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Filtration for removal of microparticles in swimming pool water

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ABSTRACT

Filtration is an effective method for removing particles larger than 10–15 μm in swimming pool water. However, the removal of smaller particles poses a significant challenge. Tests were conducted to improve the filter's performance. These tests included choice of filter cloth, long-term filtration operation, pre-coating with filter aids (Arbocel and Harbolite). As expected, the choice of filter cloth affects particle rejection, but other strategies can be employed to improve the process. During long-term operation, particle rejection continuously improved for all filter cloths, and after 30 min, 50 % of particles as small as 2 μm were removed. Since, the concentration of particles in swimming pool water is low, only part of the filter cloth is covered by particles even after 30 min. Higher particle rejection could also be achieved by recycling particles from the filter cloth or using filter aids. Additional particles have been removed from the filter cloth by rinsing the filter cloth with water followed by the recirculation of part of the rinse water or the coagulated rinse water. Higher particle removal can also be obtained by using filter aids, whereby it is possible to cover the entire surface of the filter. When using Harbolite as the pre-coat material, more than 80 % of the particles with a size of 2 μm or larger can be removed when 100 g Harbolit was used per m^2 filter cloth.

1. Introduction

Public swimming pools are popular places for people to engage in sport and leisure activities. However, it is crucial to maintain high water quality through continuous treatment, to ensure that the water is safe and healthy for pool users. The water must be continuously treated as pool users introduce skin cells, sweat, urine, faecal matter, pathogens, and care products into the water [1]. The pollutants from pool users can be classified into three main categories: initial anthropogenic pollutants, which can be washed off by showering before swimming; continuous anthropogenic pollutants, which are released into the water during swimming; and incidental anthropogenic pollutants, such as human excreta, which may enter the water accidentally or intentionally [2,3]. Furthermore, swimming pool water is disinfected to remove pathogens often by chlorination. The anthropogenic pollutants released from pool users react with chlorine and form disinfection-by-products (DBPs) which are present both in the swimming pool water and the air [3,4]. DBPs are unwanted as they are potentially linked to e.g., asthma, cancer, liver, and kidney [5–7]. Furthermore, DBPs can be more problematic for children than adults [8]. The occurrence and impact of DBPs are described in detail in the literature [4]. A method to reduce the concentration of DBPs is minimize the release of anthropogenic pollutants into the water or to rapidly remove such pollutants from the swimming pool water. Suspended particles in the water, which includes skin cells, bacteria, algae, and dust, are usually removed by sand filtration. The water may be coagulated before the sand filter to improve the removal efficiency [9]. Sand filters are typically cleaned weekly or every second week. The residence time of skin cell and other particles in the sand filter is therefore high (up to two weeks), which increases the risk of cell lysis and formation of disinfection byproducts. Sand filter operation takes up considerable space and is intensive in terms of energy and water consumption [10,11].

Alternative technologies have been considered as substitutes for sand filtration. For instance, ceramic microfiltration [12], ultrafiltration [13–16], nanofiltration [17,18] or pre-coat filters [19]. The aforementioned technologies are energy intensive as they require pressurization of the water. An alternative is to use a drum filter as an alternative to sand filtration. Drum filters are designed to remove suspended particles from water, and they are frequently backwashed. Due to frequently backwash, particles are removed within 20–90 min depending on the

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particle load in the water. This reduces the reaction between the suspended particles and chlorine, potentially leading to lower levels of disinfection byproducts when compared to sand filters. Furthermore, drum filter requires less energy than the sand filter because it operates through gravity. Even though the drum filter needs to be backwashed more frequently, it uses less water due to the much smaller back washing volume. Some small particles may still pass through the filter, creating the need for a side stream of pool water to be treated using a sand filter. Several systems have been implemented at full scale to minimize footprint, reduce water consumption, and reduce energy use. Previous studies showed that the drum filter uses approximately half the amount of water for backwash in comparison to the sand filter [20]. The total energy consumption of the drum filter was less than 75 % of that for the sand filter [21]. Additionally, the mass removal rate was marginally lower for the drum filter, recording 88 g/day compared to 95 g/day compared to the sand filter with coagulation [20]. For the sand filter, the removal of organic particles exceeded 99 % [20]. In the absence of a sand filter, water turbidity becomes noticeable in the basin after a few days. It is therefore recommended send part of the water through a sand filter to prevent the accumulation of particles in the basin [21]. As a solution, the systems are equipped with a side stream sending approximately 25 % of the water to the sand filter. In summary, the drum filter technology removes more than 90 % of the organically derived particulate matter. This eliminates the source of chlorine consumption and the formation of chlorine by-products, in contrast to conventional water treatment systems where the particulate matter is retained in sand filters and reacts with chlorine in the sand filters until the next backwash [21]. Fig. 1 outline this concept, although it should be noted that several processes are not included, for example chlorination and pH adjustment.

This study aims to evaluate various techniques to enhance the particle rejection in a filter. The study exclusively concentrates on particle rejection at the filter cloth, and a filter nutsche was used for all tests. The long-term goal is to reduce the flow of water that requires treatment with a sand filter, or even eliminating the need for a sand filter altogether. The impact of particle capture on the filter cloth has been examined, along with the option of recycling a portion of the rinse water without further treatment, recycling a portion of coagulated rinse water, and the application of filter aids. To prevent a significant pressure drop across the filter cloth, only a thin layer of filter aid was utilized. The concept of continuously removing particles from the filter while achieving enhanced particle rejection was pursued through the rinsing and recycling of particles on the filter cloth.

2. Material and methods

2.1. Filtration nutsche setup for treatment of swimming pool water

A filtration nutsche setup was installed at the public swimming pool, Gigantium in Aalborg, Denmark. The swimming pool samples were taken from the hot water pool and children's pool with the temperature of the water being recorded at 34°C.

The filtration nutsche setup received swimming pool water from pipes supplying the automatic measurement of pH and free chlorine (hypochlorous acid and hypochlorite). The inlet flow was measured using a water flowmeter (100–1000 L/h), and the water was directed into a stainless-steel cylinder that had a diameter of 64 mm. A separation unit with a filter cloth was installed at the bottom of the cylinder (Fig. 2). Seven different filter cloths were tested, five polymer filters: FibrootB, FibG260, SefarTex, InBlue Sub-5 and three metal filters ODW6, AK50, HB5S. The pressure was measured just above the filter cloth using a pressure transmitter (P12-800–3110, Nöding Messtechnik GmbH) and the pressure was adjusted to account for the distance between the pressure transducer and the surface of the filter cloth, enabling the measurement of the pressure drop across the filter cloth. After passing through the filter cloth, the purified water was transported through a pipeline equipped with a tee joint, enabling the filtered solution periodically to be pumped through an optical particle analyzer (Fig. 2). For each measurement of the particle size distribution, 15 mL filtrate was used. Extra care was taken to ensure that no air entered the pipe and to prevent air bubbles from affecting the particle size measurements. The particle size analyzer was decoupled from the system both before and after the filtration of swimming pool water. Untreated swimming pool water was collected, and particle size measurements were conducted using the particle size analyzer. In some experiments, a filter aid was applied to coat the filter. While coating, the filtrate water was recycled using a recirculation pump to capture small particles on the filter cloth (Fig. 2).

After filtration, the stainless-steel cylinder was disassembled, the separation unit with the filter cloth was gently rinsed with 50 mL demineralized water (rinse water) for 5 min, and the rinse water and the particles were collected, diluted and analyzed and for some of the experiments used to pre-coat the filter cloth.

Particles in the rinse water was diluted and analysed using a LS 13,320 MW laser diffraction particle size analyzer (Beckman Coulter,

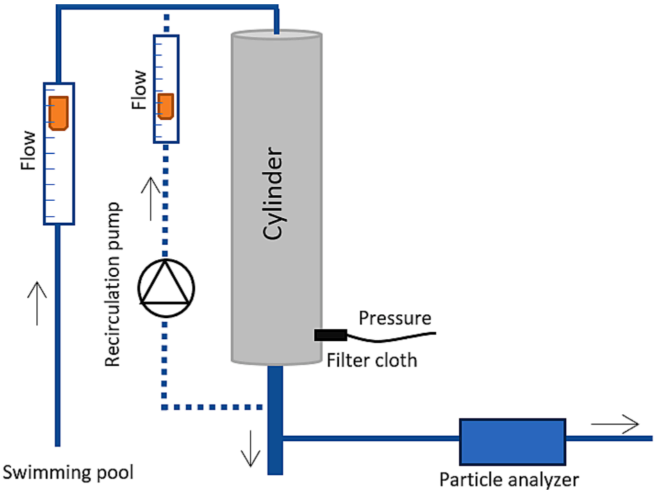

Fig. 2. Laboratory setup for filtering swimming pool water. A recirculation pump was used to recycle water while coating the filter cloth with Arbocel or Harbolite. The recirculation pump remained inactive during the filtration of swimming pool water.

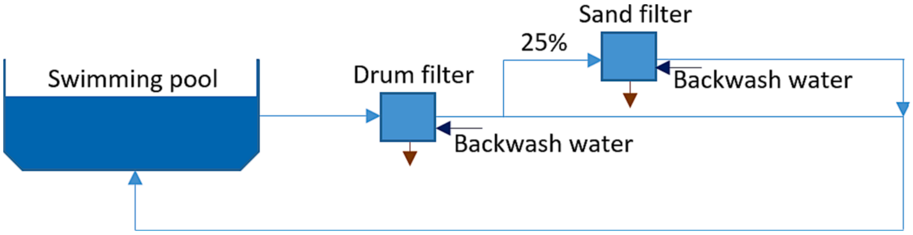

Fig. 1. Simplified sketch of swimming pool water, 25% of the water flow undergoes treatment through the sand filter.

Brea, CA, USA). The zetapotential of the particles in the rinse water was measured using a Zetasizer Nano ZS device (Malvern Instruments, Malvern, UK). The samples were diluted in swimming pool water before analysis.

2.2. Filtration of swimming pool water

Five filtration tests were conducted over a period of 30–60 min using a clean filter cloth and setting the water flow to 100–200 L/h. In addition, two tests were done filtering swimming pool water for 10 min with a flow of 200 L/h. At the end of filtration, particles were removed from the filter cloth, dispersed in approx. 50 mL tap water and the dry matter content was measured. Rinse water was necessary for removing particles from the filter cloth. The water was added and gently mixed with the filter cloth for 5 min, after which the rinse water was utilized to measure the dry matter content. Tests were done for all seven filter cloths.

Five experiments were conducted to determine if the accumulated material on the InBlue Sub-5 filter cloth could be utilized as a pre-coating agent for the filter. Particles from the rinse water were used as a coating on the filter cloth and added to the cloth before the filtration process. Tests have been conducted using both direct application of rinse water and coagulated rinse water. The process involved passing swimming pool water through a fresh filter cloth, followed by rinsing the cloth with tap water and applying a portion of the rinse water onto the filter cloth to serve as a pre-coat. The fraction of the rinse water utilized as a pre-coating agent was either 10 %, 20 %, 30 %, or 100 % of the collected rinse water. After pre-coating the filter cloth, filtration experiments were run for 30–60 min. At the end of two of the filtration tests, the particles were detached from the filter cloth and mixed with approximately 50 mL of tap water and the dry matter content was measured.

To determine whether coagulated rinse water particles to pre-coat the filter cloth would lead to improved rejection, four experiments were conducted. A suspension of particles was generated by filtering swimming pool water through a new InBlue Sub-5 filter cloth, rinsing the filter cloth with tap water and collecting the rinse water. The rinse water was coagulated with Dinofloc Aktive (Dinoflocs); polyaluminium hydroxychloride / dialuminium chloride pentahydroxide, with an aluminium content of 6 % w/w, a basicity of 85 % and a density of 1.15 g/cm^3. Three samples were prepared using Dinofloc flocculant to reduce the charge of the particles, for sample 1 the zetapotential was measured to 0.1 ± 0.2 mV, for sample 2 the zetapotential was measured to 0.62 ± 0.02 mV and for sample 3 to 3.50 ± 0.08 mV. An additional experiment was done by adding a high dose of Dinofloc flocculant to form positive charged particles. The zetapotential of this sample was measured to 22.8 ± 0.2 mV. The turbidity was measured using a portable turbidity (NTU) meter (Turbimax CUE25). The coagulated particles present in the rinse water was utilized to coat the filter cloth. For each batch, three separate experiments were conducted, where 10 %, 20 %, and 40 % of the coagulated particles were used to pre-coat the filter cloth. After coating the filter cloth, the filtration experiment was repeated and continued for 30–60 min.

During one of the tests, the particle size distribution was analyzed in the first 1 L of filtrate after coating the filter cloth. After end of filtration, particles were removed from the filter cloth, dispersed in app. 50 mL tap water and the dry matter content was measured. For all assays the particle size distribution was measured during the experiment.

2.3. Filtration with filter aid

Two types of filter aids were tested, Perlite (Harbolite® 900S) and cellulose fibers (Arbocel® B 800) hereafter called Harbolite and Arbocel powder. The density of the Harbolite powder was 2.3 g/mL and Arbocel 1.1 g/mL [19,22]. A InBlue Sub-5 filter cloth was coated with 50–200 g/m^2 of the Harbolite powder and 100–500 g/m^2 of the Arbocel powder. The powder was suspended in 1 L swimming pool water added to the filtration cylinder and cycled for 25 min. Particle size was measured in the filtrate during pre-coating and recycling of the water. After coating of the filter cloth, swimming pool water was filtrated for 30 min. Tests were conducted in which the filter cloth was coated with filter aid. Subsequently, the cylinder was disassembled, and the distribution of filter aid on the filter cloth was visually evaluated.

2.4. Analysis of filter cloth performance, swimming pool water and rinse water

The hydraulic resistance was measured as

$$R_t = \frac{\Delta P}{\mu \frac{Q}{A}} \tag{1}$$

where ΔP is the pressure drop across the filter cloth, Q is the water flow, A is the filter cloth area and μ is the viscosity of the filtrate and set to $8 \cdot 10^{-4}$ Pa s. The hydraulic resistance was measured over time and extrapolated to determine the initial hydraulic resistance of the virgin filter cloth (R_{mem}). The total resistance was also determined and reported after 10 min to show the impact of clogging on filtration performance (R_{10}).

An optical particle sizer (AccuSizer™ 780, Santa Barbara, California, USA) was used to measure particle size and concentration in swimming pool water. Measurements were carried out on swimming pool water before and after filtration. The flow through of the particle size analyzer was 30 mL/min and each sample test was continued for 30 s.

Particle rejection was evaluated as function of particle size

$$\sigma = 1 - \frac{C}{C_0} \tag{2}$$

where C is the concentration of particles measured after the filter cloth, and C_0 is the concentration of particles in the swimming pool water.

Counts of particles in the following sizes were obtained: 0.6–1 μm, 1–2 μm and 2–5 μm. The concentration of particles declined with time and the decline was fitted to an exponential equation.

$$C = C_i e^{-kt} \tag{3}$$

where C is the concentration of particles at a given time (t), C_i is the concentration of particles measured after the filter cloth at time zero, t is the time and k is the rate constant. The formula has been used to simulate particle rejection during cake filtration, where small particles are captured within the cake structure—a phenomenon referred to as cake blinding [23]. The formula has been derived from the equation for particle capture in deep filtration [24]. It assumes that the build-up of cake is proportional to the volume of filtrate and, consequently, to the time of filtration. During cake blinding, the formed cake captures small particles, whereby the filtrate turbidity decreases with filtration time. As the cake thickness increases, the particle removal also increases as $dC/dt = k'L$, where L is the cake thickness which increase proportional with time for constant flux filtrations [23].

The pressure drop across the filter cloth was measured during the test, and the pressure increase rate ($d\Delta P/dt$) was calculated, as well as the specific pressure increase rate given as the pressure increase per number of particles accumulated per unit area. The number of particles larger than 7 μm was determined and used to calculate the total number of particles accumulated on the filter cloth, including all large skin cells, while excluding smaller particles that partially pass through the filter cloth.

$$\alpha = \frac{d\Delta P/dt}{\left(\frac{Q}{A}\right)^2 c\mu} \tag{4}$$

The data was shown graphically by using a box plot with the minimum and maximum value, the median, the lower and the upper quartile.

3. Results

A filtration system was constructed and utilized to test filter cloths for treatment of swimming pool water. One filter cloth was selected for further investigation to assess the impact of particle coagulation, filter pre-coating, and long-term filtration on particle rejection.

3.1. Test of seven different filter cloths

Three metal filters and four polymer filters were used to remove particles from swimming pool water. Particle concentrations before and after filtration were measured. During the measurement of particle size distribution for untreated swimming pool water, a peak was observed for particles between 10 and 15 μm, consistent with findings from other studies [19]. The results for all seven filter cloths tested followed a comparable trend. Nearly all particles above 10 μm were removed, regardless of the filter cloth used, while particles below 10 μm was partly removed for all cloths. An exception is the SefarTex filter, where the rejection of particles between 10 and –20 μm is lower than for the other cloths.

The seven filters were compared by measuring the resistance of the virgin filter cloth, the increase in resistance after 10 min of filtration and particle rejection. Particle rejection was calculated for particles between 2 and 10 μm, which were challenging to remove. Due to the high number of particles below 2 μm and their significant variation over time, these particles were excluded in the calculation of particle rejection. Data are shown in Table 1, where the filter cloths have been arranged after the initial measured hydraulic resistance.

The initial hydraulic resistance varied from $0.7 \cdot 10^8$ m^{-1} to $8 \cdot 10^8$ m^{-1} or a factor of 10, which will have a significant impact on the capacity of e.g., a drum filter. Furthermore, a clear correlation between particle rejection and hydraulic resistance was not observed.

A better understanding of rejection was achieved by graphing particle concentrations over particle size and time. As an example, data for the InBlue Sub-5 filter cloth have been plotted (Fig. 3). For particles above 10 μm, the rejection was higher than 90 % after 10 min filtration. After 30 min, the filtration efficiency was further improved and almost all particles between 10 and 15 μm were removed.

After 10 min, 50 % of particles above 5 μm were removed. The performance of the filter improved with time and after 30 min, 80 % of the particles above 5 μm were removed. Notice that the concentration of particles in the pool water may have changed during filtration. For particles between 0.6 and 1 μm the initial concentration was measured to be 1160 ± 30 #/mL and the final concentration was 1110 ± 50 #/mL. For particles between 0.7 and 1 μm the initial concentration was 280 ± 20 #/mL and the final concentration was 220 ± 10 #/mL. For particles between 2 and 5 μm the initial concentration was 65 ± 4 #/mL and the final concentration was 46 ± 3 #/mL. The variation of particle concentration in inlet could not explain the improved quality of the filtrate (Fig. 3). Particle concentration in the filtrate declined with time (Fig. 4), which was a general trend for all experiments.

An exponential decrease in particle concentration was observed. This aligns with the theory of cake filtration and cake blinding [25,26], but also result from the blocking and restriction of pores. The improved removal rate was probably due to an increased steric hindrance due to an accumulation of particles deposited on the filter cloth or small particles that collide with larger particles and adhere to the cake structure. When more particles are trapped on the filter cloth, they begin to hinder the transport of smaller particles through the filter cloth. Overall, particles with larger sizes exhibited a more rapid exponential decrease.

Table 1
Hydraulic resistance and particle rejection (2–10 μm) for seven filter cloth.

	R_{mem} (m^{-1})	R_{10} (m^{-1})	Rejection
ODW6	$0.67 \cdot 10^8$	$0.74 \cdot 10^8$	47 %
InBlue Sub-5	$1.0 \cdot 10^8$	$1.2 \cdot 10^8$	48 %
AK50	$1.2 \cdot 10^8$	$1.8 \cdot 10^8$	55 %
FibG260	$1.4 \cdot 10^8$	$2.3 \cdot 10^8$	30 %
HB5S	$4.0 \cdot 10^8$	$4.2 \cdot 10^8$	51 %
FibrootB	$5.0 \cdot 10^8$	$8.4 \cdot 10^8$	6 %
SefarTex	$8.2 \cdot 10^8$	$14 \cdot 10^8$	3 %

3.2. Analysis of deposed particles on the filter cloth

Swimming pool water was filtered through a InBlue Sub-5 filter cloth for 30 min. After filtration, particles were detached from the cloth by rinsing the filter cloth with tap water. No particles were visually observed on the filter cloth after rinsing, and the permeability of the filter was reestablished. When considering particle volume, most of the particles on the filter cloth (volume based) where particles between 15 and 200 μm (Fig. 5). The mean size was measured to be 83 μm, d10 was 14 μm and d90 was measured to be 184 μm. Still, particles below 15 μm were collected on the filter (Fig. 5). Data confirms that smaller particles were collected at the filter cloth. An extra test was performed, filtering swimming pool water for 11 min with a flow of 27 mL/min. The number of particles larger than 5 μm was measured to be 208 #/ml in the swimming pool water. Assuming that all particles were caught by the filter and the density of the particles was 1 g/cm^3, the total mass of particles collected on the filter cloth was calculated to be 0.8 mg. The filter cloth was rinsed with water, and the dry matter content was measured to 5 mg. This experimental measured mass of particles was higher than expected, probably due to hairs and other large particles being collected by the filter. Smaller particles may also be collected during filtration, but their accumulated mass will have almost no effect on the total mass. Using the experimentally measured dry weight of particles gives an average particle coverage of the filter cloth equal to 1 g/m^2.

The number of particles in the swimming pool water was difficult to analyze due to the low concentration, but it was possible to analyze the number of particles on the filter cloth. Data shows that the particles were negatively charged with a zeta potential of −23 ± 2 mV.

3.3. Use of particles in rinse water as secondary filter

A series of tests were done where the filter was rinsed after filtration, and a portion of the particles were recycled to coat the filter cloth. The filter cloth underwent no further treatment before coating. Subsequently, a new filtration cycle was initiated. By pre-coating the filter cloth with particles, the rejection increased significantly and quickly, eventually reaching a similar level of rejection observed in longer filtration times (Fig. 6). This effect was also observed when as little as 30 % of the particles from the rinse water was recycled. However, the rejection did not show significant improvements with increasing filtration time.

The data confirmed that the particle layer on the filter cloth improves rejection of small particles. Two tests were performed, where the dry matter was measured after filtration, resuspension in water and filtering of the suspension using the filter cloth. The test was done to determine the mass of particles in the pre-coat layer. The first test was done by filtering swimming pool water for 92 min. The particle concentration in the swimming pool water was measured to be 84 #/ml (>5 μm). The dry matter of the cake after resuspension and pre-coating of the filter was measured to be 27 mg or 5.4 g/m^2. It was difficult to get precise measurement due to the small number of particles and the risk of particles being trapped in the pore structure of the cloth, but data confirm the low amount of particle on the filter cloth. The experimental measured concentration was higher than data estimated from the measured particle count in the feed giving approximately 2.6 mg. The second test was done for 15 min, the particle concentration in the swimming pool water was measured to be 134 #/ml (>5 μm). The dry weight after resuspension and pre-coating of the filter cloth was measured to be 22 mg (4.4 g/m^2). The measured particle size count was used to estimate the mass of cake

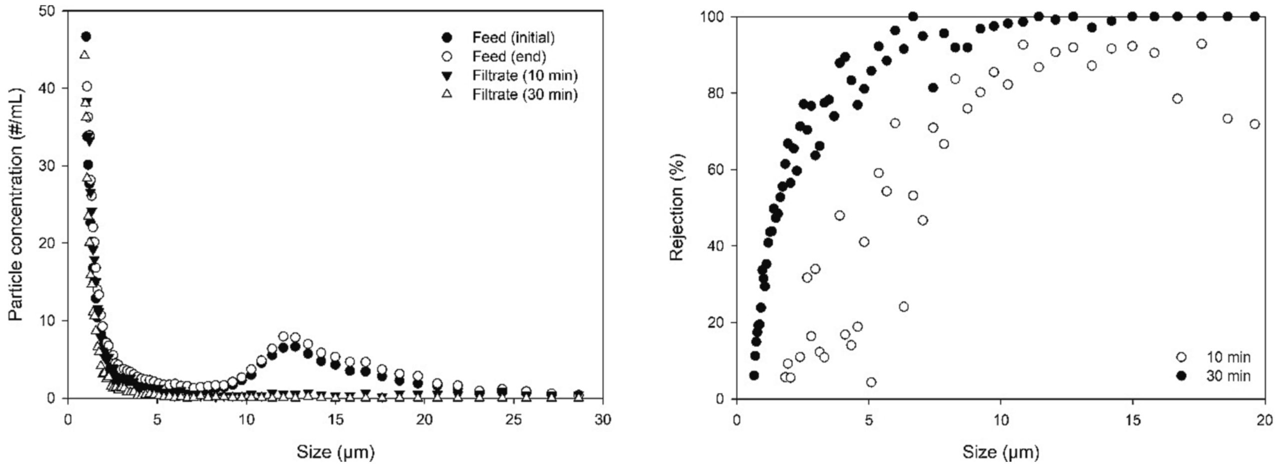

Fig. 3. Particle size distribution in swimming pool water and filtered water (left) and particle rejection measured after 10 min and 30 min of filtration (right) using a InBlue Sub-5 filter.

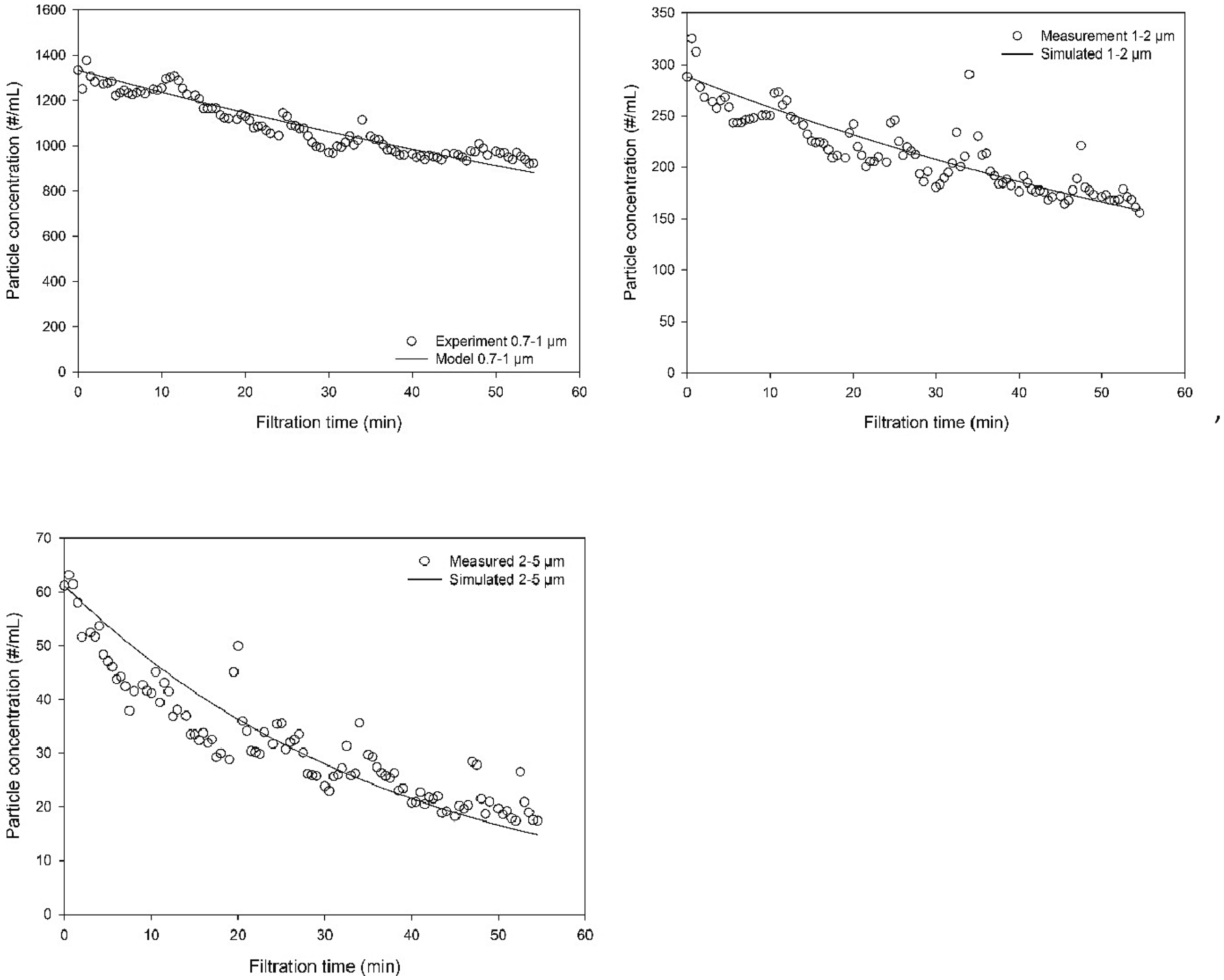

Fig. 4. Particle concentration in filtrate as function of filtration time using a InBlue Sub-5 filter.

and was calculated to be 0.7 mg setting the density to 1000 mg/cm^3. This estimate is more than 30 times lower than the measured dry content. The density of the particles is unknown, and the particle concentration may vary during the experiment. Additionally, very large like large hairs and fibers, visually observed in the rinse water, are likely not accounted for by the particle size analyzer. Nevertheless, the cause of the large discrepancy between the measured dry content and the estimation based on particle measurements remains unknown. It is not

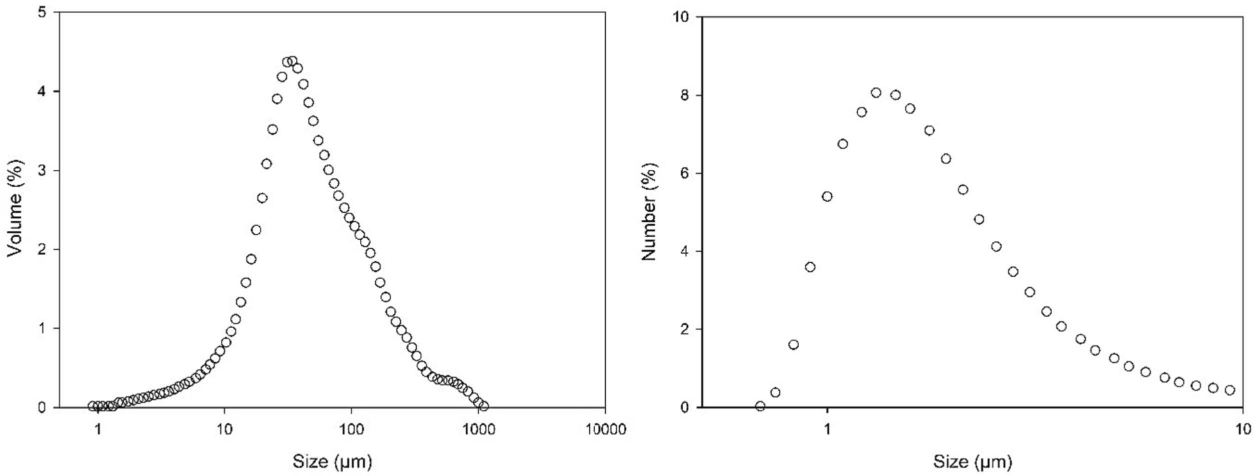

Fig. 5. Particle distribution in rinse water after cleaning filter cloth used for filtering swimming pool water for 60 min.

possible to estimate the mass of particles from the results obtained by particle size analysis.

3.4. *Coagulation of particles collected from rinse water*

To investigate the possibility of further improving the filtration, experiments were conducted in which particles from the rinse water were coagulated prior to being added to the filter cloth as a pre-coat material. The particles were coagulated with polyaluminium-chloride (Dinofloc) which is positively charged and binds to the surface of the particles. This increases the positive charge of the particles and thereby also the zetapotential (Fig. 7). The point of zero charge was measured after addition of 0.2–0.5 mg Dinofloc/g particles. The turbidity of the sample change from 27 ± 2 NTU to 34 ± 5 NTU after coagulation, indicating some aggregation of the particles.

The experiment with coagulated particles as a pre-coat was performed using neutral and positively charged particles. The neutralization of the particles was chosen because it was expected to lead to more efficient coagulation and particle collection from the rinse water. This is expected to reduce the loss of small particles through the filter during pre-coating and promote the formation of a cake structure on the filter cloth. Positively charged particles were chosen to test whether they would improve the collection of small, negatively charged particles from the swimming pool water. In one of the experiments, 40 % of the coagulated rinse water was employed as a pre-coat. The zetapotential of the particles was near zero. Despite the coagulation process, particle rejection was not improved, and in some instances, it may have even worsened (Fig. 8). The flocculant itself may form small particles that can pass the filter cloth. In addition, some of the particles may be coagulated, resulting in a more open structure.

An additional test was done to measure the cake amount after the production of the pre-coated layer with the coagulated rinse water. The test was done by filtering swimming pool water for 15 min. The particle concentration in the swimming pool water was measured to be 20 #/ml (>5 µm). The dry matter of the cake after resuspension and pre-coating of the filter was measured to be 7 mg or 1.4 g/m^2 and contains the added flocculant.

3.5. *Bleeding of particle during and after pre-coating*

Both untreated rinse water and rinse water treated with a coagulant were recycled to coat the filter cloth with particles. After recycling of the rinse water, the first liters of filtrate were collected and mixed, the particle size distribution was measured, and the total number of particles was calculated from particle concentration and filtrate volume (Fig. 9).

The rinse water recycled onto the filter cloth was obtained by rinsing a filter cloth after 10 min. filtration of swimming pool water The particle size distribution of the filtered swimming pool water during this 10-minute period was analyzed by comparing the particle size distribution before and after passing through the filter cloth. The collected data was then used to calculate the total number of particles in the untreated swimming pool water and the filtered water (refer to Fig. 9). The difference between these measurements (grey points) represents the number of particles retained on the filter cloth and thereby the number of particles that end up in the rinse water.

A significant portion of the small particles collected from the rinse water, specifically 50–80 % of the particles smaller than 8 µm, passes through the filter cloth after the coating process. The high concentration of small particles was not observed in the previous experiments, where the first particle size measurement was conducted after 1 min (Fig. 8). It appears that the small particles were washed out after 1 min, during which 1.6 L of swimming pool water was treated. This volume corresponds to 0.5 m^3/m^2 filter cloth. Coagulating particles before pre-coating or higher pressure may reduce particle leakage.

3.6. *Pressure loss across the filter cloth*

During filtration of swimming pool water, particles were deposited on the filter cloth. This leads to an increase in hydraulic resistance across the filter. The pressure loss across the filter cloth was measured in the experiment, and in general, it tended to increase nearly linearly with time. This was a general trend starting at approximately 10 mBar and gradually increasing to reach up to 400 mbar. Further, the initial pressure was higher for the pre-coated filter cloth. The linear trend corresponded well with the theory of particle deposition on the filter cloth and indicated that pore blocking mechanism was less important for the experiment, or a relatively small fraction of pores were blocked. The mathematical formula for pressure at constant flow rate filtration for pore blocking can be found in literature [26]. The slope of the line was expected to be dependent on the particle concentration in the swimming pool water, but no clear trend was observed, possibly due to the presence of hair or other particles, that were not measured. For some of the experiments, the slope was higher for the pre-coated filter cloth, while for others, it was the opposite. This lack of consistency indicates that there is no clear overall trend.

In general, the required pressure to ensure a constant flow increased with 3 – 10 mbar/min, for a few experiments up to 20–30 mbar/min, which are to some extent dependent on flow and particle concentration (Fig. 10). The specific resistance was calculated to be around 0.5–1.5 m per deposed particles. The number of collected particles was determined by considering those within the size range of 7–50 µm, as it was assumed

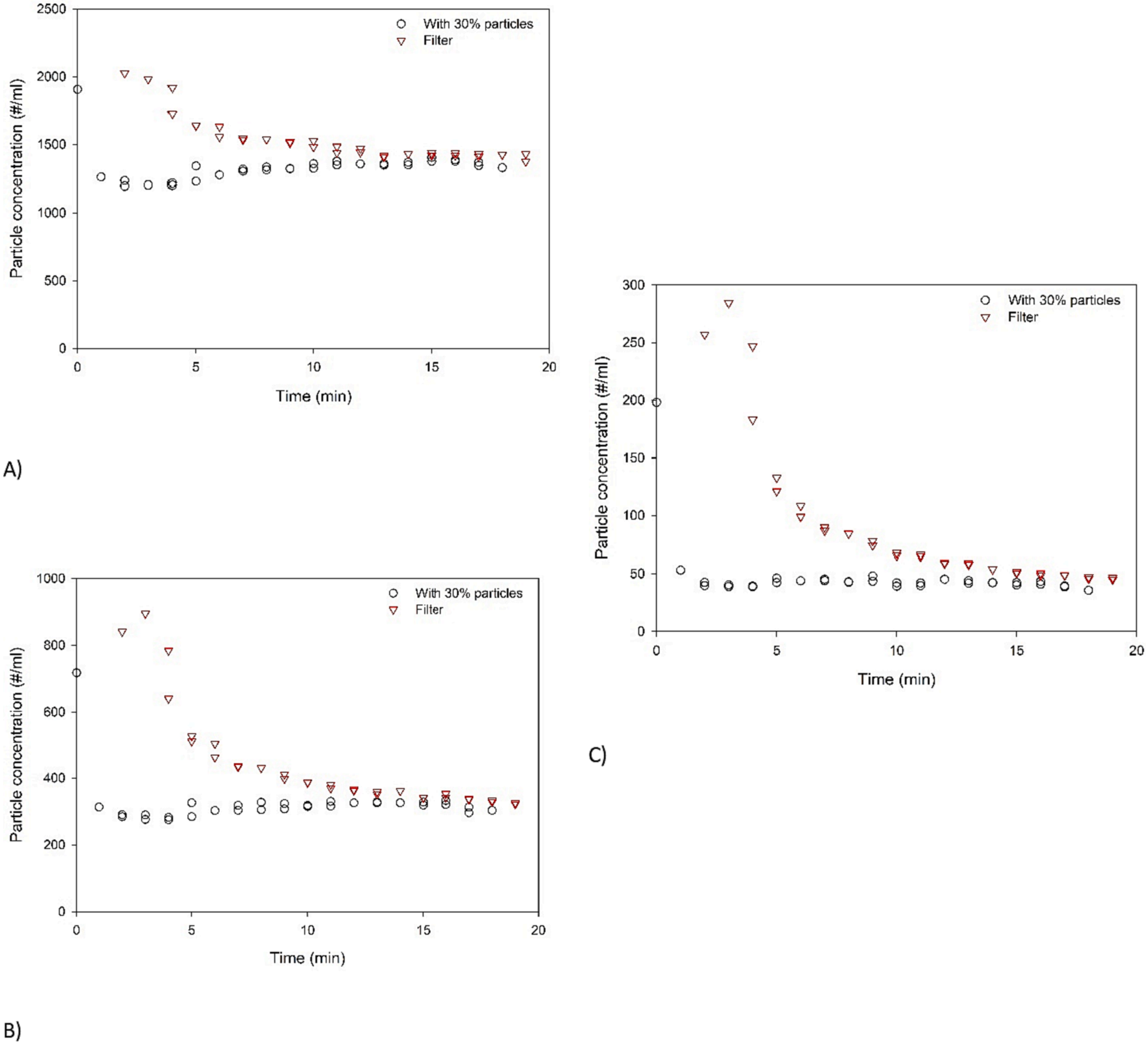

Fig. 6. Particle concentration in filtrate as function of filtration time with pre-coat (black circles) and without pre-coat (red triangle) A) 0.6–1 μm, B) 1–2 μm, and C) 3–5 μm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that the majority of particles deposited on the filter cloth fell within this range. Assuming an average diameter of 40 μm and a density of 1000 kg/m^3 gives a specific resistance of 1.5·10^{10} m/kg. This is a rough estimate, but the number is comparable with specific resistance calculated for cake filtrations.

The pressure drop across the filter typically remains below 100 mbar, for a filtrate flux of 8–17 Lm^{-2}s^{-1} and up to 30 min filtration. The pressure drop increased during filtration. There was no clear tendency observed for the pressure loss, but the pressure drop increase with up to 10 mbar per min including precoated filter cloths.

3.7. Filter aid experiments

The use of filter aids was tested as a method to enhance particle removal. During the test, the filter was coated with either Harbolite or Arbocel filter aids prior to filtration. To examine how the thickness of the pre-coat layer affects the filtration outcome, Harbolite was added in varying amounts during the experiment. During the formation of the Harbolite pre-coat layer, small particles pass through the filter cloth and enter the filtrate (Fig. 11). Thus, the water was recirculated for 5 and 10 min with a flow rate of 100 L/h. After filtration, the filter cloth was gently removed and visually examined. The Harbolite filter aid was more evenly distributed and easier to apply uniformly on the cloth compared to the Arbocel filter aid. Two examples of the coating are shown in Fig. 11. It is seen that the distribution of Arbocel filter aid on the filter cloth was uneven, needing some attempts to find an effective method for coating the filter.

During pre-coating, small filter aid particles penetrated the filter cloth. The filtrate water was recycled, and monitored for the particle concentration in the filtrate was monitored. The particle concentration declined over time, stabilizing after 10 min (Fig. 12). It is worth noting that the 10-minute duration for the coating procedures may pose a challenge that needs to be addressed prior to large scale implementation.

The pre-coated filter cloth was then tested for filtration of swimming pool water. The data shows a significant improvement of the filtrate

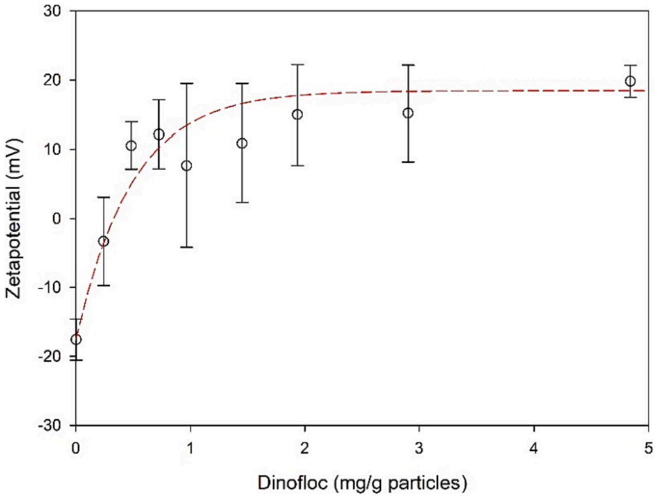

Fig. 7. Zeta potential for particles in the rinse water.

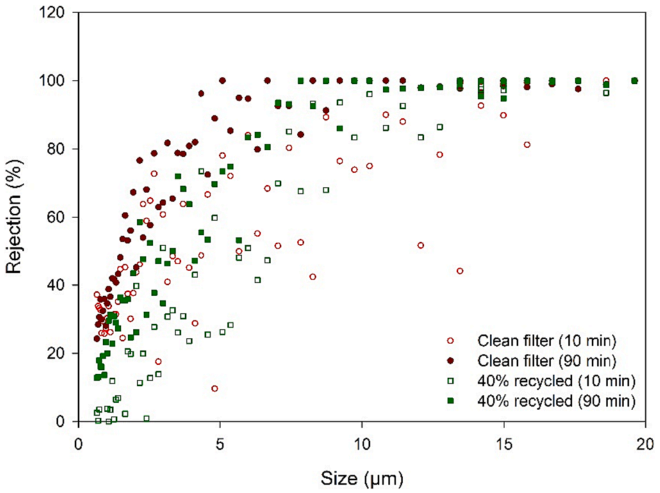

Fig. 8. Particle rejection measured after 10 and 90 min of filtration with a clean filter cloth or a filter cloth pre-coated with coagulated particles from the rinse water.

quality when using the filter aid (Fig. 13). Further, particle rejection increased with thickness of the pre-coat layer.

The particle rejection was calculated as a function of the pre-coat layer thickness. For particles between 2 and 10 μm, the particle rejection was found to be 75 % or higher. Particles of these sizes are difficult to catch with the filter cloth alone (Fig. 13). For a clean filter cloth, the rejection was measured to be 20 %. It should be noted that the particle rejection of the clean filter cloth increased during the filtration process. However, even after 45 min of filtration, the rejection for the clean filter cloth was still not as high as that achieved with the filter aid. Specifically, after 10 min of filtration, the rejection for the clean filter cloth was only 30 % (particles between 2 and 10 μm), and it increased to 75 % after 45 min. Additionally, smaller particles were also removed, with a rejection of approximately 20 % for particles below 2 μm after 45 min. The variation in the data observed for the filter cloth without Harbolite was higher than that for the pre-coated filter cloth. This is likely because the improved rejection is a result of the deposition of particles on the filter cloth, which depends on both the particle concentration in the raw swimming pool water and the morphology of the particles.

Similar data was observed, when Arbocel was used as pre-coat (Fig. 14). Small particles also passed the filter aid during coating, the total concentration of particles in the filtrate was however lower than for Harbolite and initially measured to approximately 300 #/ml.

4. Discussion

The seven filters that has been tested are all capable of effectively removing particles from 10 − 20 μm. Smaller particles are able to pass through the filter to some degree. The permeability of the tested filter cloths varies tenfold. However, no distinct correlation between permeability and particle rejection has been observed. The additional hydraulic resistance arising from particle rejection by the filter cloth is highly dependent on the type of filter cloth tested. Two distinct clogging mechanisms may affect permeability: pore blocking, where particles become trapped within the pores, or the formation of a filter cake. The fluctuating hydraulic resistance of particles suggests that pore blocking significantly contributes to filter cloth clogging.

Since all the filter cloths only partially remove particles smaller than 10 μm, other solutions have been tested including recirculation of particles from the rinse water, coagulation and pre-coating with particles from the rinse water, the use of filter aids and long-term operation.

Initially, mostly particles between 10 and 20 μm are rejected by the filter cloth, but the filtration performance increase with time. In the case of swimming pool water, it is expected that particles will partly penetrate and block the pores, as is frequently observed during the initial periods of filtration [27,28]. The filtration of swimming pool water cannot be entirely compared to other filtration studies where the feed concentration is much higher, and thick cakes are formed. Nevertheless, an exponential function was able to explain the enhanced particle rejection well. Consequently, a relationship is established between the number of large particles trapped on the filter cloth and the removal of smaller particles. The deposition of particles on or within the filter cloth materials leads to better particle removal. The measured quantity of material on the filter cloth ranges from 1 to 5.4 g/m^2. Assuming a particle density of 1000 g/L and a porosity of 0.4, the average thickness of the particles is between 2.5 and 13.5 μm. This is a rough estimate, but the calculation shows that there are not enough particles to fully cover the entire surface of the filter cloth; however, there is a potential for partial blockage of the filter cloth pores. The pressure drop across the filter cloth increases over time from 10 to 400 mbar, potentially influencing particle rejection. However, this aspect has not been further studied. Recycling particles from the rinse water to the filter cloth, with 10–40 % of the particles in the rinse water recycled, improved the initial removal of small particles. This can be a method to improve the filtrate quality, but small particles are released during pre-coating. Therefore, the first filtrate water must be removed. Coagulation with polyaluminium chloride has been tested as a method to neutralize the negatively charged particles in the rinse water but using coagulated rinse particles to pre-coat the filter does not improve the filtration. Additionally, coagulated particles with a net positive charge do not improve filtration, which suggests that particle adhesion is not important for the removal of small particles, but rather steric hindrance.

The use of filter aids such as Harbolite and Arbocel improve removal efficiency compared to recycling particles from the rinse water, likely due to the higher amount of pre-coat material. When using Harbolite and Arbocel, 50 – 200 g of particles per m^2 were added to the filter cloth, giving an estimated thickness of 50–1200 μm depending on the porosity and density. This is enough to cover the filter cloth. The pressure drop was still low after addition of the filter aid (Fig. 10). Harbolite filter aid results in a more uniform coating of the filter compared to Arbocel. It is possible to cover the entire filter cloth with the highest tested quantity of filter aid. However, it can be more challenging to achieve similar results in other filtration setup geometries.

The data obtained is consistent with the expected results of improved particle rejection due to steric hindrance. Theoretical calculations have been performed, employing a simplified model and assuming monodisperse spherical particles. The calculations showed that the pore size can be reduced to 0.155–0.414 times the diameter of the particles (D) on

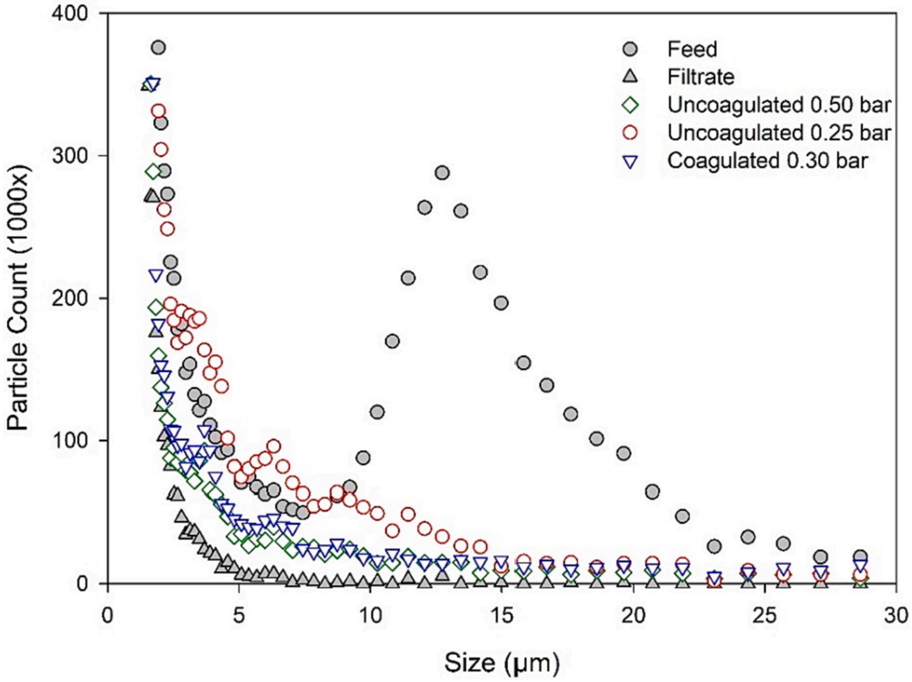

Fig. 9. Total number of particles in feed, and filtrate during filtration of swimming pool water measured during a period of 10 min (gray circles and triangles). Number of particles that pass the filter during pre-coating the filter cloth with uncoagulated (green rhomboid and red circle) or coagulated (blue triangle) rinse water. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

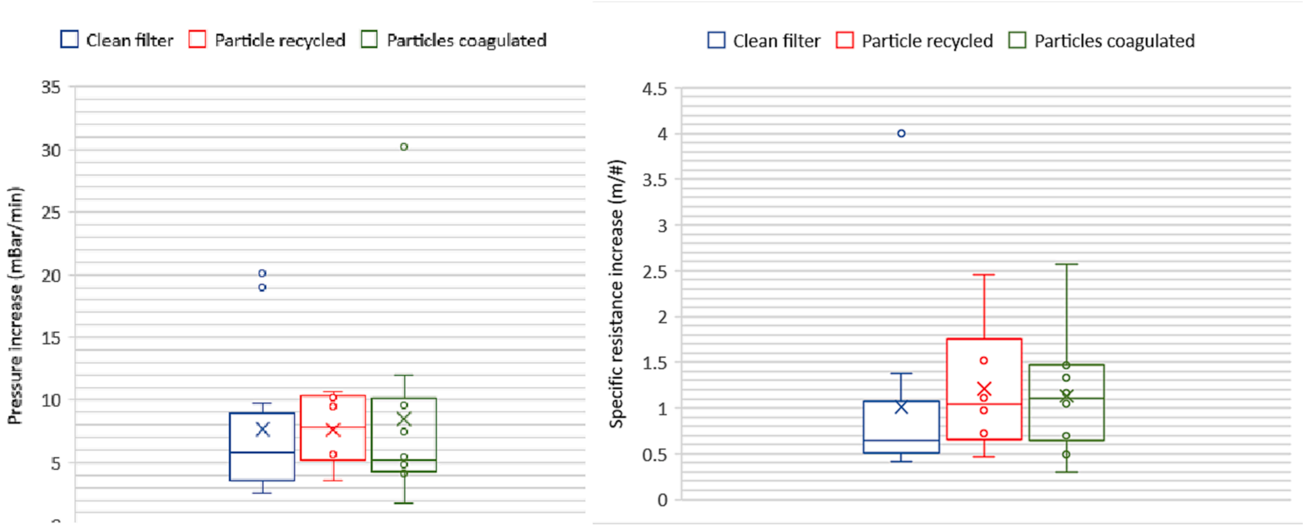

Fig. 10. Pressure loss rate for all experiments separated into filtration with clean filter, the filter pre-coated with particle from the rinse water and the filter pre-coated with coagulated particles from the rinse water (left), and the pressure rise per particle collected by the filter cloth (right).

the filter cloth, assuming closed-packed spherical particles deposed on the filter cloth (Fig. 15). The particles initially deposited on the filter cloth are larger than the pores in the cloth, but with time smaller particles are cached because the pores were partially blocked or material on the filter cloth formed a secondary filter. Particles on the filter cloth will form a cake with smaller pores than the filter cloth but as shown with the theoretical calculations, that particles smaller than 5 times the initial pore size of the filter cloth cannot be removed by steric hindrance. The same is true for filter aid. Thick pre-coat layers will further improve filtration efficiency, but it will also cause an increase in pressure drop, which may be problematic. Thus, for a 10 µm filter cloth, the best possible rejection will be around 2 µm and for 5 µm filter cloth the best possible rejection will be around 1 µm if steric hindrance is the sole mechanism for particle rejection. This is a rough estimation since the particles are not monodisperse and not necessarily spherical. However, it may provide a hint regarding the minimum particle size that can be removed.

5. Conclusion

Seven different filter cloths have been tested. The filter cloths effectively remove particles above 10 µm, but partially smaller particles are only partially removed. Nevertheless, the study indicates that alternative strategies can enhance the removal of small particles. During filtration, particles clog the filter and improve particle rejection, so after 30 min, most of the particles down to around 5–6 µm and approximately

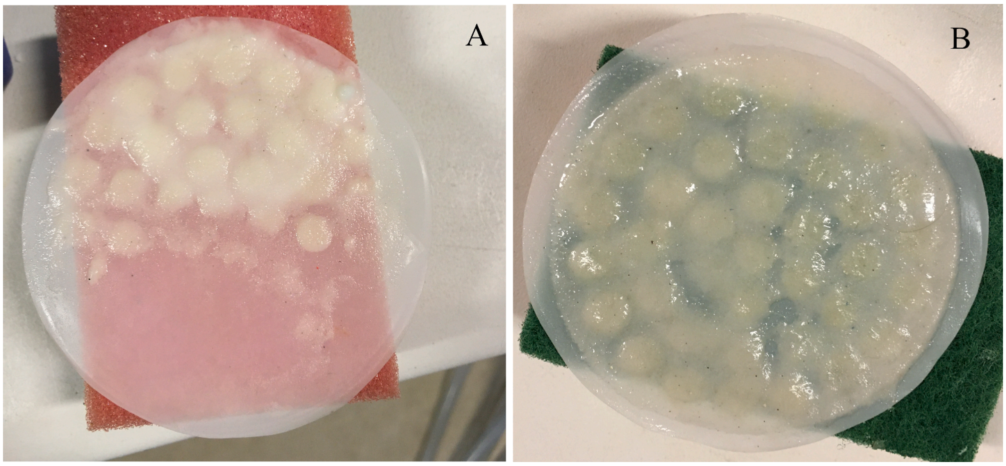

Fig. 11. Distribution of filter aid on the filter cloth, with A) 200 g/m^2 of Arbocel and B) 200 g/m^2 of Harbolit.

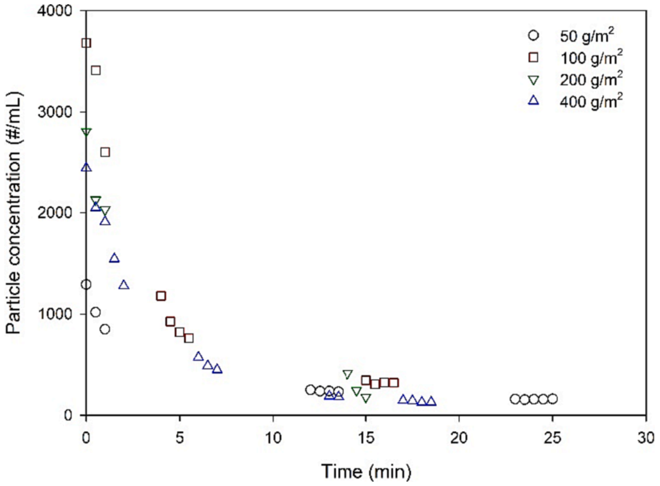

Fig. 12. The concentration of particles in the filtrate during filter coating process with Harbolite.

50 % of particles down to 2 µm were removed. Extended filtration periods between rinsing can therefore be beneficial.

To enhance initial particle rejection a portion of the rinse water can be recycled to the filter cloth before filtration. Organic particles are still removed from the filter thereby reducing pressure drop and mitigating the risk of formation of dissolved organic pollutants. The first filtrate needs to be discharged to prevent the leakage of small particles into the basin. Addition of coagulant to the rinse water may reduce particle leak.

Another approach to increase particle removal is the use of filter aids. The addition of 100 g of Harbolite or Arbocel per square meter of filter cloth significantly enhances particle rejection. Although the pre-coating extended treatment time by 10 min, resucing in a reduced system capacity, the effect was an 80 % removal of particles above 2 µm, which is significantly better than without the filtering aid where only around of the particle down to 2 µm were removed.

CRediT authorship contribution statement

Morten Lykkegaard Christensen: Formal analysis, Investigation, Supervision, Writing – original draft. **Cristina Cvitanich:** Methodology, Writing – review & editing. **Søren Fredberg Weiss:** Methodology, Formal analysis, Visualization. **Julie Byrgesen Hansen:** Methodology, Visualization. **Morten Møller Klausen:** Formal analysis, Investigation, Supervision, Writing – original draft. **Peter Vittrup Christensen:** Conceptualization, Validation, Writing – review & editing, Project administration.

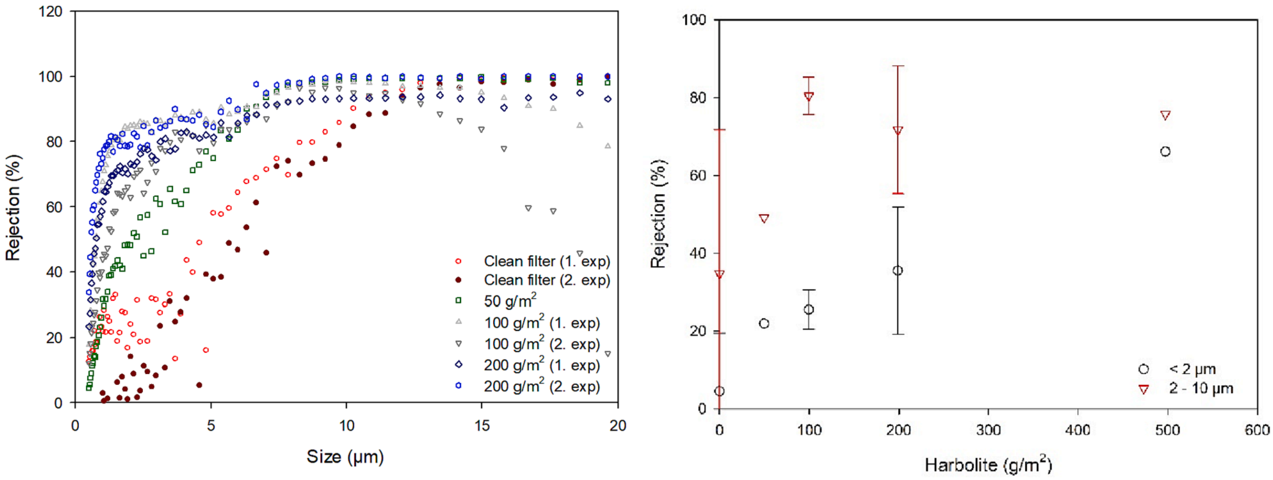

Fig. 13. Particle rejection measured after 10 min of filtration at the filter with Harbolite as filter aid shown as function of particle size (left) and pre-coat layer thickness (right).

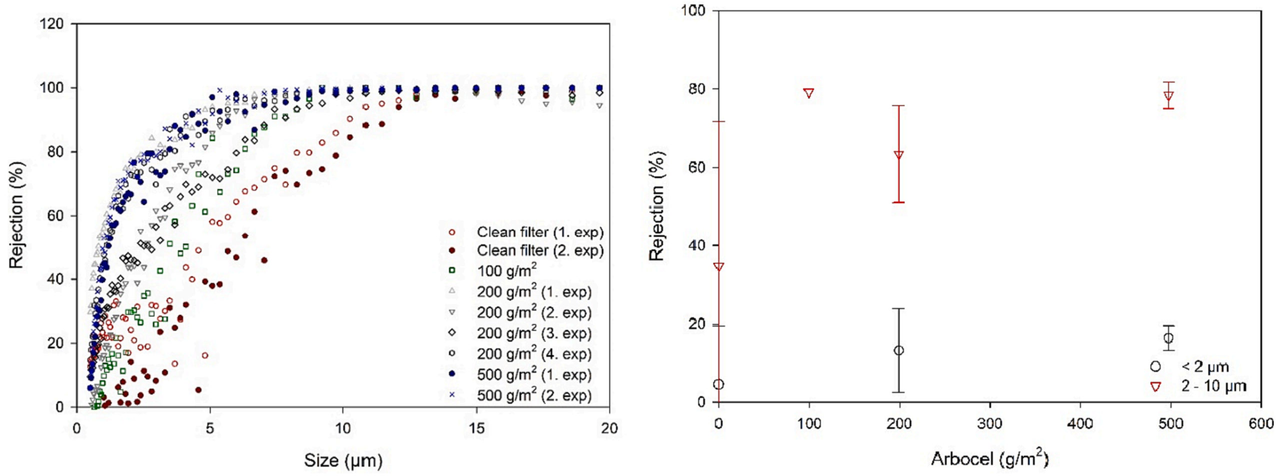

Fig. 14. Particle rejection measured after 10 min of filtration at the filter with Arbocel as filter aid shown as function of particle size (left) and pre-coat layer thickness (right).

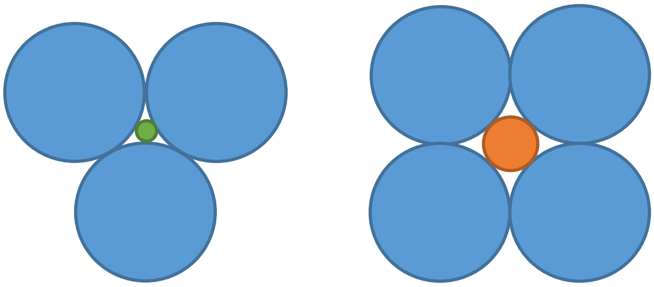

Fig. 15. Pores size in hexagonal close packed spherical particles (left) are 0.155D (green particle) and pore size in cubic close packed spherical particles (right) is 0.414D (orange particle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] J.S. Lakind, S.D. Richardson, B.C. Blount, The good, the bad, and the volatile: Can we have both healthy pools and healthy people? *Environ. Sci. Tech.* 44 (9) (2010) 3205–3210, https://doi.org/10.1021/es903241k.

[2] M.G.A. Keuten, F.M. Schets, J.F. Schijven, J.Q.J.C. Verberk, J.C. van Dijk, Definition and quantification of initial anthropogenic pollutant release in swimming pools, Water Res. 46 (11) (2012) 3682–3692, https://doi.org/10.1016/j.watres.2012.04.012.

[3] M.G.A. Keuten, M.C.F.M. Peters, H.A.M. Daanen, M.K. de Kreuk, L.C. Rietveld, J.C. van Dijk, Quantification of continual anthropogenic pollutants released in swimming pools, Water Res. 53 (2014) 259–270, https://doi.org/10.1016/j.watres.2014.01.027.

[4] R.A.A. Carter, C.A. Joll, Occurrence and formation of disinfection by-products in the swimming pool environment: A critical review, J. Environ. Sci. (China) 58 (2017) 19–50, https://doi.org/10.1016/j.jes.2017.06.013.

[5] M. Panyakapo, S. Soontornchai, P. Paopuree, Cancer risk assessment from exposure to trihalomethanes in tap water and swimming pool water, J. Environ. Sci. 20 (3) (2008) 372–378, https://doi.org/10.1016/S1001-0742(08)60058-3.

[6] C.M. Villanueva, K.P. Cantor, J.O. Grimalt, N. Malats, D. Silverman, A. Tardon, R. Garcia-Closas, C. Serra, A. Carrato, G. Castaño-Vinyals, R. Marcos, N. Rothman, F.X. Real, M. Dosemeci, M. Kogevinas, Bladder cancer and exposure to water disinfection by-products through ingestion, bathing, showering, and swimming in pools, Am. J. Epidemiol. 165 (2) (2007) 148–156, https://doi.org/10.1093/aje/kwj364.

[7] C.M. Villanueva, L. Font-Ribera, Health impact of disinfection by-products in swimming pools, Annali Dell'istituto Superiore Di Sanita 48 (4) (2012) 387–396, https://doi.org/10.4415/ANN_12_04_06.

[8] K.M. Thompson, Changes in children's exposure as a function of age and the relevance of age definitions for exposure and health risk assessment, MedGenMed Medscape General Medicine 6 (3) (2004) 2.

[9] B.T. Croll, C.R. Hayes, S. Moss, Simulated Cryptosporidium removal under swimming pool filtration conditions, Water and Environment Journal 21 (2) (2007) 149–156, https://doi.org/10.1111/j.1747-6593.2006.00065.x.

[10] A. Doménech-Sánchez, E. Laso, C.I. Berrocal, Water loss in swimming pool filter backwashing processes in the Balearic Islands (Spain), Water Policy 23 (5) (2021) 1314–1328, https://doi.org/10.2166/wp.2021.217.

[11] W. Studziński, W. Poćwiardowski, W. Osińska, Application of the swimming pool backwash water recovery system with the use of filter tubes, Molecules 26 (21) (2021) 6620, https://doi.org/10.3390/molecules26216620.

[12] B. Skibinski, P. Müller, W. Uhl, Rejection of submicron sized particles from swimming pool water by a monolithic SiC microfiltration membrane: Relevance of steric and electrostatic interactions, J. Membr. Sci. 499 (2016) 92–104, https://doi.org/10.1016/j.memsci.2015.10.033.

[13] E. Barbot, P. Moulin, Swimming pool water treatment by ultrafiltration-adsorption process, J. Membr. Sci. 314 (1–2) (2008) 50–57, https://doi.org/10.1016/j.memsci.2008.01.033.

[14] M. Dudziak, J. Wyczarska-Kokot, E. Łaskawiec, A. Stolarczyk, Application of ultrafiltration in a swimming pool water treatment system, Membranes 9 (3) (2019) 44, https://doi.org/10.3390/membranes9030044.

[15] T. Glauner, P. Waldmann, F.H. Frimmel, C. Zwiener, Swimming pool water - Fractionation and genotoxicological characterization of organic constituents, Water Res. 39 (18) (2005) 494–4502, https://doi.org/10.1016/j.watres.2005.09.005.

[16] A.M. Klüpfel, T. Glauner, C. Zwiener, F.H. Frimmel, Nanofiltration for Enhanced Removal of Disinfection by-Product (DBP) Precursors in Swimming Pool Water-Retention and Water Quality Estimation, Water Sci. Technol. 63 (2011) 1716–1725, https://doi.org/10.2166/wst.2011.213.

[17] E. Łaskawiec, M. Madej, M. Dudziak, J. Wyczarska-Kokot, The use of membrane techniques in swimming pool water treatment, Journal of Ecological Engineering. 18 (4) (2017) 130–136. https://doi.org/10.12911/22998993/74282.

[18] E. Łaskawiec, M. Dudziak, J. Wyczarska-Kokot, Evaluation of the effect of body fluid analogs on the parameters of nanofiltration during the purification of swimming pool water, SN Applied Sciences 1 (2019) 566, https://doi.org/10.1007/s42452-019-0568-3.

[19] M.L. Christensen, M.M. Klausen, P.V. Christensen, Test of precoat filtration technology for treatment of swimming pool water, Water Sci. Technol. 77 (3) (2018) 748–758, https://doi.org/10.2166/wst.2017.593.

[20] M.M. Klausen, Forundersøgelser og teknologiafprøvning til forbedret vandkvalitet og indeklima for svømmebade og badelande – Case Lalandia (in Danish), By- og Landskabsstyrelsen, 2010, www.blst.dk.

[21] O. Grønborg, G.H. Kristensen, M.M. Klausen, Udvikling og afprøvning af svømmebadsvandteknologi til energieffektiv reduktion af THM og partikulært organisk stof (in Danish), Styrelsen for Vand- Og Naturforvaltning (2016).

[22] I. Turku, T. Kärki, Reinforcing wood-plastic composites with macro- and micro-sized cellulosic fillers: Comparative analysis, J. Reinf. Plast. Compos. 32 (22) (2013) 1746–1756, https://doi.org/10.1177/0731684413496574.

[23] B. Sørensen, K. Keiding, S. Lauritzen, A therotical model for blinding in cake filtration, Water Environ. Res 69 (2) (1997) 168–173, https://doi.org/10.2175/106143097X125326.

[24] A.C. Payatakes, C. Tien, R.M. Turian, Trajectory calculation of particle deposition in deep bed filtration: Part I. Model Formulation, *AIChE J* 20 (5) (1974) 889–900, https://doi.org/10.1002/aic.690200509.

[25] S. Ripperger, W. Gösele, C. Alt, T. Loewe, Filtration, 1 Fundamentals in Ullmann's Encyclopedia of industrial chemistry, Wiley, 2013.

[26] E. Iritani, N. Katagiri, Developments of blocking filtration model in membrane filtration, Kona Powder Part. J. 33 (2016) 179–202. https://doi.org/10.14356/kona.2016024.

[27] T. Weigert, S. Ripperger, Effect of filter fabric blinding on cake filtration, Filtr. Sep. 34 (5) (1997) 507–510, https://doi.org/10.1016/S0015-1882(97)84764-7.

[28] P. Sørensen, J. Christensen, J. Bruus, Effect of small scale solids migration in filter cakes during filtratin of wastewater solids, Water Environ. Res 67 (1) (1995) 25–32, https://doi.org/10.2175/106143095x131169.