Rethinking sewage treatment by enhancing primary settling with low-dosage lime

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Abstract This work presents a thorough fractionation of COD in raw sewage, followed by pilot plant coagulation tests with low-dosage lime (pH 9). Through a physical separation (sieving and crossflow filtration) total COD in the raw sewage was partitioned among eight size fractions in the range of 150–0.02 μm. In addition, respirometric tests were performed to measure the biodegradability of the different size fractions. More than 60% of COD was associated with settleable and supracolloidal particles (size > 1 μm), which are characterised by slow biodegradability. Coagulation with lime increased COD removal efficiencies in the primary treatment from typical 30–35%, up to 65–70%, suggesting that lime may induce the almost complete removal of the slowly settling, slowly biodegradable supracolloidal particles in the primary treatment. On the basis of these results a non-conventional sewage treatment scheme is proposed, considering that there is plenty of space for improving primary treatment efficiency through sewage coagulation. Higher primary treatment efficiency may present several advantages, including lower aeration energy in the subsequent biological unit and higher energy recovery from sludge digestion.

Keywords Coagulation; COD fractionation; enhanced primary treatment; lime; sewage

Introduction

Conventional primary treatment, which consists of plain sedimentation driven by gravitational forces, yields COD removal efficiencies in the range of 30–35%, in spite of the fact that the fraction of pollutants in the suspended phase may be higher than 70% of the total load. This leads to several drawbacks of the conventional sewage treatment schemes, including:

- high load to the biological section, with high energy demand for aeration
- high space required for the biological plants, due to the slow biodegradation of the suspended fraction of COD
- waste of energy that could be recovered through the anaerobic digestion of primary sludge.

To improve the overall sewage treatment scheme, a deeper understanding of sewage characteristics is required, not only in terms of total pollutant concentration, but also in terms of pollutant size distribution. Pollutants are typically classified in four size ranges: settleable (> 100 μm), supracolloidal (1–100 μm) colloidal (0.001–1 μm), and soluble (<0.001 μm). The limits of these operationally defined ranges may slightly change depending on the experimental technique used to separate the size fractions. Numerous works performed on size classification of organic pollutants in urban wastewater suggest that only a limited fraction of total COD in raw sewage may be considered truly soluble (Rickert and Hunter, 1971; Munck et al., 1980; Levine et al., 1985; Vaillant et al., 1999).

Biodegradability of the organic compounds present in sewage is strictly related to their size distribution. The majority of slowly biodegradable organic matter entering the biological section of a wastewater treatment plant can be assumed to be in the range of
$10^3$ amu to 100 $\mu$m. Whereas particles smaller than $10^3$ amu can be directly taken up by cells, the utilisation of slowly biodegradable COD requires a preliminary slow step of hydrolysis (Morgenroth et al., 2002).

In order to improve the efficiency of primary treatment, several coagulating agents have been tested on sewage, including iron or aluminium salts, lime and polymers, both alone and in combination with organic coagulants (Harleman and Murcott, 2001). The use of lime for sewage coagulation in place of the more familiar aluminium or iron salts is suggested by two main advantages: low cost and easy availability of the chemical and easy control of the coagulant dosage through a simple pH-stat system. To prevent excessive sludge production due to the precipitation of calcium carbonate, a low dosage lime treatment ($\text{pH} < 10$) has been suggested (Marani et al., 1997).

This work was performed on a real sewage, withdrawn from the Roma-Nord sewage treatment plant (STP). With the aim of improving the conventional sewage treatment scheme, this work was addressed to three specific goals:

- to characterise the sewage in terms of COD partitioning among several size fractions
- to compare the biodegradability of the different size fractions
- to improve primary treatment with the addition of lime at low dosage ($\text{pH} 9$).

Materials and methods

Wastewater characterisation

The experimental work was performed on sewage samples withdrawn from the effluent of the degritting tank of Roma-Nord STP (780,000 p.e.; 354,000 $\text{m}^3$/d). To offset the hourly variability of sewage characteristics, sampling for size distribution studies was always performed at noon. Grab samples (20 L) of degritted sewage were split into three portions: the first small aliquot (10 ml) was used for COD measurements; the second one (about 2 L) was immediately used to measure the easily settleable fraction; the third portion (about 17 L) underwent sequential sieving and filtration. Micro and ultrafiltration tests were performed in a crossflow filtration mode to minimise cake formation on the filter. The whole sequence included three sieves and four filters of the following decreasing pore size: $150–100–50–25–1–0.2\, \mu\text{m}$, and 100 kD (about 0.02 $\mu$m).

In order to measure the amount of readily biodegradable COD (RBCOD) and slowly biodegradable COD (SBCOD) in raw and filtrate sewage, aerobic batch tests were performed under continuous stirring and at controlled temperature (25 $\degree\text{C}$). For each test 1 L of biomass was withdrawn from Roma-Nord plant and aerated for 24 h in order to remove residual COD. Before starting the test, air bubbling was shut off and the biomass was allowed to settle for 1 h. After removing 500 mL of supernatant, the concentrated biomass was kept aerated for 30 min, wherein endogenous oxygen uptake rate (OUR) was repeatedly measured. Then 500 mL of raw or filtered sewage was added at once, and OUR measurements, were continued at regular intervals until the substrate was completely removed. To perform OUR measurements air bubbling was stopped and the rate of decrease of dissolved oxygen with time was monitored. To take into account oxygen transfer through the air–medium interface during OUR measurements, the transfer coefficient of the apparatus was measured in blank tests after inactivation of the biomass with $\text{HgCl}_2$ (80 mg/L). In order to characterise the sludge under well defined conditions, batch tests with acetate as the only carbon source were initially performed.

Pilot tests on sewage coagulation with lime

The coagulation–flocculation tests were performed with two pilot plants. The first one was a continuous flow plant which included two separate reactors for coagulation and flocculation, having a total volume of 170 and 520 L, respectively. Mixing intensity was
in the shear rate ranges of 314–795/s and 13–46/s, for coagulation and flocculation, respectively. Settling was simulated through laboratory tests using an Imhoff cone. Residence times of 10 min in the coagulation tank and of 40 min in the flocculation tank were used. The unusually high residence time in the coagulation tank was prompted by the low dissolution rate of the lime slurry (Ødegaard, 1989). Lime was added (as a 2% slurry) to the coagulation tank, using a pH-stat system set at pH 9. After steady-state conditions were established in the pilot plant (in terms of pH), couples of samples of the influent and effluent wastewater were withdrawn, as grab samples, from the feed of the coagulation tank and from the outlet of the flocculation tank, respectively. pH, COD and SS were measured in the influent samples, as well as in the supernatant liquor of the Imhoff test (1 h settling) performed on influent and effluent samples. Volume and concentration of the settled solids were also measured in the Imhoff cone.

The second pilot plant was a cylindrical reactor (1.6 m of internal diameter, with a conical bottom for sludge settling), which was operated in a batch mode. The reactor was equipped with an anchor impeller. A coagulation–flocculation test included the following sequential steps:

- Filling the tank with degritted sewage: during this phase mixing was on and pH was maintained at 9 with the addition of 2% lime slurry
- Flocculation: stirring was kept on for 40 additional minutes
- Settling: also in this case settling was simulated through Imhoff settling tests on samples withdrawn from the reactor immediately after stopping the stirrer, in order to do an unbiased comparison with the results obtained in the continuous flow pilot plant.

**Analytical methods**
COD was measured using the Spectroquant COD cell test supplied by Merck (digestion with commercially available reagents followed by colorimetric measurement of excess dichromate). To offset the relatively low precision of this method in sewage samples containing suspended solids (coefficient of variation around 8%), in this work all the COD measurements were performed in three replicates. Oxygen concentration measurements for OUR determination were performed using WTW oxygen probe. Quantitative E. coli data (MPN) on raw and settled sewage were gathered using the QuantiTray-Colilert system, a commercially available enzyme substrate test, which conforms to standard methods (APHA, 1995).

**Results and discussion**

**COD fractionation and biodegradability**

*Figure 1* shows a typical cumulative size distribution curve of COD in the degritted sewage, obtained with the sequential procedure of screening, microfiltration, and ultrafiltration. The area above the dashed line shows the percentage of COD which is removed in the standard settling test. From *Figure 1* a histogram representing the distribution of COD among the different size fractions may be easily derived (*Figure 2*). *Figure 2* shows that a very high fraction of COD is associated with particles larger than 150 μm. Even though also particles in the size range 50–100 μm seem to be included in the easily settleable fraction of COD, this fraction is mostly associated to particles larger than 100 μm, in accordance with the conventional definition of the easily settleable COD. Among the supracolloidal fractions, particles in the size range 25–50 μm seem to be predominant. The colloidal and soluble fractions (≤1 μm) sum up to about 31% of total COD, with the colloidal fraction predominating over the soluble one, which is only about 11% of
total COD. This is in agreement with the results of Vaillant et al. (1999), who used similar ultrafiltration techniques to separate soluble from colloidal COD.

To compare the results of this work with literature data, the eight COD fractions determined through the fractionation procedure were grouped in the four conventional size intervals: settleable, supracolloidal, colloidal and soluble. In addition, because of the uncertainty in the definition of the borderline between colloidal and soluble matter, the two size intervals were grouped together. Table 1 compares the percentage of COD associated to each size interval, whose operational definition is reported in parentheses. Data intervals reported for this work summarise the results of a half year long survey. Table 1 shows that, in agreement with literature data, in our samples COD is also predominantly associated with suspended solids, which are only partially removed in the settling process. The supracolloidal fraction of COD determined in this work yields a contribution comparable with the settleable one.

With regard to biodegradability studies, Figure 3 shows the typical OUR profile obtained from the respirometric tests on sewage. The profile can be easily divided into a high-OUR phase (phase I, corresponding to readily biodegradable COD depletion) and a low OUR phase (phase II, related to the consumption of slowly biodegradable COD). Using the yield value obtained with acetate tests (0.78 g of COD of biomass produced per gram of COD consumed), COD relevant to phase I and phase II may be easily calculated. The results obtained with raw and filtered sewage show that only about 36% of COD is readily biodegradable, and that size fractions below 0.2 μm do not contain slowly

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**Figure 1** Size classification of COD through sequential sieving and filtration

**Figure 2** Distribution of COD among size fractions
biodegradable COD. These results suggest that eliminating the slowly degradable particles prior to aerobic biological treatment promotes more effective utilisation of the biological treatment capacity.

Sewage coagulation with lime

COD and pathogens removal. To investigate the potential removal of finely dispersed COD in primary treatment, sewage coagulation tests with lime were carried out in the continuous flow pilot plant. On the basis of previous process optimisation studies (Marani et al., 2002), lime was added up to pH 9 to avoid excessive sludge formation due to precipitation of calcium carbonate.

Figure 4 compares treatment efficiencies, in terms of percentage of COD removed, obtained in Imhoff settling tests on the degritted sewage and on the effluent from the continuous flow pilot plant. Plain settling may remove influent COD with an average efficiency of about 30%, in agreement with average efficiencies typically reported for the conventional primary treatment. In contrast, the lime-enhanced primary treatment shows an average treatment efficiency of about 65%. This additional 30–35% efficiency of COD removal suggests that the addition of lime up to pH 9 may induce the almost complete removal of the supracolloidal fraction in primary treatment.

Within the experimental conditions tested in this work, mixing conditions did not significantly affect the lime-enhanced process, which seems to be controlled by the slow lime dissolution step.

With regard to pathogens removal, Table 2 compares counts of the indicator organism *E. coli* in raw and settled sewage. The *E. coli* concentration in the raw Roma-Nord sewage is in the typical range of values reported in the literature for domestic wastewater (10⁶–10⁷/100 ml). In accordance with literature data, plain settling shows little or no

**Table 1 COD distribution in domestic wastewater**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Total COD (mg/l)</th>
<th>% of COD in size fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Settleable</td>
</tr>
<tr>
<td>Rickert and Hunter, 1971</td>
<td>418</td>
<td>29</td>
</tr>
<tr>
<td>Munck et al., 1980</td>
<td>498</td>
<td>43 (&gt;106 μm)</td>
</tr>
<tr>
<td>Orhon et al., 1997</td>
<td>410</td>
<td>27</td>
</tr>
<tr>
<td>Vaillant et al., 1999</td>
<td>430</td>
<td>29</td>
</tr>
<tr>
<td>This work</td>
<td>162–392</td>
<td>34–49</td>
</tr>
</tbody>
</table>

**Figure 3 Typical OUR profiles in batch test with raw sewage**

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effect on *E. coli* counts in the sewage (being still in the range of $10^6$–$10^7$/100 mL). In contrast, Table 2 shows that the lime-enhanced settling may decrease bacterial counts of one or two orders of magnitude. Even though not as large as the one reported for the lime treatment at pH 10.5–12, this disinfection ability may be an additional benefit in favour of the lime-enhanced primary treatment.

### Lime consumption and sludge production

Lime dosages in the range of 152–327 mg/L were used to keep the pre-set pH 9 in the coagulation tank, whereas the amount of lime required in sewage titration to increase pH up to 9 was in the range of 30–80 mg/L, with an average of 57 mg/L. The unexpectedly high lime dosages required in the pilot plant tests at pH 9 might be attributed to the slow dissolution of lime slurry and the consequent poor control of lime addition. This may induce either localised supersaturation conditions with potential precipitation of calcium carbonate, and/or incomplete dissolution of lime.

In any case, excess lime consumption is expected to induce production of excess amount of sludge in addition to the amount of sludge representing the fraction of suspended solids removed from degritted sewage. Actually, excess sludge, calculated as the difference between the amount of sludge produced and the amount of suspended solids removed from the influent sewage, was found in the continuous flow pilot plant tests, and it was in the range of 100–350 mg/L.

The hypothesis that excess lime consumption and consequent excess sludge production are due to poor control of lime dosage in the coagulation tank of the continuous flow pilot plant suggested to carry out parallel experiments on sewage coagulation with lime in a batch plant, following the procedure described in the experimental section. In this case, lime addition during the slow batch process of sewage feeding provided more
homogeneous conditions throughout the entire tank, therefore avoiding localised supersaturation conditions. Table 3 shows that, on average, the continuous flow plant consumes 47% additional lime to coagulate Roma-Nord sewage at pH 9. This supports the hypothesis that the excessive amount of lime consumed and the consequent excess sludge produced in the continuous flow tests are due to unsatisfactory control of lime addition to the sewage.

Conclusions

- COD in Roma-Nord sewage is predominantly associated with settleable and supracolloidal particles, each size range including about 40% of total COD.
- A large fraction of COD associated with supracolloidal particles is characterised by slow degradability, therefore suggesting that removal of these particles prior to biological treatment may greatly improve the overall treatment scheme.
- Pilot plant coagulation tests with lime at pH 9 showed that the lime-enhanced primary treatment may increase COD removal efficiencies from typical 30–35% up to 65–70%, by inducing the almost complete removal of the supracolloidal COD fraction.
- An additional benefit of lime-enhanced primary treatment may be a certain degree of disinfection (1–2 log reduction in *E. coli*), which is not typically obtained in conventional primary treatment.
- On the basis of these results an innovative sewage treatment scheme may be proposed, in which 60–70% of COD is removed as primary sludge. Potential advantages of this unconventional sewage treatment scheme include lower aeration energy in the subsequent biological unit and higher energy recovery from sludge digestion.

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