AMMONIUM REMOVAL FROM LANDFILL LEACHATE BY CHEMICAL PRECIPITATION

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Abstract — the landfill leachate in Hong Kong usually contains quite high NH_4^+-N concentration, which is well known to inhibit nitrification in biological treatment processes. A common pre-treatment for reducing high strength of ammonium (NH_4^+-N) is by an air-stripping process. However, there are some operational problems such as carbonate scaling in the process of stripping. For this reason, some technical alternatives for NH_4^+-N removal from leachate need to be studied. In this study, a bench-scale experiment was initiated to investigate the feasibility of selectively precipitating NH_4^+-N in the leachate collected from a local landfill in Hong Kong as magnesium ammonium phosphate (MAP). In the experiment, three combinations of chemicals, $MgCl_2 \cdot 6H_2O$ + $Na_2HPO_4 \cdot 12H_2O$, MgO + 85% H_3PO_4, and $Ca(H_2PO_4)_2 \cdot H_2O$ + $MgSO_4 \cdot 7H_2O$, were used with the different stoichiometric ratios to generate the MAP precipitate effectively. The results indicated that NH_4^+-N contained in the leachate could be quickly reduced from 5,618 mg/l to 112 mg/l within 15 minutes, when $MgCl_2 \cdot 6H_2O$ and $Na_2HPO_4 \cdot 12H_2O$ were applied with a Mg^{2+}:NH_4^+:PO_4^{3-} mole ratio of 1:1:1. The pH range of the minimum MAP solubility was discovered to be between 8.5 and 9.0. Attention should be given to the high salinity formed in the treated leachate by using $MgCl_2 \cdot 6H_2O$ and $Na_2HPO_4 \cdot 12H_2O$, which may affect microbial activity in the following biological treatment processes. The other two combinations of chemicals [MgO + 85% H_3PO_4 and $Ca(H_2PO_4)_2 \cdot H_2O$ + $MgSO_4 \cdot 7H_2O$] could minimise salinity after precipitation, but they were less efficient for NH_4^+-N removal, compared with $MgCl_2 \cdot 6H_2O$ and $Na_2HPO_4 \cdot 12H_2O$. COD had no significant reduction during this precipitation. It was found that the sludge of MAP generated was easily settled within 10 minutes to reach its solids content up to 27%. The other characteristics including capillary suction time (CST) and dry density (DD) of the MAP sludge were also tested. The experimental results indicate that the settled sludge is quite solid and can be directly dumped at a landfill site even without any further dewatering treatment.

Key words— ammonium (NH_4^+-N); landfill leachate; precipitation; magnesium-ammonium-phosphate (MAP).

INTRODUCTION

One of the major environmental concerns associated with landfilling of municipal solid wastes is related to the discharge of leachate into the environment, which may cause serious pollution to groundwater aquifers as well as adjacent surface waters[1] (Shultz and Kjeldsen, 1986). Leachates generated owing to moisture release, precipitation and infiltration, are easily increased by soluble or suspended organic matters, ammonium-nitrogen and inorganic ions such as heavy metals, and may cause severe environmental hazards if they are not properly collected, treated and safely disposed.

In Hong Kong, there are 13 municipal landfills; the high strengths of ammonium (NH_4^+-N) are a common feature of the local leachates generated at these landfills. Normally, those leachates generated at the domestic waste landfills such as the WENT landfill[2] (EPD, 1996) contain 3,000 to 6,000 mg/l of NH_4^+-N; the leachates generated at the mixed sites receiving both construction waste and domestic wastes may contain less NH_4^+-N in the range of 1,000 to 2,500 mg/l.

The leachates generated in the Hong Kong landfills have also a second common feature: the low ratios of BOD_5/COD and COD/NH_4^+-N. For example, the leachate generated at the WENT landfill contains not only a high concentration of NH_4^+-N (over 5,000 mg/l), but also a high concentration of refractory organic matter with a soluble COD concentration of 6,000 to 7,000 mg/l and a BOD_5 concentration of 1,500 mg/l. The features of this leachate are caused by domestic waste and also by long-term storage.

Leachates with such high NH_4^+-N content are generally difficult of access to conventional biological treatment processes. A previous study (Li and Zhao, 1998)[3] confirmed that the performance of a conventional activated sludge process could be significantly affected by a high concentration of NH_4^+-N. The COD removal declined from 95.1% to 79.1%, and the dehydrogenase activity of activated sludge decreased from 11.04 to 4.22 μg TF/mg MLSS, respectively, when the NH_4^+-N concentration in wastewater increased from 50 to 800 mg/l. Under certain conditions, the leachates with a high concentration of NH_4^+-N can be biologically treated, but a large amount of effluent needs to be recycled to the aeration tank so as to dilute the ammonia toxicity to a low level. This type of biological process with a high ratio of effluent re-circulation causes a much higher operation cost and also occupies a much larger aeration tank than a conventional biological process does. Therefore, it might not be the best technical solution in Hong Kong.

Nowadays, the most common method for eliminating a high concentration of NH_4^+-N (>3,000 mg/l) involved in wastewater treatment technologies is the air stripping process. But a major concern about ammonia air stripping is the release of NH_3 into the atmosphere so as to cause severe air pollution if ammonia can not be properly absorbed with either H_2SO_4 or HCl. The other concern is calcium carbonate scaling of the stripping tower, when lime is used for pH adjustment. Since the leachate from an aged landfill contains a high alkalinity just like a strong pH buffering system, the pH variation before and after stripping will consume a large amount of alkali (20 g/l of caustic soda is required to increase pH) and acid (10 ml/l of chloric acid is required to absorb NH_3 stripped out). A huge amount of carbonate precipitate is usually formed in the process and may cause severe operation and maintenance problems. Moreover, a large stripping tower will be needed due to foaming when NH_4^+-N in raw leachate is stripped out.

For the above reasons, other technically effective alternatives to eliminate NH_4^+-N in leachates need to be ascertained. The precipitation of NH_4^+-N by forming magnesium ammonium phosphate (MAP) precipitate has been studied and practised for different types of wastewater, such as tannery effluent in leather industries[4] (Tünay *et al.*, 1997), digester supernatant[5, 6] (Siegrist *et al.*, 1994; Siegrist, 1996) in wastewater treatment plants, wastewater from coke plants and nitrogen works[7] (Zdybiewska and Kula, 1991) and also sludge liquor[8] (Schulze-Rettmer, 1991). These studied results indicated very efficient removals of NH_4^+-N. Cost estimates indicated that the cost of precipitation process is roughly similar to the cost of nitrification and denitrification of 1 m³ communal wastewater[8] (Schulze-Rettmer, 1991), and similar to or about 20% more expensive than that of air stripping[5] (Siegrist *et al*, 1994).

Chemical precipitation as MAP can form virtually or completely insoluble compounds that can be easily separated from the water phase. For example, its insoluble form of $MgNH_4PO_4 \cdot 6H_2O$ with a low solubility of 0.023 g/100 ml-H_2O at 0°C is well known in analytical chemistry. This product is also mineralogically known as struvite found in guano. The reaction is expressed below:

$$Mg^{2+} + PO_4^{3-} + NH_4^+ + 6H_2O \Leftrightarrow MgNH_4PO_4 \cdot 6H_2O\downarrow \qquad pK_s = 12.6 \ (25^oC) \qquad (1)$$

Since the mole weight of $MgNH_4PO_4{\cdot}6H_2O$ is 245 g/mol, 17.5 g $MgNH_4PO_4{\cdot}6H_2O$ should be theoretically formed as precipitated sludge, when 1 g of NH_4^+-N is removed. Because MAP has a similar composition of Mg, P and N to that of commercial fertilisers in soil, this product could have potential to be utilised as an additive to compost, garden soil or dried sewage sludge[6] (Siegrist, 1996). Besides, it can also possible be used as a fire retardant in fabrics[9] (Perry and Philips, 1995).

The removal of NH_4^+-N from landfill leachate by MAP precipitation was studied by Base *et al.*, 1997 in Korea, but the concerned concentration of NH_4^+-N was not very high, just in the range of 1,400 to 1,800 mg/l. This study was aimed to study the removal of as high as over 5,000 mg/l of NH_4^+-N concentration contained in leachates by precipitating it as MAP. As a typical leachate with the high concentration of NH_4^+-N was generated at the WENT landfill, it was thus taken for the study. The leachate represented the typical composition of the leachate from an aged methanogenic landfill[11] (Henry *et al*, 1987) with high conductivity and alkalinity, a low BOD_5/COD ratio of 0.2 and a low COD /NH_4^+-N of 1.5.

BASIC CHEMICAL REACTIONS

The basic chemical reaction to form MAP has been expressed in Equation (1). The theoretical amounts of chemicals needed to precipitate NH_4^+-N can be calculated from following equations:

$$MgCl_2{\cdot}6H_2O + Na_2HPO_4{\cdot}12H_2O + NH_4^+ \Rightarrow MgNH_4PO_4{\cdot}6H_2O\downarrow + 2NaCl \qquad (2)$$

$$MgO + H_3PO_4 + NH_4^+ \Rightarrow MgNH_4PO_4{\cdot}6H_2O\downarrow + H_2O \qquad (3)$$

$$Ca(H_2PO_4)_2{\cdot}H_2O + MgSO_4{\cdot}7H_2O + NH_4^+ \Rightarrow MgNH_4PO_4{\cdot}6H_2O\downarrow + CaSO_4\downarrow \qquad (4)$$

To remove all NH_4^+-N (5,618/5,325 mg/l) contained in the 500-ml leachate, the stoichiometric amounts of chemicals are either 40.73/38.61 g of $MgCl_2 \cdot 6H_2O$ and 71.83/68.08 g of $Na_2HPO_4 \cdot 12H_2O$, or 8.03/7.61 g of MgO and 23.15/21.94 g (equivalent to 13.54/12.83 ml) of 85% H_3PO_4, or 19.66/18.64 g of $Ca(H_2PO_4)_2 \cdot H_2O$ and 38.46/36.45 g of $MgSO_4 \cdot 7H_2O$, when the Mg^{2+}:NH_4^+:PO_4^{3-} mole ratio of 1:1:1 is employed. From these calculations, the other stoichiometric amounts at the different Mg^{2+}:NH_4^+:PO_4^{3-} mole ratios can be easily obtained, as listed in Table 1.

[Table 1]

METHODS

The raw leachate was collected from the WENT landfill and stored in a cool room prior to the experiment. The basic characteristics of the leachate are summarised in Table 2. Two leachate samples collected for the study have NH_4^+-N concentrations of 5,618 and 5,325 mg/l respectively.

[Table 2]

The MAP precipitating tests were carried out in 500-ml beakers as a batch mode. The experimental procedures were outlined below:

1) to weigh chemicals (see Table 1) and to measure the 500-ml raw leachate for each test;

2) to put the measured leachate samples and the weighed chemicals into beakers;
3) to start magnetic stirrers at the bottom of beaker and to monitor pH of the samples;
4) to react for 15 minutes until a stable pH indicated (equilibrium state);
5) to stop magnetic stirrers and to settle for 15 minutes;
6) to adjust pH for the minimum MAP solubility with 10 M NaOH solution;
7) to collect the supernatant above the MAP precipitate to measure the required parameters;
8) to use mixed liquor and the generated MAP sludge to examine its characteristics.

The three combinations of chemicals, $MgCl_2·6H_2O$ + $Na_2HPO_4·12H_2O$, MgO + 85% H_3PO_4, and $Ca(H_2PO_4)_2·H_2O$ + $MgSO_4·7H_2O$, were respectively tested. Totally 13 sets of the Mg^{2+}:NH_4^+:PO_4^{3-} ratios were applied (11 sets for $MgCl_2·6H_2O$ + $Na_2HPO_4·12H_2O$; the other two for MgO + 85% H_3PO_4 and $Ca(H_2PO_4)_2·H_2O$ + $MgSO_4·7H_2O$), as listed in Table 1.

When the optimal Mg^{2+}:NH_4^+:PO_4^{3-} ratio by using $MgCl_2·6H_2O$ and $Na_2HPO_4·12H_2O$ was determined, the additional batch tests with the same leachate were undertaken to investigate the effect of pH on the remaining NH_4^+-N. After reaction and sludge sedimentation, the supernatant was separated from the settled MAP sludge and 10 M NaOH solution was progressively added into the supernatant to explore the minimum solubility of MAP sludge. The pH and remaining NH_4^+-N were carefully monitored during the addition of NaOH.

In the analyses, both the raw leachate and the supernatant were measured for the parameters of pH, NH_4^+-N, conductivity, total dissolved solids (TDS), fixed dissolved solids (FDS), and total and soluble COD. The sludge characteristics were evaluated with settled sludge volume (SSV), capillary suction time (CST), solids content (SD) and dry density (DD). pH and NH_4^+-N were measured with an expandable ion analyser (EA940, Orion Research Incorporation); conductivity was measured with a YSI model 33 S-C-T meter; the other parameters such as COD, TDS, FDS, SSV, CST, SC and DD were measured by the Standard Methods[12] (APHA, 1985).

RESULTS AND DISCUSSION

MAP precipitation

Basic batch tests with $MgCl_2{\cdot}6H_2O + Na_2HPO_4{\cdot}12H_2O$

The leachate samples containing the NH_4^+-N concentration of 5,618 mg/l were tested by adding $MgCl_2{\cdot}6H_2O$ and $Na_2HPO_4{\cdot}12H_2O$ and the precipitation results are illustrated in Fig. 1 and 2. It was found that after adding $MgCl_2{\cdot}6H_2O$ and $Na_2HPO_4{\cdot}12H_2O$ into the leachate samples, white colour precipitant was rapidly formed and it quickly settled at the bottom of beakers after stirring was stopped. The analytical results of supernatant demonstrated that NH_4^+-N was efficiently decreased from an initial concentration of 5,618 mg/l to as low as 210 mg/l at the $Mg^{2+}:NH_4^+:PO_4^{3-}$ mole ratio of 1:1:1. Overdosing either Mg^{2+} or PO_4^{3-} about 10% further lowered the remaining NH_4^+-N concentration to 112 mg/l or 158 mg/l, respectively; any further over-dosages of Mg^{2+} or PO_4^{3-} did not achieve additional NH_4^+-N removal. From an engineering point of view, it may be practical to control the $Mg^{2+}:NH_4^+:PO_4^{3-}$ mole ratio at 1:1:1 when the leachate needs to precipitate NH_4^+-N as MAP, as expressed theoretically in Equation (2).

[Fig. 1]

[Fig. 2]

In the above test, pH of the leachate from an initial concentration of 8.86 was dropped to 6.7. To identify the solubility of MAP in the leachate affected by pH, 10M NaOH solution was used to raise the pH of the treated leachate from 6.7 to 10.5 and the experimental results are plotted in Fig. 3. When the 10 M NaOH solution was dropped into the treated leachate, pH of the treated leachate was gradually increased, whereas the remaining NH_4^+-N concentration was sharply decreased. While pH was increased up to 8.64, the lowest NH_4^+-N concentration of 65 mg/l was realised from the remaining NH_4^+-N concentration of 210 mg/l (in the case of no pH adjustment). It was thus concluded that the pH range to achieve the minimum MAP solubility in the leachate was around 8.64, say pH=8.5-9.0, which is consistent with the pH range of 8 to 10 found in other studies[8,13] (Schulze-Rettmer, 1991; Zdybieska and Kula, 1991). As shown in Fig. 3, the lowest NH_4^+-N concentration began to climb along with the continuous increase of pH almost to 10. It is indicated that beyond the optimum pH of 8.64, the solubility of MAP will increase and the precipitated MAP can be re-dissolved again.

[Fig. 3]

The above experimental results testified the excellent effectiveness of removing NH_4^+-N from the leachate by the MAP precipitation. In this precipitation, however, an unwanted by-product, a high amount of salt, was generated in the treated leachate, according to Equation (2). In theory, an amount of 8.375 g of NaCl will be produced when 1 g of NH_4^+-N is removed. Such a high concentration of NaCl might affect the treatability of the treated leachate in a following biological treatment process.

Comparable batch tests with three combinations of chemicals

To minimise the high amount of salt content in the treated leachate, the other two combinations of chemicals previously mentioned (MgO plus H_3PO_4 and $Ca(H_2PO_4)_2 \cdot H_2O$ plus $MgSO_4 \cdot 7H_2O$) were also employed and the precipitation experiments were carried out under similar experimental conditions with the mole ratio of 1:1:1. In these batch tests, the leachate samples with the NH_4^+-N concentration of 5,325 mg/l were employed. The experimental conditions and dosage of chemicals used are summarised in Table 3 and 4. The experimental results by comparing NH_4^+-N residual concentrations with the additions of different chemicals are shown in Fig. 4. The combination of $MgCl_2 \cdot 6H_2O$ and $Na_2HPO_4 \cdot 12H_2O$ was most efficient for removing NH_4^+-N, but generated the highest salt concentration (see conductivity and TDS/FDS in Table 4).

[Table 3]

[Table 4]

[Fig. 4]

The comparison of the conductivity, TDS and FDS in the raw leachate and its treated supernatants by using the three combinations of chemicals are shown in Fig. 5. MgO plus 85% H_3PO_4 generated the least dissolved salts, while $Ca(H_2PO_4)_2 \cdot H_2O$ plus $MgSO_4 \cdot 7H_2O$ generated the least TDS.

The very high salt content generated by using $MgCl_2 \cdot 6H_2O$ plus $Na_2HPO_4 \cdot 12H_2O$ may prohibit the activity of bacteria if a conventional biological treatment process is followed. Application of either MgO plus 85% H_3PO_4 or $Ca(H_2PO_4)_2 \cdot H_2O$ plus $MgSO_4 \cdot 7H_2O$ can significantly minimize the salinity of treated leachate. However, some research has been also carried out to enhance the activity of biomass to treat wastewater with high salt intensity (Zhan et al. 1999).

[Fig. 5]

[Fig. 6]

Total and soluble COD concentrations in the raw and the treated leachate were also measured and are shown in Fig. 6. There was no significant reduction in either total or soluble COD in the experiment by using the three combinations of chemicals, which implies that this chemical precipitation technique has a significant selectivity to particularly remove ammonium from leachate, while it is a target of requirement in practice. After chemical precipitation, a biological treatment process can be followed to remove COD as a conventional process. In other words, MAP precipitation may be used as a pre-treatment process to minimise ammonia toxicity before biological treatment.

Characteristics of MAP sludge

By using $MgCl_2 \cdot 6H_2O$ and $Na_2HPO_4 \cdot 12H_2O$ with the $Mg^{2+}:NH_4^+:PO_4^{3-}$ ratio of 1:1:1, the sludge characteristics were studied. To determine the settability of the MAP sludge, a SSV test was conducted and a SSV curve in the process of sludge settling is illustrated in Fig. 7. It was found that the MAP sludge was settled quite easily. In only 10 minutes, the settled sludge had already reached its maximum compact density. Under this condition, the supernatant was removed and the settled sludge was separated for analyses including CST, SC and DD respectively. The measured results demonstrated CST= 41.4 s, SC= 27%, and DD= 2.05 g/ml or 2050 kg/m^3. The nature of the MAP sludge indicates that it has a very high sludge density with a fast settling velocity similar to sand or grit and a short CST which allows much easier dewatering than biosludge or flocculent sludge, if dewatering is required. Actually its solids content is much higher than the local standard of SC > 30% required for sludge dumping at a local landfill site. Since this sludge is purely inorganic matter and has very high solids content after sedimentation, it is quite stable and solid enough to be simply dumped at a landfill site without either stabilisation or dewatering treatment. Schulze-Rettmer also reported in 1991 that MAP is a white crystalline powder, not hygroscopic and dries easily in air.

[Fig. 7]

From the above experimental results, the MAP precipitation might be an ideal alternative to traditional technologies for eliminating NH_4^+-N from leachate. Chemicals consumed in the MAP precipitation process will be the main cost for operation, since its sludge treatment is very simple. From an engineering point of view, some chemical wastes or by-products from chemical industries should be considered as the required chemicals, if possible, so as to lower down the operating costs of MAP precipitation. However, this study was aimed only to evaluate the feasibility of MAP precipitation for ammonium removal from leachate. The results are not sufficient to estimate the practical costs of both capital and maintenance, until a pilot scale study is carried out later.

CONCLUSIONS

As a pre-treatment process, the MAP precipitation was technically effective to remove the high NH_4^+-N strength of over 5,000 mg/l from the raw leachate collected at the local landfill in Hong Kong. When $MgCl_2·6H_2O$ and $Na_2HPO_4·12H_2O$ were employed at the Mg^{2+}:NH_4^+:PO_4^{3-} mole ratio of 1:1:1, they demonstrated a very satisfactory removal of ammonium; an initial NH_4^+-N concentration of 5,618 mg/l contained in the raw leachate was quickly reduced to 112 mg/l within 15 minutes, while the pH producing a minimum MAP solubility was controlled between 8.5 and 9.0. Attention should be given to high salinity formed in the treated leachate during precipitation using $MgCl_2·6H_2O$ and $Na_2HPO_4·12H_2O$, which may inhibit microbial activity in a following biological treatment process. Other chemical combinations such as MgO + 85% H_3PO_4 and $Ca(H_2PO_4)_2·H_2O$ + $MgSO_4·7H_2$ were conducive to lowering salinity, but they produced lower removal efficiencies of NH_4^+-N compared with using $MgCl_2·6H_2O$ and $Na_2HPO_4·12H_2O$. Moreover, MgO + 85% H_3PO_4 generated the least dissolved salts, whereas $MgCl_2·6H_2O$ + $Na_2HPO_4·12H_2O$ generated the least TDS. During the MAP precipitation, COD was not significantly reduced. Thus, a biological treatment process may need to be followed to remove COD.

The MAP sludge formed in the precipitation demonstrated an excellent settling feature. Within 10 minutes, the sludge reached its maximum compact density. The settled sludge had the nature of capillary suction time (CST) = 41.4 s, solid content (SC) = 27% and dry density (DD) = 2,050 kg/m^3, which indicates that the settled MAP sludge can meet the disposal standard at local landfill site without any further treatment.

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Table 1. Amount of chemicals added in the 500-ml leachate at various $Mg^{2+}:NH_4^+:PO_4^{3-}$ mole ratios

$Mg^{2+}:NH_4^+:PO_4^{3-}$	$MgCl_2 \cdot 6H_2O$ + $Na_2HPO_4 \cdot 12H_2O$ (g+g)	MgO + 85% H_3PO_4 (g+g)	$MgSO_4 \cdot 7H_2O$ + $Ca(H_2PO_4)_2 \cdot H_2O$ (g+g)
1:1:0	40.73+0		
1:1:0.5	40.73+35.92		
1:1:0.75	40.73+53.87		
1:1:1	40.73+71.83		
	(38.61+68.08)*	(7.61+21.94)*	(36.45+18.64)*
1:1:1.1	40.73+79.01		
1:1:1.25	40.73+85.01		
0:1:1	0+71.83		
0.5:1:1	20.37+71.83		
0.75:1:1	30.55+71.83		
1.1:1:1	44.80+71.83		
1.25:1:1	50.91+71.83		

* Raw leachate has NH_4^+-N=5,325 mg/l (The other leachates have NH_4^+-N =5,618 mg/l).

Table 2. Characteristics of the raw leachate samples from the WENT landfill

Parameters	Values	Parameters	Values
Physical:		Total PO_4^{3-}-P	16.3
Colour	7,800 (Peaty Brown)	Alkalinity (as $CaCO_3$)	13,195
Odour	Slightly ammoniac	Chloride	3,032
		VFA	420
pH	8.22	Potassium	3,920
Conductivity	37,000	Sodium	2,505
Turbidity	4,100	Calcium	13.7
Chemical:		Magnesium	93
Total COD	7,511	Iron	3.811
Soluble COD	6,508	Manganese	0.182
BOD_5	1,436	Nickel	0.365
TSS	784	Copper	0.120
VSS	654	Zinc	1.155
TDS	12,352	Chromium	0.553
FDS	9,420	Cadmium	0.103
NH_4^+-N	5,000	Lead	n.d.(<0.01)

Note: Conductivity in μmhos/cm; Colour in Hazen and Turbidity in NTU; all other values except pH in mg/l

Table 3. pH of leachate and the amount of NaOH added with different chemical additions

Precipitant	pH		Volume of 10 M NaOH to adjust pH=9 (ml)
	Raw leachate	Treated leachate	
$MgCl_2 \cdot 6H_2O$ + $Na_2HPO_4 \cdot 12H_2O$	8.37	6.88	1.75
MgO + 85% H_3PO_4	8.37	5.28	11.3
$Ca(H_2PO_4)_2 \cdot H_2O$ + $MgSO_4 \cdot 7H_2O$	8.37	5.13	10.04

Table 4. Experimental results with 3 different combinations of chemicals in MAP precipitation

	NH_4^+-N (mg/l)			Conductivity (μmhos/cm)		TDS/FDS (mg/l)		Total/soluble COD (mg/l)	
Chemicals used	Raw	Treated	pH=9	Raw	pH=9	Raw	pH=9	Raw	pH=9
$MgCl_2 \cdot 6H_2O$ $+Na_2HPO_4 \cdot 12H_2O$	5,325	530	154	31,000	57,000	14460/ 11,700	54,500/ 49,210	7,113/ 5,522	6,905/ 5,298
MgO +85% H_3PO_4	5,325	2,381	1,952	31,000	23,000	14,460/ 11,700	41,120/ 28,540	7,113/ 5,522	5,972/ 4,669
$Ca(H_2PO_4)_2 \cdot H_2O$ $+MgSO_4 \cdot 7H_2O$	5,325	2,792	1,398	31,000	27,000	14,460/ 11,700	39,290/ 29,500	7,113/ 5,522	4,772/ 4,246

Titles of Figures:

Fig. 1. Remaining NH_4^+-N with the different mole ratios of PO_4^{3-}

Fig. 2. Remaining NH_4^+-N with the different mole ratios of Mg^{2+}

Fig. 3. Remaining NH_4^+-N affected by pH at the Mg^{2+}: NH_4^+-N: PO_4^{3-} mole ratio of 1:1:1

Comb.1: $MgCl_2 \cdot 6H_2O+Na_2HPO_4 \cdot 12H_2O$;
Comb.2: MgO+85% H_3PO_4;
Comb.3: $Ca(H_2PO_4)_2 \cdot H_2O+MgSO_4 \cdot 7H_2O$

Fig. 4. Remaining NH_4^+-N in the treated leachate with addition of different chemicals

Comb.1: $MgCl_2 \cdot 6H_2O+Na_2HPO_4 \cdot 12H_2O$;
Comb.2: MgO+85% H_3PO_4;
Comb.3: $Ca(H_2PO_4)_2 \cdot H_2O+MgSO_4 \cdot 7H_2O$

Fig. 5. Conductivity, TDS and FDS in the treated leachate with addition of different chemicals

Comb.1: $MgCl_2 \cdot 6H_2O+Na_2HPO_4 \cdot 12H_2O$;
Comb.2: MgO+85% H_3PO_4;
Comb.3: $Ca(H_2PO_4)_2 \cdot H_2O+MgSO_4 \cdot 7H_2O$

Fig. 6. Total and soluble COD in the treated leachate with addition of different chemicals added.

Fig. 7. SSV curve during MAP sludge settling