Chapter 1

Primary treatment: Particle separation by rotating belt sieves

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ABSTRACT

Fine mesh rotating belt sieves (RBSs) offer a compact solution for removal of particles in primary treatment of wastewater. This chapter shows examples from lab-scale, pilot-scale and full-scale testing of primary treatment and chemically enhanced primary treatment (CEPT). In a Norwegian full-scale survey, the use of a 350 µm belt showed more than 40% removal of total suspended solids (TSS) and 30% removal of chemical oxygen demand (COD) at sieve rates as high as 160 $m^3 \cdot m^{-2} \cdot h^{-1}$. Maximum sieve rate tested was 288 $m^3 \cdot m^{-2} \cdot h^{-1}$ and maximum particle load was 80 kg TSS $\cdot m^{-2} \cdot h^{-1}$. When the sludge mat on the belt increased from 10 to 55 g TSS $\cdot m^{-2}$, the removal efficiency for TSS increased from about 35 to 60%. CEPT is a simple and effective way of increasing the removal efficiency of an RBS. When adding about 0.7–1.0 g $\cdot m^{-3}$ of cationic polymer and using about 2 min of flocculation time, the removal of TSS typically increased from 40–50% without polymer to 60–75% with polymer. The particulate organic matter that was removed in the RBS had little or no effect on the denitrifying capacity of the wastewater. The high volatile solids (VS) content of the RBS sludge as compared to primary clarifier sludge, gave a higher methane potential in anaerobic digesters for the RBS sludge. The high caloric value of RBS sludge makes it attractive for incineration.

Keywords: Municipal wastewater, primary treatment, rotating belt sieves

1.1 INTRODUCTION

Traditionally primary treatment has been synonymous with settling in clarifiers. Primary settling may be used as the only treatment when discharging to the ocean, or as pretreatment in order to lower the load and sludge production of subsequent more advanced treatment processes. Depending on the raw water characteristics, removal efficiencies of primary settling typically range from 40–60% with respect to total suspended solids (TSS) and 15–30% with respect to biochemical oxygen demand (BOD_5).

In order to improve the separation efficiency of primary clarifiers, chemically enhanced primary treatment (CEPT) may also be used. This implies addition of coagulants and introduction of flocculation tanks ahead of the clarifier so that colloidal, non-settleable particles may be removed in addition to the suspended, settleable ones. If an inorganic coagulant is used (Al or Fe), phosphate removal is achieved as well, and in many cases this is the main purpose of using CEPT. Lately, however, focus has been on the enhanced removal of organic matter as pretreatment before de-ammonification processes (Water Environment Research Foundation [WERF], 2014; Ødegaard, 2016). Again depending on the raw water characteristics but also design and operation of coagulant mixing and flocculation, removal efficiencies of CEPT range from 70–90% with respect to TSS and 60–80% with respect to BOD_5 (Ødegaard, 1992, 2016).

Clarifiers require quite a lot of space and, since low foot-print of wastewater treatment plants has become a goal in many instances, fine mesh sieves have been introduced as an alternative to settling for primary treatment. Particularly rotating belt sieves (RBSs), also referred to as rotating belt filters (RBFs), have gained popularity. In this chapter we shall focus on the development and the experiences of rotating belt sieves for primary treatment. An overview of the RBS technology will be given, as well as examples of test results from different types of applications. These are mainly based on a R&D programme on primary treatment that was carried out in 2005 (Ødegaard, 2005; Rusten & Ødegaard, 2006) and on recent experiments at municipal wastewater treatment plants in Norway (Paulsrud *et al.,* 2014; Rusten *et al.,* 2017; Sahu *et al.,* 2017). A bench-scale procedure for choosing mesh size and evaluating potential treatment results is also presented (Rusten & Ødegaard, 2006).

1.1.1 The Norwegian primary treatment evaluation programme

Due to the European Union (EU) requirements for wastewater treatment, the Norwegian State Pollution Control Agency (SFT) took an initiative to evaluate and test several different technologies for primary treatment. This R&D programme was carried out with contributions from research institutions (NTNU, SINTEF and NIVA), consulting companies (Asplan Viak, Rambøll and Aquateam), the cities of Bergen and Tromsø, and the regional water and wastewater utility company IVAR (Ødegaard, 2005).

The goal was to find dependable and cost-efficient technologies that fulfilled the EU criteria for primary treatment, i.e. at least 20% removal of organic matter (measured as BOD_5) and 50% removal of total suspended solids (TSS). For treatment plants >10,000 pe (population equivalent), with 24 control samples per year, at least 21 samples must fulfil the requirements. This is a lot stricter than looking at average removal efficiencies and the R&D programme showed that an average TSS-removal of about 65% was necessary for enough samples to pass the 50% removal requirement.

Several types of primary treatment options, such as clarifiers, fine mesh sieves, large septic tanks, dissolved air flotation (DAF) and deep bed filtration were initially evaluated. Of the technologies that were considered fully developed, clarifiers and different types of fine mesh sieves were found most suitable for primary treatment. These technologies were then tested in full scale at several treatment plants, for both primary treatment and chemically enhanced primary treatment.

Historically primary treatment has been synonymous with sedimentation in clarifiers. The R&D programme revealed, however, that most of the primary clarifiers tested, were unable to achieve primary treatment according to the EU requirements. Surveying of data from five treatment plants showed that only one plant fulfilled the EU requirements for primary treatment, and this plant had an average surface area overflow rate (v_f) of only 0.36 m · h^{-1} (Misund *et al.,* 2004).

Often the particle size distribution of the wastewater was such that the required primary treatment removal efficiencies could not be achieved by sedimentation, regardless of how low the surface area overflow was. Therefore, chemically enhanced primary treatment (CEPT) would normally be required when using primary clarifiers to meet the standard for primary treatment (>50% TSS-removal and 20% BOD_5-removal). CEPT has commonly been used in Scandinavia, by dosing precipitation coagulants and/or polymers to the wastewater followed by flocculation and clarification. In some upgraded primary plants, only aerated sand and grit traps have been used for flocculation. The main goal has been to remove phosphorus, but removal efficiencies have also been high for both BOD (>70%) and TSS (>90%) (Ødegaard, 1992, 2016).

The R&D programme also revealed the great need for a better understanding of how to design and operate fine mesh sieves in order to optimize primary treatment performance. This became the main focus of the R&D programme and will be discussed below.

A number of fine mesh sieves are on the market and were tested in the R&D programme (Ødegaard, 2005). They include stationary sieves, rotating drum sieves, rotating disc sieves and rotating belt sieves. Full-scale tests were carried out at nine treatment plants with predominantly municipal wastewater. Six of these plants used rotating belt sieves (from two different manufacturers), two plants used rotating disc sieves and one plant had both a stationary sieve and a rotating drum sieve. Mesh sizes ranged from 80 to 850 µm. Of all the sieves

tested on predominantly municipal wastewater, only rotating belt sieves (RBSs) fulfilled the EU primary treatment requirements and this type of sieve will be focused on here.

RBS technology offers a very compact solution and has been used successfully for primary treatment of municipal wastewater (Rusten & Ødegaard, 2006; Sutton *et al.,* 2008). Advantages of RBSs include compact footprint, reduced civil engineering site work, and modular construction. The latter allowing for reduced design work, faster installation, and ease of plant expansion (Franchi & Santoro, 2015).

1.2 ROTATING BELT SIEVE (RBS) TECHNOLOGY

Rotating belt sieves (RBSs) are also referred to as rotating belt filters (RBFs) in some of the literature, but the term RBS will be used in this chapter. The experiences and data reported here, from commercial and prototype RBS systems, are based on RBSs manufactured by Salsnes Filter (Namsos, Norway). Commercial systems have a submerged belt area from about 0.1 m² for the smallest unit (SF500) to 2.5 m² for the largest unit (SFK600). For primary treatment of municipal wastewater, the most common mesh size is 350 µm, but mesh sizes from 30 µm to 2 mm are available. The SF systems, shown on the left-hand side in Figure 1.1, are free-standing and enclosed, while the SFK systems, shown on the right-hand side in Figure 1.1, are open for installation in concrete channels. The sieves are modular and multiple units are used to accommodate large flows.

Figure 1.1 Salsnes Filter RBS systems. SF systems (left) are free-standing and enclosed, while SFK systems (right) are open for installation in concrete channels. (Courtesy of Salsnes Filter AS.)

The operating principle for the Salsnes Filter RBS systems is described in Figure 1.2. Particles larger than the mesh openings are collected on the belt and

gradually these particles will create a filter mat and remove particles significantly smaller than the mesh openings. This will reduce the flow through the belt and the belt needs to rotate so that it can be cleaned and thereby sustain the necessary hydraulic capacity. The RBS can be operated with either a fixed belt speed and a variable water level, or a fixed water level and variable belt speed. The latter is most common, and the belt speed will then depend on the water flow and the amount of suspended solids in the water.
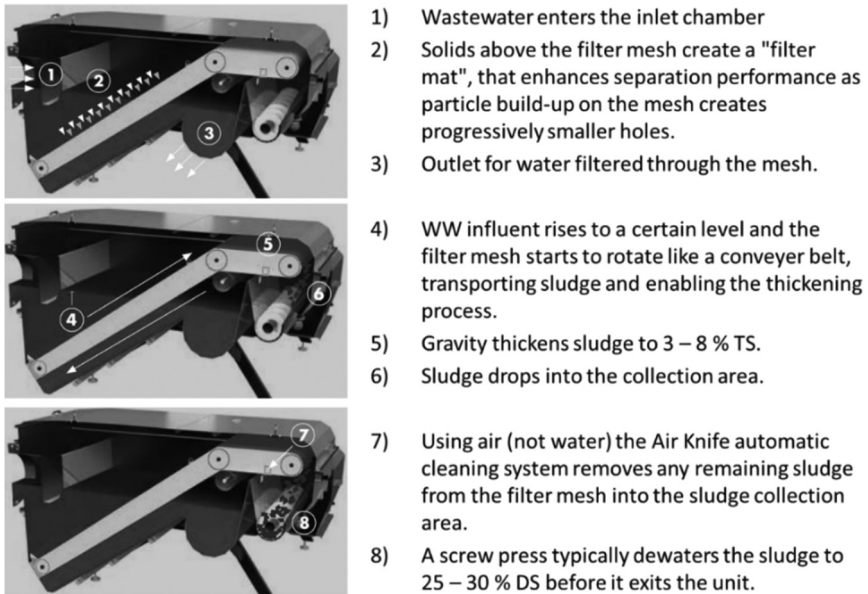

1)   Wastewater enters the inlet chamber
2)   Solids above the filter mesh create a "filter mat", that enhances separation performance as particle build-up on the mesh creates progressively smaller holes.
3)   Outlet for water filtered through the mesh.

4)   WW influent rises to a certain level and the filter mesh starts to rotate like a conveyer belt, transporting sludge and enabling the thickening process.
5)   Gravity thickens sludge to 3 – 8 % TS.
6)   Sludge drops into the collection area.

7)   Using air (not water) the Air Knife automatic cleaning system removes any remaining sludge from the filter mesh into the sludge collection area.
8)   A screw press typically dewaters the sludge to 25 – 30 % DS before it exits the unit.

Figure 1.2 Operating principle for Salsnes Filter RBS systems. (Courtesy of Salsnes Filter AS.)

A patented air knife is normally used to blow the sludge off the belt, but scrapers and intermittent water spray have also been used.

1.2.1 Characterization of wastewater through screening tests

Characterization of the wastewater is very important in order to predict the removal efficiencies and hydraulic capacities that can be expected for a given sieve. A simple screening test apparatus and procedure (Rusten, 2004) was developed and used in the R&D programme. A sketch of the equipment and photos of a 350 μm sieve cloth prior to testing and after development of a filter mat are shown in Figure 1.3.
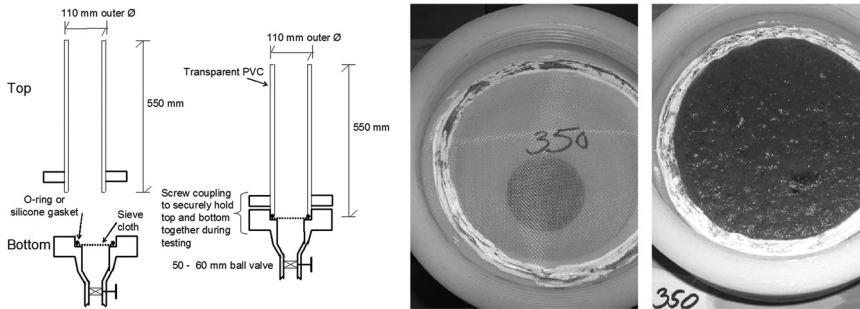
Figure 1.3 Sketch of screening test apparatus and photos of clean sieve cloth and sieve cloth with filter mat (Rusten & Ødegaard, 2006).

A batch of wastewater with sufficient volume to run tests with several different sieve cloths was placed in a large tank. To ensure a homogenous distribution of particulate material the batch would be vigorously stirred prior to taking wastewater out of the tank for analysis or to put through the test apparatus. Samples of the wastewater filtered through the sieve cloths were taken of the first litre of wastewater filtered, when the sieve cloth was clean. Then more wastewater was added until a build-up of particles on the sieve cloth had formed a filter mat. Tests with a filter mat simulated operation of a fine mesh sieve with a significant pressure drop over the sieve cloth and a low hydraulic load.

The transparent PVC tube of the apparatus had marks at 200 mm and 300 mm above the surface of the sieve cloth. After the first litre was filtered through the sieve cloth, the valve at the bottom of the apparatus was closed and more wastewater was added. Then the valve was partially opened, allowing the water level in the PVC tube to drop at a rate of 3 to 4 cm · s^{-1}. When a proper filter mat had formed on the sieve cloth, the valve was opened all the way and filtered wastewater was collected while the water level dropped from the 300 mm mark to the 200 mm mark. The time it took for the water level to drop from 300 mm to 200 mm was also recorded. For most test runs this procedure was done repeatedly after more wastewater had been added and a gradually thicker filter mat had developed, resulting in a longer period of time for the water level to drop from the 300 mm to the 200 mm mark.

1.3 RESULTS AND EXPERIENCES FROM RBS OPERATION IN THE NORWEGIAN R&D PROGRAMME ON PRIMARY TREATMENT

1.3.1 Screening test results

The screening tests showed that required primary treatment removal efficiencies could be achieved with all tested wastewaters (from 11 different treatment plants)

if the proper mesh size was used and a sufficiently thick filter mat was allowed to develop. However, use of sieves would not always be recommendable due to the low hydraulic loads necessary to achieve sufficiently high removal efficiencies with some of the wastewaters. Sieves that could not be operated with a significant filter mat would likely fail to meet primary treatment requirements, even with mesh sizes in the 50 to 100 μm range.

To be considered suitable for primary treatment with fine mesh sieves, the screening tests indicated that at least 20% of the TSS in the wastewater should consist of particles larger than 350 μm and the ratio between filtered (Whatman GF/C) chemical oxygen demand (FCOD) and total COD (TCOD) should be <0.4. Once a filter mat was formed on the sieves, there were practically no differences in the performances of sieve cloths with different mesh sizes, with regard to both % TSS removal and filtration rate. This would normally favour the use of larger mesh sizes, like the 350 μm sieve cloth. However, if the wastewater has a very small amount of larger particles there may not be enough particles present to form a filter mat, and a smaller mesh size would be recommended to initiate the formation of the necessary filter mat.

Examples of screening test results are shown in Figure 1.4. As mentioned above, the mesh sizes of the sieve cloths had very little influence on the results, within the ranges tested. With a given wastewater, the removal of TSS was mainly a function of the hydraulic flow through the sieve cloth, referred to as sieve rate, which again was a function of the development of a filter mat on the sieve. At a low sieve rate of only 20 m^3 per m^2 submerged sieve cloth area per hour ($m^3 \cdot m^{-2} \cdot h^{-1}$) more than 70% removal of TSS was achieved with wastewater from the Nordre Follo wastewater treatment plant (WWTP). When the sieve rate was increased to 100 $m^3 \cdot m^{-2} \cdot h^{-1}$ the removal efficiencies dropped to about 60%. The example from the Tiendeholmen WWTP shows a concentrated wastewater that was very well suited for fine mesh sieve treatment. Even at a sieve rate of 224 $m^3 \cdot m^{-2} \cdot h^{-1}$ the removal of TSS was 69% with a 350 μm sieve cloth.
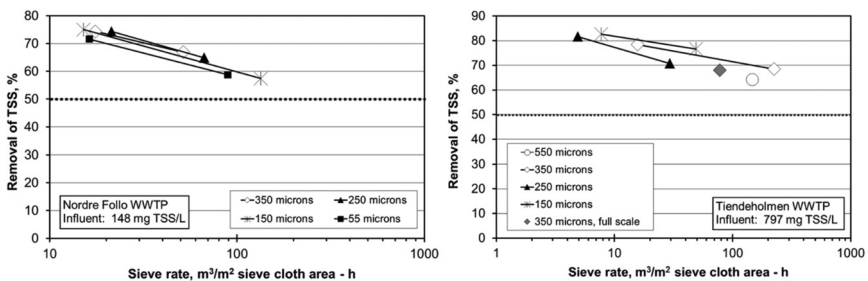

Figure 1.4 Examples of screening test results with different sieve cloths, showing removal of TSS versus sieve rate. For the Tiendeholmen WWTP the result from the full-scale plant at the time of the screening test is also shown (Rusten & Ødegaard, 2006).

1.3.2 Full-scale results

Very good agreement was found between screening tests and full-scale tests. An example of this is shown in Figure 1.4 where the full-scale result for the Tiendeholmen WWTP is shown together with the screening test results. Figure 1.5 shows a photo of the rotating belt sieves at the Tiendeholmen WWTP. Full-scale testing demonstrated the importance of gentle handling of the particles to prevent them from breaking and then going through the sieve openings. It also verified the need for a filter mat (Figure 1.6). Only rotating belt sieves had the ability to control filter mat development in our tests.

Figure 1.5 Tiendeholmen WWTP with three rotating belt sieves (Salsnes Filter SF6000) and 350 μm mesh size (Rusten & Ødegaard, 2006).

Of all the sieves tested, on predominantly municipal wastewater, only rotating belt sieves fulfilled the EU primary treatment requirements. The results from Breivika WWTP in Tromsø, summarized in Figure 1.7, show that every single sample fulfilled the EU primary treatment requirements. Average influent concentrations for 19 samples were 331 g TSS · m^{-3} and 176 g BOD$_5$ · m^{-3}, while average effluent concentrations were 34 g TSS · m^{-3} and 36 g BOD$_5$ · m^{-3}. This corresponds to average removal efficiencies of 90% for TSS and 80% for BOD$_5$. These extraordinary good results can be explained by the fact that the sieves were operated with a very thick filter mat (Figure 1.6) and at a sieve rate of only 25 m^3 · m^{-2} · h^{-1}.

At higher sieve rates the removal efficiencies will normally be lower. However, for wastewater with a very favourable particle composition very high sieve rates may be used. In cases where the focus is on high capacity and not high removal efficiencies, sieves can be operated without a filter mat, and hydraulic capacities

may be as high as $300 \, \text{m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, depending on wastewater composition and sieve cloth properties (Rusten & Ødegaard, 2006).

Figure 1.6 Thick filter mat on a rotating belt sieve with a mesh size of 350 µm at the Breivika WWTP (Rusten & Ødegaard, 2006).
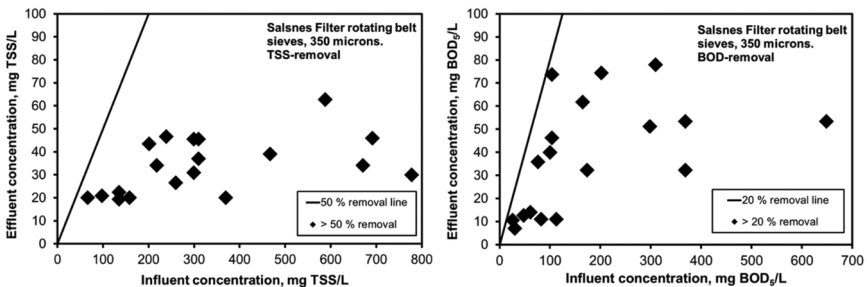

Figure 1.7 Results from primary treatment at the Breivika WWTP using three rotating belt sieves (Salsnes Filter SF4000) with 350 µm mesh size (Rusten & Ødegaard, 2006).

A broad general observation from these full-scale plants was that the highest possible removal efficiencies were achieved if the plants were operated in such a way that they treated the least amount of water over the longest possible time. This means that fine mesh sieves with pumped influent should have frequency-controlled pumps to avoid on/off operation. At plants with several sieves in parallel, all sieves should be running even at low water flows. This will enable operation with thick filter mats and high removal efficiencies (Rusten & Ødegaard, 2006). Section 1.4.1

contains a further discussion of how different operational parameters influence the particle removal in RBS systems.

1.3.3 Chemically enhanced primary treatment

Screening tests and full-scale tests at the Bangsund WWTP showed the wastewater to be unfavourable for primary treatment with conventional fine mesh sieves. Initial full-scale tests, with two rotating belt sieves in series and coagulant/flocculant addition and flocculation between the two sieves, showed that prior removal of particles smaller than 850 µm had a detrimental effect on the flocculation. Use of cationic polymer alone worked better than different combinations of metal salts and polymer, and the best results were obtained when the wastewater bypassed the first sieve. However, excellent results were achieved with a mesh size of 850 µm on the first sieve, addition of about $1 \text{ g} \cdot \text{m}^{-3}$ of a cationic polymer (Pemcat 163, medium charge density, high molecular weight), flocculation in a static flocculator and solids separation on a rotating belt sieve with a mesh size of 250 µm (Rusten & Lundar, 2004). Results achieved with a small dose of cationic polymer easily fulfilled the EU criteria for primary treatment and they are shown in Figure 1.8. For 5 of the 23 data points in Figure 1.8 the first sieve was bypassed. Average TSS-removal was 66% at an average sieve rate of $25 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ (Rusten & Ødegaard, 2006).
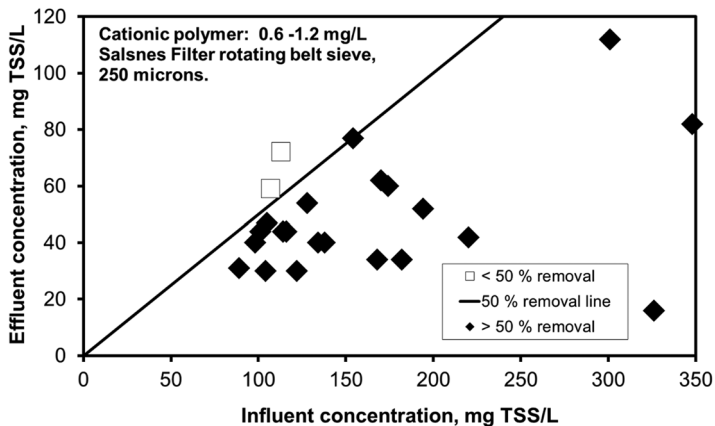

Figure 1.8 Results from the Bangsund WWTP using cationic polymer and a rotating belt sieve with a mesh size of 250 µm (Rusten & Ødegaard, 2006).

1.3.4 Sludge dewatering

All the different rotating belt sieves had simple screw presses for sludge dewatering, either integrated or as separate units. Dewatered primary sludge had total solids (TS)

concentrations from 17 to 37%, with an average of 27%. There was no significant difference between the different types of sieves or between plants with or without chemically enhanced primary treatment. The volatile solids (VS) fraction was very high in all the sludge samples and averaged 90% (Paulsrud, 2005).

1.3.5 Cost comparison

A cost comparison of primary treatment, including sludge dewatering, was carried out for rotating belt sieves and clarifiers. The cost comparison was for a dry weather flow of 200 $m^3 \cdot h^{-1}$ and an influent concentration of 250 g TSS $\cdot$ m^{-3}. The maximum wet weather flow was 400 $m^3 \cdot h^{-1}$. The clarifier overflow rate was 1.2 m $\cdot$ h^{-1} at dry weather flow and 2.4 m $\cdot$ h^{-1} at maximum flow. The sieve rate was 100 $m^3 \cdot m^{-2} \cdot h^{-1}$ at dry weather flow and 200 $m^3 \cdot m^{-2} \cdot h^{-1}$ at maximum flow. The cost of land was set at zero and the clarifiers were uncovered. A 7% annual interest rate and 15 years depreciation was used to calculate annual capital costs.

For the above conditions, savings were found to be substantial when using rotating belt sieves for primary treatment. Both investment costs and total annual costs (annual capital costs plus operation & maintenance costs) for the rotating belt sieves were about 50% of the costs for the primary clarifiers (Ødegaard, 2005).

### 1.4 RESULTS AND EXPERIENCES FROM RECENT STUDIES OF RBS

1.4.1 Primary treatment

At the Nedre Romerike WWTP (Strømmen, Norway) a Salsnes Filter SF2000 RBS, with a 350 µm belt and 0.5 m² submerged belt area, was installed and tested under a variety of operating conditions and hydraulic loads (Rusten *et al.,* 2017). The plant is in a rock cavern and had primary clarifiers followed by a MBBR (moving bed biofilm reactor) process for nitrogen removal. The objectives were to (1) see how much space can be saved by RBS primary treatment, (2) produce a primary effluent that is optimum for the downstream pre-denitrification MBBR process, and (3) produce a primary sludge with a higher methane gas potential (Paulsrud *et al.,* 2014) for future anaerobic sludge digestion.

A total of 40 test runs were performed over a period of 3 months. Wastewater was pumped to the SF2000 from the influent channel, immediately after the sand traps. Wastewater temperatures were normally between 8 and 9°C. Only one run had a temperature below 7°C.

In addition to wastewater characteristics being very important, removal rates and hydraulic capacity were influenced by water level and belt speed. The amount of particles deposited on the belt, prior to being blown off by the air knife, varied from below 10 to above 100 g TSS $\cdot$ m^{-2} and is shown in Figure 1.9. These particles created a filter mat that was important for the performance. Wet sludge blown off the belt had a total solids (TS) concentration from 4 to 10%, depending on the belt

speed. After dewatering in an integrated screw press the median concentration was 25% TS.
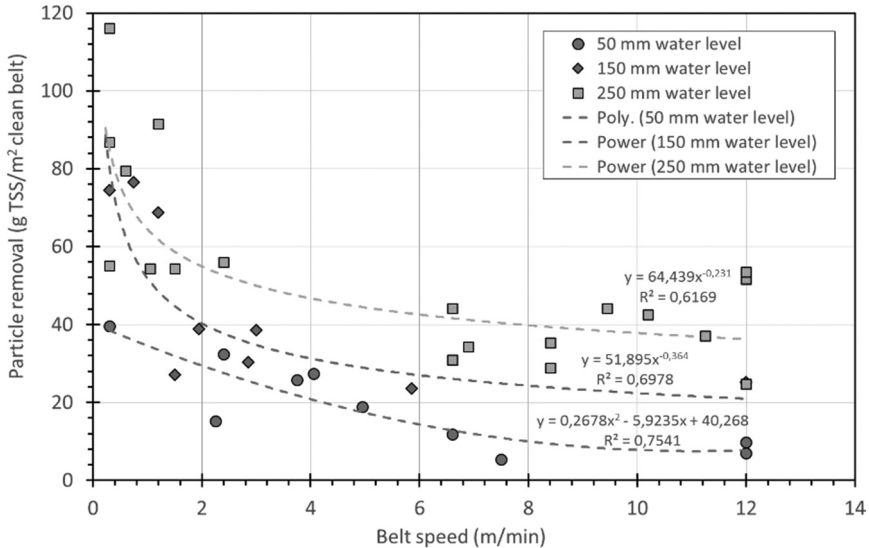
Figure 1.9 SF2000 primary treatment at Nedre Romerike WWTP. Amount of particles deposited on belt prior to removal by air knife, as a function of belt speed and water level on the inlet side of the sieve (Rusten *et al.*, 2017).

Figure 1.10 shows the TSS removal efficiency as a function of the sieve rate. Data are plotted for four different influent TSS concentration ranges as well as the three different water levels on the inlet side of the sieve. High influent TSS concentrations resulted in higher % removal of TSS than low influent TSS concentrations. More than 40% removal of TSS and more than 30% removal of COD were achieved for all test conditions at sieve rates between 140 and 160 $m^3 \cdot m^{-2}$ submerged belt area $\cdot h^{-1}$.

The maximum sieve rate tested was 288 $m^3 \cdot m^{-2} \cdot h^{-1}$ and the maximum particle load was 80 kg TSS $\cdot m^{-2} \cdot h^{-1}$. For all sieve rates above approximately 170 $m^3 \cdot m^{-2} \cdot h^{-1}$, the maximum water level of about 250 mm was needed to push the water through the sieve.

Table 1.1 shows key data for the test runs marked A, B and C in Figure 1.10. They are used to demonstrate the importance of the filter mat. Run A is an example of a very thin filter mat with visually very few particles on the belt. The water level on the inlet side of the sieve was only 50 mm and the belt speed was as high as 7.5 m $\cdot min^{-1}$, even though the sieve rate was only 63 $m^3 \cdot m^{-2} \cdot h^{-1}$. This resulted in a filter mat of only 5.3 g TSS $\cdot m^{-2}$ belt area and the removal of TSS was only 22.4%.
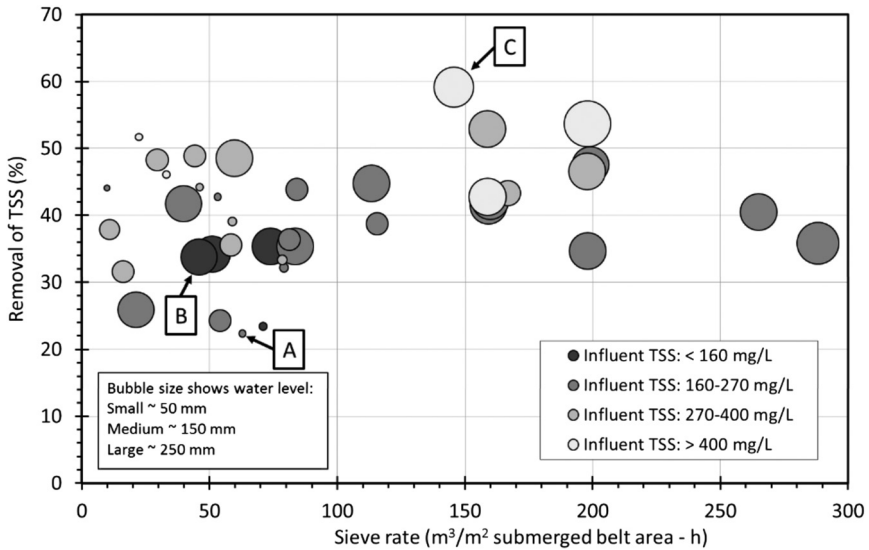
Figure 1.10 SF2000 primary treatment at Nedre Romerike WWTP. Shows removal of TSS as a function of sieve rate, influent TSS concentration, and water level on the inlet side of the sieve. Further data for the three selected test runs marked A, B and C are shown in Table 1.1 (Rusten *et al.*, 2017).

Table 1.1 SF2000 primary treatment at Nedre Romerike WWTP. Key data for test runs marked A, B and C in Figure 1.10 (Rusten *et al.*, 2017).

	Run A	Run B	Run C
Sieve rate, $m^3 \cdot m^{-2}$ submerged belt area $\cdot h^{-1}$	63	46	146
Water level on inlet side of sieve, mm	50	248	271
Belt speed, $m \cdot min^{-1}$	7.5	0.3	12.0
Particles deposited on belt (filter mat), g TSS $\cdot m^{-2}$	5.3	86.7	53.4
Influent concentration, g TSS $\cdot m^{-3}$	204	121	534
Removal efficiency for TSS, %	22.4	33.7	59.2
Removal efficiency for total COD, %	18.7	23.6	39.0

Run B is an example of a very thick filter mat. The water level on the inlet side was 248 mm and the belt moved very slowly, at a belt speed of only 0.3 m · min⁻¹. This resulted in a filter mat of 87 g TSS · m⁻² belt area. Together with a low sieve rate of 46 m³ · m⁻² · h⁻¹ very good removal of TSS should be expected (Rusten & Ødegaard, 2006), but the removal efficiency was only 33.7%. There are two reasons for this, firstly the very low influent concentration of 121 g TSS · m⁻³ (the

lowest of all the 40 test runs), and secondly the low water flow resulting in a very high proportion of the water going through the lower part of the belt where there is no or only a very thin filter mat.

Run C is an example of a relatively thick filter mat, and similar filter mats can be seen in the far-right photo in Figure 1.3 and in Figure 1.6. The water level on the inlet side was 271 mm and the sieve rate was as high as 146 $m^3 \cdot m^{-2} \cdot h^{-1}$. In spite of the belt moving at the maximum speed of 12 $m \cdot min^{-1}$ the filter mat was found to be as high as 53 g TSS $\cdot m^{-2}$ belt area. This was possibly due to the combination of a high flow rate and a very high influent concentration of 534 g TSS $\cdot m^{-3}$, the highest of all the 40 test runs. The removal efficiency for TSS was 59.2%. This was partly due to the high influent concentration, and partly due to the high flow rate that forced a significant fraction of the water to pass through the upper part of the sieve cloth (with a thicker filter mat) because the lower part of the sieve cloth rapidly reached the maximum hydraulic capacity for a clean cloth.

The achieved removal efficiencies, and the observations of how influent concentrations and RBS operational parameters influenced the removal efficiencies, were in agreement with the results found by Franchi *et al.* (2012) during a demonstration-scale operation of an RBS unit at a WWTP in California, USA.

The Nedre Romerike WWTP has decided to replace existing primary clarifiers with RBS primary treatment. Salsnes Filter type SFK600 sieves are being installed for a maximum design flow of 5040 $m^3 \cdot h^{-1}$. The goal is to operate the sieves to achieve 40–50% removal of TSS, and this can be done by the proper combination of belt speed and number of sieves in operation.

1.4.2 Chemically enhanced primary treatment in RBS

Chemically enhanced primary treatment (CEPT) can be used to increase the removal of TSS and particulate COD, either where the wastewater is not suitable for primary treatment with fine mesh sieves (Rusten & Ødegaard, 2006) or where the goal is to maximize the particle removal. When chemical precipitation of phosphorus is not an objective, the simplest form of CEPT is to add a small amount of polymer directly upstream of the RBS. This has successfully been done at full-scale primary treatment RBS plants to improve the removal efficiencies. However, a systematic approach has been taken in a R&D project, using a pilot-plant with controlled chemical dosing and mixing.

1.4.2.1 CEPT testing at the Nordre Follo WWTP

Experiments were conducted at the Nordre Follo WWTP (Ås, Norway) (Rusten *et al.,* 2017). Wastewater was pumped from the influent channel, just downstream of the 3 mm screens, and to the pilot plant. Tests were performed as a worst-case scenario, since a grinder pump was used to feed the pilot system and thus reduced the particle sizes in the wastewater.

The tank flocculator had a wet volume of 170 L and a variable speed stirrer with 3 blades. For all the tests reported here, the stirrer speed was 60 rpm. The SF500 had a belt angle of 20° and the control system was set to run the sieve with a water depth on the inlet side of 88 mm and a maximum belt speed of 4.3 m · min^{-1}. The submerged belt area was 0.09 m². Collected solids were removed by a scraper, followed by an air knife to blow off any residual particles.

Belts with 250-micron and 350-micron openings were tested. Hydraulic retention times in the flocculator varied from 1.6 to 2.8 minutes. The hydraulic loads on the RBS varied from 40 to 68 m³ · m^{-2} submerged belt area · h^{-1} and were limited by the maximum capacity of the grinder pump.

Some results are shown in Figure 1.11. Typically, a small amount of polymer (low cationic charge, very high molecular weight polyacrylamide) increased the removal efficiency by about 20 percentage points, from 40–50% TSS-removal without polymer to 60–70% TSS-removal with polymer. This increased removal efficiency is very important when the RBS is used as the only treatment step and the plant has to meet the EU requirements for primary treatment. It will be very reassuring for the plant owners that if need be, they can significantly increase the plant performance by adding a small amount of polymer.
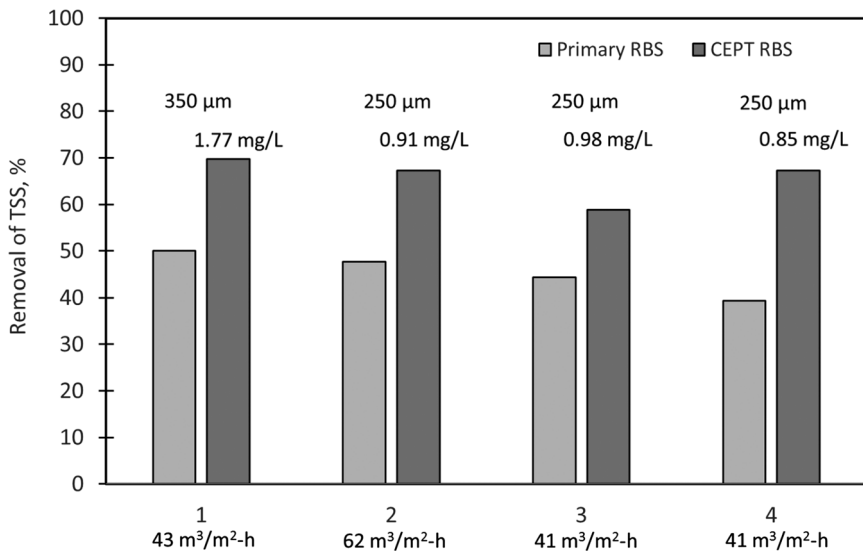

Figure 1.11 Results from pilot-scale CEPT testing with SF500 RBS at the Nordre Follo WWTP. Numbers above columns show openings in belt and polymer dose. Numbers below show test run and hydraulic load on the submerged belt area (Rusten *et al.,* 2017).

The average removal efficiency (66%) for TSS shown for the CEPT process in Figure 1.11 was identical to the removal efficiency for the CEPT process at the Bangsund RBS plant (Rusten & Ødegaard, 2006). Polymer doses were also similar. However, the Bangsund RBS plant was operated at a sieve rate of $25 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ while the runs in Figure 1.11 were performed at sieve rates from 41 to $62 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$.

The particles scraped off the SF500 belt had a concentration between 5 and 7% TS in most of the test runs. A methane potential test (Bioprocess Control AMPTS, Lund, Sweden) was performed with sieve sludge from primary treatment and CEPT, respectively. The test was run at the mesophilic temperature of 37°C and with sludge collected from run 4 (see Figure 1.11). This test showed that the primary sieve sludge produced 317 NmL $CH_4 \cdot g$ VS^{-1}, while the CEPT sieve sludge produced 483 NmL $CH_4 \cdot g$ VS^{-1}. If the sludge goes to an anaerobic digester, this will be a great advantage for the CEPT sludge. It is not clear why the CEPT sludge had so much higher methane potential, but one hypothesis is that the smaller particles captured by the polymer are easier to degrade and contribute more biogas than larger particles.

1.4.2.2 CEPT testing at the Sandefjord and Namsos WWTPs

A portable pilot-plant, mounted inside a trailer, was used at the Sandefjord and Namsos WWTPs. This pilot-plant was equipped with a control panel, auto-samplers, coagulant and polymer dosing system, coagulation and flocculation tanks, and a SF500 RBS. Different mesh sizes were investigated. The belt angle was maintained at 23° with a submerged belt area of 0.06 m². The RBS was also equipped with an air knife (AK) connected to a blower, a water knife and a mechanical scraper (SC) to scrape the sludge cake off the mesh into the sludge compartment.

Testing at Sandefjord and initial testing at Namsos were done with 250 μm and 350 μm belts, comparing addition of cationic polymer to no addition of polymer. Results were basically independent of the mesh size, and also independent of the different sieve rates tested (54–$94 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$). Flocculation time varied from 3 to 5 minutes. As an example, average results from testing with a 250 μm belt are shown in Figure 1.12. At Sandefjord the air knife was used for removing sludge from the belt, and addition of $0.7 \text{ g} \cdot \text{m}^{-3}$ cationic polymer increased the removal of TSS by 23% (from 45% to 68%). Removal of total COD was 51% with polymer addition. The Namsos wastewater was periodically heavily polluted with discharge from a local dairy and this resulted in very large variations in RBS performance when no polymer was added. However, as seen in Figure 1.12, very good results (72–73% TSS removal) were achieved with $0.85 \text{ g} \cdot \text{m}^{-3}$ cationic polymer, both when the air knife and when the scraper was used for removing the sludge cake (Sahu *et al.,* 2017).
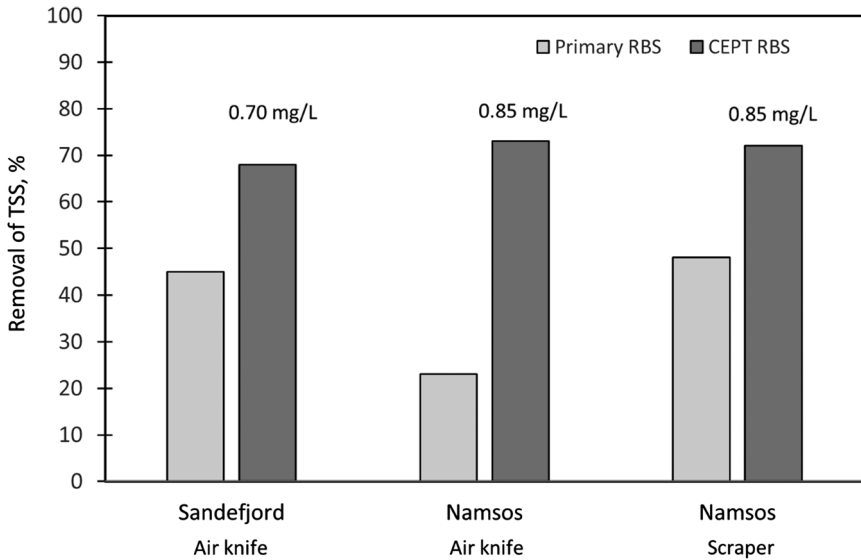
Figure 1.12 Percentage removal of TSS using SF500 RBS with 250 μm mesh, without and with addition of polymer, at Sandefjord and Namsos WWTPs. Primary RBS has no addition of polymer, for CEPT RBS the cationic polymer dose is shown above the column. Air knife or mechanical scraper shows how the sludge cake was removed from the belt. Data from Sahu *et al.* (2017).

At the Sandefjord WWTP increasing the polymer dose from 0.7 to 1.5 g · m⁻³ had no effect on the removal efficiencies (Rathnaweera, 2017). However, when the polymer dose was increased from 0.85 to 1.75 g · m⁻³ at the Namsos WWTP, the removal efficiencies for both TSS and TCOD dropped and the belt speed increased in order to handle the same flow as with the lower polymer dose (Sahu *et al.*, 2018). This indicates that optimum polymer dosing will normally be <1 g · m⁻³.

A Malvern Mastersizer was used at the Sandefjord WWTP to measure the particle size distribution (PSD), as well as the total particle volume, of influent wastewater, flocculated wastewater (after addition of cationic polymer) and RBS effluent (Rathnaweera, 2017). Area based diameter (ABD) was used to describe the particle size. These measurements were taken for two different runs with 250 μm mesh size at a sieve rate of 90 m³ · m⁻² · h⁻¹. About 70–75% of the influent particle volumes were smaller than 250 μm. After flocculation with cationic polymer, grab samples showed that 75 to 80% of particle volumes were larger than 250 μm. This explains the significant increase in removal of TSS when adding polymer. However, the PSD measurements also showed that 25–35% of the particle volumes in the

RBS effluent samples were larger than the sieve size of 250 µm. Three different phenomena may have contributed to this (Rathnaweera, 2017):

(a) Remaining particles and polymer residuals continue the flocculation process in effluent water.

(b) Wastewater particles are not spherical and particles that are larger than sieve openings based on ABD can have a dimension smaller than the sieve openings (rods etc.). These particles can easily pass through the filter.

(c) Fluffy particles (and also other particles) may be flexible and can go through the sieve, especially when there is a hydraulic force pressing the particle through the sieve.

Measurements showed 68% removal of TSS for both test runs where PSD analysis were performed, and this was close to the particle removal calculated from influent and effluent particle volumes. Polymer flocculation significantly increased the particle volume, as measured by the Malvern Mastersizer, without a similar increase in particle dry mass. So the density, as mg dry matter per ml, was significantly lower for the flocculated particles than for the particles in the influent wastewater (Rathnaweera, 2017).

During the second period of testing at the Namsos WWTP coagulants (Al or Fe based) were added, either alone or in combination with an anionic polymer, to see how much phosphorus can be removed. PO_4-P is easily precipitated, but this adds more particles to the wastewater entering the RBS and a very high removal of TSS is needed in order to get good removal of total phosphorus (TP). Belts with mesh sizes from 250 to 40 µm were tested. Despite large variations in wastewater quality, performance tests with 90 µm mesh size indicated reliable removal of 60–65% TP and 70–75% TSS at reasonable coagulant doses (12 g Al · m^{-3}, 2.1 mol Al/mol P) and high hydraulic load (90 m^3 · m^{-2} · h^{-1}) based on submerged belt area. Reported removal efficiencies are based on influent concentrations prior to coagulant dosing, so actual particle removal over the RBS will be higher. Sludge cake removal mechanisms, air knife or mechanical scraper, did not have a clear influence on the particle removal efficiency (Sahu *et al.*, 2018).

1.4.3 Sludge from rotating belt sieves

Paulsrud *et al.* (2014) carried out a survey of the sludges from primary treatment plants in Western and Northern Norway, where the discharge requirement follows the EU primary treatment criteria. As the basis for sludge characterization, grab samples of sludge were collected from 19 full-scale primary treatment plants employing fine mesh sieves (all rotating belt sieves of the Salsnes Filter type, see Figure 1.1). At those plants the separated sludge is dewatered in an integrated screw press, and all the samples were taken after dewatering. Only five of those plants had grit chambers installed ahead of the RBS and none had fine screens ahead of

the sieves. This means that the sieve sludge samples contained more debris than what would be normal in a more advanced treatment plant with fine screening and a grit chamber ahead of the RBS, where the RBS would be a substitute for primary clarifiers.

The results revealed a TS content of 13.6–36.9% TS (mean = 27.3% TS). The mean VS content of the dewatered sieve sludges was 91.6% of TS, significantly higher than the VS content (80.8% of TS) of the sludge from the primary clarifier step of full-scale wastewater treatment plants that were also analysed.

The high VS content of the RBS sludge as compared to the primary clarifier sludge, would indicate a higher methane potential in anaerobic digesters for the RBS sludge. This was supported by bio-methane potential (BMP) tests showing a mean value of 345 NmL $CH_4 \cdot$ g VS^{-1} for RBS sludge and 287 NmL $CH_4 \cdot$ g VS^{-1} for primary clarifier sludge. These benefits for RBS sludge, over sludge from primary clarifiers, were confirmed in a recent study by Ho *et al.* (2016).

When incinerating sludge or using sludge as a fuel in cement kilns, the caloric value (CV) is of great importance. The CV-analysis of the RBS sludge demonstrated CVs at a high level (about 19 MJ $\cdot$ kg TS^{-1}), indicating that the RBS sludge would be attractive for this purpose. The reader is referred to Paulsrud *et al.* (2014) for more details about this survey.

Sludge recovery from primary wastewater using coagulation/flocculation by polymer dosage ahead of RBS technology was investigated at three full-scale WWTPs in Norway (Sahu *et al.,* 2017; Sahu & Rathnaweera, 2017). The objective was to test the BMP of the sludge obtained from RBS with and without polymer addition to the municipal wastewater at the Nordre Follo, Sandefjord and Namsos WWTPs. For the tests at Nordre Follo WWTP, a tank flocculator was tested in combination with the pilot scale SF500 filter. A belt with 250-micron openings was investigated for these tests. A well-equipped pilot unit with a polymer-dosing station, a flocculator and a SF500 was used at Sandefjord and Tiendeholmen WWTPs. Belts with 250 µm and 350 µm openings were used in both tests.

A summary of the specific BMP results at these three test sites is given in Table 1.2. Addition of polymer resulted in 1.5 to 2.9 times more biogas than for tests without polymer addition. The increased biogas production at the Nordre Follo WWTP was partly due to a higher specific BMP, and partly due to the higher removal of TSS. For the Namsos WWTP the increased biogas production was primarily due to the higher TSS removal when polymer was added.

Most samples in Table 1.2 had a BMP between 330 and 400 NmL $CH_4 \cdot$ g VS^{-1}, even though there was a tendency to be in the upper BMP range for sludge samples obtained when polymer was used. However, the biggest advantage with regard to biogas production is that CEPT significantly increased the removal of organic particles and thus increased the total amount of primary VS available for gas production.

Table 1.2 Comparison of bio-methane potential (BMP) at different WWTPs using sludge from Salsnes Filter RBS. Sludge cake removal with either air knife (AK) or scraper (SC). Data from Sahu & Rathnaweera (2017).

WWTP	Scenario	BMP NmL $CH_4 \cdot$ g VS^{-1}	TSS Removal %	Ratio for net CH_4 Production (polymer/no polymer)
Nordre Follo	No Polymer – AK	317	40	2.5
	0.85 g $\cdot$ m^{-3} polymer – AK	483	67	
Sandefjord	0.75 g $\cdot$ m^{-3} polymer – AK	391	68	–
Namsos	No Polymer – AK	334	23	2.9
	0.85 g $\cdot$ m^{-3} polymer – AK	333	73	
	No Polymer – SC	350	48	1.5
	0.85 g $\cdot$ m^{-3} polymer – SC	389	72	

A simple economic calculation showed the cost of polymer for RBS CEPT to be insignificant compared to the benefits obtained in higher solids removal, more biogas generation, less particles in downstream processes and reduced oxygen consumption in downstream bioreactors (Sahu *et al.,* 2017). The sludge cake blown off or scraped from the belt had 8–10% TS at the Sandefjord WWTP and 7–12% TS at the Namsos WWTP (Rathnaweera, 2017; Sahu *et al.,* 2017). This is close to ideal for use in anaerobic sludge digesters, and there is no need for thickening of this sludge.

1.5 IMPACT OF RBS PRIMARY TREATMENT ON NITROGEN REMOVAL

It has been argued that RBSs will remove too much of the carbon that might be available as carbon source in pre-denitrification processes. However, relatively large particles that are removed by RBS are slowly biodegradable, so the question is how far down in particle size is the optimum particle removal before any negative effects are seen in biological N- and P-removal processes. Based on a literature study, Newcombe *et al.* (2011) expected the optimum particle size cut-off in front of standard biological nutrient removal processes to be in the 15–20 µm range.

A three-year R&D project was initiated in 2012 to find the optimum particle size cut-off for particle removal in front of biological nitrogen removal processes with pre-denitrification. Removal of too many particles may reduce the carbon-to-nitrogen (C/N) ratio to the point where the nitrogen removal is affected due to reduced denitrification, while not removing enough particles may negatively

affect the nitrification process. Some initial short-term tests were performed using wastewater from two municipal wastewater treatment plants that were tested separately in both small-scale activated sludge reactors and small-scale biofilm reactors (Razafimanantsoa *et al.,* 2014a). This was followed by longer-term tests (Razafimanantsoa *et al.,* 2014b) with activated sludge sequencing batch reactors (SBRs). For the wastewaters tested, the results showed that sieves with 33 µm mesh size provided the optimum primary treatment (with respect to nitrogen removal) when operated without a filter mat on the sieve cloth.

The next investigation step consisted of side-by-side continuous flow testing of nitrogen removal, where one train received screened wastewater and the other train received wastewater that had passed through a 33 µm fine mesh RBS (Salsnes Filter). Tests were completed with both MBRs (membrane bio-reactors) and MBBRs (moving bed biofilm reactors). Only the tests with MBBR (Rusten *et al.,* 2016) have been published so far, but a paper with results from the MBR tests is in preparation (Razafimanantsoa *et al.,* 2018).

The two MBBR pilot-plants and the two MBR pilot-plants were located at the Nordre Follo WWTP, south of Oslo, Norway. The Nordre Follo WWTP is a large MBBR plant with combined pre- and post-denitrification. Coarse screened wastewater was pumped from just downstream of the screens at the full-scale plant and through either a 2 mm screen or a Salsnes Filter RBS with 33 µm sieve cloth to storage tanks from where it was fed to the four pilot-scale plants. The RBS was operated without a filter mat in order to prepare wastewater for the tests, and it removed on average 41% of TSS, 31% of total COD, 12% of total N and 14% of total P. Fresh batches of wastewater were prepared three times per week and stored in tanks with mechanical mixers to prevent settling of particulate matter.

1.5.1 Impact on MBBR

The MBBR lab-scale plants for nitrogen removal were operated in parallel where each train had four reactors in series, where reactors 1 and 2 were anoxic, and reactors 3 and 4 were aerobic. Anoxic reactors had mechanical mixers and aerobic reactors had diffusers for aeration at the bottom of the tanks. All reactors had 60% fill of the Kaldnes K1 biofilm carriers, resulting in a protected biofilm surface area of 300 $m^{-2} \cdot m^{-3}$ of wet reactor volume. All anoxic reactors had a wet volume of 4.0 L and aerobic reactors had a wet volume of 6.0 L, resulting in 40% anoxic volume and 60% aerobic volume. Nitrified effluent was recycled from reactor 4 to reactor 1 at approximately two times the influent flow.

The overall results are shown in Table 1.3, with the 2 mm screened influent wastewater, the 33 µm sieved wastewater and the effluents from reactors 4 in Train A and Train B, respectively. This means biological treatment for Train A, and primary plus biological treatment for Train B. The MBBR plants did not have

final solids separation stages, so when analysing overall removal of organic matter and nitrogen, effluent concentrations measured on filtered (GF/C) samples were used. Based on this, average removal for total COD was 91% for both Train A and Train B. Average removal of total N was 68% for Train A (2 mm screen) and 66% for Train B (33 μm sieve). Average removal of total P was 70% for both trains. P was removed both as particulate P and as P assimilated in to the produced biomass.

Table 1.3 Overall results for the two pilot-scale MBBR plants. Shows averages and standard deviations. Data from Rusten *et al.* (2016).

Parameter	2 mm Screen, Train A		33 μm Sieve, Train B	
	Influent $(g \cdot m^{-3})$	Effluent $(g \cdot m^{-3})$	Influent $(g \cdot m^{-3})$	Effluent $(g \cdot m^{-3})$
TSS	281 ± 96	204 ± 85	165 ± 70	137 ± 76
Total COD	521 ± 129	302 ± 106	355 ± 93	209 ± 90
Filtered COD	168 ± 53	45 ± 9	143 ± 42	43 ± 10
BSCOD*	118 ± 45	–	98 ± 37	–
Total N	44.0 ± 11.9	23.2 ± 5.2	38.9 ± 11.1	23.0 ± 6.4
Filtered TN	33.6 ± 9.9	15.1 ± 6.3	32.2 ± 9.6	16.1 ± 5.8
NH_4-N	31.7 ± 10.7	1.3 ± 2.3	30.4 ± 10.3	1.1 ± 2.6
NO_2-N	0.03 ± 0.02	0.21 ± 0.19	0.04 ± 0.05	0.19 ± 0.26
NO_3-N	0.41 ± 0.2	10.9 ± 4.2	0.41 ± 0.2	12.5 ± 4.1
Total P	4.1 ± 1.4	3.3 ± 1.5	3.5 ± 1.1	3.4 ± 0.99
Filtered TP	1.7 ± 0.6	1.1 ± 0.6	1.3 ± 0.6	1.1 ± 0.6

*Biodegradable soluble COD.

Table 1.3 confirmed that, for the wastewater characteristics at the test plant, Salsnes Filter primary treatment with a 33 μm RBS and no filter mat, produced a primary effluent that was close to the optimum with respect to how much organic matter that is removed. Removal of organic matter with the 33 μm sieve had no significant, negative effect on the denitrification process. Nitrification rates improved by 10–15% in the train with 33 μm RBS primary treatment. Mass balance calculations showed that without RBS primary treatment, the oxygen demand in the biological system was 36% higher.

The average sludge production for the two treatment trains were 199 g TSS · m⁻³ for Train A (2 mm screen) and 244 g TSS · m⁻³ (114 g TSS · m⁻³ primary + 130 g TSS · m⁻³ biological) for Train B (33 μm sieve). The specific sludge yield for biological sludge was 0.45 g TSS · g TCOD⁻¹ removed for both trains. Using SF fine mesh sieves increased the total sludge production by about 20–25%. However, almost half of the sludge was primary sludge, which can dewater to a high solids

concentration and has a significantly higher methane gas potential (Gavala *et al.,* 2003) than biological sludge.

1.5.2 Impact on MBR

The two pilot-scale MBRs were operated in parallel. Each MBR train was composed of two anoxic reactors of 10 L, equipped with a mechanical mixer rotating at about 215 rpm, one aerobic reactor of 25 L, and a submerged hollow fibre membrane ZeeWeed-10 (ZW10, Zenon Environmental Systems Inc., Oakville, Ontario, Canada) with a 40 nm nominal pore size. Nitrified activated sludge was recycled from Reactor 3 to Reactor 1 at twice the flow of the influent wastewater. The membrane ZW10 was operated at normal forward flow for 9.5 minutes and backwashed for 0.5 minute at twice the permeate flow. All pumps (feed, recycle and permeate) were controlled by a programmable logic controller (PLC). A pressure transmitter and a dissolved oxygen probe were also connected to the PLC to record continuously the transmembrane pressure and dissolved oxygen in the aerobic reactors.

The MBRs were operated at an influent flow rate of about $5 \text{ L} \cdot \text{h}^{-1}$ and a recycle flow rate of $10 \text{ L} \cdot \text{h}^{-1}$. The hydraulic retention time was 9 h. The mixed liquor suspended solids (MLSS) in the anoxic reactors was about $5 \text{ kg} \cdot \text{m}^{-3}$, while the MLSS in the aerobic reactors were maintained at around $7 \text{ kg} \cdot \text{m}^{-3}$. The operating temperature varied between 16 and 21°C and the pH was maintained around 7. The dissolved oxygen (DO) concentration in the aerobic zones was around $4 \text{ kg} \cdot \text{m}^{-3}$. The membrane permeate flux was $6.3–6.4 \text{ L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ in both trains. Over the 96 days of active testing the transmembrane pressure (TMP) was very low, with 46 ± 9 mbar in Train A (2 mm screen) and 26 ± 7 mbar in Train B (33 µm sieve). Even though the TMP was higher in the train treating 2 mm screened wastewater, no chemical cleaning of the membrane was performed throughout the experiment as the TMPs were well below the 300 mbar maximum limit recommended by the membrane supplier.

The overall results are summarized in Table 1.4, with the 2 mm screened influent wastewater, the 33 µm sieved wastewater and the effluents (membrane permeate) from Train A and Train B, respectively. This means biological treatment for Train A, and primary plus biological treatment for Train B.

Final effluent concentrations were very similar for the two trains. With a 40 nm membrane effluent TSS should per definition be zero, and was well below the detection limit. Based on these averages removal for total COD was 94% and removal of total N was 74% for both Train A and Train B. Average removal of total P was 81% for Train A (2 mm screen) and 83% for Train B (33 µm sieve). P was removed both as particulate P and as P assimilated in to the produced biomass. The results confirmed that the selective removal of particulate organic matter with a 33 µm sieve with no filter mat was close to the optimum, and did not negatively affect the performance for nitrogen removal in the pilot-scale MBR (Razafimanatsoa *et al.,* 2018).

Table 1.4 Overall results for the two pilot-scale MBR plants. Shows averages and standard deviations. Data from Razafimanatsoa *et al.* (2018).

| Parameter	2 mm Screen, Train A		33 µm Sieve, Train B	
	Influent $(g \cdot m^{-3})$	Effluent $(g \cdot m^{-3})$	Influent $(g \cdot m^{-3})$	Effluent $(g \cdot m^{-3})$
TSS	275 ± 99	$\ll 1$	161 ± 69	$\ll 1$
Total COD	522 ± 134	32.4 ± 7.2	349 ± 88	32.1 ± 7.5
Filtered COD	168 ± 47	29.7 ± 7.3	145 ± 35	29.1 ± 7.7
Total N	43.2 ± 12.0	11.3 ± 3.5	38.7 ± 11.8	11.3 ± 2.5
NH_4-N	31.5 ± 10.5	0.24 ± 0.74	30.1 ± 9.9	0.32 ± 1.37
NO_2-N	0.03 ± 0.01	0.14 ± 0.22	0.03 ± 0.05	0.13 ± 0.19
NO_3-N	0.41 ± 0.15	8.63 ± 3.0	0.40 ± 0.15	10.0 ± 3.2
Total P	4.26 ± 1.51	0.82 ± 0.62	3.70 ± 1.25	0.74 ± 0.55
PO_4-P	1.51 ± 0.60	0.57 ± 0.44	1.09 ± 0.65	0.55 ± 0.52

In Train A (2 mm screen), the overall sludge produced from the system was only composed of biosludge. In Train B (33 µm sieve), the total sludge production was a combination of RBS sludge and biosludge. The biosludge production in Train B was only about half of the biosludge produced in Train A. However, the total amount of sludge produced in Train B was about 16% higher compared to that of Train A because of the primary sludge from the RBS. The specific biological sludge yield was slightly lower in Train B (0.31 g TSS · g COD^{-1}) than in Train A (0.34 g TSS · g COD^{-1}), which was probably due to the longer solids retention time of about 16.8 d in Train B compared to 13.7 d in Train A. The reduction of organic matter prior to biological treatment also allowed a decrease of the oxygen demand by about 30%. Therefore, removal of particles with the 33 µm sieve was beneficial for the biological process (Razafimanantsoa *et al.,* 2018).

1.5.3 Operation of RBS in front of biological nitrogen removal process

Lab- and pilot-scale testing has demonstrated that the optimum particle removal prior to biological nitrogen removal is to use a 33 µm mesh size sieve with no filter mat on the sieve (Razafimanantsoa *et al.,* 2014a,b, 2018; Rusten *et al.,* 2016). However, this is not practical for operation of RBSs at large WWTPs. Typically mesh sizes of 250 µm or 350 µm are used at municipal WWTPs, and the sieves are operated with a sludge cake on the belt that will remove a large fraction of the particles that are smaller than the openings in the mesh. This larger mesh will be much stronger, easier to clean and have a larger hydraulic capacity than a 33 µm mesh.

The question is if it is possible to operate an RBS with a filter mat on a 250 µm or 350 µm belt in such a way that we get a removal of particles that is similar to using a 33 µm belt without a filter mat. The TSS removal efficiency and effluent particle size distribution (PSD) from an RBS with filter mat on the belt can be manipulated by changing operational parameters like flow, belt speed, water level and belt cleaning procedure. A preliminary test was performed at the Nordre Follo WWTP, using a SF1000 RBS with 33 µm and 350 µm belts. A Malvern Mastersizer was used to measure the PSD of the effluent (Rusten *et al.,* 2014).

Figure 1.13 shows an example of PSD curves for three test runs, where the PSD from a run with a 33 µm mesh and no filter mat is compared to two runs with 350 µm mesh operated at different belt speeds. The belt speed is proportional to the Hz setting for the belt motor. It can be seen that at 30 Hz the shape of the PSD curve was very similar to the shape of the PSD curve for the 33 µm belt with no filter mat, but slightly less TSS was removed with the 350 µm belt. At 20 Hz belt speed the filter mat was thicker, and slightly more TSS was removed with the 350 µm belt than with the 33 µm belt and no filter mat.
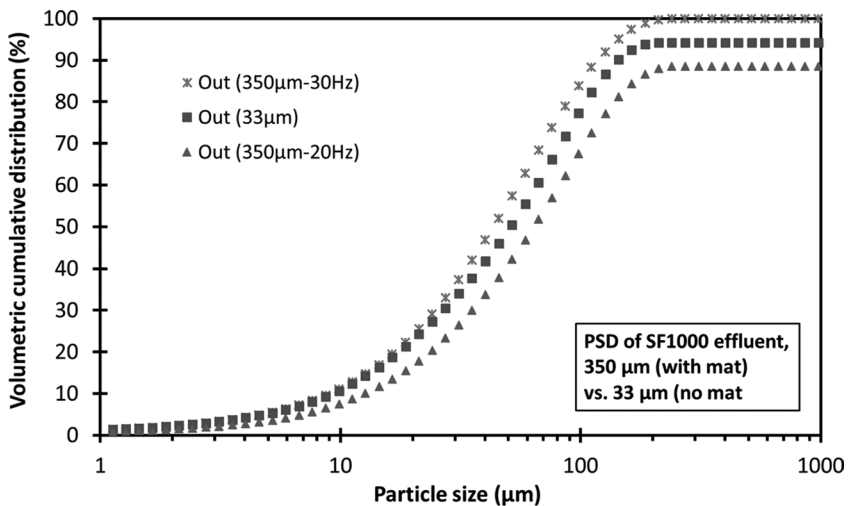
AQ2 **Figure 1.13** Example of PSD curves for three test runs with SF1000 RBS. A 33 µm belt operated with no filter mat and 350 µm belt operated at belt motor speeds of 20 Hz and 30 Hz.

The preliminary results in Figure 1.13 indicate that it will be possible to operate RBSs with filter mats in such a way that they produce a primary effluent that will be close to optimum for downstream biological nitrogen removal. A belt speed of 25 Hz would most likely have produced a PSD curve very close to the curve for the 33 µm belt with no filter mat. However, since influent wastewater characteristics

constantly change it is a challenge to come up with good control algorithms for these sieves.

1.6 CONCLUSIONS

Rotating belt sieves (RBSs) may effectively be used for compact primary treatment of wastewater. Most importantly they will remove relatively large, slowly biodegradable particles. Normally the separating efficiency is such that the defined EU removal efficiencies for primary treatment (50% removal of TSS and 20% removal of BOD_5) is achieved, if the RBSs are properly built and equipped, properly designed, and operated with a filter mat. This is achieved by operating the belt at low speed or discontinuously.

Design sieve rates should be established by screening tests (as described above) and will range from 20 $m^3 \cdot m^{-2} \cdot h^{-1}$ to about 300 $m^3 \cdot m^{-2} \cdot h^{-1}$, depending on wastewater characteristics and required removal efficiencies. To meet the EU primary treatment requirements, sieve rates will normally be below 200 $m^3 \cdot m^{-2} \cdot h^{-1}$.

To be considered suitable for primary treatment with fine mesh sieves the screening tests indicated that at least 20% of the TSS in the wastewater should consist of particles larger than 350 µm. However, cationic polymer in combination with rotating belt sieves has successfully treated wastewater that was originally classified as unfavourable for fine mesh sieves.

A sieve opening in the range of 250–500 microns will normally be the appropriate choice for typical municipal wastewater, but this should be determined after screening tests. Once a filter mat is formed on the sieve, there is practically no difference in the performance of sieve cloths within this size range, with regard to both % TSS removal and filtration rate. A mesh size of 350 µm is most commonly used for primary treatment. Removal efficiencies and hydraulic capacities have been demonstrated to be dependent on influent concentrations, water level on the inlet side of the sieve and belt speed. Creation of a filter mat on the belt is important for high removal efficiencies. Test results showed up to 60% TSS removal with a good filter mat, and less than 25% TSS removal with a very thin filter mat. Best results were achieved with maximum water level on the inlet side of the sieve and sieve rates in the range of 140 to 160 $m^3 \cdot m^{-2} \cdot h^{-1}$.

It has been argued that the use of RBS reduces the capacity to denitrify because of the removal of organic matter. However, pilot studies demonstrated that even with a sieve as fine as 33 µm (operated without a sludge mat), the removal of organic matter caused by the sieve had no negative effect on the denitrification process and overall N-removal.

Chemically enhanced primary treatment (CEPT) is a simple and effective way of increasing the removal efficiency of an RBS. Pilot-scale SF500 RBS tests with 250 or 350 µm belts and sieve rates from 40 to 94 $m^3 \cdot m^{-2} \cdot h^{-1}$, demonstrated that the removal of TSS typically increased from 40–50% without polymer to 60–75%

with polymer (with 0.7–1 g · m^{-3} of polymer and ~2 min of flocculation time). The total bio-methane potential (BMP) of the recovered sludge was significantly higher with polymer than with no polymer. A simple economic calculation shows the cost of polymer with RBS to be insignificant compared to the benefits obtained in higher solids removal, more biogas generation, and less particles in downstream processes.

Sludge scraped or blown off the belt has typically 5 to 7% TS, but has been as high as 12% TS. The most commonly used RBS (Salsnes Filter) is, however, equipped with a screw press for the sludge that typically dewaters the sludge to about 25–30% TS.

The high VS content of RBS sludge as compared to primary clarifier sludge indicates a higher methane potential in anaerobic digesters for the RBS sludge and this was supported by batch bio-methane potential (BMP) showing a mean value of 345 NmL CH$_4$ · g VS^{-1} for RBS sludge and 287 NmL CH$_4$ · g VS^{-1} for primary clarifier sludge.

When incinerating sludge or using sludge as a fuel in cement kilns, the caloric value (CV) is of great importance. The CV-analysis of the RBS sludge demonstrated CVs at a high level (about 19 MJ · kg TS^{-1}), indicating that the RBS sludge would be attractive for this purpose.

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