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Analysis of energy consumption and cost savings in the process of transporting a hydromixture with the addition of a deflocculant

Beata Jaworska-Jóźwiak[1*], Bartłomiej Szymczyk[2]

[1] Department of Production Engineering, Faculty of Management and Computer Modeling, Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland
[2] Department of Economics and Finance, Faculty of Management and Computer Modeling, Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland
* Corresponding author's e-mail: beataj@tu.kielce.pl

ABSTRACT

The paper presents a proposal to reduce the cost of the pipeline transport of hydromixture in the lime production process. The purpose of the research was to reduce the energy and water demand during the flow of lime hydromixture with a deflocculant of a specific composition in a selected pipeline. Since the addition of an appropriate deflocculant significantly reduces the effect of particle size on the flowability of the suspension, the selection of optimal transport conditions is a fundamental issue. To provide the most efficient transport condition of the hydromixture tested in the analysed pipeline, a mathematical model has been developed that assumes the most influential factors in the operation of the investigated enterprise technology. The input parameters were proposed using a statistical method. In the article, the consumption costs of the components (materials and energy) in the process of piping a lime hydromixture of different mass concentrations were compared. The analysis carried out aimed to reduce the amount of electrical energy needed to drive the pump during the flow of a hydromixture of four different mass concentrations and its volumetric flow rate in the pipeline, while maintaining a constant amount of the transported mass of the solid phase in the hydromixture. The results of the analysis revealed that controlling selected operating factors, such as the mass concentration of the hydromixture, the flow rate, and the pump head, improves the energy efficiency of the hydrotransport process in the limestone mine. As a result of the investigation, significant reduction of the total cost of the pipeline transport is possible.

Keywords: limestone hydromixture, deflocculant, energy consumption, cost savings.

INTRODUCTION

In recent years, an issue of replacing fossil fuel energy sources with renewables caused growing difficulties with obtaining cheap energy, felt especially by energy-intensive industries. This effect has been intensified by the influence of the COVID-19 pandemic on the global economy and Russian aggression against Ukraine at the beginning of the year 2022. This led to significant increases in energy prices even for individual recipients in Europe. Energy is currently one of the most desirable resources because of the economic and energy crisis, but it needs to be used in a sustainable manner [Jasińska-Biliczak, 2022]. According to the data presented in Table 1, over the years 2013–2023 the average annual sales price of electricity in Poland increased by 318% [URE: Energy Regulatory Office]. In the years 2013–2018, a relatively stable price situation was noted, and the last three years (since 2021) have been characterised by sharp increases. Moreover, the cost of 1 kWh of electricity for the C21 tariff intended for medium and large enterprises (according to PGE: Polish Energy Group S.A.) increased from PLN 0.7166 in 2021 to PLN 1.1706 in 2024 (by 63%). Therefore, it is necessary to develop new energy-saving technologies and methods of media transport that enable the reduction of energy consumption in many industrial processes, among them in mining.

In the study, an analysis of method of reduction of the electrical power consumption in the lime production plant was performed. Such studies are part of the issues of industrial process intensification and have wide practical applicability, for instance for determining the optimal energy consumption under varying tariffs in a steel plant [Ashok, 2006], in optimal scheduling at iron and steel production sites [Wang et al., 2023] or optimal decision making during ore haulage in copper mine [Skoczylas et al., 2023].

When the hydromixture transport process is considered, substantial energy consumption results from a reduction of the frictional pressure drop in the pipeline [Shook and Roco, 1991, Chhabra and Richardson, 2008]. For this reason, it is necessary to control the power requirements to pump through a given pipeline system. The search for an effective method of controlling electrical power consumption during slurry transportation in mining enterprises is attracting considerable attention from many researchers, for instance [Grobler and den Heijer, 2006]. As stated by Wu et al. [2010], to improve the energy efficiency of the hydrotransport process, it is crucial to operate at a suitable concentration of solids characterising the pumping hydromixture.

In the literature, there are many recommendations for using the mathematical model considering the technological parameters of pumping installation facilities to estimate the power consumption and the corresponding costs in the field of mining. Knowledge of these parameters facilitates controlling the total plant cost installation operation [Zhang et al., 2012]. General procedures for creating operational efficiency optimisation models are presented by Xia and Zhang [Xia and Zhang, 2015]. Brand reported an example of analysis on the identification of parameters focused on reducing the consumption of large energy consumers, such as cooling, pumping, ventilation, and compressed air systems as well as their ranges in gold mines [Brand et al., 2015]. Several studies are available in the literature to improve energy efficiency during hydromixture flow [Van Staden et al., 2009], but few of them are related to limestone hydromixture [Jaworska-Jóźwiak, 2023].

Significant effort has been put into determining general techniques in energy system operation efficiency modelling and creating an adequate predictive control approach to obtain energy optimisation in mineral processing. Recent findings of [Sinchuk et al., 2023] confirm that suitable selection of input parameters with required precision has a great importance in mathematical modelling of the electric energy distribution. The authors of the cited publication conducted an extensive analysis to determine the daily cost of energy consumption by mining equipment in the iron ore mine, which is reflected in the cost of extraction of raw materials and proportionally influences the cost of obtaining raw materials by the final consumers. In the above-mentioned paper, a mathematical algorithm considering the identification of electric consumption capacity by mining facilities, the average electric energy consumption during specified time and the electric consumption peaks for the interval, as well as the average duration of their surges, has been defined. The procedure assumed a mathematical determination of the cost of electric consumption by underground iron ore enterprises in relation to the real mining conditions. However, the selection of input parameters in the proposed algorithm depends on the kind of analysed extraction process and the specificity of the operation technology and cannot be treated as uniform for all types of mining industries.

Several studies have found an exact method of determination an algorithm of energy consumption in coal mining, among others optimal control conveyor belt systems [Middelberg et al., 2009] and supporting energy-efficient decisions

Table 1. Average sales price of electricity on the competitive market in Poland

Years	Average annual sales price of electricity on the competitive market [PLN/kWh]
2023	0.75929
2022	0.52371
2021	0.27808
2020	0.25269
2019	0.24544
2018	0.19430
2017	0.16370
2016	0.16970
2015	0.16999
2014	0.16358
2013	0.18155

Note: compiled by the authors [available online: ure.gov.pl].

in open-pit coal mines [Patterson et al., 2016]. However, the method presented by Patterson is based solely upon corresponding procedure of the coal mining enterprises and should be personalised individually for each case.

Recent studies, for example [Sinchuk et al., 2022] and [Hao et al., 2024], investigated advanced mathematical models to control the energy efficiency of raw material extraction, which changes the cost of energy consumption depending on the time of day. Such a model includes the use of electricity tariffs as the input parameters for a goal function.

The research methodology on the development of the expected structure of the algorithm should result in the achievement of sufficiently qualitative final decrease of the total cost of the operation of the enterprise [Xia and Zhang, 2013]. However, it seems essential to constantly monitor the level of energy consumption by specific equipment and correct possible deviations on an ongoing basis.

In the paper, the amount of electricity required to drive the centrifugal pump transporting the hydromixture in one hour was determined. Calculations of the energy demand of the motor driving the centrifugal pump during slurry transport in a pipeline were carried out for a basic slurry without the addition of deflocculant (C_m = 21.30% pure) compared to those for hydromixtures with mass concentrations of 28.14%, 35.00%, 42.75% and 50.00% with the addition of deflocculant. The power consumption of the electric motor driving the pump exerts influence on the power consumed by the pump. Thus, determining the hydromixture flow pressure drop was necessary. In turn, the power in the pump shaft is in accordance with the efficiency of the electric motor that drives the pump at a certain load. The presented procedure allows one to determine the amount of electricity consumption required to pump the hydromixture with selected mass concentrations. The parameters that characterise the hydromixture were set when a constant amount of the solid phase mass is transported.

On the basis of these assumptions, an investigation was conducted in a selected lime production enterprise on possible reduction in energy and water consumption during the discharge of lime hydromixture to the settling tank in the production process. The tested lime hydromixture is a residue of the washing of crushed limestones. Taking into account the specificity of the flow installation in the analysis company, an own model was designed to predict the energy consumption of a centrifugal slurry pump during the transport of hydromixture in a pipeline. The starting point of the analysis was the identification of the boundary conditions of the process according to the technology adopted in the study case. It allowed for further development of the mathematical algorithm and to choose the most efficient operation mode of the power complex. The presented method is a combination of classic multifactor regression modelling with digital modelling methods used for drainage facilities.

In the presented article, the cost of pumping hydromixtures of four different mass concentrations with the addition of a deflocculant was compared, taking into account the reduction in the amount of industrial water pumped and the electric energy consumed by the centrifugal slurry pump. The results of rheological studies have shown that the use of a deflocculant reduces the friction of the hydromixture flowing through the pipeline. At the same time, the inverse proportionality between the mass concentration of the hydromixture and its volumetric flow rate is maintained. This results in a reduction of the total cost of the hydromixture transport in the analysed pipeline by about 17–55%, depending on its mass concentration.

METHODOLOGY

This paper outlines the results of the calculation of the total cost of the flow of the lime hydromixture in a pipeline after the addition of a selected deflocculant. The calculated total cost is based on the energy and water consumption during the flow of the hydromixture with different mass concentrations and different volumetric flow rates, but with a constant amount of solid phase, and the cost of the deflocculant purchase.

The analysis was preceded by rheological measurements of the lime hydromixture tested after the application of the deflocculant. The hydromixture sample subjected to experimental tests was taken from the industrial installation of the lime production plant. The composition of a self-developed deflocculant consists of sodium-water glass and the remains of the lime slaking process, known as calcareous groats.

To achieve the objectives of the study, the following methodology was presented:

- In the first step of the investigation, the mathematical model of power consumption of the transport in the analysed pipeline was specified. The hydromixture flow model was previously determined.
- In the second part of the study, the consumption costs of the water, energy, and deflocculant used in the process of piping a lime hydromixture of different mass concentrations were analysed.

Model of the hydromixture flow

The subject of the research was the transport of the fine dispersive lime hydromixture from a reservoir (detail A in Figure 1) to the settling tank (detail B in Figure 1) in a pipeline of a total length of 632 m. The analysed pipeline is an industrial installation located in a Polish limestone mine. The distance of the reservoir from the settling tank measured in a straight line is 436 m. The Warman 4/3 AH centrifugal slurry pump operates with inflow. Hydromixture flows down by gravity from the reservoir (A) to the pump suction nozzle. The centrifugal pump is located under the reservoir (Figure 1).

The flow calculations in the pipeline were carried out for the hydromixture transported under industrial conditions, that is, with a solid phase concentration of $C_m = 21.30\%$ and a volumetric flow rate of $Q_v = 110$ m^3/h, which corresponds to a solid phase mass transport of 27 t/h. To determine the effect of the deflocculant on reducing friction losses in the flow installation, a diagram

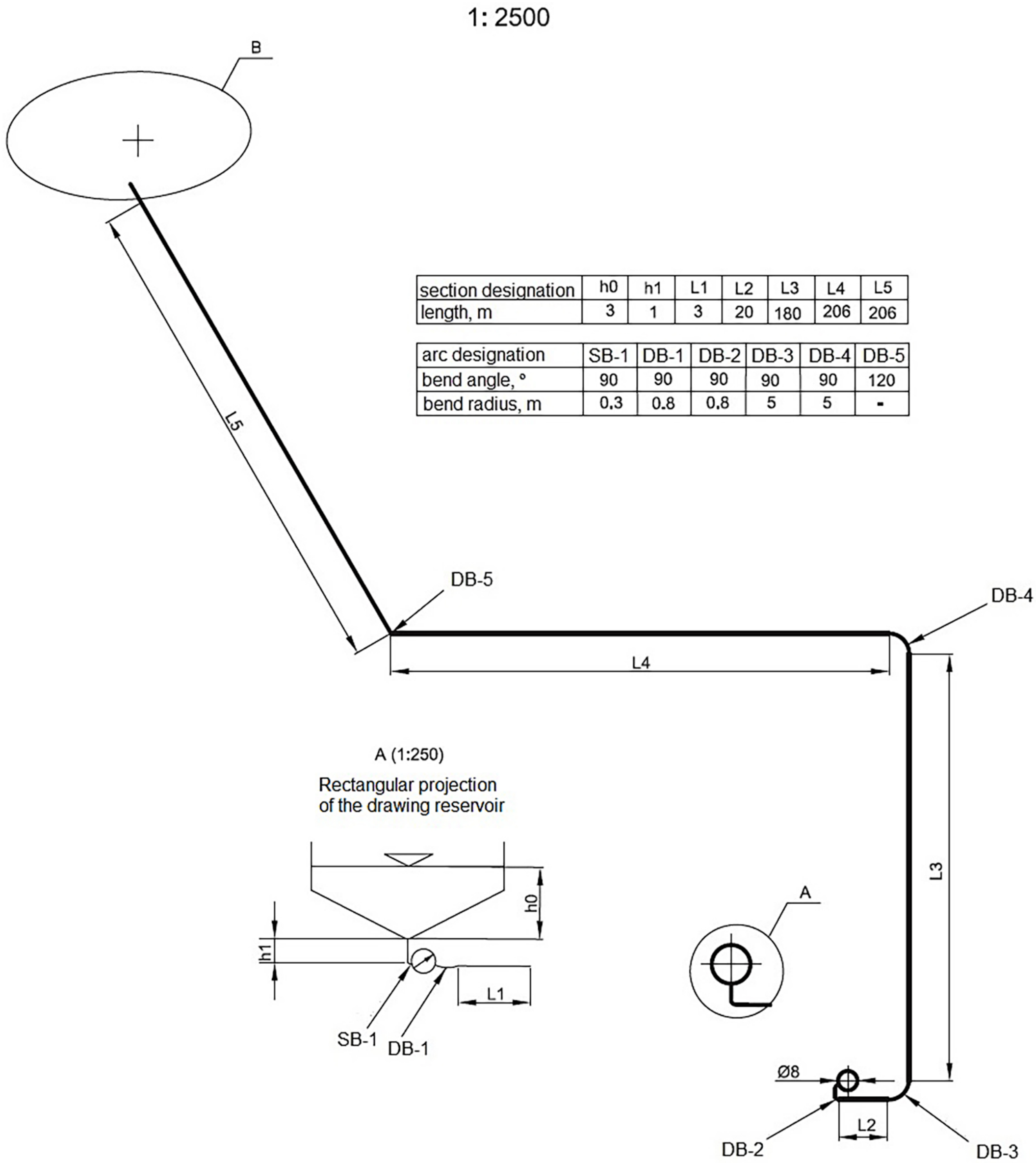

Figure 1. Drainage pipeline diagram – top view

of the installation was drawn and a physical and mathematical model of the turbulent flow of the hydromixture was developed. The results of the calculations performed for the base hydromixture were compared with the flow parameters for hydromixtures with mass concentrations of 28.14%, 35.00%, 42.75% and 50.00%, to which the deflocculant additive was applied. The physical model assumes that the flow of the tested hydromixture is fully developed, axially-symmetrical and isothermal. The detailed assumptions made in the physical model are as follows:

- The flowing medium is a homogeneous and incompressible mixture of water and fine limestone particles, referred to as a hydromixture.
- The carrier phase is water with a density of 998.2 kg/m^3.
- The solid phase consists of hydrophobic solid particles with a density of 2400 kg/m^3.
- The diameters of the solid phase particles range from 0.5 μm to 163.5 μm.
- The average diameter of the solid particle grains is 45.5 μm.
- The flow is carried out in a circular cross section, where the inner diameter of the suction and discharge pipes are the same and equal 200 mm.
- The flow of the hydromixture occurs in a smooth steel pipe.
- The total height difference between the inlet and the outlet length of the pipeline is 11 m. Due to the uphill topography of the area where the pipeline is located, the difference between the pipeline inlet and outlet is considered a net increase.
- The flow of the hydromixture is turbulent.

On the basis of the assumptions made in the physical model, the final form of the Bernoulli equation describing the total pressure drop of the hydromixture flow in the analysed pipeline can be written as Equation (1).

The values of the local loss coefficient on the individual bends of the analysed pipeline are presented in Table 2.

Using the relationship presented in Equation 1, the pressure drop during the flow of hydromixture in the flow installation was determined in compliance with the method presented in [Jaworska and Dziubiński, 2022].

Assumptions in the model of power consumption in the pipeline transport

Calculations of the energy demand of the motor driving the centrifugal pump during the transport of the hydromixture in a pipeline were performed for parameters corresponding to industrial conditions. The power consumed by the pump was obtained by calculating the power consumption of the electric motor driving the pump. Knowing the efficiency of the electric motor driving the centrifugal slurry pump, the amount of electricity consumption required to pump the lime hydromixture with different mass concentrations was determined. Further details on the adopted methodology can be found in [Jaworska-Jóźwiak, 2023].

To build a mathematical model of power consumption during the flow of lime hydromixture in the pipeline, the starting point is to determine the individual technological conditions of the industrial installation. The article adopted a method that is coherent and consistent with those proposed and discussed in [Sinchuk et al., 2022]. The

$$\Delta p = \frac{\rho_m \cdot U_S^2}{2} \cdot \left(1 + \lambda \cdot \frac{h_1 + L_1 + L_2 + L_3 + L_4 + L_5}{d_r} + \zeta_{SB1} + 2 \cdot \zeta_{\mathrm{DB}\,1,2} + 2 \cdot \zeta_{DB\,3,4} + \zeta_{DB\,5}\right) + \gamma_m \cdot (z_2 - h_0 - h_1) \quad (1)$$

where: Δp – pressure drop (Pa), ρ_m – density of hydromixture (kg/m^3), U_S – mean flow velocity (m/s), λ – friction factor (-), dr – pump diameter (m), γ_m – specific gravity of the hydromixture (N/m^3), h_{0-1}, L_{1-5} – straight sections of the pipeline (m), ζ – loss coefficient of local curved sections of the pipeline, where $_{SB}$ denotes the suction bend and $_{DB}$ denotes discharge bend, respectively, (-), z_2 – the difference between the axis of symmetry of the suction nozzle of the centrifugal pump and the axis of symmetry of the pipeline at the outlet (m).

Table 2. Local loss coefficient on the individual bends of the pipeline

Indication	$\zeta_{SB\,1}$	$\zeta_{DB\,1}$	$\zeta_{DB\,2}$	$\zeta_{DB\,3}$	$\zeta_{DB\,4}$	$\zeta_{DB\,5}$
φ, [°]	90	90	90	90	90	120
ζ	0.170	0.132	0.132	0.131	0.131	1.860

Note: compiled by the authors.

authors of the mentioned publication suggested the application of mathematical modelling of specific technological parameters typical of drainage facilities, such as water inflow, the level of pump head (pump discharge height), pump capacity, the number of pumps, etc. to calculate the daily costs of the selected ore mine at an established level. Simultaneously, the proposed solution was selected as the most economically effective for adoption in the automation of the control systems for electricity consumption by the drainage facilities located in the mine.

Table 3 presents specific technological parameters of the pumping system during the transport of hydromixture with different mass concentrations and with the addition of selected deflocculant in the hydrotransport process carried out in the Polish lime production mine. The presented data consider the specificity of the drainage in the analysed enterprise and are dedicated to the existing pipeline equipment.

The hydromixture marked as 'pure' is free of additions, while the hydromixture marked as '+ DFL' indicates the hydromixture with the addition of the deflocculant.

Presented in Table 3, the indices determine the impact of values of the key technical parameters on the power consumption of the centrifugal pump during the transport of hydromixture in the pipeline.

To determine the significance importance of the influence of input factors, that is, the flow rate of the hydromixture (X1), the height of the pump head (X2) and the nominal pressure (X3) on the amount of electricity consumed by the pump during the pumping of the hydromixture (Y), a statistical analysis of variance of the measurement results was used. The proposed analysis includes the following [Chłopek and Piaseczny, 2002]:

- evaluation of main effects determining the impact of independent variables on the dependent variable,
- determination of the coefficient of determination R^2, which is a measure of the fit of the model to the experimental data,
- determination of regression coefficients of approximating functions,
- assessment of approximation accuracy using approximation functions.

Analysis of variance and determination of the significance of regression coefficients were performed on the regression model defined by the Equation 2:

$$y = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2 + a_3 \cdot x_3 \qquad (2)$$

where: y – the expected value of the dependent variable being tested, x_1, x_2, x_3 – input factors, $a_0, a_1 \ldots a_k$, ($k = 1 \ldots i$, $k > 0$) – regression coefficients.

The presented model was verified at a significance level of 0.05.

Assumptions in the consumption costs analysis

The analysis performed assumed the cost calculation based on the volumetric flow rate of the hydromixture with different mass concentrations in the process of transporting a hydromixture with a constant amount of solid phase mass of 27 t/h. The deflocculant was added to decrease the viscosity of the hydromixture while increasing its mass concentration values. It should be emphasised that the comparative cost analysis refers only to those positions that result from the properties and composition of the hydromixture (its variants), as well as from the technical parameters of the installation (pipeline) and devices ensuring flow such as slurry pump. The mentioned factors affect the consumption of energy, industrial water and sodium water glass. Cost items, such as: pipeline operation and maintenance (salaries,

Table 3. Statistical indices of pump power consumption in the hydrotransport process in the tested pipeline

Cm, %	Results	Starting parameters		
	Y	X1	X2	X3
21.30 pure	8.83	110	14.99	1.68
28.14 + DFL	5.81	80	12.96	1.52
35.00 + DFL	4.43	61	12.33	1.52
42.75 + DFL	3.59	48	11.96	1.56
50.00 + DFL	2.99	38	11.89	1.64

Note: Y – power consumption, kWh, X1 – hydromixture flow rate, m^3/h, X2 – pump head, m, X3 – nominal pressure, bar.

outsourced services), purchase costs such as transport and storage of the material were not taken into consideration.

Considering hydromixture transport process, defined as ‘pure’ (without deflocculant addition), there are only two main positions of operating costs that can be distinguished, i.e. electricity and industrial water consumption. The addition of a deflocculant, consisting of sodium water glass and calcareous groats, is to ensure a significant drag reduction in the flow of the hydromixture. Reducing the friction factor of the hydromixture increases the concentration of solids in the hydromixture and thus reduces the consumption of electricity and water in the hydrotransport process. The addition of a deflocculant also reduces the critical velocity and prevents the formation of bottom sediment in the pipeline. Therefore, the cost resulting from the use of different dispersant variants, are generated by the expenses on one of deflocculant components, i.e. sodium water glass.

The total consumption costs were described with Equation 3:

$$TCC = C_{EN} + C_{Ind.H2O} + C_{DFL} \quad (3)$$

where: TCC – total consumption costs, C_{EN} – energy costs, $C_{Ind.H2O}$ – cost of industrial water, C_{DFL} – cost of deflocculant that equals the purchase price of the sodium water glass.

In the analysis of cost and material consumption, five selected mass concentrations of the mixture and two different deflocculant recipes were taken into consideration (with a ratio of calcareous groats to water sodium glass of 1:1 and 1:2). The hydromixture of mass concentration 21.30% was defined the “pure” one. For the next four combinations with mass concentration of 28.14%, 35.00%, 42.75%, and 50.00%, the optimal deflocculant parameters that ensured the greatest decrease in the viscosity of the hydromixture were determined. These optimal deflocculant parameters (Table 4) were developed through many years of experimental research, the knowledge obtained from scientific studies available in the literature and in cooperation with the producer of lime.

RESULTS AND DISCUSSION

Model of energy consumption in the hydrotransport process

Due to the fact that for the independent variable marked as nominal pressure (X3) included in Equation (2), no statistically significant impact on the dependent variable was identified (p – value is higher than the assumed level of significance, $p = 0.762$), Model 1 was modified. The final form of the model prepared using the backward stepwise regression method is as follows:

$$y = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2 \quad (4)$$

The results of the regression analysis for Model 2 are presented in Table 5. On the basis of the application data available in Table 5, the adopted model is the following:

$$y = -8.0919 + 0.0469 \cdot x_1 + 0.7846 \cdot x_2 \quad (5)$$

The proposed model is statistically significant, as evidenced by the value of the F statistic equal to 0.0002 at the assumed significance level of 0.05. For the analysed model, the standard error value is 0.042. This means that the predicted power consumption values differ from the observed values by an average of 0.042 kWh. In the case discussed, the value of the variation coefficient remains at a satisfactory level of 0.8194%, which means that there is very little variability.

The fit of the model presented with the experimental data is very good, as evidenced by the value of the coefficient of determination R2 of 0.9997. As a result of using the backward stepwise regression method, the X3 variable defining

Table 4. Optimal deflocculant parameters for hydromixtures with different concentrations of solids

Mass concentration of the hydromixture Cm (%)	Percentage (mass) addition of deflocculant (%)	Mass fraction of sodium water glass in the deflocculant (%)	Mass fraction of calcareous groats in the deflocculant (%)
21.30	-	-	-
28.14	0.5	50	50
35.00	0.5	67	33
42.75	0.5	50	50
50.00	0.5	67	33

Note: compiled by the authors.

Table 5. Results of statistical analysis obtained for the dependent variable power consumption after applying the backward stepwise regression method – Model 2

Regression statistics						
Multiple R			0.9999			
R Square			0.9998			
Adjusted R2 Square			0.9997			
Standard Error			0.0420			
Observations			5			
Analysis of variance		df	SS	MS	F	Significance F
Regression		2	21.5901	10.7950	6109.7279	0.0002
Residual		2	0.0035	0.0018		
Total		4	21.5936			
Coefficients		Standard error	*t Stat*	*P-value*	*P-value*	*Upper 95%*
Intercept	-8.0919	0.6342	-12.7600	0.0061	-10.8205	-5.3633
X1	0.0469	0.0029	16.3353	0.0037	0.0345	0.0592
X2	0.7846	0.0638	12.2906	0.0066	0.5099	1.0593

Note: compiled using MS Excel.

the nominal pressure, for which the probability value reached a value greater than 0.05 (statistically insignificant), was excluded from the model. This procedure did not significantly change the fit of the model to the empirical data (fitted R2 = 0.9997, while for Model 1 fitted R2 = 0.9994). Moreover, the standard error decreased from 0.0553 to 0.0420.

When analysing the model presented, it can be concluded that an increase in factor feature (X1) – the flow rate of the hydromixture – of 1 m^3 causes an increase in pump power consumption of approximately 0.0469 kWh. Accordingly, an increase in the factor feature (X2), the pump head (pump discharge height), by 1 m causes an increase in pump power consumption by 0.7846 kWh. On the contrary, a decrease in the flow rate and pump discharge height causes a decrease in the amount of electricity consumed by the pump by approximately 0.469 kWh and 0.7846 kWh, respectively.

The purpose of the research is to reduce the consumption costs of the components (materials and energy) in the process of piping a lime hydromixture using a deflocculant, resulting in a reduction in the electricity consumption of the engine that drives the centrifugal slurry pump and the water that circulates in the process. This goal can be achieved by reducing the volumetric flow rate of the hydromixture from 110 m^3/h to 38 m^3/h while increasing its mass concentration from the

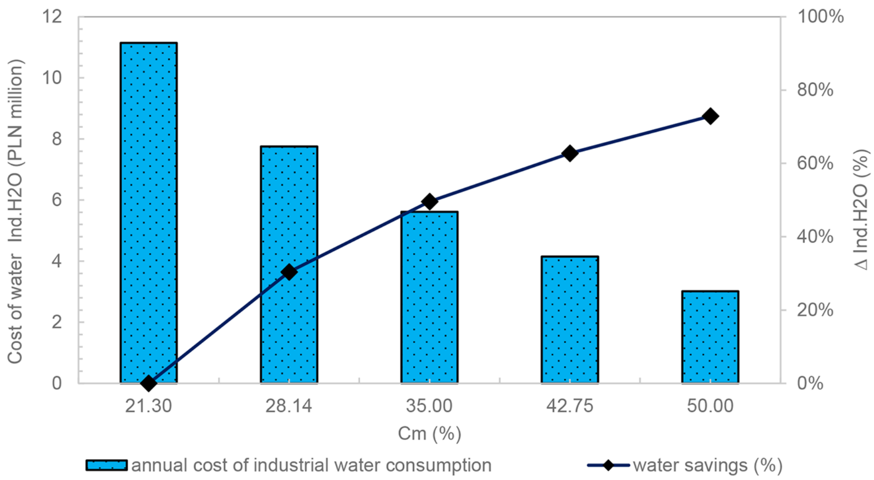

Figure 2. Industrial water costs and savings

base value, i.e. 21.30%, more than twice, i.e. to 50.00%, as a result of use of the addition of the proposed deflocculant. This will save the water circulating in the flow installation by approximately 72 m^3/h. At the same time, the amount of dry matter contained in the hydromixture and pumped per hour will not change, remaining at a constant level of 27 t/h.

Referring to the values of the upper and lower confidence intervals for the independent variables X1 and X2 in the proposed mathematical model, at the adopted significance level, it can be estimated that the total amount of electricity saved in this way will range from 3.69 to 6.88 kW within the installation operating hour. The average hourly value of energy savings as a result of the use of the selected deflocculant can be up to 5.28 kWh.

Components consumption costs analysis

The use of a deflocculant reduces the consumption of industrial water in the process of transporting the hydromixture. Changing the composition of the pumped mixture and its properties (viscosity) has an impact on reducing the power consumed by the electric motor driving the slurry pump. The amount of water used (Ind. H_2O) in the process in m^3 per hour varies, depending on the mixture variant, in the range of 27–69, where the transport of pure hydromixture (without the addition of deflocculant) requires the consumption of 99 m^3 of water per hour. This reduces the volume of water needed from 30 to 72 m^3 per hour (the annual operating time of the pipeline is determined as 8680 hours). Reducing water consumption has a significant impact on costs incurred. For the purposes of the analysis, the price of water for enterprises was assumed to be PLN 13.00 per m^3 (as of April 2024), however, this price/cost varies depending on the voivodeship or region.

Chemical treatment of drilling fluid by the application of the selected deflocculant leads to a significant reduction in water consumption by 30 to 73 percent and can reduce costs from PLN 11.1 million to even PLN 3.0 million, which equals a maximum of PLN 8.1 million in savings (Fig. 2).

Not only is usage of renewable energy sources necessary but also, above all, reducing energy consumption through the use of alternative, easily available solutions. It is shown that the application of deflocculant in a hydromixture transportation process enables both economic benefits and policies towards sustainable development owing to significant energy savings.

In Figure 3, the electricity costs for different variants of hydromixture, i.e. are the pure one and with deflocculant for various mass concentrations, were presented. These are the annual costs of electricity consumed by a pump operating in three shifts, excluding break in winter season (from December to March) and maintenance in the summer season (in July it is the period of time lasting approximately 14 days). The maximum energy saving is 66% (for the mixture with Cm 50%) in comparison with basic hydromixture of concentration 21.3% (pure).

Sodium water glass is a non-toxic material, commonly used, among others, in water treatment processes [Koźlak, 2012]. Liquid glass applications continue to grow in such areas as detergents, adhesives, sealants, water treatments,

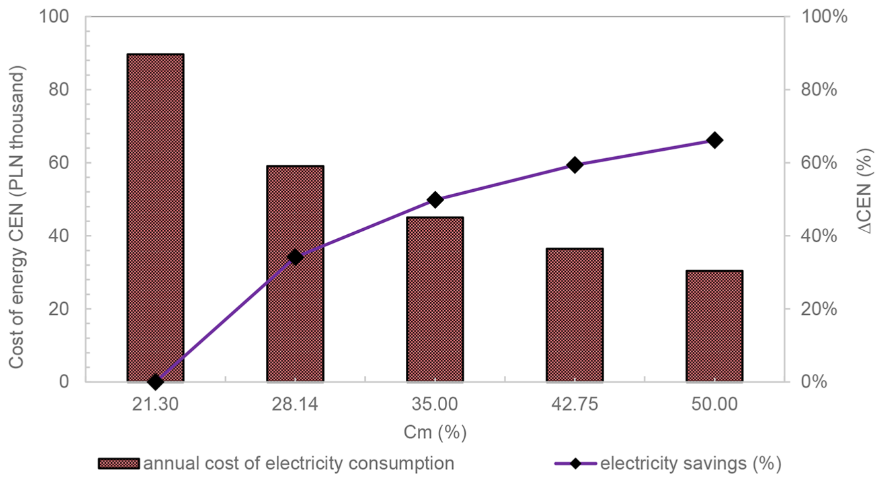

Figure 3. Electricity consumption costs and savings

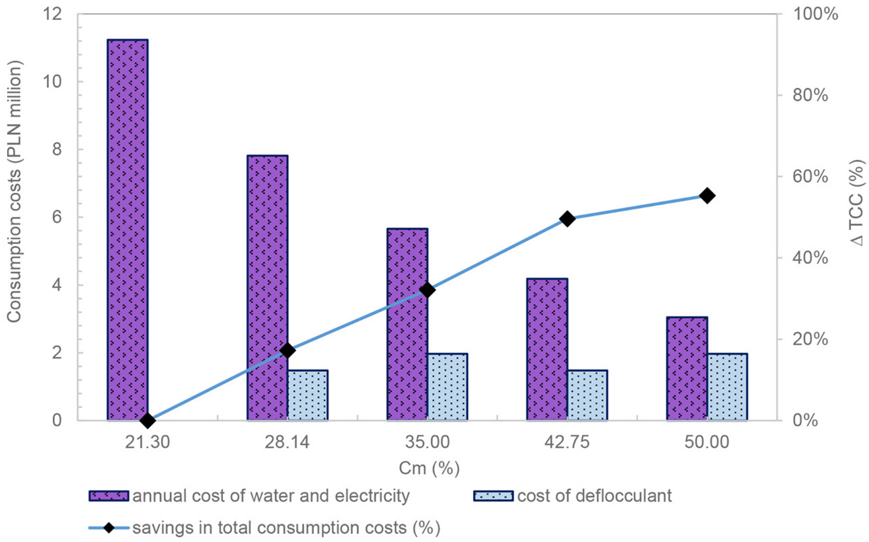

Figure 4. Total consumption costs and savings

cements, deflocculants, protective coatings, catalysts, buffers, paper industries, zeolites, and geopolymers. The multi-functionality of water glass is due to many factors including its relatively low cost, abundance, alkalinity, buffering ability, emulsification, non-toxicity, and viscosity-regulating properties [Matinfar and Nychka, 2023]. In the case of sodium water glass, the unquestionable advantage is its common occurrence and low purchase cost. The price of the sodium water glass in 2024 is PLN 2823.96 (net value, excluding VAT) per canister with a capacity of 1120 kg which gives an average market price of PLN 2.52 per kg (data as of July 1, 2024). When analysing the costs it was necessary to consider two optimal deflocculant recipes with a ratio of calcareous groats to water glass of 1:1 and 1:2. The calculations indicate costs of PLN 1,477,284.08 for hydromixtures with the first deflocculant applied (Cm 28.14% and 42.75%) and PLN 1,969,712.10 for hydromixtures treated with the second deflocculant (Cm 35% and 50%). The results are presented in the Figure 4.

Calcareous groats consist of mineral particles with a grain diameter of less than 1.8 mm and an average grain diameter of 240 μm. As it is a residue from the lime slaking process that produces hydrated lime, the component does not have to be purchased by the analysed enterprise, therefore it does not generate any costs.

CONCLUSIONS

The process described in the article is mainly focused on the pipeline transport of hydromixture arising as a result of the rinsing of extracted and crushed stones in the limestone mine. To improve the analysed transport process, the addition of an additive called deflocculant as a drag reduction agent was applied. The selected deflocculant consists of the waste material from the lime slaking process and an environmentally neutral chemical substance in the form of sodium water glass. The application of a deflocculant to the transported hydromixture reduces the friction coefficient during its flow in the pipeline. This results in a reduction of the viscosity as a consequence of the reduction of the shear stress in the hydromixture. Furthermore, the application of the proposed deflocculant to the transported hydromixture enables an increase in the concentration of solid particles of the hydromixture. This allows control of the hydrotransport process and influence of the prevention of pipe clogging of the pipeline installation. Another advantage of the proposed solution is the limitation of the number of flow facilities. Implementing the proposed solution is relatively easy and does not require large financial outlays.

In terms of analysis of energy consumption in the process of transporting a hydromixture with the addition of a deflocculant during the daily operation of the limestone mine, a generalised mathematical model referring to the transport of lime slurry from the reservoir to a settling tank has been developed. Mathematical modelling of the flow of lime hydromixture with the addition of deflocculant in a pipeline revealed the most efficient technology parameters connected with mass concentration, flow rate, and pump head. In the case of the analysed pumping installation, the optimal transport parameters for the flow of hydromixture with the addition of deflocculant assume the mass concentration of the hydromixture equal 50.00%, the flow rate of 38 m^3/h and the height of the pump head equal 11.89 m.

The proposed solution resulted in a decrease in the pump power consumption of the motor and obtained significant energy savings in the hydromixture transport process. Thus, it is possible to pump the hydromixture with a concentration of solids more than twice as high with almost three times lower flow rate. This resulted in a reduction in industrial water to a level of approximately one-third in relation to the base hydromixture and optimisation of the total costs of the hydrotransport process. At the same time, the amount of dry matter contained in the hydromixture and pumped per hour will not change, remaining at a constant level of 27 t/h.

The cost analyses clearly indicate the profitability of using the deflocculant. For all variants of hydromixtures, deflocculation results in significant savings in total consumption costs. For hydromixtures with different mass concentrations, i.e. 28.14%, 35%, 42.75%, 50%, the savings are 17%, 32%, 50% and 55%, respectively.

The achievement of significant energy savings in the hydromixture transport process is indispensable in times of crisis, continuous climate changes, and high-energy prices. The results of the analysis showed that controlling the mass concentration of the pumping hydromixture with the addition of a selected deflocculant, flow rate, and pump head improves the energy efficiency of the analysed hydrotransport process in the limestone mine. The application of a deflocculant not only increases the economic efficiency of the lime production process but is also a highly ecological method consistent with the principles of Corporate Social Responsibility. Under the conditions of rising energy prices and the climate crisis, achieving high profits without waste and by maximum possible reduction of the consumption of resources, such as water and energy, is crucial in an enterprise strategy and indispensable for its survival and further development. Moreover, the developed method helps expand the research boundaries involving other elements of the industrial installation operation performed during daily limestone mining.

REFERENCES

1. Jasińska-Biliczak, A. Smart-city citizen engagement: the answer to energy savings in an economic crisis? Energies 2022, 15, 8828. https://doi.org/10.3390/en15238828
2. URE: Energy Regulatory Office. Average selling price of electricity on the competitive market (annual and quarterly) in Poland in 2018–2024. Available on: https://www.ure.gov.pl/pl/energia-elektryczna/ceny-wskazniki/7852,Srednia-cena-sprzedazy-energii-elektrycznej-na-rynku-konkurencyjnym-roczna-i-kwa.html
3. PGE: Polish Energy Group S.A. Tariff for electricity distribution services of PGE Distribution S.A. Available on: https://pgedystrybucja.pl/strefa-klienta/informacje-dla-konsumenta/taryfy-i-cenniki
4. Ashok, S. Peak-load management in steel plants. Applied Energy. 2006, 83(5), 413–424. https://doi.org/10.1016/j.apenergy.2005.05.002
5. Wang, J., Wang, Q.,Sun, W. Optimal power system flexibility-based scheduling in iron and steel production: A case of steelmaking-refining-continuous casting process. Journal of Cleaner Production. 2023, 414, 137619. https://doi.org/10.1016/j.jclepro.2023.137619
6. Skoczylas, A., Stefaniak, P., Gryncewicz, W., Rot, R. The Concept of an intelligent decision support system for ore transportation in underground mine. Procedia Computer Science. 2023, 225, 922–931. https://doi.org/10.1016/j.procs.2023.10.079
7. Energy Regulatory Office in Poland. Average selling price of electricity in the competitive market. https://www.ure.gov.pl/pl/energia-elektryczna/ceny-wskazniki/7852,Srednia-cena-sprzedazy-energii-elektrycznej-na-rynku-konkurencyjnym-roczna-i-kwa.html (accessed on 20 July 2024)
8. Chhabra, R.P. and Richardson, J.F. Non-Newtonian Flow and Applied Rheology, 2nd ed. Butterworth-Heinemann: Oxford, UK, 2008.
9. Grobler, L.J. and den Heijer, W.L. The effect of data period selection for the development of measurement and verification baselines for mine pumping projects. Energy Engineering, 2006, 103(3). https://doi.org/10.1080/01998590609509466
10. Wu, J., Graham, L., Wang, S. and Parthasarathy, R. Energy efficient slurry holding and transport. Minerals Engineering. 2010, 23, 705–712. https://doi.org/10.1016/j.mineng.2010.04.008
11. Zhang, H., Zhang, J. and Xia, X. Optimal sizing and operation of pumping systems to achieve

energy efficiency and load shifting. Electric Power Systems Research. 2012, 86, 41–50. https://doi.org/10.1016/j.epsr.2011.12.002

12. Xia, X. and Zhang, J. operation efficiency optimisation modelling and application of model predictive control. In IEEE/CAA Journal of Automatica Sinica. 2015, 2(2), 166–172. https://doi.org/10.1109/JAS.2015.7081656
13. Brand, H., Vosloo, J. C. and Mathews, E. H. Automated energy efficiency project identification in the gold mining industry. Proceedings of the Conference on the Industrial and Commercial Use of Energy, 2015, 17–22. https://doi.org/10.1109/ICUE.2015.7280241
14. Van Staden, A.J., Zhang, J. and Xia, X. A model predictive control strategy for load shifting in a water pumping scheme with maximum demand charges. Applied Energy, 2009, 88(12), 1–7. https://doi.org/10.1016/J.APENERGY.2011.06.054
15. Jaworska-Jóźwiak, B. Assessment of slurry transport efficiency after applying deflocculant in the lime production process. Management and Production Engineering Review, 2023, 14(4), 1–8. https://doi.org/10.24425/mper.2023.147203
16. Sinchuk, O., Strzelecki, R., Beridze, T., Peresunko, I., Baranovskyi V., Kobeliatskyi D. and Zapalskyi V. Model studies to identify input parameters of an algorithm controlling electric supply/consumption process by underground iron ore enterprises. Mining of Mineral Deposits. 2023, 17(3), 93–101. https://doi.org/10.33271/mining17.03.093
17. Middelberg, A., Zhang, J., and Xia X. An optimal control model for load shifting with application in the energy management of a colliery. Applied Energy, 2009, 86, 1266–1273. https://doi.org/10.1016/j.apenergy.2008.09.011
18. Patterson, S.R., Kozan, E. and Hyland, P. An integrated model of an open-pit coal mine: improving energy efficiency decisions. International Journal of Production Reserach, 2016, 54(14). https://doi.org/10.1080/00207543.2015.1117150
19. Sinchuk, O., Strzelecki, R., Sinchuk, I., Beridze, T., Fedotov, V. and Baranovskyi, V. Mathematical model to assess energy consumption using water inflow-drainage system of iron-ore mines in terms of a stochastic process. Mining of mineral Deposits, 2022, 4, 19–28. https://doi.org/10.33271/mining16.04.019
20. Hao, C.H., Wesseh, P.K.Jr., Wang, J., Abudu, H., Dogah, K.E., Okorie, D.I. and Opoku, E.E.O. Dynamic pricing in consumer-centric electricity markets: A systematic review and thematic analysis. Energy Strategy Reviews, 2024, 52, 101349. https://doi.org/10.1016/j.esr.2024.101349
21. Xia, X. and Zhang, J. Mathematical description of the performance for the measurement and verification of energy efficiency improvement. Applied Energy, 2013, 111, 247–256. http://dx.doi.org/10.1016/j.apenergy.2013.04.063
22. Shook, C. and Roco, M. Slurry Flow: Principles and practice. 1991, Boston: Butterworth-Heinemann.
23. Jaworska-Jóźwiak, B. and Dziubinski, M. Effect of Deflocculant Addition on Energy Savings in Hydrotransport in the Lime Production Process. Energies, 2022, 15(11), 3869. https://doi.org/10.3390/en15113869
24. Chłopek, Z. and Piaseczny, L. Application of the theory of experimental planning in the study of the ecological properties of combustion engines. Automotive Archive, 2002, 2(3), 69–93.
25. Koźlak, W. Evaluation of possibility to use sodium water glasses produced in Poland to remove Ag+ ions from aqueous media. Ecol Chem Eng A. 2012, 19(10), 1289–1295. https://doi.org/10.2428/ecea.2012.19(10)124
26. Matinfar, M., Nychka, J.A. A review of sodium silicate solutions: Structure, gelation, and syneresis. Advances in Colloid and Interface Science 2023, 322, 103036. https://doi.org/10.1016/j.cis.2023.103036