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Mature Landfill Leachate Treatment from an Abandoned Municipal Waste Disposal Site

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Abstract−We investigated treatment techniques for the leachates derived from an abandoned waste disposal landfill facility known as Nan Ji Do in Seoul, Korea. To this end, the general characteristics of those leachates were carefully examined. The feasibility of leachate handling techniques was then examined through an application of both off- and on-site processes as a combination of direct treatment methods and/or pretreatment options. They include operation of such systems or methods as: (1) activated sludge process, (2) adsorption-flocculation methods, and (3) anaerobic digestion. When the fundamental factors associated with the operation of an activated sludge process were tested by a simulated system in the laboratory, those applications were found to be efficient at leachate addition of up to 1%. Application of adsorption/precipitation method was also tested as the pretreatment option for leachates by using both powdered activated carbon (PAC) as adsorbent and aluminum sulfate (alum) as flocculant. Results of this test indicated that the removal of chemical oxygen demand (COD) was optimized at PAC and alum contents of 100 to 300 mg/L, respectively. In addition, an anaerobic digester also examined the effect of leachate components on the rate of anaerobic digestion. According to our study, treatment and pretreatment options investigated were, in general, effective enough to reduce the rate of organic loading and the occurrences of hazardous incidents.

Key words: Adsorption-Flocculation, Combined Treatment, Pretreatment, Landfill Leachate

INTRODUCTION

Proper treatment of municipal and industrial wastes is now considered to constitute an essential part of environmental conservation in most urbanized nations around the world. From 1978 to 1992, the Seoul metropolitan government had operated a gigantic solid waste disposal site at Nanjido located 10 km west of central Seoul, the capital of Korea. The Nanjido landfill had been a unique disposal site available for Seoul area having a population of over ten million. The landfill had also received industrial wastes such as wastewater sludge without record as well as municipal solid waste (MSW). The total quantity of municipal waste including construction wastes landfilled for fifteen years was approximately estimated at 160 million tons [Seoul Metropolitan Government, 1994]. The site after closure looks like a huge riverside mountain, 95 m high and 2.72 km^2 wide. A plan of the Nanjido landfill included two parts, site 1 and site 2. Site 1 had been filled with solid wastes earlier than site 2, and its area after closure was 1.6 times larger than site 2.

The site has received environmental attention because it was operated as an uncontrolled codisposal site without proper sanitary means and legal regulations. Therefore, an integrated program including urgent remedial actions and a landfill closure plan has just begun for accelerated stabilization and rehabilitation of the site by the Seoul metropolitan government. The program involved final covering, drainage control, control of landfill gases, leachate control, and environmental monitoring. Leachate control was considered the most urgent among the environmental issues to be solved, because the leachate had leaked to the surrounding environment without any appropriate control facility. A collection and treatment method was selected for leachate control. Groundwater extraction by pumping will be adopted with slurry trench cutoff walls for leachate collection. Most of the physicochemical and biological leachate treatment methods were extensively reviewed for selection of an appropriate process for the landfill leachate. Leachate treatment options included off-site combined treatment at a nearby large municipal wastewater treatment plant with or without pretreatment as well as various on-site treatments [Chang and Chung, 1994]. Several investigators [Rantala and Lehtonen, 1980; Henry, 1985; Robinson and Maris, 1985; Kelly, 1987; Park, 1999] have carried out researches on the combined treatment of landfill leachate with municipal wastewater. Previous studies just showed that general design criteria for combined leachate treatment could not be made because every landfill had its own history and leachate. Moreover, off-site treatment of leachate from uncontrolled codisposal landfill and its on-site pretreatment after closure has never been experienced.

Unexpected leakage of unpredictable hazardous substances might occur from industrial wastes in the codisposal area scattered in the Nanjido landfill, and since leachates were collected and treated without proper regulation, selection of their treatment method is very simple. Although, exceedingly high concentrations of hazardous substances have not been monitored from Nanjido site yet since 1992. Unexpected high COD loading as well as hazardous substances from the landfill could also deteriorate the performance of

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an adjacent municipal wastewater treatment plant, when combined leachate treatment is adopted. It was hence recommended that provisions against such emergency situations should be provided to protect the municipal wastewater treatment plant against any potential hazards from the leachate prior to combined leachate treatment. Previous study on biological treatment of the leachate using the upflow anaerobic sludge blanket process showed that the reactor had a maximum COD removal of only 10%, and almost failed after three months of operation [Chang and Chung, 1994]. Lee et al. [1999] carried out aerobic treatment of leachate using an innovative nutrient removal system. Hur and Kim [2000] reported that a combined adsorption and coagulation process for MSW leachate showed higher COD removals. Biological pretreatment of the leachate was therefore discarded, and a physicochemical process such as adsorption and chemical precipitation was considered as one of effective pretreatment options reviewed.

In an effort to comply with such demand, we investigated many options to assess the feasibility of off-site treatment of leachate from an uncontrolled mature codisposal landfill at a nearby large municipal wastewater treatment plant, of which the main processes are activated sludge process and anaerobic digestion, and examine its on-site physicochemical pretreatment option prior to combined treatment.

MATERIALS AND METHODS

Upon the closure of the Nanjido site, leachate samples were taken on a monthly basis from all of the fourteen discharge points shown in Fig. 1, and their characteristics have been extensively monitored after closure of the landfill. Most leachate was discharged from the landfill slopes or toes except one leachate spring on the top of site 1. Boring samples were also taken from 11 and 30 m below the top of site 1. All of these samples were analyzed once a month for 9 months except during winter periods, not only for their general physical and chemical properties but also for the contents of hazardous substances including volatile organic compounds and heavy metals. The flowrate from every leachate discharging point was also measured. Laboratory-scale continuous flow activated sludge systems were used to investigate the effect of leachate inflow into a municipal wastewater treatment plant. Each system consisted of an aeration tank having a liquid volume of 5 liters, a settling tank, and airlift pump for sludge recycle. The activated sludge systems were operated at feeding conditions of leachate dilution of 0.2, 1, 10, 25, and 50% by volume with a municipal wastewater at the temperature range of 19 to 28 °C. Individual leachate from the landfill slopes and toes was mixed in volumes proportional to flowrate, and the mixed leachate was used for the preparation of combined feed. Operating conditions for the systems fed with practically anticipated leachate percent lower than 1% were identical with the design criteria of the adjacent Nanji municipal wastewater treatment plant, while systems with higher leachate strength of 10, 25, and 50% were also operated at a longer aeration time and solid retention time to examine the system performances at critical conditions. Two control systems fed only with a municipal wastewater were simultaneously operated to compare their baseline performances with those of the systems fed with combined influent. The detailed operating conditions of the activated sludge systems are included in Table 4.

Table 1. Characteristics of a municipal wastewater for combined leachate treatment (Average±standard deviation)

Parameters	Concentration (mg l^{-1})[a]
pH	7.2±0.1
Total biochemical oxygen demand	93±21
Soluble biochemical oxygen demand	48±15
Total chemical oxygen demand	139±36
Soluble chemical oxygen demand	88±24
Total Kjeldahl nitrogen	46±5
Ammonia nitrogen	31±6
Total phosphorus	5±1
Suspended solids	49±7

[a]Except pH

All systems had been operated with a municipal wastewater for more than three months to confirm identical system performances prior to introduction of the leachate. Table 1 shows characteristics of a municipal wastewater used for combined leachate treatment.

Laboratory-scale anaerobic digesters were also operated to examine the effect of leachate components on anaerobic digestion by using combined mixed sludge produced from the activated sludge systems for combined leachate treatment. Each digestion system consisted of a daily-fed stirred anaerobic reactor with a liquid volume of 4 liters, and a floating type gas collector equipped with a counterweight. All digesters were operated at the same hydraulic retention time (HRT) of 20 days and temperature of 35 °C as design criteria of the adjacent Nanji municipal wastewater treatment plant. The combined sludge was prepared by using thickened and mixed primary and excess activated sludge obtained from the activated sludge systems operated at feeding conditions of leachate dilution of 0.2% and 1% with a municipal wastewater. A control digester fed with a mixed municipal sludge from the control activated sludge system was simultaneously operated. Characteristics of the mixed feed sludge for anaerobic digestion are presented in Table 2.

Batch experiments on adsorption and chemical precipitation were conducted to examine the performance of the process as a pretreatment option. All experiments were performed by using a jar test apparatus at a temperature of 25 °C. Raw leachate for pretreatment

Table 2. Characteristics of feed sludge for anaerobic digestion (Average±standard deviation)

Parameters	Municipal sludge	Combined sludge (Leachate 0.2%)	Combined sludge (Leachate 1%)
pH	6.3±0.1	6.3±0.1	6.3±0.1
Total solids (g l^{-1})	26.0±3.0	27.5±2.1	20.1±1.3
Volatile solids (g l^{-1})	11.9±0.7	12.8±1.4	11.1±0.4
COD (g l^{-1})	20.9±1.3	21.7±1.6	16.5±0.8
Volatile acids (mgHAc l^{-1})	100±8	110±16	110±11
Alkalinity (mg$CaCO_3$ l^{-1})	800±54	790±12	780±50

was taken from site 2, which had higher leachate strength compared with that of site 1. Powdered activated carbon smaller than 100 mesh and aluminum sulfate were used as adsorbent and coagulant, respectively, and these chemicals were analytical reagent grade. Adsorption and chemical precipitation proceeded as a series of contact mixing with powdered activated carbon for 20 minutes, rapid mixing for 5 minutes after addition of aluminum sulfate, slow mixing for 15 minutes, and 2-hours settling. Mixing intensity during contact and rapid mixing was 140 rpm, and that during slow mixing was 30 rpm. Supernatant after settling was analyzed to evaluate COD and color removals. Sludge production was measured as settled volume (SV) after 2-hours settling. All analyses in this study were conducted as per procedures in the APHA Standard Methods [APHA, 1992].

RESULTS AND DISCUSSIONS

1. General Leachate Characteristics

Most leachates from the Nanjido landfill have been discharged either on the landfill slopes or toes mainly through localized collection systems using perforated pipes, since no integrated leachate collection system for the whole area of the site has been made yet. One of the leachates discharged as a spring on the top of the site 1, but it infiltrated again into the landfill. The sum of the measured flowrates from those discharging points could not represent the total leachate generation rate in the landfill because leachate percolation rate to the ground was not measured. A hydrological computer simulation using a data set from hydrogeologic studies and flowrate analysis estimated maximum daily leachate generation-rate of 6,450 m^3 after closure covering. Hydrogeologic studies showed that some leachate was randomly accumulated above the ground water level as unstable perched water [Seoul Metropolitan Government, 1994]. Leachate generation and its characteristics varied widely with collection time and point. The leachate was highly turbid, malodorous, and had a strong dark yellowish orange color. Recent typical characteristics of the leachate from the landfill slopes and toes and its flowrate are summarized in Table 3. The average leachate strength in Table 3 was the flow-weighted average. The leachate from the landfill slopes and toes showed typical characteristics of a leachate from mature landfill in a methanogenic phase. The spring and boring sample had exceptionally higher strength than those of the leachate from the landfill slopes or toes.

Table 3. Typical characteristics of the leachate from landfill slopes and toes

Parameters	Average	Range
Flowrate (cubic meter per day)	281.4	250.8-317.8
Temperature (°C)	37	33-40
pH	8.0	7.5-8.6
BOD (mg l^{-1})	230	60-342
COD (mg l^{-1})	2,400	1,080-4,750
Total organic carbon (mg l^{-1})	1,510	1,060-2,380
Suspended solids (mg l^{-1})	33	11-67
Total kjeldahl nitrogen (mg l^{-1})	1,780	1,480-3,350
Organic nitrogen (mg l^{-1})	200	50-490
Ammonia nitrogen (mg l^{-1})	1,580	1,073-2,890
Nitrite (mg l^{-1})	ND	ND
Nitrate (mg l^{-1})	1.0	0.08-2.1
Total phosphorus (mg l^{-1})	7.3	2.9-15.7
Oil & Grease (mg l^{-1})	0.23	0.02-0.82
Alkalinity (mg $CaCO_3$ l^{-1})	6,740	3,790-8,840
Hardness (mg l^{-1})	370	150-520
Chloride (mg l^{-1})	2,430	1,680-4,120
Sulfate (mg l^{-1})	1,310	870-2,010
Aluminum (mg l^{-1})	1.65	1.1-2.2
Barium (mg l^{-1})	0.72	0.27-1.08
Calcium (mg l^{-1})	33.6	13.8-52
Magnesium (mg l^{-1})	87.5	64-117
Potassium (mg l^{-1})	1,290	1,250-2,070
Arsenic (mg l^{-1})	0.4	0.19-0.57
Cadmium (mg l^{-1})	0.02	0.01-0.05
Chromium (mg l^{-1})	0.95	0.57-1.6
Copper (mg l^{-1})	0.09	0.02-0.25
Iron (mg l^{-1})	4.4	0.56-12.2
Lead (mg l^{-1})	0.035	0.003-0.19
Manganese (mg l^{-1})	0.16	0.075-0.4
Nickel (mg l^{-1})	0.22	0.073-0.42
Selenium (mg l^{-1})	0.31	0.16-0.62
Zinc (mg l^{-1})	0.13	0.01-0.2
Phenol (mg l^{-1})	0.38	0.21-0.5
Trichloroethylene (μg l^{-1})	ND	ND
Benzene (μg l^{-1})	2.4	1.0-6.5
Toluene (μg l^{-1})	ND	ND
Xylene (μg l^{-1})	ND	ND
Color		
Dominant wavelength (nm)	580-587	
Hue	Yellowish orange	
Luminance (%)	42	
Purity (%)	70	
ADMI value	1,471	

ND: Not Detected

The leachate temperature was between 33 and 40 °C throughout the period investigated, except the temperature over 55 °C of the leachate from the spring. Difference in leachate temperature between summer and winter was within 5 °C at any discharging point, though atmospheric temperature varied from −15 to 35 °C. Typical pH of the leachate ranged from 8 to 8.5, and this alkaline condition was maintained regardless of sampling time and point. The strength of the leachate from the landfill slopes and toes averaged 230 mg l^{-1} of BOD. The biochemical oxygen demand (BOD) of the spring and boring sample averaged as high as 1,740 and 1,530 mg l^{-1}, respectively. Average BOD/COD ratio of the leachate from the slopes and toes was as low as 0.096, while that of the boring sample was 0.17. Average BOD : N : P ratio of the leachate from the landfill slopes and toes was 32 : 244 : 1. Most organics in the leachate comprised soluble forms. Biological on-site treatment would not be applied to this leachate due to such a low biodegradable organic content, although high concentration of hazardous substances detrimental to biological processes has not been monitored yet.

Nitrogen, of which the major form was ammonia, was higher than that in the literature because food waste accounts for about 40%

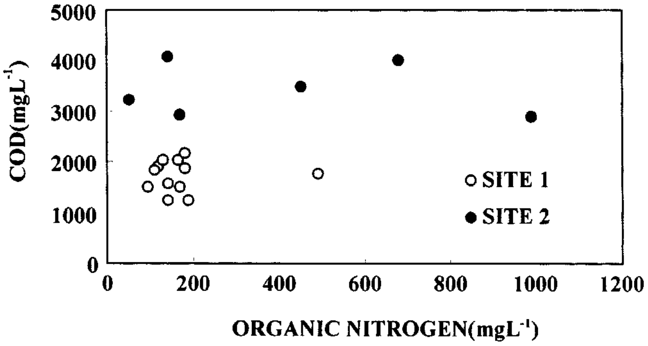

Fig. 1. Correlation between COD and organic nitrogen of the leachate from site 1 and site 2.

of municipal solid waste in Korea [Seoul Metropolitan Government, 1994]. Long landfill age also contributed to relatively higher concentration of ammonia nitrogen compared with organics. Average organic nitrogen of the leachate from the landfill slopes and toes was as low as 11% of total Kjeldahl nitrogen (TKN). Degree of organics conversion may be represented by the ratio of ammonia to COD, since conversion rate of ammonia nitrogen is much slower than that of organics. The ratios of the leachate from the slopes and toes, the boring sample, and the spring were 0.65, 0.4, and 0.1, respectively. Thus, the ratio decreased at the upper part of the landfill, which has relatively younger landfill age. The leachate from site 2 had higher COD and wider variation of organic nitrogen than that of site 1, as shown in Fig. 1. Relatively wider variation of ammonia concentration was also observed at site 1, compared with that of COD and organic nitrogen. These differences between site 1 and site 2 could be explained by the relatively younger landfill age of site 2. Most heavy metals, except chromium and arsenic, were trace and below the Korean discharge guideline for industrial effluent. Among the volatile organic compounds analyzed, only benzene was detected as trace concentration.

2. Combined Leachate Treatment by Activated Sludge Process

Leachate inflow into the adjacent Nanji municipal wastewater treatment plant was anticipated between 0.25% and 0.73% by volume of the total plant flow, based on leachate generation rate estimated by computer simulation and designed average and peak flow of the plant, of which hourly peak flow is one million cubic

Table 4. Operating conditions and steady-state performances of activated sludge process (Average±standard deviation)

Parameters	Control	Leachate percent (V/V%)				
		0.2 %	1 %	10 %	25 %	50 %
Operating conditions						
Aeration time (hours)	6	6	6	15	15	15
SRT (days)	7	7	7	25	25	25
Temp. (°C)	22±5	22±5	22±5	22±5	22±5	22±5
pH	7.3±0.4	7.3±0.2	7.2±0.2	7.1±0.2	7.1±0.1	6.2±1.0
DO (mg l^{-1})	8.0±0.2	8.1±0.4	7.9±0.5	8.4±0.2	8.4±0.2	9.0±1.6
MLSS (mg l^{-1})	1,120±136	1,050±37	1,230±106	1,140±58	1,390±19	1,700±95
MLVSS/MLSS ratio	0.63	0.63	0.63	0.70	0.59	0.63
F/M ratio (kgBODkgMLSS^{-1} d^{-1})	0.31±0.08	0.38±0.1	0.45±0.1	0.30±0.1	0.25±0.1	0.24±0.1
Respiration rate (mgO$_2$mgMLVSS^{-1} h^{-1})	17.2	15.0	15.6	13.3	13.7	9.8
SVI (ml g^{-1})	67±10	74±7	65±6	72±8	61±3	50±6
Removal efficiencies						
BOD (%)	90.3±2.7	92.5±2.9	90.1±3.6	74.3±4.1	68.0±3.9	62.3±4.5
COD (%)	88.4±4.6	85.8±4.1	80.3±4.1	73.1±9.3	67.7±9.1	63.3±8.3
SS (%)	88.9±8.6	89.1±6.8	88.7±6.4	93.4±6.5	93.8±1.1	96.1±1.0
TKN (%)	61.0±6.7	59.4±7.7	58.3±8.7	35.7±10.7	31.0±11.5	32.1±10.9
NH_3-N (%)	54.3±6.1	49.3±8.7	50.1±8.5	28.4±12.3	29.7±9.3	31.3±0.4
Color						
Dominant wavelength (nm):						
Influent/Effluent[a]	500-505	500-505	500-505	575-580	575-580	575-580
Hue						
Influent/Effluent[a]	Green	Green	Green	Yellow	Yellow	Yellow
Luminance (%):						
Influent/Effluent	84/84	76/77	79/79	82/82	76/77	47/51
Purity (%):						
Influent/Effluent	3/3	3/3	3/3	20/20	30/30	40/40
ADMI value:						
Influent/Effluent	438/437	437/437	439/438	658/639	711/653	1,232/1,214

[a]Specified color characteristics of effluent are the same as those of influent.

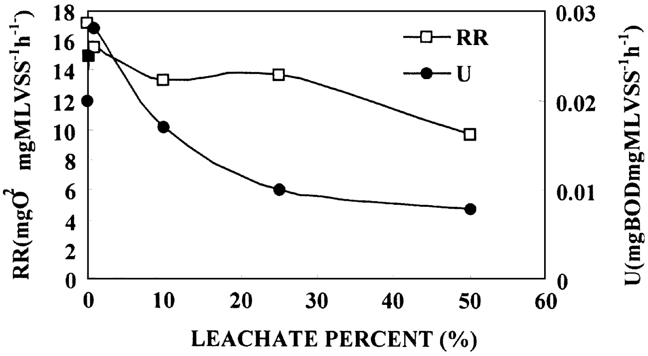

Fig. 2. Specific substrate utilization rate and respiration rate of activated sludge.

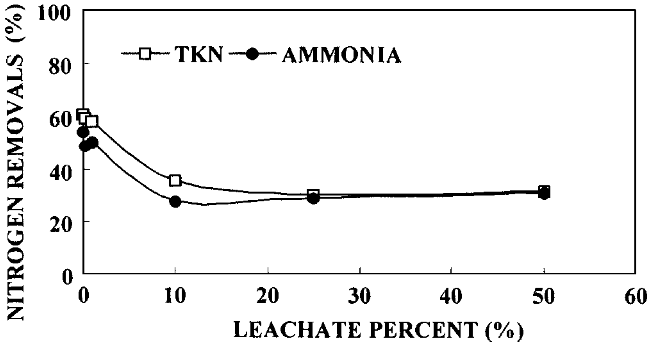

Fig. 3. The TKN and ammonia removals of combined treatment using activated sludge process.

meter per day. Therefore, leachate combination of 1% by volume was believed to be a practical upper limit for combined treatment. Expected increase in influent BOD of the plant would be negligible, while that in COD, ammonia, and TKN was 16%, 50%, and 38%, respectively, with 1% leachate addition to the plant. A summary of the operating conditions and steady-state performance of the activated sludge systems is presented in Table 4. The performance with extremely high leachate addition of 10, 25, and 50% was also included to evaluate biodegradability of the leachate at critical conditions.

BOD removals over 90% and COD removals over 80% were maintained with addition of leachate up to 1%, and gradual decrease in organics removals was observed as leachate percent increased from 10% to 50% as illustrated in Table 4. The COD removal was almost identical with the BOD removal at a leachate addition higher than 10%. It was noted that the BOD and COD removals higher than 60% could be achieved even at the reactor with 50% leachate addition.

Fig. 2 shows the specific substrate utilization rate (U), which represents amount of organics removed per unit weight of microorganisms per unit time, and the respiration rate at different leachate percent. The specific substrate utilization rate increased at leachate addition up to 1%, and decreased at higher leachate percent, probably due to an inhibitory effect at higher leachate percent. The specific substrate utilization rate based on BOD at 50% leachate was 0.4 times that of the control, while that based on COD at 50% leachate was 1.7 times that of the control. Respiration rate (RR) of the activated sludge gradually decreased with increase in leachate percent; however, that of the culture even with 50% leachate was kept in the favorable range of the literature.

The effect of leachate addition on nitrogen removals was significant compared with that on organics removals, as shown in Fig. 3, because of relatively higher nitrogen contents than biodegradable organics in the leachate. The TKN and ammonia nitrogen removals decreased remarkably at leachate addition between 1% and 10%, while decrease in the removals was not significant at leachate addition lower than 1%. The difference between the TKN and ammonia removals was reduced with an increase in leachate percent. Nitrification efficiencies at 0.2% and 1% leachate addition were above 70%, and almost equal to that of the control, whereas the efficiencies decreased significantly below 40% with leachate addition higher than 10%. Suspended solids removal increased with higher leachate percent, and good sludge settleability was maintained regardless of influent leachate percent. Increase in sludge settling velocity with leachate addition was also reported in almost all combined leachate treatment [Ahnert and Ehrig, 1992]. Influent color increased linearly with increase in leachate percent. Strong colored influents and effluents were observed at the systems with leachate addition higher than 10% along with changes of color characteristics. Color removals were negligible at all activated sludge systems examined.

3. Anaerobic Sludge Digestion from Combined Treatment

The effect of leachate components in combined sludge on anaerobic digestion was also evaluated by using mixed primary and excess activated sludge produced from combined treatment. The operating conditions and performance of mesophilic anaerobic digesters are summarized in Table 5. The pH, ORP, volatile acids, and alkalinity of the digested sludges from the control digester fed with municipal sludge and the digesters fed with combined mixed sludge were almost identical in the ranges, indicating a favorable anaerobic digestion. The digester fed with the sludge from combined treatment of 1% leachate showed lower volatile solids (VS) and COD removals. However, gas production rates were almost the same regardless of feed sludge. VS removals below 30% and gas yields below 0.2 liter per gVS added were lower than those reported in the literature due to low biodegradable organics content of municipal sludge in Korea [Choi and Chang, 1988]. Combined treatment up to 1% leachate addition had no detrimental effect on anaerobic digestion.

4. Adsorption and Chemical Precipitation Process for Pretreatment

Experiments on adsorption and chemical precipitation were conducted to evaluate the performance of the process as one of the options for pretreatment prior to combined leachate treatment. Removal of raw leachate COD was achieved by powdered activated carbon (PAC) adsorption and subsequent settling of PAC. At the PAC dosage ranging from 100 to 1,000 mg l^{-1}, the COD removal had a tendency to increase from 20 to 45%, while amount of COD removed per unit mass of PAC decreased with increase in PAC dosage. However, consistent COD removal at any PAC dose could not be accomplished even with one-day settling of PAC after adsorption, because settled PAC was unstable and organic adsorbates on carbon particles remaining in the supernatant could cause high COD exertion. Stable COD removals were achieved with improved set-

Table 5. Operating conditions and performances of anaerobic digesters (Average±standard deviation)

Parameters	Feed sludge		
	Municipal sludge	Combined sludge (Leachate 0.2%)	Combined sludge (Leachate 1%)
Operating conditions			
HRT (days)	20	20	20
Organic loading rate			
($gVSL^{-1}$ d^{-1})	0.60±0.04	0.64±0.13	0.56±0.02
($gCODL^{-1}$ d^{-1})	1.05±0.07	1.09±0.08	0.82±0.04
Digested sludge characteristics			
pH	6.95±0.09	6.95±0.1	6.95±0.03
ORP (mV)	−210±11.1	−213±24.7	−213±19.9
Volatile acids (mgHAc l^{-1})	83±8.7	113±4.1	94±11.3
Alkalinity (mg $CaCO_3$ l^{-1})	1,934±260	1,974±110	1,790±321
Solids and COD removals			
VS (%)	27.7±5.1	28.7±8.5	24.1±2.5
COD (%)	37.2±5.9	34.5±6.1	29.7±7.2
Gas production			
Gas production rate (LL^{-1} d^{-1})	0.11±0.02	0.12±0.01	0.11±0.02
Gas yield (Lg^{-1}VSadded)	0.18±0.03	0.19±0.03	0.19±0.03
Gas yield (Lg^{-1}VSremoved)	0.68±0.21	0.75±0.37	0.81±0.20
Methane content (%)	69±0.9	68±0.9	68±1.0

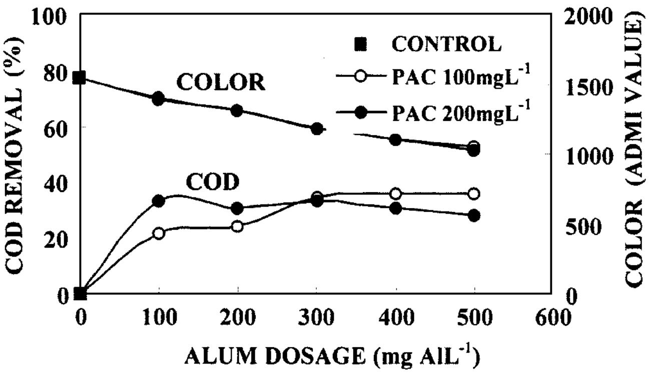

Fig. 4. The COD and color removals of adsorption and chemical precipitation.

tleability of PAC by chemical precipitation using aluminum sulfate (alum) as a coagulant. Two hours were enough for settling of flocculated PAC after alum dosage.

Fig. 4 illustrates the COD and color removals by combination of adsorption and flocculation process at fixed PAC dosages of 100 and 200 mg l^{-1} chosen based on the COD removal as well as in the economic aspect. The COD removal did not change significantly at an alum dosage over 100 mg l^{-1} with a preceding adsorption by PAC dosage of 100 mg l^{-1}, while gradual increase in COD removal was observed as alum dosage increased with a preceding PAC dosage of 200 mg l^{-1}. Lower COD removal at higher preceding PAC dose at an alum dose below 300 mg/L was due to insufficient alum dose to precipitate larger amount of carbon particles. Settleability of the chemical sludge increased with increasing alum dose. Satisfactory zone settling occurred at an alum dose higher than 300 mg l^{-1} regardless of PAC dose. Fig. 4 demonstrates that the COD removal was accomplished mainly by PAC adsorption rather than alum coagulation in the range of PAC dosages investigated, although flocculation to improve settleability of PAC resulted in improved COD removal at higher PAC dose. Adsorptive capacity of PAC was 5.5 to 6.5 mgCOD per mgPAC at a PAC dose of 100 mg l^{-1}. Identical linear color removal of a unit ADMI value per mg alum added was obtained with increasing alum dose regardless of PAC dose. As alum dose increased at any PAC dose, effluent luminance increased, and purity decreased, while predominant hue of yellow did not change. The color was removed principally by coagulation. The removals of COD and color were 33% and 24% at an alum dose of 300 mg l^{-1} with a preceding PAC dose of 100 mg l^{-1}, respectively. Such removals were considered to be effective for a pretreatment prior to combined treatment, and other researchers [Kim et al., 1997; Chang and Kim, 1998] reported similar results. Contact time for adsorption between 5 to 90 minutes did not affect the COD removal, as illustrated in Fig. 5.

Thus, the adsorption-flocculation process proved to be an effective on-site pretreatment option, because it can reduce not only or-

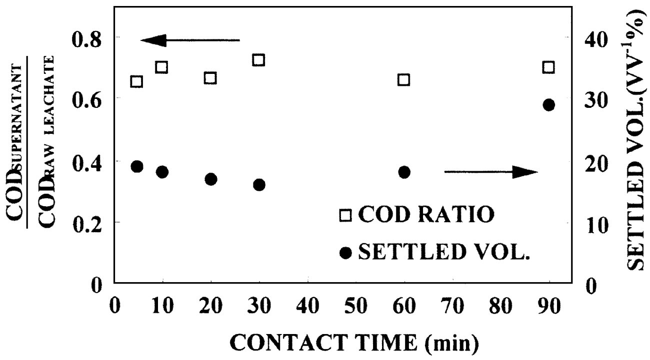

Fig. 5. Effect of contact time on adsorption and sludge production at a dosage of 100 mg l^{-1} PAC and 300 mg l^{-1} alum.

ganic loading but also unexpected hazardous substances, and has distinct features of simple, flexible, stable, and reliable operation against fluctuation of leachate quality and flowrate. This process can also cope with an extremely high COD shock loading by higher removals at higher chemical dosages. Expected process train for on-site pretreatment would be grit removal, flow equalization, PAC adsorption, coagulation, and flocculation followed by settling.

CONCLUSIONS

Feasibility of off-site combined treatment of leachate from a mature codisposal landfill and its on-site pretreatment option were evaluated in this research. No adverse effect was observed in activated sludge systems with leachate addition up to 1% by volume. The performance of the system, when checked carefully, deteriorated with leachate addition higher than 10% despite enhancement of removal efficiency for suspended solids and good sludge settleability. Reduction in nitrogen removals was relatively greater than that in organics removals at higher leachate percent. Combined treatment with leachate addition up to 1% had no detrimental effect on the anaerobic digestion process. Adsorption-flocculation process was considered to be an effective on-site pretreatment option for protecting a municipal wastewater treatment plant against potential hazards or unexpected high organic loading from the landfill. COD removal was accomplished mainly by adsorption, and color was removed principally by coagulation in the adsorption-flocculation process.

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