International Conference
ENGINEERING MECHANICS 2010
Svratka, Czech Republic, May 10 – 13, 2010

EFFECT OF DENSE SLURRY COMPOSITION ON ITS FLOW BEHAVIOUR IN HORIZONTAL PIPE

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Summary: *The paper deals with experimental investigation of the dense fine-grained slurries focused on the slurry pressure drops versus average velocity relationship. The content of fine, especially colloidal solid particles evokes a complex non-Newtonian behaviour of the slurry. Flow behaviour of dense slurry depends on particle size distribution, shape, density and chemical composition of the solid phase as well as on concentration of solids and carrier liquid properties. The re-circulation pipe loop with horizontal hydraulically smooth stainless steel pipes was used for measuring the slurry flow parameters. Different slurries containing kaolin, stony dust or sand conveyed in water were measured to document effect of the size distribution and chemical composition on the slurry flow behaviour.*

1. Introduction

The paper deals with the effect of particle size distribution and volumetric concentration on flow behaviour of slurries containing colloidal, clay, dust and also coarse-grained particles. It presents the results of experimental investigation of sand, stony dust and clay slurries.

The flow behaviour of dense slurries with colloidal particles is strongly affected by the mutual particle-particle and particle-liquid interactions, by the attractive and the repulsive forces acting between solid particles in the slurry. After mixing of fine-grained particles, especially colloidal particles, with water attractive forces between particles initiate the slurry coagulation. During the slurry flow, shear-induced translation and rotational motions of the particles cause hydrodynamic interactions resulting in the increase of viscous energy dissipation and the slurry apparent viscosity. Inter-particle interactions of non-hydrodynamic origin are the most significant in systems with colloidal particles and usually evoke non-Newtonian behaviour of the slurry. In the highly concentrated fine-grained suspensions both types of the interactions are present.

For the higher slurry concentration and contents of colloidal particles voluminous aggregates with a loose structure, where a large deal of water is fixed, are formed and a viscous friction can act only in a small-scale. More energy is consumed on the aggregate deformation. The higher the contents of colloidal or very fine particles, the greater the tendency of slurry to coagulate. An intensive turbulent shearing or addition of coarse particles

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often results in the destruction of the aggregates. Water originally fixed in aggregates is liberated and the slurry becomes peptized, the viscous friction can play a larger role - an apparent viscosity decreases and the slurry is liquefied (Vlasak et al., 1999, 2002b).

2. Experimental material and equipment

Experimental values of the slurry velocity V_s, volumetric transport concentration c_v, and hydraulic gradient i_s were determined from the measured values of the flow-rate, pressure drops, and slurry density. The hydraulic gradient i_s versus slurry velocity V_s relationship (i_s / V_s relationship) makes possible to compare the flow behaviour of slurries, which differ mutually by solid contents and concentrations.

The particle size distributions of the measured materials differ significantly. Three kinds of quartz sand of uniform size distribution from Provodin (d_{50} = 0.2, 0.7 and 1.4 mm, ρ_s = 2650 kg/m^3) and natural polydisperse sand Zavada (d_{50} = 0.3 mm, ρ_s = 2650 kg/m^3) were used as experimental material for sand slurries investigation. Volumetric concentration c_v of the sand slurries varied from 6 to 45%. Zavada natural sand (d_{50} = 0.35 mm, d_{max} = 9 mm, ρ_s = 2 650 kg/m^3) is significantly different, it is a coarse-grained relatively narrow-sized natural sand with content of sand particles about 91 %. The content of gravel particles is only 4 % and dust and clay particles about 5 %. In contrast to the stone dust or quartz sand the Zavada sand particles have smooth surface.

Kaolin from Horni Briza (d_{50} = 2.8 µm, ρ_k = 2546 kg/m^3) was added to sand-water slurry to create non-Newtonian carrier liquid. To compare the effect of Newtonian and non-Newtonian carrier, a chemical agent with peptizing effect was used to change physical-chemical behaviour of the slurry and to suppress attractive inter-particle forces, which evoke non-Newtonian behaviour of the slurry.

Stony dust from quarry Bohuchovice (d_{50} = 33 µm, d_{max} = 2 mm, ρ_s = 2 679 kg/m^3) is the fine-grained dust material with high content of dust particles (61%) and clay particles (10%). Due to the high content (71%) of particles less than 63 µm the hydro-mixture will be the non-Newtonian slurry with significant yield stress. To obtain the optimal flow behaviour, stony dust was mixed with Zavada sand. Water was used as the carrier liquid. Volumetric concentration reached up to about 50 %. Composition (i.e. mass contents of dust and sand), slurry densities ρ_s, and volumetric transport concentration c_v of the individual measured slurries of Bohuchovice stone dust and its combination with Zavada sand are listed in Table 1.

Table 1 Density ρ_s and volumetric transport concentration c_v of the measured slurries of Bohuchovice stony dust and Zavada sand

material	Bohuchovice 100 : 0	Bohuchovice/ Zavada sand 79 : 21	Bohuchovice/ Zavada sand 50 : 50	Bohuchovice/ Zavada sand 40 : 60
ρ_s [kg/m^3]	1815	1745	1828	1850
c_v	0.485	0.445	0.498	0.512
ρ_s [kg/m^3]	1765	1813		
c_v	0.456	0.486		

All studied slurries were due to the high content of clay and dust particles relatively homogeneous with significantly non-Newtonian behaviour. Particle size distribution of the material used is illustrated in Figure 1.

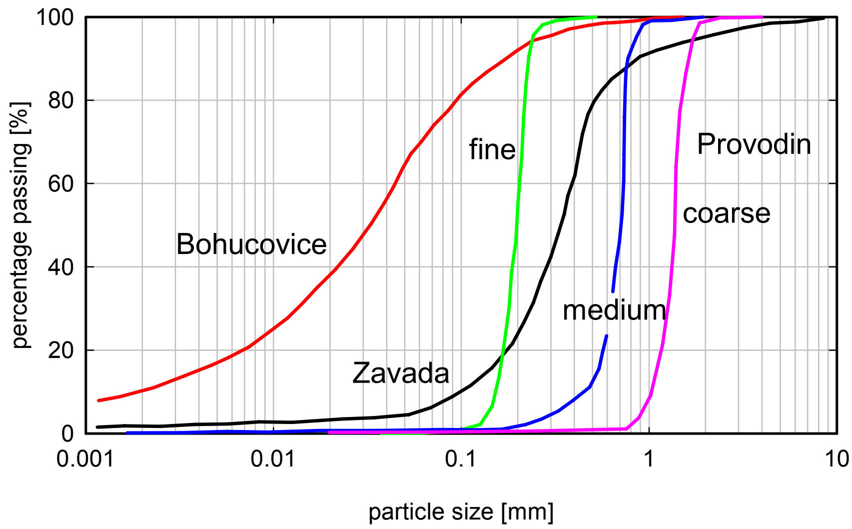


Figure 1 Particle size distribution of materials used

The studied slurries flow parameters were measured on the experimental re-recirculation pipe loop with smooth stainless steel pipes of diameter D = 26.8 mm (Vlasak & Chara, 2001). The slurry was forced by EPS-125-6-60 screw pump from an agitated open storage tank to the transport pipe. Phase advancer was used to reach the different slurry flow rate. The measurement section was equipped with three pressure tapings connected with the Hottinger-Baldvin PD-1 differential pressure transducers monitored by a computer. The slurry flow-rate and concentration were measured by the electro-magnetic flow-meter KROHNE-PROFILUX IFM 5080 K A and the mass flow-meter KROHNE-CORIMASS-800 G+. The loop also allowed the direct measurement of mass flow rate and of slurry density. The temperature of the slurry was maintained at about 18 °C by the heat exchanger situated at the beginning of the transport pipe. The loop can operate in the laminar as well as turbulent regime, the maximum average slurry velocity $V_{s,max}$ reached value up to 8 m/s.

3. Results and Discussion

The effect of the average slurry velocity V_s and concentration c_v on the hydraulic gradient i_s versus slurry velocity V_s relationship of different sand slurries is illustrated in Figures 2 and 3. The effect of particle size distribution depends on the slurry velocity and concentration. The coarse sand slurry reaches higher hydraulic gradient i_s than the fine sand slurry, the difference decreases with the increasing velocity.

Some attributes of a non-Newtonian behaviour can be found for the sand slurries of concentration higher than $c_v \approx 20$ %. The pressure gradient tends to reach the similar values as that of water alone with an increasing flow velocity. However, after the velocity exceeds certain threshold value the difference between slurry and water pressure gradients again increases.

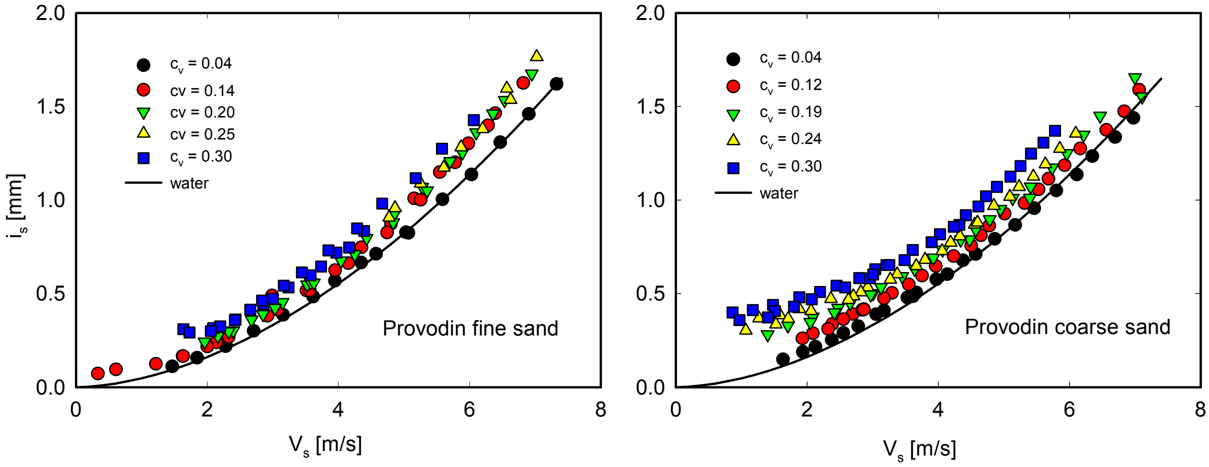


Figure 2 Hydraulic gradient i_s versus average slurry velocity V_s for sand slurries (fine and coarse Provodin sand, D = 26.8 mm)

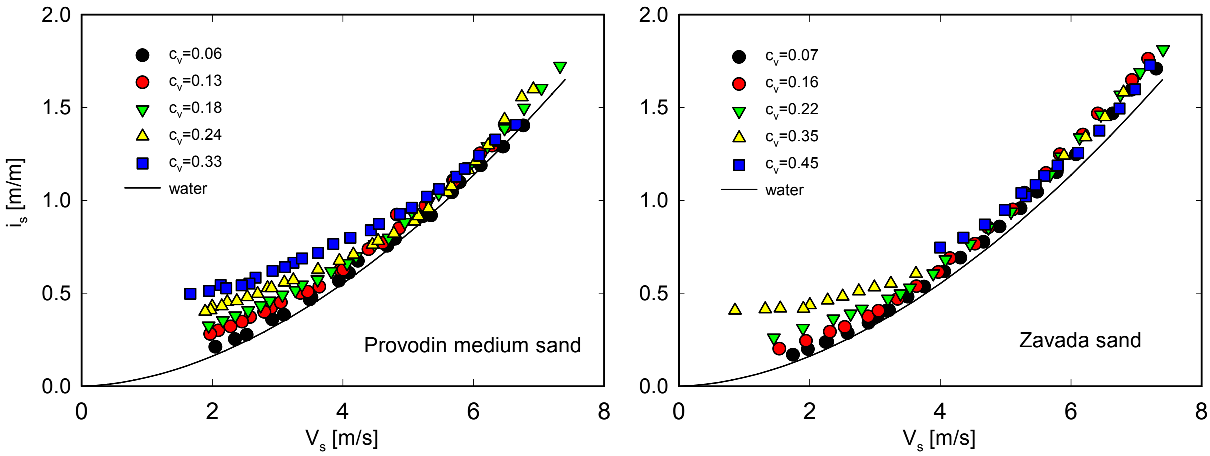
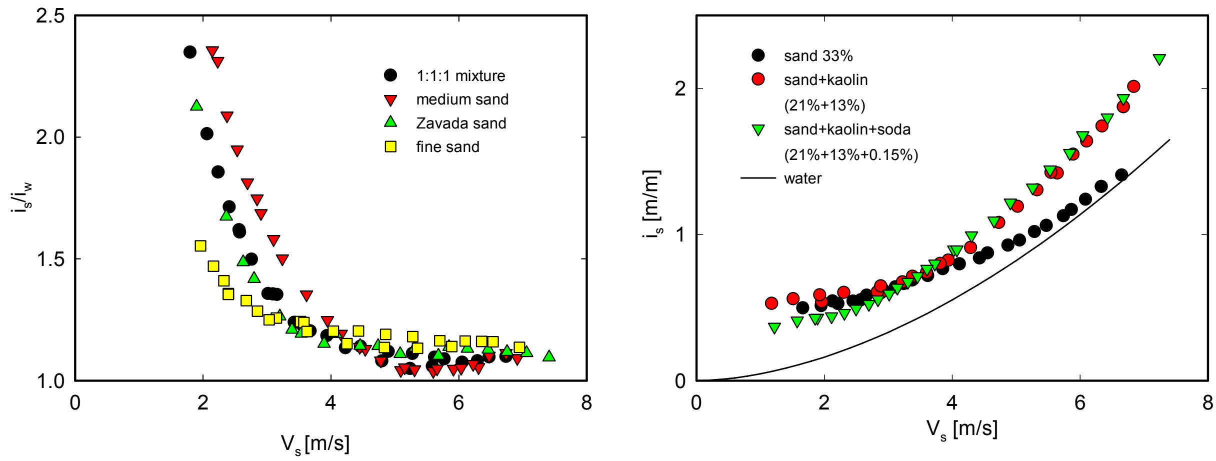


Figure 3 Hydraulic gradient i_s versus average slurry velocity V_s for sand slurries (medium Provodin sand, Zavada sand, D = 26.8 mm)

Poly-disperse sand slurries (sand mixture 1:1:1 or natural sand Zavada) can reach even lower values of the pressure gradient at higher values of slurry concentration and average velocity than the less concentrated slurry. This tendency, which can be explained due to the laminar/turbulent (L/T) transition of more concentrated slurry at higher velocity, is illustrated for the sand Zavada in Figure 3. The value of threshold velocity grows with an increasing slurry concentration. This flow pattern is similar to non-Newtonian behaviour of clay slurries, if the threshold velocity is compared with the velocity value of laminar/turbulent transition.

Special attention attracts the flow behaviour of the medium sand slurry. For the average slurry velocity lower than 4 m/s it reaches higher values of the hydraulic gradient ratio i_s / i_w than that of the fine sand or the sand mixtures, see Figure 4a. For the average slurry velocity between 4 and 6 m/s the medium sand hydraulic gradient ratio i_s / i_w is surprisingly even less than that of the fine sand. For the slurry velocity higher than 6 m/s the hydraulic gradient ratio of the medium sand slurry again increases and approaches values of the sand mixture, natural sand, and fine sand.



4a) **4b)**

Figure 4 Hydraulic gradient ratio i_s/i_w versus average slurry velocity V_s for sand slurries (D = 26.8 mm, c_v = 23 %)

To describe the effect of fine particles contents and of Newtonian and non-Newtonian carrier on flow behaviour, the slurry consisting of sand conveyed in water, natural and peptized kaolin slurry was measured (Vlasak et al., 2002a). The hydraulic gradient versus average velocity relationship i_s/V_s for medium sand slurry of total concentration $c_v \approx 34$ % is illustrated in Figure 4b. The slurry with content of 21% of the medium sand and 13% of kaolin exhibits a non-Newtonian behaviour in the laminar regime. For higher velocity values the hydraulic gradient i_s markedly increases compared to the water alone or sand-water slurry.

When the carrier slurry is peptized (addition of 0.15% of sodium carbonate) the hydraulic gradient in the laminar region becomes significantly lower (Vlasak et al., 2002b). However, for slurry velocity $V_s > 3$ m/s the peptized slurry reaches higher hydraulic gradient than the medium sand slurry and practically the same as the untreated sand-kaolin slurry. This confirms the fact that favourable effect of the slurry peptization in transitional and turbulent regions vanishes.

The same trend was observed for coarse sand slurry of total concentration $c_v \approx 32$ %, see Figure 5a. Figure 5b illustrates the effect of increasing kaolin contents (for constant total slurry concentration $c_v = 24\%$). For low velocity range the effect of different kaolin contents seems to be negligible, with increasing velocity the hydraulic gradient increases with growing kaolin contents. However, the addition of small kaolin contents (concentration of kaolin about 3%) affects favourable the flow behaviour of the sand-kaolin slurry even in the turbulent region.

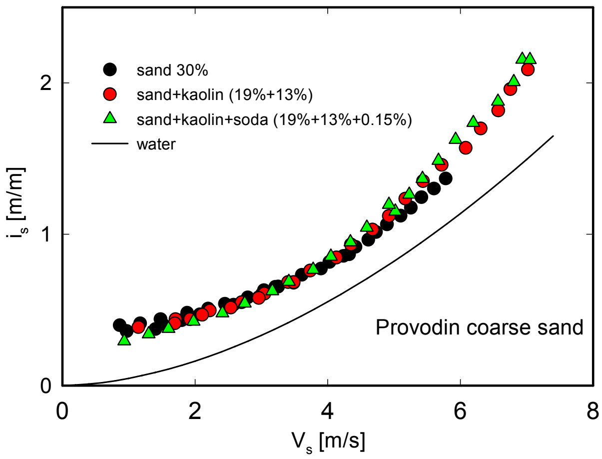
The Bohuchovice slurry dust slurries contain a high percentage of very fine (clay and dust) particles and their flow behaviour is similar to the well-known kaolin slurries. They are the time independent yield pseudo plastic slurries and their flow behaviour in the laminar regime can be well modelled by the Bulkley-Herschel rheological model

$$\tau = \tau_y + K\ (-\,\mathrm{d}u/\mathrm{d}r)^n, \tag{1}$$

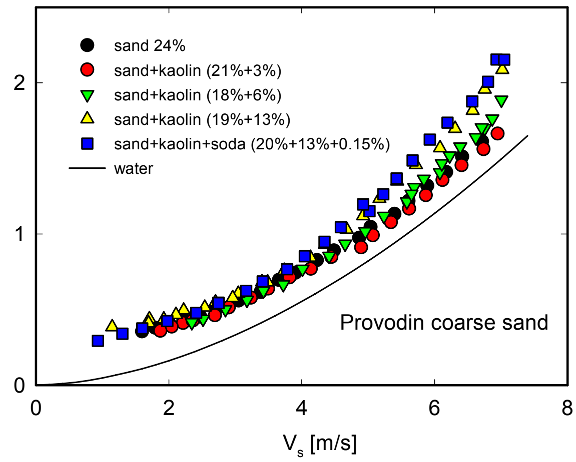
where τ_y, K and n are the yield stress, fluid consistency, and flow behaviour index, respectively, du/dr is velocity gradient. The rheological parameters are dependent on the particle size and density, and slurry concentration, and they have to be determined experimentally. Since rheograms τ / V_s of the slurries with concentrations c_v over 40 % are practically linear, the Bingham model (Govier & Aziz, 1972).

$$\tau = \tau_B + K_B\ (-\,\mathrm{d}u/\mathrm{d}r), \tag{2}$$

where τ_B *and* K_B are the Bingham yield stress and fluid consistency (Vlasak & Chara, 1999) was used for experimental data processing.



5a)



5b)

Figure 5 Hydraulic gradient ratio i_s/i_w versus average slurry velocity V_s for sand slurries (D = 26.8 mm, c_v = 23 %)

Dependence of the experimental values of the hydraulic gradient i_s on the slurry velocity V_s for Bohuchovice stony dust slurries of volumetric transport concentration c_v of 45.6 % and 48.5 % is illustrated in Figure 6.

The Bohuchovice stony dust was used as filling material of large-voluminous bags used for landscape protection against floods (i.e. for fast and effective closing of breakdown, heightening, consolidation and solidification of the contemporary levees or building new ones, elimination of local impact of water erosion or scour, for saving and security measures against landslide during flood events. (Vlasak et al., 2009, Vatolik et al., 2002). The stony dust is localy available and cheap material. However, relatively high energy consumption is needed for the pumping of the concentrated stony dust slurry. According to our experience with ash-water slurries, addition of coarse particles has favourable effect on the fly ash slurry flow behaviour and especially on decreasing of pressure drops and energy consumption during pumping (Vlasak et al., 2004, Vlasak & Chara, 2009).

The same idea was applied for stony dust slurries. To determine the effect of coarse particle addition the slurries consisting of the mixture of Bohuchovice stony dust and Zavada sand (mass ratio 79:21, 50:50, and 40:60) with different concentration c_v between 48 % and 51 % were investigated. The result illustrated in Figure 7 confirms that addition of coarser Zavada sand causes significant decreasing of the hydraulic gradient. The slurry of concentration $c_v \approx 45\%$ with 21% of the Zavada sand reached markedly lower hydraulic gradient i_s, e.g. for the slurry velocity V_s = 2.0 m/s about 32% lower than slurry without the sand addition, for slurry concentration $c_v \approx 49\%$ even about 34%. Obtained rheological parameters of the studied stony dust and stony dust-sand slurries are listed in Table 2.

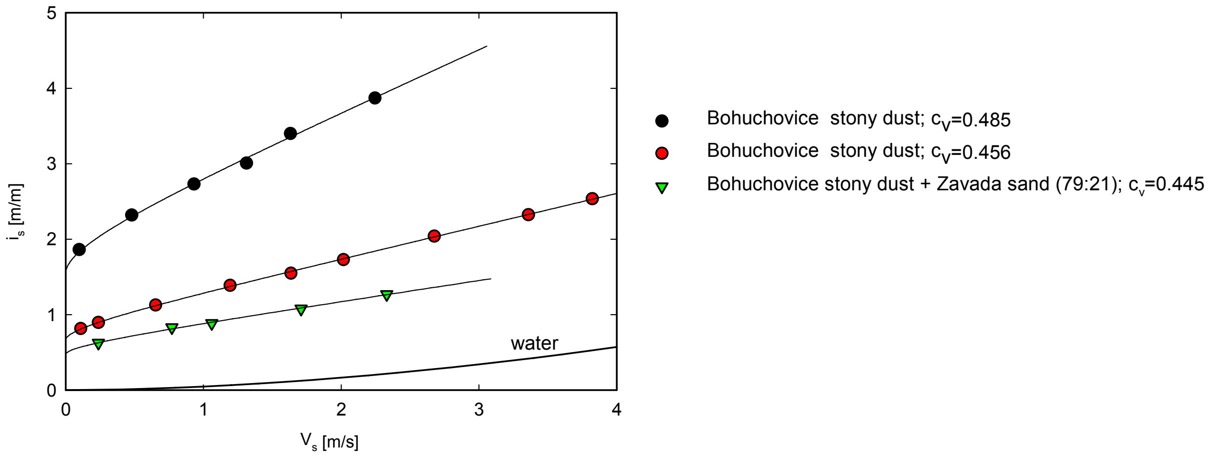


Figure 6 Hydraulic gradient i_s versus average slurry velocity V_s for stony dust slurries (Bohuchovice stony dust, D = 26.8 mm)

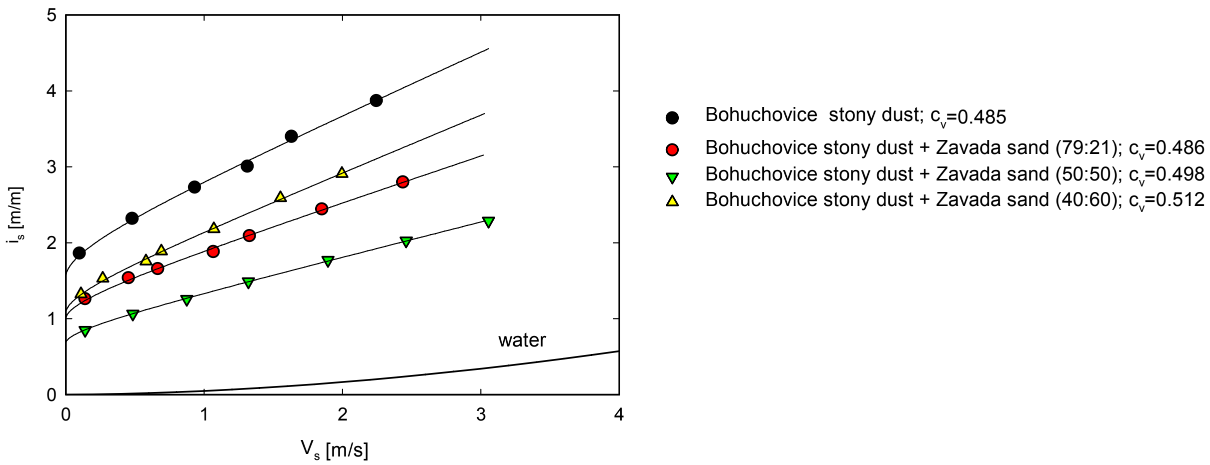


Figure 7 Hydraulic gradient i_s versus average slurry velocity V_s for stony dust-sand slurries (Bohuchovice stony dust, Zavada sand, D = 26.8 mm)

The hydraulic gradient reduction is a result of less content of very fine particles and mutual effect of the slurry components, the fine-grained and coarse-grained particles. The effect of coarse particle addition depends on the total slurry concentration and velocity, both the fine and coarse particles proportion and on the contents of colloidal particles.

Table 2 Rheological parameters of measured stony dust and stony dust-sand slurries

Material	c_V [%]	yield stress τ_B [Pa]	fluid consistency K_B [Pa s]
Bohuchovice stony dust	45,6	43,47	0,1813
Bohuchovice stony dust	48,5	101,5	0,0951
Bohuchovice stony dust and Zavada sand (ratio 79:21)	44,5	30,98	0,0608
Bohuchovice stony dust and Zavada sand (ratio 79:21)	48,6	65,23	0,1342
Bohuchovice stony dust and Zavada sand (ratio 50:50)	49,8	44,34	0,1012
Bohuchovice stony dust and Zavada sand (ratio 40:60)	51,2	70,2	0,1662

4. Conclusion

The coarse sand slurry reaches a higher hydraulic gradient than the fine sand slurry, and the difference decreases with increases in velocity. The poly-disperse sand slurries reach nearly the same values of hydraulic gradient as the fine sand slurry. The effect of particle size of the sand slurry depends on the flow velocity.

The study reveals the non-Newtonian behaviour of highly concentrated stony dust and sand-kaolin slurries. At low and medium slurry velocities the flow resistance increases with the increasing concentration, at high velocities the effect of concentration can be opposite. For the sand slurries of concentration higher than about 20 % some attributes of a non-Newtonian behaviour was found.

The addition of small contents of fine-grained material (kaolin) favourably affects the flow behaviour of the sand slurry. When the carrier kaolin slurry is peptized, hydraulic gradient in the laminar region becomes markedly lower. The favourable effect vanishes in transitional and turbulent regions.

The study revealed also a yield pseudo-plastic behaviour of the concentrated fine-grained stony dust slurries as well as stony dust-sand mixture slurries and the possibility of reducing flow resistance by adding coarse-grained material (sand). The hydraulic gradient in the laminar region becomes markedly lower and the effect is more significant for the higher slurry concentrations.

The flow behaviour of the stony dust slurries and stony dust-sand mixtures slurries can be approximated by Herschel-Bulkley or Bingam models in the laminar region. The rheological parameters should be determined from experimental data.

The understanding of complex flow behaviour of the slurry and control of its composition and inner structure makes possible to optimize energy and water consumption and to improve quality, safety, economy, and reliability of the transport processes.

5. Acknowledgement

The support under the project P105/10/1574 of the Grant Agency of of the Czech Republic and the Institutional Research Plan No. AV0Z20600510 of Academy of Sciences of the Czech Republic is gratefully acknowledged.

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6. Symbols

c_v	slurry volumetric concentration, -
d	particle diameter, m
D	pipe diameter, m
i	hydraulic gradient, m/m
K	fluid consistency, Pa s^n
n	flow behavior index, -
du/dr	velocity gradient, s^{-1}
V	velocity, m/s
ρ	density, kg/m^3
τ	shear stress, Pa
τ_y	yield stress, Pa

Subscripts

B	Bingham
max	maximum
p	particle
s	slurry
w	water
50	mean