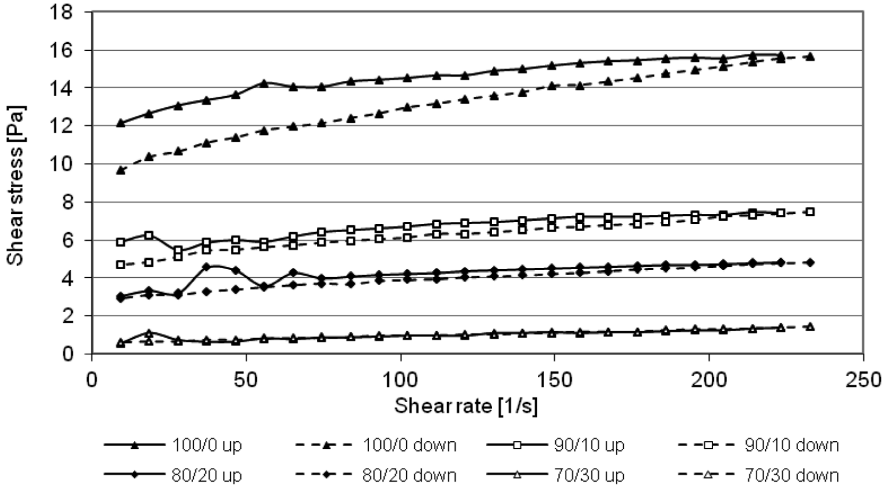

Fig. 3. Flow curve of slime waste, measured with Brookfield DV III, SC4-21viscometer

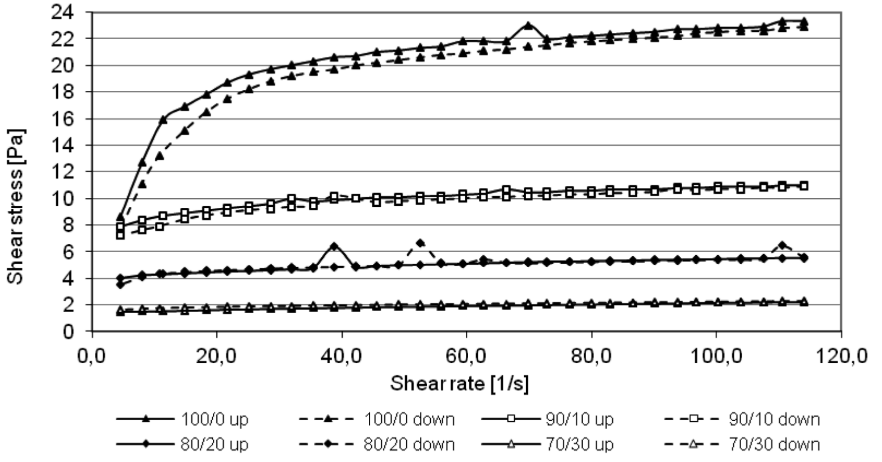

Fig. 4. Flow curve of slime waste, measured with Physica Anton Paar viscometer, PP50 d = 1 m

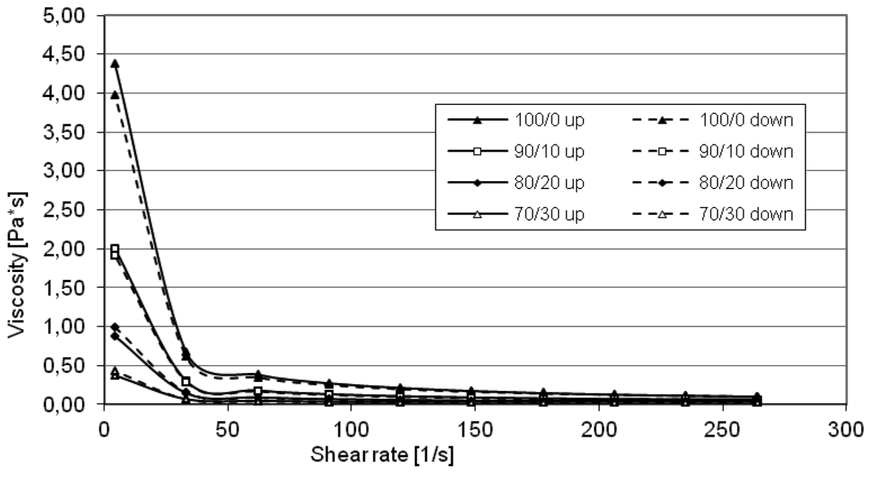

Fig. 5. Viscosity curve of slime waste measured with Rheotest RN 4.1 G1-H2

From rheological point of view, slime waste suspension correspond to aqueous systems and have pseudoplastic behavior. It means that it characterize of distinct yield point and shear-thinning flow behaviour — with higher shear rates lower viscosity is apparent (Figs. 2–4). Shearing can cause the change of particles orientation accordance with the flow direction, as well as disintegration of agglomerates or change of the particles form. It causes a reduction the forces between the particles, and thus decreases the flow resistance.

Moreover, investigation of flow curves in suspensions 100/0 and 90/10 shows small hysteresis area enclosed between the two curves. It indicating the occurrence of the thixotropy phenomena. It is also confirmed by analysis of the viscosity curves (Figs. 5–7). Measurement using Brookfiled rheometer shows much greater differences between upper and lower curves than for the other sets. The reason for this may be a greater sedimentation of the sample, because of a longer measurement time for every data point, in this device.

This can be key matter for operations involving with high shear rates, e.g., for hydraulic transporting. In this case decreasing viscosity is observed during higher flow speed. Thanks that phenomenon hydraulic flow resistances of such liquids are growing slower than the flow speed. It facilitate pressure transport of suspension with pseudoplastic course.

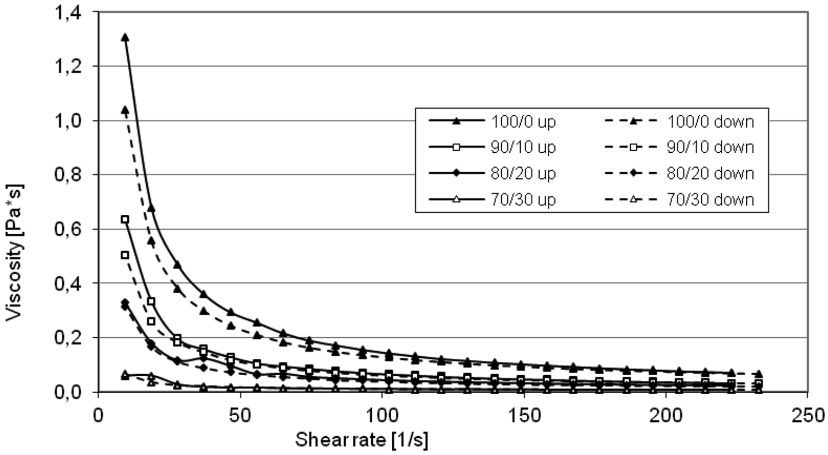

Fig. 6. Viscosity curve of slime waste measured with Brookfield DV III, SC4-21viscometer

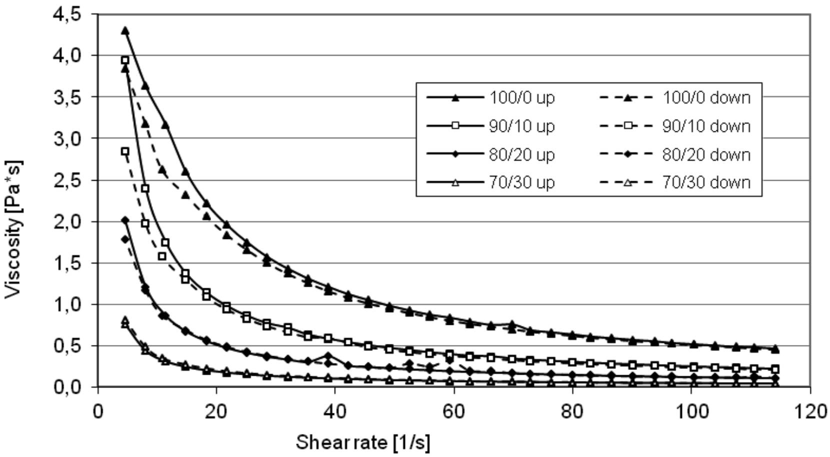

Fig. 7. Viscosity curve of slime waste, measured with Physica Anton Paar viscometer, PP50 d = 1 m

Value analysis of the measurements shows well-defined diferences between samples, depended on measuring system as well as samples volumes. However comparing courses of flow curves (Fig. 2–4) allowed to observe general relations. For all measurement systems diferences in flow curves course mainly for 100 and 90/10 slim waste suspension were observed, especially in low range of share rate. This compares also fitting rheological models (Tab. 3), and course of viscosity curves (Fig. 5–7).

TABLE 3

Rheological formulas with determination ratio for investigated suspensions

Sample	Rheological model	Rheotest	R^2, [%]	Brookfiled DV III	R^2, [%]	Physica Antoon Paar	R^2, [%]
100/0	Bingham	τ_o – 20.3 Pa η_p – 31.8 mPa·s	73.9	τ_o – 11.5 Pa η_p – 19.6 mPa·s	94.4	τ_o – 12.5 Pa η_p – 0.26 Pa·s	47,5
	Casson	τ_o – 17.85 Pa η_p – 4.57 mPa•s	93.1	τ_o – 10.0 Pa η_p – 2.28 mPa·s	94.5	τ_o – 10.11 Pa η_p – 0.065 Pa·s	70,2
	Ostwald de Waelle	k – 15.45 Pa·s n – 0.1	94.1	k – 7.941 Pa·s n – 0.12	94.4	k – 9.63 Pa·s n – 0.24	85,5
90/10	Bingham	τ_o – 8.86 Pa η_p – 26.2 mPa·s	94.1	τ_o – 5.31 Pa η_p – 9.9 mPa·s	96.0	τ_o – 8.08 Pa η_p – 0.065 Pa·s	89,8
	Casson	τ_o – 7.42 Pa η_p – 5.22 mPa·s	92.2	τ_o – 4.60 Pa η_p – 1.47 mPa·s	96.2	τ_o – 7.10 N/m η_p – 0.009 Pa·s	81,8
	Ostwald de Waelle	k – 6.37 Pa·s n – 0.14	71.4	k – 3.68 Pa·s n – 0.12	95.7	k – 6.68 Pa·s n – 0.13	89,8
80/20	Bingham	τ_o – 3.70 Pa η_p – 24.25 mPa·s	93.1	τ_o – 3.28 Pa η_p – 7.17 mPa·s	95.2	τ_o – 4.27 Pa η_p – 0.028 Pa·s	56,6
	Casson	τ_o – 2.86 Pa η_p – 7.31 mPa·s	80.1	τ_o – 2.75 Pa η_p – 1.28 mPa·s	95.7	τ_o – 3.81 Pa η_p – 0.004 Pa·s	63,3
	Ostwald de Waelle	k – 2.51 Pa·s n – 0.22	52.6	k – 2.07 Pa·s n – 0.15	95.4	k – 3.59 Pa·s n – 0.11	67,7
70/30	Bingham	τ_o – 1.29 Pa η_p – 22.55 mPa·s	92.2	τ_o – 0.62 Pa η_p – 3.35 mPa·s	95.8	τ_o – 1.61 Pa η_p – 0.014 Pa·s	90,9
	Casson	τ_o – 0.82 Pa η_p – 10.8 mPa·s	88.4	τ_o – 0.44 Pa η_p – 1.05 mPa·s	95.3	τ_o – 1.40 Pa η_p – 0.002 Pa·s	92,8
	Ostwald de Waelle	k – 0.79 Pa·s n – 0.35	59.3	k – 0.29 Pa·s n – 0.27	93.1	k – 1.33 Pa·s n – 0.13	89,6

Changes in water contain causes generally decreasing of shear stress and changes type of flow curve as following:

- Flow curve of high density suspensions (100% of slime waste) has two main courses depended on measuring system. With respect to the classical cylindrical measuring systems, Casson model with explicit yield point may be the best fit. In plate-plate system, the best fit were achieved for Ostwald de Waelle model, without yield point.
- For medium density suspensions (90/10: 90% of slime waste + 10% of water) Casson or Bingham models can be fitted, however Casson is more suitable because course of flow curve is not linear.
- Flow curves for low density suspensions (80/20 and 70/30) are best fitted for Bingham model with obvious yield point and linear course.

6. Summary and conclusions

The measurements of the rheological properties of slime waste suspensions with various solids content were carried out, with use three different viscometers, based on different measurement systems. The obtained results are presented in the form of flow curves and viscosity curves, and also presented the best matching to the three, the most popular rheological models. It was found that solids content in the slime waste suspensions is a key factor not only of the shear stress values for a specific shear rate, but also on the behaviour of such liquids. Depending on this factor the best fit of flow curves corresponds to different rheological models.

All suspensions have features of pseudoplastic liquids. This kind of liquids is characterized of distinct yield point and shear-thinning flow behaviour — with higher shear rates lower viscosity is apparent. It is particularly pronounced for those with higher solids contents (suspensions 100/0 and 90/10 with, respectively 38.5 and 34.65% of solid). Furthermore, in those suspensions thixotropic properties are revealed.

Measurements of rheological properties of multicomponent liquid, like these suspensions, require the inclusion of a number of factors. It turned out that even the use of sophisticated measuring equipment does not guarantee the same results, because they depend not only on the measuring system used, but also on the method and time of measurement, temperature and sample volume. The results obtained from three different measurement systems differ in absolute terms, despite a clear coincidence in the qualitative analysis.

Using measurement systems based on a larger sample volumes, and to account the best fit of results tor a specific rheological model seems be the best solution for engineering applications, e.g. designing of flow in pipelines. Nevertheless, the results of conducted calculations concerning e.g. flow resistances, based on such measurements should be reviewed and verify with at least semi-technical scale.

In the following research undertakings, the authors, will be seeking the best methods for the transformation of rheological characteristics different kinds of suspensions, obtained in laboratory measurements, to the real parameters of specific hydraulic flow.

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