CHAPTER 4

RESULTS AND DISCUSSION

For explication the data obtained from the experiments, details of experiment
conditions, results and discussion for each particular topic are presented separately as
follows

## 4.1 Characteristics of Treated Industrial Estate Wastewater

As can be seen in Figure 4.1 which illustrates the weekly variation of pH and turbidity
of treated industrial estate wastewater, it showed that pH and turbidity of treated
industrial estate wastewater ranged between 6.80 and 7.73 and from 10.8 to 30.9
NTU, respectively.
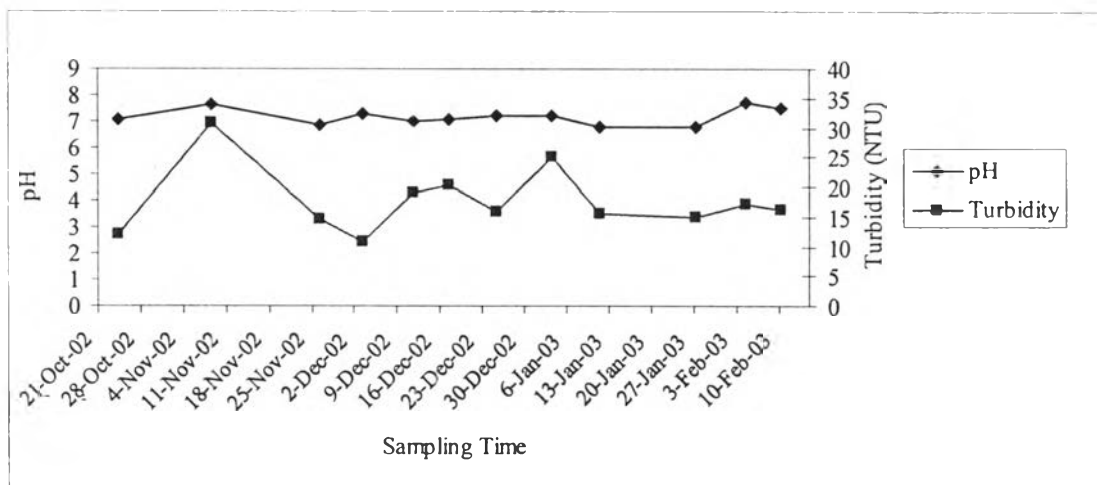
Figure 4.1 Weekly variation of pH and turbidity of treated industrial estate
wastewater over the period of study.

Looking at Figure 4.2, temperature and alkalinity of treated industrial estate
wastewater during the period of study were presented, temperature and alkalinity
ranged from 22 °C to 24.6 °C and from 53.38 mg/L as CaCo3 to 116.40 mg/L as
CaCo3, respectively.

As can be seen in Figure 4.3, UV-254, TOC, DOC and SUVA of treated industrial estate wastewater with sampling time were demonstrated. It showed that UV-254 were in the range of 0.1527 and 0.3024 cm-1.Unforetunately, due to unavailable TOC analyzer at the beginning of this study, the measurement of TOC and DOC were done only in last two month of the study. However, the results of TOC and DOC observed in January and February ranged between 5.18 and 7.29 mg/L and from 4.52 to 5.92 mg/L, respectively. Regarding SUVA value, it has been presented by Reckhow (1990) that SUVA of fulvic and humic acid ranged from 2.9 to 4.3 L/mg-m and from 4.8 to 7.4 L/mg-m, respectively, and the SUVA obtained in this study were in the range of 3.63 and 6.68 L/mg-m. This may be stated that treated industrial estate wastewater used as raw water in this study may contain both fulvic and humic acid.
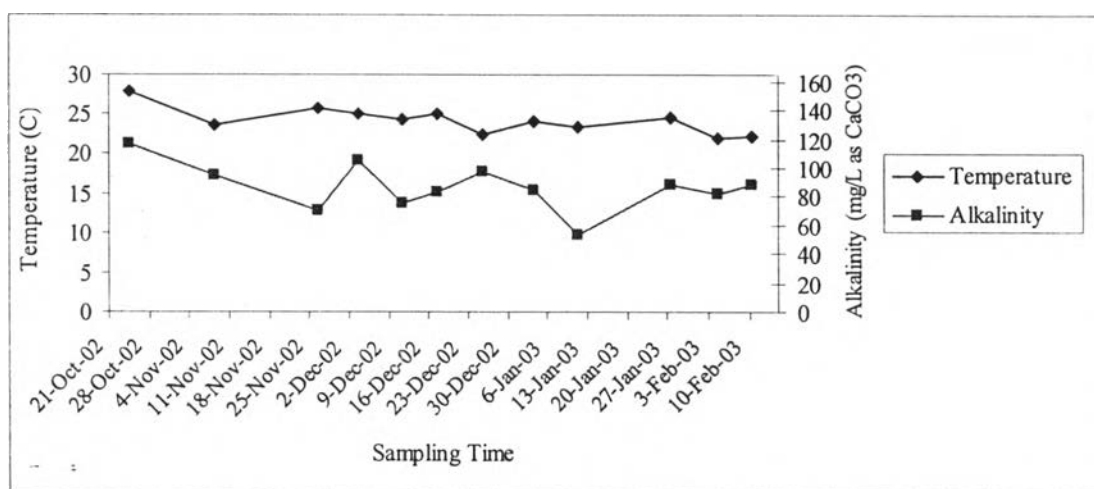
Figure 4.2 Weekly variation of temperature and alkalinity of treated industrial estate wastewater over the period of study.
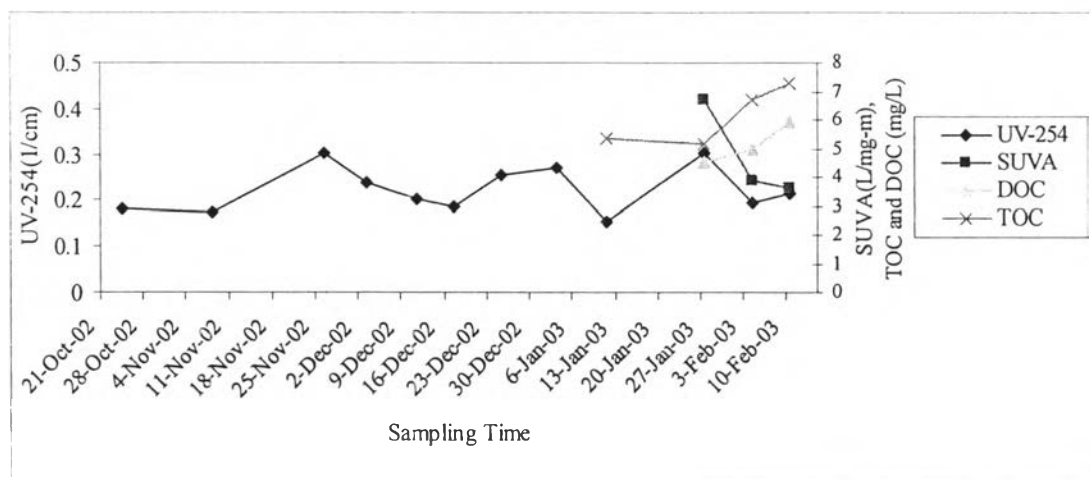
Figure 4.3 Weekly variation of UV-254, SUVA, TOC and DOC of treated industrial estate wastewater over the period of study
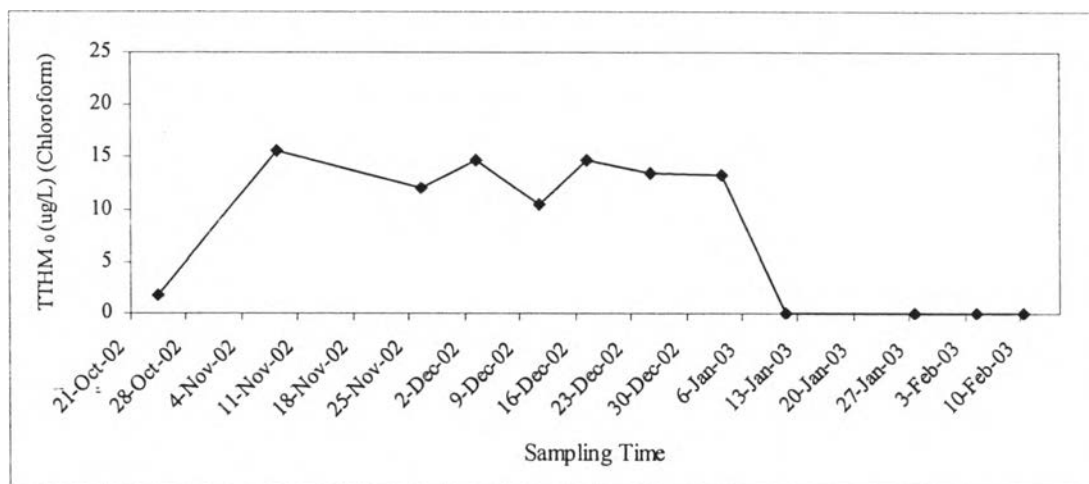
Figure 4.4 Weekly variation of THMFP of treated industrial estate wastewater over the period of study

Based on $TTHM_0$ results as shown in Figure 4.4, $TTHM_0$ investigated between November and December was more or less 15 µg/L while nearly zero of $TTHM_0$ in October as well as in between January and February were obtained. This may be caused by reason that chlorine from industrial process and/or from chlorination in on-site waste wastewater treatment process of some industries may contain in water samples during such period of time in which relatively high $TTHM_0$ was found.

However, the overall characteristic of treated industrial estate wastewater could also be summarized in term of the range and the average values with standard deviation as depicted in Table 4.1

**Table 4.1 Characteristics of treated industrial estate wastewater**

Parameters	Range of Values	Average Values	Standard Deviation
pH	6.80- 7.73	7.20	±0.31
Turbidity (NTU)	10.8 – 30.9	17.7	±5.58
Alkalinity (mg/L as $CaCO_3$/L)	53.38 – 116.40	86.4	±16.38
Temperature(°C)	22.0 - 24.6	24.2	±1.67
UV absorbance at 254 nm.(cm-1)	0.1527 - 0.3024	0.2221	±0.05
TOC (mg/L)			
DOC (mg/L)	5.18 - 7.29	6.127	±1.02
SUVA (L/mg-m)	4.52 - 5.92	5.144	±0.71
$TTHM_0$ (µg/L)	3.63 – 6.68	4.733	±1.69
	0 – 14.8	8.006	±6.89

4.2 Turbidity Removal and Alkalinity Reduction by Alum and Ferric Chloride

The results in this part showed the optimum condition of alum and ferric chloride for turbidity removal. It was generally believed that a conventional water treatment operation only focuses on turbidity removal and ignores other parameters such as TOC, DOC, UV-254 and SUVA. Therefore, it must be advantageous to apply the results from this experiment in a real operation of water treatment plant.
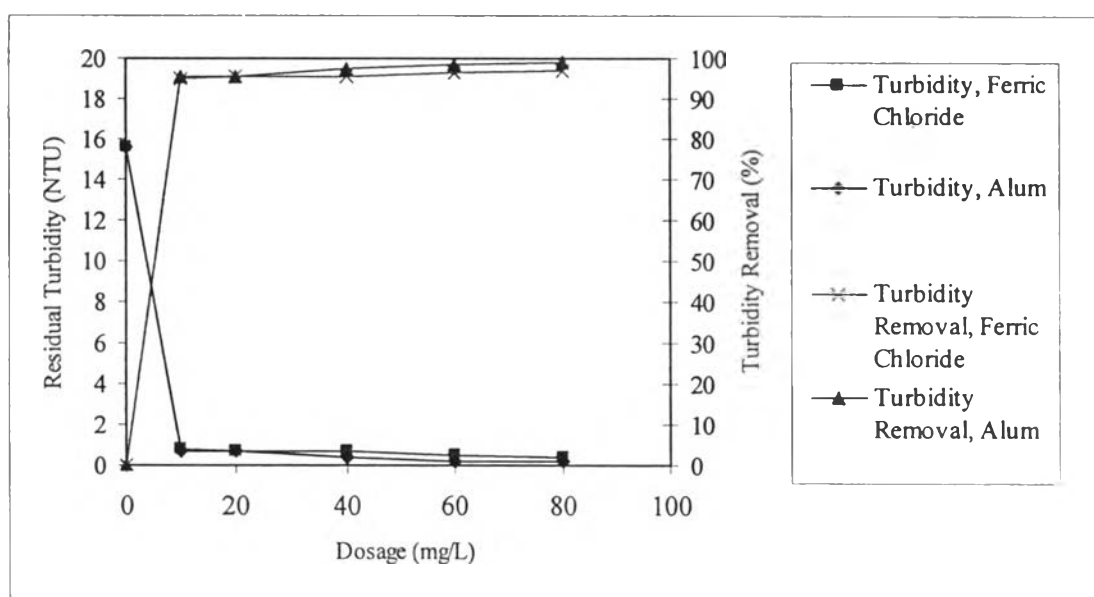
4.2.1. The Uncontrolled pH Experiments

As can be seen in Figure 4.5, residual turbidity and percent removal of turbidity in supernatant as a function of alum and ferric chloride dosages at uncontrolled pH were presented. It showed that at the alum and ferric chloride dosages of about 10 mg/L could be promptly removed turbidity in supernatant to approximately 80 percent, where as the maximum turbidity removal in supernatant was approximately 97 percent occurred at alum and ferric chloride dosage up to 80 mg/L.
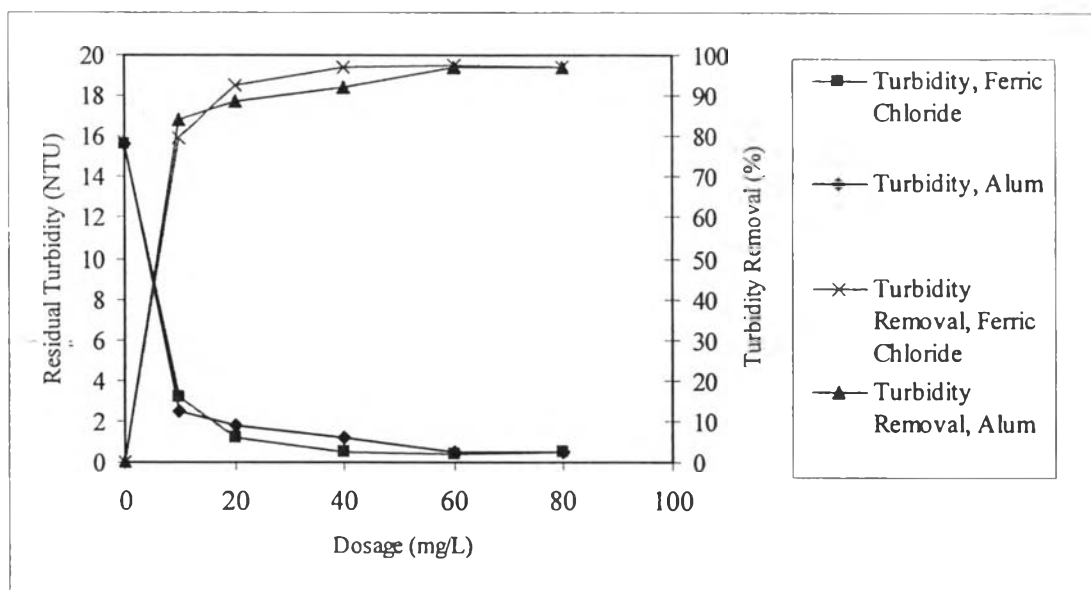
Figure 4.5 Residual turbidity and percent removal in turbidity of supernatant as a function of alum and ferric chloride dosages at uncontrolled pH

It was also observed that at the alum and ferric chloride coagulation dosages of about 10 mg/L, success in reducing turbidity in supernatant to the level of about 3 NTU in reclaimed water could be performed without pH control.
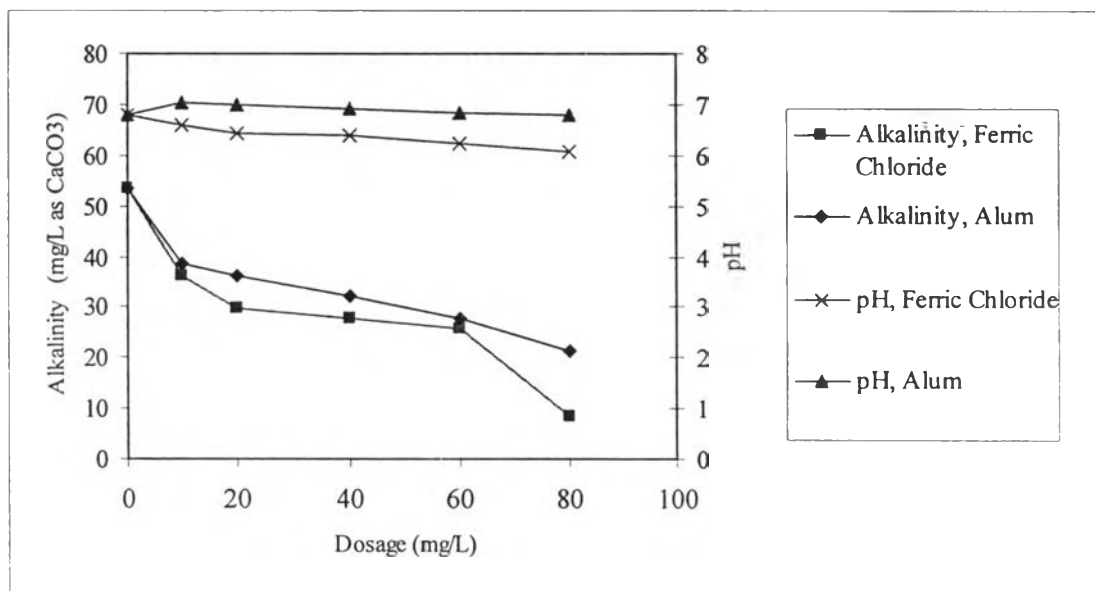
Additionally, r esidual t urbidity a nd p ercent r emoval o f t urbidity i n f iltered supernatant as a function of alum and ferric chloride dosages at uncontrolled pH are also shown in Figured 4.6. It similarly appeared that alum and ferric chloride dosages of about 10 mg/L brought about instant reduction of turbidity in filtered supernatant to approximately 95 percent, while turbidity removal in filtered supernatant increased only about 5 percent as alum and ferric chloride dosages was increased to 80 mg/L. Lastly, the maximum removal of turbidity approximately 99 percent occurred at alum and ferric chloride dosage 80 mg/L.

Figure 4.6 Residual turbidity and percent removal of turbidity in filtered supernatant as a function of alum and ferric chloride dosages at uncontrolled pH

Furthermore, turbidity in filtered supernatant could be reduced to as low as 1 NTU in the experiment as in Figure 4.6. As results, it is able to point out that practically, alum and ferric chloride coagulation followed by filtration could produce very clear reclaimed water from treated industrial estate wastewater even under the condition of uncontrolled pH.

Theoretically, sufficient alkalinity must be present in water to react with alum and ferric chloride so that the hydroxide floc is produced and alkalinity is destroyed during the reaction. Figure 4.7 shows alkalinity and pH of filtered supernatant as a function of alum and ferric chloride dosages at uncontrolled pH, it was noticed that alkalinity and pH of filtered supernatant decreased as alum and ferric chloride dosages increased. Since, alkalinity in ferric chloride coagulation is theoretically consumed higher than that of in alum coagulation, correspondingly, higher alkalinity remaining in coagulated water by alum was observed in comparison with that of ferric chloride.

Figure 4.7 Alkalinity and pH of filtered supernatant as a function of alum and ferric chloride dosage at uncontrolled pH

Profiles of pH in alum and ferric chloride in alum and ferric chlorine coagulations as shown in Figure 4.7 were comparable to the profiles of alkalinity as discussed earlier because lower alkalinity in water generally leads to lower pH.

4.2.2 The Controlled pH Experiments

4.2.2.1 Coagulation by Alum

As shown in Figure 4.8, residual turbidity and percent removal of turbidity in supernatant versus alum dosage at various pH of 5.5, 6 and 6.5 were presented. It were appeared that turbidity removal efficiencies obtained in the controlled pH of 5.5 and 6 experiments were not significantly different and distinctly lower than obtained in the controlled pH of 6.5. In case of controlled pH at 6.5, turbidity was shapely remove to 3 NTU or about 80 percent removal at alum dosage of approximately 10 mg/L. However, the maximum turbidity removal of all cases were about 90 percent at the same dosages of alum at approximately 80 mg/L

This could be clearly stated that alum coagulation of treated industrial estate wastewater for turbidity removal was performed best at controlled pH of 6.5
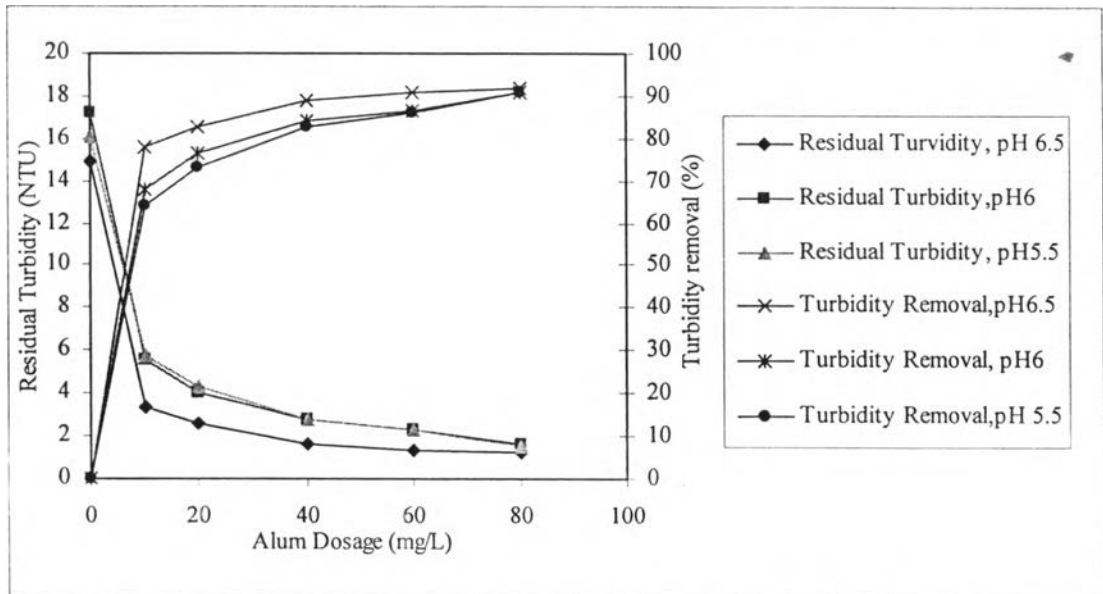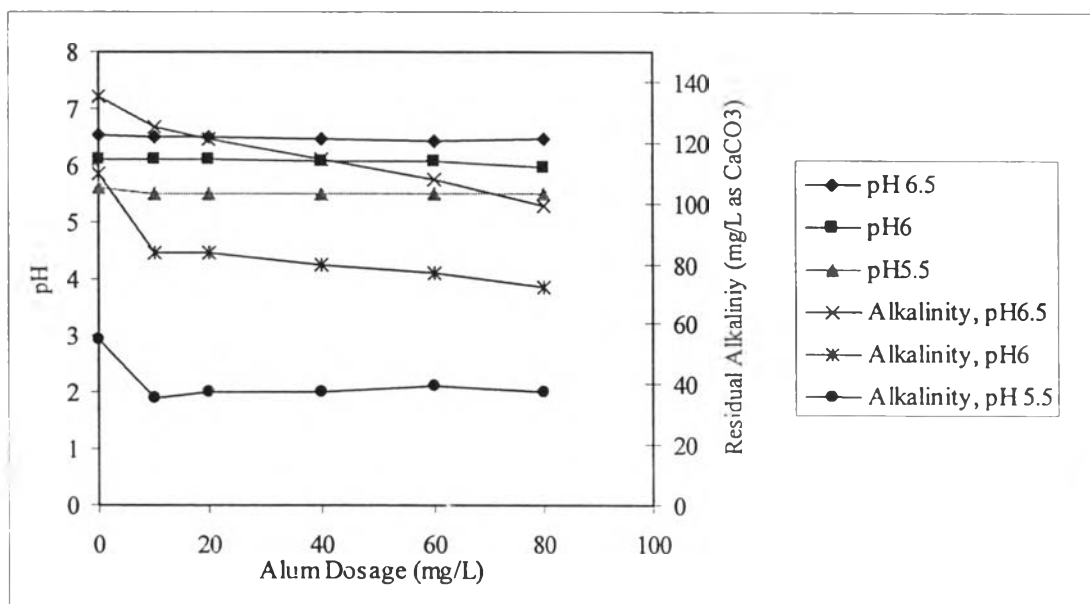

Figure 4.8 Residual turbidity and percent removal of turbidity in supernatant as a function of alum dosage at different controlled pH
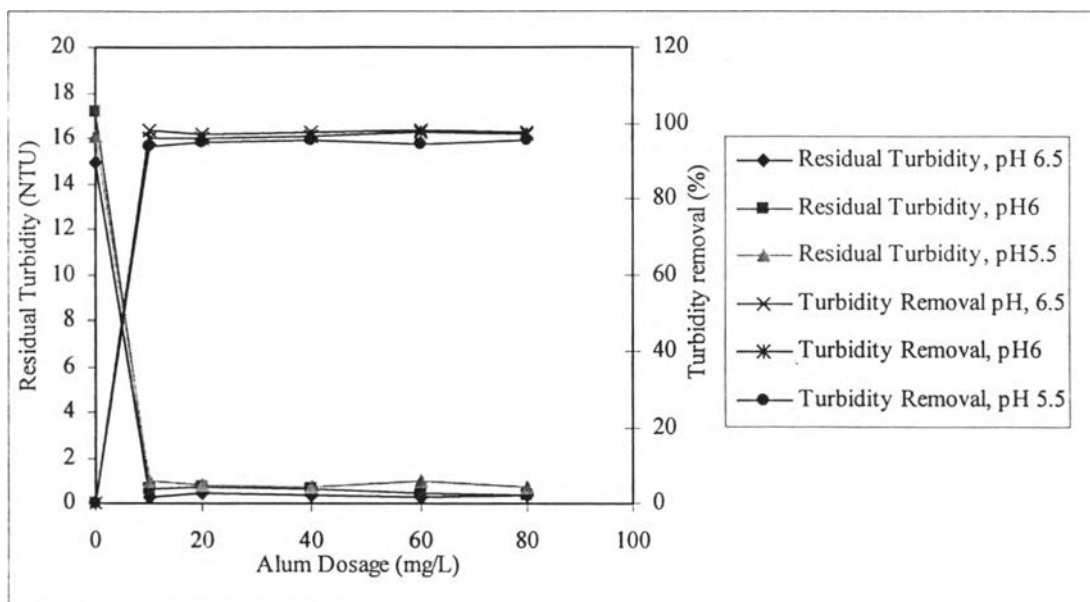
Figure 4.9 Residual turbidity and percent removal of turbidity removal in filtered supernatant as a function of alum dosage at different controlled pH
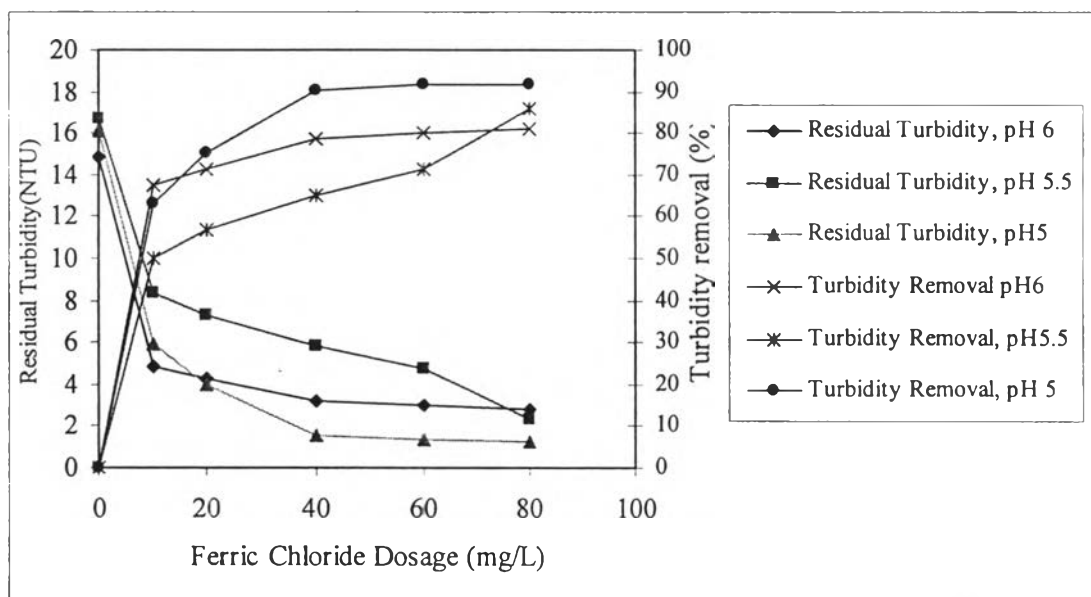

Figure 4.10 Alkalinity and pH in supernatant as a function of alum dosages at different controlled pH

The results of turbidity and percent turbidity removal in filtered samples after coagulation of different controlled pH are illustrated in Figured 4.9, wherein no different results among different controlled pH experiments were observed. This could be easily explained by the fact that same turbidity removal efficiencies must be obtained as results of using the same pore size of filtration (filtered by the same 1.12 μm GFC in the experiments). In addition, residual turbidity in filtered coagulated water, by the contrary that in supernatant, could not be used to express the performance coagulation for turbidity removal.
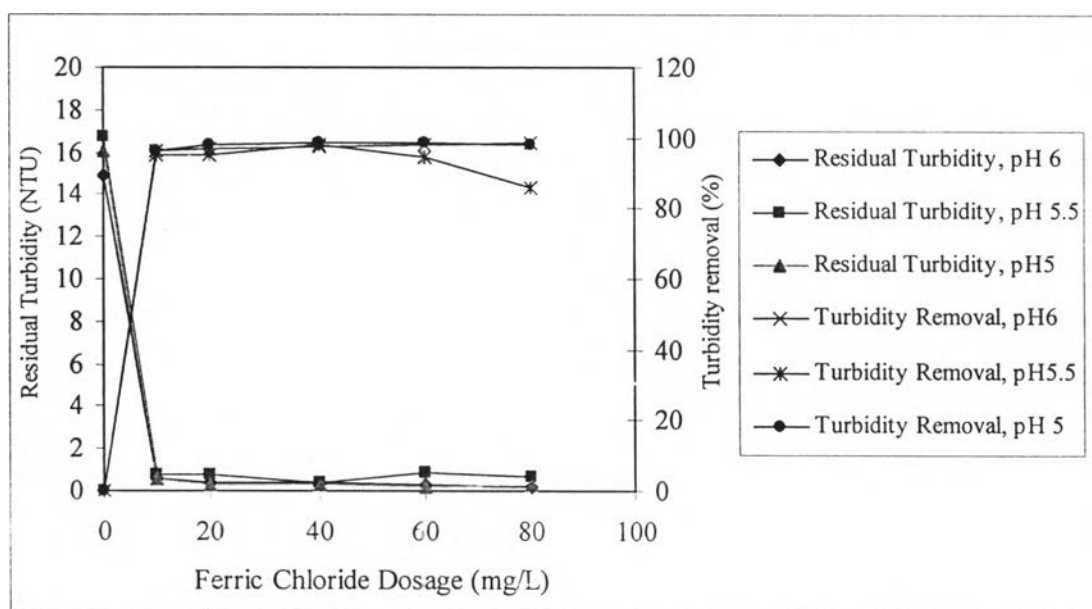
Alkalinity and pH of supernatant as a function of alum dosage at controlled pH was shown in Figure 4.10. It demonstrated that in almost all cases of variation in controlled pH of 5.5, 6, and 6.5, pH of supernatants were entirely the same as each controlled pH values. Under the condition of controlled pH value of 6.5, alkalinity gradually decreased as alum dosages increased. In case of controlled pH value of 6 and 5.5, dosage of about 10 mg/L shapely decreased alkalinity, but after increment in dosage from 20 mg/L to 80 mg/L alkalinity was nearly constant because the reason that during coagulation NaOH and H_2SO_4 were utilized for control pH of water sample at the controlled level.

4.2.2.2 Coagulation by Ferric Chloride

Looking at Figure 4.11, residual turbidity and percent removal of turbidity in supernatant as a function of ferric chloride dosage at controlled pH were demonstrated; it appeared that turbidity removal performances of ferric chloride coagulation at controlled pH ranged from 5 to 6.5 were in order efficiently from at pH 5, pH 6 and pH 5.5, respectively. In case of controlled pH at 5, turbidity was largely removed to 6 NTU or about 65 percent removal at ferric chloride dosage of approximately 10 mg/L. However, the maximum turbidity removal of nearly all cases were about 85 percent at the same dosages of ferric chloride dosage at approximately 80 mg/L

Figure 4.11 Residual turbidity and percent removal of turbidity in supernatant as a function of ferric chloride dosage at different controlled pH

Figure 4.12 Residual turbidity and percent removal of turbidity in filtered supernatant as a function of ferric chloride dosage at different controlled pH

Figured 4.12 showed the results of turbidity and percent turbidity removal in filtered samples after coagulation of different controlled pH. It also appeared that no different results among different controlled pH experiments were observed with the same reason as mention earlier.

As can be seen in Figure 4.13, alkalinity and pH of supernatant as a function of ferric chloride dosage at controlled pH was illustrated. It showed that in almost all cases of variation in controlled pH of 5, 5.5, and 6, pH of supernatants were entirely the same as each controlled pH values. Under the condition of controlled pH value of 6, alkalinity gradually decreased as alum dosages increased. In case of controlled pH value of 6 and 5.5, dosage of about 10 mg/L shapely decreased alkalinity, but after increment in dosage from 20 mg/L to 80 mg/L alkalinity was nearly constant because the reason that stated previously.
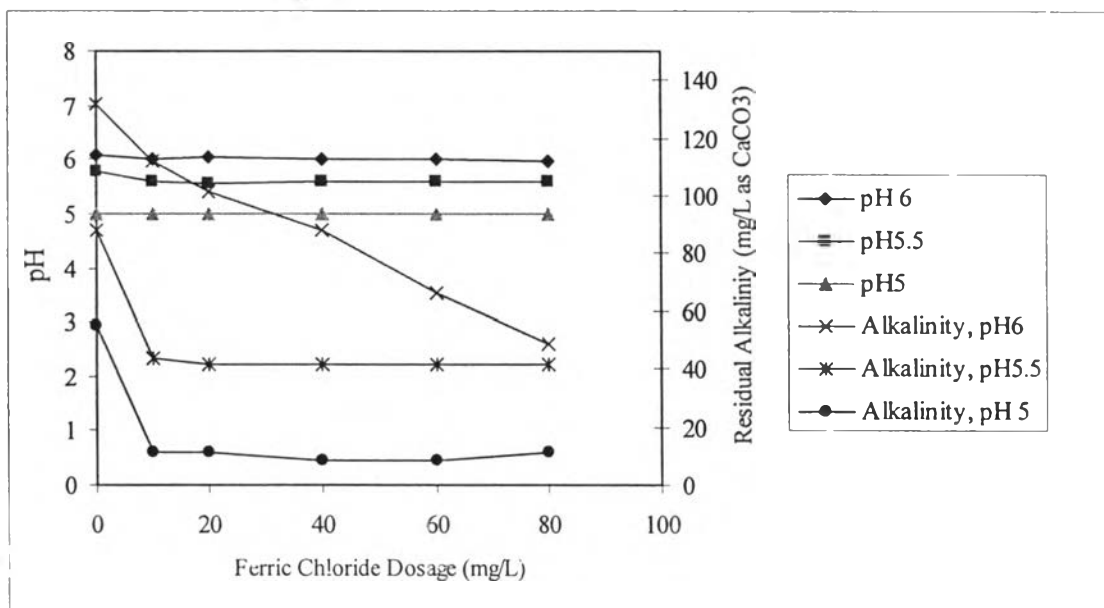
Figure 4.13 Alkalinity and pH in filtered supernatant as a function of ferric chloride dosage at different controlled pH

4.3. Correlation among Surrogates for NOM.

Generally, natural organic matter (NOM) was the term used to describe the complex metric of organic material in natural water. As mention earlier, it is not practical to analyze individual chemical compound of NOM. Consequently, NOM may be separated in term of surrogate parameters including TOC, DOC, UV-254, SUVA and THMFP.

In this study, a number of surrogate parameters were considerably utilized to measure the quantity of NOM such as TOC, DOC, UV-254, SUVA and THMFP. From this point, the purpose of this section was to demonstrate the correlation and regression among surrogates for NOM so as to allow one parameter such as DOC to be used as a surrogate for another parameter such as THMFP. Data of raw water and coagulated water were utilized to evaluate the regression and correlation coefficients in this study.

According to AWWA (1993), it had been recognized that the correlation levels were divided in four categories as an $R^2 > 0.9$ was considered a good correlation, $0.7 < R^2 > 0.9$ a moderate correlation, $0.5 < R^2 > 0.7$ a fair correlation and $R^2 < 0.5$ a poor correlation. For the considerably poor correlation ($R^2 < 0.5$), regression analysis was not performed, hence, the slope and intercept for the equation were not accepted.

From the results obtained in the experiments, the correlation among surrogates for NOM were performed and the regression and correlation coefficients determined were illustrated in Figure 4.14 to 4.23 and the overall correlations among surrogates for NOM were also conclusively demonstrated in Table 4.2.
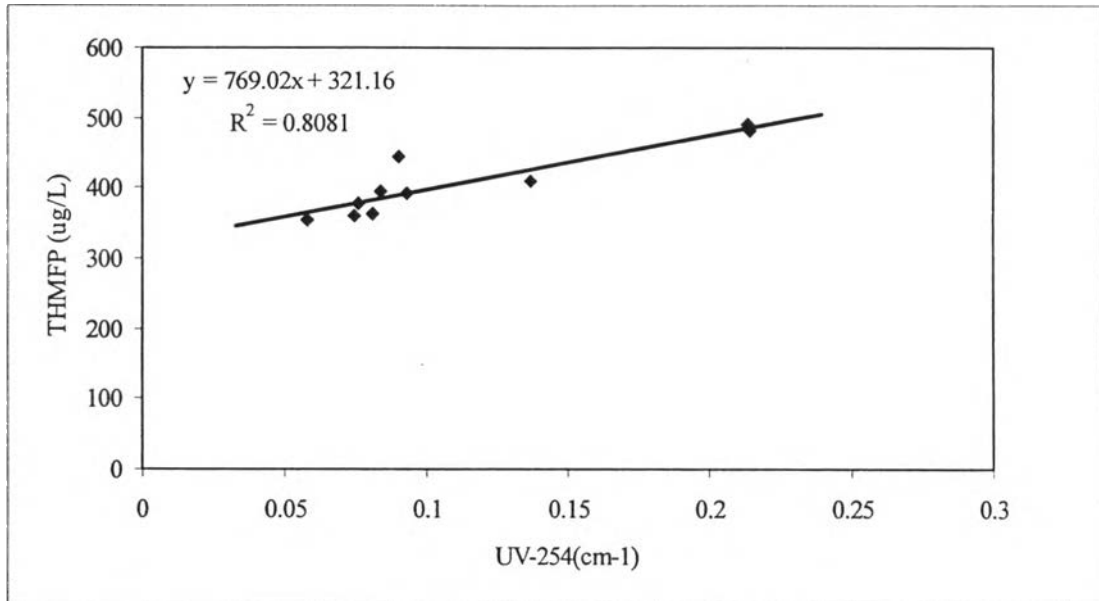
Figure 4.14 Correlation between THMFP and UV-254
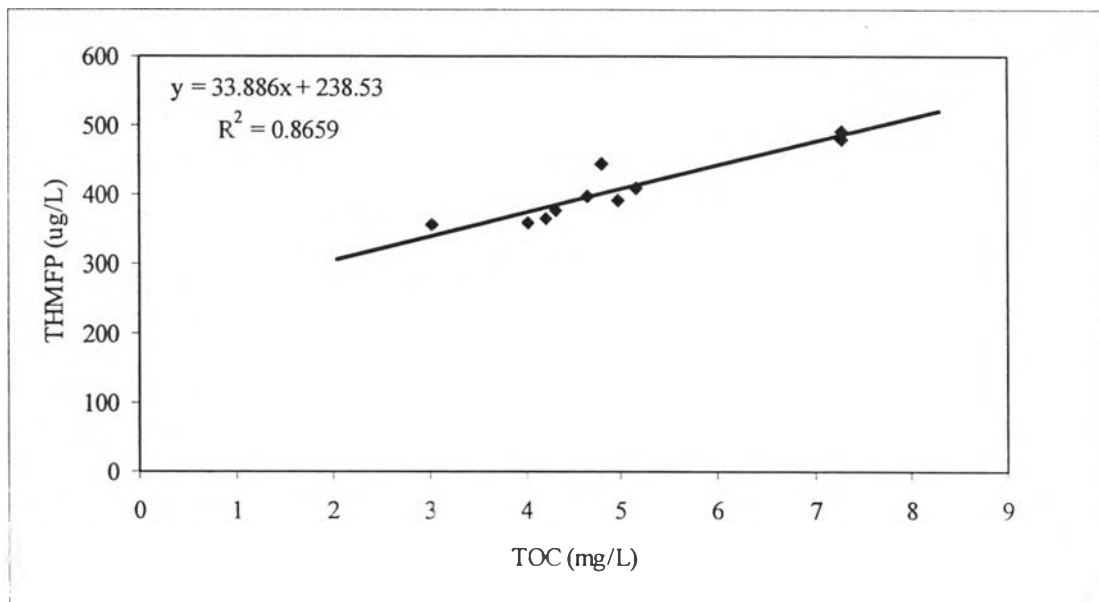
Figure 4.15 Correlation between THMFP and TOC
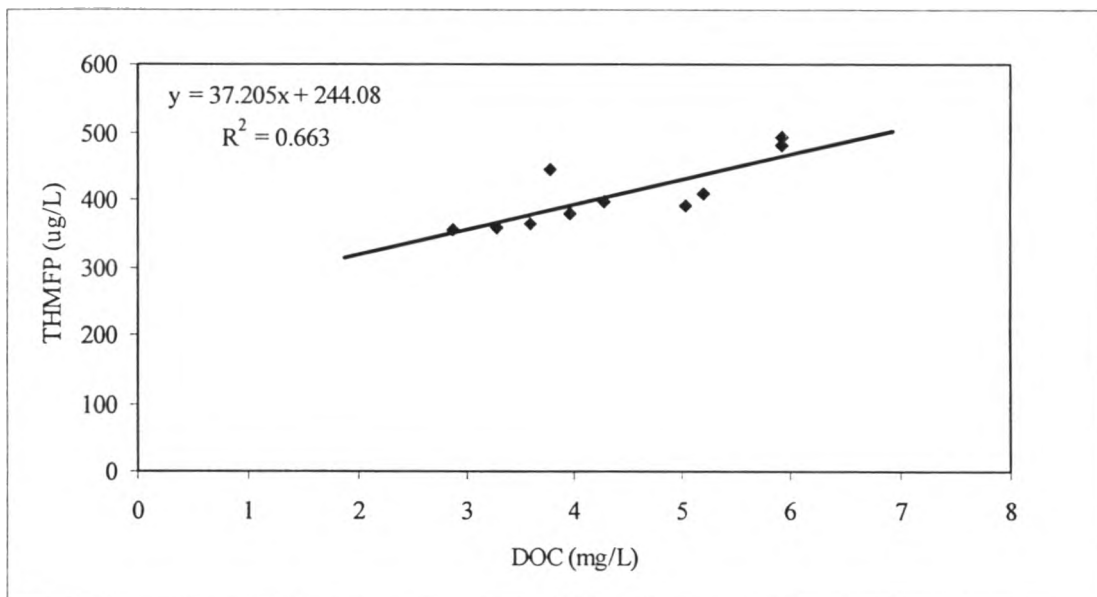
Figure 4.16 Correlation between THMFP and DOC

Figure 4.17 Correlation between THMFP and SUVA
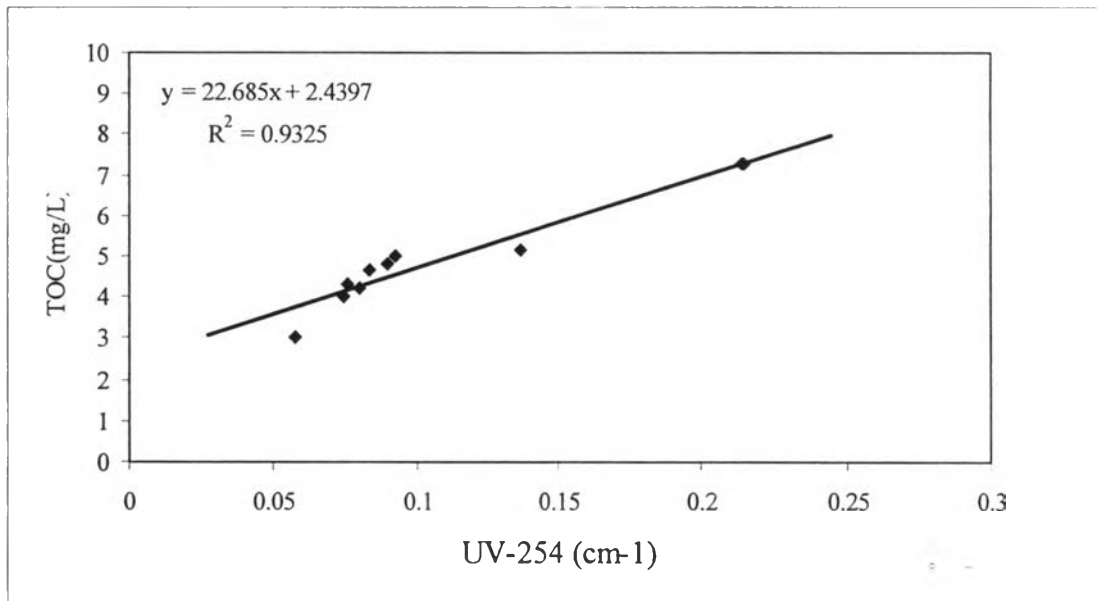
Figure 4.18 Correlation between TOC and UV-254
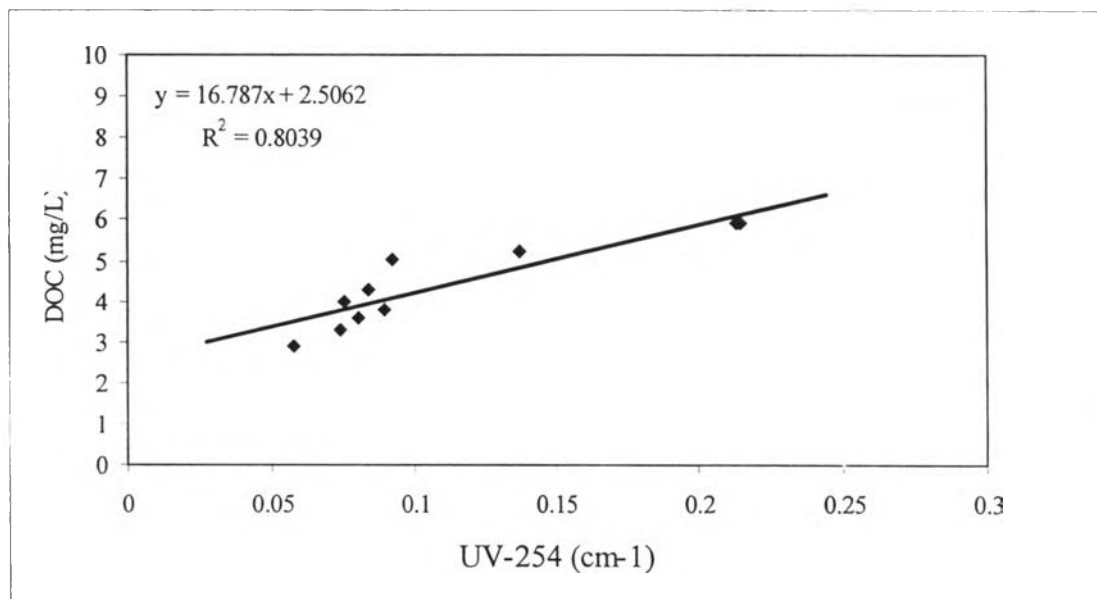
Figure 4.19 Correlation between DOC and UV-254

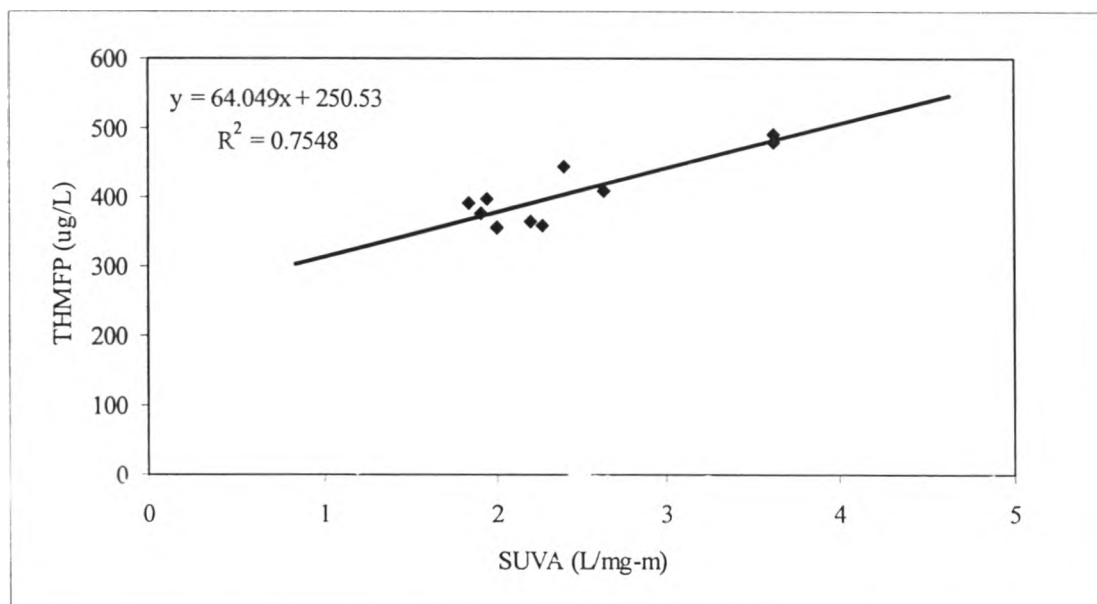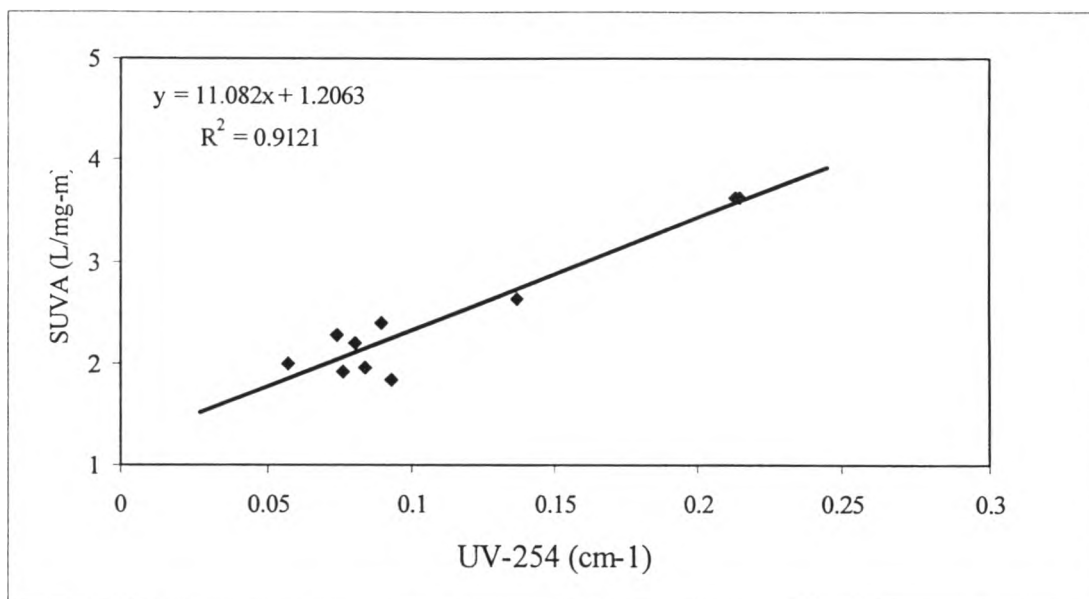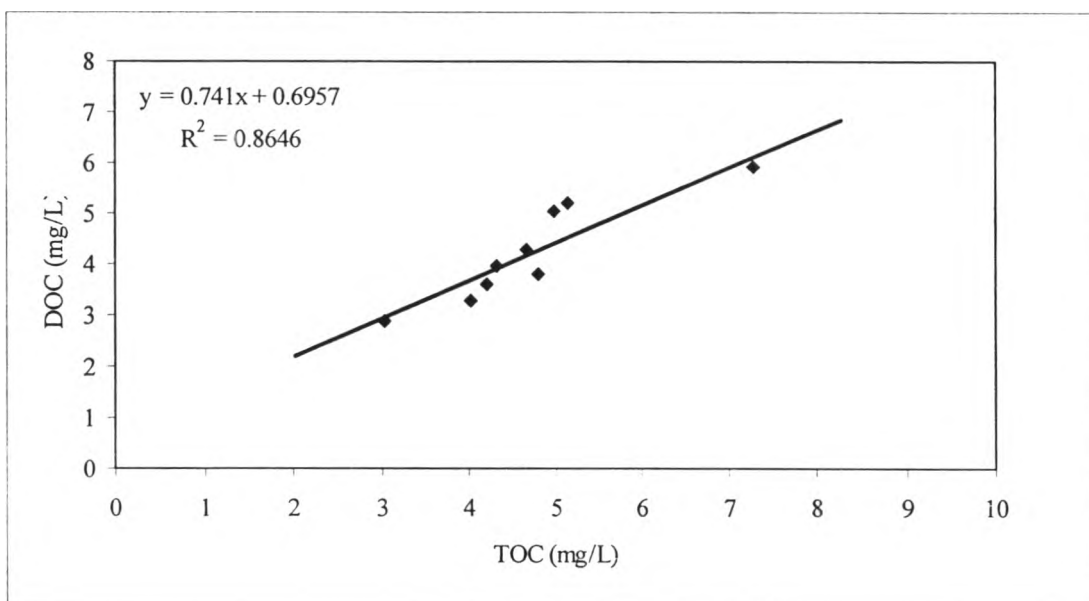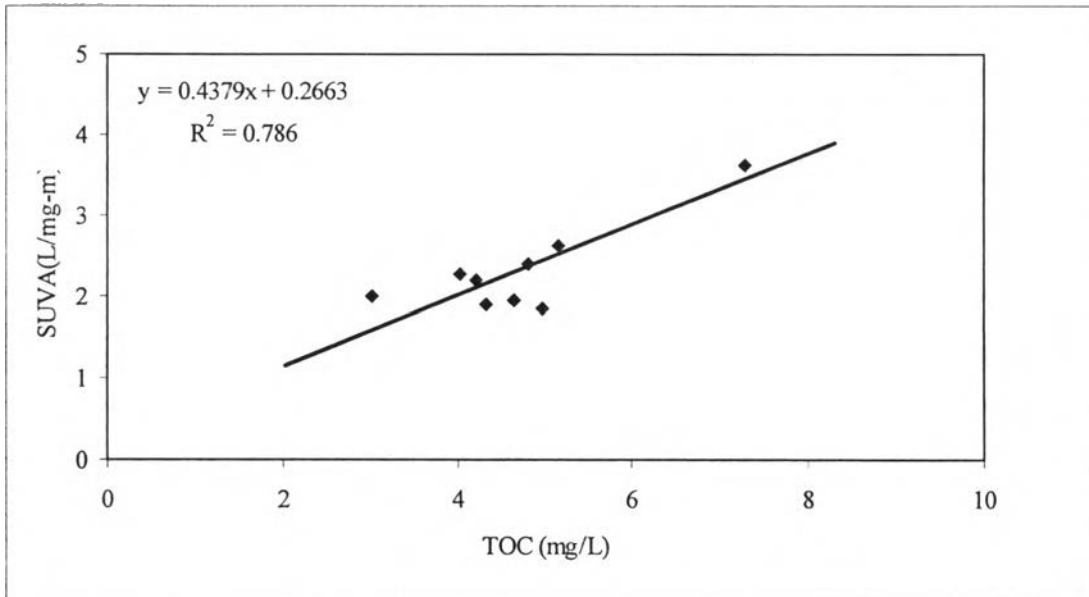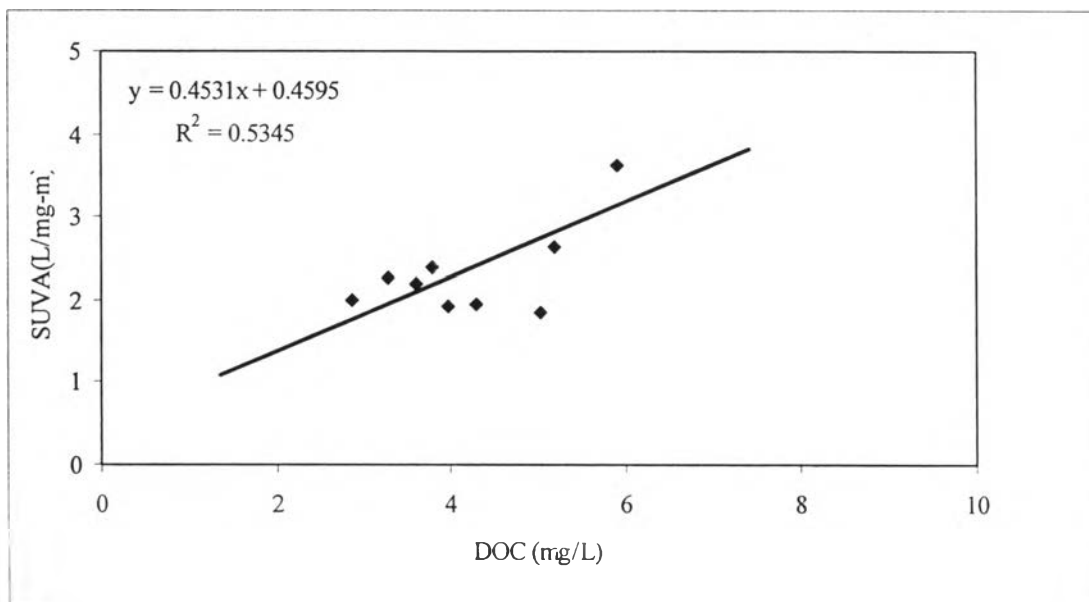**Figure 4.20** Correlation between SUVA and UV-254

Figure 4.21 Correlation between DOC and TOC

$y = 0.4379x + 0.2663$

$R^2 = 0.786$

Figure 4.22 Correlation between SUVA and TOC

$y = 0.4531x + 0.4595$

$R^2 = 0.5345$

Figure 4.23 Correlation between SUVA and DOC

Looking at the conclusive results as shown in Table 4.2 and the considerations of using THMFP as dependent variable with UV-254, TOC, DOC and SUVA as independent variables, it was found that the correlation coefficient (R^2) of the regression analysis of THMFP and UV-254, of THMFP and TOC and of THMFP and SUVA were classified as moderate correlation levels which were values of 0.801, 0.8659, and 0.7548, respectively, while that of THMFP and DOC was 0.6630, a fair correlation level. These results were not corresponding to those of stated by AWWA (1993) in which the relationship of THMFP and UV-254 and THMFP and DOC in raw water and coagulated water of natural water sources were mostly poor correlations with R^2 of only 0.57 and lower than 0.5.This is attributed to the fact that different results obtained due to different characteristics of treated industrial wastewater and natural water were compared. The explanations for supporting the results of above-mentioned correlations among NOM surrogates and THMFP are not clear, therefore, data sets which will be further subdivided into lower and higher AMW- NOM including humic and nonhumic fractions in an attempt to determine the contribution of these fractions to NOM properties and reactivity must be performed in the future work.

Based on the results in this study it is possible to suggest that TOC was the most suitable NOM surrogate parameter used to describe the quantity of THMFP, however, UV-254, SUVA and DOC were also considerably acceptable for treated industrial estate wastewater and reclaimed water.

Not only the relationship between THMFP and NOM surrogates but also the matrix relationship among NOM surrogates was performed and correlation coefficients of each relationship were also depicted in Table 4.2. It was found that the good correlation coefficients of 0.9325 and 0.9121 were obtained for the relationship between TOC and UV-254 and that of SUVA and UV-254. In cases of DOC and UV-254, of DOC and TOC and of SUVA and TOC, it could be categorized as moderate correlation levels while that of SUVA and DOC was a fair correlation.

Regarding to the relationship between THMFP and NOM surrogates, the best correlation of THMFP and TOC was determined and the equation that could be used to represent such correlation was THMFP = 238.55 + 33.886 TOC.

Table 4.2 Regression and correlation coefficients for bulk NOM parameters

Dependent Variable	Independent Variable	The results obtained in this study					AWWA (1993)			
		Status	N	R^2	Equation	Remark	Status	N	R^2	Equation
THMFP	UV-254	Raw water and coagulated water	9	0.8081	a = +321.16 b = +769.02	A moderate correlation	Raw Ozoned Coagulated	13 8 6	<0.5 0.64 0.57	a = +690 b = +77 a = +550 b = +73
THMFP	TOC	Raw water and coagulated water	9	0.8659	a = +238.53 b = +33.886	A moderate correlation	-	-	-	-
THMFP	DOC	Raw water and coagulated water	9	0.6630	a = +244.08 b = +37.205	a fair correlation	Raw Ozoned Coagulated	14 8 6	<0.50 0.66 <0.50	a = +75 b = +9.5
THMFP	SUVA	Raw water and coagulated water	9	0.7548	a = +250.53 b = +64.049	A moderate correlation	-	-	-	-
TOC	UV-254	Raw water and coagulated water	9	0.9325	a = +2.4397 b = +22.685	A good correlation	-	-	-	-

Regression analysis was not performed for $R^2 \leq 0.5$; hence the slope (b) and intercept (a) for equation were not computed.

Table 4.2 Regression and correlation coefficients for bulk NOM parameters (Con't)

Dependent Variable (Y)	Independent Variable (X)	The results obtained in this study					AWWA (1993)			
		Status	N	R^2	Equation	Remark	Status	N	R^2	Equation
DOC	UV-254	Raw water and coagulated water	9	0.8039	a = +2.5026 b = +16.787	A moderate correlation	-	-	-	-
SUVA	UV-254	Raw water and coagulated water	9	0.9121	a = +1.2063 b = +11.082	A good correlation	-	-	-	-
DOC	TOC	Raw water and coagulated water	9	0.8646	a = 0.6957 b = 0.741	A moderate correlation	-	-	-	-
SUVA	TOC	Raw water and coagulated water	9	0.786	a = + 0.2663 b = + 0.4379	A moderate correlation	-	-	-	-
SUVA	DOC	Raw water and coagulated water	9	0.5345	a = +0.4595 b = +0.4531	A fair correlation	-	-	-	-

Regression analysis was not performed for $R^2 \leq 0.5$; hence the slope (b) and intercept (a) for equation were not computed

## 4.4 Optimal pH Condition for TOC and THMFP Reduction by Alum and Ferric Chloride Coagulations

Based on the results of correlation among surrogates for NOM as previously discussed in section 4.3, it has already concluded that TOC could be used to describe quantity of THMFP in treated industrial estate wastewater and reclaimed water. Since, long period of analysis (7 days) and complicated procedures are required for THMFP determination. Therefore, TOC were determined instead of THMFP in order to consider the optimal pH of alum and ferric chloride coagulation in this study.

Figure 4.24 and 4.25 show the profile of TOC and percent TOC removal as a function of various dosages of alum and ferric chloride at different pH between 5 and 6.8. From these graphs, it could be pointed out that the optimal pH for TOC removal (in other hand, for THMFP removal) were at pH of 5.5 and 5 in alum and ferric chloride coagulation, respectively.
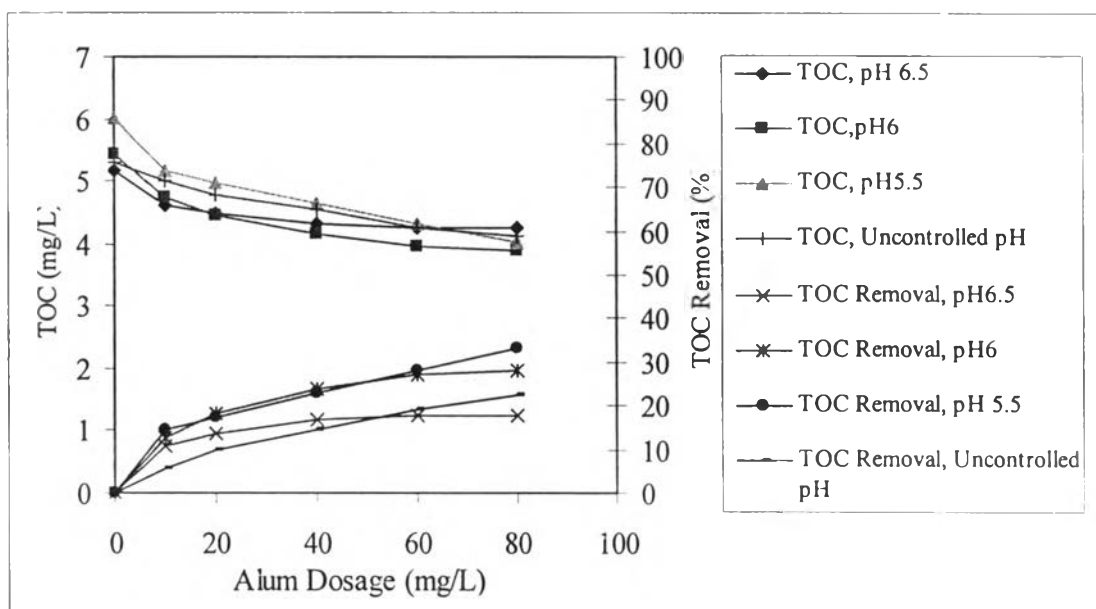
Figure 4.24 TOC of and percentage of TOC removal as a function of alum dosage at uncontrolled and different controlled pH
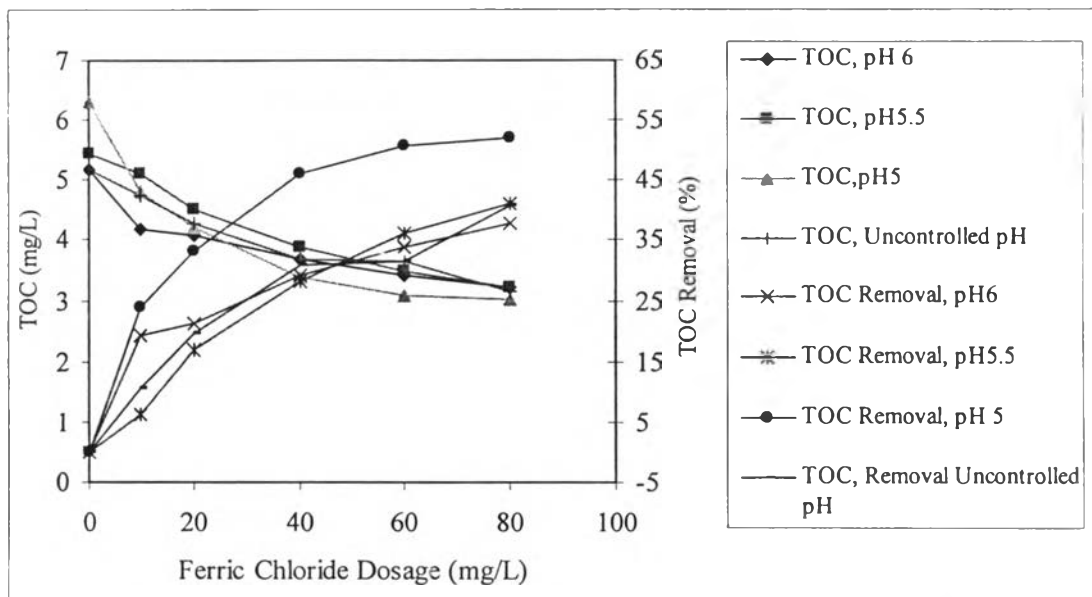
Figure 4.25 TOC and percentage of TOC removal as a function of ferric chloride dosage at uncontrolled and different controlled pH

Furthermore, the profiles of other NOM surrogates namely UV-254, DOC and SUVA versus various dosages of alum and ferric chloride at different controlled pH were also established as shown in Appendix C for additional consideration.

4.5 THMFP Species and its Reduction at Optimal pH Coagulation

As stated in the previous chapter, THMs was produced during chlorination of water. Four THM compounds namely chloroform dichlorobromoform, dibromochloroform and bromoform were determined as THMFP species in this study. The aim of this section was to present THMFP species formed in treated industrial estate wastewater (raw water) and in reclaimed water (coagulated water) including its reduction by alum and ferric chloride coagulation.

4.5.1 Coagulation by Alum at Optimal pH of 5.5

Based on data of THMFP species in raw water and in filtered supernatant after coagulation (coagulated water) by alum as shown in Figure 4.26 and Table 4.3, it was observed that chloroform in raw water and coagulated water were approximately 65 and 60 percent of total THMFP, respectively. Dichlorobromoform, dibromochloroform, and bromoform were also found in raw water and in coagulated water.
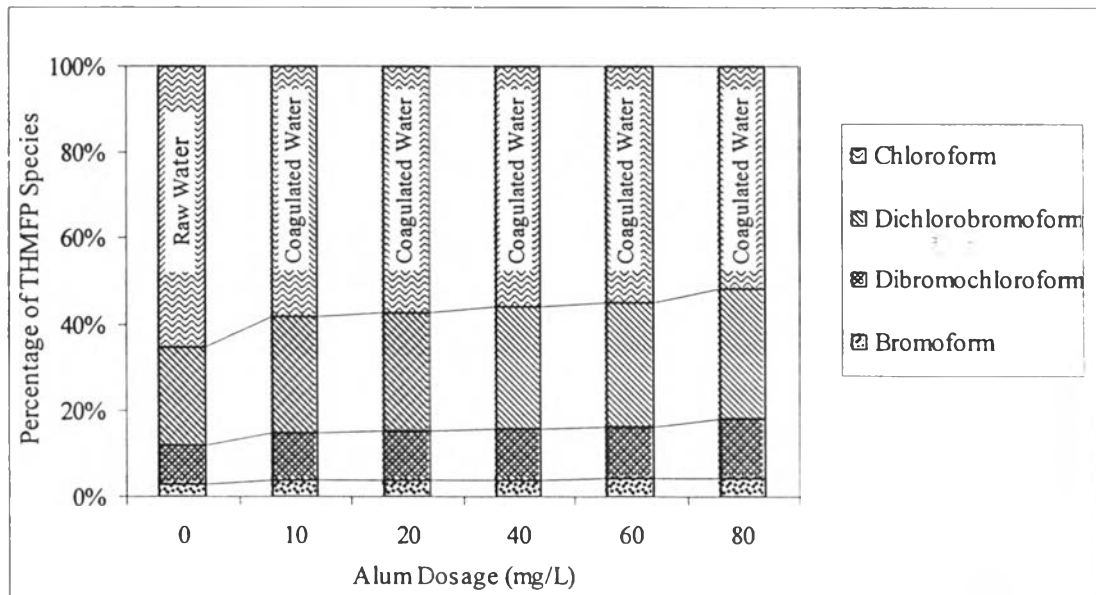
Figure 4.26 THMFP species in raw water and in coagulated water with various alum dosages at optimal pH of 5.5

The percentages of dichlorobromoform, dibromochloroform, and bromoform in raw water were approximately 20, 10 and 5 percent, respectively, whereas in nearly all cases of different alum dosages concentration, the percentages of dichlorobromoform, dibromochloroform, and bromoform in coagulated water were approximately 25, 10 and 5 percent of total THMFP, respectively.

This could be indicated that chloroform was the predominant THMFP species in treated industrial estate wastewater and reclaimed water while dichlorobromoform, dibromochloroform, and bromoform were found in minority.

Table 4.3 THMFP species and percent reduction of THMFP species in raw water and in coagulated water with various alum dosages water at optimal controlled pH of 5.5.

THMFP Species	Raw water	Coagulated water					Percent reduction				
		Alum dosages (mg/L)					Alum dosages (mg/L)				
		10	20	40	60	80	10	20	40	60	80
$CHCl_3$ ($\mu g/L$)	313.26	239.34	224.95	221.32	207.3	185.36	23.59%	28.19%	29.34%	33.82%	40.82%
$CHCl_2Br$ ($\mu g/L$)	109.44	110.55	108.23	113.24	109.83	109.25	0% (-)	0% (-)	0% (-)	0% (-)	0.17%
$CHClBr_2$ ($\mu g/L$)	43.58	44.41	44.00	45.89	45.34	48.72	0% (-)	0% (-)	0% (-)	0% (-)	0% (-)
$CHBr_3$ ($\mu g/L$)	14.39	14.99	15.00	15.39	15.35	16.05	0% (-)	0% (-)	0% (-)	0% (-)	0% (-)
Total ($\mu g/L$)	480.68	409.37	392.19	395.88	377.85	359.39	14.84%	18.41%	17.65%	21.39%	25.23%

The concentrations in term of µg/L of each THMFP species in raw water and in coagulated water were also established in Table.4.3. It can be seen in Table 4.3, chloroform, dichlorobromoform, dibromochloroform, and bromoform were found in treated industrial estate wastewater of 313.26, 109.44, 43.58 and 14.39 µg/L, with total THMFP of 480.68 µg/L.

In addition, it was also noticed that the best alum coagulation condition for total THMFP removal in this study was at alum dosage of 80 mg/L at pH 5.5 by which total THMFP could be only reduced from 480.68 µg/L to 359.39µg/L.

Concerning reduction of THMFP species by alum coagulation at optimal pH of 5.5 as depicted in table 4.3, it would be said that chloroform removal efficiency by alum coagulation of 40.82 percent was observed while other species could not be efficiently reduced. However, it can be presented that total THMFP of 25.23 percent could be removed by coagulation of alum dosage of about 80 mg/L at pH 5.5

4.5.2 Coagulation by Ferric Chloride at Optimal pH of 5

As can be seen in Figure 4.27 and Table 4.3, data of THMFP species in raw water and in coagulated water by ferric chloride were presented, it was observed that chloroform in raw water and coagulated water were approximately 60 and 55 percent of total THMFP, respectively. In other word, Dichlorobromoform, dibromochloroform, and bromoform were also found in raw water and in coagulated water.

The percentages of dichlorobromoform, dibromochloroform, and bromoform in raw water were approximately 20, 15 and 5 percent, respectively, while in almost all cases of different ferric chloride dosages concentration, the percentages of dichlorobromoform, dibromochloroform, and bromoform in coagulated water were approximately 25, 15 and 5 percent of total THMFP, respectively.
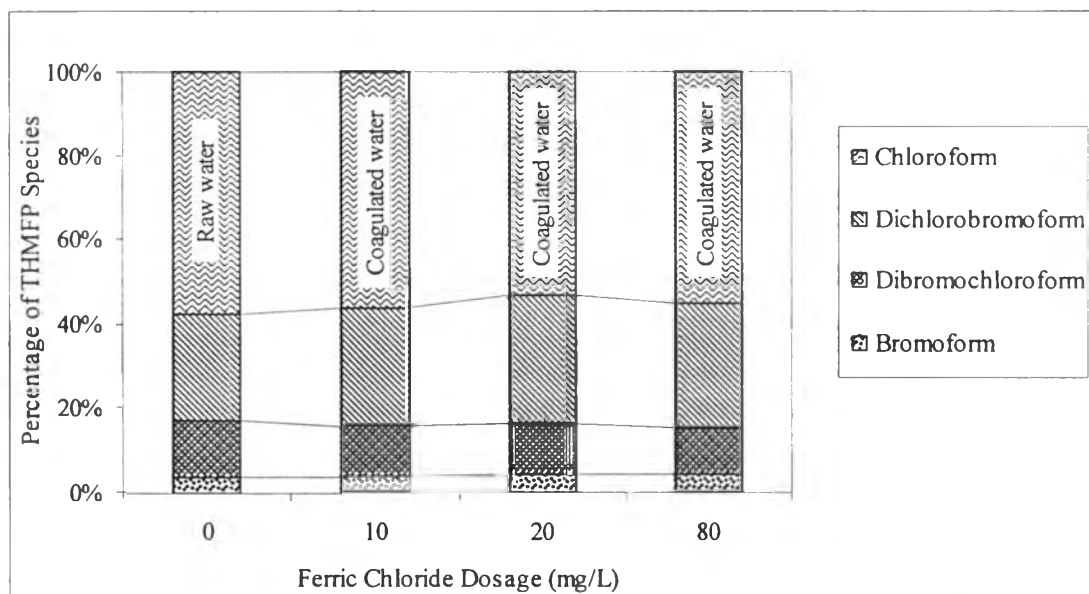
Figure 4.27 THMFP species in raw water and in coagulated water with various ferric chloride dosages at optimal pH of 5.5

This could be also indicated once again that chloroform was the dominant THMFP species in treated industrial estate wastewater and reclaimed water while dichlorobromoform, dibromochloroform, and bromoform were found in order of minority.

The concentrations in term of µg/L of each THMFP species in raw water and in coagulated water were also demonstrated in Table.4.4. It showed that, chloroform, dichlorobromoform, dibromochloroform, and bromoform were found in treated industrial estate wastewater of 284.23, 123.11, 65.54 and 18.92 µg/L, with total THMFP of 491.80 µg/L.

Additionally, it was also noticed that the best ferric chloride coagulation condition for total THMFP removal in this study was at ferric chloride dosage of 80 mg/L at pH 5 by which total THMFP could be only removed from 491.80 µg/L to 355.54µg/L.

Table 4.4 THMFP species and percent reduction of THMFP species in raw water and coagulated water with various ferric chloride dosages at optimal controlled pH of 5

THMFP Species	Raw Water	Coagulated water			Percent reduction		
		Ferric Chloride Dosages (mg/L)			Ferric Chloride Dosages (mg/L)		
		10	20	80	10	20	80
$CHCl_3$ ($\mu g/L$)	284.23	213.99	195.16	196.04	24.71%	31.33%	31.03%
$CHCl_2Br$ ($\mu g/L$)	123.11	108.12	109.56	104.28	12.17%	11.00%	15.29%
$CHClBr_2$ ($\mu g/L$)	65.54	44.64	44.70	40.16	31.88%	31.78%	38.72%
$CHBr_3$ ($\mu g/L$)	18.92	15.30	15.44	15.05	19.13%	18.39%	20.45%
Total ($\mu g/L$)	491.80	382.06	364.88	355.54	22.31%	25.80%	27.71%

Eventually, with respect to coagulation by ferric chloride, chloroform, dichlorobromoform, dibromochloroform and bromoform removal efficiency at pH 5 and 80 mg/L dosage were 31.03, 15.29, 38.72 and 20.45 percent, respectively, as a result, total THMFP removal of 27.71 percent was reckoned in this study.

With regard to the performance of ferric chloride coagulation in compared with that of alum coagulation as described earlier in 4.7.1, it would be implied that total THMFP reduction efficiencies by ferric chloride and alum coagulation were comparable by 27.71 percent and 25.23 percent, respectively. However, alum coagulation could only remove chloroform but not removed dichlorobromoform, dibromochloroform and bromoform efficiently, which were in the contrary of ferric chloride coagulation.