Slow Sand Filtration Performance: A Systematic Investigation on the Influence of Uniformity Coefficient (C_u)

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Abstract
History acclaims that slow sand filtration (SSF) is the first documented water purification method. Being successful on securing water quality since the beginning of 19th century, SSF is still becoming one alternative for water treatment to date even though there are many advanced technologies. There are many variables influencing the SSF performance. One of variables that have significant role is grain size distribution of media represented by effective size (d_{10}) and uniformity coefficient (C_u). According to the guidance for SSF, d_{10} of media lies between 0.15 – 0.35 mm. Uniformity coefficient of less than 3 shall be selected to ensure the regular pore size and sufficient porosity. The focus of this paper is to study the influence of C_u to the SSF performance which is still missing from the literature. Systematic experiment was conducted in order to achieve the objective. Nine filter columns were divided into three sets and each set involved three different values of C_u. Turbidity, Total Suspended Solid (TSS), particle size, head loss and hydraulic conductivity development are parameters used to evaluate the filter performance. Effluent quality was statistically analysed with ANOVA test. Results showed that the effluent quality of filter columns having C_u of 5 was not significantly different compared to the columns with lower C_u.

Keywords
Uniformity coefficient; slow sand filtration; water treatment; systematic investigation; grain size distribution

INTRODUCTION

As a simple, low-cost and effective water purification method, slow sand filtration (SSF) is still being used in many parts of the world (Huisman & Wood, 1974). This method is suitable for small and rural communities in developing countries because it does not need special skills to operate the filter (Washington State Department of Health, 2003). In order to construct a slow sand filter, there are many design criteria available. These design criteria define recommended range values for every significant variable in SSF. Table 1 shows some examples of design criteria according to three different sources (Hazen, 1908) (Huisman & Wood, 1974) (Visscher, 1990).

Table 1. Design criteria for SSF

Variable	Recommended Values		
	Hazen (1908)	Huisman & Wood (1974)	Visscher (1990)
Effective size (d_{10}) of media (mm)	0.20 – 0.35	0.15 – 0.35	0.15 – 0.30
Uniformity coefficient (C_u) of media	< 3	< 3 preferably < 2	< 5 Preferably < 3
Filtration rate (m/h)	0.06 – 0.1	0.1 – 0.4	0.1 – 0.2
Bed depth (m)	0.75 – 1	0.6 – 1.2	0.8 – 0.9

The first two variables listed in Table 1 describe the grain size distribution of filter media which has a significant role in the SSF performance. According to recommended values, sand grains should be fine and their size distribution as narrow as possible to achieve low filtration rate which in turn ensures a good SSF performance. However, many literature studies concluded that even coarse filter media acquired high removal efficiencies. A coarse sand with d_{10} 0.615 mm still attained high bacteria removals up to 99.7% (Bellamy, et al., 1985). Muhammad et al. (1996) found out that coarse sand with d_{10} 0.45 mm performs satisfactorily on removing fecal coliform, total coliform, turbidity and color. Anggraini, et al., 2015 also observed that filter performance with d_{10} 0.50 mm was not significantly different compared to finer sand (d_{10} 0.15 mm) in terms of turbidity removal. These findings in regard to the influence of d_{10}, especially those which do not comply with recommended values, questioned the applicability of using fine sand as filter media. In line with the researches on d_{10}, Di Bernardo & Rivera (1996) studied the influence of C_u to the filter performance. Surprisingly, it resulted in a conclusion that the higher the C_u, the better the effluent quality was.

Regarding to the filtration rate, Bellamy, et al. (1985) observed slightly lower performance of filter operated under 0.4 m/h. Di Bernardo & Alcocer Carrasco (1996) demonstrated a similar behavior of filters operated under filtration rates of 3.0 m/d, 6.0 m/d, 9.0 m/d and 12.0 m/d. Studied on the influence of bed depth indicated that filter could perform properly without following the recommended values. Lowering the bed depth into 0.5 m did not impair the effluent quality significantly (Bellamy, et al., 1985). Media thickness could be reduced into 0.4 m without deteriorating the bacteriological quality of effluent (Muhammad, et al., 1996).

Contradiction on the previous studies may lead into the next question on variable which gives more effect to the SSF performance. Considering the fundamental removal mechanisms of SSF is still limited in the literature (Haig, et al., 2011) (Graham & Collins, 2014), conclusion is difficult to be drawed into a straight line. Gap in this knowledge may restrict the improvement in the utilization of SSF (Haig, et al., 2011). Studies on the influence of each variable are necessary to be conducted systematically in order to connect the missing link. Furthermore, it is expected that the results of this research will be able to support the improvement of adaptable design especially for developing countries with limited sources.

As part of systematic investigation on significant variables of SSF, this paper presents the influence of C_u to the SSF performance. Assessment of SSF performance was based not only on the removal of turbidity and Total Suspended Solid (TSS), but also the particle size of effluent and development of head loss in relation with hydraulic conductivity.

MATERIALS AND METHOD

Experimental design

A method chosen to study the influence of C_u in the SSF performance was by conducting systematic experiment consisted a three-set of filter columns. Systematic experiment meant that variation was applied to one variable only while others were under control. In this investigation, different values of C_u were tested since the focus of investigation was on the influence of C_u. Narrow C_u values, 2.5 and 3, represented the recommended values and C_u 5 was considered as the extreme. Figure 1 shows three different grain size distributions involving the same d_{10} 0.26 mm.

A three-set of columns was prepared concerning the reliability of the experiment results. Every set consisted of three different grain size distributions. Therefore, nine filter columns with Ø 125 mm were constructed following the scheme as shown in Figure 2. Each filter column contained gravel layer as supporting layer at the base followed by quartz sand layer, and atop of sand layer, another gravel layer acted as protection layer was added. Outlet position was above the protection layer to ensure the saturated condition.

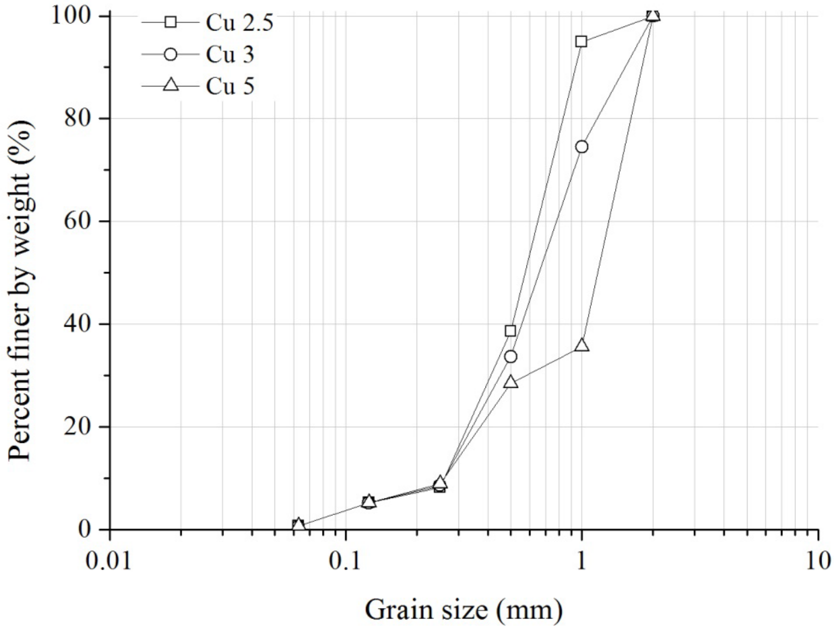

Figure 1. Comparison of grain size distribution

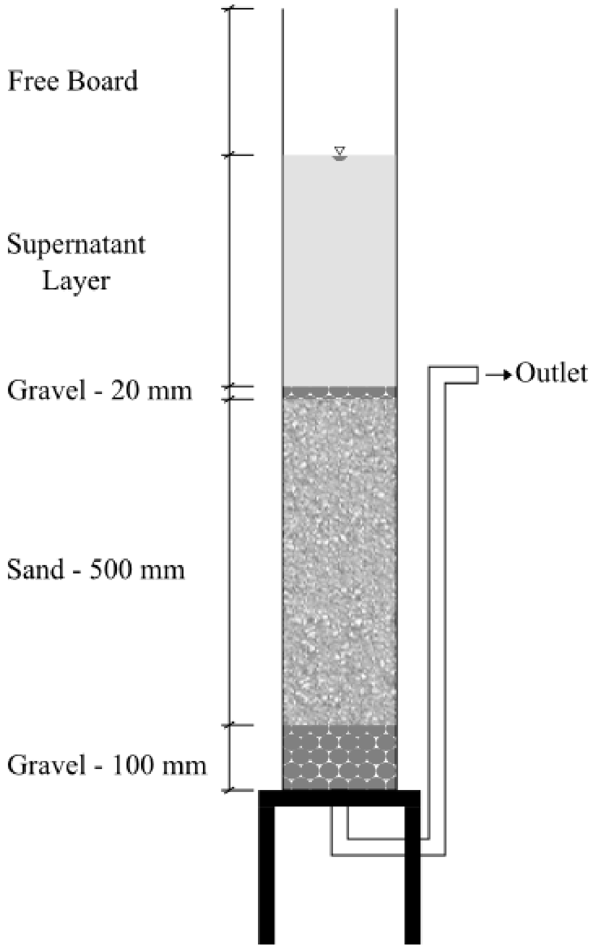

Figure 2. Sketch of filter column

Filter operation

After the filter column construction, properties of filter represented by void ratio and hydraulic conductivity, as can be seen in Table 2, were measured. At the beginning water was introduced to the filter by up-flow direction. Void ratio was calculated from the correlation of water content and specific gravity of media. A leaking problem occurred in Set 3, particularly in Column C33. In regard to solve the problem, the water must be emptied from the column. Therefore, the determination of void ratio could not be executed.

Hydraulic conductivity within this experiment was determined by doing the constant head test. There are many factors influencing the degree of hydraulic conductivity, such as the size and shape of grains, shape and arrangement of voids, void ratio, degree of saturation and temperature (Bardet, 1997). Shape and arrangement of voids are factors that could not be controlled during the column construction as the same as inclusion of air. In the case of Column C33, its initial hydraulic conductivity was lower compared to the filter columns with the same configuration. As it was mentioned before, in this column the water must be emptied because of the leaking problem. By turning the saturated condition into unsaturated, proportion of air within the media was also changed. Air within media contributed to the blocking of water path which led into lower value of hydraulic conductivity.

Filter columns were operated intermittently with constant supernatant layer during seven weeks. Filtration rate of 0.2 ± 0.02 m/h was controlled from the inlet which was based on the hydraulic conductivity. Therefore, the initial head loss for one column to another was dissimilar.

Table 2. Properties of filter columns

Set	Configuration	Column	C_u	d_{10} (mm)	Initial Void Ratio	Initial Hydraulic Conductivity (m/s)	Initial Filtration Rate (m/h)	Initial head loss (cm)
1	1	C11	2.5	0.26	0.48	3.72×10^{-4}	0.22	9.6
	2	C12	3	0.26	0.42	2.00×10^{-4}	0.21	17.6
	3	C13	5	0.26	0.47	4.72×10^{-4}	0.21	7.8
2	1	C21	2.5	0.26	0.48	4.00×10^{-4}	0.20	8.3
	2	C22	3	0.26	0.42	2.21×10^{-4}	0.21	16.2
	3	C23	5	0.26	0.48	6.01×10^{-4}	0.22	6.2
3	1	C31	2.5	0.26	0.48	3.55×10^{-4}	0.21	10.0
	2	C32	3	0.26	0.45	2.61×10^{-4}	0.21	13.5
	3	C33	5	0.26	-	2.78×10^{-4}	0.22	11.8

Influent water was synthetic raw water created by mixing tap water at the laboratory and quartz powder (Millisil W12). Before the mixing process, Millisil was sieved in order to get particles with the size of < 63 µm. Every litre of mixture contained 220 mg Millisil to generate the turbidity value of ~100 FNU. At the beginning of every week, head drop for each column was created using 2.5 L of synthetic raw water. Then, for the next five days columns were fed with 2.5 L/day followed by the hydraulic conductivity measurement by the end of week.

Data sampling and analysis

Assessment on this research experiment was based not only on the turbidity and TSS removal, but also the behaviour of head loss and hydraulic conductivity after certain amount of particles added.

Another measured parameter was size of particle in the effluent. Particles sized < 63 µm were considered as Millisil while the bigger size were regarded as sand. Cumulative particle mass was calculated without including the mass of sand founded. Turbidity of the effluent was measured three times: at the beginning, in the middle and at the end of filter run, using Hach Lange Turbidimeter. Effluent sample of around 400 mL was taken for the particle size measurement using EyeTech Particle Size and Shape Analyser followed by the measurement of TSS which was determined based on Standard Method 2540 D (Branigan, 2013).

As the focus of this research experiment was to find out the influence of Cu to the SSF performance, the capability of each filter on removing the turbidity and TSS was compared. The differences of effluent turbidity and TSS in every filter column were statistically analysed by ANOVA test using Origin 8, after ensuring the data were normally distributed. The statistical analyses were conducted at 95% level of confidence ($\alpha = 0.05$). Development of head loss and hydraulic conductivity was plotted to understand the influence of additional particle to the filter capacity.

RESULTS AND DISCUSSION

Turbidity removal

It was observed that the entire filter columns performed satisfactorily regarding the turbidity removal. Overall, minimum percentage of removal that could be achieved was 96% considering the influent turbidity of ~100 FNU. According to the results of ANOVA test as shown in Table 3, columns in Set 1 are indicated to be significantly different with a p-value of 3.087×10^{-5} which was lower than α value. However, means comparisons assessed by Tukey test demonstrated that two columns, C12 and C13, were not significantly different based on the p-value of 0.095 which was higher than α value.

Table 3. Summary of ANOVA and Tukey tests' of effluent turbidity at 0.05 level

Set	p-value ANOVA Test	Tukey Test	
		Columns Compared	p-value
1	3.087×10^{-5}	C12 – C11	0.019
		C13 – C11	1.740×10^{-5}
		C13 – C12	0.095
2	0.183	C22 – C21	0.335
		C23 – C21	0.940
		C23 – C22	0.191
3	0.135	C32 – C31	0.496
		C33 – C31	0.649
		C33 – C32	0.114

In contrast to the result of Set 1, Set 2 and Set 3 showed that the p-values were higher than α value. Since Set 2 and Set 3 showed similar behaviour, they may be taken as representative on interpreting the influence of C_u to the filter performance. Based on Figure 3, it can be assumed that filter columns in both Set 2 and Set 3 achieved good effluent quality as the turbidity were reduced up to below 5 FNU which is usually acceptable (WHO, 2008). According to the ANOVA test and the effluent quality, it can be inferred that there is no influence of low (represented by 2.5 and 3) and high (represented by 5) C_u on the turbidity removal of filters under intermittent operation and low filtration rate 0.2 m/h.

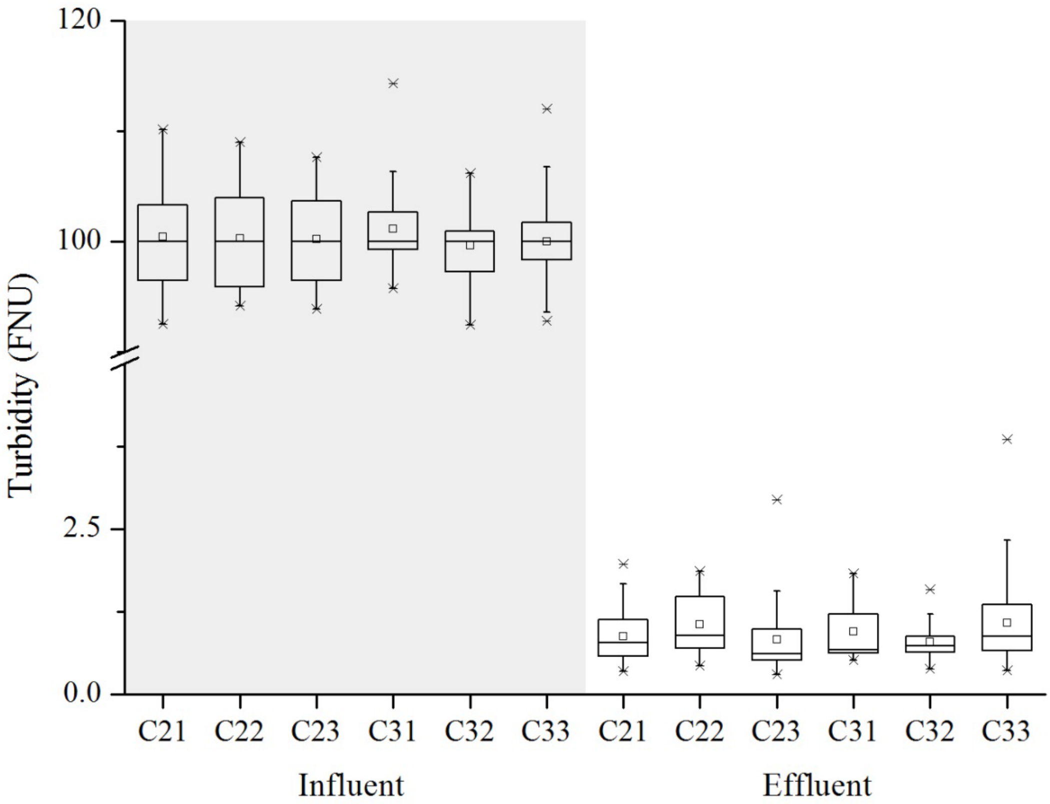

Figure 3. Comparison of influent and effluent turbidity in Set 2 and Set 3

TSS removal

Taking Set 2 and Set 3 as the representatives, ANOVA test results as can be seen in Table 4 show similar behaviour of each configuration. Significant differences were not found in the performance of filter columns regarding TSS removal as the p-values were > 0.05. According to the Tukey test, comparison of all configurations results in p-values higher than α value. Thus, it can be stated that regarding to the TSS removal, Cu of 2.5, 3 or 5 did not have any influence to the filter performance under the low filtration rate of 0.2 m/h.

Figure 4 shows the comparison of influent quality 220 mg/L and the effluent quality of each filter in both Set 2 and Set 3. Both sets performed satisfactorily as the TSS removal was in average higher than 98%.

Table 4. Summary of ANOVA and Tukey tests' of effluent TSS at 0.05 level

Set	p-value ANOVA Test	Tukey Test	
		Columns Compared	p-value
2	0.541	C22 – C21	0.516
		C23 – C21	0.774
		C23 – C22	0.908
3	0.118	C32 – C31	0.375
		C33 – C31	0.731
		C33 – C32	0.106

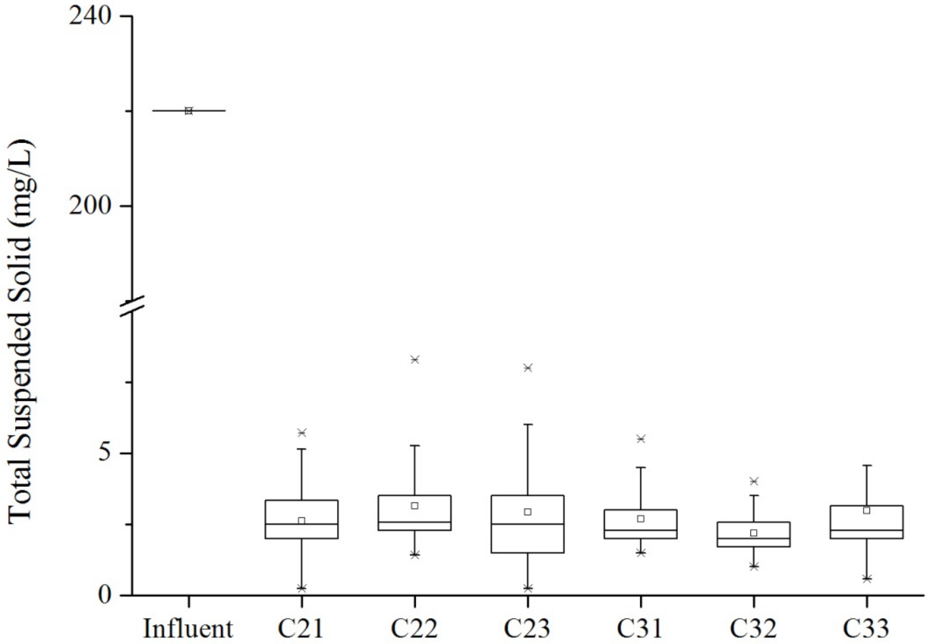

Figure 4. Comparison of influent and effluent TSS in Set 2 and Set 3

Development of hydraulic conductivity and head loss

Hydraulic conductivity describes the capacity of filter media on passing the water on. Capacity of filter was influenced by the addition of particle as can be seen in Figure 5 where Set 2 and Set 3 were taken as representative. Mass added to the filter column increased the resistance of the water to flow. As a result, the more particles were added, the lower the hydraulic conductivity was. In both Set 2 and Set 3, hydraulic conductivity was found to be slightly decreased along with the particle addition except to the configuration of C_u 3. Configuration of C_u 2.5 had higher hydraulic conductivity compared to the C_u 3. This phenomenon might be caused by higher variation of grain sizes in configuration of C_u 3 therefore the finer ones could occupy the void created by the coarser grains. However, this might not valid for the configuration Cu 5 because in order to create this grain size distribution, percentage of coarse sand used was too high compared to the finer grains. Therefore, configuration with Cu 5 has the highest hydraulic conductivity compared to the other configurations. An exception was in filter column C33. As mentioned before, C33 has the initial value of hydraulic conductivity much lower than the others with the same configuration as shown in Table 2.

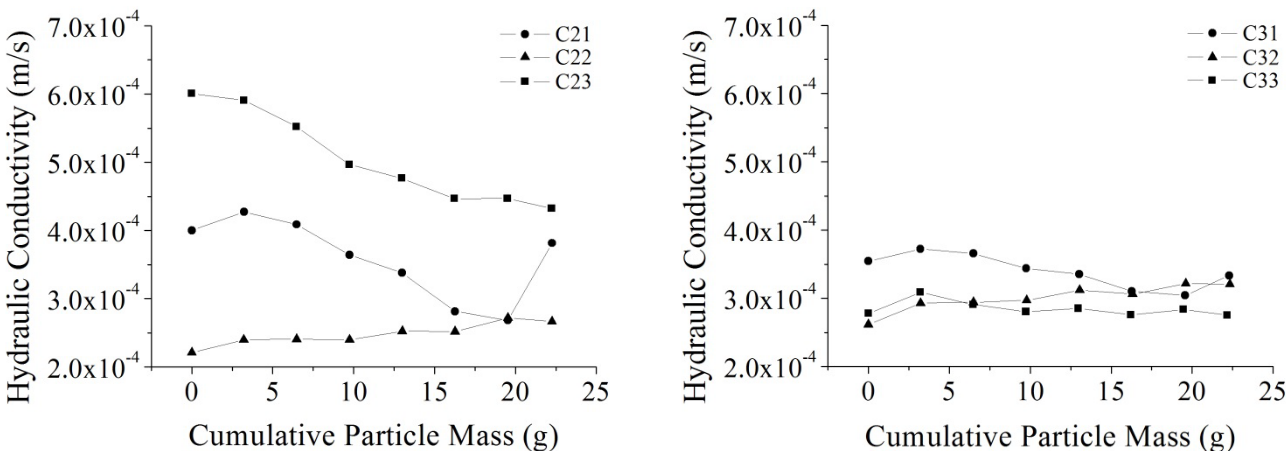

Figure 5. Development of hydraulic conductivity in Set 2 and Set 3

In consequence to the hydraulic conductivity, as the filter was more resistant, head loss slightly increased as shown in Figure 6. Normalized head loss was calculated based on the equation used by Sugimoto (2014) as following:

$$\text{Head loss normalization (cm)} = \frac{\text{Head loss (cm)}}{\text{Flow rate } \left(\frac{\text{m}}{\text{h}}\right)} \times \text{Normalized flow rate } \left(\frac{\text{m}}{\text{h}}\right)$$

Normalized value will lead into comparable head loss of each filter column.

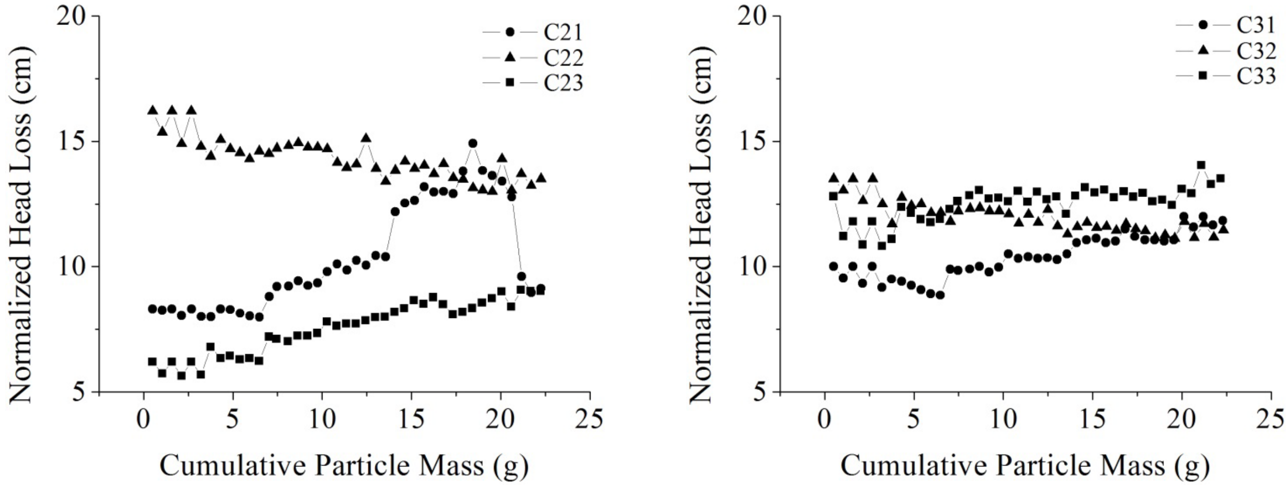

Figure 6. Development of normalized head loss at 0.2 m/h in Set 2 and Set 3

CONCLUSION

According to the research work done, it may be concluded that there is no influence of the different uniformity coefficient to the slow sand filtration performance under the low filtration rate 0.2 m/h and intermittent operation. This was proved by not only the success of turbidity and TSS removal which reached above 96 % and 98% respectively, but also by the results p-values from ANOVA test. Addition of particles into the filter column may increase the resistant which lead into lower hydraulic conductivity and the head loss must be increased regarding the desired flow rate. However, in regard to understand the clogging pattern, the filter columns must be operated longer.

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REFERENCES

Anggraini, A K, E Grotelüschen, A Silva, und S Fuchs. „Investigation on Slow Sand Filtration Performance: Influence of Effective Grain Size on the Particle Removal.“ *Proceedings of the IWA 7th Eastern European Young Water Professionals Conference.* Belgrade, 2015. 312-319.

Bardet, J P. *Experimental Soil Mechanics.* New Jersey: Prentice Hall, Inc., 1997.

Bellamy, W D, D W Hendricks, und G S Logsdon. „Slow Sand Filtration: Influences of Selected Process Variables.“ *American Water Works Association* 77 (1985): 62-66.

Branigan, J. „Digital Commons University of Nebraska-Lincoln.“ 1. December 2013. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1071&context=civilengdiss (Zugriff am 14. Juli 2016).

Di Bernardo, L, und A E Rivera. „Influence of Sand Uniformity Coefficient on Slow Sand Filtration

Performance.“ *Advances in Slow Sand and Alternative Biological Filtration*, 1996: 179-188.

Di Bernardo, L, und N E Alcocer Carrasco. „Variable versus Constant Supernatant Water Layer in Slow Sand Filtration.“ London: Wiley, 1996.

Graham, N J D, und M R Collins. „Slow Sand Filtration: Recent Research and Application Perspectives.“ In *Progress in Slow Sand and Alternative Biofiltration Processes*, von N Nakamoto, N Graham, M R Collins und R Gimbel, Herausgeber: N Nakamoto, N Graham, M R Collins und R Gimbel, 3-16. London: IWA Publishing, 2014.

Haig, S J, G Collins, R L Davies, C C Dorea, und C Quince. „Biological Aspects of Slow Sand Filtration: Past, Present and Future.“ *Water Science and Technology: Water Supply*, September 2011: 468-472.

Hazen, A. *Public Water Supplies.* 3rd. New York: John Wiley & Sons, 1908.

Huisman, L, und W E Wood. *Slow Sand Filtration.* Geneva: World Health Organization, 1974.

Muhammad, N, K Ellis, J Parr, und M D Smith. „Optimization of Slow Sand Filtration.“ *22nd WEDC Conference, Reaching the Unreached: Challenges for the 21st Century.* New Delhi, 1996. 283-285.

Sugimoto, T. „Schmutzdecke Development and Treated Water Quality.“ In *Progress in Slow Sand and Alternative Biofiltration Processes*, Herausgeber: N Nakamoto, N Graham, M R Collins und R Gimbel, 121-129. London: IWA Publishin, 2014.

Visscher, J T. „Slow Sand Filtration: Design, Operation, and Maintenance.“ *American Water Works Association*, 1990: 67-71.

Washington State Department of Health. *Guidance Document: Slow Sand Filtration and Diatomaceous Earth Filtration for Small Water Systems.* Washington: Training and Outreach Section, Division of Drinking Water, 2003.

WHO. *Guidelines for Drinking-water Quality.* Geneva: WHO Press, 2008.