CZASOPISMO TECHNICZNE M
WYDAWNICTWO POLITECHNIKI KRAKOWSKIEJ

z. 5-M/2008
ISSN 0011-4561
ISSN 1897-6328

JIŘÍ MORAVEC, FRANTIŠEK RIEGER*

RHELOGICAL BEHAVIOR OF HIGH--CONCENTRATED FINE-GRAINED SUSPENSION

REOLOGICZNE WŁASNOŚCI DROBNOZIARNISTYCH ZAWIESIN O DUŻYM STĘŻENIU

A b s t r a c t

The high-concentrated and fine-grained suspensions are often met in different industries. The rheological behavior of these suspensions is different from behavior of suspensions with low concentration of solid phase or with bigger particles. The behavior of the suspensions is frequently described as viscoplastic. In this paper, newly proposed combined Bingham model is used for description of rheological behavior of chalk suspension in wide range of shear rates. The change in rheological behavior with change of solid phase concentration is determined on the basis of model parameters change. The effect of flow enhancing substance on the behavior of suspension is also shown.

Keywords: rheology, high-concentrated suspension, fine suspension, combined Bingham model

S t r e s z c z e n i e

Drobnoziarniste zawiesiny o dużym stężeniu są często stosowane w przemyśle. Własności reologiczne takich zawiesin różnią się od własności suspensji o niskim stężeniu lub cząstek lub zawierających większe cząstki. Własności suspensji określane są jako lepkoplastyczne. W artykule zaproponowano nowy, złożony model Binghama do opisu własności reologicznych zawiesiny kredy. Zmiany własności reologicznych zawiesiny wraz ze zmianą stężenia określano na podstawie zmian parametrów modelu. Wykazano wpływ wzrostu intensywności przepływu na zachowanie się suspensji.

Słowa kluczowe: reologia, zawiesiny o wysokim stężeniu, zawiesiny drobnoziarniste, złożony model Binghama

* Ing. Jiří Moravec, Prof. Ing. František Rieger, DrSc.,
Ústav procesní a zpracovatelské techniky, České vysoké učení technické v Praze.

1. Introduction

The high-concentrated and fine-grained suspensions are often met in different industries. The rheological behavior of these suspensions is different from behavior of suspensions with low concentration of solid phase or with bigger particles. The behavior of the suspensions is frequently described as viscoplastic. In this paper, newly proposed combined Bingham model is used for description of rheological behavior of chalk suspension in wide range of shear rates. The change in rheological behavior with change of solid phase concentration is determined on the basis of model parameters change. The effect of flow enhancing substance on the behavior of suspension is also shown.

2. Theory

The rheological behavior of high-concentrated fine-grained suspensions can be measured in rotational viscometer with coaxial cylinders. The dependence of shear stress τ_1 on the Newtonian shear rate $\dot{\gamma}_{1N}$ at the radius of inner cylinder is usually obtained from measurements. Most of the suspensions behave like viscoplastic fluids and the simplest model describing this behavior is the Bingham model

$$\dot{\gamma} = 0 \quad \text{for} \quad |\tau| \le \tau_0 \tag{1a}$$

$$\tau = \left(\mu_p + \frac{\tau_0}{|\dot{\gamma}|} \right) \dot{\gamma} \quad \text{for} \quad |\tau| \ge \tau_0 \tag{1b}$$

where μ_p is plastic viscosity and τ_0 stands for yield stress.

The parameters of the model must be recalculated from measured data with respect to the size of the gap between the inner (rotating) and outer (stationary) cylinders. There exist two possibilities, how to calculate the parameters of the Bingham model from measured data. These ways can be found in [1].

For many suspensions the two Bingham models must be used for description of rheological behavior in wide range of shear rates. The first model with parameters τ_{01} and μ_{p1} holds at low shear rate values and the second model with parameters τ_{02} and μ_{p2} relates to high shear rates. The following relation was proposed for rheological behavior description in the whole measured shear rate range in the work [1]

$$\tau = \frac{\tau_{01} + \mu_{p1}\dot{\gamma}}{\left[1 + \left(\dfrac{\tau_{01} + \mu_{p1}\dot{\gamma}}{\tau_{02} + \mu_{p2}\dot{\gamma}} \right)^{b} \right]^{1/b}} \tag{2}$$

The adjustable parameter b characterizes the transition between both models. Thanks to the model, effective viscosity can be determined without necessity of knowledge of shear rate region. Moreover practical measurements take place in the transition region very often and then the model simplifies determination of the viscosity.

3. Experimental

The rheological experiments were carried out using rheometer RC20 (RheoTec) with coaxial cylinders whose diameters ratio was κ = 0,98 (configuration CC48). The rheometer was controlled by PC and the measurements were done automatically according to a predefined measure program of shear rate course.

The tested suspensions were created from water and chalk. The mean volumetric particle diameter of chalk was d_p = 6 μm and it was received from particle size distribution obtained from measurements in particle size analyzer A22 Compact (Fritsch). The distribution is shown in Fig. 1. The density of chalk was ρ_s = 2580 kg·m^{-3} and the mean volumetric concentration of the solid phase changed in range from 25% to 40%.

During the experiments, effect of NaCl in the suspension was also observed. Therefore, all concentrations were measured without and with 5% b. w. of NaCl in liquid phase.

It is very problematic to prepare the suspension properly in case of fine-grained suspensions. Fine particles create aggregates when they are added into the liquid. But it is necessary to destroy these aggregates because they can markedly change the rheological behavior of the suspension. This is a problem especially in case of highly concentrated suspensions, where the aggregates are difficult to destroy. Therefore, in our experiments the suspensions were prepared by gradual adding of chalk into the batch mixed by a sawtooth high shear stress impeller. After adding all necessary solid phase for a given concentration, the batch has been dispersed for several minutes in addition.

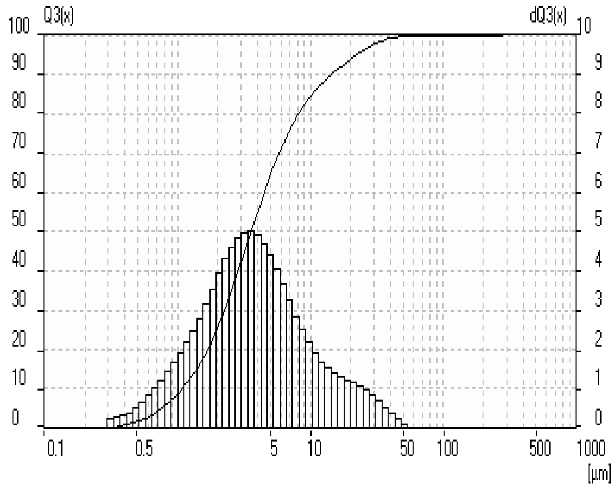


Fig. 1. Particle size distribution of chalk

Rys. 1. Skład ziarnowy kredy

Another problem can occur during measurements of rheological behaviour using rotational viscometer. The particles in the suspension can settle down during the measurements and the results can then be irregular. In case of highly concentrated suspension it isn't such a problem, as it can be seen from Fig. 2, where the dependence of solid cloud height on time is shown. The particles practically didn't settle during the rheological experiments, which took max 40 minutes.

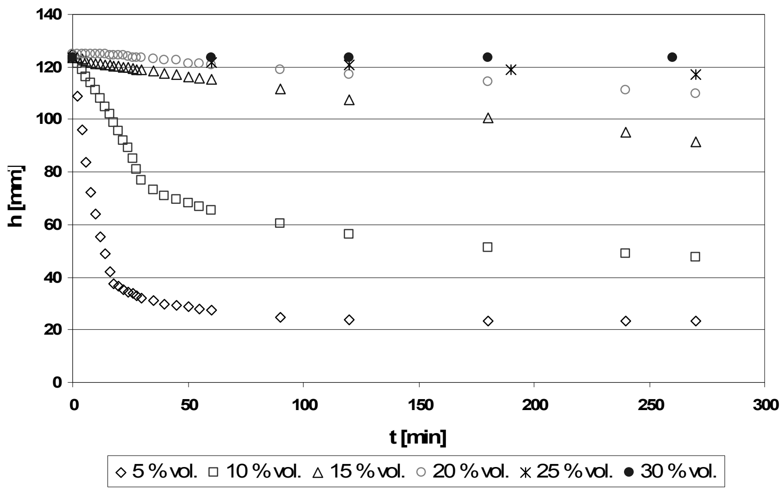


Fig. 2. Dependence of solids cloud height on time

Rys. 2. Zależność wysokości zawiesiny od czasu

4. Experimental results and discussion

The process of each experiment was controlled by predefined program of shear rate course. This course was set up by the following way. Firstly the shear rate was increasing from the lowest to the highest value. Immediately after reaching the highest value, the shear rate was again decreasing from the highest to the lowest value. This process was repeated twice for each suspension so that four dependencies of rheological behavior of one suspension were obtained.

The illustration of measured data for suspensions with 25% resp. 40% of solid phase is shown in Fig. 3. In case of low concentration the values of τ_1 obtained during increasing of shear rate (steps 1 – squares and 3 – triangles) are higher then the values obtained during decreasing way (steps 2 – diamonds and 4 – circles). The difference was observed at high shear rates only. At low share rates all measured points fell in the same dependence. This was probably caused by short time set for measurement of particular points (10 s). The difference between data obtained during increasing and decreasing values of shear rate were decreasing with growing amount of solid phase in suspension. At the highest concentrations there was only difference in the first step of increasing of shear rate while all other steps fell in the same dependence.

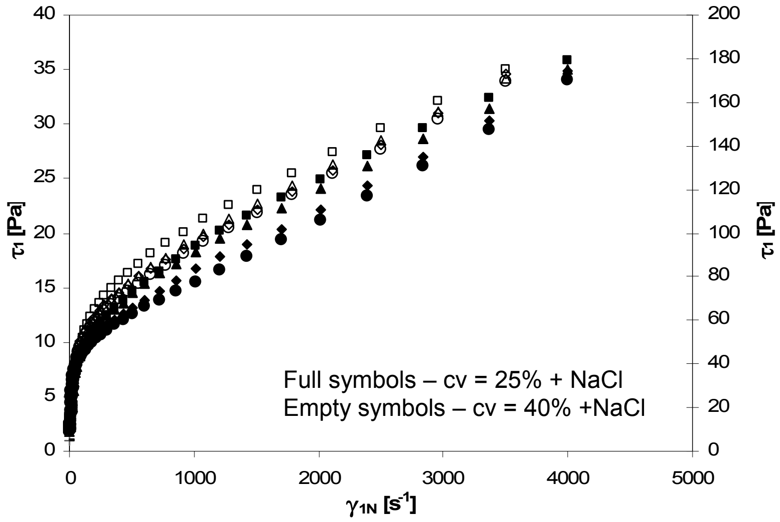


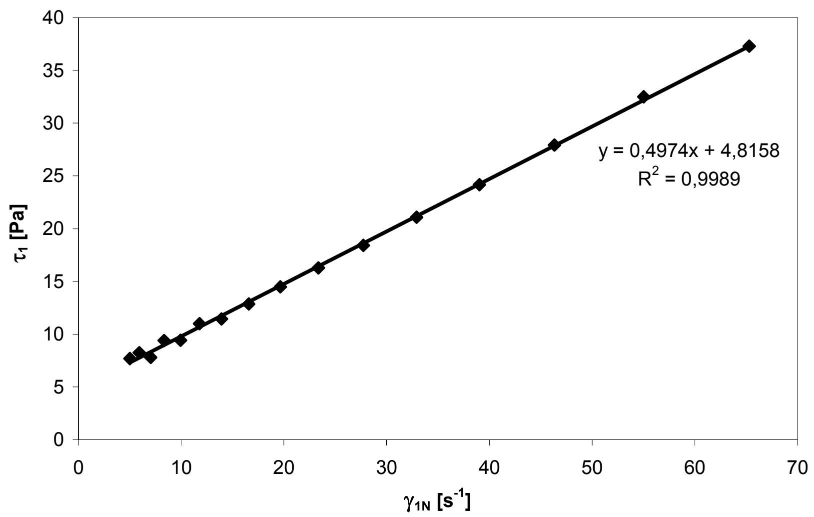
Fig. 3. Rheological measurement of suspensions with 25% resp. 40% of solid phase

Rys. 3. Własności reologiczne zawiesiny o zawartości 25–40% ciała stałego

Each measured dependence of shear stress on shear rate (each step) was handled separately. Parameters of two Bingham models (one in low shear rate region and one in high sear rate region) and also the parameter *b* characterizing the transition region were determined. The effect of cylinder diameter ratio was considered too. Final parameters for each suspension were obtained as an average value of values in all four measured steps.

The linear regression of dependence of shear stress on shear rate at regions of low (upper) and high (lower) shear rate values are shown for illustration in Fig. 4. The sense of parameter *b* can then be seen from Fig. 5, where the combined Bingham model is used for description of rheological behavior of suspension with 30% of solid phase.

Final comparison of rheological behavior of suspensions with different concentration of solid phase and also with and without NaCl in water is shown in Fig. 6. Parameters of the combined Bigham model for all tested suspension are mentioned in Table 1. It can be clearly seen what effect has the presence of NaCl in water on rheological behavior of the suspension. If NaCl is present, the values of yield stress are about 50–70% lower than in case without NaCl. Also parameter *b* has lower values, which means that the transition region between two Bingham models is narrower. The plastic viscosity is practically not influenced by the presence of NaCl (at the highest solids concentration in suspension without NaCl the measurement stopped in transition region). This substance has thus very positive effect on flow enhancement of the chalk suspension. From the results it can be also seen how the values of all parameters increase with increasing amount of solid phase.



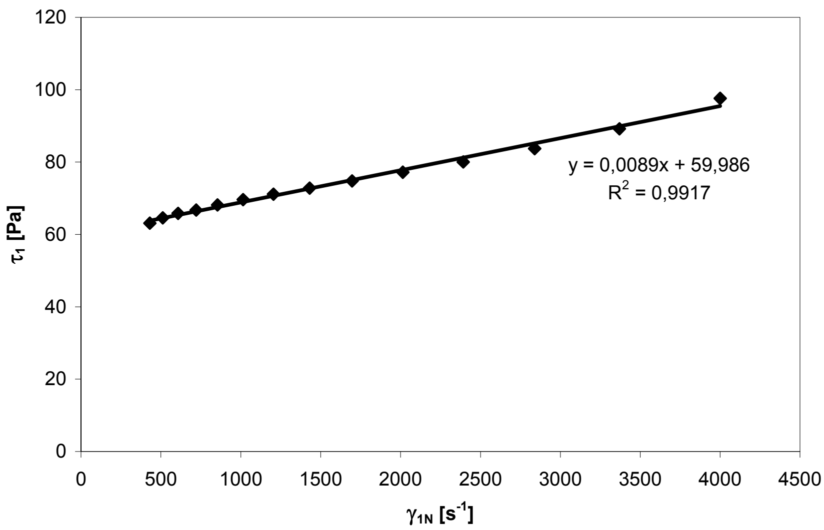


Fig. 4. Linear regression of data at low (upper) and high (lower) share rates – concentration c_v = 30%

Rys. 4. Regresja liniowa wyników dla niskich (dolne) i wysokich (górne) prędkości ścinania – stężenie c_v = 30%

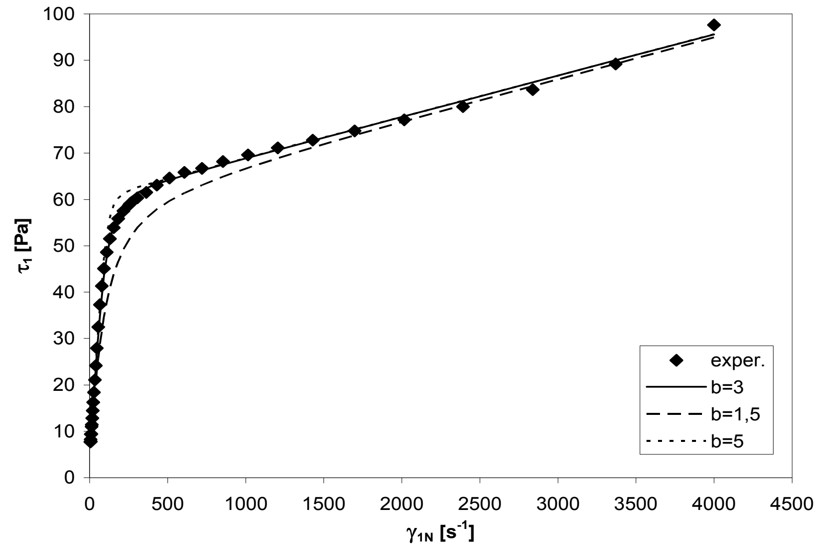


Fig. 5. Rheological behavior of chalk suspension with 30% vol. of solid phase

Rys. 5. Reologiczne zachowanie zawiesiny kredy o zawartości 30% ciała stałego

Table 1

Parameters of the combined Bingham model of all tested suspensions

	Without NaCl				With NaCl			
c_v [%]	25	30	35	40	25	30	35	40
μ_{p1} [Pa·s]	0,2459	0,3946	0,5473	0,6569	0,2861	0,4591	0,5248	0,7064
τ_{01} [Pa]	1,91	3,71	6,91	14,09	0,97	1,69	3,75	5,59
μ_{p2} [Pa·s]	0,0048	0,0077	0,0150	0,1747	0,0058	0,0092	0,0141	0,0302
τ_{02} [Pa]	35,49	71,38	110,52	121,28	11,15	19,26	35,86	65,47
b [-]	2,4	2,7	3,3	10,5	1,4	1,5	1,9	1,9

5. Conclusions

Rheological parameters of highly concentrated fine-grained suspensions can be measured in rotational viscometers. New combined Bingham model can be used for description of the behavior in wide range of shear rates. The parameters of the model must be evaluated considering the size of the gap between diameters of inner and outer cylinder. The parameters of the combined model for description of rheological behavior of chalk suspension were determined and their change with change of solids concentration can be described. It was also shown that NaCl markedly improves flow parameters of chalk suspension and it can serve as a flow enhancer.

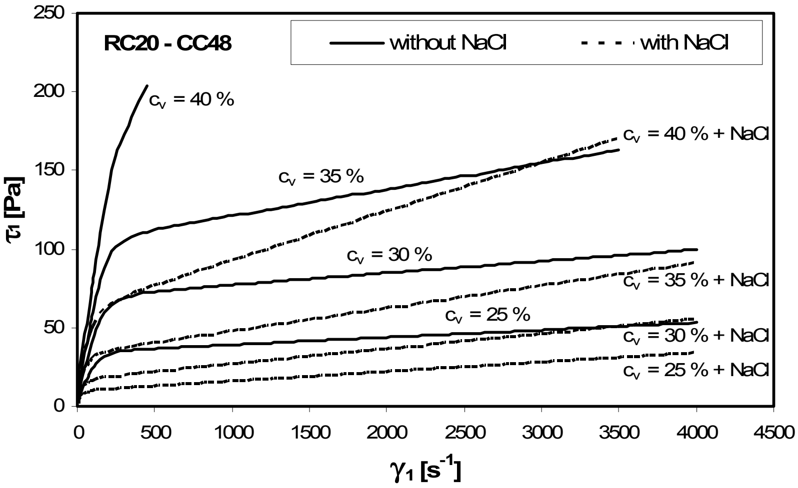


Fig. 6. Rheological behavior of chalk suspension with different amount of solid phase

Rys. 6. Reologiczne zachowanie zawiesiny kredy o różnej zawartości ciała stałego

Symbols

b	–	parameter of the combined Bingham model (eq. 2)	
h	–	height of particles cloud	[m]
R_1	–	inner rotating cylinder radius	[m]
R_2	–	outer stationary cylinder radius	[m]
t	–	time	[s]
$\dot{\gamma}$		shear rate	[1/s]
$\dot{\gamma}_{1N}$		shear rate of Newtonian fluid at radius R_1	[1/s]
κ		R_1/R_2 ratio	
μ_p		plastic viscosity	[Pa·s]
μ_{p1}		plastic viscosity of the first model	[Pa·s]
μ_{p2}		plastic viscosity of the second model	[Pa·s]
τ		shear stress	[Pa]
τ_0		yield stress	[Pa]
τ_{01}		yield stress of the first model	[Pa]
τ_{01}		yield stress of the second model	[Pa]

References

[1] Rieger F., Moravec J.: *Rheometry of the Fine Concentrated Suspensions. Teoretičeskie osnovy sozdanija, optimizacii i upravlenija energo-i resursosberegajuščimi processami i oborudovaniem*, Sbornik trudov, Ivanovo 2007, 75-83.