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Research Article

Investigation of the settling behavior of lateritic nickel ores in the CCD process after HPAL

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ABSTRACT

In this study, the settling performance of lateritic nickel ores in the Counter Current Decantation (CCD) thickeners following the High-Pressure Acid Leaching (HPAL) process was investigated in detail. The samples used within the scope of the study were obtained from the overflow of the 2nd CCD thickener under the condition that Manisa-Gördes and Eskişehir-Karaçam lateritic nickel ores were fed to the plant at different times. A series of settling tests were performed for both ores using anionic, cationic, and nonionic flocculants of various ionicity and molecular weight. Sedimentation performance was evaluated based on parameters such as settling time, clarity, and compression. To determine the optimum conditions for the tests, a preliminary test was performed, and the pulp solids content was determined as 7% and the flocculant dosage as 850 g/t. According to the test results, nonionic and very low anionic flocculants gave better results. It was found that flocculation was negatively affected with increasing anionicity, and results could be obtained only with very low anionicity flocculants. It was determined that the settling rate was very fast with cationic flocculants, but the amount of compression was not favorable, especially for Gördes ore. However, it is envisaged that the amount of consumption can be reduced if cationic flocculants are used especially for Karaçam ore. When a comparison was made between the ores, similar results were obtained in general and only for Karaçam ore, thickener underflow density gave a successful result for all flocculant performances. On the other hand, it was concluded that variable ore structures and unstable process parameters influence the flocculant adsorption mechanisms and thus on the settling behavior.

Introduction

The leaching process under high temperature and pressure with sulfuric acid solution, which is one of the methods for the enrichment of lateritic nickel ores by hydrometallurgical methods, is called High Pressure Acid Leaching (HPAL) [1]. This method has been used in recent years and consists of wet process steps from start to finish without dry processes such as drying, roasting, etc. This is preferable in terms of energy and cost savings [2].

Metal recovery efficiencies for lateritic ores in the HPAL method are quite high compared to other methods. In this process, neutralization is performed after leaching and in the next stage, CCD (Counter Current Decantation) circuits are used to recover the pregnant solution in the leach residue. The basis of the CCD process is to increase the concentration by precipitating the solid particles in the suspension and to wash the pregnant solution in this sludge flowing in one direction by diluting it in several stages with wash water in the opposite direction. The number of stages of this process, i.e. the number of tanks, is determined by the soluble precious metal content of the underflow stream. [3]. If no other recovery process is applied to the underflow of the final thickener of CCD circuit, it is usually transferred to the tailings dam as final waste. Therefore, washing and settling efficiency in this unit is important. Polymeric flocculants are commonly used in solid-liquid separation operations [4]. A typical laterite CCD circuit includes seven stages and recovers 99% of the dissolved nickel back to the clarified pregnant leach solution [5].

Flocculation is defined as the breaking of the stabilization between the solid particles in a suspension by means of a flocculant chemical so that the particles come together and reach a larger size. Flocculation can generally be regarded as a two-stage process including the formation of flocs and the growth period of flocs [6]. Polyelectrolytes used as flocculants in practice mainly include water-soluble polyacrylamides, polyphosphates and modified natural polymers (gelatins, chitosan and carrageenan as well as starch and cellulose derivatives). Polyelectrolytes are classified as cationic, anionic and nonionic according to the nature of the functional groups along the polymer chain. A polyelectrolyte is characterized by its molecular weight, the nature of the functional group and the charge density. The coagulation (destabilization of the colloid by neutralization) and flocculation (bridging between particles) potential of the polyelectrolyte is an important consideration in polyelectrolyte selection. The pH is also an important parameter to consider [7].

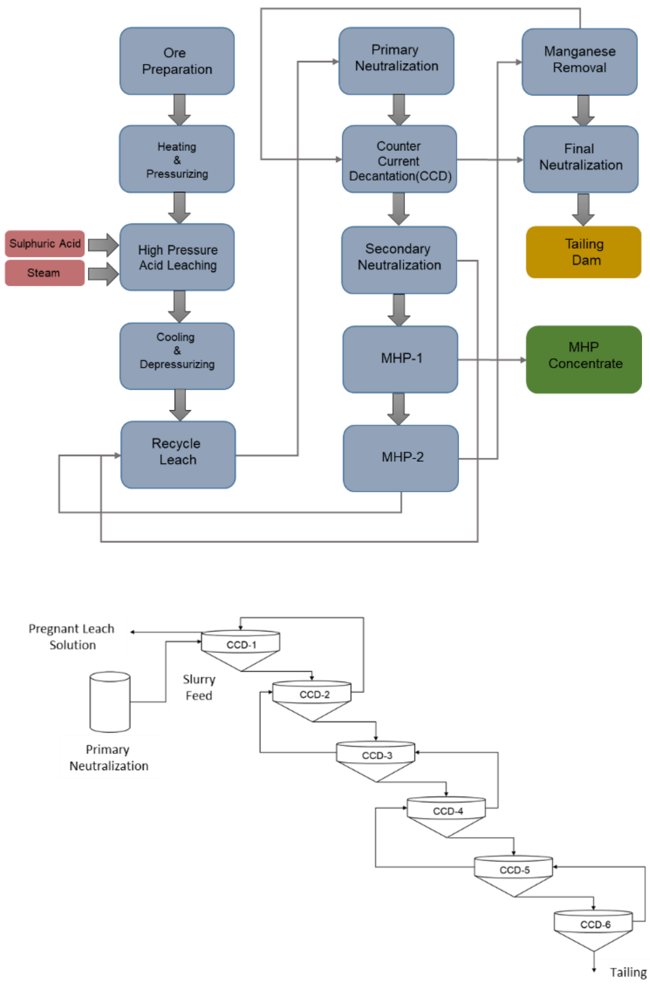
There are many studies investigating the effect of flocculation on the according to changing parameters or the effect of flocculants with different properties on the process. In a study investigating the effect of flocculant ionicity and different molecular weights on the flocculation characteristics of chromite process ore tailings; it was observed that there was no change in the settling rate of nonionic type flocculant due to dosage increase, but the settling rate of anionic and cationic flocculants was directly proportional to dosage, and polymer ionicity had a significant effect on flocculation rate, settling and consolidation rate. It was also found that low anionic and low molecular weight anionic flocculants showed improved flocculation properties, while cationic flocculants performed better at higher cationicity and molecular weight, and nonionic flocculant did not have any flocculation effect on the tailing material. [8]. It was reported that anionic flocculants performed better than cationic and nonionic flocculants in terms of settling rate and provided positive results even at low dosages on coal washing plant tailings [9]. Other study is about characterizing fine-particle coal tailings and using an anionic, high molecular weight flocculant, the optimum slurry solids content was determined as 8% and pH value as 8. The decrease in settling rates at higher pHs was explained as the suspension pH changes the charge properties of the polymer chain and its compatibility with the solution, which directly affects the floc forming power of the polymer and may lead to a change in the settling rate of the particles. It was noted that a clearer overflow was obtained with increasing flocculant dosage, but there was no visible change after a certain dosage and at the same time, the amount of waste solids increased considerably [10]. It is reported by Göçer that another group of materials in which anionic flocculants give positive results are clay minerals such as kaolin, Na-Bentonite, Ca-Bentonite and intermediate type (Na,Ca)-Bentonite [11]. It is stated that the reason for this situation is the polymer bridging mechanism that allows the particles to come together by clustering. There is also an investigation on the electro kinetic properties and flocculation of clays, it was determined that although the surface charge of all clay minerals was found to have negative valence as a result of the measurements, the flocculant that gave the most positive result was again anionic. As the flocculant dosage increased, flocculation was better, but no change was observed after a certain amount of increase. It was observed that the settling velocity of the anionic flocculant decreased at high pH values, and the reason for this was that the suspended solid particles repelled each other as a result of the increase in pH value and reached a more stable position [12]. In a study investigating the settling characteristics of very fine particle iron ore slurry, a combination of anionic and cationic flocculants at a ratio of 4:1 was tested as well as flocculants separately. When the results were evaluated according to different dosages and pH, it was observed that the anionic flocculant performed better than other types of flocculants and the settling rate increased with increasing dosage. At the same time, the reason for the good performance of anionic flocculants was shown to be the positive surface charge of the material used for the test, and it was concluded that if polyacrylamide is used, it can significantly increase the settling rate or ratio and therefore it can be used practically for the settling process [13].

Solid liquid separation and washing efficiency in this process are of high importance in terms of obtaining the pregnant solution after HPAL with minimum loss by washing in CCD stages. For this reason, flocculant selection also becomes an important factor. The processing of two different lateritic nickel ores in the plant results in different precipitation behavior. Therefore, the aim of this study is to determine the settling characteristics for both ores using a wide range of flocculants with different properties and to determine the flocculant that provides the best conditions according to the performance criteria and to evaluate the settling behavior in the CCD process.

Material and Method

The tests were performed for two different ore types, Manisa-Gördes and Eskişehir-Karaçam, due to the reason that two ore types are fed to the plant. Therefore, both Gördes and Karaçam ores were used as samples, with the slurry sample fed to the CCD thickeners and the overflow solution of the second CCD thickener for dilution. The flow diagram of the plant and the operation diagram of the CCD unit are given in Figure 1.

(a)



(b)

Figure 1. (a) Plant Flow Diagram (b) CCD circuit

Physical, chemical, and mineralogical characterization studies were carried out for all test samples in order to determine the characteristics and content of the slurry sample taken from the primary neutralization area and to examine its effect on the settling performances. In this context, the particle size distribution of both Gördes and Karaçam ores were measured using the Mastersizer device. The mineral composition of both samples was analyzed by X-ray diffraction (XRD) method. The elemental content of the primary neutralization sample in both liquid and solid phases was determined by ICP-OES method. Within the scope of the experimental method, a series of settling tests were performed with primary neutralization slurry sample and CCD-2 thickener overflow solution samples using anionic, cationic, and nonionic flocculants of various molecular weights. Gördes ore was used in Tests 1, 2 and 3 and Karaçam ore was used in Tests 4, 5 and 6. Slurry and solution sample temperatures were kept the same with the plant values. Temperature, pH and potential values were measured and monitored during the test. For each test, a stock flocculant solution was prepared at a concentration of 0.1% using plant process water as fresh solution. It was stirred with a magnetic stirrer for about 3 hours and completely dissolved.

The flocculants used were anionic, cationic, and nonionic, with anionicity ranging from 3% to 70% and cationicity ranging from 1.5% to 100%. The types and molecular weights of the flocculants used in the tests are given in Table 1.

Table 1. Properties of flocculants used in the tests

Flocculant	Ionicity %	Type	Molecular Weight
FA 920	0	Nonionic	Medium
FA 920 SH	0	Nonionic	High
FA 920 VHM	0	Nonionic	Very High
AH 912	1	Low anionic	Medium
AH 912 SH	1	Low anionic	High
AN 905	5	Low anionic	Medium
FO 4125 SH	2.5	Low cationic	Medium
FO 4650 SH	55	Very high cationic	Medium
FO 4700 SH	70	Very high cationic	Medium
FO 4800 SH	80	Very high cationic	Medium
FO 4990 SH	100	Very high cationic	Medium
FO 4115 SSH	1.5	Low cationic	High
FO 4650 SSH	55	Very high cationic	High
FO 4700 SSH	70	Very high cationic	High
FO 4800 SSH	80	Very high cationic	High

Preliminary tests were carried out with a high molecular weight nonionic flocculant to determine the optimum solid percentage and flocculant dosage to be used as a constant condition in all settling tests for both ore types. In these tests, solid percentages of 5%, 7% and 10% and flocculant dosages of 560 g/t, 850 g/t and 1130 g/t were determined for both ores and the settling performances such as settling time, compaction and clarity were compared. When the results were examined, although the values seemed positive in terms of 5% solids rate, it is not a reason for preference because the settling rate was too fast. Considering the current design and capacity of the plant, it is possible that a very fast settling rate may lead to accumulation in the thickener and destabilization of the system as a result of insufficient underflow discharge of the thickener. Concerning the determination of flocculant dosage, 850 g/t and 1130 g/t provided very similar settling times. At this point, 850 g/t was accepted as the optimum value based on the consumption amount. It was concluded that the optimum operating conditions for both ores were 7% solids ratio and 850 g/t flocculant dosage. The pH and potential measurements of the settling tests performed under these operating conditions are given in Table 2.

Table 2. Operating conditions of the diluted slurry sample prepared for the settling test

	Primary Neutralization + CCD-2 (Diluted Slurry)			
	pH	Potential (mV)	Flocculant Dosage (g/t)	Solid Content (%)
Test1	3.29	392.5	850	7
Test2	3.53	512.5	850	7
Test3	3.60	513.0	850	7
Test4	3.35	296.7	850	7
Test5	3.38	510.7	850	7
Test6	3.43	504.9	850	7

All settling tests were made using a 500 mL volume measuring cylinder and plunger. The plunger is like a piston, its end is round and 2-dimensional also has holes in this part. It is used to mix the slurry and flocculant in the cylinder by up and down movement. The primary neutralization slurry was diluted with CCD-2 thickener overflow solution to a slurry solid content of 7%. Flocculants were grouped according to their molecular weights and ionic properties and settling tests were performed in sets. Flocculant dosing was carried out in two stages to represent the plant's thickener dosing and slurry mixing system. Mixing was carried out between both dosing with a plunger apparatus After dosing, 450- 300 mL, the settling times were recorded with a stopwatch and the volumetric compaction values of the settled solids after 30 minutes were determined. To determine the clarity value, suspended solids (SS) were measured by taking a sample from the clean solution. The mentioned procedure was applied to both ore types with three repetitions.

Ore Characterization

The nickel laterite deposits in the Gördes and Karaçam area are developed on serpentinites and peridotites which are interlayered in an Upper Cretaceous sedimentary package of limestone and associated sediments. Both ores are of limonitic type.

According to XRD analysis of Gördes and Karaçam samples, the major minerals in Gördes ore are quartz, gypsum, pyroxene, hematite and calcite, while Karaçam ore consists of goethite, hematite, cristobalite and Mg containing compounds.

The solid and liquid analysis results of the primary neutralization slurry sample were determined for all six tests and the results are given in Table 3. It is seen that especially Fe, Ca and Al elements are present in the solid phase in both samples, and the Ni and Co content of Karaçam ore is higher than Gördes ore.

The particle size distributions of representative samples taken from each slurry sample drawn from the operating plant flow for settling tests are shown in Figure 2. According to this, especially below 300µm, Karaçam ore exhibits a much finer particle size distribution, p80:97 µm, while this value is p80:136 µm in Gördes ore.

Table 3. Solid and liquid elemental analysis of the primary neutralization sample used in all tests

	ICP-OES Results in Solid Sample								
	Al, %	As, %	Ca, %	Co, %	Cr, %	Fe, %	Mg, %	Mn, %	Ni, %
Test1	2.628	0.349	10.454	0.004	0.794	21.35	0.266	0.055	0.087
Test2	1.814	0.251	11.560	0.003	0.452	15.64	0.219	0.053	0.072
Test3	2.420	0.295	11.827	0.003	0.490	15.40	0.238	0.052	0.072
Test4	1.965	0.272	8.472	0.005	0.818	26.71	0.169	0.144	0.097
Test5	1.744	0.221	7.920	0.006	0.846	27.86	0.190	0.135	0.132
Test6	1.911	0.234	10.830	0.005	0.813	21.45	0.171	0.082	0.088
	ICP-OES Results in Liquid Sample								
	Al, %	Ca, %	Co, %	Cr, %	Fe, %	Mg, %	Mn, %	Ni, %	Si, %
Test1	0.937	0.068	0.014	0.035	0.045	0.927	0.129	0.293	0.034
Test2	0.670	0.077	0.013	0.016	0.020	1.313	0.118	0.286	0.022
Test3	0.700	0.066	0.014	0.013	0.026	1.184	0.121	0.326	0.021
Test4	1.276	0.070	0.015	0.058	0.051	0.827	0.183	0.280	0.024
Test5	1.117	0.070	0.018	0.064	0.062	0.747	0.168	0.313	0.033
Test6	1.272	0.079	0.016	0.053	0.028	0.892	0.136	0.298	0.033

The important part in the results is the nickel content in the liquid. As the nickel in the liquid increases, the importance of the washing efficiency in the CCD increases in terms of losses. Flocculation is also an important factor affecting the washing efficiency.

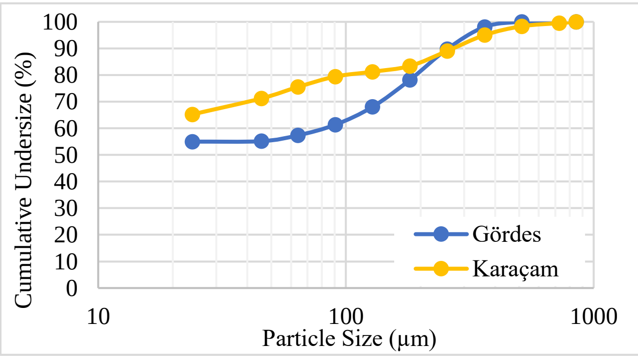


Figure 2. Particle size distribution of Gördes and Karaçam ore

The optimum value ranges of the performance parameters were determined for the purpose of interpreting the settling tests and are given in Table 4. Range values were determined according to the optimum process conditions based on plant design values. The results obtained were interpreted based on these values.

Table 4. Optimum value ranges of evaluation parameters

Parameter	Optimum Range
Settling time (s)	10-30
Compaction (mL)	100-130
Thickener U/F Solid (%)	30-35
Suspended Solids (SS) (mg/L)	100-200

Results and Discussion

With the completion of the test studies, the settling performances of the flocculants were evaluated for both ore types based on all measured and recorded data. The parameters obtained from the tests such as settling time, volumetric compaction, clarity, which elucidate the performance evaluation, were examined. Nonionic, anionic and cationic flocculants were grouped separately, and all tests were compared with each other. To ensure reliability the tests were repeated, and evaluation was made with average results.

Tests performed with Nonionic Flocculants

Tests were conducted for both Gördes and Karaçam samples using flocculants with different molecular weights. Data on settling times are given in Figure 3.

When the settling times for Gördes ore were analyzed, it was seen that FA 920 and FA 920 SH flocculants gave similar settling trend in the three tests. However, there is a noticeable difference in the performance of FA 920 VHM flocculant in terms of settling time in test No. 2 and it is seen that it provides very fast settling times in other tests. In Karaçam ore, although the settling rates were generally very high, an optimum settling rate was reached only in test No. 6.

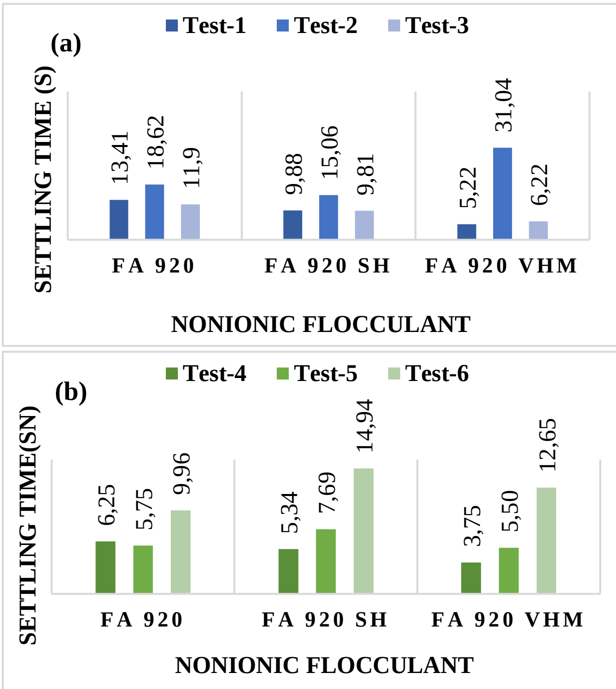


Figure 3. Settling times with nonionic flocculants a) Gördes b) Karaçam

Although settling time is an important criterion for the evaluation in the first stage, the amount of compaction of the settled solid, underflow (U/F) solid ratio and clarity are also important parameters and the values of nonionic flocculants obtained for both ores are summarized in Table 5. When the volumetric compaction of the settled solid for Gördes ore was examined, it was seen that FA 920 flocculant gave reasonable results in all tests. FA 920 SH and FA 920 VHM flocculants had high compaction amounts for test results No. 2 and No. 2 and 3, respectively. When the Karaçam ore results are evaluated, it is seen that the compaction amounts are acceptable for all tests. The low volumetric compaction indicates that the solid ratio in the underflow of the thickener will remain at high values. This is a desirable situation for a successful solid liquid separation and CCD operation.

The underflow solids by mass ratio values are calculated based on the volumetric compaction amounts obtained as a result of the tests and provide better information as a performance indicator. Acceptable solid by mass ratio for this plant condition CCD thickener underflow is in the range of 30%-35%. These values may vary according to plant design and operating conditions. When these values are considered, it is seen that there is a difference between Gördes and Karaçam ores in terms of the underflow density of nonionic flocculants and Karaçam ore has a very positive effect. When the clarity results for Gördes ore were analyzed, it was determined that FA 920 flocculant SS values were close to the limit. When a comparison was made according to molecular weights, it was observed that a clearer overflow solution was obtained due to the increase in molecular weight.

Table 5. Other settling parameters using nonionic flocculants

		Gördes			Karaçam		
		Test1	**Test2**	**Test3**	**Test4**	**Test5**	**Test6**
Compaction (mL)	FA 920	119	120	126	100	98	115
	FA 920 SH	121	138	130	110	95	115
	FA 920 VHM	130	138	140	110	105	125
U/F % Solid	FA 920	31.7	31.4	30.2	36.5	37.1	32.6
	FA 920 SH	31.2	27.9	29.4	33.8	38.1	32.6
	FA 920 VHM	29.4	27.9	27.5	33.8	35.1	30.4
SS (mg/L)	FA 920	172	255	202	183	235	100
	FA 920 SH	142	112	140	132	130	63
	FA 920 VHM	69	136	87	105	80	66

Under the mentioned test conditions and in cases where overflow clarity values are high, it is predicted that SS amounts can reach an acceptable value by increasing the flocculant dosage, but it should also be taken into consideration that the consumption amount will increase. The same situation is also valid in Karaçam ore, and it was observed that a clearer overflow solution was formed with the increase in molecular weights. It can be said that in the test results of nonionic flocculants 4 and 5, the overflow SS values were slightly high due to the very fast settling time.

Tests performed with Anionic Flocculants

As a result of the settling tests performed with anionic flocculants of different molecular weights and anionicity grades, only flocculants with low and very low anionicity achieved results. Flocculants with medium or high anionicity were observed to interact with the slurry, but no flocculation occurred to show the settling effect. Data on settling times are given in Figure 4.

AH 912 flocculant gave positive results by providing fast settling time in all test conditions for the first three tests. AH 912 SH flocculant, which has a higher molecular weight, provided a slower settling time compared to AH 912 flocculant and there is a big difference in terms of settling time in test No. 3 results. A similar situation was observed for AN 905 flocculant, which showed a very slow settling performance in tests 1 and 2 but was faster in test 3. For Karaçam ore, there were different and inconsistent results between the tests. The effect of AN 905 flocculant on settling performance was negative in all tests. Even if it has a positive result in terms of compaction or clarity, the settling time gives a better insight when evaluating its performance. In test No. 6, the effect of all anionic flocculants on settling time was slower than the other test results.

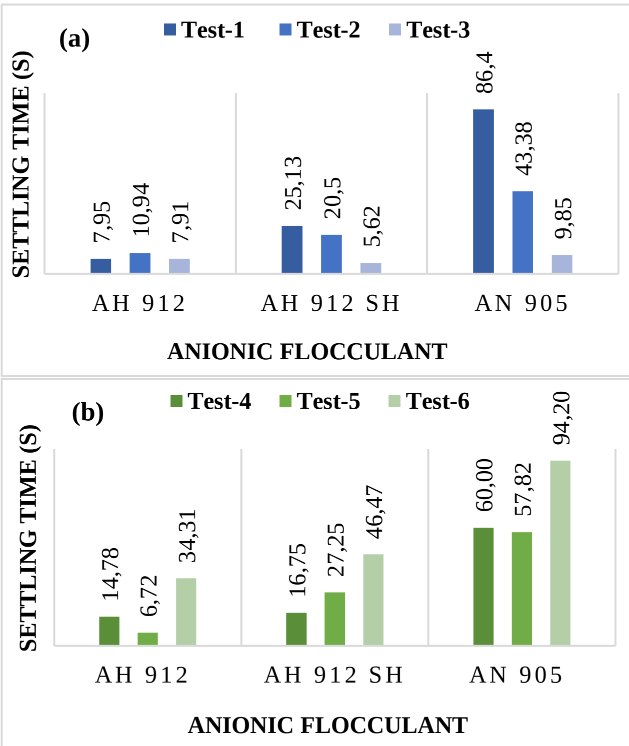


Figure 4. Settling times with anionic flocculants a) Gördes b) Karaçam

Although the settling time of AH 912 flocculant was acceptable in all tests, the compaction was optimum only for test No. 1 (Table 6). AH 912 SH flocculant, on the other hand, showed high values in terms of the compaction despite acceptable settling times. The AN 905 flocculant gave results with appropriate compaction amounts in tests 1 and 2. However, due to ineffective settling in test No. 3, impurity occurred in the overflow and therefore the amount of solids settled decreased. For this reason, the compaction value seems to be within reasonable ranges. This proves that all parameters should be analyzed in combination [14]. Similar to nonionic flocculants, anionic flocculants did not give a stable and positive result in the mass solids content of the underflow for Gördes ore, while they were generally successful for Karaçam ore.

Table 6. Other settling parameters using anionic flocculants

		Gördes			**Karaçam**		
		Test1	**Test2**	**Test3**	**Test4**	**Test5**	**Test6**
Compaction (mL)	AH 912	120	130	140	100	99	115
	AH 912 SH	121	140	149	101	94	110
	AN 905	120	121	140	95	97	105
U/F % Solid	AH 912	31.5	29.4	27.5	36.5	36.8	32.6
	AH 912 SH	31.2	27.5	26.0	36.3	38.4	33.8
	AN 905	31.5	31.2	27.5	38.1	37.4	35.1
SS (mg/L)	AH 912	83	135	81	280	92	89
	AH 912 SH	114	87	54	149	178	81
	AN 905	478	143	51	144	261	296

Tests performed with Cationic Flocculants

In the case of cationic flocculants, it was observed that the storage time of the flocculants was too short, and they decomposed too fast, which negatively affected the settling performance. The settling test results were compared according to the average settling time and given in Figure 5.

According to the results of Gördes ore, it was observed that the settling times of all flocculants were close to each other and at reasonable values. The same situation was also found for Karaçam ore; however, it was determined that flocculants with high molecular weight and very high cationic properties did not cause settling effect in test No. 4 and gave successful results in other tests. On the other hand, it was also determined that there were differences between the tests in terms of settling time.

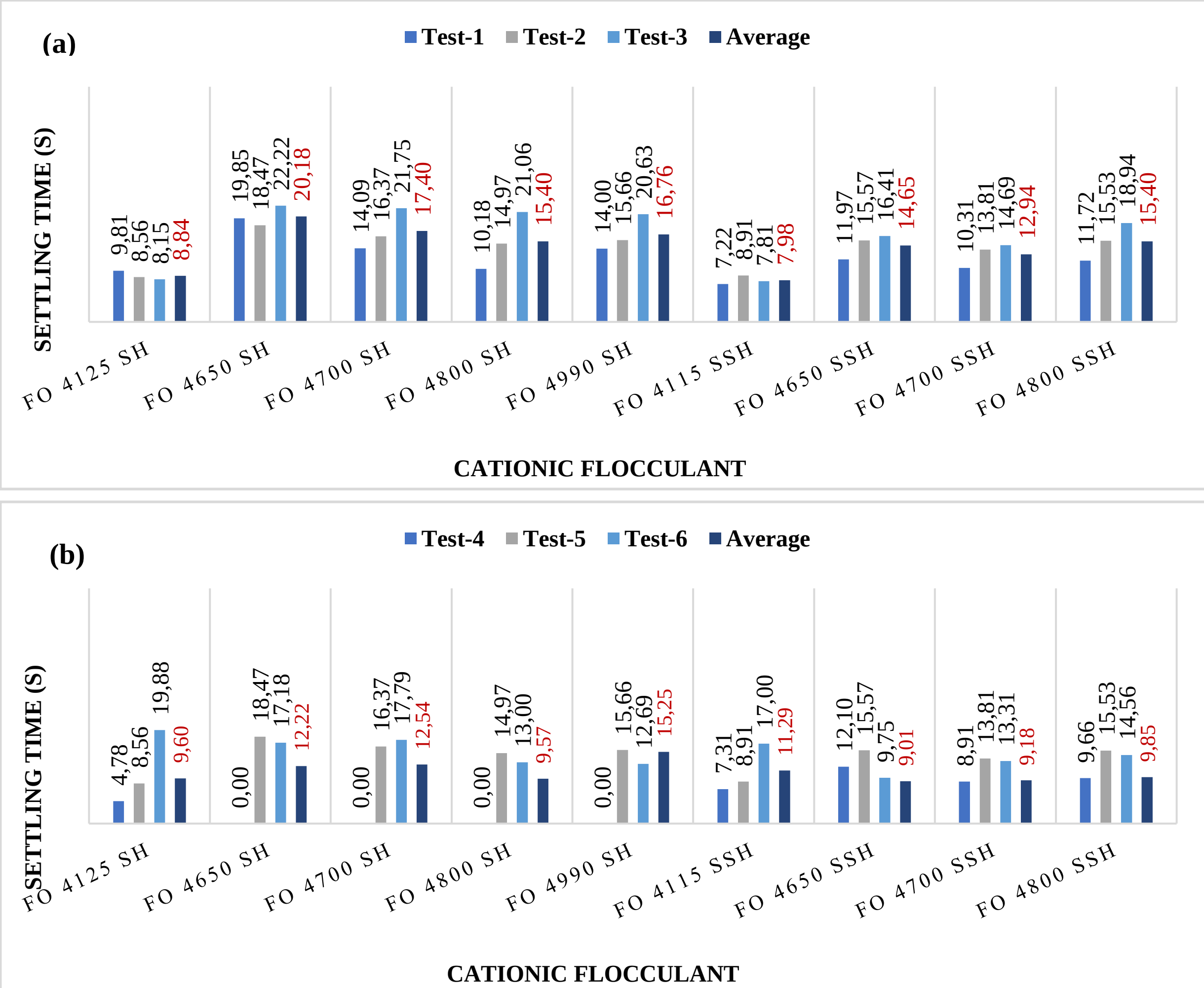


Figure 5. Settling times with cationic flocculants a) Gördes b) Karaçam

Although the settling times gave positive results in general, the volumetric compaction, especially in Gördes ore, were very high and did not show an effective compaction (Table 7). Since the flocculation formed after flocculant dosing was very coarse, it was observed that the voids between the settling material were high and thus the compaction was not too much. In Karaçam ore, it was observed that the results of test No. 4 and 5 showed positive results, but in test No. 6, except for the flocculants with low cationicity, the other flocculants had high compaction. For Gördes ore, the underflow solid content of the thickener was below 30%, which was a negative situation for settling and CCD process performance. For Karaçam ore, although the results were inconsistent, values of 30% and above were recorded.

Table 7. Other settling parameters using anionic flocculants

		Gördes			Karaçam		
		Test1	Test2	Test3	Test4	Test5	Test6
Compaction (mL)	FO 4125 SH	131	136	140	120	100	121
	FO 4650 SH	135	150	150	0	110	135
	FO 4700 SH	150	155	155	0	115	132
	FO 4800 SH	155	160	165	0	125	137
	FO 4990 SH	165	170	171	0	110	148
	FO 4115 SSH	135	145	140	110	100	119
	FO 4650 SSH	140	155	155	115	111	140
	FO 4700 SSH	145	160	155	115	120	135
	FO 4800 SSH	150	165	165	120	130	136
U/F % Solid	FO 4125 SH	29.2	28.2	27.5	31.5	36.5	31.2
	FO 4650 SH	28.4	25.9	25.9	0	33.8	28.4
	FO 4700 SH	25.9	25.1	25.1	0	32.6	29.0
	FO 4800 SH	25.1	24.4	23.7	0	30.4	28.1
	FO 4990 SH	23.7	23.1	22.9	0	33.8	26.2

	FO 4115 SSH	28.4	26.7	27.5	33.8	36.5	31.7
	FO 4650 SSH	27.5	25.1	26.7	32.6	33.6	27.5
	FO 4700 SSH	26.7	24.4	25.1	32.6	31.5	28.4
	FO 4800 SSH	25.9	23.7	23.7	31.5	29.4	28.2
SS (mg/L)	FO 4125 SH	65	106	117	100	95	86
	FO 4650 SH	41	76	16	0	54	45
	FO 4700 SH	48	75	15	0	55	46
	FO 4800 SH	53	86	28	0	69	34
	FO 4990 SH	108	85	57	0	144	36
	FO 4115 SSH	66	87	82	97	93	56
	FO 4650 SSH	51	81	35	78	46	32
	FO 4700 SSH	45	73	36	38	60	41
	FO 4800 SSH	41	85	21	50	72	47

All test results are summarized in Table 8 according to which parameter is within the optimum value ranges.

In the settling tests with Gördes ore, the settling rate of nonionic flocculants was acceptable at medium and high molecular weights but showed a faster settling rate with very high molecular weight nonionic flocculants. This is an exception only for Test 2. In most flocculant applications higher molecular weight results in better settling efficiency. However, increasing molecular weight can lose its effectiveness after a certain point. High molecular weight flocculants are generally more viscous and are not easily dispersed in suspension. Since adsorption is very fast, a loss of activity occurs. With increasing molecular weight, the number of polymer chains per weight unit decreases and this can affect flocculant performance [15]. The overflow solution clarity of medium and high molecular weight nonionic flocculants has a high SS value, especially when compared to cationic flocculants. It was observed that the floc sizes formed had a small structure. Considering that molecular weights are parallel to the chain length of polymers, this can be expected to occur. Accordingly, this is seen as the main reason for the low clarity and compaction amounts. Due to the large size of the flocs formed by the very high molecular weight FA 920 VHM flocculant, the settling rate was high especially in tests 1 and 3 and therefore the compaction did not give good results. In the case of anionic flocculants, only flocculants with very low ionicity (close to nonionic) gave results. No flocculation was observed due to the increase in ionicity or molecular weight. Only visually there was an interaction between the solid particles and the flocculants, but it had no effect on the settling. At pH 4 and lower, nonionic flocculants perform best. In this pH range, anionic flocculants coil like nonionic flocculants but their activity is very low. This is because the amide groups in nonionic flocculants are replaced by inert carboxyl groups, which reduce the number of hydrogen bonding sites present in the flocculant structure at low pH. Thus, flocculants without any ionicity perform better at a lower pH range [15]. This explains why nonionic and low anionic flocculants produce flocculation but do not show any effect with increasing ionicity.

Table 8. Summarized performance data

Flocculant	**Type**	**Molecular Weight**	**GÖRDES**			**KARAÇAM**		
			Settling Time	**Clarity**	**Compaction**	**Settling Time**	**Clarity**	**Compaction**
FA 920	Nonionic	Medium	✓	✗	✓	✓	✓	✓
FA 920 SH	Nonionic	High	✓	✓	✓	✓	✓	✓
FA 920 VHM	Nonionic	Very High	✓	✓	✗	✓	✓	✓
AH 912	Anionic	Medium	✓	✓	✓	✓	✓	✓
AH 912 SH	Anionic	High	✓	✓	✗	✓	✓	✓
AN 905	Anionic	Medium	✗	✗	✓	✓	✗	✓
FO 4125 SH	Low Cationic	Medium	✓	✓	✗	✓	✓	✓
FO 4650 SH	Very High Cationic	Medium	✓	✓	✗	✓	✓	✓
FO 4700 SH	Very High Cationic	Medium	✓	✓	✗	✓	✓	✓
FO 4800 SH	Very High Cationic	Medium	✓	✓	✗	✓	✓	✓
FO 4990 SH	Very High Cationic	Medium	✓	✓	✗	✓	✓	✓
FO 4115 SSH	Low Cationic	High	✓	✓	✗	✓	✓	✓
FO 4650 SSH	Very High Cationic	High	✓	✓	✗	✓	✓	✓
FO 4700 SSH	Very High Cationic	High	✓	✓	✗	✓	✓	✓
FO 4800 SSH	Very High Cationic	High	✓	✓	✗	✓	✓	✓

In the studies performed with Karaçam ore, results close to Gördes ore were obtained. Nonionic flocculants with low and medium molecular weights generally provided a fast settlement and for this reason, a very clear solution could not be obtained. There is a direct correlation between the molecular weights and the size of the flocs formed, with the higher molecular weight flocculants forming larger flocs. Although settling rate and clarity parameters are affected by floc structure, they are primarily related to floc size distribution. The rapid settling rate associated with low clarity is often related to the bi-shaped floc size distribution resulting from poor flocculation and, in particular, the failure to achieve adequate destabilization prior to the application of high molecular weight flocculants [16]. An overall analysis of all tests for both ores showed that medium and high molecular weight nonionic flocculants showed the most consistent and positive results with respect to performance criteria such as settling time, clarity and compaction, as well as compared to anionic and cationic flocculants.

Laterite ore is defined as a complex and highly swellable ore [17]. Nevertheless, this definition should not be considered as a general definition for all laterites [18]. The fact that the ore structure fed to the plant is very variable, the process controllability is difficult and at the same time there are instantaneous changes in the system continuously caused the test results with the same type of flocculants to be different from time to time. Since the tested slurry is leached, it is very likely that the ore rheology will change due to changing leaching mechanisms and mineralogy. For this reason, the differences in pH, potential and elemental content between the working conditions of the tests also changed the adsorption mechanism of the flocculants and prevented the tests from producing close results.

Conclusion

Following results can be deduce

✓ In both ores, nonionic flocculants performed better and provided more stable results than other types of flocculants.

✓ Anionic flocculants with very low anionicity showed positive results, however, as the molecular weight and anionicity grade increased, an effective flocculation did not occur.

✓ Clarity values with cationic flocculants have given very good results and generally provided a fast settling. For this reason, it is predicted that the amount of consumption can be reduced especially by using high molecular weight cationic flocculants. However, the compaction should also be taken into consideration. Cationic flocculants are not preferred in Gördes ore due to the low solid content.

✓ As a result of the fact that the ore content is not stable and there are many parameters in the process where instantaneous changes occur, it is concluded that the settling behavior is open to variability.

✓ Although it was not clearly demonstrated that pH and potential values have a direct effect on flocculation characteristics, it was concluded that changes in these parameters may cause differences between test results.

Declaration of Competing Interest

"There is no need to obtain ethics committee permission for the prepared article"

"There is no conflict of interest with any person/institution in the prepared article"

Author contributions

Keskin: Data collection, Data analysis and interpretation, Draft creation, Revision.

Can: Study concept, Analysis and interpretation of data, Draft creation.

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