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Study of Flow Rate Effect on Horizontal Flow Concrete Sand Filter Filtration Performance

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ABSTRACT The need for clean water during the pandemic is significantly increasing due to high public awareness of adopting a clean and healthy lifestyle (PHBS), necessitating more water treatment. Conventional methods are used for water treatment, including coagulation-flocculation system, rapid sand filter, and disinfection. However, these methods have limitations such as reduced capacity and sand filter efficiency, leading to increased backwash costs due to the need for sand replacement caused by particle stratification. In response to these challenges, an innovative method to water treatment is the use of concrete sand filter (CSF). Previous studies predominantly focused on downflow filtration, but there has been limited analysis of horizontal flow. Therefore, this study aimed to assess filtration and backwash effectiveness of CSF with horizontal flow, specifically focusing on the capacity performance in treating water with varying levels of turbidity. Filtration experiment was carried out using simulated water at turbidity of 125 NTU based on the Mataram Channel Turbidity with variations of 0.2, 0.5, 1.0, 5.0, and 10.0 m hour^{-1}, as well as backwash at flow rate of 40.91 m hour^{-1} for 3 minutes. The variables measured during filtration process included head losses and turbidity at the inlet and outlet of CSF. The results showed that the capacity performance during filtration process was directly proportional to flow rate. Meanwhile, the effectiveness of concrete filter was inversely proportional to flow rate. At initial turbidity $\leq$617 NTU, the 3 minutes backwash process obtained lower final turbidity compared to the raw water used, which was 5.19 NTU. Meanwhile, at turbidity 617 NTU, the final turbidity was still high, reaching approximately 14.6 – 26.4 NTU.

KEYWORDS Filter; Filtration; Rates; Horizontal Turbidity; Water

1 INTRODUCTION

The water availability on Earth is abundant, predominantly consisting of seawater (94%) and freshwater (6%) (Encyclopædia Britannica Inc., 2008). In Indonesia, the average demand for clean water between 2015 and 2020 was 3,915,724 thousand m^3(Badan Pusat Statistik Indonesia, 2020). According to the Indonesia Water Institute (IWI), clean water consumption increased during the COVID-19 pandemic from total consumption of 415 – 615 to 995 – 1,415 liters day^{-1} household^{-1} (CNN Indonesia, 2021). To address this increasing demand, there is a need to improve the quality and quantity of water treatment.

In Indonesia, drinking water treatment technology applied by Municipally Public Company (Perusahaan Umum Daerah/Perumda) is conventional methods such as coagulation-flocculation (chemical sedimentation), rapid sand filter, and disinfection processes using chlorine compounds. Although chlorine plays a crucial role in reducing ammonia and Coli bacteria, its excessive use can form trihalomethanes (THMs) and other organic halogen compounds. THMs are compounds with carcinogenic properties, posing a potential risk of causing cancer (Said and Yudo, 2008).

Filtration process is significantly influenced by some filter performance parameters, including pores, particle uniformity, particle shape, material hardness, filter porosity, and surface area (Crittenden et al., 2012). This essential aspect must continue to develop water treatment filter technology to enhance the effectiveness of filtration process.

Sand filter is commonly used as water purification tool in Indonesia due to the effectiveness in retaining suspended particles. This allows water to pass through filter with low turbidity values and a good filtration result. However, sand filter has lim-

Table 1. Concrete Sand Filter Characteristic

Properties	Concrete Sand Filter-F1
Sand samples	Progo River (Godean)
Specific weight (kg m^{-3})	2.723
Sand diameter (mm)	0.425 - 0.850
Effective size, ES (mm)	0.47
Uniformity coefficient, UC	1.40
Sand-cement ratio	10
Water-cement ratio	0.40

ited rate, and increased pressure during backwash process is required to remove sand particles, leading to high backwash costs (Kamulyan, 2014).

Pervious Concrete is an innovation in highway pavements to channel rainwater runoff to the layers below. In mix design, it uses coarse aggregate or gap-graded rock by removing fine aggregate or sand to form a high degree of porosity (20% – 30%) with pore openings of 2 – 6 mm (Rehder et al., 2014). Based on the comparison, Pervious Concrete uses coarse aggregate. Meanwhile, concrete sand filter (CSF) uses fine aggregate as a filler and cement mixed with water as a binder in a specific ratio to obtain the desired porosity permeability value, pore size, and pore distribution levels. This filter uses pore space as a filtration system to permeate and filtrate contaminated water. Practically, CSF is a cast mixture in cylindrical shape within a PVC pipe with 4 inches diameter and a specific length installed in a filtration installation.

Kamulyan (2014) investigated the relationship between the physical properties of CSF based on the size of the sand particles, the sand-cement ratio, filtration rate, the capability of reducing turbidity per particle suspension in water, and backwash performance of the downflow filtration CSF. The results showed that CSF could be backwashed at a rate of 55 -149 m $hour^{-1}$ for 3 minutes, higher than a sand filter at 50 m $hour^{-1}$ with backwash period of approximately 16 minutes (Mahanna et al., 2018). This efficiency in backwash makes CSF a superior alternative to sand filter. Concrete sand filter technology still requires further investigation, as several variables in filter structure demand more in-depth study. Although previous studies have predominantly reviewed downflow filtration (top to bottom), there is no analysis of up-flow and horizontal flow. Based on the background above, this study aimed to investigate the development of CSF with horizontal flow direction to determine the effect of water flow direction on filtration rate, filter ability to reduce turbidity, and backwash performance.

2 METHODS

2.1 Materials and Installation

Concrete sand filter (F1) is a concrete sand filter used in previous studies (Kamulyan et al., 2009), as shown in Table 1, a mixture of fine aggregate from the Progo River, with cement and water as a binder, with a ratio of cement to sand 1:10, and 0.40 water to cement ratio resulting a specific gravity filter around 2,723 kg m^{-3} on a diameter of 0.105 m (inside diameter of 4 inches pipe) and a length of 0.50 m. Filter media commonly used for filtration are generally diverse; silica sand has a specific weight of 2,650 kg m^{-3}, granular activated carbon with a weight of about 1,300 – 1,500 kg m^{-3}, and others (Droste and Gehr, 2019). The flow and CSF instruments used are shown in Figure 1.

Based on the American Water Works Association (AWWA), there are variations in the effective size and uniformity coefficient of several filter media are different. The effective size of silica sand ranges from 0.35 – 0.65 mm with a uniformity coefficient of 1.70 or lower, high-density sand has 0.18 – 0.60 mm and 2.20 or lower, respectively. When activated carbon granules are used as filter media, the effective size ranges from 0.50 – 1.50 mm but produced activated carbon granules have a value of 0.35 – 2.00 mm (*AWWA B100-16: Granular Filter Material*, 2016). Slow sand filter uses an effective size ranging from 0.15 – 0.30 mm with a uniformity coefficient <2.50, while rapid sand filter has 0.50 – 1.2 mm and <1.40 (Crittenden et al., 2012). In this study, concrete filter has an effective size of 0.47 mm with a uniformity coefficient of 1.40 due to the adoption of sand filter criteria. This design offers several advantages, including a high-speed backwash process without wasting filter media granule.

2.2 Simulation Water Preparation

The simulated water used in this study was sourced from the Sanitary and Environmental Engineering Laboratory, Department of Civil Engi-

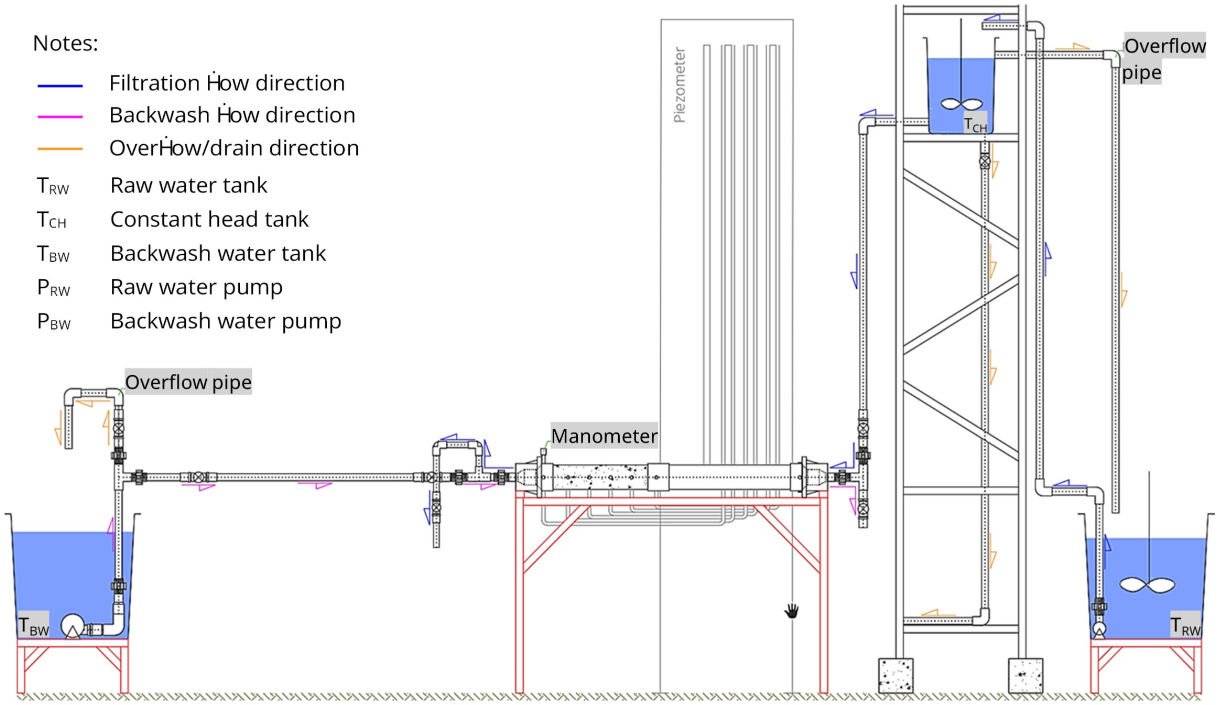

Figure 1 Schematic of horizontal flow concrete sand filter instruments

neering, Universitas Gadjah Mada, and mixed with Sukabumi clay obtained from UD. Subsequently, Yogyakarta Kartiyasa was dried and filtered using sieve number 200 (opening size 0.075 mm) to obtain the same turbidity as the water in the Yogyakarta Mataram channel.

2.3 Filtration Experiment

Concrete sand filter filtration experiment with a horizontal flow was started by closing all filtration and backwash valves. The only exceptions were backwash overflow and first inlet valves, which had been adjusted according to the degree of opening at the pre-trial backwash stage. To prepare filtration tank, clay powder was introduced into the water and stirred with a stirrer until turbidity value in the simulated water was close to the Mataram channel, which had a value of 125 NTU. After the appropriate turbidity value was achieved, the water in filtration tank flowed to the pressure controller tank using a filtration pump to reach overflow point. The inlet filtration and the piezometer valves were opened and adjusted carefully to prevent air bubbles from trapping into the pipe. Furthermore, the adjusting valve was closed for the initial piezometer water level to be uniform with the pressure controller tank. The outlet filtration faucet was opened based on the settings in the pre-trial stage and the initial discharge was measured until it reached the desired level. Subsequently, the discharge occurred three times, and the results of the piezometer height at each point were recorded. Samples were collected from CSF inlet and outlet valves at the start of the 0-minute measurement. This process was repeated at 20, 40, 60, 90, 120, 150, 180, 240, 300, and 360 minutes. The final results data of filtration were the piezometer height at each point, filtration discharge value, and the turbidity of the inlet and outlet filtration samples at several observation times. Multiple filtration experiments were conducted at five different rate variations for a comprehensive analysis. After each filtration experiment, all machines working on filtration process were turned off, cleaned, and dried filtration tank and pressure controller tank by opening the drain valve.

2.4 Backwash Experiment

The experiment for CSF backwash with a horizontal flow commenced by closing all filtration valves, including those attached to CSF. The first inlet backwash valve and backwash overflow valve were in an opening position according to the degree at the pre-trial stage. Subsequently, the outlet backwash valve was opened to ensure total removal of the trapped water in filter. Backwash pump was turned on, followed by opening of the second inlet backwash valve. The water flow at backwash

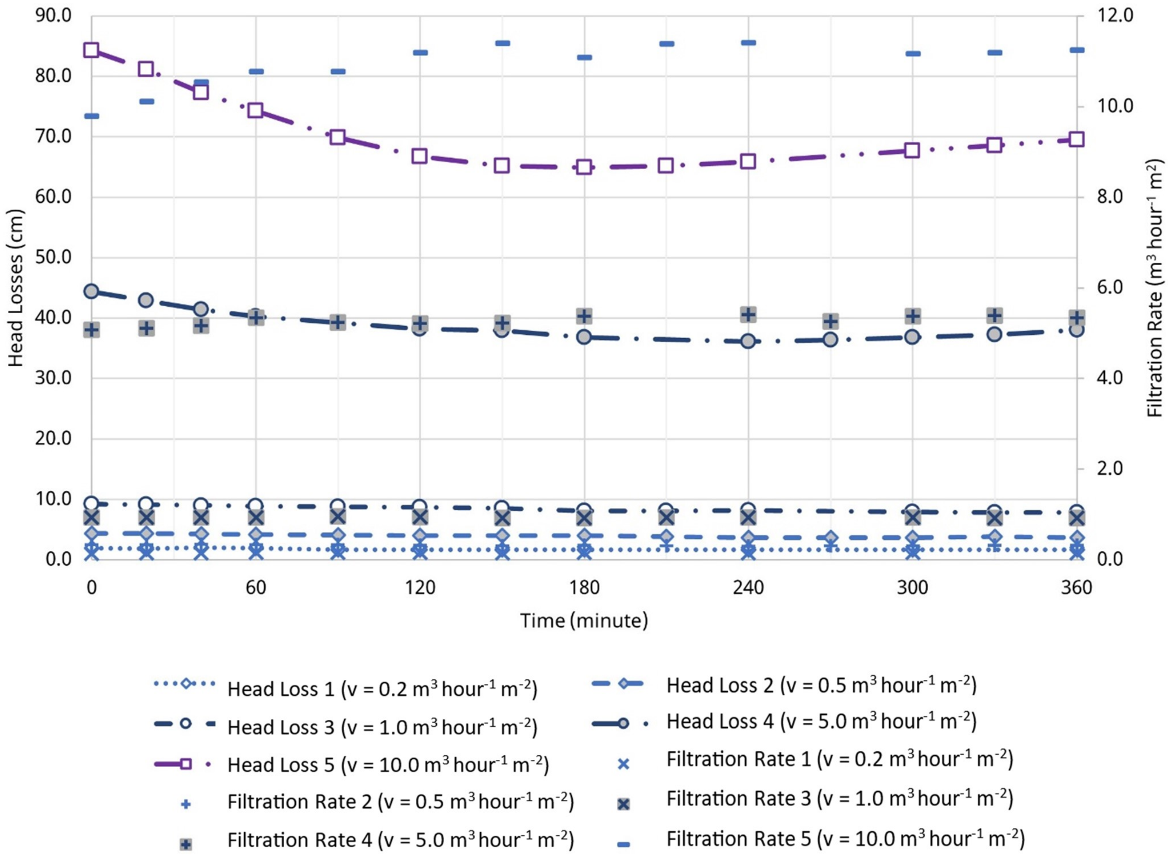

Figure 2 Graph of head losses and filtration rate over time

outlet is collected up to ± 2850 ml (half of the free space volume) because this water is leftover filtration water. After the water was collected, the sampling process was carried out and the manometer pressure was recorded at 0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-60, 60-80, 80- 100, 100-120, 120-140, 140-160, and 160-180 seconds. Discharge measurements were performed three times at the end of backwash experiment. The results were presented as backwash flow rate, pressure on the manometer, and backwash outlet turbidity sample. After backwash experiment, the remaining water in filter was removed and drained by opening the attached valve and rotating 90 degrees to facilitate water drainage. Subsequently, when filter had completely dried, it was rotated back to the original position.

3 RESULTS

3.1 CSF Filtration Performance Due to Head Losses by Filtration Rate

The behavior of CSF filtration in horizontal flow can be observed through rate variation and measurement of head losses during filtration time. Head losses were measured by the difference between the inlet and outlet CSF piezometer water levels. Furthermore, the water level in CSF piezometer inlet was stable during filtration process but fluctuation at the outlet affected the head losses.

The results showed that CSF head losses vary in filtration rate variation. At the beginning of filtration, there was an inverse relationship between filtration rate and head losses, as shown in Figure 2. When the rate was set to 0.2 m^3 $hour^{-1}$ m^{-2}, 0.5 m^3 $hour^{-1}$ m^{-2}, and 1.0 m^3 $hour^{-1}$ m^{-2}, head losses remained constant and tended to decrease. In comparison, there was a significant increase at 5.0 m^3 $hour^{-1}$ m^{-2} and 10.0 m^3 $hour^{-1}$ m^{-2} after 240 minutes per 4 hours and 180 minutes per 3 hours of filtration, respectively.

3.2 CSF Filtration Performance Due to Turbidity Removal Percentage by Filtration Rate

The effectiveness of horizontal flow CSF filtration was assessed through rate variation and measure-

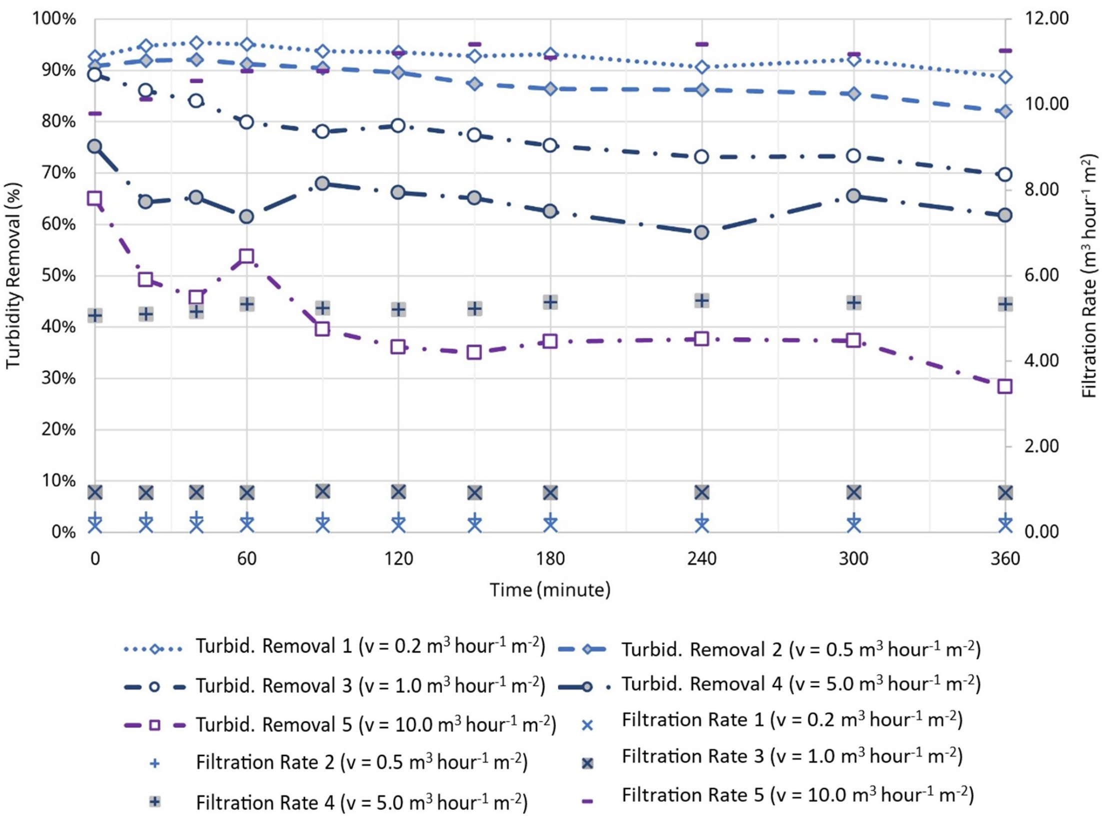

Figure 3 Graph of filtration rate and turbidity removal percentages over time

ment of the inlet and outlet turbidity during filtration time. This allowed for the determination of the turbidity removal percentage. The results showed that turbidity removal percentage at low rates yielded a higher value than those at high rates, as shown in Figure 3. Furthermore, there was a range expansion of turbidity removal percentage at the high filtration rate.

At 0.2 m^3 $hour^{-1}$ m^{-2} filtration rate, the removal range was 88.74% - 95.10%, with a minimum outlet turbidity of 3.75 NTU. Meanwhile, at 0.5 m^3 $hour^{-1}$ m^{-2}, the removal range was 81.98% – 92.07%, with minimum outlet turbidity of 6.29 NTU. The 1.0 m^3 $hour^{-1}$ m^{-2} showed a removal range of 69.65% – 89.06% with a minimum outlet turbidity of 9.67 NTU. At 5.0 m^3 $hour^{-1}$ m^{-2} and 10.0 m^3 $hour^{-1}$ m^{-2}, the removal range was 58.37% – 75.08% and 28.32% – 65.04%, with a minimum outlet turbidity of 26.0 and 43.7 NTU, respectively.

3.3 CSF Backwash Performance

Conventional filter backwash, such as slow and rapid sand filtration, has some areas for improvement due to the loss and transport of filter media during backwash process at high rates and pressure. Consequently, effective backwash in sand filter requires adherence to specific rates and pressure limits, typically ranging from 37 - 56 m $hour^{-1}$ for 3 - 15 minutes (Kamulyan et al., 2009). In this study, CSF backwash at a 40.91 m $hour^{-1}$ rate was based on the pre-trial valve opening settings.

The effectiveness of horizontal flow CSF backwash was observed in turbidity value at backwash output during backwash process. The results showed that at a design velocity of 40.91 m $hour^{-1}$, the percentage of turbidity removal was above 98% with varying initial turbidity levels at backwash outlets, as shown in Figure 4.

In first experiment, backwash ran without removing ± 2850 ml of filtered residual water in filter-free space (0.5 the volume), at a 0.2 m $hour^{-1}$ rate after filtration process. The results showed that the highest turbidity that occurred during and at the end of backwash was 108 NTU and 1.96 NTU, with turbidity removal percentage of 98.19%.

The rest of the experiments followed a similar procedure, which included the initial removal of ± 2850 ml of filtered residual water in filter-free

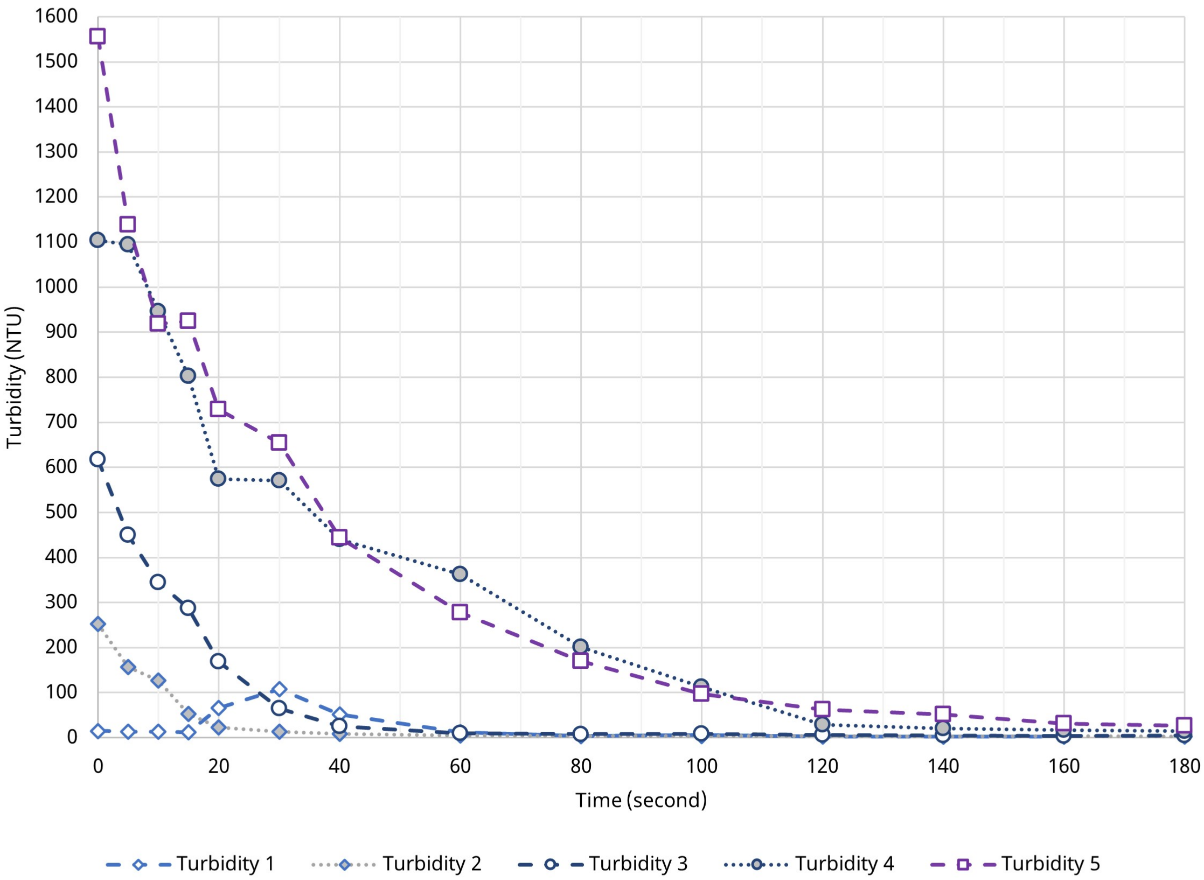

Figure 4 Graph of backwash turbidity over time

space (0.5 the volume). Subsequently, second experiment ran after filtration process with a rate of 0.5 m hour^{-1}. The initial turbidity of backwash was 253 NTU and 2.41 NTU at the end of the process, with a removal percentage of 99.05%. The third experiment ran after filtration process with a rate of 1.0 m hour^{-1}. The initial and final turbidity was 617 NTU and 4.63 NTU with turbidity removal percentage of 99.31%. The fourth experiment ran after filtration process with a 5.0 m hour^{-1} rate. Based on the results, the initial and final turbidity was 1104 NTU and 14.6 NTU with a removal percentage of 98.68%. The last experiment ran after filtration process at a rate of 10.0 m hour^{-1}. The initial and final turbidity of backwash was 1556 NTU and 26.4 NTU with a removal percentage of 98.30%.

4 DISCUSSION

Generally, higher filtration rate result in increased head losses and decreased filtration effectiveness. This phenomenon occurs because, at high filtration rate, more suspended particles flow into filter bed, leading to a decrease in the contact time between these particles and filter media grains (Hasan et al., 2020). Consequently, these particles are transported out with the water without passing through various mechanisms such as interception, sedimentation, and diffusion (Yao et al., 1971).

The results of this study confirmed the statement above, showing increased head losses at 5.0 m hour^{-1} and 10 m hour^{-1}, followed by decreased effectiveness at high filtration rate. Effectiveness decreased from the percentage of turbidity removal at filtration speed of 1.0 m hour^{-1}, 5.0 m hour^{-1}, and 10.0 m hour^{-1} has an extensive range with the lowest percentages of 69.65%, 58.37%, and 28.35%, respectively. These results varied significantly compared to filtration rate of 0.2 m hour^{-1} and 0.5 m hour^{-1}, which had the lowest percentages of 88.74%, and 81.98%, respectively.

In head losses graph for filtration rate of 5 m hour^{-1} and 10 m hour^{-1}, there was a change in the graph line. At the beginning of the graph, the value decreased to a specific time, followed by an increase to end of the process. At a high filtration rate, a change in pressure loss was obtained, which decreased over time (Khelladi et al., 2020). This phenomenon occurs because when the rate increases, a large number of suspended particles penetrate filter media per unit of time (Davies, 2012). However, the clogging process can be delayed due to increased filtration rate. Subsequently, the hydrodynamic force will increase, generating repulsive force for particles clogged and breaking bonds between particles and filter media (Sendekie and Bacchin, 2016).

Backwash process of CSF horizontal flow has turbidity removal of 98.30% - 99.31%. Meanwhile, turbidity of the raw water used for backwash ranged from 4.04 - 5.19 NTU. At a level of ⩽ 617 NTU for 3 minutes, the final turbidity result was the same and lower with raw water at ⩽ 5.19 NTU. At turbidity > 617 NTU for 3 minutes, the final turbidity was still high, ranging from 14.6 – 26.4 NTU. This variation occurred due to different filtration rate, which was lower at a similar backwash time. Kamulyan et al. (2009) conducted backwash test at rates between 55 – 149 m $hour^{-1}$ and reported that CSF could be backwashed at high rates.

In this study, it was observed that when approximately ± 2850 ml of residual filtered water was collected in backwash experiments, the water had a high turbidity value. Consequently, a deeper investigation is needed regarding this phenomenon.

5 CONCLUSION

In conclusion, CSF horizontal flow filtration obtained the best filtration results at rates of 0.2 m $hour^{-1}$ and 0.5 m $hour^{-1}$. The results indicated that lower rates provided a high percentage of turbidity removal because the water flow in filter pore was more stable and consistent compared to high filtration rate. This showed that as the rates increased, turbidity removal percentage range also widened significantly. CSF backwash at 40.91 m $hour^{-1}$ showed good results at different initial turbidity levels, implying promising potential at a higher rate. Moreover, further studies were recommended regarding concrete filter with various conditions.

DISCLAIMER

The authors declare no conflict of interest.

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