International Journal of Mining and Geo-Engineering IJMGE

IJMGE 53-1 (2019) 1-6 DOI: 10.22059/ijmge.2018.245520.594705

Investigating the effects of particle size and dosage of talc nanoparticles as a novel solid collector in quartz flotation

Abdolmotaleb Hajati [a, b, *], Ziaedin Shafaei [b], Mohammad Noaparast [b], Saeed Farrokhpay [c], Soheila Aslani [b]

[a] *Department of Mining Engineering, Arak University of Technology, Arak, Iran*
[b] *School of mining, College of Engineering, University of Tehran, Tehran, Iran*
[c] *Université de Lorraine, GeoRessources Laboratory, Vandœuvre-lès-Nancy, France.*

Article History:
Received: 10 November 2017,
Revised: 24 February 2018,
Accepted: 29 March 2018.

ABSTRACT

In this study, hydrophobic talc nanoparticles were applied as a novel class of solid flotation collector. The aim of this work was to understand the effect of talc nanoparticles size and dosage on the quartz flotation recovery. X-ray analysis, dynamic light scattering, and scanning electron microscopy were conducted. Flotation tests were performed in modified a Hallimond flotation cell. The Zeta potential measurement identified the pH value of 1.5 as the best condition for nano-talc powders to be electrostatically adsorbed on the quartz particle surfaces. Talc particles were adsorbed onto the hydrophilic quartz particles to encourage the air bubble attachment and improve the quartz flotation recovery. It was found that as the quartz particle size decreased, the amount of quartz flotation recovery increased. Talc size reduction from 567 nm to 235 nm, decreased the amount of required talc from 45 to 1.7 kg/t within 30 minutes of the flotation time span, and achieved a recovery of more than 90%. Practically, it was demonstrated that by using smaller talc nanoparticles, it was possible to decrease the talc dosage to obtain a similar level of quartz recovery over the same flotation time span and pH.

Keywords : *Flotation, Quartz, Talc nanoparticles, Solid collector*

1. Introduction

Froth flotation is a highly versatile method for separation of mineral particles based on the differences in their ability to attach air bubbles in a mineral-water slurry. A collector is generally required in flotation to assist the attachment of particles and bubbles. On a broad basis, collectors can be defined as organic chemical substances in which the molecular structure is divided into a non-polar and a polar group [1]. There are two types of water-insoluble collectors: oily hydrocarbons and long-chain amphipathic compounds. All these materials are widely used as flotation collectors for the beneficiation of minerals [2-3].

Collectors can selectively bind to the mineral-rich particles and increase their hydrophobicity and promote the selective flotation. Conventional collectors are small surfactants with a short hydrocarbon tail (2-6 carbons) and a head group (e.g. xanthates). The conventional collectors are different types of liquid with an extended molecular length of about 1 nm. In contrast, the average diameter of natural hydrophobic nanoparticles varies generally between 50 to 600 nm. Therefore, it may be possible to introduce larger hydrophobic nanoparticles based on their natural hydrophobicity as potential flotation collectors. For example, inorganic nanoparticles have been applied as a collector in the flotation of glass beads and preparing thin films of nickel sulfide [4]. Commercial grades of precipitated calcium carbonate (PCC) and colloidal silica have been employed as collectors for flotation of glass beads and the flotation results have shown a high recovery of glass beads [5]. The ability of cationic polystyrene nanoparticles to induce the flotation has been also demonstrated by the floating hydrophilic, negatively charged glass beads [4, 6, 7]. Electrostatic attraction promotes the spontaneous deposition of the nanoparticles on the glass surfaces, raising the effective contact angle to facilitate the adhesion of beads to air bubbles. Coating with nanoparticles allows the beads to attach firmly to the air bubbles. Even a 10% coverage of the bead surfaces with the most effective nanoparticles could promote high flotation efficiencies, whereas a conventional molecular collector requires 25% or higher coverage for a good recovery [6].

Previous work on the application of conventional liquid collectors has shown that quartz can be floated in the presence of sulfonate or soap [8-14]. It is well known that quartz cannot be floated by potassium amyl xanthate at any pH value [10, 12]. Long-chain alkyl ammonium salts are the most commonly used collectors for the beneficiation of silicates due to their relatively high solubility [2, 15-16]. The flotation of quartz has been also studied as a function of pH using N-alkyl-1, 3 diaminopropanes and n-dodecylamine as collectors [17]. Some authors studied the effect of alkalinity on the floatability of quartz with an amine-type collector and with sodium oleate, in the presence of calcium ions at alkaline pH values [18]. A combined quaternary ammonium salt was used as a better collector than dodecyl amine chloride and cetyltrimethyl ammonium bromide for quartz flotation [19]. The adsorption mechanism of mixed cationic alkyl diamine and anionic sulfonate-oleate collectors at acidic pH values has been investigated [20, 21]. Surprisingly, the physical adsorption has been found to be the main adsorption module of amine collectors on muscovite and quartz [22].

In this paper, we report a new application of talc nanoparticles as a solid collector for quartz (as a mineral model). Untreated natural talc nanoparticles were used as a collector to increase the hydrophobicity of hydrophilic quartz and to enhance the quartz flotation recovery.

---

* Corresponding author Tel: +989122881851,+988633670021-3. *E-mail address:* am_hajati@arakut.ac.ir, amhajati@ut.ac.ir, zshafaie@ut.ac.ir (A. Hajati).

2. Experimental Methods

2.1. Materials and mineral characterization

In this study, crystalline quartz and pure talc powders were used. The mineralogy and chemical composition of the samples were determined by X-ray fluorescence (XRF, Philips X Unique II), X-ray Diffractometer (XRD, D8 Advance), and microscopy (Philips XL30 model scanning electron microscopy, SEM). Dynamic light scattering device (DLS) (Malvern, Nano-ZS, UK) was used to measure the size distribution of talc nanoparticles and zeta potential values.

2.1.1. Quartz

The quartz sample (Tekno Silica Ltd., Iran) contained 98.51% SiO_2 as analyzed by XRF. The main mineral phase analyzed by XRD, was quartz. The sample was crushed, ground and then classified into different sizes: -500 +38 µm, -250 +38 µm and -125 +38 µm.

2.1.2. Talc

A high grade talc sample was obtained from Tanin Arad Yekta Ltd., Iran, and it contained 61.95% SiO_2, 30.29% MgO and 4.82% L.O.I. The powdered compound constituted over 96% of $Mg_3Si_4O_{10}(OH)_2$. Talc was found to be the major mineral phase in the XRD analysis and microscopy data.

In addition, the talc sample was crushed, ground by laboratory ball mill and finally reground using planetary ball mill in different vibrations and time spans to produce different sizes of talc nano-powder in each steps that were analyzed using dynamic light scattering, DLS (Fig. 1) and examined by SEM (Fig. 2). Also, SEM images were used to investigate the quality attachments of talc nanoparticles adsorbed on the quartz surfaces in flotation. Separate visualization of nanoparticles on the mineral surfaces by SEM as shown in Fig. 1. In this study, as half the total weight passes the size 567 nm, 350 nm and 235 nm, the talc samples are called Talc-A, Talc-D0 and Talc-D5, respectively (Table 1).

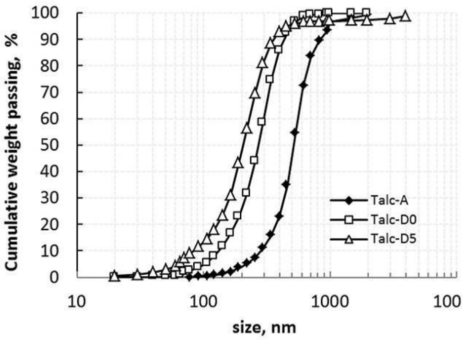

Fig. 1. Size distribution of different talc nanoparticles powder detected by dynamic light scattering (DLS).

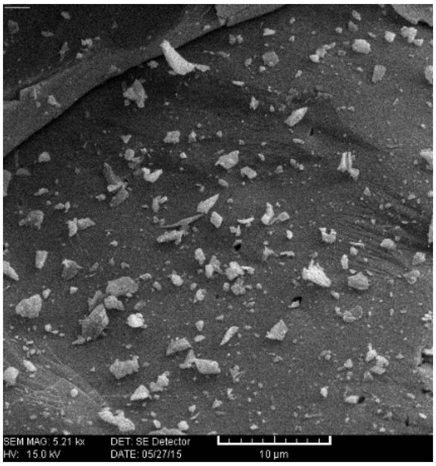

Fig. 2. SEM image of talc nanoparticles in different size (white color) on the quartz mineral surface (dark color in the background) (Quartz size; -250, +38 microns and talc size coated on the quartz surfaces; Talc-A; 1.5 µm-80 nm.

Table 1. Talc nanoparticles size ranges used in flotation tests.

Talc sample code	Weight %	Size (nm)	
	< 100 nm	D_{50}	D_{80}
Talc-A	0.3	567	700
Talc-D0	5.1	350	370
Talc-D5	14.1	235	295

2.2. Zeta potential measurements

Zeta potential of the minerals in suspension was measured using a Malvern instrument (Nano-ZS, UK). Different size classes of quartz and talc mineral suspensions with 0.1% solids were first conditioned for 2-5 minutes in distilled water containing 0.01 M NaCl as a supporting electrolyte. The resultant suspension was conditioned for 15 minutes during which the suspension pH was measured. The pH was adjusted using NaOH or H_2SO_4 solutions over the pH range. The suspension was further treated in an ultrasonic bath for an additional minute and then it was transferred to the rectangular capillary cell of the instrument. The reported results are the average of at least three full replications. The repeated tests showed a measurement error of ±0.01 mV. Temperature was kept at 25.0 ±0.1 °C through the whole measurements.

2.3. Flotation experiments

The flotation experiments were conducted using a 500 mL modified Hallimond tube cell (Fig. 3). This Pyrex flotation cell has a fixed diameter of 35 mm and height of 300 mm. It has also two feeding parts for pH probe and materials injection syringes, as well as air bubble flow rate controller throughout a sinter glass at the bottom. The upper part of the cell is inclined 50° to collect the floated particles. It has a sampler valve to collect the floated materials during the flotation time span, and the cell water level can be controlled by another valve at the top of the cell [23].

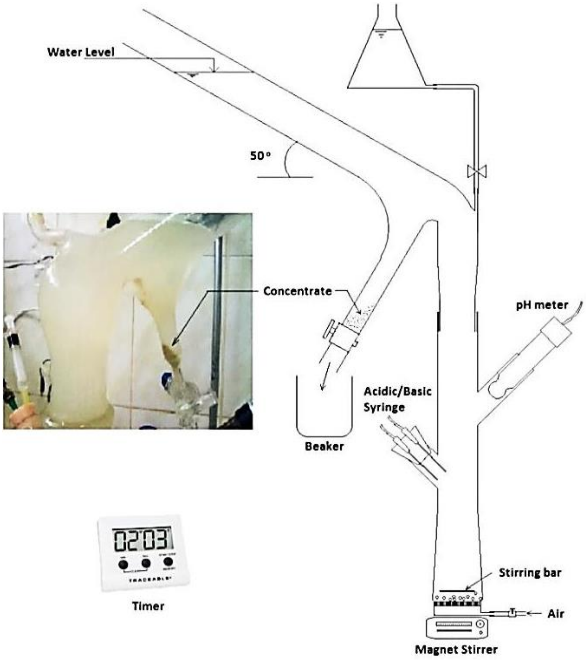

Fig. 3. Scalded up flotation cell as a modified large scale Hallimond tube [23].

In all tests, 10 grams of quartz sample with different particle size was prepared and conditioned for 2-4 minutes with NaOH or H_2SO_4 solutions and was preconditioned by ultrasound if needed. Then, the suspension was conditioned by different dosages and sizes of talc nanoparticles. The flotation tests were conducted at desired pH and agitated by magnet stirrer (fixed rpm) at a constant airflow rate of 1 L/min. Flotation was investigated at different talc nanoparticles dosage and sizes as a collector and 75 ppm poly propylene glycol (A65, Dow) as frother [24]. In addition, different sizes of quartz and pH during the flotation time spans were applied in the tests. Conditioning times for adjusting pH and collector were both 5 minutes. Other factors including conditioning time, frother, solid percentage and air feeding were kept constant at 7 min, A65 75 g/t, 2% and 2 l/min. Finally, concentrates and tailings were filtered, dried and weighed for analysis and flotation recovery calculations.

3. Results and discussion

3.1. Zeta potential effects

To understand the behavior of negatively and positively charged surfaces of minerals, the electrokinetic potentials of quartz and talc were measured as a function of pH (Fig. 4). As it is seen, once the suspension pH shifts from one extrema to another, the zeta potential of these minerals undergoes changes from positive to negative. The isoelectric points (iep) of the minerals have been shown based on the isotropic (quartz) or anisotropic (talc) structure of the minerals.

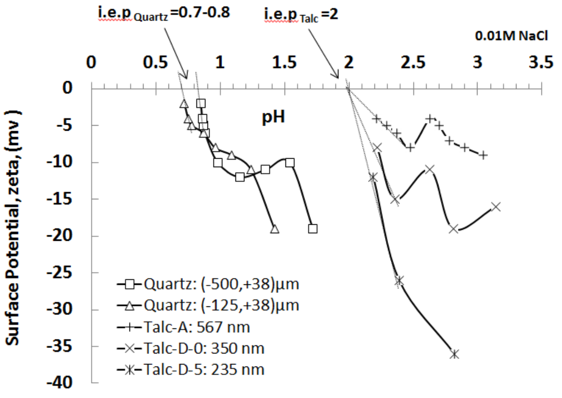

Fig. 4. Zeta potential changes versus pH for quartz size -125 +38 µm and several sizes of talc.

Quartz mineral was chosen as a mineral model due to its approximate homogenized shape and general mineral paragenesis. Estimating the flotation behavior using quartz has been previously reported in different resources [4-6, 25]. The results clearly show that all samples have a negative zeta potential in the pH range tested. The isoelectric point of quartz was estimated at about pH 0.75. To understand the pH value in which talc is able to attach onto the surfaces of quartz particles, electrostatically, the zeta potential of quartz and talc nanoparticles are needed to be compared with each other (Fig. 4). Fig. 4 represents the isoelectric point, i.e.p of quartz sample with the size of -125 +38 µm which is less than 1 (i.e. about 0.75), while i.e.p of talc-A and talc-D5 are estimated to be around pH 2. In addition, i.e.p. of talc and quartz have been reported by a number of researchers at pH 2-3 [26-31] and 0.5-3 [32-37], respectively.

The ratio between zeta potential and surface potential depends on the double layer thickness. Fig. 4 shows the fluctuation of zeta potential versus pH. This can be due to the low dissolved solids and NaCl ion strength level, which are usually resulted in a relatively large double layer made a bit higher zeta potential. In this case, the zeta potential is a good approximation of the surface potential. Otherwise, the high level of ions compresses the double layer and the potential curve. Thus, the zeta potential is only a fraction of the surface potential [38]. This was anticipated for talc whose silica T layer makes up two thirds of the mineral structure. The typical high aspect ratio of talc also enhances the likelihood of measurement along the faces relative to the edges. Nonetheless, this trend was similar to the typical observations in previous studies on talc [25, 31, 34, 39].

3.2. Quartz flotation using talc nanoparticles as collector

Fig. 5 shows the solids and water recoveries in the presence and absence of talc nanoparticles in the flotation of quartz size -250 +38 µm. The total amount of solids recovery after 60 minutes of the flotation time span, increased remarkably compared to the state when no talc was used, especially in the liner part of the graph. The relation between water and solid recovery has been also used by other researchers to determine the level of entrainment in the flotation [40]. It is assumed that at the same water recovery, the amount of solids is the same as that of recovered by entrainment [41]. The amount of quartz recovered by true flotation could be calculated from the differences between the mass of solids recovered in the presence and absence of collector, at the same water recovery. This method was therefore regarded as a suitable method to study the rate of true flotation and entrainment [42, 43]. Therefore, there is approximately 34% recovery due to the true flotation at 60 minutes, which is because of the presence of the talc nanoparticles (Fig. 5).

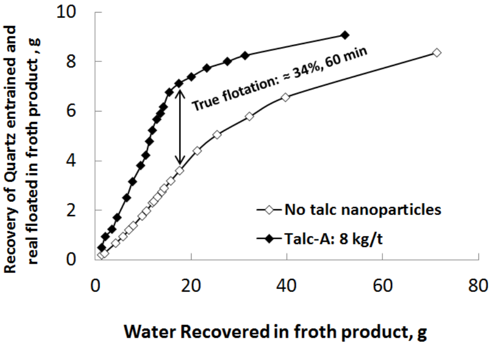

Fig. 5. Quartz and water recovery in the presence and absence of talc nanoparticles. Quartz size -250 +38 µm, pH 1.5, Frother A65 75 ppm, Talc-A 8 kg/t [44].

Fig. 6 presents the flotation recovery of quartz sized, -500 +38 µm, as a function of flotation time span at different pH and talc dosages. Without talc nanoparticles, quartz recovery increased 17% within 30 minutes at pH 2.5. At pH 6 and 80 kg/t talc nanoparticles, quartz recovery was considerably lower than when no talc was used. This could be attributed to the entrainment, pulp density, rheology changes as well as the same negative surface potential of talc and quartz at pH 6. In the presence of 8 kg/t talc-A and pH 1.5, 27% of quartz recovered within 30 minutes compared with no talc consumption at pH 2.5, which is resulted at around 10% of the true flotation. Following that, different flotation tests at various pH and talc dosages were carried out. It was resulted that the best flotation recovery was achieved at pH 1.5 and talc dosage of 8 kg/t, respectively (Fig. 6). It should be noted that in this condition (i.e. pH 1.5), the positive charges of talc nanoparticles are electrostatically adsorbed onto the negatively charge surfaces of quartz particles. However, due to the negative effect of the gravity forces of quartz particles, i.e. -500 µm, the flotation recovery was generally low. Therefore, a number of flotation experiments were conducted using smaller size ranges that include -250 +38 µm and -125 +38 µm at fixed pH of 1.5.

The results in Fig. 7 and 8 show the quartz recovery as a function of the flotation time span by changing the dosage of Talc-A nanoparticles at pH 1.5. Fig. 7 shows the effective real flotation recovery of quartz, i.e. 30%, when 8 kg/t Talc-A compared with no talc usage. Increasing the Talc-A dosages from 2 to 8 kg/t and the quartz size of -250 +38 µm, the recovery increased from 41% to 56% after 30 minutes. Clearly, the maximum quartz recovery increased twice compared with the quartz size -500 +38 µm. Following that, the recovery decreased significantly from 56%, to 32% when 80 kg/t of talc was applied. Similarly, using quartz size -125 +38 µm, the maximum recovery was obtained more than 90%. Therefore, decreasing the quartz size increased the quartz recovery. However, reducing the quartz size from -250 +38 µm to -125 +38 µm caused the dosage of Talc-A nanoparticles to increase from 8 kg/t to 45 kg/t to reach the maximum level of quartz recovery (Fig. 8). In fact, as the specific surface areas of the finer particles increased, the amount of required collector increased as well. It is the common behavior of conventional chemical flotation collectors.

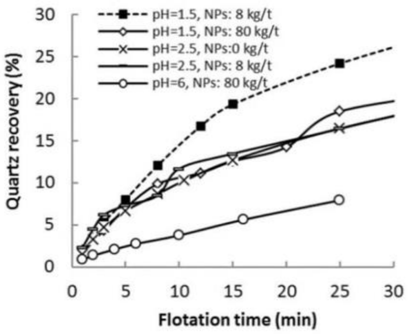

Fig. 6. Flotation recovery of quartz size -500 +38 µm at different pH and Talc-A dosage versus flotation time.

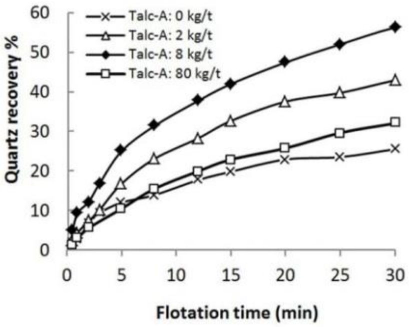

Fig. 7. Flotation recovery of quartz size -250+38 µm at various dosage of Talc-A versus flotation time at pH 1.5.

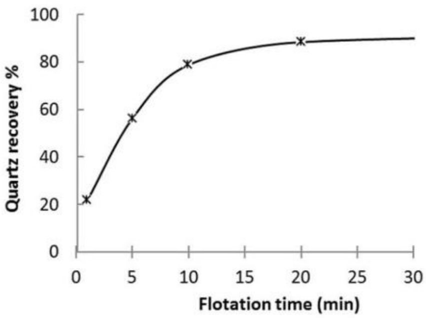

Fig. 8. Flotation recovery versus flotation time, quartz size -125+38 µm, Talc-A 45 kg/t at pH 1.5.

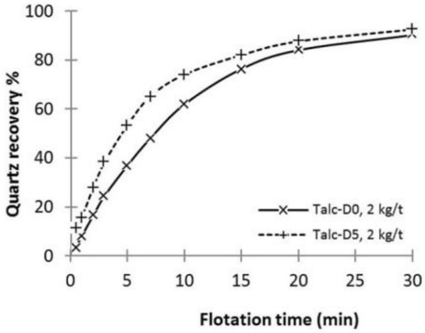

Fig. 9. Flotation recovery versus flotation time, quartz size -125+38 µm, Talc-D0 and Talc-D5 2 kg/t at pH=1.5.

In order to decrease the talc dosage, the talc particle size was reduced by a planetary ball mill and classified as Talc-D0 and Talc-D5 (Table 1). Fig. 9 shows that the maximum quartz recovery took place when smallest talc size, Talc-D0 and Talc-D5, were used. It is clearly seen that quartz recovery at pH 1.5 and 2 kg/t of Talc-D5 is significantly higher than the recovery obtained by Talc-D0, D_{50} 276 nm. This is due to the talc nanoparticle size effect and higher surface charge density (Fig. 9).

3.3. Relationship between talc nanoparticle size and required dosage in flotation

As it was previously discussed (section 2.2), reducing the quartz particle size at various talc dosages, Talc-A, D_{50} 512 nm, increases the talc dosage to obtain high level of recovery. In order to determine how much talc is required to achieve the maximum quartz recovery, it is necessary to assess the relationship between the talc size and dosage. Fig. 10 shows that the required amount of talc to reach the maximum quartz recovery in shorter period of time is higher than that needed in a longer period of flotation time. This kind of pattern can be observed by Talc-D0 and Talc-D5. Fig. 11 shows how much talc nanoparticles are required to obtain the maximum quartz recovery within a specific flotation time span. In fact, the smallest talc nanoparticles recorded the lowest dosage. Therefore, it is logical to decrease the talc dosage by reducing the size of the talc particles from 512 nm (Talc-A) to 208 nm (Talc-D5). Fig. 11 also shows that talc consumption with an average size of 208 nm is considerably at the lowest level of talc consumption (i.e. 1.7 kg/t). According to the results, it was estimated that decreasing the talc size particles down to less than 100 nm could result in further decrease in the talc dosage to achieve the same level of flotation recovery.

Table 2 presents the low, high and average levels of quartz recovery using talc nanoparticles at different sizes. It can be seen that Talc-A, 512 nm, and Talc-D0, 276 nm are more effective when the flotation time span is less than 15 minutes. On the other hand, for a longer flotation time (i.e. 30 minutes), Talc-D5, 208 nm, is more effective than the other types of talc nanoparticles. Comparing more experimental data, it can be demonstrated that smaller talc particle especially in flotation time spans shorter than 15 minutes, resulted in lower recoveries (Table 2). These observations underscore one of the challenges in the design of solid nanoparticle collectors. In one hand, the hydrophobic surface of talc is in favor of the flotation process, but on the other hand, hydrophilic ionic groups are required for nanoparticle colloidal suspension to be stable [6].

It is suggested that for the sake of surface modification of talc characters, the grinding quality of talc nanoparticles needs to be further investigated to achieve nanoparticles less than 100 nm. Also, it may be possible to chemically modify the hydrophilic talc nanoparticle edges to become more hydrophobic. These results can help increase the talc particle contact angles and consequently, better surface attachments between quartz particles and bubbles to promote the flotation recovery.

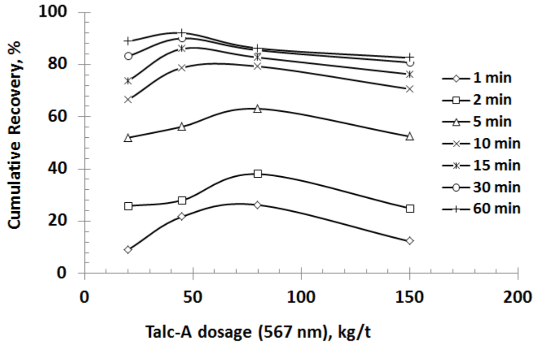

Fig. 10. Quartz recovery as a function of talc dosage at different times, quartz size -125, +38 µm, at pH 1.5.

Table 2. Different levels of quartz -125, +38 µm recovery using various talc sizes during flotation times.

Flotation time (min)	Quartz recovery using talc nanoparticle size, nm								
	Talc-A			Talc-D0			Talc-D5		
	low	high	Ave.	low	high	Ave.	low	high	Ave.
1	6.7	15.6	11.6	8.0	23.6	17.4	9.0	26.2	17.0
3	23.8	41.0	33.1	24.5	40.0	35.1	34.1	48.5	40.2
5	36.8	53.3	46.7	36.8	47.2	44.3	52.4	63.1	55.3
10	56.6	75.7	68.5	62.0	72.6	65.6	66.5	79.3	74.2
15	67.3	86.7	78.9	73.1	82.9	75.6	73.7	88.0	80.4
30	78.4	93.0	88.7	84.8	92.4	88.9	80.8	92.5	86.0

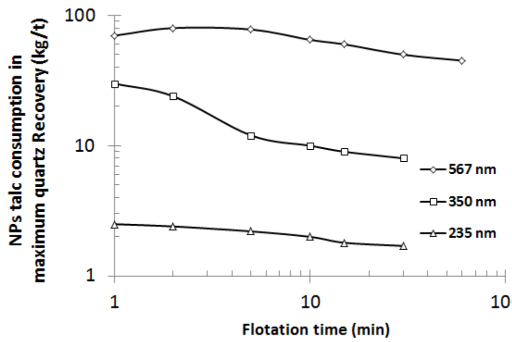

Fig. 11. Talc dosage to obtain the highest quartz recovery value vs. flotation time for different types of talc nanoparticles, quartz size: -125+38 μm at pH 1.5.

4. Conclusion

This work aimed to identify a novel application of natural hydrophobic talc nanoparticles as a collector in the flotation of quartz, as a hydrophilic mineral model. It was found that the efficiency of quartz flotation using talc nanoparticles as a collector depends on the talc and quartz particle sizes, talc dosage, flotation pH and time span. The parameters talc nanoparticles size distribution and its dosage played an important role to enhance the flotation recovery. Coarse quartz particles need less amounts of talc compared to the finer quartz particles. However, the recovery of coarse quartz particles was much lower than the smaller particles, especially due to the effect of the gravity forces. It was concluded that smaller talc nanoparticles having a natural hydrophobic property could be able to increase the quartz flotation recovery. To obtain the maximum recovery, one needs to understand the interactions between the flotation parameters including talc dosage, talc and quartz particles size ranges, time span and pH. The results need to be validated for different mineral systems such as coal, graphite and other natural hydrophobic minerals in future studies.

Acknowledgment

The authors are grateful to Mineral Processing and Geochemical Laboratories of School of Mining, College of Engineering, University of Tehran for their contribution to this research. Also, the authors would like to acknowledge the financial support of University of Tehran Science and Technology Park under the grant number 94048.

REFERENCES

[1] Bulatovic, S.M. (2007). Handbook of flotation reagents: chemistry, theory and practice: Volume 1: flotation of sulfide ores. *Elsevier.*

[2] Ari, V., (2001). Flotation of silicate minerals physico-chemical studies in the presence of alkylamines and mixed (cationic/anionic/non-ionic) collectors, [PhD thesis] (Sweden), Lulea University.

[3] Leja, J., (1982). Flotation surfactants, Surface Chemistry of Froth Flotation. *Springer.*

[4] Yang, S., (2012). Nanoparticle Flotation Collectors", [PhD Thesis] (Canada), McMaster University.

[5] Naderizand, B., (2011). Studies of inorganic nanoparticles as collectors for flotation", [Master Thesis] (Canada), McMaster University.

[6] Yang, S., Pelton, R., Raegen, A., Montgomery, M., and Dalnoki-Veress, K., (2011). Nanoparticle flotation collectors: mechanisms behind a new technology", *Langmuir 27.*

[7] Ivanova, T. A., Chanturia, V. A., and Zimbovsky, I. G., (2013). New Experimental Evaluation Techniques for Selectivity of Collecting Agents for Gold and Platinum Flotation from Fine-Impregnated Noble Metal Ores, *J. Min. Sci., Vol. 49, No. 5* .

[8] Cooke, S.R., and Digre, M., (1949). Studies on the activation of quartz with calcium ion, *Trans. AIME, 184.*

[9] Eigeles, M., and Volova, M., (1964). On the mechanism of activating and depressant action in soap flotation, *Proc. 7th Int. Mineral Processing Congress (N. Arbiter, ed.), Gordon and Breach.*

[10] Fuerstenau, M., Atak, S., (1965). Lead Activation in Sulfonate Flotation of Quartz, *Trans. AIME, 232.*

[11] Fuerstenau, M., Martin, C., and Bhappu, R., (1963). The role of hydrolysis in sulfonate flotation of quartz, *State Bureau of Mines and Mineral Resources* .

[12] Fuerstenau, M., Miller, J., Pray, R., and Perinne, B., (1965). Metal ion activation in xanthate flotation of quartz, *Trans. AIME, 232.*

[13] Gaudin, A., and Chang, C., (1952). Adsorption on quartz, from an aqueous solution, of barium and laurate ions, *Trans. AIME, 193 (1952).*

[14] Sekulić, Ž., Canić, N., Bartulović, Z., and Daković, A., (2004). Application of different collectors in the flotation concentration of feldspar, mica and quartz sand, *Miner. Eng., 17 (2004).*

[15] El-Salmawy, M., Nakahiro, Y., and Wakamatsu, T,. (1993). The role of alkaline earth cations in flotation separation of quartz from feldspar, *Miner. Eng., 6.*

[16] Shimoiizaka, J., Nakatsuka, K., and Katayanagi, T., (1976). Separation of feldspar from quartz by a new flotation process, *World Mining and Metals Technology, Port City Press, Inc Baltimore, Md.*

[17] Scott, J., and Smith, R., (1991). Diamine flotation of quartz, *Miner. Eng., 4.*

[18] Sayilgan, A., and Arol, A., Effect of carbonate alkalinity on flotation behavior of quartz, *Int. J. Miner. Process. 74.*

[19] Yuhua, W., and Jianwei, R., (2005). The flotation of quartz from iron minerals with a combined quaternary ammonium salt, *Int. J. Miner. Process. 77.*

[20] Vidyadhar, A., and Rao, K.H., (2007). Adsorption mechanism of mixed cationic/anionic collectors in feldspar-quartz flotation system, *J. Colloid Interface Sci., 306* .

[21] Kondrat'ev, S. A., (2012). Activity and Selectivity of Carboxylic Acids as Flotation Agents, *J. Min. Sci., Vol. 48, No. 6.*

[22] Wang, L., Sun, W., and Liu, R.Q., (2014). Mechanism of separating muscovite and quartz by flotation, *Journal of Central South University, 21.*

[23] Hajati, A., Khodadadi, A., and Koleini, S.M.J., (2010). Flotation of zinc oxide minerals from low-grade tailings by oxine and dithizone using the Taguchi approach, *Miner. Metall. Process., 27.*

[24] Shahbazi, B., and Rezai, B., (2009). The effect of type and dosage of frothers on coarse particles flotation, *Iran. J. Chem. Chem. Eng., Research Note Vol 28.*

[25] Burdukova, E., (2007). Surface properties of new york talc as a function of pH, polymer adsorption and electrolyte concentration, *University of Cape Town, IMPC.*

[26] Steenberg, E., and Harris, P., (1984). Adsorption of Carboxymethylcellulose, Guar Gum, and Starch Onto Talc, Sulphides, Oxides, and Salt-type Minerals, *Mintek, S. Afr. J. Chem., 37.*

[27] Morris, G.E., Fornasiero, D., and Ralston, J., (2002). Polymer depressants at the talc–water interface: adsorption isotherm,

microflotation and electrokinetic studies, *Int. J. Miner. Process., 67 (2002).*

[28] Fuerstenau, D., and Huang, P., (2003). Interfacial phenomena involved in talc flotation and depression, *XXII International Mineral Processing Congress, South Africa.*

[29] Wang, J., and Somasundaran, P., (2005). Adsorption and conformation of carboxymethyl cellulose at solid–liquid interfaces using spectroscopic, AFM and allied techniques, *J. Colloid Interface Sci., 291.*

[30] Bremmell, K.E., and Addai-Mensah, J., (2005). Interfacial-chemistry mediated behavior of colloidal talc dispersions, *J. Colloid Interface Sci., 283.*

[31] Ndlovu, B., Forbes, E., Farrokhpay, S., Becker, M., Bradshaw, D., and Deglon, D., (2014). A preliminary rheological classification of phyllosilicate group minerals, *Miner. Eng., 55.*

[32] P. Patra, and K. Natarajan, (2004). Microbially induced flocculation and flotation for separation of chalcopyrite from quartz and calcite, *Int. J. Miner. Process., 74.*

[33] Kim, J.K., and Lawler, D.F., (2005) Characteristics of zeta potential distribution in silica particles, *Bull. Korean Chem. Soc., 26.*

[34] Alvarez-Silva, M., Uribe-Salas, A., Mirnezami, M. and Finch, J., (2010). The point of zero charge of phyllosilicate minerals using the Mular–Roberts titration technique, *Miner. Eng., 23.*

[35] Andrade, E., Costa, B., Alcântara, G. and Lima, R., (2012). Flotation of manganese minerals and quartz by sodium oleate and water glass, *Latin American Applied Research, 42 .*

[36] Choi, J., Kim, W., Chae, W., Kim, S.B. and Kim, H., (2012). Electrostatically controlled enrichment of Lepidolite via Flotation, *Mater. Trans., 53.*

[37] Júnior, J.A.A. and Baldo, J.B., (2014). The behavior of zeta potential of silica suspensions, *New Journal of Glass and Ceramics, 4.*

[38] Ravina, L. and Moramarco, N., (1993). Everything you want to know about coagulation & flocculation, *Zeta-Meter Inc.*

[39] Laskowski, J.S. and Ralston, J., (2015). Colloid chemistry in mineral processing, *Elsevier.*

[40] Konopacka, Z. and Drzymala, J., (2010). Types of particles recovery-water recovery entrainment plots useful in flotation research, Adsorption, 16.

[41] Trahar, W., (1981). A rational interpretation of the role of particle size in flotation, *Int. J. Miner. Process., 8 .*

[42] Wang, L., Peng, Y., Runge, K., and Bradshaw, D., (2015). A review of entrainment: Mechanisms, contributing factors and modelling in flotation, *Miner. Eng., 70 .*

[43] Abidia, A., Elamarib, K., Bacaouic, A. and Yacoubic, A., (2014). Entrainment and True Flotationof a Natural Complex Ore Sulfide, *J. Min. Sci., Vol. 50, No. 6.*

[44] Hajati, A., Shafaei, S. Z., Noaparast, M., Farrokhpay, S., & Aslani, S. (2016). Novel application of talc nanoparticles as collector in flotation. RSC Advances, 6(100), 98096-98103.