Research Article

Comparing Aluminium Sulfate and Poly-Aluminium Chloride (PAC) Performance in Turbidity Removal from Synthetic Water

Ali Daryabeigi Zand[1*], Hassan Hoveidi[2]

Abstract

Colloids are small suspended particles in water which cannot be settled or removed naturally due to their light weight and stability. These particles pose some degree of stability and cause water turbidity. There are some concerns regarding colloid removal efficiency in water treatment plants of Iran. In this study, the effectiveness of aluminium sulfate and poly-aluminum chloride was evaluated at different pH values and coagulant dosage in order to find optimal operational conditions for low to high turbidity waters. The influence of lime, as a coagulant aid, on coagulation process was also studied. A set of jar test experiments was conducted to find the optimal pH and coagulant dosage. Results demonstrated that coagulation process can assure turbidity removal from low to medium turbidity waters effectively using relatively low levels of aluminium sulfate and poly-aluminum chloride (10 to 20 mg/L). Turbidity removal efficiency still remained high when the initial turbidities of water were increased to 500 and 1000 NTU. Results showed that turbidity removal is dependent on pH, coagulant dosage, as well as initial turbidity of water for both used coagulants. The highest turbidity removal efficiency was within 82.9-99.0% for alum and 93.8-99.6% for poly-aluminum chloride over the applied range of turbidity. Both applied coagulants demonstrated promising performance in turbidity removal from water; however, poly-aluminum chloride showed better performance compared to aluminium sulfate. The results of the current study can be used as a baseline data for drinking water treatment facilities which uses these two types of coagulants.

Keywords: Coagulation, Aluminium Sulfate, Poly-Aluminum Chloride, Turbidity, pH

1. Faculty of Environment, University of Tehran, Tehran, Iran
2. Faculty of Environment, University of Tehran, Tehran, Iran

* **Corresponding Author**
Ali Daryabeigi Zand
Faculty of Environment, University of Tehran, Tehran, Iran
E-mail: adzand@ut.ac.ir

Submission Date: 7/11/2015
Accepted Date: 9/12/2015

Introduction

Coagulation, flocculation, sedimentation, filtration, and disinfection are the most common treatment processes used in the production of drinking water in Iran. Coagulation/flocculation processes are of great importance in solid–liquid separation practice [1-3]. Solid-liquid separation processes of coagulation/flocculation and subsequent filtration, when optimized, can remove all organic, inorganic and suspended matter to a level below water quality standards in most cases [4, 5].

Colloids are tiny particles in water which are suspended and cannot be settled or removed naturally due to their light weight and stability. These particles pose some degree of stability and cause water turbidity. Turbidity caused by particulate suspended material such as clay minerals, silt, viruses, bacteria, some organic matters as well as inorganic matters like asbestos, silicate and also radioactive particles.

Turbidity may contain many contaminants like pathogenic organisms. Many pollutants of concern to human health e.g. metals or some synthetic organic chemicals are also associated with turbidity. Thus, effective turbidity removal is necessary to ensure removal of many health-related contaminants. In addition, effective removal of turbidity may facilitate subsequent water treatment processes [4-5].

Aluminium salts are the most widely used coagulants in Iran as well as many other countries in the drinking water industry. They are mainly used in Iran because of their effectiveness, accessibility, and relatively low price. Two primary mechanisms are thought to be responsible for removal of colloids by coagulation, namely enmeshment within precipitated floc particles and charge neutralization/stabilization. Aluminium salts are rapidly hydrolysed in water to give a range of products including cationic species, which can absorb on negatively charged particles and neutralize their charge, thereby destabilize them. Precise control of coagulant dosage is necessary since overdosing may lead to charge reversal and restabilization of particles. Sludge production is also increased when using extra amounts of alum and poly-aluminum chloride coagulants.

The influence of dosage and mixing conditions on the flocculation of concentrated suspensions using polymeric coagulants; coagulation of synthetic water by plant seeds as well as coagulation of low turbidity water using bentonite have been reported in the literature [6-8]. In a study by Guida et al., (2007) alum was used as coagulant to remove COD and total suspended solids (TSS) from municipal wastewater samples [6-8].

The coagulation experiments indicated that alum effectively removed COD (65%) and TSS (>75%) on the average values of COD using 150 mg/L aluminum sulfate at a pH range of 5-8 [9]. The coagulation process is generally influenced by the type of colloids in suspension, pH, chemical composition of the water, the type of coagulant and coagulant aid, and mixing intensity and duration provided for chemical dispersion and floc formation [6].

The main objective of this study was to compare the effectiveness of poly-aluminum chloride (PAC) and aluminum sulfate (alum) in reducing turbidity levels in synthetic water. PAC and alum are extensively used in water treatment plants in Iran. Their performance was evaluated at different pH values and coagulant dosage in order to find optimal operational conditions for low to highly turbidity waters. The influence of lime, as a coagulant aid, in accompany with alum and PAC was also studied.

Materials and Methods

Jar test experiments were conducted within a pH range of 4-8. Aluminium sulfate and poly-aluminum chloride were used in the current study, as the most common types of coagulants used in many water treatment plants. Distilled water was used in this study to avoid probable interference of any elements in water with turbidity removal. Desired turbidity was provided synthetically by kaolin powder. A calibration curve of the turbidity versus kaolin concentration was obtained. Sodium hydroxide and sulfuric acid were used for pH adjustment. Prepared samples were placed in a 1000 ml beaker and stirred at 350 rpm for 1 min (rapid mixing). The mixing speed was reduced to 30 rpm for 20 min for flocculation (slow mixing). Within 5 min from the beginning of flocculation pH was checked and adjusted (if necessary) to keep the desired pH value ±0.05 units. Any floc formed was allowed to settle for 45 min. Supernatant samples were taken from 20 mm below the water surface for turbidity measurements. Supernatant turbidity was measured with a HACH 2100A turbidimeter and expressed in Nephelometric Turbidity Units (NTU).

Residual turbidity was used as the indicator of performance. The optimal pH and dose for turbidity removal with both aluminium sulfate and PAC were attained by the jar test experiments. In addition, lime was also used in accompany with alum and PAC at optimum pH values to investigate its influence on coagulation process and turbidity removal efficiency. All jar test experiments were conducted at room temperature because low temperature may have an adverse effect on coagulation and flocculation kinetics as suggested by Kang and Cleasby (1995) [10]. Experimental characteristics for the jar test experiments in this research were summarized in Table 1.

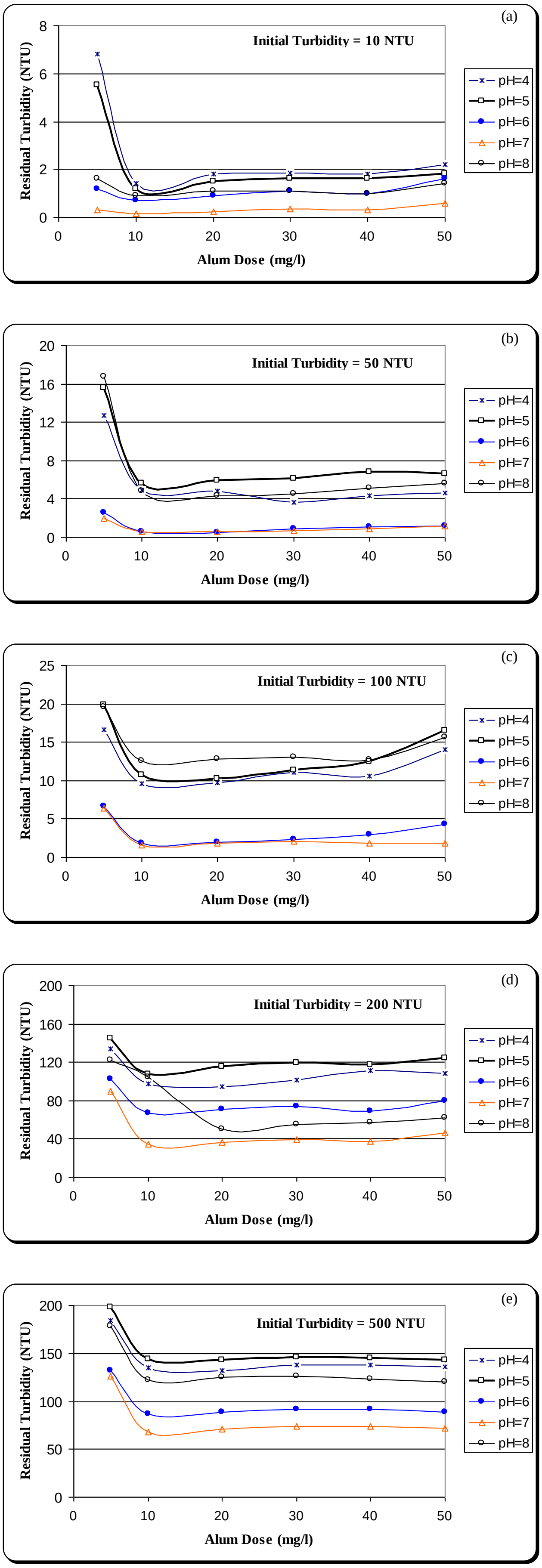
Table 1. Experimental characteristics for jar test experiments conducted in this study

Characteristics	Description
Coagulants	Aluminium sulfate and poly-aluminum chloride
Coagulant dose range	5-50 mg/L
Coagulant aid (dose)	Lime (5 mg/L)
pH range	4-8
Initial turbidity	10-1000 NTU
Rapid mixing	60 seconds at 350 rpm
Slow mixing	20 minutes at 30 rpm
Settling	45 minutes

Results and Discussion

Turbidity removal efficiency as a function of aluminium sulfate dose at pH range of 4-8 is shown in the Figure 1. Initial turbidities of water samples were adjusted to be 10, 50, 100, 200, 500, and 1000 NTU. Initial turbidities of 10 and 50 NTU, 100 and 200 NTU, and 500 and 1000 NTU were respectively considered as low, medium, and highly turbidity levels in water, based on the applied turbidity levels. However, this classification may be somewhat different in other texts. High initial turbidities were considered in this research because such high turbidities commonly occur in many storm waters [11, 12]. Low turbidity waters are usually hard to coagulate due to low concentrations of stable particles. Turbidity can be synthetically added to the water to form heavier flocs which can be settled [4, 13]. However, in the current study the lowest applied turbidity i.e. 10 NTU was not too low to disturb coagulation process. The best performance of alum was observed at pH 7 over the selected range of turbidity but its performance decreased to some extent at pH values of 4, 5, and 8. Coagulation efficiency of alum at pH 6 was almost close to that of at pH 7. The highest turbidity removal was attained at pH 7 when 10 mg/L alum was used except for initial turbidity of 1000 NTU. The optimum alum dosage was higher (20 mg/L) for initial turbidity of 1000 NTU which was the lowest required dosage obtained the highest turbidity removal. The best performance of alum in removing turbidity from water was obtained at pH 7 following by pH 6. The coagulation efficiency of alum remained almost constant within the dosage range of 10 to 40 mg/L at pH range of 4-8 (Fig. 1). In other words, results showed that alum dosage range for good coagulation was almost wide in this study. However, over-dosing was observed for low to medium turbidity waters when 50 mg/L alum was used. Turbidity removal efficiency was slightly decreased by increasing alum concentration from 40 to 50 mg/L, e.g. turbidity removal decreased from 97.1% to 95.7% at pH 6 (initial turbidity of 100 NTU).

This reduction may be attributed to charge reversal and restabilization of colloidal particles due to overdosing as also suggested by some other authors [8]. Overdosing can disrupt this phenomenon, therefore fairly precise control of coagulant dosage should be considered in water treatment plants. At the optimum condition (optimal dose and pH), turbidity removal efficiencies of alum were 98.5, 99, 98.3, 82.9, 86.3, 84.3 percent for initial turbidities of 10, 50, 100, 200, 500, and 1000 NTU, respectively. Results indicated that turbidity removal efficiency was varied by pH, alum dose and initial turbidity of water. The obtained results are in accordance with those obtained by Volk et al., (2000) which were indicated that the pH of coagulation was the most influential parameter affect NOM removal from water [14]. They also suggested that the amount of NOM removed from water is also dependent on the type of coagulant. They used aluminium and iron salts as coagulants in their jar test experiments. In coagulation study conducted by Annadurai et al., (2004) simultaneous removal of turbidity and humic acid from high turbidity synthetic raw water was investigated using another aluminium salt, i.e. polyaluminum chloride (PACl) [11].



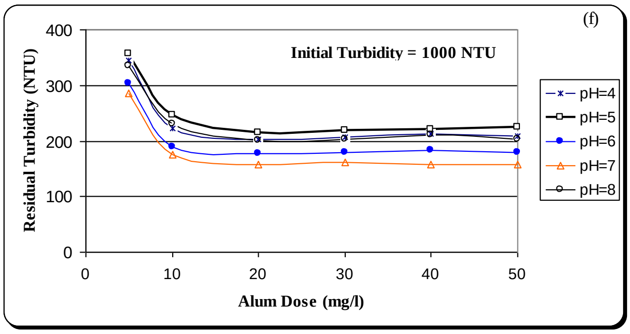


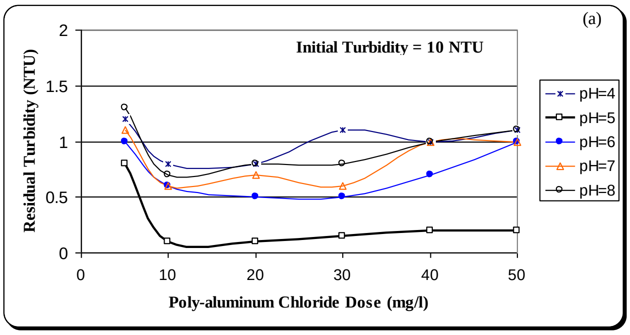
Figure 1. Turbidity removal as a function of aluminium sulfate dose at pH range of 4-8 (a-f).

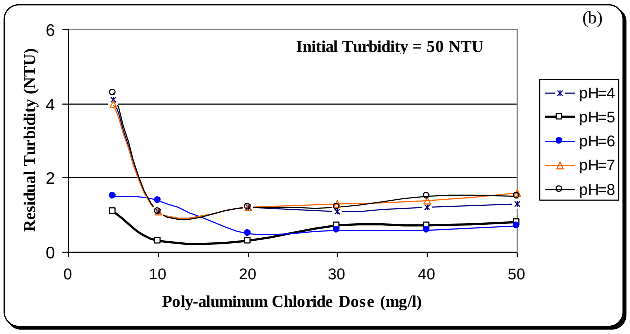
Results indicated that turbidity removal efficiency declined to some extent by increasing initial turbidity level from 100 to 200, 500, and 1000 NTU. Application of higher alum dosage range may improve turbidity removal from relatively high turbidity waters. However it should be considered that coagulation with alum may increase aluminium concentration in drinking water. Aluminium in coagulated drinking water has been regarded as a subject of human and environmental health concern [9].

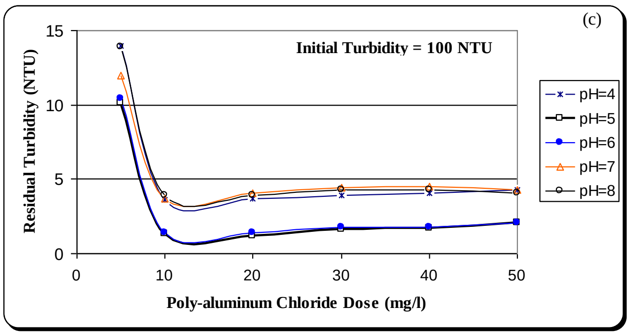
Figure 2 illustrates the influence of PAC dose on turbidity removal at different pH values. Under-dosing was observed when 5 mg/L PAC was used over the applied range of turbidity. Turbidity removal efficiency was considerably increased by increasing PAC dosage from 5 to 10 mg/L in all cases (Fig. 2). The highest performance of PAC was observed at pH 5 and subsequently pH 6. The optimum coagulant dosage for initial turbidities of 10, 50, 100, and 200 NTU was obtained when 10 mg/L PAC was used. However, the highest turbidity removal efficiency for initial turbidities of 500 and 1000 NTU was achieved when 20 and 30 mg/L PAC was used, respectively. It should be noted that increase in PAC concentration from 10 to 20 mg/L and from 20 to 30 mg/l, respectively, for initial turbidities of 500 and 1000 NTU did not enhance turbidity removal considerably. Turbidity removal was almost stable at all dosages greater than 10 mg/L when pH was kept constant. Therefore optimal dosage of 10 mg/L PAC can be selected over the applied range of turbidity except for initial turbidity of 1000 NTU. Based on the obtained results, the optimum PAC dosage for initial turbidity of 1000 NTU is considered to be 20 mg/L in this study. Khan and Thiem (2008) conducted a jar-test study to explore optimum coagulant dose and optimum pH for low turbidity (0.1-3 NTU) water. They used ferric sulfate as a coagulant and a cationic polyelectrolyte to remove color from water. The optimum coagulant dose and pH was found to be 6 mg/L for ferric sulfate and 1 mg/L for the polymer used at pH 7 [4]. The lower optimum dosage found in their study (6 mg/L) compared to the current research (10 mg/L) may be attributed to lower initial turbidity, coagulant type, as well as using a polymer in accompany with ferric sulfate.

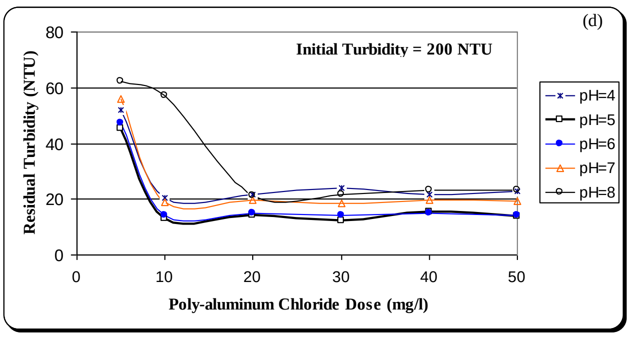
Over-dosing was also observed for low turbidity waters when 50 mg/L PAC was used, similar to alum coagulant. Turbidity removal efficiency was slightly decreased by increasing PAC concentration from 40 to 50 mg/L in low-turbid waters. Turbidity removal efficiencies of PAC at the optimal pH and PAC dosage were 99.0, 99.6, 98.8, 93.8, 94.1, 94.6 percent for initial turbidities of 10, 50, 100, 200, 500, and 1000 NTU, respectively.

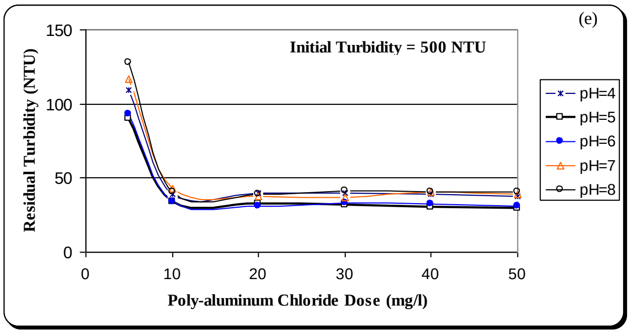
The highest turbidity removal efficiency for PAC was almost constant (more than 90%) over the selected range of turbidity. Results indicated that turbidity removal is dependent on pH, coagulant dosage, as well as initial turbidity of water for both alum and PAC. Variation of pH considerably affected turbidity removal. When pH was kept around its optimal value (5-6 for PAC and 6-7 for alum) the highest turbidity removal was achieved.











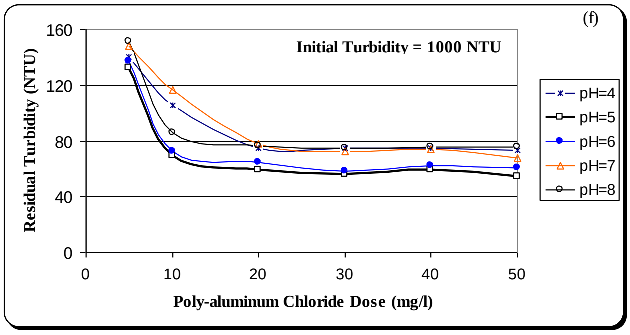


Figure 2. Turbidity removal as a function of PAC dose at pH range of 4-8 (a-f).

Rapid mixing parameters including time and intensity of mixing, as well as slow mixing parameters may also affect turbidity removal efficiency in coagulation process. In literature there are rather contradictory recommendations for rapid mix parameters. Some researchers suggest long mixing time of a few minutes whereas others recommend instantaneous mixing [15]. Since mixing time is important factor affecting the turbidity removal efficiency it should be further investigated to obtain a better insight into its role for optimizing the coagulation process.

Results showed that performance of PAC was better than alum in all cases particularly for high turbidity waters, however, turbidity removal efficiency showed an almost similar pattern for both alum and PAC. Coagulation and flocculation processes are primary and cost-effective processes in water treatment plants which can effectively remove turbidity from low to high turbidity waters when operational condition is optimized. Optimization of pH and coagulant dose may increase the coagulation efficiency and reduce the sludge volume and subsequently sludge management costs. Coagulant aids may improve coagulation process and turbidity removal. But it should be considered that coagulant aids should not increase water treatment costs significantly. Their accessibility and preparation procedure should also be considered when selecting a coagulant aid. Lime was selected as the coagulant aid in this study because it is easily accessible and widely used in water treatment industry in Iran as well as many other countries.

Preliminary jar test experiments obtained the optimal level of 5 mg/L for lime. Lime was applied only at optimal pH values for both alum and PAC. Table 2 indicated that lime (5 mg/L), as a cost-effective coagulant aid, improved coagulation efficiency and turbidity removal to some

extent when using in accompany with alum and PAC. However, lime dosage should be carefully controlled and lowered in coagulation process due to the production of excess amounts of sludge, as considered in this research. As it can be observed in Table 2, the highest improvement in turbidity removal efficiency was found at pH 5 for initial turbidity of 50 NTU when lime was applied in accompany with 10 mg/L PAC (66.7% increase). In general, lime addition could not increase turbidity removal efficiency considerably in most cases; however, its application improved coagulation process to some extent. For instance, lime addition reduced residual turbidity from 0.3 to 0.1 mg/L and 1.4 to 0.9 mg/L, respectively for water samples with initial turbidities of 10 and 50 NTU, at pH 5 and PAC dosage of 10 mg/L. Make a decision on using lime as a coagulant aid strongly depends on accessibility of other types of coagulant aids and their costs as well as available legislations to limit sludge production and disposal in water treatment plants. This study demonstrated that coagulation process can assure turbidity removal from low to medium turbidity waters effectively using relatively low levels of aluminium sulfate and PAC (10 to 20 mg/L). Turbidity removal efficiency still remained high when the initial turbidities of water were 500 NTU and 1000 NTU, particularly for coagulation with PAC.
Variation of pH, coagulant dosage and initial turbidity of water found to be important factors affect turbidity removal efficiency. Both alum and PAC demonstrated promising performance in turbidity removal from water.

Conclusion

Results demonstrated that coagulation process can assure turbidity removal from low to medium turbidity waters effectively, using relatively low levels of aluminium sulfate and poly-aluminum chloride (10 to 20 mg/l). The optimum pH range for turbidity removal was found 5-6 and 6-7, respectively, for PAC and alum resulting in the maximum turbidity removal. The highest turbidity removal efficiency was more than 82% for alum and more than 93% for PAC over the applied range of turbidity. Turbidity removal efficiency was higher for poly-aluminum chloride compared to aluminium sulfate at optimum conditions. Turbidity removal efficiency was sufficient to meet national drinking water limits of Iran (5 NTU) at optimum alum and PAC dose for waters with initial turbidity of 10-100 NTU. Using 5 mg/l lime as a coagulant aid could improve turbidity removal in some cases. Application of different dosage and alternative coagulants to meet allowable limits should be further studied. However, national standards vary among different countries. In this research, the coagulation process and turbidity removal was considerably affected by pH, coagulant dosage, as well as initial turbidity of water for both alum and PAC. Turbidity removal was relatively stable at all selected dosages greater than 10 mg/l when pH was kept constant, whereas turbidity removal using both used coagulants is seemed to be more influenced by pH variation than coagulant dosage. Both applied coagulants demonstrated promising performance in turbidity removal from water.

Table 2. Variation of turbidity removal after coagulation process due to addition of 5 mg/L lime (%).

	Coagulant						Aluminium sulfate (Alum)					
	Variation (%) at pH = 6						Variation (%) at pH = 7					
Dosage (mg/L)	**5**	**10**	**20**	**30**	**40**	**50**	**5**	**10**	**20**	**30**	**40**	**50**
Initial Turbidity (NTU)												
10	-8.3	0.0	-11.1	-18.2	-5.0	-25.0	0.0	-33.3	-60.0	-57.1	-16.7	-16.7
50	-15.4	-25.0	-10.0	-11.1	0.0	-8.3	-10.0	-45.4	-33.3	0.0	-11.1	4.3
100	3.0	5.6	5.0	-4.2	-8.6	4.6	-1.6	-9.1	5.6	4.8	5.3	36.8
200	2.5	4.3	2.4	1.3	6.0	8.5	-6.7	-6.4	0.0	3.5	14.9	3.7
500	-21.7	-21.5	-13.4	-8.7	-10.5	-9.5	-22.2	-29.1	-28.5	-31.1	-27.3	-26.1
1000	-15.6	-13.8	-7.3	-8.7	-9.2	-6.7	-29.0	-23.6	-11.6	-13.0	-11.0	-10.6
	Coagulant						**Poly-aluminum Chloride (PAC)**					
	Variation (%) at pH = 5						**Variation (%) at pH = 6**					
Dosage (mg/L)	**5**	**10**	**20**	**30**	**40**	**50**	**5**	**10**	**20**	**30**	**40**	**50**
Initial Turbidity												
10	-10.9	0.0	-31.2	0.0	0.3	-15.3	-17.1	-42.2	-28.4	-17.3	-14.5	-11.4
50	-15.8	-64.8	-29.9	-33.0	-34.5	-32.0	-23.5	-42.0	-48.3	0.3	-11.3	-24.3
100	-27.8	-34.8	-32.3	-37.8	-37.0	-34.6	-28.3	-29.3	-28.4	-38.4	-31.2	-37.2
200	-27.6	-31.5	-29.8	-25.6	-37.6	-38.2	-28.7	-31.5	-24.3	-21.3	-30.9	24.0
500	-5.7	-12.6	-7.3	-5.9	-4.8	-6.6	-4.7	-5.6	1.7	2.2	3.1	2.4
1000	-10.2	-7.8	-22.6	-20.4	-19.9	-18.8	-11.3	-4.0	-26.2	-21.9	-19.6	-23.6

Finally, the results of the current study can be used as a baseline data for drinking water treatment facilities which use aluminum sulfate and poly-aluminum chloride.

Acknowledgments
Special thanks to the Vice President Office for Research of University of Tehran for their support.

References

1. Yukselen, M.A., Gregory, J., The effect of rapid mixing on the break-up and re-formation of flocs. *J Chem Technol Biotechnol*, 2004, Vol. 79, pp. 782-788.
2. Nurudeen, A.A., Headway on natural polymeric coagulants in water and wastewater treatment operations. *J Water Process Eng*, 2015, Vol. 6, pp. 174-192.
3. Sudoh, R., islam, M.S., Sazawa, K., Okazaki, T., hata, N., Taguchi, S., Kuramitz, H., Removal of dissolved humic acid from water by coagulation method using polyaluminum chloride (PAC) with calcium carbonate as neutralizer and coagulant aid. *J Environ Chem Eng*, 2015, Vol. 3, pp. 770-774.
4. Khan, Z., Thiem, L.T., Optimizing coagulation process for a low turbidity, low temperature water, *Electron J Environ Agric Food Chem*, 2008, Vol. 7, pp. 2599-2610.
5. Van Haute, S., Uyttendaele, M., Sampers, I., Coagulation of turbidity and organic matter from leafy-vegetable wash-water using chitosan to improve water disinfectant stability. *LWT-Food Sci Technol*, Vol. 64, pp. 337-343.
6. Fatoki, O.S., Ogunfowokan, A.O., Effect of coagulant treatment on the metal composition of raw water. *Water SA*, 2002, Vol. 28, pp. 293-297.
7. Diaz, A., Rincon, N., Escorihuela, A., Fernandez, N., Chacin, E., Forster, C.F., A preliminary evaluation of turbidity removal by natural coagulants indigenous to Venezuela. *Process Biochem*, 1999, Vol. 35, pp. 391-395.
8. Shen, Y.H., Treatment of low turbidity water by sweep coagulation using bentonite, *J Chem Technol Biotechnol*, 2005, Vol. 80, pp. 581-586.
9. Guida, M., Mattei, M., Della Rocca, C., Melluso, G., Meric, S., Optimization of alum-coagulation/flocculation for COD and TSS removal from five municipal wastewater. *Desalination*, 2007, Vol. 211, pp. 113-127.
10. Kang, L.S., Cleasby, J.L., Temperature effects on flocculation kinetics using Fe(III) coagulant. *J Environ Eng*, 1995, Vol. 121, pp. 893-901.
11. Annadurai, G., Sung, S.S., Lee, D.J., Simultaneous removal of turbidity and humic acid from high turbidity stormwater. *Adv Environ Res*, 2004, Vol. 8, pp. 713-725.
12. Lin, J.C.T., Chen, J.J., Lee, D.J., Guo, W.M. Treating high-turbidity storm water by coagulation-membrane process. *J Taiwan Inst Chem Eng*, 2012, Vol. 43, pp. 291-294.
13. Ho, L., Newcombe, G., Effect of NOM, turbidity and floc size on the PAC adsorption of MIB during alum coagulation. *Water Res*, 2005, Vol. 39, pp. 3668-3674.
14. Volk, C., Bell, K., Ibrahim, E., Verges, D., Amy, G., Lechevaller, M., Impact of enhanced and optimized coagulation on removal of organic matter and its biodegradable fraction in drinking water. *Water Res*, 2000, Vol. 34, pp. 3247-3257.
15. Rossini, M., Garrido, J.G., Galluzzo, M, Optimization of the coagulation-flocculation treatment: influence of rapid mix parameters. *Water Res*, 1999, Vol. 33, pp. 1817-1826.