

Article

Effect of Deflocculant Addition on Energy Savings in Hydrotransport in the Lime Production Process

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Abstract: The subject of the research was limestone hydromixture consisting of particles of a mean size of 45.5 μm conveyed by water in a pipeline of a total length of 632 m. In the paper, the results of rheological measurements of tested hydromixtures after the application of deflocculant consisting of waste product from the lime production process in the form of mineral particles and commonly known dispersant were presented. Calculations of pressure drop including hydromixtures with volume concentrations in the range of 21.30–50.00%, and density ranging from 1140–1410 kg/m^3 in a pipeline of 200 mm diameter are presented. A decrease in friction losses in the flow in the pipeline of hydromixtures with different mass concentrations after the addition of deflocculant was observed. The study revealed that the addition of deflocculant resulted in a reduction of friction in the pipeline, enabling the pumping of hydromixtures with twice higher solids concentrations than originated from industrial installation, with a lower volumetric flow rate. This resulted in a decrease of the power consumption of the motor driving the pump, and obtained significant energy savings in the hydromixture transport process. The maximum energy saving achieved was equal to 58%.

Keywords: hydrotransport; energy savings; Bingham plastic fluids; deflocculant; pressure drop



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1. Introduction

Transportation of liquids or hydromixtures through conduits is an important element of technological solutions in many industries. The advantages of such transport include: low costs, maintaining high purity of the transported medium, the elimination of environmental pollution, as well as easy monitoring and automation of such a process.

The demand to pump hydromixtures consisting of increasingly finer solid particles with their increasing concentration in industrial installations has been growing. Pumping hydromixtures with high solids concentrations in pipelines requires the application of pumps with a high discharge pressure, which results in a significant energy consumption and leads to greater pump wear [1–3].

During the transportation process of hydromixture, a substantial reduction of frictional pressure drop in the pipeline may occur. It is therefore often necessary to consider the problems of calculating the power requirements for pumping through a given pipeline system, the selection of the optimum pipe diameter, the measurement and control of the flow rate, etc. The knowledge of these factors facilitates controlling the total plant cost installation operation [4]. Several studies for pressure drop prediction in slurry flow are available in the literature, for instance [5–7].

It is clear that the transportation of utilities through pipelines involves significant energy expenditure. In recent years, with the growing difficulties with obtaining energy and the need to optimize transport costs, it has become necessary to develop new energy-saving technologies and methods of media transport that enable the reduction of energy

consumption [8–10]. Such methods include: methods using the phenomena of the abnormal reduction of any pressure drop when macromolecular polymers are added to the transported medium (Toms effect), methods using surfactants (surface-active substances) or deflocculants (a chemical or compound that prevents flocculation) as additives to reduce pressure drop during media transport, two-phase liquid-gas transport methods using compressed air (mainly used while concentrated suspensions exhibit complex rheological properties, especially when non-Newtonian shear thinning liquids are transported), and methods of modifying the rheological properties of the transported media. Each of these methods has found a wide application in practice and has been the subject of many research works [11–15].

A great deal of works have been published in the literature devoted to explanation of the mechanism of pressure drop reduction [16–22]. Despite the fact that many hypotheses of this phenomenon have been put forward, it has not been possible to propose universal model equations for predicting the frictional pressure drop.

The objective of this study is to develop a method of reduction of the electrical power consumption in the transportation of hydromixture in the pipeline. Such studies are part of the issues of industrial process intensification and multiphase fluid mechanics due to their wide applicability.

2. Materials and Methods

The hydromixture used in the study originated from an industrial installation of a Polish limestone mine. The solid fraction contained in the hydromixture consisted of dusty particles of quarried stone containing a high percentage of calcium carbonate. The grain composition of the solid fraction, determined using a laser grain size analyzer, is shown in Figure 1.

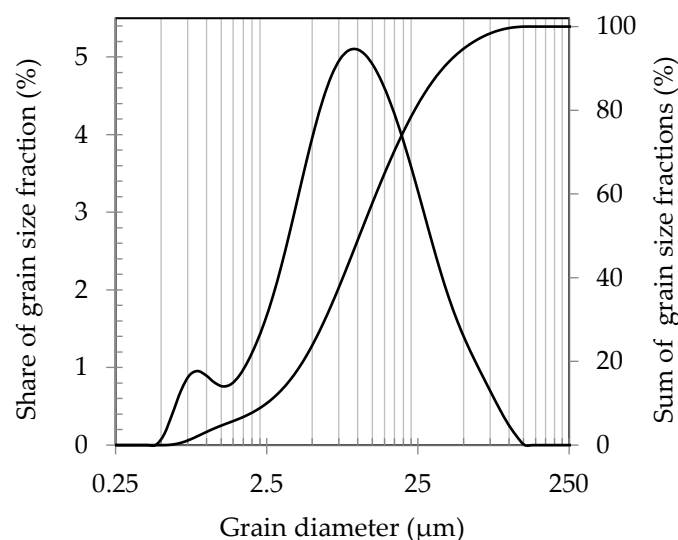


Figure 1. Grain size distribution curve of the tested hydromixture.

The grain size ranged from 0.5 μm to 163.5 μm , with an average grain size of 45.5 μm . The dust fraction with a mean grain diameter ranging from 2 μm to 50 μm had the largest share in the sample (about 65%). The sand fraction, characterizing particles with an average grain diameter larger than 50 μm , represented almost one third of all particles. The clay particles constituted only 3.38% of all the particles contained in the hydromixture. Chemically, the test hydromixture consisted mainly of calcium oxide CaO (73.6%) and silicon oxide (SiO_2 —13%). The other chemical compounds in the hydromixture were: magnesium oxide (MgO —0.6%), iron oxide (Fe_2O_3 —0.3%), aluminum oxide (Al_2O_3 —1.1%) and sulfur trioxide (SO_3 —0.3%). Substances that could not be identified accounted for approximately 11.1% of the total.

Rheological studies of hydromixture were performed using an Anton Paar (Lyon, France) MCR 302 rotational viscometer at $T = 20\text{ }^{\circ}\text{C}$ for hydromixtures with a mass concentration of $C_m = (21.30\text{--}50.00)\%$ and a solid volume concentration of $C_v = (10\text{--}29)\%$ in a range of hydromixtures density from about 1140 kg/m^3 to 1410 kg/m^3 .

The effect of frictional pressure drop reduction in the pipeline was obtained by introducing to the hydromixture an addition of substances with highly dispersive properties, in the form of fine mineral particles and chemical compounds, called deflocculants (drag reduction agents—DRA). Such an effect is called chemical treatment and, due to its potential practical use, has become the subject of much interest in various branches of industry and scientific works [23–28]. This effect should result in frictional pressure drop reduction in the flow of the hydromixture with an increase in the concentration of the solid phase contained in it, and result in a reduction of the energy consumption necessary to overcome the friction occurring in the pipeline. The reduction in the frictional pressure drop entails a reduction in the total cost of the hydrotransport process.

The composition of the proposed deflocculant was developed based on years of experimental research, knowledge derived from the literature, and cooperation with an industrial enterprise.

Sodium water glass and calcareous groats were selected as the deflocculant components based on their easy access in the product market, low manufacturing/acquisition cost and environmental neutrality. In the case of sodium water glass, the unquestionable advantage is its common occurrence and low purchase cost. Sodium water glass is formed by the reaction between silica and sodium hydroxide or silica and sodium carbonate. The addition of sodium water glass was intended to lower the viscosity, leading to a reduction in the shear stress created in the transported hydromixture. Calcareous groats, a residue from the lime slaking process that produces hydrated lime, consist of mineral particles with a grain diameter of less than 1.8 mm and an average grain diameter of $240\text{ }\mu\text{m}$. Figure 2b presents an image of the calcareous groats grains surface made by a Phenom Pro X (Thermo Fisher Scientific, Waltham, MA, USA) scanning electron microscope (SEM) after applying a 10 kV electron accelerating voltage.

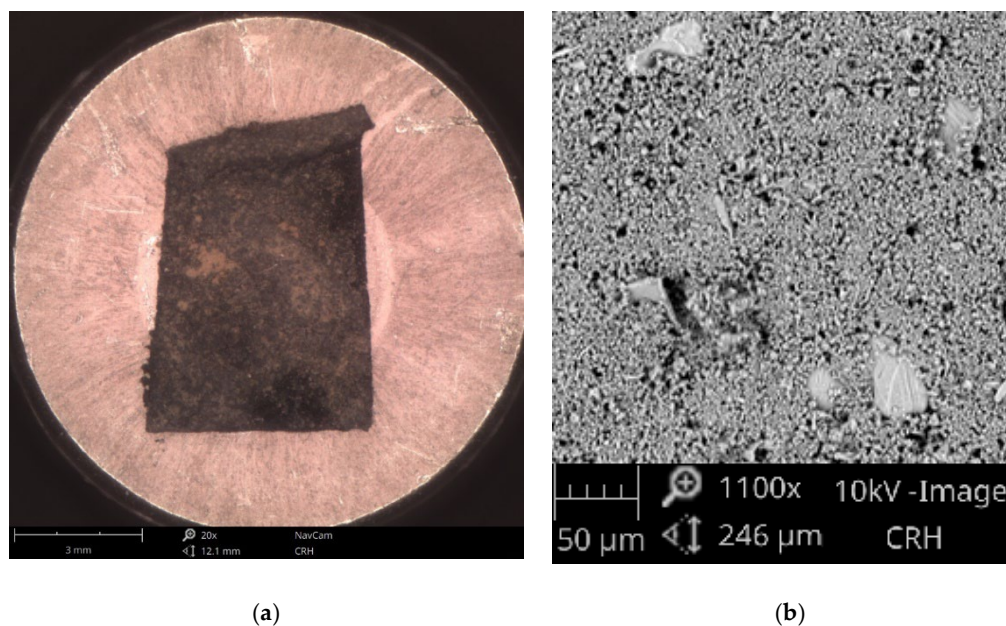


Figure 2. (a) Picture of dried lime slurry sample. (b) Surface image of calcareous groats grains made by scanning electron microscopy (SEM) with $1100\times$ magnifications.

This substance is inexpensive and easy to obtain, and is stored in large amounts in the production plant area. Chemically, calcareous groats are mostly composed of calcium oxide and magnesium oxide (70.81%), silicon dioxide (1.52%) and aluminum (0.84%).

The remaining substances are minor impurities formed in the process of hydration of a mixture of lime and water. Table 1 presents the results of the chemical composition analysis of calcareous groats performed with a scanning electron microscope integrated with an energy-dispersive X-ray spectrometer (EDS).

Table 1. Chemical composition of calcareous groats made using an energy-dispersive X-ray spectrometer (EDS).

Element Number	Element Symbol	Element Name	Atomic Concentration (%)	Error (%)
20	Ca	Calcium	13.1	0.0
8	O	Oxygen	79.7	0.1
6	C	Carbon	2.2	0.9
53	I	Iodine	0.2	0.0
7	N	Nitrogen	4.3	2.1
12	Mg	Magnesium	0.5	0.8

These two substances (sodium water glass and calcareous groats) combined together in appropriate proportions, depending on the mass concentration of the hydromixture, were added to tested samples with a high solid phase concentration in order to reduce the viscosity of the hydromixture.

Method of Measurement

The rheological parameters of hydromixtures used in this study were performed by an Anton Paar MCR 302 rotational viscometer. A coaxial double-gap cylinder system was chosen to measure the shear stresses generated in the hydromixture. In this measuring system, the outer cylinder, which is also the vessel into which the sample is applied, is a stationary element that allows for easy temperature control and stabilization. The inner cylinder (rotor) is driven by a motor for which the speed can be determined and the torque measured. The torque is proportional to the power of the current supplying the motor. It is converted to shear stress, and the rotor speed to the shear rate. In the performed measurements, the value of the shear rate was set, while the value of the shear stress was measured by the device. The measurements were carried out at 20 °C in the range of a shear rate from about 8–10 s^{−1} to 100 s^{−1}.

3. Results

Hydraulic conveying belongs to the most reliable and economically justified modes of hydrotransport. Due to its ecological values, it is also the preferred solution applied in environmental engineering. Transport of hydromixture with significant amounts of solids requires determination of the hydromixture's rheological properties to adopt an appropriate rheological model of the hydromixture. Such a model, determined on the basis of experimental research, allows the calculation of the frictional pressure drop during the flow of a given mixture through industrial installation. It is also essential to determine a condition at which laminar flow transforms into turbulence.

3.1. Rheological Description of Tested Hydromixture

The flow curves of hydromixtures with mass concentrations of 21.30%, 28.14%, 35.00%, 42.75% and 50.00% without addition (denoted as 'pure') and with deflocculant addition (denoted as '+DFL') are presented in Figure 3. The rheometric measurements were compared with the results calculated for the Bingham plastics model where the solid line indicates the fit of the rheological model to the experimental data. The shape of the flow curves indicates that the tested hydromixtures belong to the group of non-Newtonian, pseudo-plastic fluids.

Non-Newtonian fluids are generally highly viscous systems throughout the technically important range of the shear rate and are very difficult to transport in a pipeline.

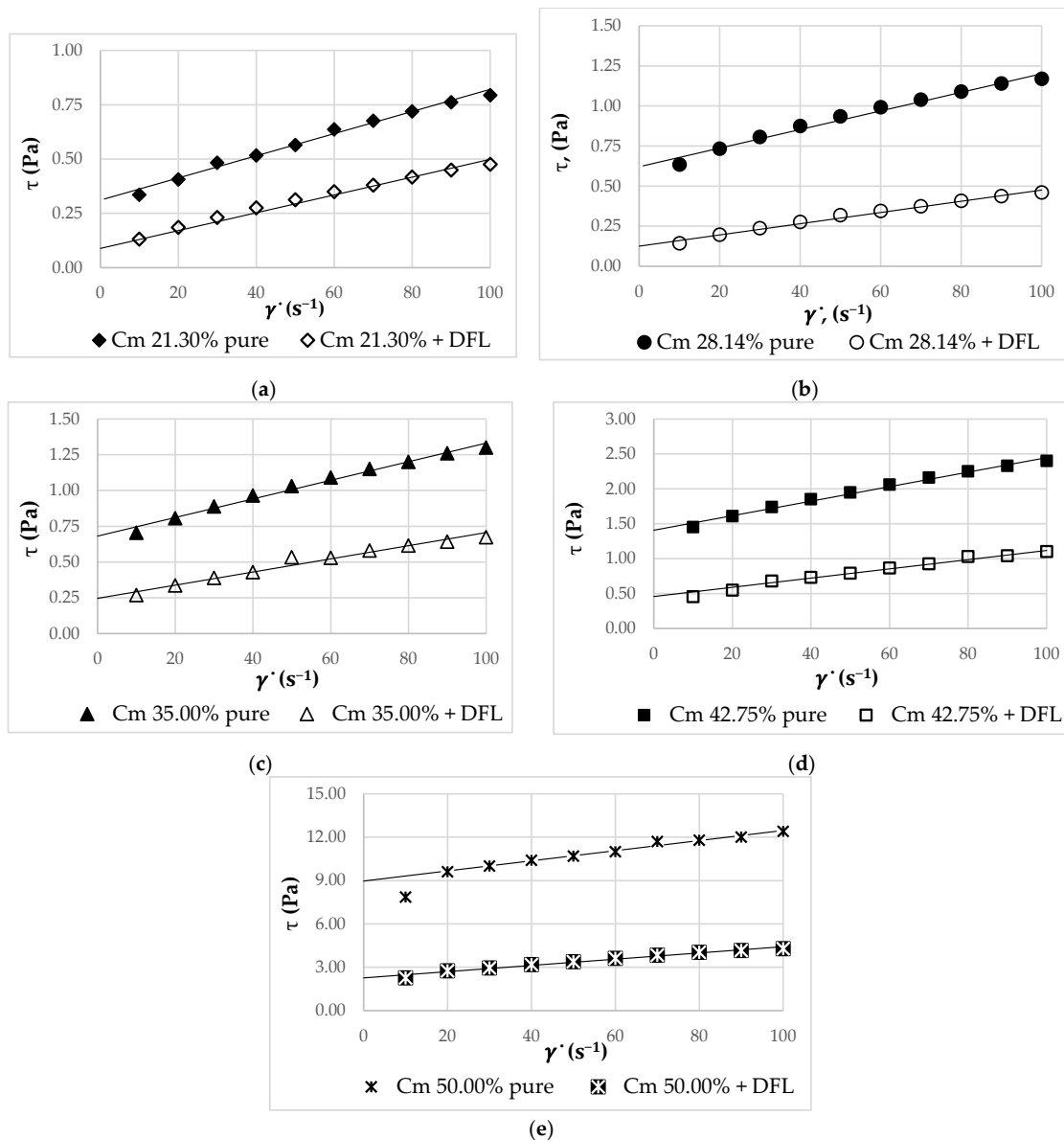


Figure 3. The experimental flow curves of tested hydromixtures with a mass concentration of: (a) 21.30%; (b) 28.14%; (c) 35.00%; (d) 42.75%; and (e) 50.00%.

The flow curves of hydromixtures were described by the Bingham model as follows:

$$\tau = \tau_y + \eta_p \cdot \dot{\gamma} \quad (1)$$

where η_p is plastic viscosity and τ_y is a yield stress.

The rheological properties of the tested hydromixtures can be described by the rheological Bingham plastics model in the shear rate range from about $8\text{--}10\text{ s}^{-1}$ to 100 s^{-1} . This range of shear rate occurs in the hydromixture flow in the analyzed pipeline.

In Table 2, the parameters of analyzed hydromixtures with defloculant (+DFL) and without the addition of defloculant (pure), such as density (ρ_m), yield stress value (τ_y), plastic viscosity (η_p) and the coefficient value of fitting the mathematical model to the experimental data (R^2) are shown.

Table 2. Rheological parameters of the tested hydromixtures.

Parameters		ρ_m (kg/m ³)	τ_y (Pa)	η_p (Pa·s)	R ² (%)
C _m 21.30%	pure +DFL	1140	0.3109	0.0051	98.90
			0.0887	0.0041	98.88
C _m 28.14%	pure +DFL	1195	0.6209	0.0058	98.26
			0.1253	0.0035	99.51
C _m 35.00%	pure +DFL	1254	0.6812	0.0065	98.69
			0.2461	0.0046	98.62
C _m 42.75%	pure +DFL	1330	1.4073	0.0104	98.96
			0.4576	0.0066	98.55
C _m 50.00%	pure +DFL	1410	8.9667	0.0350	98.53
			2.2654	0.0216	97.85

3.2. Mathematical Model

Calculation of the pressure drop of the tested hydromixture depends on the character of the flow (laminar or turbulent), determined by the Reynolds number for Bingham fluids. The critical value of the Reynolds number is described by an empirical equation of the form [4]:

$$(N_{Re})_{cr} = \frac{1 - \frac{4}{3}\phi_c + \frac{\phi_c^4}{3}}{8 \cdot \phi_c} \cdot N_{He} \quad (2)$$

where the parameter ϕ_c and the Hedström number are calculated as follows:

$$N_{He} = \frac{\rho \cdot d^2 \cdot \tau_y}{\eta_p^2} \quad (3)$$

and

$$\frac{\phi_c}{(1 - \phi_c)^3} = \frac{N_{He}}{16800} \quad (4)$$

Flow of the Bingham plastics fluid is laminar if the calculated Reynolds number (6) is below the critical value (2), above which the transition to turbulent flow occurs.

The critical value of the Reynolds number for Bingham plastic fluids describing transition from laminar to turbulent flow for tested hydromixtures were calculated from Equation (2), and is presented in Table 3.

Table 3. Parameters at the transition from a laminar to turbulent flow regime of tested hydromixtures.

Parameters		$(N_{Re})_{cr}$	N_{He}	ϕ_c
C _m 21.30%	pure +DFL	12,350	545,116	0.7191
		9261	240,638	0.6443
C _m 28.14%	pure +DFL	14,620	881,926	0.7567
		11,878	488,744	0.7100
C _m 35.00%	pure +DFL	14,222	809,050	0.7500
		12,621	583,611	0.725
C _m 42.75%	pure +DFL	13,417	692,408	0.7385
		12,478	559,037	0.721
C _m 50.00%	pure +DFL	11,218	412,770	0.695
		9695	273,810	0.657

The friction factor for the laminar flow of Bingham plastic fluids (f_L) was calculated from the expression known as the Buckingham–Reiner equation [4]:

$$f_L = \frac{16}{N_{Re}} \cdot \left[1 + \frac{1}{6} \cdot \frac{N_{He}}{N_{Re}} - \frac{1}{3} \cdot \frac{N_{He}^4}{f_L^3 \cdot N_{Re}^7} \right] \approx \frac{16}{N_{Re}} \cdot \left[1 + \frac{N_{He}}{8 \cdot N_{Re}} \right] \quad (5)$$

where the Reynolds number is given by:

$$N_{Re} = \frac{U_s \cdot d \cdot \rho}{\eta_p} \quad (6)$$

For the Bingham plastics fluids there is a gradual deviation from purely laminar to fully turbulent flow. For turbulent flow, the friction factor (f_T) can be represented by the empirical expression of Darby and Melson [21], and modified by Darby [22]:

$$f_T = \frac{10^a}{N_{Re}^{0.193}} \quad (7)$$

where

$$a = -1.47 \cdot \left[1 + 0.146 \exp(-2.9 \cdot 10^{-5} \cdot N_{He}) \right] \quad (8)$$

The friction factor for Bingham plastics fluids can be calculated for any Reynolds number, from laminar through turbulent, from the equation [22]:

$$f = (f_L^m + f_T^m)^{1/m} \quad (9)$$

where f_L is calculated from the Equation (5) and f_T is given by the Equation (7).

The m value is calculated from the expression:

$$m = 1.7 + \frac{40000}{N_{Re}} \quad (10)$$

Equation (9) was applied for calculations of pressure drop under turbulent condition for $d < 335$ mm, $N_{Re} \leq 3.4 \cdot 10^5$, and $1000 \leq N_{He} \leq 6.6 \cdot 10^7$, and were used in further calculations of the friction factor.

3.3. Physical Model of Hydromixture Transport

The subject of the research was the transport of finely dispersed hydromixture from a reservoir to the settling tank in a pipeline of a total length of 632 m and a diameter equaling 200 mm. The total height difference between the inlet and the outlet length of the pipeline was 11 m.

We assumed that the flow of the tested hydromixture is fully developed, axially-symmetrical and isothermal. The flowing medium consisted of a solid phase and water as a carrier liquid.

The calculations of the total pressure drop in the pipeline was carried out for the hydromixture transported under industrial conditions, i.e., with a solid phase concentration of $C_m = 21.30\%$ and a volumetric flow rate of $Q_v = 110$ m³/h, which corresponds to a solid phase mass transport of 27 t/h. The results of the calculations performed for the base hydromixture were compared with the flow pressure drop values for hydromixtures with mass concentrations of 28.14%, 35.00%, 42.75% and 50.00%, to which the deflocculant additive was applied.

Based on the assumptions of the physical model, the pressure drop (Δp) of the hydromixture flow in the tested pipeline was calculated from the expression:

$$\Delta p = \frac{\rho_m \cdot U_s^2}{2} + \rho_m \cdot g \cdot \Delta h + \cdot p_{1-2} \quad (11)$$

where ρ_m is the density of the hydromixture, U_s is the mean flow velocity, and Δh is the difference in level between the pump inlet and the pipeline outlet. Δp_{1-2} is the linear losses due to friction in pipeline sections, which were calculated from the Darcy–Weisbach equation as follows:

$$\Delta p_{1-2} = \lambda \cdot \frac{\rho_m \cdot U_s^2}{2} \cdot \frac{L}{d} \quad (12)$$

where λ is the friction factor, L is the total length of the pipeline, and d is the pipeline diameter.

The values of the friction factor λ were determined from the equation:

$$\lambda = 4 \cdot f \quad (13)$$

3.4. Results of the Pressure Drop Calculation

The results of the pressure drop calculations for the example hydromixtures of mass concentrations of 21.30%, 42.75% and 50.00%, without the addition of deflocculant (pure) and with deflocculant (DFL), are presented in Figure 4.

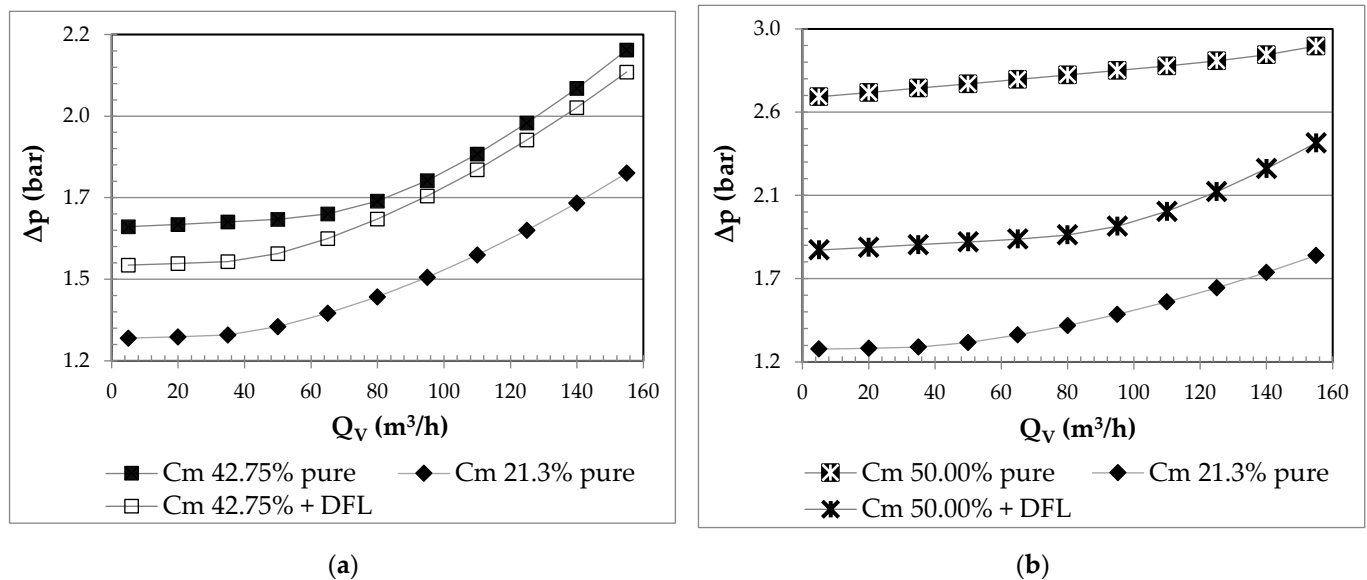


Figure 4. The results of frictional pressure drop calculations for hydromixtures of selected solid phase concentrations: (a) 42.75%, and (b) 50.00%.

The pressure drop values presented in the graphs above Figure 4 show an increasing trend of increasing volumetric flow rate and mass concentration of the hydromixture. However, the growth is smaller for the hydromixtures with the addition of deflocculant due to the viscosity decrease. This effect allows for the transportation of a constant amount of solid phase mass in hydromixtures of higher mass concentrations and a smaller pressure drop.

3.5. Electricity Consumption in the Hydromixture Transport

As a result of the deflocculant addition, an economic effect was achieved by the reduction of electricity consumption when pumping the hydromixture in a pipeline. In order to determine the obtained economic effect, the power at the pump shaft (P_w) required to pump the hydromixture was calculated using the equation:

$$P_w = \frac{Q_v \cdot \Delta p}{\eta} \quad (14)$$

where Q_v is the volumetric flow rate and η is the pump efficiency.

According to data acquired from the manufacturer of the equipment used in the production plant, the pump efficiency is 62%.

Knowing the pump motor efficiency of $\eta_s = 93.6\%$, the power consumption of the motor driving the pump (P_s) can be expressed as:

$$P_s = \frac{P_w}{\eta_s} \quad (15)$$

Assuming the constancy of the transported solid particles equal 27 t in the transport of hydromixtures with higher than 21.30% mass concentrations, the volumetric flow rates decrease and equal 80 m³/h for a hydromixture with a mass concentration of 28.14%, 61 m³/h for a hydromixture with a mass concentration of 35.00%, 48 m³/h for a hydromixture with a mass concentration of 42.75%, and 38 m³/h for a hydromixture with a mass concentration of 50.00%, respectively.

A decrease in the viscosity of hydromixture was achieved as the result of deflocculant addition, which can be observed in the flow curves of hydromixtures shown in Figure 3. Transport of hydromixture with a smaller volumetric flow rate but the same amount of solids is possible. This results in a significant decrease of energy consumption during the transportation of such hydromixtures compared to transportation of base hydromixture, with the mass concentration of 21.30%, which is presented in Table 4.

Table 4. Power consumption of the electric motor driving the centrifugal pump.

C_m (%)	C_m 21.30% Pure	C_m 28.14% + DFL	C_m 35.00% + DFL	C_m 42.75% + DFL	C_m 50.00% + DFL
Q_v (m ³ /h)	110	80	61	48	38
P_s (kW)	8.03	5.55	4.27	3.5	3.34

Figure 5 presents the electricity consumption during pumping of the hydromixture with the addition of deflocculant as a function of the mass concentration of the hydromixture. The maximum energy savings is 58% over the transport of basic hydromixture with the concentration of 21.30% by mass.

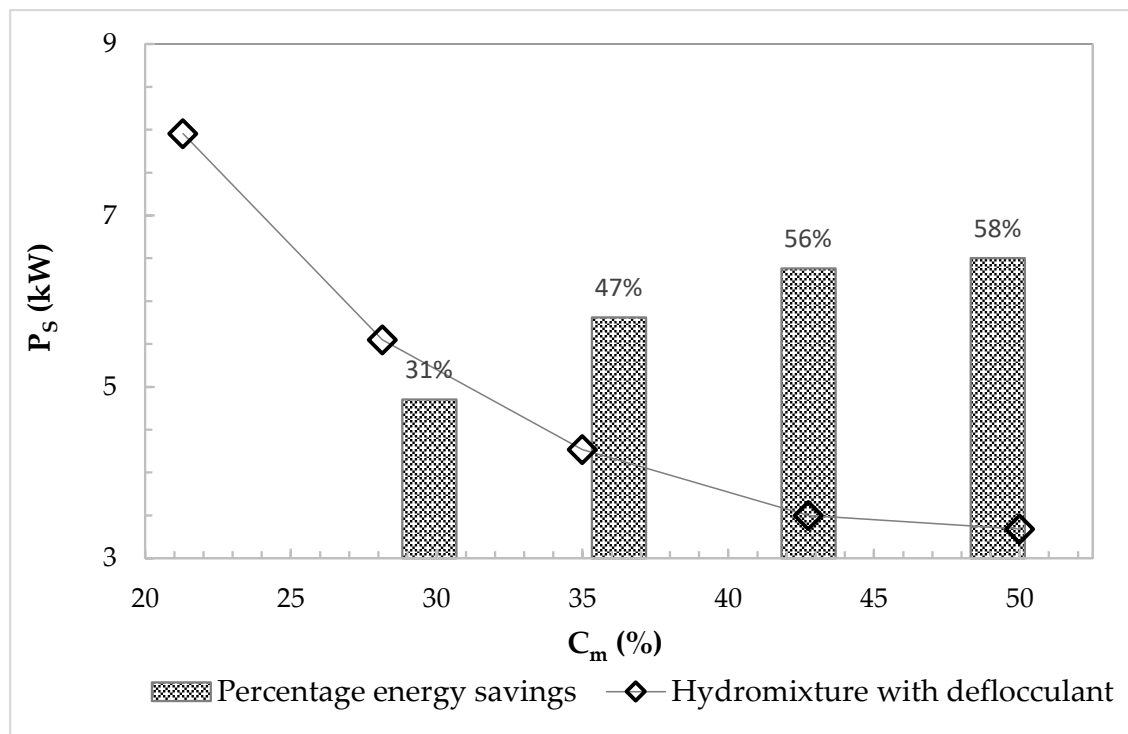


Figure 5. The electricity consumption during pumping of the hydromixture.

4. Discussion

The basis for the calculation of the pressure drop during the transportation of hydromixture in a pipeline is a determination of the rheological properties of tested hydromixtures.

The results of rheological behaviour measurements of hydromixture with different mass concentrations were described by the Bingham plastics model in the shear rate range from about $8\text{--}10\text{ s}^{-1}$ to 100 s^{-1} with high accuracy (98–99%), which confirms that the studied hydromixtures were shear-thinning non-Newtonian fluids with a yield stress. For all the tested hydromixtures, decreases in viscosity with increasing shear rate were observed.

Calculations of the friction factors of the analyzed hydromixtures in a 200 mm diameter pipeline was performed using Equations (5), (7) and (9). The friction factor values in the range of laminar flow calculated from Equations (5) and (9) were almost identical. Similarly, the friction factor values for the turbulent flow of non-Newtonian liquid calculated from Equations (7) and (9) were also very similar. In the paper, the possibility of friction factor calculating for non-Newtonian fluids in large diameter pipelines in turbulent flow using both Equations (7) and (9) is confirmed. The calculated friction factors of the hydromixtures in a pipeline of 200 mm diameter and 632 m length confirmed that the addition of deflocculant affects the reduction of friction factors for all the analyzed hydromixtures. Therefore, it was possible to pump hydromixtures with higher solids concentrations, resulting in significant energy savings in their hydrotransport and reduced water consumption in the limestone hydromixture transport process.

The positive effect of using a deflocculant in the transport of the hydromixture occurring in the analyzed pipeline has an influence on the increase in the efficiency of the whole production process. The additional effect that increases the efficiency of the hydromixture transport process is the reduction of the amount of water used in the pumping process, which improves environmental protection by reducing the amount of burdensome slurry. As a result, the estimated operating cost of the industrial installation of hydromixture transportation in a pipeline is significantly reduced.

5. Conclusions

The paper presents a new possible method of hydromixture transportation in pipelines, enabling significant energy savings in such transportation. This effect was achieved by using an additive of deflocculant, whose composition was self-developed and contains environmentally neutral mineral particles. The proposed method, except for the energy savings, reduces the amount of water used in such transportation, thus reducing the amount of burdensome slurries, which is an additional ecological aspect of the proposed method.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

a	parameter given by Equation (8)
C_m	mass concentration of hydromixture, (%)
C_v	volume concentration of hydromixture, (%)
d	pipe diameter, (m)
DFL	deflocculant
f	friction factor for Bingham plastic fluids
f_L	friction factor for laminar flow
f_T	friction factor for turbulent flow
L	total length of a pipeline, (m)
m	parameter given by Equation (10)
N_{He}	Hedström number
$(N_{Re})_{cr}$	critical value of Reynolds number
P_w	power at the pump shaft, (W)
P_S	power consumption of the motor driving the pump, (W)
Q_v	volumetric flow rate, (m ³ /h)
U_s	mean flow velocity, (m/s)

Greek letters

Δh	difference in level between the pump inlet and the pipeline outlet, (m)
Δp	pressure drop, (Pa)
Δp_{1-2}	flow pressure drop due to friction, (Pa)
η	pump efficiency, (%)
η_p	plastic viscosity, (Pa·s)
λ	friction factor
ρ_m	density of hydromixture, (kg/m ³)
τ	shear stress, (Pa)
τ_y	yield stress, (Pa)
$\dot{\gamma}$	shear rate, (s ^{−1})
φ_c	parameter calculated from Equation (4)

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