The Effect of Sodium Hexametaphosphate on Natural Flotation Kinetics of Talc Ore

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Abstract

Ground high-grade ore with the d80 of 150 μm was subjected to a series of batch laboratory flotation tests, aimed at determining the natural flotation kinetics of talc mineral, using Methyl isobutyl carbinol (MIBC) frother as the only reagent. Classical first-order flotation model was used and the flotation kinetics are interpreted using the ultimate recovery (R_∞) and flotation rate constant (k). Results are then compared with the kinetics of flotation in the presence of different dosages of the frother, Sodium hexametaphosphate (SHMP) and a mixture of SHMP and Soluble starch (SS) in various ratios. The design of experiment (DoE), evaluated using the Analysis of variance (ANOVA) test for multiple factors was used to calculate the statistical significance of the individual factors on the outcomes of the flotation tests – yield of the froth product, talc concentrate grade, talc recovery and flotation kinetics of both talc and gangue minerals. The effect of SHMP on the flotation kinetics of talc and gangue minerals in terms of affecting the R_∞ and k parameters is here discussed in greater detail. Although both SHMP and SHMP/SS mixture was found to improve the overall grade of the talc concentrate, this was achieved at the expense of significantly lower recoveries of the valuable mineral.

Keywords: froth flotation, natural floatability, flotation depressor, flotation kinetics, talc ore

Introduction

Talc is a naturally floatable mineral, which is often accompanied by hydrophilic minerals such as carbonates, quartz, and silicates. This allows some talc ores to be treated by froth flotation using frother as the only reagent (Aghazadeh et al. 2015).

However, other flotation reagents might be used for improving the recovery of talc, selective depression of gangue minerals or pH adjustment. Fatty acids can be e.g. used as collectors for talc and their effect can be further improved by using kerosene, SHMP can be used as a selective depressant for CaO and Al_2O_3 containing minerals and pH can be adjusted as the recovery of talc increases as the value of pH increases up to 11 (Mahmoud et al. 2011).

According to Feng et al. (2012), floatability of talc particles is reduced by formation of coatings of slime mineral coatings on the talc surface. These fine particles with opposite charge are attracted to talc particles through an electrostatic mechanism. Authors draw a conclusion that SHMP acts as a dispersant, it adsorbs to a surface of the slime mineral particles and renders the charge of these particles negative. Particles with negatively charged surfaces are thus electrostatically repulsed from also negatively charged talc particles.

Our intention is to evaluate the effect of SHMP on froth flotation of talc ore mainly in terms of flotation kinetics. The aim of this study is to provide some basic information whether SHMP improves results of froth flotation processing by affecting the rate of flotation or the portion of recoverable minerals.

Materials and methods

Ore analysis and comminution

In experimental section of this work, talc-magnesite ore from a local supplier in Slovakia was used. A sample of the ore from different locations of the ore body was manually inspected. Besides talc lumps, at least five other mineral species were identified. Individual mineral specimens were based on their properties classified according to Nickel-Strunz classification as three silicate minerals (talc and laminated phyllites), one oxide mineral (quartz), carbonate (dolomite) and sulfide mineral (pyrite). Individual samples were crushed in a crucible and analyzed. The result of the chemical analysis is shown in Table 1.

Sample with lumps up to several centimeters in size was then crushed in two stages and ground in a dry ball mill with steel ball charge according to flowsheet shown in Figure 1. Screening or sieving was used prior to each comminution stage as a means to avoid over-grinding of the ore. It was previously shown, that the presence of very fine particles has a negative effect on the concentrate grade due to entrainment effect (Brezáni et al., 2013) and possibly also because of formation of slime

Tab. 1 Chemical analysis of minerals identified in the sample of the ore Note: Loss on ignition (LOI) at 1000°C.

Tab. 1. Analiza chemiczna minerałów zidentyfikowanych w próbce [Uwaga: starty prażenia (LOI) w 1000°C]

		Talc	Silicate I	Silicate II	Quartz	Dolomite	Pyrite
LOI	(%)	4.54	7.97	3.55	2.09	47.54	32.74
SiO_2	(%)	61.32	58.1	64.82	85.32	3.44	-
MgO	(%)	30.84	10.45	11.61	7.74	19.75	-
CaO	(%)	0.52	2.15	3.23	2.15	27.46	-
Fe_2O_3	(%)	0.87	2.96	3.45	0.69	0.99	63.74
Al_2O_3	(%)	0.42	17.58	12.64	1.27	0.19	0.59
Mn	(%)	0.202	0.234	0.245	0.169	0.215	0.312
Cu	(%)	0.074	0.08	0.095	0.064	0.054	0.115
Zn	(%)	0.006	0.01	0.012	0.008	0.009	0.006
Pb	(%)	0.007	0.012	0.022	0.015	0.028	0.021
Σ	(%)	98.799	99.546	99.674	99.516	99.676	97.524

mineral coatings on surfaces of talc particles (Feng et al. 2012).

Froth flotation

Flotation experiments were carried out in automated laboratory froth flotation machine described in Brezáni and Zeleňák (2011) using 3 L Denver type flotation cell. The slurry contained 300 $g.L^{-1}$ solids and the temperature was kept at 20°C during all the experiments. After the weighed material was transferred to the agitated cell (1600 rpm), reagents were added and 5 to 25 minutes of conditioning were allowed depending on the number and character of the reagents used in individual flotation tests. After the end of the conditioning period, the air was introduced into the cell with airflow electronically regulated to 5 $L.min^{-1}$. Three froth products were collected in each flotation tests: skimmed for 2, 3 and 5 minutes resulting in a cumulative flotation time of 10 minutes. Four products (the three froth products and a cell product) were then filtered, dried, weighed and a representative sample was taken for analysis. Each laboratory froth flotation test was repeated twice.

Results

A custom fractional factorial design plan used in this study is summarized in Table 2. The plan involves three factors – dosage of Methyl isobutyl carbinol (MIBC) frother at two levels, Sodium hexametaphosphate (SHMP) and Soluble starch (SS), both at three levels. The plan also includes two tests with MIBC only. Native flotation using frother as the only reagent in froth flotation of a primary talc ore is a common way for the preparation of concentrates (Brezáni et al., 2013, Aghazadeh et al. 2015). Because of the focus of the investigation on the effect of SHMP, tests with only SS and MIBC, without SHMP were not planned.

Table 1 also shows direct results of the froth flotation tests – yields of the four individual products and their LOI values. In the case of optimization towards the highest recovery of talc to froth product (e.g. roughing or scavenging operations) the native flotation of talc can be recommended, producing tailings (after 10 minutes of flotation) with the highest LOI (lowest talc content). If product grade is the optimization factor (cleaning operations), the use of SHMP and SS might be considered.

Due to a relatively large number of products prepared in the test a decision was made to evaluate the results using only the LOI. Such an approach was proven sufficient, time and cost effective in former studies conducted with talc ore (Brezáni et al., 2013, Zeleňák and Škvarla, 2001). Nevertheless, the interpretation of results using effects of individual factors (whether it increases or decreases response variable) rather than the interpretation of absolute values allows such a simplification.

For the calculation of product grades from the loss on ignition, following equation was used:

$$\beta = \frac{LOI_P - LOI_G}{LOI_T - LOI_G} 100\%$$

where LOI_P, LOI_T and LOI_G is a loss on ignition (wt. %) of the product, pure talc and gangue minerals, respectively. First, the LOI of gangue minerals were determined. The LOI of the cell product resulting from roughing and scavenging flotation, containing mostly gangue minerals and only small amounts of talc was 20.15%. For the calculations, a value of LOI of gangue minerals (LOI_G) of 22% was used, leading to a calculation of more conservative results in terms of both recovery and product grade.

A theoretical value of LOI of pure talc (LOI_T) of 4.75% was used. The same equation was also used for calculation of talc content in the feed (α).

Recovery of talc and gangue minerals to individual products was then calculated. Results of the calculations – flotation kinetics (time-dependent recoveries) of talc and the gangue minerals are shown in Figure 2.

Results were fitted with classical first order flotation kinetics model described in Gupta and Yan, (2006):

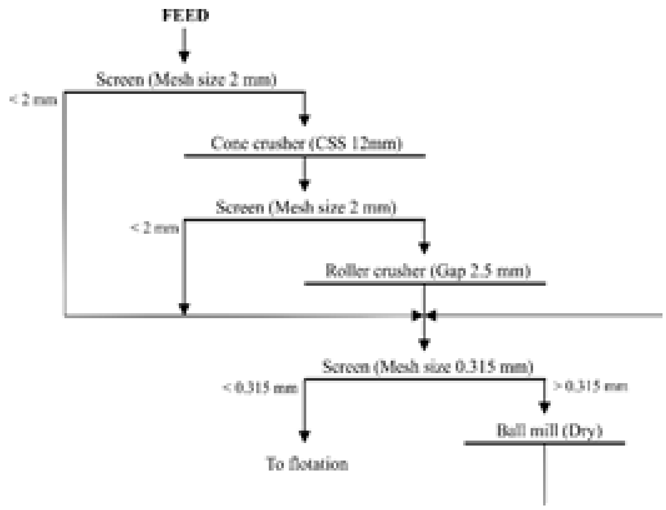

Fig. 1 Flowsheet of comminution of the head sample prior to froth flotation tests

Rys. 1. Schemat rozdrabniania przed flotacją

Tab. 2 Factorial plan used in this study and results of the laboratory froth flotation tests. Note: Partial flotation time (0-2, 2-5 and 5-10) in minutes, cell product (C). The # notation based on 1, 2 and 0 digits represent low, high and null factor values of the three investigated reagents.

Tab. 2. Plan czynnikowy eksperymentu w warunkach laboratoryjnych. Uwaga: Czasy flotacji (0-2, 2-5 i 5-10) min, produkt komorowy C. Oznaczenie # cyfry: 1, 2 i 0 oznacza niski, wysoki I zerowy zawartość od-czynnika

#	Reagent dosage ($g.t^{-1}$)			Froth yield (%)			Loss on ignition (%)			
	MIBC	SHMP	SS	$^{0-2}\gamma$	$^{2-5}\gamma$	$^{5-10}\gamma$	^{0-2}LOI	^{2-5}LOI	^{5-10}LOI	^{C}LOI
100	50	0	0	54.20	12.54	3.79	6.62	6.01	6.33	15.98
110	50	500	0	49.01	8.64	4.56	5.90	5.82	5.84	14.55
111	50	500	250	34.03	11.65	6.74	5.53	5.74	5.70	14.52
112	50	500	500	28.80	12.55	7.32	5.42	5.55	5.96	14.41
120	50	1500	0	47.99	9.22	4.08	5.92	5.73	5.71	15.26
121	50	1500	250	37.79	10.04	5.99	5.58	5.99	6.14	14.36
200	80	0	0	57.36	10.40	3.46	6.42	6.36	7.14	18.40
210	80	500	0	50.82	9.28	3.99	5.96	5.87	5.74	16.94
211	80	500	250	45.43	9.75	5.44	5.70	6.13	6.41	16.35
220	80	1500	0	52.98	8.58	4.12	5.98	6.07	6.17	16.81
221	80	1500	250	46.32	9.90	4.39	5.92	6.84	6.71	15.03
222	80	1500	500	32.63	11.42	7.09	5.82	6.30	6.40	14.30

$$\varepsilon = \varepsilon_{\infty}\left(1 - e^{-k\tau}\right)$$

where ε is the cumulative recovery of mineral (wt./wt.) and τ is a flotation time (min) at which the cumulative recovery is calculated. ε∞ and k are model parameters: ultimate (infinite) recovery (wt./wt.) and flotation rate constant (min-1), respectively. This was done in order to obtain numerical values representing the kinetics of flotation of talc and gangue minerals, which could then be statistically evaluated. Parameters of the fitted model are summarized in Table 3.

Results (p-values) were calculated for response variables – cumulative yield of the froth product after 2, 5 and 10 minutes of flotation, cumulative grade of the froth product and kinetics parameters. Results of the N-Way ANOVA test calculated using MATLAB function *anovan* is summarized in Table 4.

The purpose of ANOVA is to test if two or more groups differ from each other significantly in one or more characteristics. A significance level of 0.05 was chosen for the interpretation of the results. The null hypothesis (that the population means are all equal) can, therefore, be rejected for all of the p-values in Table 4 accentuated by italics. The differences between the means of these factors are statistically significant. For these factors, also covariation was calculated (the + and – superscript in Table 4) as a means of determining whether the effect of the factor is positive – increases the value of the response variables, or negative – decreases it. As for the other factors (p-values wrote using regular font), there was not enough evidence to prove the statistical significance of the response variables.

Based on the results of the ANOVA test and covariation of the factor levels with the response variables,

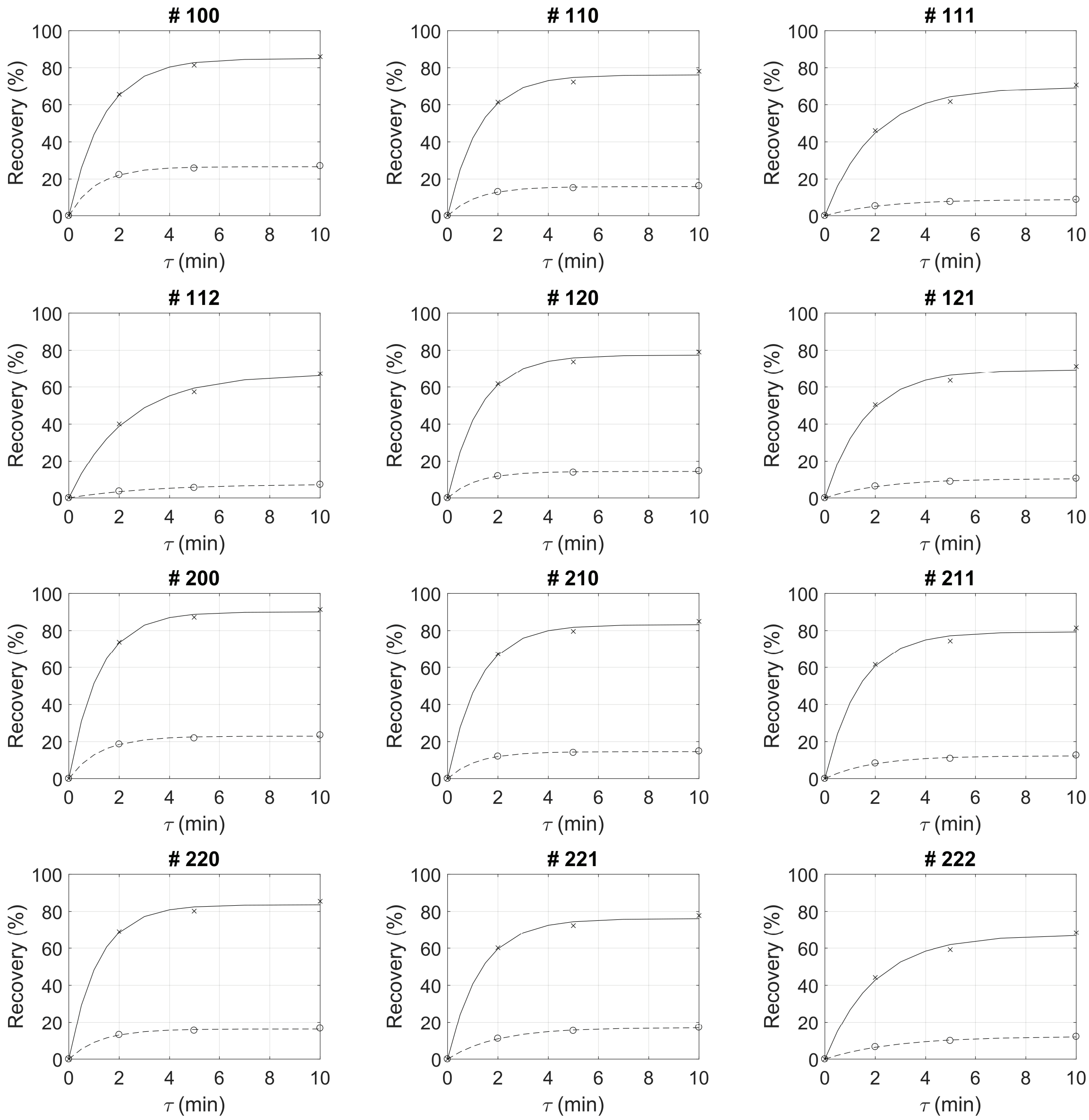

Fig. 2 Calculated recovery of talc (x) and gangue minerals (o) and fitted classical flotation kinetics model (lines)

Rys. 2 Obliczony odzysk minerałów talku (x) i skały płonnej (o) oraz dopasowany klasyczny model kinetyki flotacji (linie)

Tab. 3 Estimated parameters of the classical flotation kinetics model. Note: Ultimate recovery (ε_∞), flotation rate constant (k) and coefficient of determination (R2).

Tab. 3 Oszacowane parametry klasycznego modelu kinetyki flotacji. Uwaga: Ostateczny odzysk (ε_∞), stała szybkości flotacji (k) i współczynnik determinacji (R2).

#	Talc kinetics			Gangue kinetics		
	ε_∞	k	R^2	ε_∞	k	R^2
	(-)	(min^{-1})	(-)	(-)	(min^{-1})	(-)
100	0.850	0.729	0.986	0.266	0.897	0.957
110	0.761	0.803	0.930	0.156	0.841	0.923
111	0.695	0.519	0.967	0.087	0.438	0.985
112	0.671	0.434	0.984	0.074	0.300	0.981
120	0.774	0.784	0.952	0.142	0.873	0.946
121	0.695	0.623	0.944	0.104	0.436	0.972
200	0.901	0.845	0.974	0.230	0.815	0.937
210	0.832	0.812	0.952	0.145	0.863	0.959
211	0.794	0.727	0.936	0.123	0.529	0.949
220	0.836	0.861	0.936	0.162	0.811	0.932
221	0.762	0.765	0.954	0.170	0.516	0.990
222	0.673	0.507	0.963	0.122	0.365	0.987

Tab. 4 Analysis of variance table investigating the effects of the three reagents on kinetics of froth flotation. Note: Table shows calculated p-values. Cumulative flotation time (^{2}, ^{5} and ^{10}) in minutes. The + and – superscripts denote whether the effect of the factor is positive or negative.

Tab. 4 Analiza wariancji dla wpływu trzech odczynników na kinetykę flotacji pianowej. Uwaga: w tabeli wyliczono wartość - p. Sumaryczny czas flotacji (2, 5and 10) minut. Oznaczenie + ai – świadczy czy wpływ czynnika jest pozytywny czy negatywny.

Factor	Froth yield			Froth grade			Talc kinetics		Gangue kinetics	
	$^2\gamma$	$^5\gamma$	$^{10}\gamma$	$^2\beta$	$^5\beta$	$^{10}\beta$	ε_∞	k	ε_∞	k
MIBC	0.009^+	0.013^+	0.012^+	0.174	0.082	0.045^-	0.002^+	0.014^+	0.283	0.536
SHMP	0.097	0.019^-	0.012^-	0.005^+	0.008^+	0.006^+	0.012^-	0.565	0.010^-	0.975
SS	0.001^+	0.001^-	0.001^-	0.042^+	0.175	0.341	0.001^-	0.001^-	0.106	0.001^-

following assumptions were made:

- Increased dosage of the MIBC frother increases the yield of the froth product but has a negative effect on froth grade (talc content in concentrate) when flotation time is longer than 5 minutes. This can be attributed to increasing both of the model parameters – ultimate recovery and flotation rate constant of talc, while not affecting flotation kinetics of gangue minerals. Most of the recoverable talc particles report to froth product in first minutes of flotation and prolonged flotation time is coupled with the formation of froth with higher content of gangue minerals.
- The addition of SHMP decreases the yield of the froth product while increasing the froth grade. This is achieved by decreasing the ultimate recovery of both talc and gangue minerals, flotation rate constant is however not affected. The higher grade of the froth product can be in terms of flotation kinetics explained by a higher decrease in the portion of floatable gangue minerals particles in relative terms than that of talc.
- In the presence of SHMP, use of SS results in a statistically very significant ($p \leq 0.001$) decrease in froth product yields. The positive effect of SS on froth grade was however statistically proven only in early stages of flotation. While SS decreases the rate of flotation of gangue particles, the rate of flotation and portion of floatable talc particles also decreases.

Conclusion

Native flotation, using frother such as MIBC as the only reagent was found to be a good method for achieving a high recovery of talc to froth product at natural pH. Such an approach could be advised for roughing or scavenging operations of the talc ore processing using the froth flotation method. Should the concentrate grade be the main concern, use of the SHMP is advised. While it does improve the grade of the froth product by decreasing the portion of floatable gangue particles, lower recoveries of talc must be expected when compared to native flotation. It is also notable that SHMP does not affect the rate of flotation of gangue, nor talc particles, it only affects infinite recoveries.

Use of the combination of SHMP an SS is however not recommended. While SS does improve the grade of concentrate (when short flotation time is used), the penalty comes in form of lower portion of recoverable talc particles and also their lower flotation rate.

Although the effect of SHMP in terms of affecting main response variables (yield and grade) and flotation kinetics is here described, this paper does not investigate or discuss phenomena behind it. Also, evaluation of the results using surface methodology might bring an even better understanding of the presented results. Further in-depth investigations should therefore follow.

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Wpływ heksametafosforanu sodu na kinetykę flotacji naturalnej rudy talkowej

Zmielona wysokowartościowa ruda o ziarnie podziałowym d80 = 150 μm została poddana serii laborato-ryjnych prób flotacji, mających na celu określenie kinetyki flotacji naturalnej minerałów talku, w obec-ności jedynego środka zbierającego metylo-izo-butylokarbinol (MIBC). Zastosowano klasyczny model flotacji pierwszego rzędu gdzie kinetykę flotacji interpretuje się za pomocą współczynnika uzysku R∞ i stałej szybkości flotacji (k). Wyniki porównano z kinetyką flotacji w obecności różnych dawek spienia-cza, heksametafosforanu sodu (SHMP) i mieszaniny SHMP i rozpuszczalnej skrobi (SS) w różnych pro-porcjach. Plan eksperymentu (DoE), oceniono za pomocą analizy wariancji (ANOVA) dla wielu czynni-ków użyto do obliczenia istotności statystycznej parametrów flotacji - wydajność produktu pianowego, zawartość talku, uzysk talku i kinetyka flotacji zarówno minerałów talku, jak i skały płonnej. Wpływ SHMP na kinetykę flotacji minerałów talku i skały płonnej na parametr R∞ i k są omówione bardziej szczegółowo. Chociaż stwierdzono, że dla obu mieszanek SHMP i SHMP / SS poprawie uległ stopień koncentracji talku odbyło się to jednak kosztem znacząco niższych wartości uzysku cennego minerału.

Słowa kluczowe: flotacja pianowa, flotowalność naturalna, depresor, kinetyka flotacji, ruda talku