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Filtration and Backwashing Studies: Obafemi Awolowo University Waterworks as A Case Study

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Abstract

This research centres on the study of the filtration and backwashing operations of the filtration unit of the Opa Waterworks and a detailed laboratory study of the filtration and backwashing characteristics of the filter medium being used at the treatment plant. A detailed study of the filtration unit of Opa Waterworks was undertaken with particular emphasis placed on the estimation of the volume of water used during backwashing, the backwashing procedure and the average backwashing time. Specific properties of the filter medium used in the gravity filter such as porosity, density, equivalent density, specific gravity and unhindered settling velocity were investigated in the laboratory. The backwashing properties of the filter medium was also studied using the DSF (Dynamic Shape Factor) and Sphericity models and the predicted results obtained were compared to the actual laboratory results.

Based on works carried out, the volume of wash-water required for the gravity filters was estimated as 14,200 litres (14.2 m3) which is about 3.12% of the total volume of the clear water tank, with an outflow rate of 0.01 m3/s. The accuracy of the Blake – Kozeny equation in predicting head loss across a filter bed using clean water runs was investigated and found to be reasonably accurate, and the prediction errors

Keywords: Filtration, backwashing, head loss, dynamic shape factor and Blake-Kozeny equation

Introduction

Water treatment involves processes that alter the chemical composition or natural "behaviour of water". Primary water availability includes surface or ground water. Most municipal or public water comes from surface water while private water supply usually comes from ground water (Abdel-Shafy et al., 2010).

Filtration is a mechanical or physical operation which is used for the separation of solids from fluids by interposing a medium to fluid flow through which the fluid can pass, but the solids in the fluid are retained. This separation depends on the pore size and the thickness of the medium as well as the mechanism that occurs during filtration (Abdel-Shafy et al., 2016). Gravity filters consist essentially of an open topped box usually made of concrete, drained at the bottom and partially filled with a filter medium. Gravity filters are subdivided into rapid and slow filter.

The most common method of surface and ground water treatment is filtration using a sand medium. The modern sand filter used in municipal practice consists of an open water tank generally greater than 3 m deep, containing a layer of sand 600 – 900 mm thick supported on gravel 150 – 300 mm thick. As the filtration continues, the sediment removed from the water builds up in the sand layer resulting in an increasing head loss through the sand layer. The filter is cleansed by reversing the flow of water. This process is known as backwashing. Water is admitted under pressure into the underdrain system at such a rate that the upward flow of water will expand the sand bed about 50% (Abdel-Shafy *et al*., 2010).

Backwashing refers to the pumping of water backwards through the filter media, sometimes including intermittent use of compressed air during the process. Proper backwashing is a very important step in the operation of a filter. This is to prevent the development of operational problems. If a filter is to operate efficiently, it must be cleaned before the next filter run. Treated water is used for the backwash cycle and is generally taken from elevated storage tanks or pumped in from the clear well (APHA/AWWA/WEF., 2012). Water treatment filters that can be backwashed include rapid sand filters, pressure filters and granular activated carbon filters. Diatomaceous earth filters are backwashed according to the proprietary arrangement of pumps, valves and filters associated with the filtration system. Slow sand filters and self-cleaning screen filters employ mechanisms other than backwashing to remove trapped particles Cai *et al*., 2015; Jeje *et al*.,2020). In water treatment plants, backwashing can be an automated process that is run by local programmable logic controllers (PLCs). The backwash cycle is triggered after a set time interval, when the filter effluent turbidity is greater than the treatment guideline or when the differential pressure (head loss) across the filter exceeds a set value (Sravanthi and Sharma, 2015).

This study aimed at the filtration and backwashing processes at the Opa Waterworks of Obafemi Awolowo University.The objectives are to determine the physical properties of the filter medium of the gravity filter, investigate the backwashing characteristics of the gravity filter and evaluate the backwashing characteristics of the filter medium in a laboratory model. It includes filtration and backwashing parameters which include density, porosity, hindered settling velocity, head loss, turbidity, flow rate, wash water volume, etc.

Materials and Methods

The materials and equipment that were used in the project are sand, gravel, water obtained from Opa Dam, (Fig. 1) sieves, pilot filter, manometer, pumps, tanks, pipes and appurtenances, stop watch and calibrated drum.

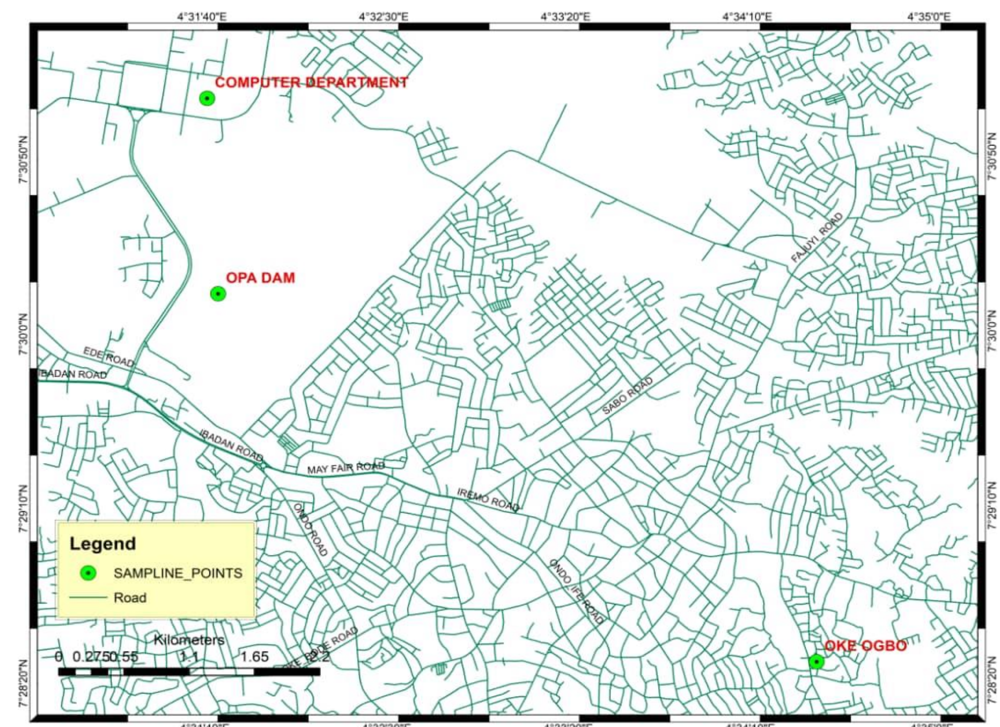

Figure 1. Map of the Study Area
Source: Jeje *et al*., (2021)

Preliminary Test

Sieving and determination of equivalent diameter

The portion retained on the size range of 0.8 mm – 2.36 mm was used for this research work.

The mean equivalent spherical diameter (deq) for each filter material was determined by the count and weigh technique suggested by (Sravanthi and Sharma, 2015). A representative sample of the grains (of predetermined relative density) was removed from the bulk dry sample. 100 grains of the sample was counted and weighed. This procedure was repeated for three other representative samples. The average weight of 100 grains was then determined and the deq was obtained as shown in Equation 1.

$$deq = \left[\frac{6V}{\pi}\right]^{1/3} \quad (1)$$

Where V is volume of 1 grain given as:

$$V = {}^{W_a}/_{\rho_s} \quad (cm^3) \qquad \text{(Skolubovich } et\ al \text{ 2011)}$$

Wa = average weight of 1 grain (g)

ρ s = density of the material in (g/cm3)

The density, porosity and unhindered settling velocity (Vs) were also determined.

Treatment Plant Experiments

Determination of flow rate of the backwashing process at the Opa Waterworks

A calibrated 30 litres drum was used to collect water from the discharge point for a specified amount of time. This was carried out for three different backwashing runs. The flow rate for each backwashing run was calculated using equation (2).

$$Flow\ rate, Q = \frac{volume\ of\ water\ in\ the\ drum}{time\ taken} \quad (2)$$

Determination of wash water volume

The time for the backwashing process was recorded for three different backwashing runs using a stopwatch and the average time was taken (Equ. 3)

$$Volume\ of\ water\ = flow\ rate\ \times Average\ time\ of\ backwashing \quad (3)$$

This was achieved by first loosely dropping coarse gravel (5.0 – 10.0 mm) to a depth of 100 mm, then fine gravel (3.35 – 5.0 mm) to a depth of 100 mm. this was followed by pouring the filter medium to the required depth of 500 mm. the filter was charged by backwashing to segregate the medium with the heaviest grains at the bottom and the lightest ones at the top.

Experimental Runs and Backwashing

For the clean water runs, different heads of water above the bed were used (10 cm – 50 cm) and filtration runs of four hours was used. Backwashing was carried out to clean the filter bed using duration of three hours for the runs. The expansion of the bed due to backwashing was measured and the results obtained were compared (equ. 4) with the predicted results obtained from equation (2) (Voitov and Skolubovich, 2010).

$$e^n = V/V_i \tag{4}$$

where V = superficial velocity of fluid above the bed
Vi = intercept velocity at a porosity ratio of one; and
n = slope of log V versus log e plot and is characteristic for grains of a particular size, shape and density

The predicted values of n were obtained using equations (v) and (vi). The predicted values of le/lo values were obtained from equation (vii) after computing the predicted expanded porosity from equation (iv) with the already predicted values of vi and the average of the predicted values of n.

$For\ 15 < R_0 < 200$
where Ro = particle Reynold's number; (Kim, 2014).
Using Dynamic Shape Factor (DSF),

$$n = \left(4.45 + \frac{18d}{D}\right) R_0^{(-0.1)} (DSF)^{\alpha} \tag{5}$$

Where:

$$\propto = (-2.2715DSF)^{0.420} R_0^{(-0.441)}$$

Using Sphericity,

$$n = \left(4.45 + \frac{18d}{D}\right) R_0^{(-0.1)} \varphi^{k} \tag{6}$$

Where:

$$k = (-2.9237\varphi)^{0.884} R_0^{(-0.363)}$$

For 200 < Ro < 500 n = 4.45Ro-0.1 (7)

Flow Rate and Head loss Measurement

The flow rate was measured with the aid of a measuring cylinder and a stopwatch by collecting water from the effluent point for 10 seconds and checking to ensure consistency at 15 minutes intervals. The Blake – Kozeny equation was investigated in the prediction of head loss across a filter bed using clean water runs. The predicted head loss was theoretically obtained by substituting appropriate values into equation (iii). The manometer was used to determine the actual head loss of the filtration runs when the head of water in the pilot filter is at 10 cm, 20 cm, 30 cm, 40 cm and 50 cm above the filter bed. The arrangement of the pilot filter and the manometer is shown in Figure 2.

$$\frac{h}{l} = 5u\mu/\rho g(\frac{1-f)^2}{f^3\left(\frac{A}{V}\right)^2} \tag{8}$$

where: h = head loss (m) l = depth of filter bed (m)
g = acceleration due to gravity (9.81 m^2/s) ρ = density (1000 kg/m^3)
f = porosity u = face velocity (m/s)
μ = dynamic viscosity of fluid (1.0 × 10-3 kg/m.s)
A = surface area of grains (m^2) V = Volume of grains (m^3).

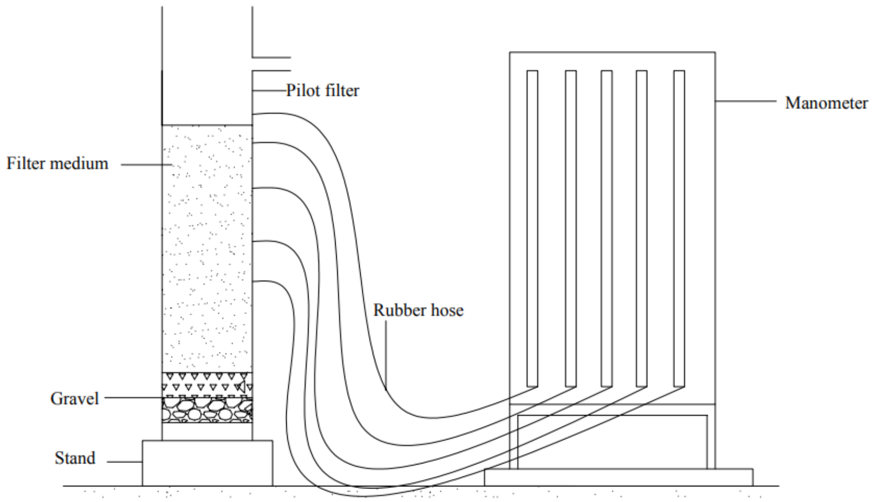

Figure 2. Schematic Diagram of Filter Setup

Results and Discussion

The purpose of the filtration studies was to determine the accuracy of the Blake – Kozeny equation in predicting head loss across a clean bed. The stipulated flow rate for a rapid filter is between 65 – 198 l/min-m^2, hence 65 l/min-m^2 and 198 l/min-m^2 were adopted for the experiment indicating the upper and lower limit of the filter. The plots of head loss against filtration time at varying depths and filtration rates are shown in Figures 3 and 4. The plots indicate that the depth of bed significantly contributes to the head loss build up across the bed. It also shows that the head loss increases with filtration rate.

The equivalent head losses were manually calculated using the Blake – Kozeny equation (equation (iii) and the average prediction error is shown in Tables 1 and 2. This shows that the Blake – Kozeny equation was able to predict the head loss with reasonable accuracy (Pharand, 2014; Skolubovich and Voitov,2015). The standard range of accuracy is between 1.9 and 2.5.

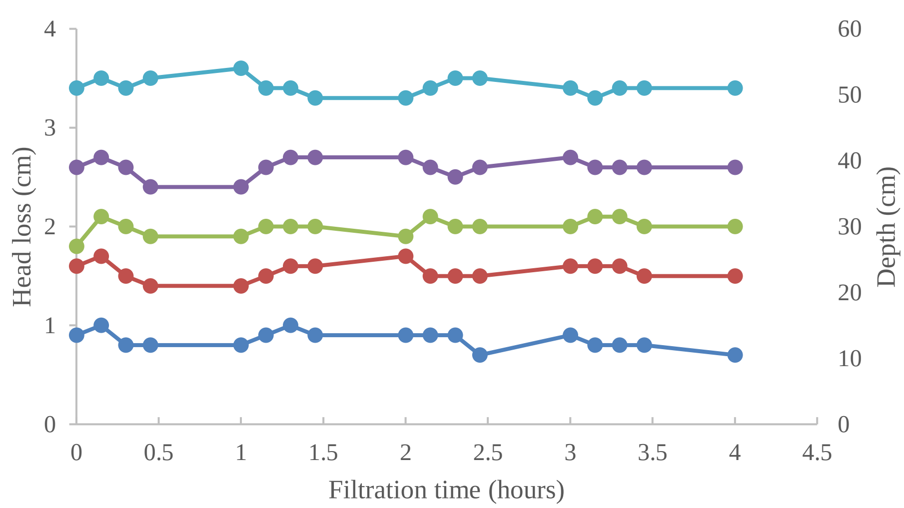

Figure 3. Head loss and filtration time at varying depths (65 l/min-m^2)

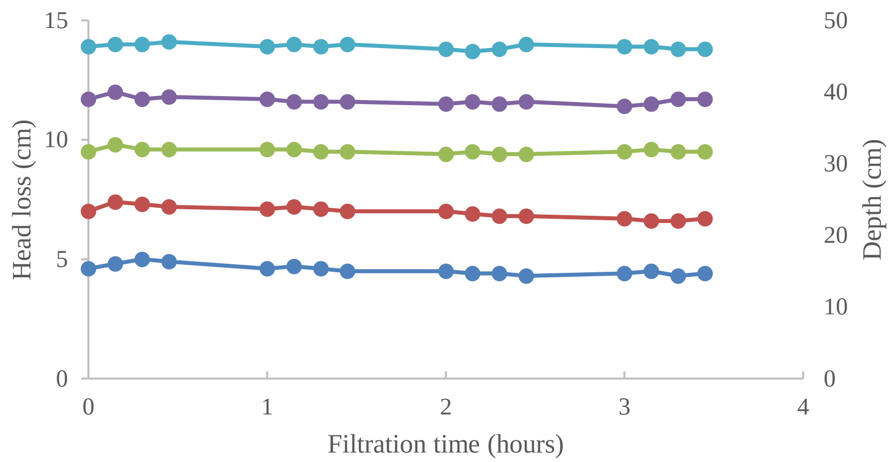

Figure 4. Head loss and filtration time at varying depths (198 l/min-m^2)

Table 1. Measured and predicted head loss (Blake – Kozeny equation) Filtration Rate: 65 l/min-m^2

Ports	h/l	Predicted Head loss	Measured Head loss	Prediction Error
10 cm	0.075	0.75	0.90	0.15
20 cm	0.075	1.49	1.55	0.06
30 cm	0.075	2.23	2.10	0.13
40 cm	0.075	2.98	2.60	0.38
50 cm	0.075	3.72	2.40	0.32
Average prediction error = 0.21				

Table 2. Measured and predicted head loss (Blake – Kozeny equation) Filtration Rate: 198 l/min-m^2

Ports	h/l	Predicted Head loss	Measured Head loss	Prediction Error
10 cm	0.22	2.20	4.30	2.1
20 cm	0.22	4.40	6.60	2.2
30 cm	0.22	6.60	9.50	2.9
40 cm	0.22	8.80	11.40	2.6
50 cm	0.22	11.00	13.80	2.8
Average prediction error = 2.5				

Backwashing Studies

The relationship between the superficial velocity (V) and bed expansion during backwashing is shown in Table 3. Table 4 shows that Sphericity model predicted the values of n fairly accurately compared to the DSF model. This shows that the predicted and observed values are of comparable accuracy.

Since the volume of media grains is constant in the fluidized bed for aa column of constant cross-sectional area, the fixed bed porosity (e_o) and height l_o are related to the expanded porosity (e_o) and height (l_o) by equation (9):

$$I_o (I - e_o) = I_o (I - e_o) \qquad (9)$$

Table 3. Expansion of sand during backwashing

Superficial Velocity (l/min-m^2)	Depth of bed during backwashing (cm)	Expansion		e_c	Log e	Log V
		cm	%			
358.49	80.3	0.03	0.04	0.40	-0.398	2.554
425.93	80.5	0.05	0,06	0.40	-0.398	2.656
566.04	85.6	5.60	7.00	0.44	-0.356	2.753
584.91	86.4	6.40	8.00	0.44	-0.356	2.767
773.58	87.5	7.50	9.38	0.45	-0.347	2.888
1,113.21	91.8	11.8	14.75	0.48	-0.319	3.047
1,188.68	93.3	13.3	16.63	0.49	-0.310	3.075
1,792.45	107.0	27.0	33.75	0.55	-0.260	3.253
1,905.66	113.8	33.8	42.25	0.58	-0.237	3.280

Table 4. Actual and predicted values of backwashing parameters

Parameter	Predicted value	Actual value
Superficial velocity, V_i	7994.91 l/min-m^2	9544.93 l/min-m^2
Minimum fluidization, V_{mf}	733.06 l/min-m^2	676.00 l/min-m^2
Slope, n	DSF: 2.78 Sphericity: 2.86	2.92

Conclusion

From the laboratory experiments, the Blake – Kozeny model was used to predict the head loss across a clean bed at different depths of bed and it was found to be reasonably accurate with a minimum prediction error. The Sphericity model was found to be more accurate in the prediction of the slope of the backwashing graph, with the le/lo values having a mean prediction error of 0.07.

It is necessary that further studies be carried out using other filtration and backwashing models to also determine their accuracy. Considering the age of the treatment plant, it is recommended that there be improvement in the general maintenance of the treatment plant, but specifically the pressure and gravity filters should be focused on. Equipment such as pressure gauges, flow rate meters should be provided for proper monitoring of daily production rates and more accurate filtration and backwashing rates.

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