Wat. Sci. Tech. Vol. 20, No. 4/5, pp. 189–198, 1988.
Printed in Great Britain. All rights reserved.

0273–1223/88 $0·00 + ·50

ANAEROBIC–AEROBIC TREATMENT OF INDUSTRIAL WASTEWATER

H. Bode

Ruhrverband, Kronprinzenstrasse 37, 4300 Essen, F.R.G.

ABSTRACT

The paper evaluates the question of whether a combined anaerobic-aerobic or a solely aerobic treatment of some particular industrial wastewaters leads to better results. Therefore three different industrial wastewaters were treated in two different process lines: one line consisted of anaerobic treatment prior to aerobic treatment and in the other, only aerobic treatment was applied. The experiments were run with wastewater from:

- the pectin industry
- the sugar industry (beet sugar)
- the animal pulp industry.

The data presented in this paper were gained from experimental work which was conducted over a period of two years. Different scales of treatment plants were used. The anaerobic treatment was done in full- and semitechnical scale reactors, while the aerobic treatment took place in labscale and semitechnical scale plants.

Surprisingly in all three cases the solely aerobic treatment led to slightly better results in terms of residual pollution.

Finally the paper presents data gained from a recently built, full-scale anaerobic-aerobic process which treats pectin waste. The aerobic stage of the process was designed on the basis of the results from the experimental work which was mentioned above. The results from the former experimental work and from the full-scale operation are compared.

KEYWORDS

Anaerobic treatment, aerobic treatment, industrial wastewater, ammonia.

INTRODUCTION

Low energy requirement, a smaller excess sludge production and a smaller demand for nutrients are the primary advantages of anaerobic wastewater treatment as compared to the aerobic process. This often allows a cost-effective means of significantly reducing the polluting load (Kroiss, 1985).

If one compares the operating costs of the aerobic activated sludge process to the initial investment for an anaerobic plant, the following picture emerges for those waters suited to anaerobic treatment: the accumulated cost of oxygen transfer for aerobic oxidation of waste content that could easily be anaerobically degraded, would equal the initial investment required for an anaerobic plant in only two to six years of operation. While demonstrating in simple terms the anaerobic system's potential for cost reduction, such a comparison neglects savings generated through biogas production. This sum generally exceeds the relatively low operating costs of anaerobic plants.

The greatest disadvantage, however, of anaerobic wastewater treatment is that the effluent quality is inferior to that of the aerobic process. The anaerobic process is thus often employed by those who discharge their effluent into the sewer system, where it provides them with significant reductions in load-rated discharge fees. Final clarification is performed by the municipal treatment plants. If wastewater is discharged, however, directly into the receiving body, the anaerobic process must be complemented by the addition of aerobic treatment. In such two stage biological treatment plants the economical considerations mentioned above are clearly relevant.

Coordination of the two process steps is a major problem in the planning of two-stage anaerobic-aerobic treatment plants because:

1. The process stability of the anaerobic stage is relatively low.
2. The two stages possess fundamentally different biocenoses, their differences far exceeding those of a two-stage aerobic plant. In the latter case, the two stages differ only in substrate composition due to previous breakdown and in loading rates resulting in differences in sludge age. In contrast, anaerobic-aerobic treatment combines two completely different biological processes. The two biocenoses make use of dissimilar metabolic pathways.

It follows from the first point that the aerobic stage is oversized during those periods in which the anaerobic stage is operating at high efficiency.

The second point raises a more general question: do the two stages constructively complement or rather hinder each other in the treatment of wastewater?

DESCRIPTION OF THE EXPERIMENTAL CONDITIONS

All anaerobic as well as aerobic tests were conducted in continuous flow stirred reactors with biomass recycle. Long start-up phases were chosen, and evaluated measurements were only made after stable states had been achieved. An adequate nutrient level was maintained during aerobic treatment by the addition of phosphorous and nitrogen as needed. In keeping with the applied nature of the investigation raw wastewater from sugar, pectin and animal pulp processing was employed with the typical fluctuations of influent concentration and composition characteristic for each wastewater type.

The flow sheet in Fig. 1 depicts the parallel array used. Tests were conducted with parallel activated sludge tanks of equal size. Sludge loading in the aerobic stages was adjusted to equal values by regulating the inflow of raw wastewater.

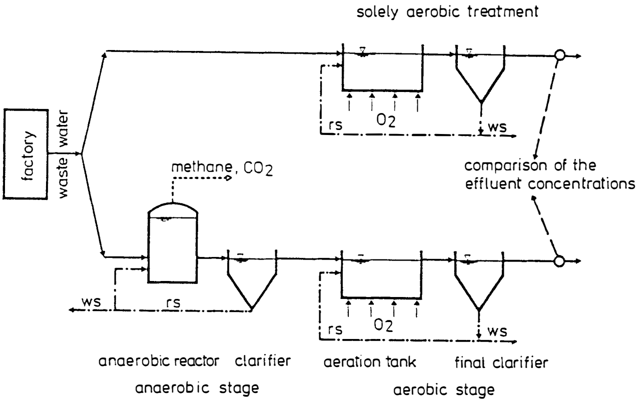

Fig. 1. Flow sheet for the parallel experimental array

The anaerobic pretreatment was conducted either in full- or semitechnical scale. Aerobic treatment took place in laboratory installations whereby the pectin wastewater was additionally treated on a semitechnical scale.

All influent samples were thoroughly mixed. Effluent samples from the laboratory installations were paper-filtered and those of the semitechnical plants were allowed to settle before analysing their composition.

In the laboratory, the volume of the activated sludge tanks was 10 l and that of the settling tanks 5 l each. The activated sludge tanks were equipped with blade mixers to improve the mixing provided by aeration.

The activated sludge tanks of the semitechnical scale plants were rectangular with dimensions of h x w x d of 1.8m x 0.5m x 1.5m and were filled to the level of 1.35m. Aeration and mixing were provided by compressed air through porous filter stones. Pretreated wastewater was taken from the effluent of the anaerobic stage in on-line operation whereas the raw wastewater was pumped from a small tank the contents of which were renewed daily.

TESTS WITH PECTIN WASTEWATER

Pectin has properties similar to those of polysaccharides and occurs naturally in the middle lamella between the cell walls of adjacent plant cells. It is used in the food industry as a thickener and as a jelly base (marmalade, etc.). The wastewater resulting from pectin production contains approximately 100 mg/l pectin and approximately 150 mg/l alcohol; the bulk of the organic waste is comprised of natural compounds such as carbohydrates, protein, organic acids and lipids. Additionally, the wastewater retains high concentrations of nitrate from the extraction process with nitric acid.

Anaerobic treatment of the pectin wastewater took place in a 3500 m^3 reactor with a detention time of 6 d, behind which a settling tank was located for sludge return. Table 1 gives the wastewater parameters before and after the anaerobic stage. The distribution of COD values in the influent and effluent are shown in Fig. 2, indicating the wide fluctuation range (1000 to 8000 mg COD/l) with which the subsequent aerobic stage has to cope.

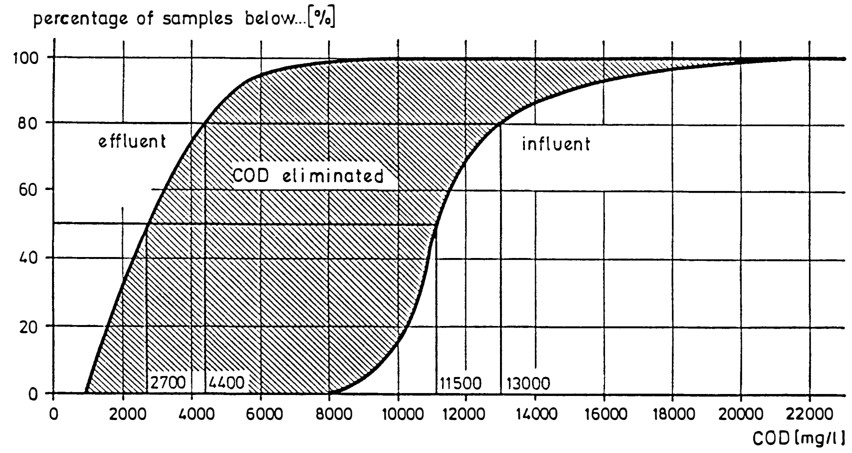

Fig. 2. Distribution frequencies for COD concentrations in pectin wastewater for influent and effluent of the anaerobic activated sludge tank (mixed samples)

Whereas the BOD_5/COD ratio in the influent was fairly constant at around 0.63, the corresponding effluent ratio varied with the effluent concentration $C_{e,COD}$ as shown in Fig. 3. At high operating efficiencies in the anaerobic stage, i.e. at values of $C_{e,COD}$ under 2000 mg/l, most of the substrate easily degraded in the aerobic system was removed, resulting in BOD_5/COD ratios lower than the value of 0.63 for the influent. In the range of $2000 < C_{e,COD} < 4000$ mg/l, BOD_5/COD ratios both lower and higher than 0.63 were observed. At concentrations of $C_{e,COD} > 4000$ mg/l, the ratio was generally greater than that of the influent. This increase in the ratio above the influent value is indicative of a composition shift in the polluting matter emerging from the anaerobic stage towards a greater portion of substances degradable under BOD_5 test conditions. Those substances difficult to degrade aerobically were either preferentially removed in the anaerobic stage or - more probably - converted to a form more easily degraded under aerobic conditions (e.g. organic acids). This is in contrast to the effect of aerobic pretreatment, which - barring adsorption processes - always results in a worse (i.e. lower) BOD_5/COD ratio.

(Note: For definition of terms, see Nomenclature at end of paper.)

TABLE 1 Arithmetic mean values and ranges for pectin wastewater before and after anaerobic treatment (January 1983 to June 1984)

		influent	effluent after settling tank
$C_{COD,mix}$	(mg/l)	11,860	3,075
BOD_5/COD ratio	(-)	0.63	0.14 - 0.89
$C_{organic\ acids\ (CH_3COOH)}$	(mg/l)	350	strong fluctuations
settleable solids	(mg/l)	0 - 300	0.69
filterable solids	(g/l)	1.21	0.26
coloration of the membrane filtrate (Hazen-coloration, 0.45 µm)	(mg/l)	7,500	2,600
$C_{org.N}$	(mg/l)	124	128
$C_{NH_4\text{-}N}$	(mg/l)	66	without ammonification: 130 with ammonification: 704
$C_{NO_2\text{-}N}$	(mg/l)	n.d.	n.d.
$C_{NO_3\text{-}N}$	(mg/l)	1,077	0 - 10
$C_{Phosphorus}$	(mg/l)	10.0	9.0

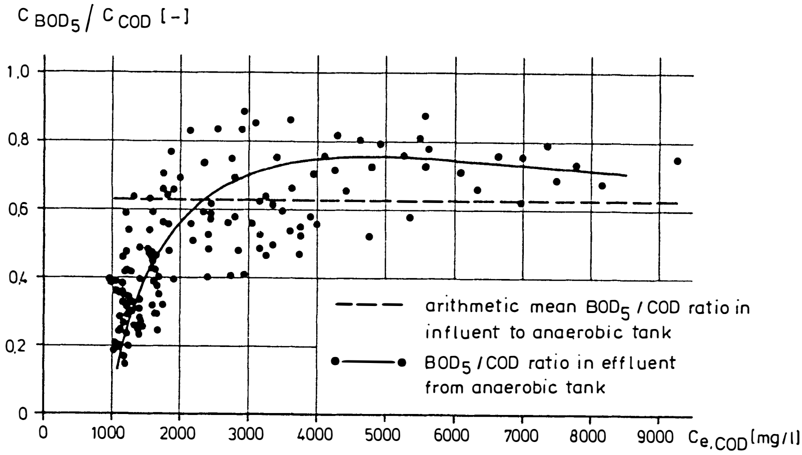

Fig. 3. BOD_5/COD ratio for the anaerobic pretreated effluent as a function of the effluent concentration $C_{e,COD}$ (mixed samples)

Nitrate contained in the wastewater was denitrified in the anaerobic tank, this process occasionally being accompanied by ammonification. The ammonification process could not, however, completely displace denitrification, so that also during periods of heavy ammonium production in which the NH_4-content of the tank effluent reached mean values of up to 700 mg N/l (see Table 1), considerable amounts of NO_3-nitrogen were still converted to gas.

Nitrification of the anaerobic effluent was a prerequisite of effective aerobic treatment of the pectin wastewater particularly during periods of ammonification. Fig. 4 clearly shows that for high loading rates, effluent COD values between 300 and 600 mg/l could only be reached at relatively low influent ammonium concentrations.

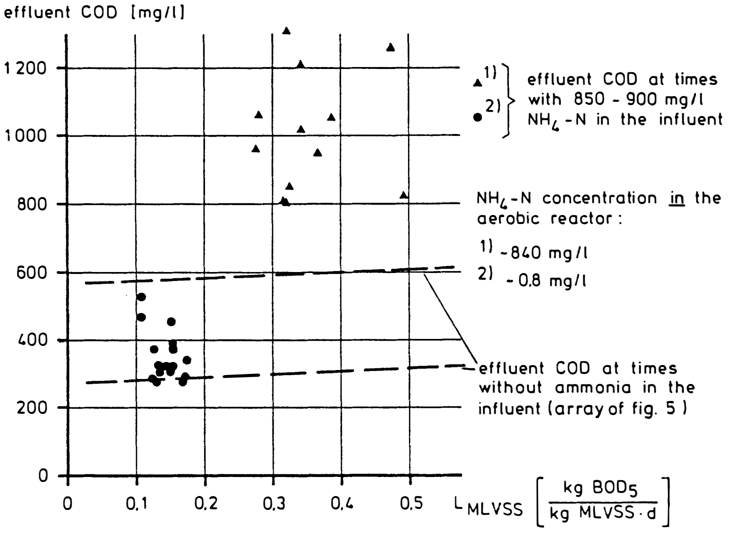

Fig. 4. Comparison of COD effluent concentrations for tests at low and high ammonium concentrations

Figs 5 and 6 depict the results obtained in aerobic treatment for those tests in which the ammonium concentration was low and/or complete nitrification took place, thus permitting non-inhibited degradation of organic compounds. A comparison of values obtained in laboratory and semitechnical scale tests for COD effluent concentrations with the activated sludge process reveals no significant differences. Fig. 5 shows the values obtained with anaerobic pretreated wastewater and Fig. 6 those for untreated raw wastewater. The results of the laboratory tests in Fig. 5 (except the square points at very low loading rates, poor BOD$_5$/COD influent ratio) generally lie in the more favorable range as they were not settled but rather filtered. Filtration resulted in a COD elimination of 30 - 100 mg/l.

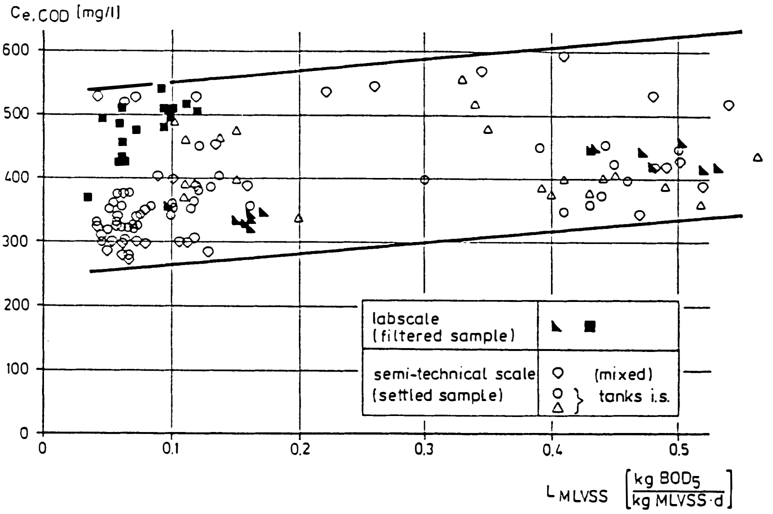

Fig. 5. COD effluent concentration plotted against sludge loading L_{MLVSS} for pretreated pectin wastewater in laboratory and semitechnical scale tests

Projection of the value distribution range for Fig. 5 on to Fig. 6 reveals that the effluent concentrations for raw pectin wastewater lie in the same range as those for pretreated influent, whereby the former tend towards lower values at high loading rates. Values for raw wastewater averaged out slightly better. The high residual content of chemically oxidizable substances after aerobic treatment of anaerobic pretreated pectin wastewater is thus primarily specific to the wastewater involved and not attributable to anaerobic pretreatment.

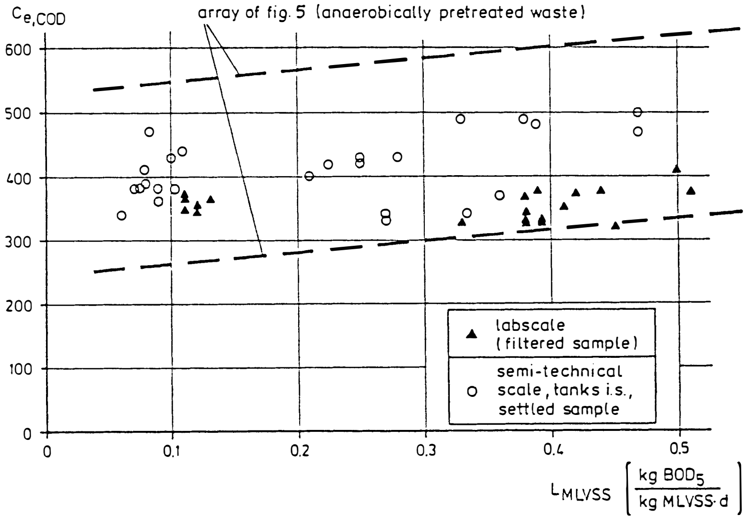

Fig. 6. COD effluent concentrations plotted against loading rate L_{MLVSS} for untreated raw pectin wastewater in laboratory- and semi-technical scale tests

Figs 5 and 6 clearly show a residual COD of at least 270 - 320 mg/l for both wastewaters which, even at low loading rates and consequently increasing sludge age, cannot be removed.

Both untreated and pretreated pectin wastewaters required the addition of phosphorus for effective aerobic treatment, but in the case of the solely aerobic treatment the required amount was 5 to 7 times higher.

TESTS WITH WASTEWATER FROM SUGAR PRODUCTION AND ANIMAL PULP INDUSTRY

The condensed results of the experiments with the wastewaters from the sugar industry and the animal pulp industry are given in Fig. 7. The detailed results of the tests have already been published (BODE, 1986 a and 1986 b).

It has often been reported that the results obtained from the solely aerobic treatment of sugar wastewater were unsatisfactory (Roennefahrt, 1968, among others). In this context, Kollatsch (1968, 1974) recognized the necessity of anaerobic pretreatment to permit further aerobic treatment. In the cases described there, the aerobic degradation did not fail due to problems relating to microbial metobolism of waste content but rather was due to difficulties with biomass accumulation. Report 1.1 (NN. 1979) suggests that biological treatment is only possible in a two-stage process (first stage anaerobic, second stage aerobic). In contrast, Reinefeld et al. (1979) found in their extensive laboratory tests that untreated and anaerobic pretreated sugar wastewater was equally effectively treated in the aerobic stage as long as the C:N:P nutrient ratio was balanced and the sludge load did not exceed L_{MLVSS} = 0.25 (kg BOD$_5$/kg MLSS d). In industrial sugar wastewater, the nitrogen content is often sufficient relative to carbon, whereas the phophorus content is usually too low due to addition of lime in wash- and rinse water which precipitates almost all phosphate out of the wastewater.

Sugar Wastewater Tests

The study employed wastewater from a sugar factory in Northern Germany which produces the sugar from beets by the usual process (ATV Report 1.1, N.N. 1979).

Fig. 7 shows that the values achieved by the experiments are quite satisfactory. Clearly, anaerobic pretreatment is not a prerequisite for the successful aerobic treatment of sugar wastewater. The results for the untreated raw wastewater are superior to the ones obtained after anaerobic pretreatment, but it could be taken into consideration that the sludge loading for the untreated wastewater could be kept more constant and, in addition, it averaged out somewhat lower.

Phosphorus was added in both treatments as phosphoric acid. Untreated wastewater was also supplemented with nitrogen in the form of urea yielding a final ratio BOD_5:N:P (removed) of 100:1.9:0.43, i.e. lower than average consumption of nitrogen and phosphorus. However, the endogenous content of nitrogen and phosphorus alone would have been insufficient for effective aerobic treatment.

Animal Pulp Wastewater Tests

The wastewater used in these experiments was generated by an animal pulp factory in which by-products from chicken and turkey slaughterhouses were processed. The material to be processed consisted mainly of blood, inner organs and feathers. Carcasses were not processed. As in the processing of other slaughterhouse by-products, the material was exposed to high temperatures, whereby the feathers were autoclaved at temperatures of up to 180°C. The wastewater contained large amounts of Kjeldahl-nitrogen and organic acids. High fat content was also encountered.

At the beginning of the experiments rapid changes of pH were observed in the aerobic treatment stage. These changes in pH in the tanks relative to be influent were mainly due to the degradation of organic acids, the conversion of organic nitrogen to ammonium (i.e. protein degradation) and nitrification. The first two processes raise the pH, the last decreases it.

Depending upon the interaction of these three biological processes, phosphoric acid or sodium bicarbonate was added after having run some tests without pH control.

Some test periods of treating the anaerobically pretreated wastewater suffered from the formation of high nitrite-concentrations (up to 900 mg/l NO_2-N). Not only was nitrification hindered, but also the oxidation of carbonaceous compounds.

The results obtained in the aerobic treatment of raw wastewater can be contrasted to those obtained with anaerobic pretreated wastewater in the following points:

- On the whole, treatment of raw wastewater yielded better effluent values for both BOD_5 and COD.
- Nitrite concentrations did not reach levels observed for pretreated wastewater.
- In the tests without pH adjustment, the pH value and consequently the ammonia concentration were lower in the case of the raw wastewater. (For both types of wastewater, however, the adjustment of the pH was a necessity.)

In the tests with pH adjustment, the BOD_5 effluent concentrations for raw wastewater at high sludge loadings fell between 90 and 250 mg/l and at low sludge loadings between 40 and 75 as compared to 250 - 400 mg/l and 80 - 150 mg/l, respectively, for pretreated wastewater.

COMPARISON OF TREATMENT PROPERTIES OF ANIMAL PULP, PECTIN AND SUGAR WASTEWATER

For the construction of Fig. 7, in which the treatment of animal pulp, pectin and sugar wastewater are compared, the distributions of individual measurements were condensed into arithmetic means. The effluent values listed represent the mean values for trouble-free operation of the aerobic stage. They are based on a broad range of primary data, whereby measurements made during periods of ammonium and/or ammoniac inhibition were excluded. The concentrations were translated into areas of common units. The BOD_5 component is shown as hatched areas. The following conclusions can be drawn from the values shown:

- Sugar wastewater yielded with both types of treatment final effluent concentrations about an order of magnitude better than those for animal pulp wastewater. The final concentrations for pectin wastewater lay in between.
- Raw wastewater yielded final concentration values better than those for anaerobic pretreated wastewater. This difference was significant for animal pulp wastewater but only slight for the other two types.
- Contrary to reports in the literature, the aerobic treatment of raw pectin wastewater (Kunst, 1982) and raw sugar wastewater (Roennefahrt, 1968, Kollatsch 1968 and 1974) presented no major difficulties.

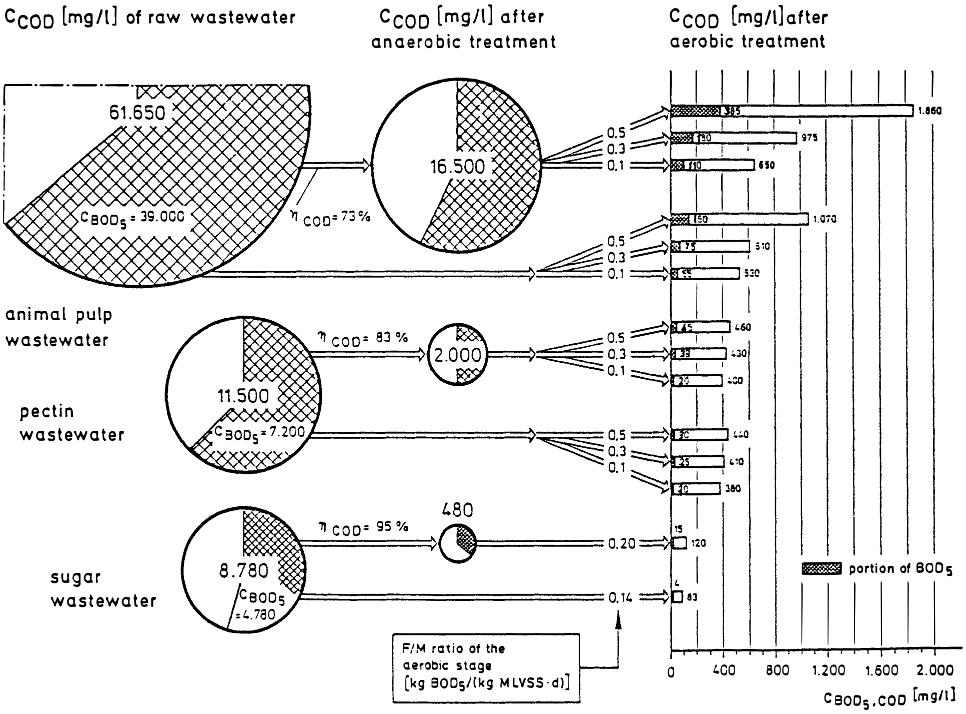

Fig. 7. Comparison of removal properties for animal pulp, pectin and sugar wastewaters under anaerobic-aerobic and solely aerobic conditions

- The effluent concentrations for the aerobic stage increased with decreasing operating efficiency of the anaerobic stage, i.e. substances poorly degraded in the anaerobic stage were no better removed by the aerobic stage. The presented data therefore do not indicate that certain classes of substances are preferentially degraded in either the aerobic or anaerobic environment.
- The final effluent concentrations were independent of the BOD_5/COD raw influent ratio. Sugar wastewater had the lowest ratio (0.54), although, based on its favorable degradation properties, theroretical considerations (Malz, 1980) would predict precisely the opposite. This also applies to the BOD_5/COD ratio after anaerobic pretreatment. If one compares the BOD_5 component of all three wastewaters as shown in Fig. 7, values decrease from top to bottom in the diagram even though accompanied by steadily more effective aerobic treatment as measured by final effluent concentrations. This is all the more surprising since the aerobic systems (again from top to bottom) had to cope with increasing COD sludge loadings as they were regulated on the basis of BOD_5 influent concentrations. The BOD_5/COD effluent ratio from the anaerobic stage can therefore not be employed as a criterium for the degradation properties of the residual wastewater content. Moreover, a low ratio indicated good degradation in the anaerobic stage and predicted continuation of same in the aerobic stage.
- The hierarchy of the three wastewaters with respect to their final effluent values after anaerobic-aerobic treatment was primarily determined by the wastewaters themselves - as confirmed by the parallel hierarchy for raw wastewater treatment - and thereby does not represent an effect induced by anaerobic pretreatment.

DESIGN AND PERFORMANCE OF A FULL SCALE TREATMENT PLANT FOR PECTIN WASTE

To cope with the problems due to the ammonification mentioned above, tests for high rate denitrification were conducted in addition to the described aerobic experiments (Bode et al., 1987). On the basis of the experimental data the existing anaerobic treatment process (Seyfried et al., 1984) was completed by erecting a predenitrification and an aerobic aftertreatment (Fig. 8).

Biomass is recycled into the denitrification reactor from a separator, where the sludge can be withdrawn from the bottom as well as from the top, since a significant portion of sludge tends to float due to the degassing of nitrogen. The process is run at temperatures between 40 and 50°C and at detention times of about 6 hours. The NO_3-N concentration decreases down to values between 5 and 30 mg/l even in cases where the influent concentration is up to 2000 mg/l. The figures given in the graph (Fig. 8) represent the average values during two months. Influent concentrations differ quite often from the given values according to the kind of pectin produced.

The aerobic stage produces results which are exactly in the same range as were expected from the conducted labscale and semitechnical experiments. The results were gained from the third and fourth months of operation. Nitrification of the remaining ammonia is achieved, but there are still some problems to be solved since denitrification has not occurred so far in the first unaerated tank as was planned.

The performance of the anaerobic stage became much better and more stable after denitrification could take place in a controlled way in the added high-rate denitrification stage instead of in the anaerobic reactor itself. Whereas now the average value of the effluent COD lies at about 1500 mg/l, the 50 percent value was before, in times without that additional process (Fig. 2), 2700 mg/l.

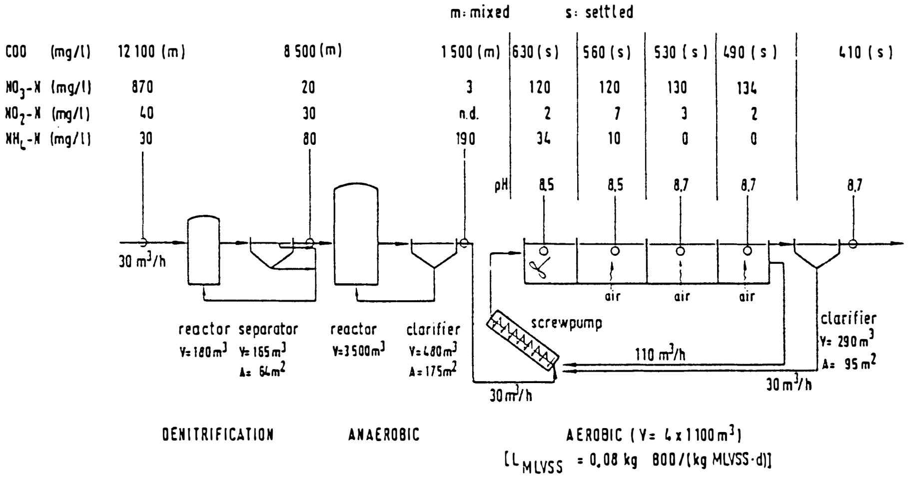

Fig. 8. Full scale process configuration and operational results of a plant treating pectin wastewater

SUMMARY AND CONCLUSIONS

Aerobic treatment alone yielded slightly better final effluent concentrations for sugar and pectin wastewater, the trend becoming more clearly visible for animal pulp wastewater. The differences are, however, so minor for the former two wastewater types that they can be neglected when it comes to deciding between treatment systems. This gives the chance to decide on the basis of solely economical aspects and therefore means in most cases an advantage for the combined treatment, especially when dealing with large flows. It is a well known fact that the anaerobic treatment is operated with an extreme energy economy and that less sludge is produced in the combined system compared to a solely aerobic treatment (Kroiss, 1985).

In the case of animal pulp wastewater anaerobic-aerobic treatment cannot be recommended. The selective elimination of carbonaceous compounds in the anaerobic process leaves behind much higher loads of NH_4-N in terms of $L_{NH4-N,MLVSS}$ than in a solely aerobic process. This causes severe operational problems.

The experiments with the pectin wastewater led to the design of a full-scale treatment process. This plant has been in operation for several months now. The results of the treatment are satisfactory. They are very similar to what was to be expected from the experimental work. The denitrification of the nitrate prior to the anaerobic treatment leads to a better and more stable anaerobic process.

NOMENCLATURE

$L_{d,x}$	load per day
$L_{MLVSS,x}$	sludge load of parameter x related to mixed liquor suspended solids
$C_{e,x}$	effluent concentration
$C_{o,x}$	influent concentration
C_x	concentration of parameter x
mix.	analyzed as mixed sample
MLVSS	mixed liquor volatile suspended solids
n. d.	not detected
η_x	efficiency relative to parameter x
tanks i.s.	tanks in series

REFERENCES

Bode, H. (1986 a). Vergleich der kombinierten anaerob-aeroben mit der ausschließlich aeroben Behandlung von Zucker- und Pektinabwasser. gwf - Wasser/Abwasser 127, 3, 123 - 129.

Bode, H. (1986 b). Reinigung von stark stickstoffhaltigem Abwasser der Tiermehlindustrie - Gegenüberstellung der aeroben und der anaeroben-aeroben Behandlung. gwf - Wasser/Abwasser 127, 5, 223 - 229.

Bode, H., Seyfried, C.F. and Kraft, A. (1987). High-Rate Denitrification of Concentrated Nitrate Wastewater. Wat. Sci. Tech. 19, (1/2), pp. 163-174

Kollatsch, D. (1968). Das "Anaerob-Aerob" Verfahren in der biologischen Abwasserreinigung. wasser, luft und betrieb, 12, 4, 236 - 242.

Kollatsch, D. (1974). Besonderheiten bei der Reinigung kohlenhydrathaltiger Abwässer. Die Stärke, 26., 10, 349 - 352.

Kroiss, H. (1985). Anaerobe Abwasserreinigung. Habilitationsschrift an der technischen Universität Wien.

Kunst, S. (1982). Untersuchungen zum anaeroben Abbau polymerer Kohlenhydrate zur Optimierung der Versäuerungsstufe bei anaeroben Abwasserreinigungsanlagen. Veröffentlichungen des Institutes für Siedlungswasserwirtschaft der Universität Hannover, Heft 54.

Malz, F. (1980). Begriffserklärung von BSB_5, CSB, TOC und Veränderungen des CSB/BSB_5-Verhältnisses bei der Abwasserreinigung. Gewässerschutz, Wasser, Abwasser, 12.

N.N. (1979). ATV-Arbeitspapier 1.1 Zuckerfabriken. Korrespondenz Abwasser 3, 26, 156 - 161.

Reinefeld, E., Hofmann-Walbeck, H.P., Pellegrini, A. and Wittek, J. (1979). Untersuchungen über die Belebtschlammentartung bei der Aufbereitung von Zuckerfabrikabwässern sowie über schwer abbaubare Inhaltsstoffe. Zuckerindustrie 104, 10, 931 - 938.

Roennefahrt, K. (1968). Die biologische Abwasserreinigungsanlage einer Zuckerfabrik und Raffinerie. wasser, luft und betrieb 12, 10, 625 - 628.

Seyfried, C.F., Bode, H. and Saake, M. (1984). Anaerobic Treatment of Pectin Wastes: Experience with a full-scale and a semitechnical plant. Wat. Sci. Tech., 16 (12), 343-356.