Contents lists available at *Dergipark*

Journal of Scientific Reports-A

journal homepage: *https://dergipark.org.tr/tr/pub/jsr-a*

E-ISSN: 2687-6167 ***Number 60, March 2025***

RESEARCH ARTICLE

Receive Date: 16.02.2025 *Accepted Date: 17.03.2025*

Feldspar flocculation performance using cationic and anionic flocculants in dual system: evaluation by turbidity, settling rate and flocculation efficiency

Özlem Kaya[a]*, Ahmet Özkan[b]

[a] *Department of Metallurgical and Materials Engineering, Sivas Cumhuriyet University, Sivas 58140, Türkiye, ORCID: 0000-0001-7613-3609*
[b]*Republic of Türkiye Ministry of Environment, Urbanization and Climate Change, Ankara 06510, Türkiye, ORCID: 0000-0002-7544-3709*

Abstract

This study investigated the flocculation performance of feldspar using combinations of cationic and anionic flocculants in a dual flocculation system. Flocculation tests were performed with five different flocculants (C.1597, A.336, A.338, A.1011 and A.5250) at various dosages (0.2 mg/L to 12.5 mg/L). Flocculation performance was evaluated based on turbidity, settling rate, and flocculation efficiency. Among the flocculant combinations tested, the C.1597-A.338 combination showed that the most effective performance of both turbidity reduction and flocculation efficiency. In the flocculation tests, the highest settling rate was observed with the C.1597-A.338 and C.1597-A.1011 combinations. The C.1597-A.338 combination achieved 98.6% flocculation efficiency at a dosage of 1.6 mg/L and with the lowest turbidity value of 6.1 NTU (Nephelometric Turbidity Unit). The highest settling rate of 2700 mm/min was achieved for the C.1597-A.338 and C.1597-A.1011 combinations at the dosages of 8.5 mg/L and 12.5 mg/L values. This experimental study showed that optimum flocculation performance depends on the different flocculant combinations and dosages used in the dual flocculation system.

Keywords: feldspar; flocculation system; flocculation efficiency; settling rate; turbidity

* Corresponding author. Tel.: +90 346 487 28 03; fax: +90 346 219 11 65.
E-mail address: okaya@cumhuriyet.edu.tr

1. Introduction

Feldspar is a very important mineral that was used widely in a many industries such as ceramics, glass, paper, paint and polymers. The classification of feldspar is based on the dominant alkali metals which are Ca, Na and K. The main types of feldspar are Ca-feldspar (anorthite; $CaAl_2Si_2O_8$), Na-feldspar (albite; $NaAlSi_3O_8$) and K-feldspar (orthoclase or microcline; $KAlSi_3O_8$). Approximately 60% of world's feldspar is used in the glass industry because of its role in melting and improving the glass quality. The ceramics industry accounts for approximately 35% of feldspar consumption, which contributes to vitrification process and imparts desirable properties to ceramics products. The remaining 5% is used in various applications, such as electrodes, papers, paints and polymers, where feldspar improves product performance and processing efficiency [1].

The basic structure of feldspar consists of a ring of four tetrahedral units; K-feldspar and Na-feldspar have three silicon tetrahedra and one aluminium tetrahedron, whereas in Ca-feldspar, half of the four tetrahedral units are silicon-based and the other half are aluminium-based. Feldspar surfaces have both positive and negative charges. The positive surface charges are due to presence of Na^+ (in albite) and K^+ (in orthoclase) ions, while the negative charges are formed by polar silanol (Si-OH) and non-polar siloxane (Si-O-Si) groups. In particular, the surface silanol groups (Si-OH) provide amphoteric characteristics, allowing the formation of both positive and negative surface charges [2, 3].

The electrokinetic properties of fine particles in an aqueous solution, such as the point of zero charge (PZC), play an important role in understanding the adsorption mechanism of inorganic and organic species at the solid/solution interface. The point of zero charge (PZC) of individual feldspar minerals varies slightly with composition. Typically it is around 2.5 anorthite, 2.0 for albite, and 1.5 for orthoclase. Many researchers also report variations in the sign and magnitude of the zeta potential as a function of solution pH. However, direct comparison of PZC values is often difficult due to the wide variety of solution conditions (electrolyte type and concentration) and mineral processing methods used in different studies [3].

Fine particles cause various problem in mineral processing operations, affecting handling, drying, dewatering, transportation, and storage, and creating economic an environmental pressure. Flocculation is an important process in mineral processing and plays a key role in facilitating dewatering and solid-liquid separation. Effective flocculation not only facilitates the removal of solids from suspension, but also reduces the total solids volume, contributes to cost saving, energy conservation and environmental sustainability in mineral processing operations [4, 5].

The flocculation process consists of the following stages:

- Addition of flocculants: The first step is to add flocculants to the suspension. These flocculants can be organic polymers, inorganic materials, or a combination of both.
- Floc formation: When flocculants are added, they interact with suspended particles and act as bridges, initiating the formation of bonds and flocs.
- Agglomeration and flocculation: As the process progresses, individual particles begin to agglomerate by interactions facilitated by flocculants. This agglomeration results in formation of larger visible particles known as flocs.
- Sedimentation or filtration: The last step of the process is for the separation of the flocs from suspension by either sedimentation or filtration methods.

Anionic, cationic, and non-ionic flocculants that have different characteristics and mechanisms are mostly used in the flocculation process. Adsorption of flocculants onto particle surfaces is very in the flocculation as it directly affects the efficiencies and mechanisms of flocculants. It is an inherently complex process for the interaction of flocculants and particles. Therefore, flocculation process is influenced by various properties of flocculants, including type and dosage, molecular weight, chain length, and charge. Operating parameters such as particle size, suspension pH, solid ratio, stirring time and speed, temperature, and settling time affect flocculation performance [6]. One of the main challenges in flocculation is to achieve the optimum balance by increasing settling rate of flocs while simultaneously reducing the turbidity of the suspension. The success of this process therefore requires a clear understanding of the nature of the suspension and appropriate selection and use of flocculants. Flocculation performance is typically evaluated using key parameters, including supernatant turbidity, floc settling rate and flocculation efficiency [7, 8, 9].

In recent years, flocculation studies have demonstrated the significance of multi-component flocculants, particularly dual flocculation systems. A dual flocculation system, in which two types of flocculants are added sequentially, has been reported to provide a more efficient performance than a single flocculant system. Through the complementary effects of different flocculants, a dual flocculation system can improve the overall efficiency of the flocculation process [7, 9, 10, 11, 12, 13, 14].

This study investigates the flocculation performance of feldspar using cationic, and anionic flocculants in dual system to improve solid-liquid separation efficiency in mineral processing. Feldspar is a critical raw material in the ceramic, glass and paints industries where high purity concentrates are required for product quality. However, fine-particle feldspar suspensions present challenges in beneficiation, water recovery and tailing management. By optimizing flocculation conditions, this study aims to enhance the selective separation of feldspar from impurities and improve the overall efficiency of feldspar processing plants for industrial applications.

2. Materials and Methods

2.1. Materials

In this study, flocculation experiments were carried out on feldspar sample obtained from Muğla/Yatağan, Türkiye. The elemental analysis, determined by X-ray fluorescence (XRF) analysis, is shown in Table 1. Five different types of flocculants, cationic (Magnafloc 1597) and anionic (Magnafloc 336, Magnafloc 338, Magnafloc 1011 and Magnafloc 5250), purchased from BASF SE Company, were used in the experiments. The properties of the flocculants used in this study are shown in Table 2.

Table 1. Elemental analysis of feldspar sample.

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	TiO_2 (%)	Na_2O (%)	K_2O (%)	CaO (%)	MgO (%)	P_2O_5 (%)
70.07	17.34	0.12	0.34	10.64	0.40	0.61	<0.01	0.24

Table 2. Properties of the flocculant used in this study.

Flocculant name	Flocculant code	Flocculant type	Physical form	Molecular weight
Magnafloc 1597	C.1597	Cationic, polyamine	Liquid	Medium
Magnafloc 336	A.336	Anionic, polyacrylamide	Powder-off white	High
Magnafloc 338	A.338	Anionic, polyacrylamide	Powder-off white	High
Magnafloc 1011	A.1011	Anionic, polyacrylamide	Powder-off white	High
Magnafloc 5250	A.5250	Anionic, polyacrylamide	Powder-off white	High

2.2. Methods

In the experiments, the flocculants were tested individually, and successful flocculation did not occur when the flocculants were used alone. Therefore, cationic flocculant (C.1597) was examined in combination with anionic flocculants (A.336, A.338, A.1011 and A.5250) as a dual flocculation system. The results of the flocculation experiments have been evaluated in terms of turbidity, settling rate, and flocculation efficiency.

Before the experiments, homogeneous stock solutions of 0.5% (w/w) concentration of each flocculant were prepared using distilled water. Diluted solutions of 0.05% (w/w) concentration were prepared from these stock solutions for use in the experiments. The flocculation experiments were performed at the natural pH (6.1) of the suspension. The flocculant combinations dosages ranged from 0.2 mg/L to 12.5 mg/L.

For each experiments, a suspension was prepared by adding 1 g of feldspar to 600 ml of distilled water in a 750 ml glass beaker. The suspension was stirred at 500 rpm for 5 minutes to ensure its homogeneity. The first flocculant (C.1597) was added at the desired dosage to the suspension and stirred with 500 rpm for 1 minute. A second flocculant (A.336, A.338, A.1011 or A.5250) was added to the suspension at the desired dosage and stirring continued at same speed for 1 minute. After adding two flocculants, the stirring speed was reduced to 200 rpm and stirred 2 minutes to form flocs. Then, the system was stopped and waited settlement of the flocs. After a 2 minutes settling time, a 10 ml supernatant sample was carefully collected. Sample was taken from a fixed distance of 4 cm below the air-liquid interface. The turbidity of the supernatant was measured using a model MicroTPI turbidimeter.

At the end of experiments, the flocculation efficiency (%) was calculated using the following equation:

$$Flocculation\ efficiency\ (\%) = \left[\frac{(T_0 - T_f)}{T_0}\right] * 100 \tag{1}$$

T_0 = the initial suspension turbidity (NTU) (Nephelometric Turbidity Unit)
T_f = the final turbidity after flocculation (NTU) (Nephelometric Turbidity Unit)

The flocculation settling rate was measured during the second part of experiments. This was done by observing the time dependent change in height (4.5 cm) in a 750 ml glass beaker after a 2 minutes floc growth period. The 600 ml and 300 ml marks on the beaker were used as reference points for this measurement.

3. Results and Discussion

3.1. Effect of flocculant combination and dosage on turbidity

Fig. 1 shows the turbidity results for cationic flocculant C.1597 in combination with anionic flocculants (A.336, A.338, A.1011 and A.5250). The initial turbidity of the feldspar suspension was 430.1 NTU, indicating a high concentration of suspended particles.

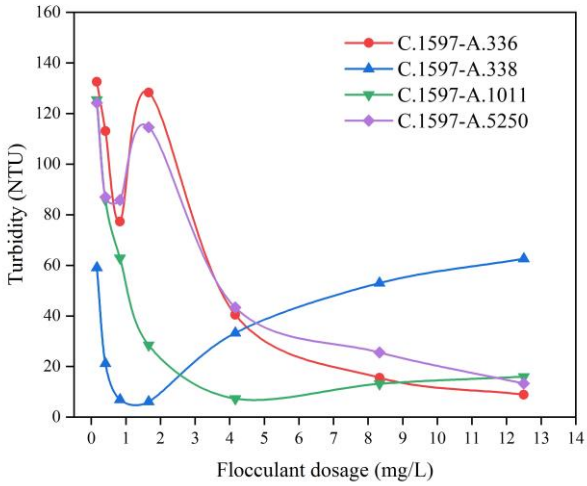

Fig. 1. Effect of flocculant combination and dosage on the turbidity of feldspar suspension.

The turbidity curves of the C.1597-A.336 and C.1597-A.5250 flocculant combinations were similar. The initial high turbidity decreased at 0.8 mg/L flocculant dosage, increased again at 1.6 mg/L dosage and decreased again after this dosage. The C.1597-A.338 and C.1597-A.1011 flocculant combinations also showed a decrease at 1.6 mg/L dosage and a slight increase at a dosage of 4.0 mg/L. The initial increase in turbidity with all flocculant combinations may be due to charge neutralization effects. As the C.1597 cationic flocculant neutralizes the negative surface charge of feldspar particles, it may cause some destabilization before effective flocculation occurs. Above 4.0 mg/L flocculant dosage, all flocculant combinations had relatively low turbidity. This results indicates that the synergistic effect of combining cationic (C.1597) and anionic flocculants (A.36, A.338, A.1011, A.5250) is highly effective in reducing turbidity. The mechanism probably involves charge neutralization by the cationic flocculant and bridging by the anionic flocculant [15].

3.2. Effect of flocculant combination and dosage on settling rate

Fig. 2 shows the settling rates for cationic C.1597 in combination various anionic flocculants (A.336, A.338, A.1011 and A.5250).

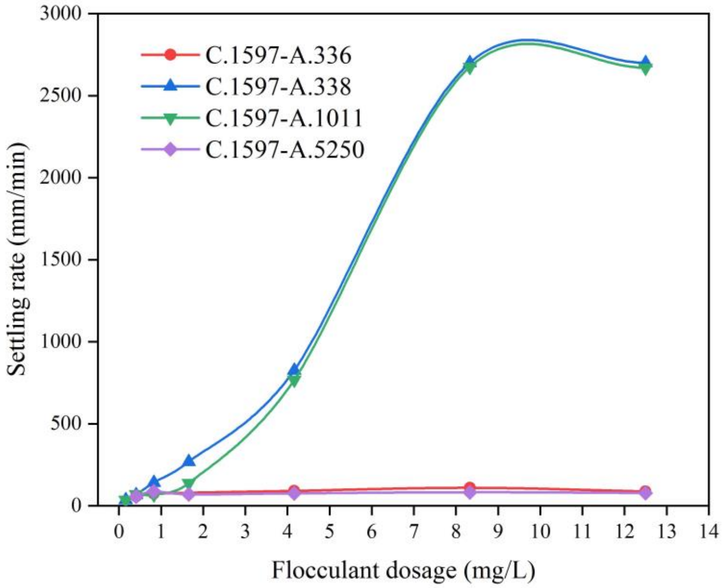

Fig. 2. Effect of flocculant combination and dosage on the settling rate of feldspar suspension.

The settling rate of the C.1597-A.338 and C.1597-A.1011 flocculant combinations increased particularly above 1.6 mg/L, with the highest settling rate of 2700 mm/min being achieved at 8.5 mg/L and 12.5 mg/L values. This increase in the settling rate at higher dosages for these combinations can be attributed to the dual flocculation mechanism. The C.1597 cationic flocculant probably neutralized the negative surface charge of the feldspar particles, whereas the anionic flocculants (A.338 and A.1011) bridged the neutralized particles. As the dosage increased, complete charge neutralization and extensive bridging occurred, resulting in larger and denser flocs that settled rapidly [16]. This result is consistent with decrease in suspension turbidity values after 1.6 mg/l flocculant dosage as shown in Fig. 1 for these flocculant combinations.

For the C.1597-A.336 and C.1597-A.5250 flocculant combinations, the settling rates did not change significantly with increasing flocculant dosage. The flocs formed at these dosages may have reached their maximum density or size, limiting the settling rate. Adding more flocculant might not significantly increase the strength or compactness of the flocs and therefore, the settling rates remain constant.

3.3. Effect of flocculant combination and dosage on flocculation efficiency

Fig. 3 shows the flocculation efficiency for cationic flocculant C.1597 in combined with anionic flocculants (A.336, A.338, A.1011 and A.5250).

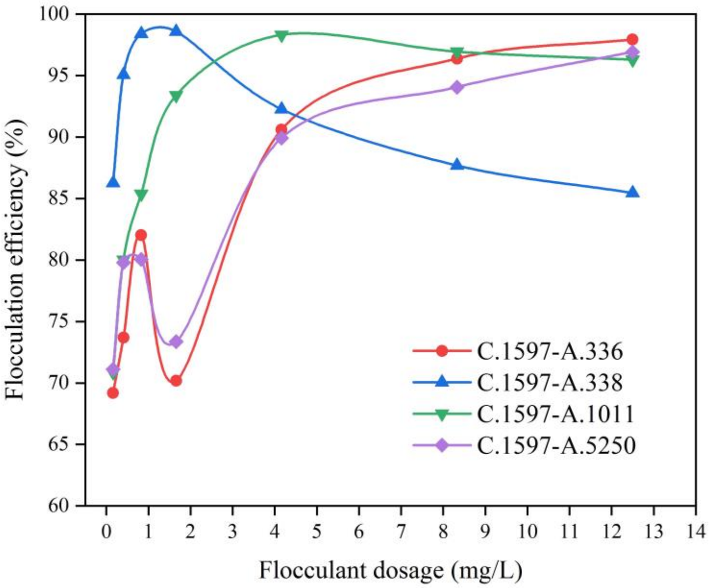

Fig. 3. Effect of flocculant combination and dosage on the efficiency of feldspar flocculation.

The efficiency curves for the C.1597-A.338 and C.1597-A.1011 flocculant combinations show an increase up to their optimum dosages (1.6 mg/L and 4.0 mg/L). Beyond these dosages, a gradual decrease in efficiency is observed. This trend is consistent with the bridging flocculation mechanism, where oversaturation of flocculant can results in steric stabilization, thereby reducing the flocculation efficiency [17].

The C.1597-A.338 combination showed the highest efficiency of 98.6% at a dosage of 1.6 mg/L. The superior performance of A.338 in dual flocculation can be attributed to its molecular structure and physicochemical properties. In the C.1597-A.338 combination, if the molecular structure of A.338 contains functional groups that are complementary to the surface charge or chemical nature of feldspar (e.g. polar and ionic groups), this would improve adsorption and flocculation efficiency. In addition, the high molecular weight of A.338 and flexibility of its polymer chains may allow it to effectively bridge more particles to form strong and stable flocs, which explains its superior performance.

The C.1597-A.336 and C.1597-A.5250 flocculant combinations show different efficiency curves. The efficiency, which is high at a 0.8 mg/L dosage, decreases at 1.6 mg/L dosage and increases significantly again at 4.0 mg/L dosage.

These combination curves show a balance between turbidity reduction and flocculation efficiency. Fig. 1 shows that a dosage of 1.6 mg/L, the maximum turbidity values were 128.3 NTU for the C.1597-A.336 combination and 114.6 NTU for the C.1597-A.5250 combination. As shown in Fig. 3, these combinations achieved the lowest flocculation efficiencies of 70.2% and 73.4% respectively at a dosage of 1.6 mg/L dosage maximum turbidity value obtained.

4. Conclusions

This study investigated the effects of various flocculant combinations and dosages on feldspar flocculation, focusing on the turbidity, settling rate, and flocculation efficiency. The results showed that flocculation performance was significantly affected by the combination and dosage of flocculants used. Among the combinations tested, C.1597-A.338 combination showed superior flocculation performance, achieving a flocculation efficiency of 98.6% at a dosage of 1.6 mg/L. This condition also produced the lowest turbidity value of 6.1 NTU (Nephelometric Turbidity Unit). The C.1597-A.338 and C.1597-A.1011 combinations also showed the highest settling rate of 2700 mm/min at the dosages of 8.5 mg/L and 12.5 mg/L values. In conclusion, this study highlights the complexity of feldspar flocculation and importance of suitable flocculant selection and dosage optimization.

Acknowledgements

This study has not received specific funding or financial support from any government, commercial or non-profit organization.

References

[1] A. Vidyadhar, K. Hanumantha Rao and K.S.E. Forssberg, "Adsorption of N-Tallow 1,3-Propanediamine-Dioleate collector on albite and quartz minerals, and selective flotation of albite from Greek Stefania feldspar ore," *J. Colloid Interface Sci.*, vol. 248, pp. 19-29, Apr. 2002, doi: 10.1006/jcis.2001.8174.

[2] S. Prasanphan and A. Nuntiya, "Electrokinetic properties of kaolins, sodium feldspar and quartz," *Chiang Mai J. Sci*., vol. 33, no. 2, pp. 183-190, May 2006.

[3] G.E. Heyes, G.C. Allan, W.J. Bruckard and G.J. Sparrow, "Review of flotation of feldspar" *Mineral Processing and Extractive Metallurgy (Trans. Inst. Min. Metall. C)*, vol.121, no.2, pp.72-78, Jan.2012, doi: 10.1179/1743285512Y.0000000004.

[4] V. Vajihinejad, S.P. Gumfekar, B. Bazoubandi, Z.R. Najafabadi and J.B.P. Soares, "Water soluble polymer flocculants: Synthesis, characterization, and performance assessment," *Macromol. Mater. Eng.*, vol. 304, no. 2, 1800526, 2019, doi: 0.1002/mame.201800526.

[5] F. AlMubaddal, K. AlRumaihi and A. Ajbar, "Performance optimization of coagulation/flocculation in the treatment of wastewater from a polyvinyl chloride plant," *J. Hazard. Mater.*, vol. 161, no. 1, pp. 431-438, Jan. 2009, doi: 10.1016/j.jhazmat.2008.03.121.

[6] R. Hogg, "The role of polymer adsorption kinetics in flocculation," *Colloids Surf. A: Physicochem. Eng. Aspects*, vol. 146, no. 1-3, pp. 253-263, Jan. 1999, doi: 10.1016/S0927-7757(98)00723-7.

[7] Q. Lu, B. Yan, L. Xie, J. Huang, Y. Liu and H. Zeng, "A two-step flocculation process on oil sands tailings treatment using oppositely charged polymer flocculants," *Sci. Total Environ.*, vol. 565, pp. 369-375, Sep. 2016, doi: 10.1016/j.scitotenv.2016.04.192.

[8] C.Y. Teh, P.M. Budiman, K.P.Y. Shak and T.Y. Wu, "Recent advancement of coagulation-flocculation and its application in wastewater treatment," *Indus.&Eng. Chem. Res.*, vol. 55, no. 16, pp. 4363-4389, Marc. 2016, doi: 10.1021/acs.iecr.5b04703.

[9] R. Xu, W. Zou, T. Wang, J. Huang, Z. Zhang and C. Xu, "Adsorption and interaction mechanisms of Chi-g-P(AM-DMDAAC) assisted settling of kaolinite in a two-step flocculation process," *Sci. Total Environ.*, vol. 816, 151576, Apr. 2022, doi: 10.1016/j.scitotenv.2021.151576.

[10] J. Gregory and S. Barany, "Adsorption and flocculation by polymers and polymer mixtures," *Adv. Colloid Interface Sci.*, vol. 169, no. 1, pp. 1-12, Nov. 2011, doi: 10.1016/j.cis.2011.06.004.

[11] C.H. Lee and J.C. Liu, "Sludge dewaterability and floc structure in dual polymer conditioning," *Adv. Environ. Res.*, vol. 5, no. 2, pp. 129-136, May. 2001, doi: 10.1016/S1093-0191(00)00049-6.

[12] Y. Yang, A. Wu, B. Klein and H. Wang, "Effect of primary flocculant type on a two-step flocculation process on iron ore fine tailings under alkaline environment," *Miner. Eng.*, vol. 132, pp. 14-21, Marc. 2019, doi: 10.1016/j.mineng.2018.11.053.

[13] Y. Yang, H. Wang, B. Klein and A. Wu, "Shear-dependent yield stress of iron ore fine tailings in two-step flocculation process," *Adv. Mater. Sci. Eng.*, 6611392, Nov. 2020, doi: 10.1155/2020/6611392.

[14] Y. Yang, A. Wu, X. Wang and G. Wang, "Effect of shear ratio rheological properties of suspension in two-step flocculation process for fine iron tailings," *Front. Mater.*, vol. 10, pp. 1-8, Jun.2023, doi: 10.3389/fmats.2023.1217947.

[15] W. Yu, J. Gregory, L. Campos and G. Li, "The role of mixing conditions on floc growth, breakage and re-growth," *Chem. Eng. J.*, vol. 171, no. 2, pp. 425-430, Jul. 2011, doi: 10.1016/j.cej.2011.03.098.

[16] W. Yu, J. Gregory and L. Campos, "Breakage and re-growth of flocs formed by charge neutralization using alum and polyDADMAC," *Water Res.*, vol. 44, no. 13, pp. 3959-65, Jul. 2010, doi: 10.1016/j.watres.2010.04.032.
[17] B. Bolto and J. Gregory, "Organic polyelectrolytes in water treatment," *Water Res.*, vol. 41, no. 11, pp. 2301-24, Jun. 2007, doi: 10.1016/j.watres.2007.03.012.