Laboratory-scale UASB digesters (with/without conditioning tank and recycle): Efficacy to treat increased hydraulic loads

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Abstract

Digester failure often results from hydraulic overload or organic shock load. Possible obviation of the former by the intervention of a conditioning tank and recycle was investigated with laboratory-scale upflow anaerobic sludge blanket (UASB) digesters. Brewery waste water (COD 4 500 mg·ℓ$^{-1}$) was the substrate of choice and the temperature used was 32°C. The results of this study demonstrated that the characteristic problems of lowered gas production rates, reduced soluble and total COD removals and lowered pH and bicarbonate alkalinity concentrations which accompany anaerobic digester hydraulic overload were not effectively negated by the provision of a conditioning tank and recycle. Under hydraulic overload conditions (scale equivalent to >3 000 m^3·d^{-1} at the full-scale plant (1 700 m^3)) the provision of a conditioning tank and recycle was required to maintain digester sludge physical integrity. Image analysis summarises visual information into practical and productive statistical information which we have shown has an application in the monitoring of UASB digesters.

Introduction

The use of upflow anaerobic sludge blanket (UASB) digesters for high hydraulic load operation has received many endorsements (Hulshoff Pol et al., 1988; Morvai et al., 1990). Under normal operating conditions this technology is, often, self-regulating. Hydraulic or organic overload conditions or low influent alkalinity can, however, effect fermentation balance shifts so that resultant acidification may lead to process failure (Sam- Soon et al., 1991). To obviate the problems of low alkalinity, influent chemical oxygen demand (COD) variations and high COD *per se* provision of liquid recycle may be considered (Sam-Soon et al., 1991).

Further problems, typical of the full-scale Prospecton Brewery (South Africa, SA) digester under investigation, include the maintenance of operating conditions to provide constant selection pressure for sludge with good settleability (Ross and Louw, 1987; Isherwood, 1991). Selection pressures are those conditions, such as high upflow velocity, which allow well-settling granule formation to occur. Thus, for example, blocked sparge pipes have effected a volatile suspended solids (VSS) reduction in excess of 85%. Concomitant granule changes from black (1 mm dia.) particles to brown (0,5 mm) structures entrained within a filamentous matrix were also apparent (Isherwood, 1991). These results provided circumstantial evidence to support the selection theory of Hulshoff Pol et al. (1988) which states that retention of sludge within the digester is dependent on the selection pressures applied. Thus, appropriate upflow conditions facilitate the selection of microorganisms which adhere to each other and form granules which settle well (Guiot et al., 1991).

The number and size of granules within UASB digesters may provide an indication of prolonged digester stability (Dubourguier et al., 1988; Ross and Louw, 1987; Sam-Soon et al., 1987) and monitoring these parameters should allow continued optimisation of the granulation process. Use of image analysis simplifies this process as it combines the inherent accuracy and precision of microscopic techniques, based on direct visual observations of the object, with the speed of the digital computer (Kiss and Pease, 1982). It also reduces the human error factor especially when microscopic measurements must be made. Using image analysis an alteration in growth can easily be quantified and measured regularly (Bolton et al., 1991), without modifying the operating conditions.

This paper reports on laboratory studies made to examine the effects of increased hydraulic loading rates on granule integrity and the obviation of characteristic problems of lowered gas production rates, reduced soluble and total COD removals and lowered pH and bicarbonate alkalinity concentrations which accompany anaerobic digester hydraulic overload, by the inclusion of a conditioning tank and partial recycle.

Materials and methods

Digester

The laboratory-scale UASB digester (operating liquid volume 5,1 ℓ) was based on the design of Sam-Soon et al. (1987). A 45° cone in the upper part of the digester acted as a phase separator and was intended to prevent granule loss. The operating temperature used was 32°C. Two identical digesters were built (Fig. 1) one of which had, in addition, a conditioning tank (1,14 ℓ), fitted with a mechanical stirrer, and recycle. The recycle was maintained at approximately 20% (from the full-scale digester operating parameters (Isherwood, 1991)) of the current hydraulic loading rate.

Sludge inoculum

Granular sludge was collected from the Prospecton Brewery (SA) UASB digester and 104,67 gVSS (calculated to give an equivalent loading to the full-scale digester) inoculated into each digester. After 24 h under batch culture conditions continuous flow operation was initiated.

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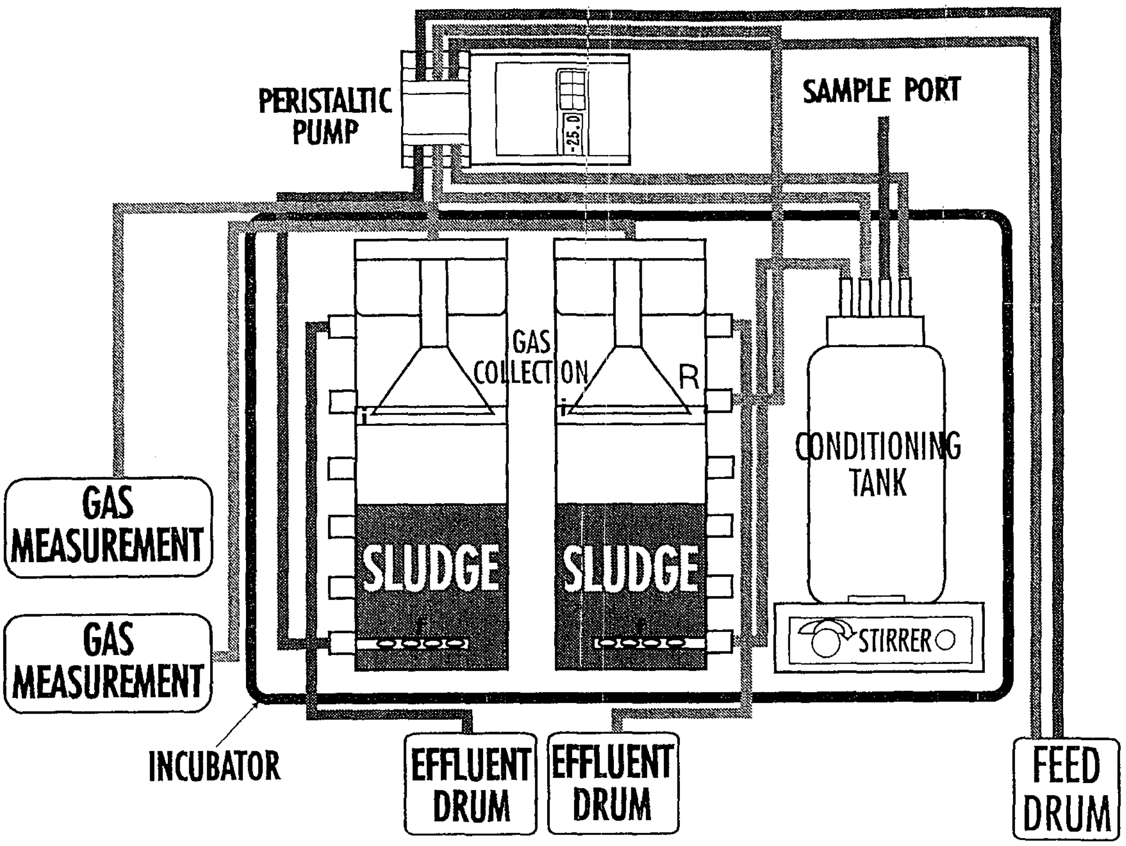

Figure 1

Diagram of the laboratory-scale UASB digesters showing the feed drum (influent reservoir), peristaltic pump (flow inducer), conditioning tank, magnetic stirrer, recycle (r), feed distribution pipes (f), sludge, inner ring (45° cone) preventing granule washout (i) and gas measurement. The conditioning tank and recycle were absent in the control digester (left)

TABLE 1

VOLUMETRIC FLOW AS A PERCENTAGE (SCALE EQUIVALENT TO 3 000 $m^3\cdot d^{-1}$) OF THE FULL-SCALE UASB DIGESTER (1 700 m^3); FEED RATE IN THE LABORATORY SCALE DIGESTERS; AND DILUTION RATES FOR THE TWO LABORATORY SCALE DIGESTERS, ONE WITH A CONDITIONING TANK (TAKEN INTO CONSIDERATION AND NOT CONSIDERED) AND ONE WITHOUT

Flow as a % of the flow in the full-scale digester	Feed rate for laboratory-scale digesters ($\ell\cdot d^{-1}$)	Soluble feed load for laboratory scale digesters ($g\cdot\ell^{-1}$)	Dilution rate (digester without a conditioning tank) d^{-1}	Dilution rate (digester with a conditioning tank taken into consideration) d^{-1}	Dilution rate (digester with a conditioning tank not taken into consideration) d^{-1}
20	2,07	10,999	2,464	2,110	1,725
35	3,31	15,951	1,540	1,570	1,283
70	6,62	30,170	0,770	0,785	0,642
100	10,08	49,956	0,506	0,516	0,422
135	13,39	56,621	0,381	0,388	0,317
170	16,84	70,762	0,303	0,309	0,252

Influent substrate

Prescreened (as per full-scale digester (Isherwood, 1991)) brewery waste water (av. COD 4 500 $mg\cdot\ell^{-1}$) was collected from the same brewery. For full details of feed composition see Isherwood (1991). Within 24 h of collection the waste water was supplemented with urea (0,025 $g\cdot\ell^{-1}$ waste water feed) and the pH adjusted to between 7,2 and 7,8 with sodium hydroxide or orthophosphoric acid prior to steaming, as the pH of the feed drops during refrigerated storage. For low volumes (5 ℓ), steaming was continued for 30 min while higher volumes (25 ℓ) were subjected to 2 h of steaming. The supplemented waste waters were then stored at 4°C until required.

Hydraulic loading

The hydraulic loading initially applied was 6,624 $\ell\cdot d^{-1}$ which equated to 70% of the loading rate of the full-scale digester of 3 000 $m^3\cdot d^{-1}$. This led to severe overload conditions so the experiment was restarted with an initial hydraulic loading of 2,07 $\ell\cdot d^{-1}$, which equated to 20% of the loading rate of the full- scale digester (Table 1). Subsequently, 5 other loadings (35, 70, 100, 135 and 170% of the full-scale digester) were examined (Table 1). Due to blockages in the influent feed pipe in the digester with a conditioning tank and recycle at 2,07 $\ell\cdot d^{-1}$, results are only quoted from an equivalent of 35% flow in the full-scale digester. Following each loading rate adjustment, a minimum of 3 digester volume changes were allowed to elapse before analyses were made.

Both digesters were under the same hydraulic load for the duration of the experiment, if the recycle flow rate and volume of the conditioning tank are taken into consideration. If the conditioning tank volume is not considered, then this digester was under a significantly higher hydraulic load (Table 1). Both digesters were subjected to the same soluble feed (Table 1) and initial sludge loading rates. Due to slight variations in the influent soluble COD and desired retention time during the experiments the soluble feed load (Table 1) insignificantly oscillated from the desired. The initial space loading rate was 0,564 $kgCOD\cdot m^{-3}\cdot d^{-1}$ for the digester without a recycle or conditioning tank and 0,308 $kgCOD\cdot m^{-3}\cdot d^{-1}$ (at an equivalent of 35% flow) for the digester with a conditioning tank and recycle. The final space loading rate was 0,049 $kgCOD\cdot m^{-3}\cdot d^{-1}$ for the digester without a recycle or conditioning tank and 0,041 $kgCOD\cdot m^{-3}\cdot d^{-1}$ for the digester with a recycle and conditioning tank. The sludge loading rate is calculated from the soluble feed load and the amount of sludge in the digester. The initial sludge load rate for the digester without a conditioning tank or recycle was 0,029 $kgCOD\cdot kgVSS^{-1}\cdot d^{-1}$ while the digester without a conditioning tank or recycle was 0,018 $kgCOD\cdot kg\ VSS^{-1}\cdot d^{-1}$ (at an equivalent of 35% flow). This did not increase for both digesters at the same rate as the digester with the recycle slowly lost a greater amount of biomass. The final sludge loading rate for the digester without a conditioning tank or recycle was 0,004 $kgCOD\cdot kgVSS^{-1}\cdot d^{-1}$ while for the digester with a conditioning tank and recycle it was 0,003 $kgCOD\cdot kg\ VSS^{-1}\cdot d^{-1}$.

Gas

Generated digester biogas was collected by displacement of citric acid (0.5% w/v) - acidified sodium chloride (20% w/v) solution. Methane analysis was direct with a Baccarach Fyrite CO2 analyser and absolute methane volumes (at S.T.P) calculated.

Volatile fatty acids and bicarbonate alkalinity

Concentrations of volatile fatty acids (VFA) and bicarbonate alkalinity were determined according to the Prospecton Brewery effluent pretreatment plant process control tests manual (Hoffmann, 1986).

pH

The pH of the effluent was determined according to the Prospecton Brewery effluent pretreatment plant process control tests manual (Hoffmann, 1986).

COD

Total and soluble COD was determined according to the Prospecton Brewery effluent pretreatment plant process control tests manual (Hoffmann, 1986).

Total suspended solids

The total suspended solids (TSS) (total non-filterable residue at 105°C) was determined according to the Prospecton Brewery effluent pretreatment plant process control tests manual (Hoffmann, 1986).

Volatile suspended solids

The determination of the volatile suspended solids (VSS) (total volatile residue at 550°C) was done according to Prospecton Brewery effluent pretreatment plant process control tests manual (Hoffmann, 1986).

Image analysis

Image analysis was carried out using a Kontron Vidas digital image processing unit, system 2.0 attached to a Sony CCD video camera, model AVC-D7CE, fitted with a 25 mm TV lens (Dudley et al., 1992).

Results and discussion

Many problems were encountered during the early stages of the study. The bactericidal/bacteriostatic effects of steaming proved insufficient to prevent waste-water biodegradation in the influent reservoir. To minimise this, low volume (4,5 ℓ) reservoirs were introduced. Gravitational return flow from the conditioning tank proved inconsistent and was replaced by flow induction (Fig. 1). Initial start up at 70% hydraulic loading proved unsuccessful and major fermentation balance changes and concomitant low pH values (2.1) resulted. Two types of sludge were apparent at the end of this period. A dark, high-density, granular sludge at the bottom of both digesters was overlaid by a grey-coloured flocculant sludge similar to that reported by Hulshoff Pol et al. (1988). Paula and

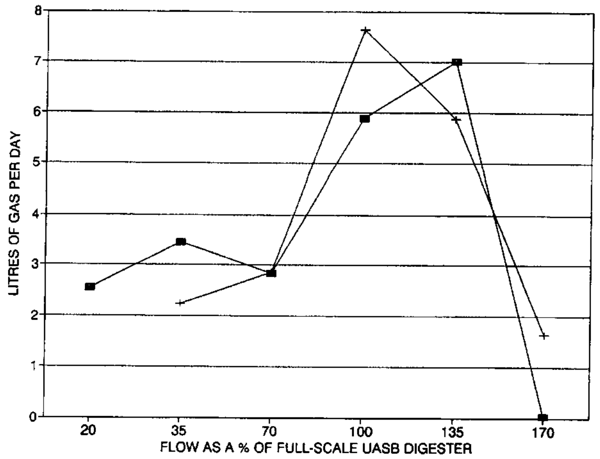

Figure 2
Gas production rates in laboratory-scale UASB reactors with (■)/without (+) a conditioning tank and recycle

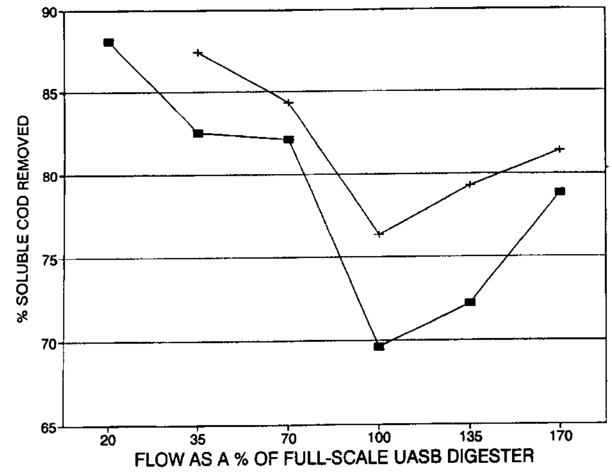

Figure 3
Percentage soluble COD removals in laboratory-scale digesters equipped with (■)/without (+) a conditioning tank and recycle

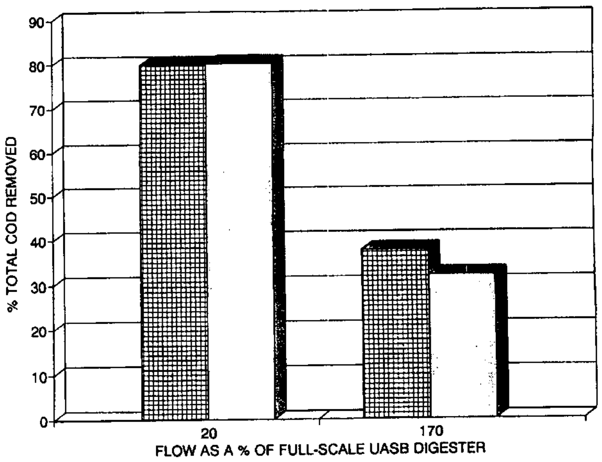

Figure 5
Percentage total COD removals in laboratory-scale UASB reactors with (▦)/without (⬚) a conditioning tank and recycle at discrete hydraulic loadings

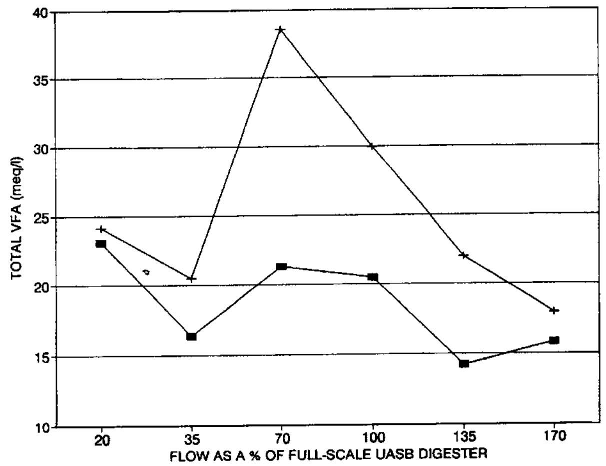

Figure 4
Changes in volatile fatty acid concentrations during residence in a conditioning tank subjected to increasing hydraulic loads. (■) and (+) denote conditioning tank influent and effluent concentrations respectively

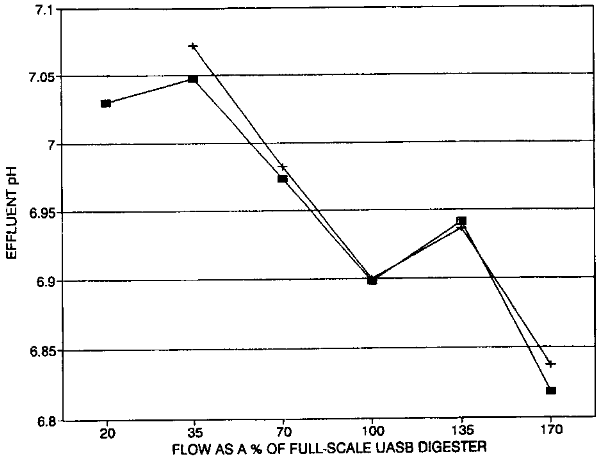

Figure 6
Changes in effluent pH in response to changes in hydraulic loadings of laboratory-scale UASB reactors equipped with(■)/without (+) a conditioning tank and recycle

Foresti (1991) also recorded sludge colour changes, from black-grey to grey-white, in response to increased influent COD in a single-stage UASB reactor. These were attributed to population changes to non- methanogenic biomass.

A priori of high-rate anaerobic waste-water treatment is a high specific activity sludge (Hulshoff Pol et al., 1983) which may be monitored indirectly by gas evolution analysis (Ross and Louw, 1987). In our study, treatment efficiency, in the presence of high hydraulic loadings, was only partially maintained by the provision of a conditioning tank and recycle (Fig. 2). With a hydraulic loading equivalent to the full-scale digesters (100%, Table 1), a conditioning tank and recycle appeared unwarranted since the rates of biogas (Fig. 2) and methane evolution were both lower in the digester with a conditioning tank and recycle than in the digester without these.

When a second analytical criterion, soluble COD removal, was then employed for all hydraulic loadings a conditioning tank and recycle were disadvantageous since reduced efficiency resulted (Fig. 3) which could be ascribed to volatile fatty acid production in the conditioning tank (Fig. 4). Consideration of total COD removal at 2 discrete loadings rates (20 and 170%), however, revealed a less clear picture (Fig. 5) since slightly improved removal was effected by the presence of a conditioning tank with recycle. COD removal efficiency under organic shock load conditions has also been reported previously (Hawkes et al., 1991). These workers showed that removal efficiency could be retained by the use of a two-stage UASB digester.

Both digesters were under a similar hydraulic load for the duration of the experiment, if the recycle flow rate and volume of the conditioning tank are taken into consideration. If the conditioning tank volume is not considered, then the digester with the conditioning tank was under a significantly higher hydraulic load (Table 1). If the loading rate is near the maximum loading rate that can be imposed without an overload situation developing (in this

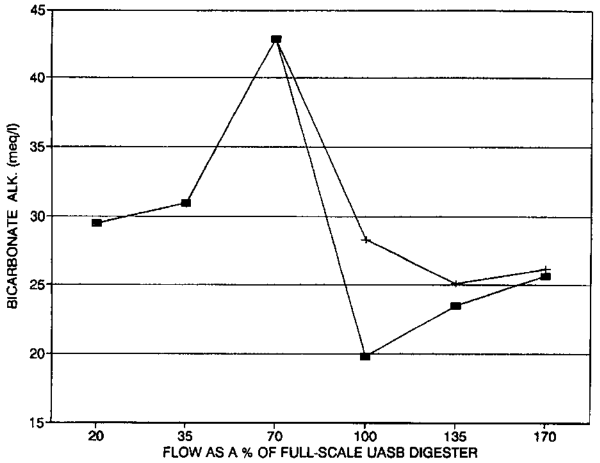

Figure 7
Changes in effluent bicarbonate alkalinity in response to changes in hydraulic loadings of laboratory-scale UASB reactors equipped with (■)/without (+) a conditioning tank and recycle

study equivalent to 135% of the full-scale digester load rate), the addition of a conditioning tank and recycle does not affect the system performance adversely, although it may interactively increase the loading rate above the maximum by recycling VFAs and COD that "leak" through the sludge bed.

The final analytical criterion used in the study was pH which may be used as an indicator of digester overload (Archer, 1988). In our study, however, significant pH changes in the effluent were not recorded (Fig. 6) due to the continued high bicarbonate alkalinity concentrations (Fig. 7) and, thus, absence of a bicarbonate alkalinity deficit (Ross and Louw, 1987). It has, however, been reported (Sam Soon et al., 1991) that alkalinity requirement per influent COD can be reduced by the imposition of a recycle.

Although none of the potential problems of lowered gas production rates, reduced soluble and total COD removals, lowered pH and bicarbonate alkalinity resulting from hydraulic overloads were effectively obviated by the provision of a conditioning tank and recycle, sludge retention and quality must also be considered. At the end of the research programme the concentration of VSS in the digester equipped with a conditioning tank and recycle was 89,04 gVSS (a reduction of 15% in VSS) compared with 65,84 gVSS in the control digester (a loss of 37% of the VSS).

Perhaps of greater significance was the possible change in granule size or number due to the different selection pressures imposed. Two-dimensional image analysis was applied to counting and sizing determinations of granules in laboratory-scale UASB digesters. An advantage of this technique for monitoring laboratory-scale digester sludge is the small amount of material required for analysis (Dudley et al., 1993). Based on VSS of granules from the laboratory-scale digesters upon completion of the study (Fig. 8) it would seem that a conditioning tank and recycle are beneficial to the operation of a UASB digester since decreased wash out of the sludge occurred. This was reinforced by the number of granules·$m\ell^{-1}$ in the digester and distinguished granule size determined by image analysis (Dudley et al., 1993). The latter technique showed the digester with a conditioning tank and recycle retained granules of a similar size and number of granules·$m\ell^{-1}$ to those in the original inoculum (Fig. 8). This system is thus conducive to granule formation and hence the establishment of optimal conditions for biomass retention (Frankin and Otten, 1992). The digester without a conditioning tank or recycle had less granules·$m\ell^{-1}$ (Fig. 8) demonstrating that this design is not conducive to the establishment of optimal conditions to facilitate biomass retention and hence stable digester operation. The selection pressures applied by the implementation of a conditioning tank and recycle have been reported to facilitate optimum digester performance (Archer, 1988; Hulshoff Pol et. al., 1988). For both digester types low hydraulic loads were accompanied by a light grey-coloured flocculent biomass, thus stressing the importance of the applied hydraulic load as a selection pressure.

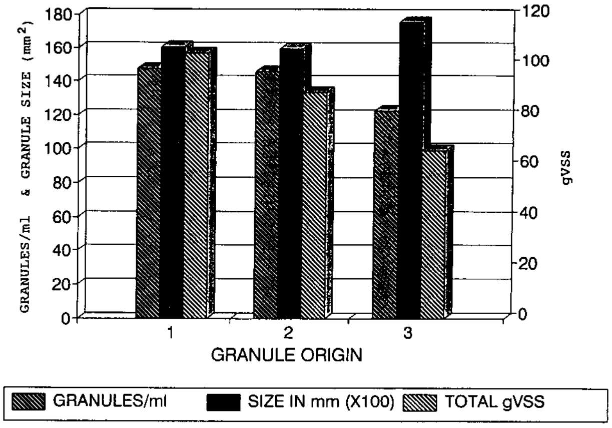

Figure 8
Image analysis and VSS determinations to monitor growth of granules in 2 different laboratory-scale UASB reactors. A well mixed granular suspension was used to calculate the number ($m\ell^{-1}$) and size (mm^2) by image analysis. 1 - Granules in the original inoculum; 2 - final granular suspension from the digester with a conditioning tank and recycle; 3 - final granular suspension from the digester without a conditioning tank or recycle

Conclusion

The results of this study clearly demonstrated that the characteristic problems of lowered gas production rates, reduced soluble and total COD removals and lowered pH and bicarbonate alkalinity concentrations which accompany anaerobic digester hydraulic overload were not effectively negated by the provision of a conditioning tank and recycle. Good sludge quality was, however, retained which, in itself, is sufficient justification for equipping a full-scale UASB digester with these facilities.

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