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Using Filter Sand Abrasion to Predict Flow Rate and Filter Bed Management

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Abstract: Most Waterworks in Nigeria and other African developing countries still import filter sand from developed countries for the operation of rapid filter beds in water treatment facilities. The variation of the physical characteristics such as permeability (k), equivalent diameter (d_{eq}) and sphericity (Ψ) of three types of filter sand (FS) grains were studied as they were degraded by simulated abrasion. The flow rate and permeability coefficient of raw imported FS at Ado-Ekiti waterworks and a locally-sourced FS at OAU waterworks were the same at 1.5 $cm^3\ s^{-1}$ and 2.79×10^{-3} cm s^{-1}, respectively compared with erosion sand's values of 1.77 $cm^3\ s^{-1}$ and 3.3×10^{-3} cm s^{-1} for the parameters. At the end of more than 12% degradation, the flow rates for the imported, locally-sourced and erosion sands reduced to 0.45, 0.35 and 0.23 $cm^3\ s^{-1}$, respectively. The coefficient of permeability of the imported, local and erosion FS also reduced to 8.38×10^{-4}, 6.52×10^{-4} and 4.28×10^{-4} cm s^{-1}, respectively. The work established that d_{eq} might be used to predict when the filter media are due for replacement. The method may be useful to engineers for FS material selection and projecting what quantity may be required for stocking a water treatment plant.

Key words: Abrasion number, equivalent diameter (d_{eq}), filter sand (FS), flow rate, rapid filter beds, water treatment

INTRODUCTION

Filtration of suspensions in water from clarifiers or settling tanks through porous media is an important stage in the treatment of potable water to achieve final clarification in waterworks[1,2]. The mechanism of removal of impurities is a combination of mechanical straining, sedimentation and adsorption, electrical effects and biological changes. Although about 90% of turbidity and colour are removed in coagulation and sedimentation, a certain amount of floc is carried over from settling tanks and requires removal[1]. The theory and principle of filtration is well established in literature[1-4].

The bed in rapid sand filters usually consists of 750 mm depth of sand or a combination of sand and crushed coal, on 450 mm of gravel both on floor drains. Rapid sand filters require good pretreatment of raw water via coagulation, flocculation and settling in a clarifier before the influent water is received by the bed[4-6].

Conventionally, filter sand (FS) for use in rapid filters is specified on the basis of its effective size (d_{10}) and uniformity coefficient (U_c) and these range, respectively from 0.45-0.55 mm and 1.2-1.7[3,7]. The sand materials usually have grains size ranging between 0.45 and 1.5 mm with U_c of between 1.3 and 1.8[8]. Over time the grains are abraded during backwashing and by chemical weathering through interaction with water and coagulant resulting in loss of grains and of efficiency of filtration through shorter filter runs.

The filter media controls the performance of a filter unit, the finer the grains the better the quality of effluent but the faster the head loss increases hence the shorter the run; the coarser the media the less the quality though the head loss is reduced. A balance of media type and grain size could be made to achieve an optimum filter performance[8]. The efficiency of a rapid filter is directly related to the media depth. The porosity of the filter bed determines the head loss and suspended solids removal characteristics of the filter media. The size and shape of the media govern the size distribution of voids in porous media[9]. A filtration rate of 0.08-0.244 m^3/m^2.min is considered good operating rate for rapidfilters[2,3].

The resistance of a clean bed of sand to the filtration of clean water is given by the Blake-Kozeny equation[3]:

$$h/l = k/g \cdot \mu/\rho \cdot v(1-f)^2/f^3 \cdot (A/v)^2 \qquad (1)$$

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where:

- μ = viscosity of the water
- ρ = density of the water
- A = surface area of the grains within the bed relative to their volume, v
- ν = kinematic viscosity of water
  h is head loss in bed of depth, l
- k = is permeability of the media
- g = gravitational constant
- f = porosity of media.

Backwashing is also an important aspect of filtration through which entrapped dirt between and within the filter media are dislodged by the shearing action of the water or by abrasive action resulting from contacts made between the rising bed particles[4]. During backwashing, grains of FS are mixed in the turbulent flow of the expanded bed and materials get progressively lost due to the abrasion of particles[2,10].

Most African developing countries, Nigeria inclusive, presently import FS from Europe and other developed countries for local use in water treatment plants. Ogedengbe[7] established that erosion sand when properly graded has the same quality for water filtration as imported FS. The objective of this work is to determine the variation of the physical characteristics of three selected filter sand media with progressive abrasion and degradation and the effect of degradation effect on the efficiency of filtration.

MATERIALS AND METHODS

A sample of imported FS was obtained from Ado-Ekiti waterworks. A sample of locally sourced FS was collected from Opa dam water treatment plant, Obafemi Awolowo University, Ile-Ife (OAU). Erosion sand deposited by storm run-off was collected within the OAU campus.

Preparation of samples: All the sand samples were washed clean and air-dried. A batch of 1kg each of the imported sand sample, the OAU plant sand and erosion sand was first graded on an ELE sieve machine and the weights of grain retained on each sieve and pan were recorded. The sieve analysis was replicated thrice and the average weight of each grain size was used in plotting the grain curve for each sample source. The OAU plant sand and erosion sand were then sorted and combined to obtain the same grain curve as the imported sand sample.

Physical characteristics determination: The density of grab samples of each sand sample was determined according to standard methods[11]. The porosity of each sand sample was determined using the method developed by Amirtharajah[12]. This requires filling a 1-L measuring cylinder with the sand sample to the 400 ml mark and shaking the cylinder to ensure a uniform level. Exactly 500 ml of water, recorded as V_1, was then run down the side of the upright cylinder to obtain a total volume, V_2. The cylinder was then sealed with plastic sheet held in place around the top with a rubber band. The cylinder was inverted a few times to dislodge trapped air and then allowed to settle for about one hour. The final volume of sand submerged was recorded as V_{sd} Porosity, f, is given by Amirtharajah[12] as:

$$f = 1 - (V_2 - V_1)/V_{sd} \tag{2}$$

The analysis was replicated thrice for each sand sample before and after each abrasion exercise.

The equivalent diameter, d_{eq}, of each sample was determined using the method developed by Cleasby and Fan[13]. The density of the material is first determined. Exactly 100 grains of each sample of sand was counted and weighed. The average weight of 1 grain was therefore computed. The equivalent volume, V, of a single grain was found from mass/density relationship. The value of d_{eq} is got from:

$$d_{eq} = v^3(6V/\pi) \tag{3}$$

The Sphericity ,Ψ, of each sand sample was determined using the ratio[14]:

$$\Psi = d_{eq}/d_s = (V_s/V_{eq})^{½} \tag{4}$$

where:

- d_{eq} = diameter of equivalent sphere
- d_s = diameter of grain
- V_s = the grain's settling velocity
- V_{eq} = the settling velocity of a sphere of equal volume as the grain

For practical purposes, Huisman and Wood[14] showed that d_s could be calculated from,

$$d_s = d_{10}(1 + 2\log U_c) \tag{5}$$

The permeability of the sand samples was determined using the constant head permeameter as described in standard methods[11]. The volume of water filtered through each sand bed in the permeameter unit in 10 min was used in computing the flow rate, q. One kilogram of each sample of sand was abraded in a Ro-Tap abrasion machine following the procedure described in Sheffler[15]. Before each abrasion operation, the sand samples were separately sieved using sieve sizes 4.75, 2.36, 1.18 and 0.85 mm and the bottom pan. The sand was then recombined and loaded into the steel container of the abrasion machine along with 10-19 mm diameter steel balls and 10-12.5 mm diameter steel balls. The abrasion was timed for 15±1 min each of the two times of analysis for each sample source. The sieve analysis was repeated after each abrasion operation. The physical characteristics of each abraded sample were also analyzed and flow rate through it determined. The whole experiment was replicated thrice.

RESULTS AND DISCUSSION

The values of the effective grain size, d_{10} and uniformity coefficient, U_c, of the unabraded imported sand sample were 1.66 mm and 2.26, respectively (Table 1). Both were beyond the range of 0.45 mm < $d_{10} \leq$ 0.55 mm and 1.2< $U_c \leq$ 1.7, respectively specified for rapid sand filters. The samples were deliberately used as obtained to determine the characteristics of unsorted sand samples. For satisfactory filter operation the sands have to be graded, sorted and combined to obtain the desired ranges of d_{10} and U_c[2,3].

For the same reason of uniform comparison the OAU sample and the erosion sand were graded to have similar d_{10} and U_c as the imported sand. After final abrasion by more than 10% it was the imported sand only that had its U_c remaining within the range specified for filter beds but its d_{10} was still higher than recommended for all samples as shown in Table 1.

The flow rates through the raw imported sample and the locally sourced sample were the same at 0.397 m^3/m^2.min while the erosion sand's flow rate was 0.469 m^3/m^2.min. The high rates are expected because of the higher values of d_{10} and U_c than recommended. After abrasion by 11.28% the final flow rate of the imported sand was 0.119 m^3/m^2.min while those of the OAU and erosion sands after abrasion by 11.56 and 11.49%, respectively were 0.112 and 0.114 m^3/m^2.min. The flow rate through the abraded samples of imported sand, OAU sand and erosion sand was respectively 48.75, 40 and 42.5% more than the minimum recommended for rapid filters. Noting that most of the finer grains would have been flushed out of the filter bed during backwashing the quality of the filtered water would decrease by the time this range of flow rate is observed.

From Table 1, as the value of d_s decreases the flow rates decrease. When one calculates the value of d_{eq} from Equation (4), it could be noted that for the imported FS collected from Ado-Ekiti waterworks d_{eq} peaked in the first abrasion regime and finally came down to its initial value of 0.33. The other two samples were almost mirror image, as their values dropped and rose back. No ready explanation could be offered except to relate it to the physical characteristics of the quartz materials. The authors agreed that the value of d_{eq} could be used to fix the time when replacement of feed FS is due. This is when the d_{eq} returns to its initial value after undergoing abrasion.

From the trendline equation in Fig. 1-3 for the flow rates in the different sand samples, the lower limit of filtration rate (0.08 m^3/m^2.min) for the imported sand, OAU sand and erosion sand will be reached when the degradation by abrasion is 12.83, 13.15 and 12.88%, respectively. Since field evaluation may be difficult, the average depth of filter sand after backwashing may be used to monitor when replacement of the media would be necessary. This, as presented in this work, would be when the depth of sand has been reduced by the corresponding percentage degradation computed from the trendline equation equivalent to the lower limit of flow rate of 0.08 m^3/m^2.min. Better still a rule of thumb guide to replace the media when degradation equals or exceeds 12% is justifiable from the findings of this work. So, when a depth of 750 mm sand bed is reduced to 660 mm after commission or record of previous replacement with attendant frequent backwashing, fresh media should be installed.

Good quality quartz erosion sand may thus be graded and processed for use as filter sand after determination of its degradation rate; and d_{eq} before, during and after degradation by abrasion, to know what percentage reduction in its volume must be reached before need for replacement. Such development would reduce frequent backwashing and poor budgeting. Most importantly, African and other developing countries could source filter sand materials locally for use in water treatment. White quartz sand should be preferred above other types of sand.

Recent works[16,17] showed that there is the need for a paradigm shift from the public or government sponsored water supply development and management programmes to a public-private sector partnership management of such facilities. This is informed by the habitual treatment of public utilities as a no-man's property with the attendant mismanagement. For instance, most waterworks mostly have FS and other equipment spares that is just enough for the commissioning of a new facility, which soon need replacement that may be out of stock from the foreign suppliers of such materials and equipment. Using the Lagos state Water Corporation as a basis for the private sector participation Coker[16] noted the introduction of

Table 1: Results of abrasion test and physical characteristics of three samples of sand as filter media

	Sand before abrasion			Sand after 1st abrasion			Sand after 2nd abrasion		
Tests on sand	Ado-Ekiti	OAU	Erosion	Ado-Ekiti	OAU	Erosion	Ado-Ekiti	OAU	Erosion
Sphericity, Ψ	0.11	0.09	0.12	0.19	0.11	0.14	0.25	0.12	0.17
Permeability, k ($x10^{-3}$) cm/s	2.79	2.79	3.30	1.06	0.80	0.65	0.93	0.65	0.42
porosity, f	0.48	0.45	0.45	0.46	0.43	0.43	0.45	0.42	0.43
flow rate, q $q = cm^3/s$	1.50	1.50	1.77	0.67	0.69	0.68	0.45	0.35	0.23
$q = m^3/m^2.min$	0.39	0.39	0.46	0.17	0.18	0.18	0.11	0.11	0.11
d_{10}	1.66	1.66	1.66	1.34	1.22	1.18	1.1	1.05	1.05
U_c	2.59	2.59	2.59	1.69	2.94	2.44	1.26	3.66	2.78
Cumulative Abrasion number, A	-	-	-	90.43	90.37	90.76	98.18	98.16	97.82
Cumulative Degradation, %	-	-	-	9.41	9.60	9.31	11.28	11.56	11.49
$d_s = d_{10}(1 + 2\log U_c)$, mm	3.03	3.03	0.03	1.95	2.36	2.09	1.32	2.23	1.98
$d_{eq} = \Psi . d_s$	0.33	0.27	0.36	0.37	0.26	0.29	0.33	0.27	0.34
U_c / d_s	0.85	0.85	0.85	0.87	1.25	1.17	0.95	1.64	1.40

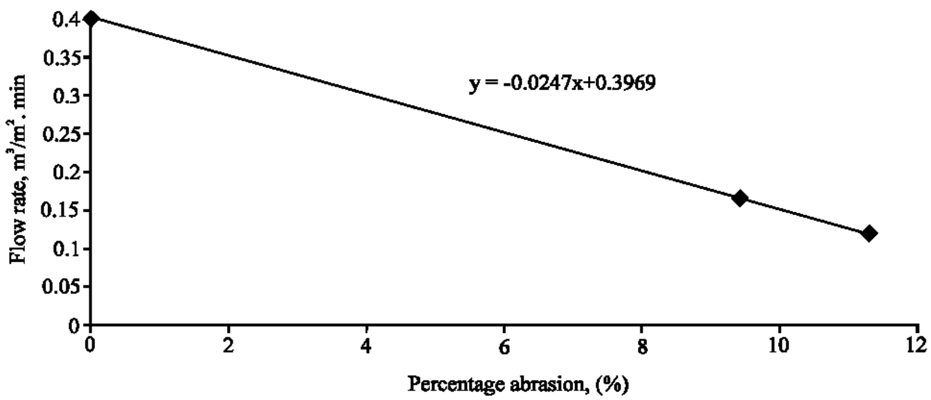

Fig. 1: The variation of flow rate with degradation of filter sand by abrasion for imported sand used in Ado-Ekiti waterworks

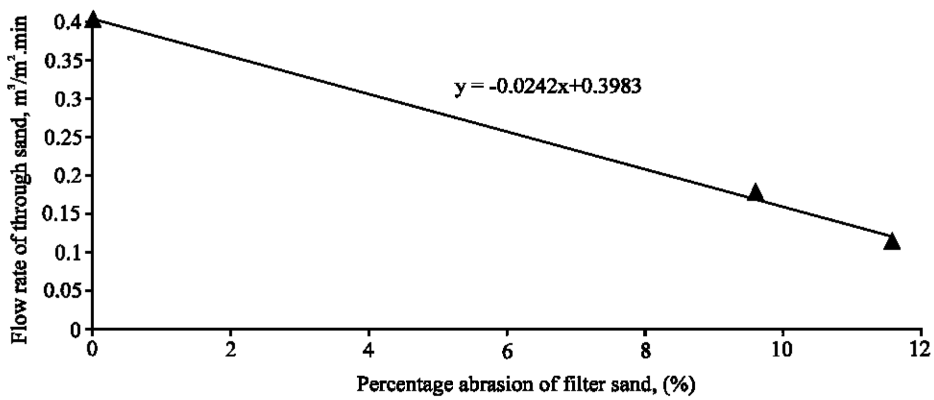

Fig. 2: The variation of flow rate with degradation of filter sand by abrasion for locally sourced filter sand used in OAU waterworks

Zero based budgeting system and deliberate cost control to eliminate wastage as gains over the erstwhile sole public/government management that generally lacked accountability.

The abrasion analysis procedure presented in this work could be used to determine the quality of a proposed media before procurement and also to estimate the quantity of material needed for stocking a water treatment

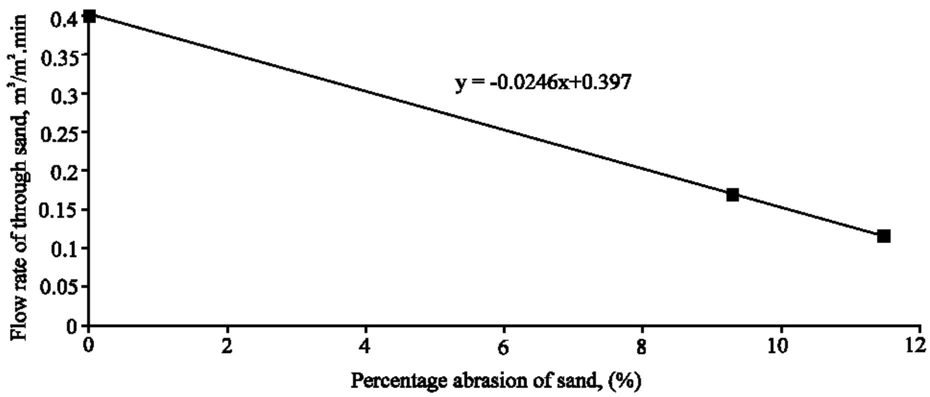

Fig. 3: The variation of flow rate with degradation of filter sand by abrasion for erosion sand

facility. Engineers especially those in Waterworks would find this procedure useful for the management of a treatment plant.

The equivalent diameter, d_{eq}, of a FS material and its abrasion number could be used to predict the time when spent media would need replacement. A method of evaluation of the quality of filter media and for budgeting for the stocking of a waterworks with media considered suitable has been presented. The filter media used in this work, for instance, would need to be replaced when the degradation has reached 12%. The work would be useful to engineers in the management of a Waterworks in developing countries.

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