Performance review of large scale up-flow anaerobic sludge blanket sewage treatment plants

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ABSTRACT

This article evaluates the performance of 10 large scale upflow anaerobic sludge blanket (UASB) sewage treatment plants (STP) located in semi-tropical areas, 7 plants were located in Brazil, 2 in India and 1 in the Middle East. In addition to the UASB, essential functional units of the STP which potentially impact on the UASB are also evaluated. Most grit removal systems were performing adequately, however in one plant very little grit was being removed. This could have serious implications for the performance of the plant as in a relatively short period of time the reactors could become full of grit. The performance results obtained in this study (COD, BOD and TSS removal efficiencies) are compared to the results of recent literature publications and also to the results of some early pilot and full scale studies. The results found here are broadly similar to those result reported in the recent literature but show a lower performance in comparison with the early pilot scale plants. Factors such as improper design, poor operating procedures, insufficient maintenance and the presence of high sulphate concentrations have been identified as the main reasons for the lower performance.

Key words | grit removal, municipal sewage, sulphate, treatment performance, UASB

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INTRODUCTION

Since the mid 1990s, approximately 10 years after the installation of the first pilot scale municipal UASB in Cali Columbia (Schellinkhout *et al.* 1985; Vieira & Souza 1986; Lettinga *et al.* 1993), there has been a rapid increase in the number of large scale municipal UASB plants installed in tropical countries, particularly in Brazil and India. For example the authors were able to identify over 45 municipal UASB plants in India designed for an average daily flow rate of 10,000 m^3 or more, whereas 15 such plants were identified in Brazil, and this is by no means an exhaustive list. The reason for the rapid uptake of the municipal UASB technology was based on the excellent performance of the Cali pilot plant and some other early municipal UASB plants such as Pedregal, Bucaramanga and Kanpur (Draaijer *et al.* 1994; van Haandel & Lettinga 1994; Schellinkhout & Osorio 1994). However, recent literature reports suggest that the performance of the more recently constructed large scale municipal UASBs is inferior to the results reported for the early pilot and full scale plants (Sato *et al.* 2006; Oliveira & von Sperling 2009).

In order to investigate what causes, if any, are responsible for this lower performance 10 large scale municipal UASB plants located in Brazil, India and the Middle East were visited. This paper evaluates and identifies the main reasons for the lower performance.

METHODS

The authors visited a total of 10 UASB based STPs (sewage treatment plants) located in semi-tropical regions. The design capacities and parameters of these plants are listed in Table 1, all STPs visited were large plants with sizes varying from a design flow rate of 30,000 to 164,000 m^3/d. The data presented in this study was obtained directly from the operational records of the companies responsible for operating the plants. All STPs visited had the same general layout as shown in Figure 1, an exception being the BR1 STP, where the post-treatment unit was currently under construction. There was

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Table 1 | Design parameters and dimensions of municipal UASB based sewage treatment plants

STP	Capacity (m^3/d)	Country	Dimension of UASB reactor (L × W × H)	No. of reactors	Volume per reactor (m^3)	HRT (h)	Up-flow velocity (m/h)	Start up date
BR1	164,000	Brazil	38.4 × 12.8 × 4.65	24	2286	8	0.57	2008
BR2	100,000	Brazil	21.0 × 28.0 × 4.6	16	2705	10	0.44	2007
BR3	90,000	Brazil	21.0 × 21.0 × 4.6	16	2029	8	0.53	1997
BR4	70,000	Brazil	21.0 × 28.0 × 4.6	8	2705	7.3	0.65	2009
BR5	48,000	Brazil		12				2004
BR6	38,000	Brazil	21.0 × 21.0 × 4.6	6	2029	7.5	0.60	1999
BR7	30,000	Brazil		4				2004
IN1	120,000	India	20.0 × 20.0 × 4.9	20	1960	7.8	0.62	2003
IN2	43,000	India	20.0 × 24.0 × 4.8	6	2304	7.7	0.62	2004
ME1	49,000	UAE	23.0 × 23.0 × 5.0	8	2645	10.3	0.48	2008

very little variation in individual reactor dimensions and there was also very little variation between the design hydraulic retention times (HRT) and up-flow velocities, these varied between 7.3 and 10.3 h and 0.44 and 0.65 m/h, respectively. The operating managers of the various STPs were interviewed in an attempt to elucidate any operational issues affecting the performance of these plants.

RESULTS AND DISCUSSION

The performance of the screens, grit chambers, UASB reactors (in detail), and gas utilization will be discussed in more detail here. The performance of the post-treatment step will not be discussed as it is not the focus of this paper. Possible post-treatment options for municipal UASBs that are pilot tested or applied at full-scale, were recently reviewed by Chernicharo (2006).

Screens

In all STPs screens were installed for the removal of coarse material as a pre-treatment step. A large variety of screens, including bar screens, continuous belt screens and step screens, were installed at the various STPs. The typical distance of a bar rack screen was 3–10 cm and that of a step screen was 0.6–2 cm. It was visually observed that most of the screens retained a significant quantity of screenings, however, the quantity present in the raw sewage and after the screens was not measured thus it is not possible to quantitatively determine the performance of the screens. There was only one example of a poorly constructed screen, resulting in

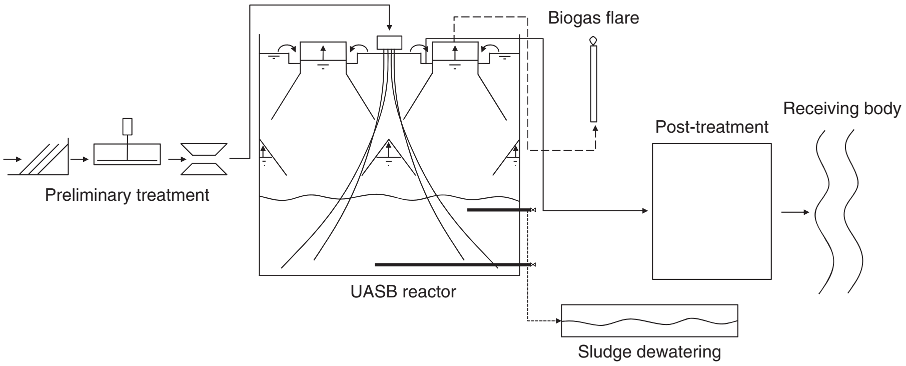

Figure 1 | General process train for a UASB based sewage treatment plant.

a large number of blockages in the downstream influent distribution system (IDS), while debris was seen floating on the surface area of the effluent section. The only other issue concerning the performance of the screens was the fact that hairs were not retained, which contributes to IDS blockages and possibly also to scum formation. In general, screens perform well when properly engineered and maintained.

Grit chamber

The importance of removing sand and grit from the sewage before it enters the UASB reactor cannot be overemphasised. Given the applied hydraulic loading rate of a UASB, the rate of grit accumulation in a UASB can be quite high. Thus, in order to prevent the accumulation of grit, which would reduce the size of the digestion zone of the UASB reactor, grit chambers are installed. The majority of plants inspected were equipped with square horizontal flow grit chambers or elongated channels for the removal of sand and grit, an exception being the BR4 plant where an aerated grit chamber was installed. The quantity of grit in the raw sewage and after the grit chambers was not measured thus it is not possible to quantitatively determine the performance of the grit chambers. However, the volume of grit removed from the sewage is generally measured and it is displayed in (Figure 2).

There was a large degree of variation between the plants but the average concentration of grit removed (77 cm^3 grit per m^3 sewage) was very similar to the value of 75 cm^3/m^3 sewage found by van Haandel & Lettinga (1994) for typical Brazilian sewage. The maximum quantity of grit removed from any plant was that of BR2 (231 cm^3/m^3), but in this case it seems likely that organics were also being removed together with grit. The minimum volume removed was for the BR4 plant (8 cm^3/m^3) where the aerated grit chamber was installed. Accepting 75 cm^3/m^3 as a typical value of grit in sewage, then it is possible to estimate the rate at which grit accumulates in the reactor. An example is BR4, with a retained grit volume of only 8 cm^3/m^3 in the grit chamber, therefore 67 cm^3/m^3 accumulate in the UASB reactor. The hydraulic retention time is 12 h so the grit accumulation rate is $67 \times 2 \times 10^{-6}$ m^3/d. Hence, the amount of grit accumulating in one year is $67 \times 365 \times 2 \times 10^{-6} = 0.05$ m^3/m^3 or stated differently, the volume of grit accumulated per year is 5 percent of the total reactor volume, or approximately double if only the digestion zone volume is considered. The BR4 plant is currently being commissioned and has only been receiving wastewater for 6 months, consequently the effect of this accumulation of grit in the reactors has not yet be observed as the layer of grit (if present) will be located below the sampling and/or sludge withdrawal points. The grit removal system in place at the BR4 plant was an aerated grit chamber. Visually, high turbulence was observed at the grit chamber of the BR4 plant thus it appears that the low volume of grit removed was due to excessive aeration. The air flow rate governs the velocity of agitation which in turn governs the size of particles of a given specific gravity that will be removed. Too small a velocity and organics will be removed together with the sand and grit, if it is too high grit will be carried out of the chamber. With proper adjustment of air flow almost 100 percent grit removal can be attained, so it should be relatively easy to correct this problem.

Performance of UASB reactors

Removal efficiencies

The performance of the plants was determined in terms of COD, BOD and TSS removal efficiency (Table 2). Performance in terms of COD removal ranged from 44 to 77 percent, 37 to 80 percent for BOD and 45 to 84 percent for TSS. The average removal efficiencies for all the plants in terms of COD, BOD and TSS were 57, 60 and 57 percent respectively.

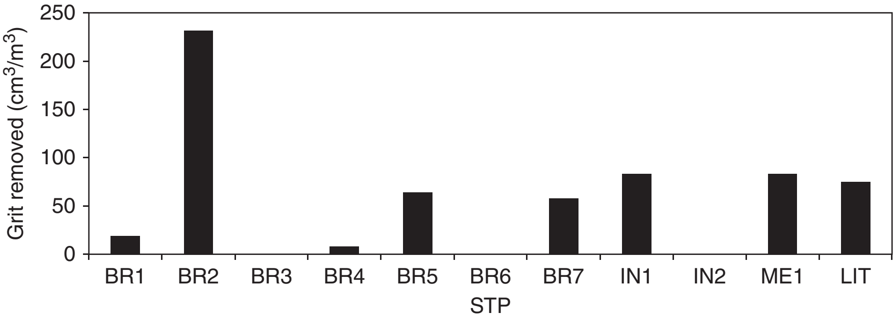

Figure 2 | Grit removal at the various STPs in terms of cm^3 of grit removed per m^3 of sewage. No data was available for plants BR3, BR6 and IN2. LIT from Lettinga & van Haandel (1994).

Table 2 | Performance of the STPs visited in terms of COD, BOD and TSS removal efficiency, influent and effluent COD, BOD and TSS concentrations are also shown

	Influent			**Effluent**			**Removal efficiency %**		
STP	**COD mg/l**	**BOD mg/l**	**TSS mg/l**	**COD mg/l**	**BOD mg/l**	**TSS mg/l**	**COD**	**BOD**	**TSS**
BR1	440	267	236	178	78	120	60	71	49
BR2	–	–	–	–	–	–	–	–	–
BR3	549	233	262	182	77	79	67	67	70
BR4	–	–	–	–	–	–	–	–	–
BR5	544	320	327	230	113	154	58	65	53
BR6	519	360	169	264	128	85	49	65	50
BR7	1293	381	294	293	76	130	77	80	56
IN1	602	202	189	338	112	103	44	45	45
IN2	459	207	228	233	131	111	49	37	51
ME1	697	268	252	337	130	40	52	51	84

Operational HRTs and up-flow velocities are compared with their corresponding COD removal efficiencies in Figure 3A and B. There was a general increase in performance as the HRT increased but no clear trend was obvious. Similarly, there appears to be a small improvement in performance as the upflow velocity decreased but overall no clear trend is discernable. It seems the impact of other factors, e.g. operator attendance, has a larger impact on performance than the operating HRT and up-flow velocity do. The COD removal efficiencies as a function of HRT obtained during this study are also compared with an empiric equation derived by von Sperling & Chenicharo (2005) from operational results obtained from 16 full scale UASB reactors. In that study the operational results were fitted and the following efficiency curve was obtained:

$$E_{COD} = 100 \times (1 - 0.68 \times t^{-0.35}) \qquad (1)$$

where E_{COD} = efficiency of the UASB reactor, t = hydraulic retention time, 0.68 and 0.35 = empirical constants.

From Figure 3 it can be seen that the performance of all the STPs investigated in the present study was less than the empiric equation predicts. However, these seemingly disappointing results can be fully explained.

- Plant maintenance issues, especially (but not restricted to) the alignment of effluent weirs, seem to have a much greater impact on performance than the HRT does. This is best illustrated by comparing the performance of the BR3 and BR6 STPs, both of these plants are located in the same city, are operated by the same company and have the same reactor design, thus the sewage characteristic and the local environmental conditions (e.g. temperature) can be considered very similar. BR3 is operating at a lower HRT of 11 h compared to 13 h for BR6. Based on Figure 3, one would have expected the BR6 plant to have the same or even better performance than the BR3 plant. However, this was not the case and the BR3 plant performs better in terms of COD, BOD and TSS removal efficiencies.

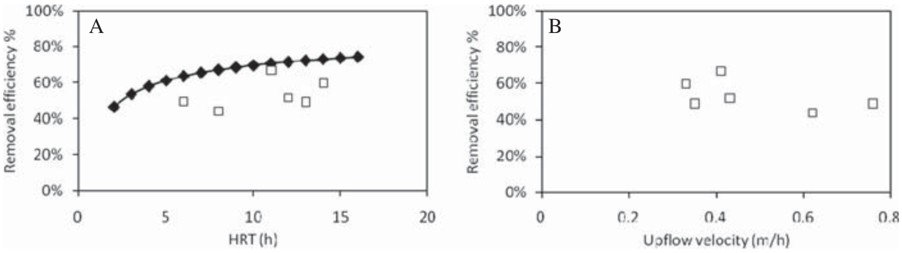

Figure 3 | Influence of HRT on COD removal efficiency, present study (□), predicted performance (■) (von Sperling & Chenicharo 2005) (A) and influence of up-flow velocity on COD removal efficiency (B).

The local operators suggest that the difference in performance was due to improperly aligned effluent weirs in the BR6 plant. Improperly aligned weirs can result in non-defined upflows (hydraulic short circuits) in the UASB reactor. Considering that all other parameters are broadly the same this suggestion is highly credible.

- The negative impact of sulphate on COD removal is often overlooked. This point will be discussed in more detail in the next section.
- Plant operations can have a large impact on performance, for example BR1 was operated for over a year without any sludge withdrawal due to problems with the dewatering facilities. Thus, the reactors were operated at the maximum sludge hold-up where the sludge production rate is equal to the TSS concentration in the effluent. Recently, the problems with the sludge dewatering facilities have been rectified and sludge withdrawal has begun again. However, there is still considerable excess sludge hold-up in the reactor, which results in a relatively high effluent TSS concentration of 120 mg/l. This high TSS concentration also contributes to the final COD demand, thus it is expected that when the operators are able to reduce the sludge blanket level both TSS and COD performance will improve.

Sulphate

Typical the sulphate concentration in municipal sewage is considered to be approximately 20–50 mg/l (Metcalf & Eddy 2003). However in this study concentration of up to 388 mg/l were observed, whereas Mahmoud (2002) reported SO_4^{2-} concentration as high as 900 mg/l in the sewage of Ramallah, Palestine. Sulphide production can cause a number of process problems (Lens *et al.* 1998) but from a performance perspective the most important problem is the competition between sulphate reducing bacteria (SRB) and methanogenic bacteria (MB) for available substrate. As a consequence of this competition, part of the biodegradable COD is not removed but merely converted by the SRB from an organic form into an inorganic form. Thus the COD removal efficiency will be significantly reduced, the quantity of methane generated will be reduced and there also will be an additional oxygen demand in the subsequent aerobic step.

The impact high SO_4^{2-} concentrations have on the performance of a municipal UASB is best illustrated with an example. As it is notoriously difficult to measure H_2S accurately at an STP site, the impact of the inorganic COD (sulphide) fraction on the COD removal efficiency can only be approximated. The authors have estimated the value of this inorganic COD fraction based on the assumption that the difference in measured SO_4^{2-} concentration in the influent and the effluent is representative of the concentration of HS^-/H_2S produced in the UASB reactors. Here, possible S^0 formation at e.g. the effluent weirs is not taken into account. The amount of COD in the form of dissolved HS^- depends on the fraction of non-dissociated H_2S (f_{H2S}), which is dependent on pH:

$$f_{H2S} = \frac{1}{10^{pH-pKa} + 1}$$

Considering a pKa of 6.96 and a reactor pH of 7.4, it can be calculated that the ionised form of H_2S (HS^-) predominates (27% H_2S and 73% HS^-). The calculated COD fraction attributable to HS^- was then subtracted from the reported effluent COD value and the new removal efficiency without the presence of HS^- in the effluent was determined. The impact of a high SO_4^{2-} influent concentration on performance, particularly in terms of COD removal efficiency, is demonstrated in Table 3. Here the BR1 STP had a typical (low) influent SO_4^{2-} concentration (41 mg/l), consequently, there was very little improvement in COD removal efficiency when corrected for H_2S. On the other hand there was a 14 and 4% improvement in performance for the ME1 and IN1 STPs respectively when the effect of H_2S was considered.

Performance comparison of recently built UASB STPs with early pilot plants

There have been a number of recent publications reporting the performance of full scale UASB plants in Brazil, India and the Middle East (Oliveira & von Sperling (2009); Sato *et al.* (2006) and Nada *et al.* (2006)). The performance results reported from these studies are compared with the results

Table 3 | COD removal efficiency corrected for sulphate for the BR1, IN1 and ME1 STPs

Influent			Effluent			Removal efficiency %	
						Original	Corrected
STP	COD	SO_4-S	COD	SO_4-S	HS-S	COD	COD
BR1	440	14	178	10	3	60	61
IN1	602	41	338	29	21	44	48
ME1	697	130	337	79	50	52	66

Table 4 | The average treatment performance of the STPs visited in this study are compared to the results acheived at the more recently installed full scale UASB plants treating municipal sewage in different parts of the world. COD refers to total COD of the raw wastewater

	Effluent			**Removal efficiency %**		
STP	**COD mg/l**	**BOD mg/l**	**TSS mg/l**	**COD**	**BOD**	**TSS**
India[a]	364	137	357	43	55	18
India (survey)	285	121	107	46	41	49
Brazil[b]	251	98	85	65	74	71
Brazil (survey)	247	97	112	62	67	54
Middle East Lit[c]	221	83	63	71	70	85
Middle East (survey)	337	130	40	52	51	84

[a] Sato *et al.* (2006).
[b] Oliveira & von Sperling (2009).
[c] Nada *et al.* (2006).

achieved at the STPs visited during this study and are shown in Table 4. The performance of the Brazilian plants reported in the literature was broadly comparable to the performance of the Brazilian UASBs observed in the present study. A similar conclusion can be drawn from the performance of the Indian plants. Table 4 also shows that the performance of the Brazilian plants is considerably better than the performance of the Indian plants. A possible explanation for this discrepancy is improved quality of design and distinctly better operator attendance in Brazil. In Brazil, for example, the sludge bed height is regularly determined, which allows the operators to devise an appropriate sludge discharge regime. Compared to India where, according to Sato *et al.* (2006), sludge bed height determinations and sludge withdrawal are almost entirely absent. The absence of a regular sludge withdrawal regime would also explain the very high effluent TSS concentrations at the Indian plants.

The average COD, BOD and TSS removal efficiencies for the early pilot scale plants, reported by van Haandel & Lettinga (1994), were 67, 78 and 63% respectively while the average COD, BOD and TSS removal efficiencies of the more recently constructed plants, determined from Table 4, were just 56, 60 and 60% respectively. Clearly the performance of the more recently constructed plants is inferior to that of the early pilot and demonstration plants. The factors discussed previously such as poor operations and maintenance and high influent SO_4^{2-} content can explain these lower performance data.

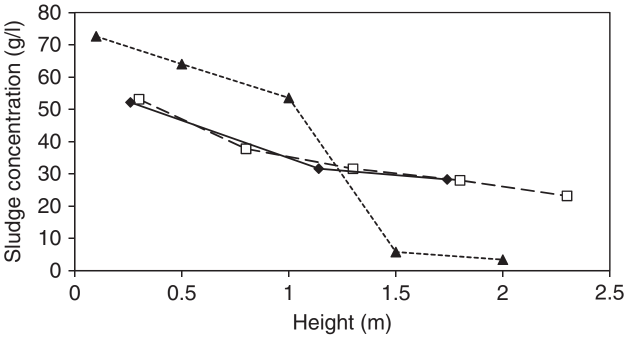

Figure 4 | Sludge profiles for the BR1 and ME1 compared to the sludge profile obtained by van Haandel & Lettinga (1994) for Pedregal.

Sludge profiles

Few studies report sludge profiles for UASB reactors more commonly, the average sludge concentration in the reactor is reported. Both sludge profiles for BR1 and ME1 are shown in Figure 4. The sludge concentrations were calculated according to the method described by van Haandel & Lettinga (1994). By using this method the total sludge mass can be expressed as:

$$M_{s1} = A\sum_{i=1}^{I} L_i C_i \tag{2}$$

where M_{S1} = sludge hold up in the reactor; L_i = height of layer i; C_i = sludge concentration at layer i (total of i layers); A = cross sectional area of the reactor.

The results reported for the Pedregal plant show a high concentration of solids at the bottom of the reactor which decreases sharply between 1 and 1.5 m above the reactor floor. In contrast the profiles found for both the BR1 and ME1 plants show a much more gradual decrease in the sludge concentration over the height of the reactor and in the case of BR1 there was still a high concentration of solids >20 g/l at a height of 2.3 m above the reactor floor. This finding has important implications; a sludge blanket with a height of 2.3 m is very close to (perhaps even extends above) the entrance of the gas liquids solids separator. Apparently, there is a much higher probability that solids will be discharged with the effluent, particularly at occasions of high turbulence when entrapped gas bubbles are released from the sludge bed. The assumed high sludge carry over at high sludge bed levels corroborates with the high effluent TSS concentration (120 mg/l) reported for BR1. There were 5 sample points installed per reactor at the Pedregal and the BR1 STP, but only 3 installed for the ME1 STP, the highest of which was 1.74 m above the reactor floor. The total height of the

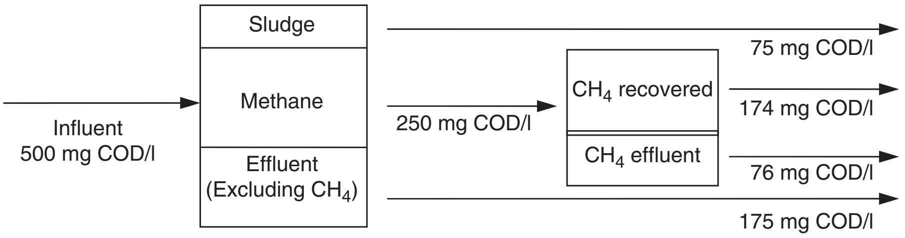

Figure 5 | Typical division of influent COD fractions in a municipal UASB.

digestion zone was 2.78 m thus there is 1.04 m of reactor height where the operator has no means of determining the sludge concentration. The low number of sample points has important implications when using these average sludge concentrations for calculating the total sludge mass of the reactor and for managing the level of the sludge blanket.

Gas utilization

Gas recovery systems

One potential advantage of the UASB system is the potential for resource recovery in the form of biogas. However, only one plant, of the 10 plants visited, had installed a gas turbine for energy recovery, in all other plants the biogas was flared. In general the biogas collection and disposal systems were in a very poor state of repair, with significant corrosion issues due to inappropriate material selection. In some cases flares did not work and gas was vented to the atmosphere. Furthermore, in all plants the installed gas meter had failed and was not operational, BR4 being an exception. Unfortunately, it is thus not possible to report actual gas production rates.

Methane dissolved in the effluent

Between 20 and 40% of the methane produced in municipal UASB reactors may remain dissolved in the effluent, directly dependent on the influent COD concentration and the applied HRT. The loss of methane has two negative effects (1) energy is lost and (2) CH_4, a potent green house gas, is released to the atmosphere. The amount of methane dissolved in the effluent can be calculated relatively easily using Henry's law. At a temperature of 20°C, 1 atm and an 80% CH_4 content, the equilibrium methane concentration is calculated as 19 mg CH_4/l, which results in a COD demand of $19 \times 4 = 76$ mg/l. Given an influent COD concentration of 500 mg/l and assuming 50% conversion to methane then the methane fraction dissolved in the effluent is equal to 30% (Figure 5). At lower temperatures or influent COD concentrations the fraction of methane discharged with the effluent will increase. No measures were put in place to prevent the release of methane to the atmosphere at any of the STPs visited.

CONCLUSIONS

The UASB system has developed into a mature technology that has been applied successfully for the treatment of municipal sewage in regions with a warm climate. However, the performance of the large STPs built in the last ten years is inferior to that of the original pilot- and full scale STPs built in the late 1980s and early 1990s. However, in all cases the inferior performance can be explained by poor design and construction, insufficient or unqualified operator attendance or to the presence of high SO_4 concentrations in the sewage. A reason for the insufficient operator attendance might, perhaps, be due to earlier publicity where the UASB was often portrayed as a low cost and low maintenance solution. While yes, the UASB is a low maintenance system, low maintenance does not equate to **no** maintenance, which seems the meaning taken all too often. An example of the performance that can be achieved by a well operated and maintained municipal UASB, without sulphate problems is the BR3 plant. Here removal efficiencies of 67, 67 and 70 percent were achieved for COD, BOD and TSS, respectively.

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