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THE EFFECT OF HIGH SOLIDS CONCENTRATION ON THE RHEOLOGY OF LIMESTONE SLURRY

12.1 INTRODUCTION

Rheology is a science of deformation and flow of materials. The constitutive relations between shear stress and shear rate, and dependence of shear rate on viscosity are the base to solve the engineering problems. In many industry sectors used raw materials, semi-finished and finished products show non-Newtonian fluids characteristics. Number of non-Newtonian fluids that occur in a technological complex processes is growing very fast. This creates serious problems in processing and prompting fluids conducted with processes. It is particularly important to determine the rheological properties in the production process such as plastics, pharmacy, as well as in the environmental engineering and mining processes. Properties of non-Newtonian fluids may be completely determined by various types of rheometers [7].

Rheometric measurements of liquids demonstrate viscous and elastic features. Characteristics of the viscous properties refer to determination of flow curve, which is dependent on shear stress and shear rate.

In slurry composed of solid particles in a carrier liquid, the combination of the size and quantity of particles with the type of the transporting liquid determines the characteristics and flow properties of the hydro-mixture. Those factors can have a significant impact on performance and costs. Non-settling mixtures contain very fine particles that can form stable homogeneous system which require very careful consideration when selecting the correct pump. It is important that such slurries often do not behave in the manner of a pure liquid. When mixture has sufficient quantity of fine solids particles, it causes non-Newtonian behavior. Settling mixtures have a tendency to form an unstable system [3]. It is worth to mention that viscous properties are difficult to measure in an unstable system of settling particles [5].

One of the most important factors in slurry is a solids concentration which is often a variable value in manufacturing process. At limestone factory, where the slurry is a transported over long distances, it is important to determine the rheological properties of transported solid-liquid mixture. Different flow conditions and frictional losses require knowing properties due to choosing the right pump capacity used in hydrotransport. Moreover, particles in a carried liquid have a natural tendency for degradation and to settle when slurry is transported through a pipe. It is important to determine terminate velocity, which determines slurry velocity in a pipe, as slurry velocity supposes to be higher comparing to terminate velocity. If slurry velocity is below terminate velocity particles start forming a bed on the bottom of the pipe. This is undesired process because it can cause a pipe plugging. Remove of the blockage, even at a simple pipe system, is a very expensive incident, which could result a downtime in the production.

Considering the fact that the slurry can have different composition, there is a limited knowledge on concerning the limestone slurry rheological properties, especially when yield stress appears. Slurries with higher yield stresses require a higher initial input energy before the fluid starts to flow. Experience shows that rheological parameters should be measured for different mining because slurry components are always different.

It is observed that even small increments of the solids concentration bring the increase of the viscosity [9]. At high solids concentrations the particle-particle interactions increases, which cause a significant impact on the viscous properties [2]. Mostly in fine particle suspensions interparticles attraction could promote the formation of flocs. Hydrodynamic interactions give rise to viscous dissipation in the liquid [4], however, in some cases opposite result like turbulence damping could appears [1].

The main objective of the paper is to determine the flow curves for high solids concentration of slurry at limestone factory and to fit the proper rheological model.

12.2 EXPERIMENTS

12.2.1 Raw material

The raw material was obtained from "ZPW Trzuskawica" mine in Poland at the final stage of production, where the fine particles are carried by the water. At the mine the slurry is treated as a waste and finally deposited on the landfill.

Table 12.1 shows the chemical analysis of the limestone. The size distribution of the particles was measured using Sympatec Helos BR and the weighted-average particle diameter of the sample was determined to be 7.6 μm, [10].

Table 12.1 Chemical analysis of composition of the limestone slurry

Main chemical composition	Percent (%)
CaO	73.64
SiO_2	13
Al_2O_3	1.11
MgO	0.61
Fe_2O_3	0.319
SO_3	0.28

12.2.2 Experimental procedure

Procured raw material from manufacturing process has a low solid concentration. In order to obtain higher solids concentration, pure water was manually pulled above the sediment. Solids concentration (C_m) was calculated as a ratio of mass of solid particles (m_s) to total mass of slurry, which is sum of solid particles (m_s) and liquid phase (m_l). The solids concentration is described by equation (12.1). Evaporating of water from the slurry allowed us to determine the mass of solids while mass of liquid was determined by subtraction of mass of solids from the total mass of slurry (solids and liquid). Solids concentration varied from

C_m = 20% to C_m = 35% and was arbitrary chosen for the measurements. Such values of chosen solids concentration frequently exist in industry application.

$$C_m = \frac{m_s}{m_s + m_l} \cdot 100\% \tag{12.1}$$

Determination of the shear stress and viscosity was performed using the Anton Paar rheometer (model MCR 302). To provide accurate results it was important to choose a proper measuring system. We have decided that CC27 measuring system is appropriate for such slurry. It uses concentric cylinder geometry with stationary outer cylinder and rotating inner cylinder with a gap equal 1.1 mm. This measuring system requires about 18 ml of a sample. Experiments were performed at temperature of 20°C with accuracy of ± 0.01°C.

We observed phase separation in the experiments above the critical shear rate. Similar results were obtained in silica sand based suspensions [8]. Schramm noticed that the inertia forces push the solid particles in the direction of the outer cylinder [11]. Besides, in the cylinder-cylinder measuring system above the critical shear rate value the turbulent flow appears and that phenomenon interfere with the measurement results. Above critical shear rate value shear stress start to grow significantly. For the C_m = 20% this phenomena was observed around the 385-390s^{-1} shear rate. If C_m increases the critical shear rate increases too, which fig. 12.1 demonstrates. Therefore, considering the nature of the slurry, our measurements were analyzed at the shear rates from 0.001s^{-1} to 380s^{-1}.

To avoid sedimentation process, which naturally exists in such a type of slurry, each slurry sample was pre-sheared for 1 minute at the 1000s^{-1} shear rate prior to the measurements. Afterwards, measurements started from the higher shear rate value (380s^{-1}) and stepped down linearly one by one until the shear rate reaches the minimum setpoint value (0.001s^{-1}). The results of measured shear stress (τ) and viscosity (η) were recorded at each share rate (□) and analyzed afterwards.

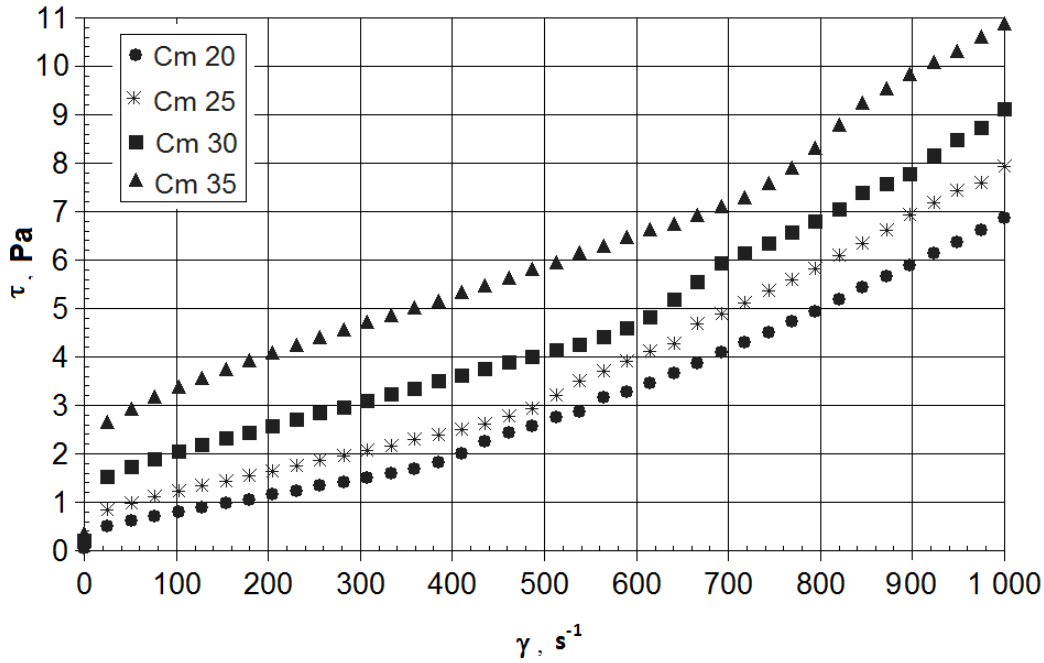

Fig. 12.1 Occurrence of the phase separation at different solids concentration

12.2.3 Experimental results and discussion

For each solid concentration the variation of the shear stress with the shear rate was recorded. Fig. 12.2 shows flow curves for the C_m = (20-35)%. For all solids concentrations flow curves are non-Newtonian. It is worth mentioning that for higher shear rate values flow curves looks like Newtonian, but non-Newtonian behavior was visible in the range of (0-20) s^{-1} shear rate. There was a considerable fall in shear stress in that range.

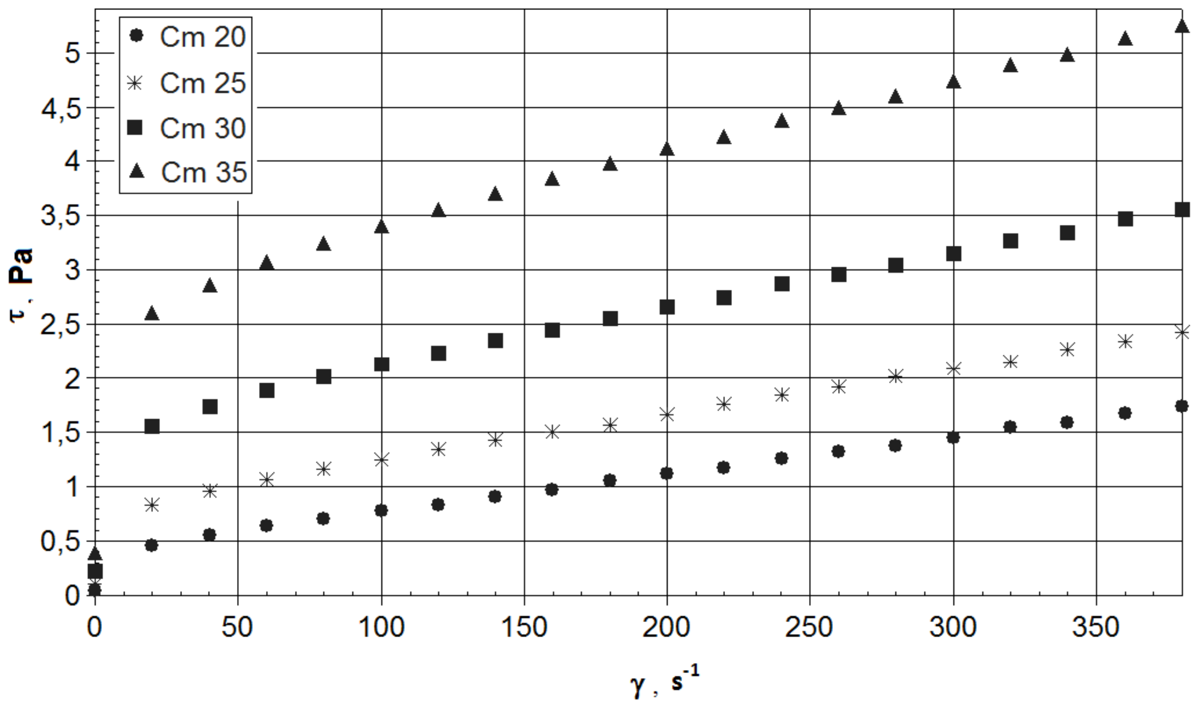

Fig. 12.2 Dependence of the shear rate on shear stress at different solids concentration

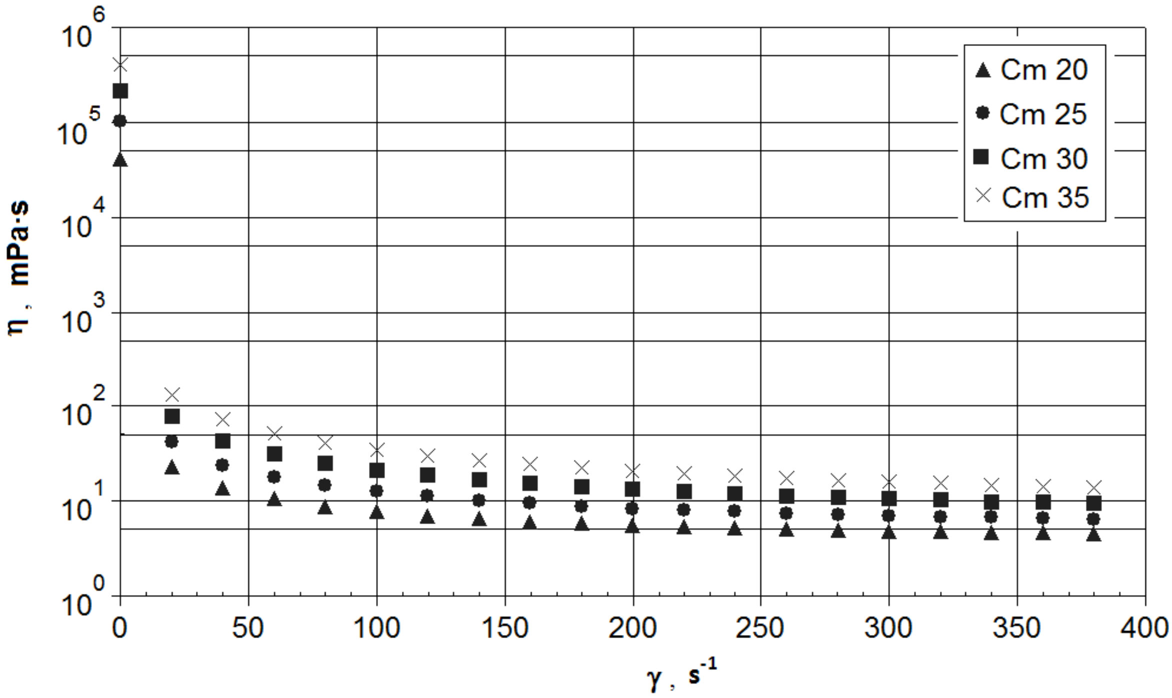

Fig. 12.3 Dependence of the shear rate on viscosity at different solids concentration

It was observed that the shear stress increased with increase of shear rate for all cases. The results indicate a pseudoplastic behavior of limestone slurry. It can be also seen that the shear stress and yield stress increased with the increase of solids concentration.

The variation of viscosity with shear rate at different solids concentration is shown on fig. 12.3. The curves indicating the viscosity are non-Newtonian. Viscosity is decreasing with increase of shear rate for all solids concentrations (shear thinning) and there is a considerable fall between $0.001s^{-1}$ and $20s^{-1}$ shear rates in all cases. For a very low shear rate values of viscosity are extremely high. Slurry behavior is similar to a solid body. This is a result of the particle-particle contact that brings the interactions at high solids concentrations [4]. It can be also seen that the viscosity increases with increase of solids concentration.

Comparing the results to low and medium solids concentration in the limestone slurry, the results are unequivocal [10]. Shear stress values at low and medium concentration are considerably lower and have tendency to follow Newtonian liquids. Moreover, the shear stress value for C_m = 5% at $160s^{-1}$ shear rate is more than ten times smaller in comparison to results for C_m = 35%.

Table 12.2 Herschel-Bulkley parameters for test performed at C_m=20-35%

C_m	20%	25%	30%	35%
τ_0 (Pa)	0.039154	0.095635	0.1738	0.24704
η_{pl} (Pa·s)	0.074889	0.17534	0.45777	0.94343
n	0.50961	0.42102	0.32512	0.27091

Viscosity values at high solids concentration in the limestone slurry are also higher comparing to low and medium solids concentration.

Various rheological models were analyzed in an attempt to find the model that best fit the experimental data of the shear stress. On the base of analyzes the Herschel-Bulkley model achieved the best fitting (R^2 = 0.97). Parameters of the Herschel-Bulkley rheological model for performed experiments at different solids concentration are listed in table 12.2, fig. 12.4 and fig. 12.5 show a comparison of the Herschel-Bulkley fit for C_m = (20-35)%.

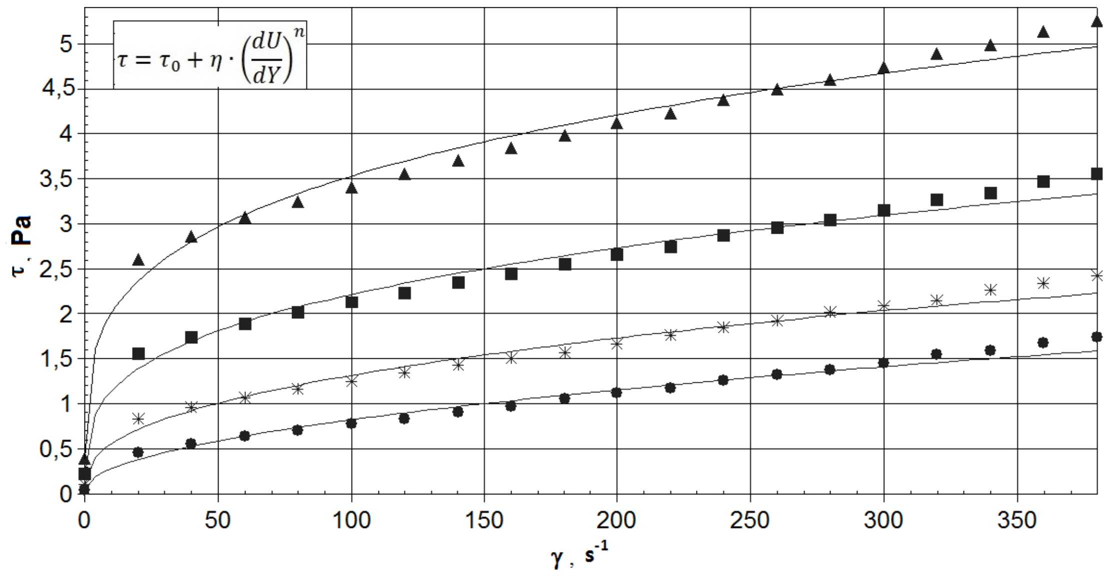

Fig. 12.4 The Herschel-Bulkley model fit to shear stress for different solids concentration

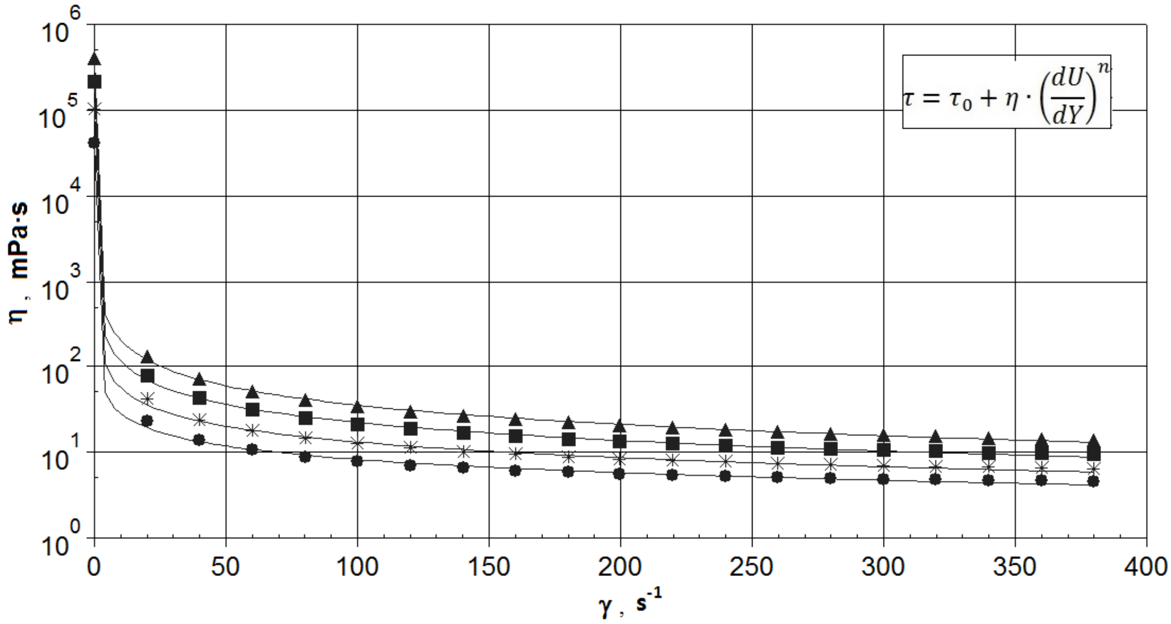

Fig. 12.5 The Herschel-Bulkley model fit to viscosity for different solids concentration

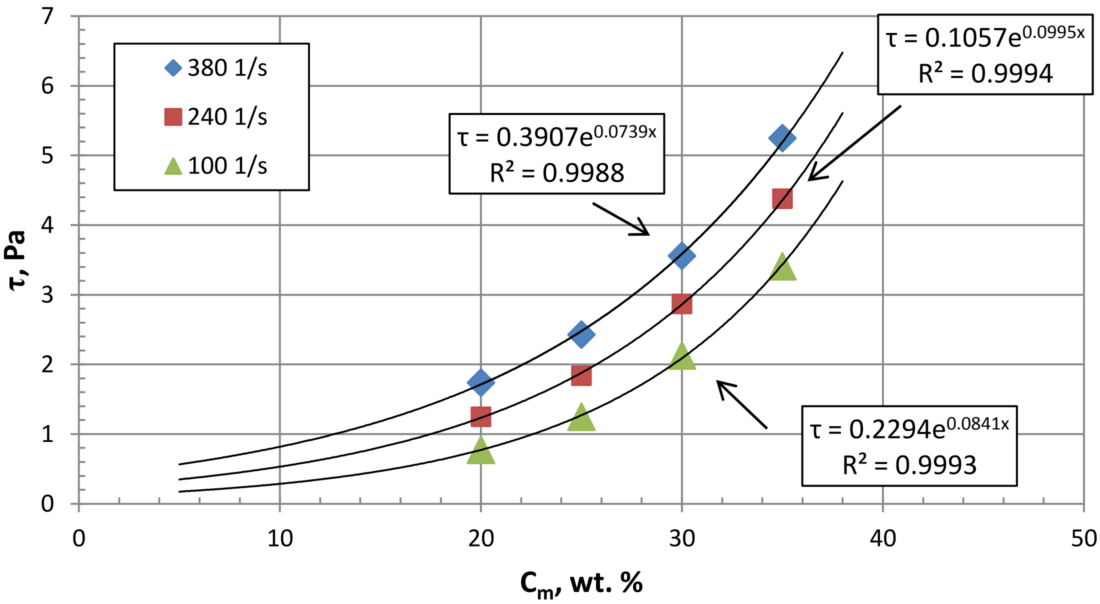

Fig. 12.6 Dependence of solids concentration on the shear stress for a given shear rate

The shear stress of the limestone slurry increases exponentially with increasing the solids concentration. Fig. 12.6 shows dependence of solids concentration on the shear stress at $100 s^{-1}$, $240 s^{-1}$, $380 s^{-1}$ shear rate values.

The viscosity of the limestone slurry also increases exponentially with increasing the solids concentration which is shown in fig. 12.7.

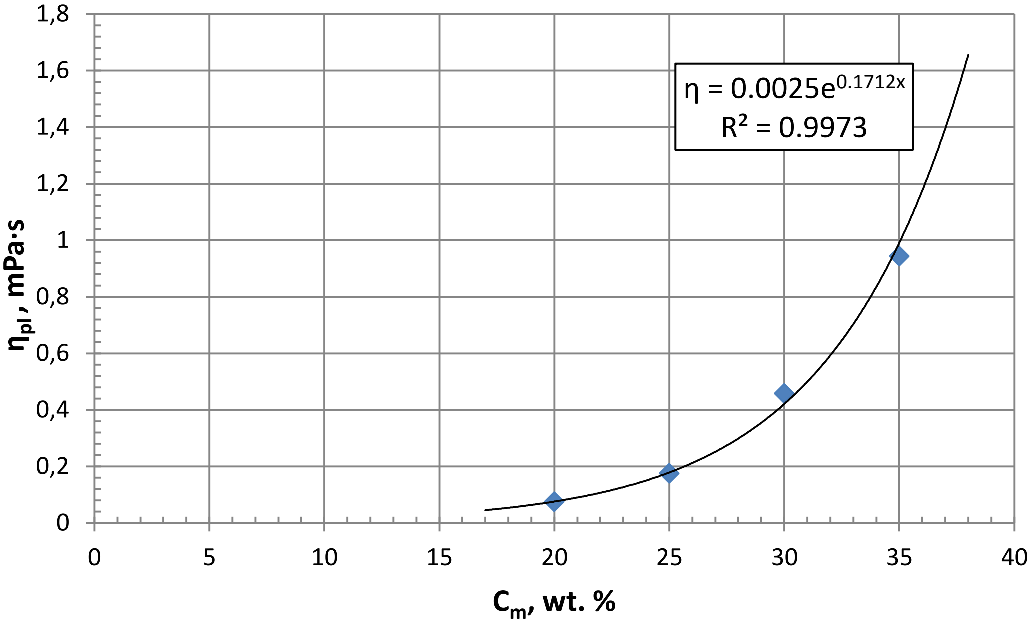

Fig. 12.7 Dependence of solids concentration on plastic viscosity

CONCLUSION

The effects of high solids concentration on the rheological behavior of limestone slurries have been examined. It was noticed during experiments that turbulent flow and phase separation appeared for C_m = 20% above 380s^{-1} shear rate and its tendency was the same with increase of solids concentration. Therefore, measurements were performed at the shear rates from 0.001s^{-1} to 380s^{-1}.

The flow curves are non-Newtonian in chosen range of solids concentration, (20-35)%. A shear thinning behavior was observed at all solids concentrations. It was also observed that the shear stress increased exponentially with increase of solids concentration in all cases. For the slurry from ZPW Trzuskawica mine the Herschel-Bulkley rheological model achieved best fitting and well described flow curves and viscosity. The viscosity increased exponentially with increase of solids concentration due to the frictional interactions per unit volume. The yield stress also increased with solids concentration.

High solids concentration gives considerably higher values of shear stress and viscosity than low and medium solids concentration at the same shear rate.

REFERENCES

1. Bartosik, A.: Laminarisation effect in fine-dispersive slurry flow. Archives of Thermodynamics. vol. 29. No.3, 2008, pp. 69-82.
2. Bartosik A.: Simulation and Experiments of Axially-Symmetrical Flow of Fine- and Coarse-Dispersive Slurry in Delivery Pipes. Monograph M-11. Kielce University of Technology 2009.
3. Benretem A.: Benidir M., Chaib R.: Factors Influencing Slurry Rheology. World Pumps, July 2010, p. 30-32.
4. Cheng.: Viscosity-Concentration Equations and Flow Curves for Suspensions. Chemistry and Industry. vol. 17, 1980, pp. 403-406.

5. Clarke B.: Rheology of Coarse Settling Suspensions. Trans. Inst. Chem. Engrs. vol. 45, 1967, pp. 251-256.
6. Ferguson J., Kembłowski Z.: Reologia stosowana płynów. DWN. Lódź 1995.
7. Kiljański T., Dziubiński M., Sęk J., Antosik K.: Wykorzystanie pomiarów właściwości reologicznych płynów w praktyce inżynierskiej. EKMA. Warszawa 2009.
8. Mangesana N., Chikuku R.S., Mainza A.N., Govender I., Westhuizen A.P., Narashima M.: The Effect of Particle Sizes and Solids Concentration on the Rheology of Silica Sand Based Suspensions. The Journal of The Southern African Institute of Mining and Metalurgy. vol. 108, 2008, pp. 237-243.
9. Rutgers R.: Relative Viscosity and Concentration. Rheologica Acta, vol. 2, 1962, pp. 305-348.
10. Sarnecki K., Bartosik A.: The Effect of Low and Medium Solids Concentration on the Rheology of Limestone Slurry, (in printing).
11. Schramm G.: Reologia. Podstawy i zastosowanie. OWN. Poznań 1998.
12. Shi F.: Slurry rheology and its effects on grinding. PhD Thesis. Julius Kruttschnitt Mineral Research Centre. University of Queensland 1994.

THE EFFECT OF HIGH SOLIDS CONCENTRATION ON THE RHEOLOGY OF LIMESTONE SLURRY

Abstract. *The paper deals with solid-liquid limestone slurry with a high solids concentration, which appears widely in a mining and civil engineering industries. Experiments performed in the paper deal with influence of solids concentration on the shear stress. Solids concentration various from 20% wt. to 35% wt. which is most suitable to industry. The main objective of the paper is to determine the flow curves for high solids concentration of slurry at limestone factory and to fit the proper rheological model. The paper proves that most suitable model which fits measured dependence of shear rate on the shear stress is the Herschel-Bulkley rheological model. The exponential increase of shear stress and plastic viscosity with increasing the solids concentration is demonstrated for high solids concentration of limestone slurry.*

Key words: *limestone slurry, non-Newtonian slurry, shear stress in slurry, experiments in rheology*

WPŁYW WYSOKIEJ KONCENTRACJI FAZY STAŁEJ NA WŁASNOŚCI REOLOGICZNE HYDROMIESZANINY

Streszczenie: *W artykule przedstawiono wyniki badań dla wysokiej koncentracji fazy stałej hydromieszaniny wapiennej, która szeroko występuje w przemyśle wydobywczym i budowlanym. Przedstawiono badania wpływu koncentracji fazy stałej na naprężenie styczne. Masowa koncentracja fazy stałej zmienia się od 20% do 35%, co odpowiada warunkom przemysłowym. Celem artykułu jest wyznaczenie krzywych płynięcia dla wysokiej koncentracji fazy stałej w hydromieszaninie oraz dopasowanie właściwego modelu reologicznego. W pracy udowodniono, że najlepsze dopasowanie do mierzonych zależności naprężenia stycznego od szybkości ścinania daje model reologiczny Herschela-Bulkleya. Ukazano również, że dla wysokich koncentracji fazy stałej w hydromieszaninie wraz ze wzrostem koncentracji fazy stałej lepkość i naprężenie styczne rosną wykładniczo.*

Słowa kluczowe: *hydromieszanina wapienna, hydromieszanina nienewtonowska, naprężenie ścinające w hydromieszaninie, badania reologiczne*.

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