

**ORIGINAL RESEARCH ARTICLE****Evaluation of crushed slates as a suitable capping material for rapid gravity sand filters****Maina Oscar Njung'e¹, Beatrice Katheu Kakoi² , Njenga Mburu³ **¹*Faculty of Sustainable Materials Research and Technology Centre (SMARTEC)
Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya*²*Department of Civil, Construction and Environmental Engineering, JKUAT*³*School of Engineering, Dedan Kimathi University of Technology, Nairobi, Kenya*Corresponding author email: mainaoscar10@gmail.com**Abstract**

In the potable water treatment process, Rapid Gravity Sand Filters (RGSF) are commonly adopted as the last solid-liquid separation stage. Cleaning of the RGSF is done through backwashing. RGSF is widely adopted all over the World due to its ease of operation and high filtration rates. However, these filters suffer from stratification of the sand media, which causes floc removal to occur only at the topmost layer of the filter bed, leaving the remaining depth unutilized. Capping is a technique whereby a thin layer of sand filter media is replaced with a suitable coarse material to overcome the problem of stratification and transform a single-media RGSF into a dual-media filter. The objective of this study is to determine the suitability of crushed slates as a capping material. The study evaluated the performance of a crushed expanded slate-capped filter against a conventional single-media RGSF, the effects of its physical and chemical characteristics, and varying the depth of the capping material. Laboratory tests were conducted to assess the physical and chemical characteristics of slates from Maji ya Chumvi (Coast, Kenya). This included specific gravity, acid solubility, water extractable substances, silica content, and friability. A performance comparison was carried out by means of a fabricated model filtration unit set up within an existing community water treatment plant. The model filtration unit was fed with pretreated raw water of varying influent turbidities. Crushed expanded slates met the minimum physical and chemical requirements for use as a capping material for RGSF. The crushed expanded slate-capped RGSF model demonstrated high robustness under high shock turbidity loads (above 150 NTU), which is illustrated by an increased length of filter run of 27% (50–150 NTU) and 45% (150–300 NTU). Increasing the depth of capping material from 25mm to 50mm did not yield any significant improvement or deterioration in the filter run length. At influent turbidities below 150 NTU, the effluent water quality for all three scenarios (uncapped, 25 mm, and 50mm crushed expanded slates capped) is below 5 NTU and therefore meets the Kenyan drinking water standards. Above 150 NTU influent turbidity, the effluent water quality for the uncapped RGSF deteriorates, whereas for the 25mm and 50mm capped RGSF, it remains consistently below 5 NTU. This demonstrates the usefulness of the crushed expanded slates in improving the turbidity removal of RGSF for high (above 150 NTU) turbidity loads. This study recommends a full-scale trial of crushed expanded slates to facilitate a more precise estimation of the overall benefit of full-scale community water filtration systems.

Keywords: Crushed expanded slates, capping material, rapid gravity sand filtersURL: <https://ojs.ikuat.ac.ke/index.php/JAGST>

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1.0 Introduction

The Kenyan potable water standards have been developed and published under schedules 1 to 5 of the Water Services Regulatory Board (WASREB) guidelines on water quality and effluent monitoring of March 2008. The degree and type of treatment required for raw water to meet potable water standards primarily depend on the raw water's characteristics (Malcolm, 2017). There are notable seasonal variations especially on Turbidity levels for surface raw water sources (Hadgu *et al.*, 2014). Different water treatment technologies have been developed and are considered either conventional or advanced treatment systems. The Kenyan Water Supply Design Manual (MWI, 2005) recommends the adoption of conventional water treatment systems with minimal mechanisation and energy efficiency. These systems have proven to be economical and sustainable. The preference for conventional water treatment processes in other developing countries is reported by Sabale *et al.* (2014).

A conventional water treatment process entails pretreatment (screening, flocculation, and clarification), filtration, and disinfection. Depending on the raw water quality, pretreatment can be excluded (MWI, 2005). In any domestic water treatment process, filtration and chlorination remain the basic and widely adopted stages (Lin, 2010). Nyagwencha *et al.* (2012) notes that disinfection using chlorine has now become a common practice at homes in developing countries. Sabale *et al.* (2014) define filtration as a physical, chemical, and, in some instances, biological process involving the separation of suspended and colloidal impurities from water by passage through porous media. Malcolm (2017) discusses the different types of filtration systems and further notes that Rapid Gravity Sand Filters (RGSF) remain the most widely and commonly adopted all over the world due to ease of operation and high filtration rates.

RGSF consists of a layer of graded sand supported on a gravel bed through which the raw water percolates and gets filtered. Cleaning of the filter is done through backwashing. The frequency of backwashing and the general performance of the filter are highly dependent on the influent water quality and the filter media characteristics (Jusoh, 2007). Al-Rawi (2017) indicates that Sand as a filter media has widely been adopted because of its (local) availability, low cost, and satisfactory results obtained in turbidity removal. A minimum depth of Sand must be provided to ensure flocs are captured within the filter media before breaking through to the supporting gravel bed (Ansari *et al.* 2017).

Numerous studies indicate that during backwashing of RGSF, stratification of sand media takes place (Sabale *et al.*, 2014; Al-Rawi, 2017; Frajana and Kallesh, 2018; Ansari *et al.*, 2017; Delbazi *et al.*, 2011). Sand grains with small particle sizes rise to the top of the RGSF. During the next cycle of filtration, removal of flocs occurs at the topmost layer of the filter bed; this leaves the remaining depth of the RGSF bed unutilized. It is estimated that sand has a voidage ratio of 40–45%, which is available for sludge storage during filtration. However, due to the stratification arising during backwashing, only about a quarter of the available voidage is utilised (Malcolm, 2017). Stratification reduces the sludge storage capacity of the filter bed and further reduces the porosity of the top layer of the filter media, thereby increasing the head loss, which results in short filter runs. Short filter runs demand a high frequency of backwashing, which increases energy consumption and hence the operating cost (Kalibbala, 2007). In developed countries,

the problem of stratification has been progressively solved by the introduction of capping materials such as anthracite coal (Al-Rawi, 2007). Among all other coals, anthracite coal has the highest carbon content and is commonly used as a source of energy. In all the coal mines in the world, anthracite coal accounts for approximately 1% of the total coal reserves (Tenge, 2009). According to Shirule and Sonware 2019, anthracite coal is not only costly but also difficult to obtain in a uniform grade with adequate wear resistance and a satisfactory length of useful life. Anthracite coal problems are further reported by Cescon (2020), who indicates that there are limited sources for anthracite all over the World. Researchers continue to evaluate the suitability of other locally available materials as capping materials for RGSF. This includes bituminous coal, PVC granules, crushed coconut shells, fibre mats, and synthetic nylon fibres, among others (Sabale et al., 2014).

Davies and Wheatley (2012) reported that slates have a relatively low specific gravity compared to sand and demonstrate good performance in turbidity removal despite their low sphericity. This makes slate a probable material for capping conventional RGSF. The objective of this study was to determine the suitability of crushed expanded slates from Maji ya Chumvi (Coast Region, Kenya) as a capping material and to evaluate the performance of a crushed expanded slate-capped filter against a conventional single-media RGSF, the effects of its physical and chemical characteristics, and varying the depth of the capping material.

2.0 Materials & methods/methodology

2.1 Materials

Slate is a fine-grained, repetitively layered, homogeneous metamorphic rock derived from an original shale-type sedimentary rock composed of clay or volcanic ash through low-grade regional metamorphism (Marshak, 2009). Shale is found in large quantities in the Maji ya Jumvi formation in the Coastal region of Kenya. Maji ya Chumvi beds overlie the Taru grits with a slight disconformity. In Kenya, slate quarries are found in Galana, Mazeras, Mariakani, Maji Ya Chumvi, Lunga Lunga, and Shimba Hills. Maji-ya-Chumvi beds, which yield slates, continue to accumulate slowly in semi-arid climates (Caswell, 2007).

Slates were obtained from *Maji ya Chumvi* (Coast region, Kenya), crushed, and expanded through continuous heating in a kiln to temperatures between 1200 and 1350°C. Sand filter media was sourced locally with an Effective Size (ES) of 0.6 and a uniformity coefficient (UC) of 1.5.

2.2 Methods

The acid solubility test entailed the immersion of three 50-gramme samples of each slate and sand in Hydrochloric (HCL) acid for 24 hours and the determination of the mass loss. This is a standard procedure given in BS EN 12902-2004 (Products used for treatment of water intended for human consumption—Methods of Test). The test was carried out at the JKUAT Materials Laboratory.

Water extractable substances test entailed immersing the samples in extraction water for 30 minutes and analysing the leachate for the presence of metals and cyanide. This is a standard

procedure given in BS EN 12902-2004. Extraction water was prepared in the JKUAT chemistry laboratory, with the majority of the other specific tests carried out at the Ministry of Public Works, Nairobi.

The silica content test was carried out through the XRF (X-ray fluorescence) method. Crushed expanded slates were ground into a powder and subjected to XRF spectroscopy (ASTM D5381-93, 2021) at the Ministry of Mining and Geology Laboratories, Nairobi. A printout was obtained from the spectrometer giving the elemental composition of crushed slates.

Specific gravity for crushed slates (expanded and unexpanded) and sand was determined through standard procedures given in BS 812-2:1995: Testing Aggregates. For aggregates larger than 10mm, a wire basket method was adopted, whereas for aggregate sizes below 10 mm, a pycnometer method was used. The tests were carried out at the JKUAT Materials Laboratory.

The friability test was carried out through the Los Angeles Abrasion Test (LAA) supplemented by Aggregate Crushing Value (ACV), both in accordance with the standard method given in ASTM C131/C131M-20. The tests were carried out at the Ministry of Public Works laboratories.

Based on the determined Specific Gravity of crushed expanded slates, the Effective Size was determined through Stoke's Law to ensure that crushed expanded slate particles and small grains of sand had equivalent settling velocity. A declining rate model RGSF unit was designed for an average filtration rate of 6m³/m²/hr to limit the risk of particulate breakthrough.

The model filtration unit (Figure 1) consisted of the following components: an inlet pipe with a sampling point (1" diameter hosepipe and PPR pipe), a 4" uPVC inlet channel, a 3mm thick acrylic rectangular filter unit (0.3m x 0.3m x 1m high) strengthened by mild steel angle sections, a perforated pipe underdrain outlet, and a 1 ½" overflow uPVC pipe. The backwash system consisted of a ½" hosepipe tapped from an existing pressurised 6" HDPE-treated water main connected to the filter underdrain system with multiple regulating valves. The primary filter media was sand, supported by a gravel bed with a perforated pipe underdrain system. Through the Hudson Formula (Equation 1), the minimum depth of sand to limit floc breakthrough was determined. Considering the model filtration unit was designed as a declining rate filter with an average filtration rate of 6m³/m²/hr (equivalent to 0.15 liters/sec), the filtration unit required backwashing when the filtration rate reduced below 50% (0.08 liters/sec).

Hudson formula:

$$Q * D^3 * \frac{H}{L} = Bi * 29323 \dots\dots\dots \text{Equation 1}$$

Where;

Q = filtration rate in m³/m²/h, *D* = sand size in mm, *L* = depth of sand in meters,

H = terminal headloss in meters, *B_i* = breakthrough index whose value ranges between 0.00004 to 0.006 depending on response to coagulation and degree of pretreatment in the filter influent.

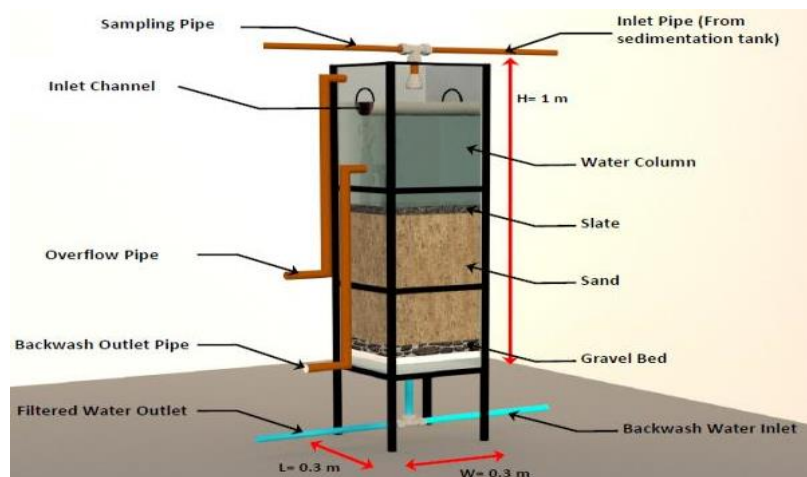


Figure 1: Model Filtration Unit (Authors, designed)

The model greatly benefited from the transition from the wet season to the dry season, reflecting considerable variations in influent turbidities. To consider the effect of the varying influent turbidities, in the processing of this data, influent turbidity was analysed in bands of <20 NTU, 50–150 NTU, and 150–300 NTU. The categorization of the turbidity bands was guided by existing literature that has illustrated a significant change from one upper limit to the next with marginal variations within a given turbidity band (Malcolm, 2017; Tamakhu, 2021).

The model filtration unit was continuously run from 0900 hours to 1600 hours, and both the effluent turbidity and length of the filter run were observed. Backwashing was done every morning before commencing a new filtration cycle. The adequacy of the backwashing was judged by observing the clarity of the backwash effluent. The filtration unit was designed and operated as a declining rate RGSF, with the throughput at the start adjusted to ensure the model operated within the designed filtration rate; otherwise, rapid development of headloss would be experienced.

A stopwatch and a calibrated one-litre glass jar were used to determine the flow rate at one-hour intervals. A calibrated turbidimeter (HACH 2100Q Model - USA), with an accuracy of $\pm 2\%$ of the reading plus stray light, was used to measure the influent and effluent turbidities similarly at a one-hour interval.

During the operation of the model filtration unit, data for the decreasing filtration rate and effluent turbidities were collected on an hourly interval from 0900 hours to 1600 hours for varying influent turbidities for the uncapped filtration model. The same procedure was repeated when crushed expanded slate was added for both 25mm and 50mm depths.

The significance of capping a RGSF with crushed expanded slates was evaluated using a one-tailed t-test with a significance level of 5%. The results were further verified using an ANOVA. Null and alternative hypotheses were developed and tested for the length of the filter run and the efficiency of turbidity removal. Statistical data processing and analysis were carried out using the add-in data analysis tool in Microsoft Excel.

3.0 Results & discussion

3.1 Chemical and physical characteristics of slates

3.1.1 Acid loss

After 24-hour contact time with Hydrochloric Acid (HCL), the weight of Sand remained intact, whereas crushed expanded Slates experienced 0.003% weight loss.

The acid loss test is important in determining the presence of acid-soluble minerals or other impurities that may be present in the filter material. The maximum published limits of acid loss ensure that there is no substantial loss of the filter media in acidic waters or during an acid cleaning (AWWA, 2001). The limits for acid loss for filter media are published in ANSI/AWWA B100-01 and BS EN Standards. BS EN 12905-2012 is the most stringent standard, giving a maximum acid loss of 2%. Crushed expanded Slates from Maji ya Chumvi have an acid loss of 0.003%, which is within the set maximum limit of 2%.

Davies and Wheatley (2012) reported an acid loss of 2.58% for slates obtained from New York. This was higher than the acid loss reported in the current study, mainly due to mineral composition and the heating aspect of the current research. Expanded slates are known to be chemically inert (Davies and Wheatley, 2012).

3.1.2 Water extractable substances

The water extractable substances test evaluates the probability of a filter media releasing any harmful compounds into the filtered water, which can be harmful to public health. The test was carried out on a sample of the crushed expanded slate from Maji ya Chumvi.

The results of the water extractable substances for crushed slates against the limits set in BS EN 12903:2009 are provided in Table 1.

Table 1: Results of Water Extractable Substances

Element	Slates (%)	% Limits (Max.)
Cadmium	Nil	0.0005
Chromium	1.81x10 ⁻⁵	0.005
Lead	Nil	0.001
Mercury	6.0 x 10 ⁻⁵	0.0001
Nickel	Nil	0.002
Cyanide	Nil	0.005

The results above indicate that most of the hazardous heavy metals are completely absent in slate. Traces of Chromium and Mercury were identified, but in negligible quantities, which are within acceptable limits. There is very little literature in regard to similar tests that have been carried out on slates or other materials intended for use in water filtration. As noted in the preceding section, expanded slates are thermally processed and chemically inert, which contributes to the inability of water to extract any harmful elements if they ever existed.

3.1.3 Silica content

The XRF results indicate that slates from *Maji ya Chumvi* have a silica content of 80.4%, whereas river sand has 91.3%. According to BS EN 12904, the minimum Silica content for Sand for use as a filter media is 80%. Expanded aluminosilicate, which is an approved filter media, should have a Silica content of 55 – 75% (BS EN 120905). Quartz (Silica) is one of the hardest naturally known existing materials, with a value of seven on the Mohs scale of mineral hardness. Silica is also chemically sound and thus does not degrade when exposed to acidic solutions such as those used in water treatment. A high content of Silica implies lesser fractions of other impurities in the filter material, hence better suitability (Platias et al. 2014). Inferring from the limits of both sand and expanded aluminosilicate, slates from *Maji ya Chumvi* meet the minimum silica content for use as a filter media. The high silica content in slates demonstrated their good physical and chemical inertness for use in water filtration.

3.1.4 Specific gravity

The specific gravity of sand was 2.55, 2.20, and 1.68, respectively. Davies and Wheatley (2012) reported a specific gravity of 1.5 for crushed expanded slates sourced from New York. The density of rocks is specific to their mineral composition and varies with their origin, hence the variation reported in the two studies. The majority of the minerals that form the rocks have densities ranging from 2600 Kg/ m³ to 3000 kg/m³. Slates, when heated to temperatures of 1200–1350 – 1350°C, go through a physical change known as exfoliation. Internal gases form, which results in a porous structure that is retained during cooling, giving a lightweight aggregate. This is why, in the current study supported by Davies and Wheatley (2012), there was a substantial decrease in the relative density of the crushed slates after heating to the recommended temperature above 1200 °C.

A significant lower relative density between the capping material and the primary filter media (sand) is critical to maintaining the coarse-to-fine gradation and relative position during filtration and after repeated backwashing. The recommended relative density of anthracite, which is an approved capping material, is between 1.4 and 1.95 (AWWA, 2001). Crushed expanded slates are within the Specific Gravity requirement for consideration as a capping material for Rapid Gravity Sand Filters.

3.1.5 Friability and mechanical durability

The friability test gives an indication of the mechanical strength of the aggregates to resist substantial physical breakdown (attrition). Based on the test carried out, crushed expanded slates had a Los Angeles Abrasion (LAA) value of 27.2% and an Aggregate Crushing Value (ACV) of 21.6%.

The Geological Society, London (GSL) has provided indicative acceptance criteria for filter media which is based on LAA (<40%) and ACV (<30%).

A comparison of attrition levels of crushed expanded slates against pumice was conducted through extended backwashing for 50 hours, which is equivalent to 2 years of normal operation

(Davies and Wheatley 2012). Results indicate that crushed expanded slates from New York had an average loss of 8% compared to pumice, which had an average loss of 27%.

The results of the current study, supported by Davies and Wheatley (2012), indicate that crushed expanded slates have good resistance to attrition. However, considering the shape of the crushed slates, irregular plate-like attrition is expected at the initial period, which rapidly reduces once all the sharp corners and edges are worn away. Davies and Wheatley (2012) indicates that the method of rotating the drum with steel balls, similar to LAA, tends to exaggerate the level of attrition, which can never be experienced in the life span of a filtration unit. A filter medium experiences attrition only during backwashing and cannot be categorised as severe.

3.2 Comparison of Filter Performance

3.2.1 Length of Filter Run

The length of a filter run is the maximum number of hours of operation of a filtration unit to warrant backwashing (Piyali, 2013). The fabricated model filtration unit used in this research required backwashing when the rate of filtration was below 0.08 litres per second.

The raw hourly data collected for the rate of filtration was translated to the length of the filter run. This implies that the daily data collected from 0900 hrs to 1600 hrs would equate to a single filter run length. Raw data for the rate of filtration was collected for 45 days, i.e., 15 days for each influent turbidity range (0–50 NTU, 50–150 NTU, and 50–300 NTU). In each influent turbidity range, data was collected for 5 days for each of the three scenarios, i.e., uncapped, 25mm capped, and 50mm capped.

In the 0–50 NTU Influent Turbidity range, the collected raw data for the filtration rate was analysed, and the results are presented graphically in Figure 2. The cut-off point for the backwash requirement was not achieved by 1600 hrs. Thus, the length of the filter run was determined through extrapolation of the collected data.

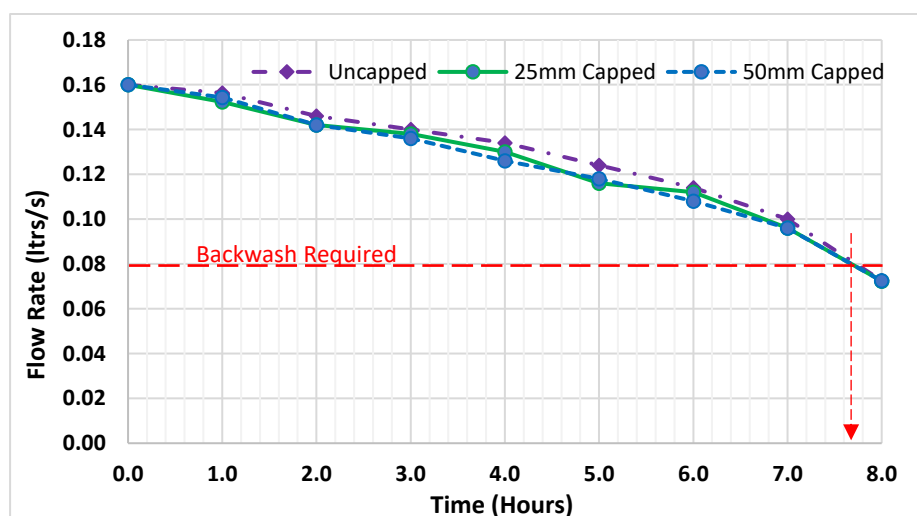


Figure 2: Results of Filter Run Length (0 – 50NTU)

The length of filter run for each of the 5 sampling days is given in Table 2.

Table 2: Filter Run Length (hrs) for 0-50NTU Influent Turbidity Range

	Uncapped	25mm Capped	50mm Capped
Day 1	7.75	7.67	7.67
Day 2	7.71	7.71	7.56
Day 3	7.69	7.69	7.69
Day 4	7.90	7.77	7.87
Day 5	7.56	7.56	7.56
Avg	7.72	7.68	7.67
St. Dev.	0.12	0.08	0.13

In the 0–50 NTU influent turbidity range, the average length of the filter run for the model filtration unit was 7.72, 7.68, and 7.67 hours for uncapped, 25mm, and 50mm capped, respectively, illustrating very marginal variation between the three scenarios.

The low (less than 0.5) standard deviation for all the scenarios indicates that the daily data collected for determining the filter run length is clustered closely to the mean. The mean filter run length is a good representation of the data and is reliable for further statistical analysis.

The results of the one-tailed test with a significance level of 5% are as follows:

The length of the filter run for the 25mm capped filter ($M = 7.67$, $SD = 0.08$, $n = 5$) is equal to the uncapped filter ($M = 7.72$, $SD = 0.12$, $n = 5$), with the difference being statistically insignificant ($t(8) = 0.654$, $p = 0.266$, one tail).

The length of the filter run for the 50mm capped filter ($M = 7.67$, $SD = 0.13$, $n = 5$) is equal to the 25mm capped filter ($M = 7.68$, $SD = 0.08$, $n = 5$), with the difference being statistically insignificant ($t(8) = 0.173$, $p = 0.434$, one tail).

In the 50–150 NTU Influent Turbidity range, the collected raw data for the filtration rate was analysed, and the results are presented graphically in Figure 3.

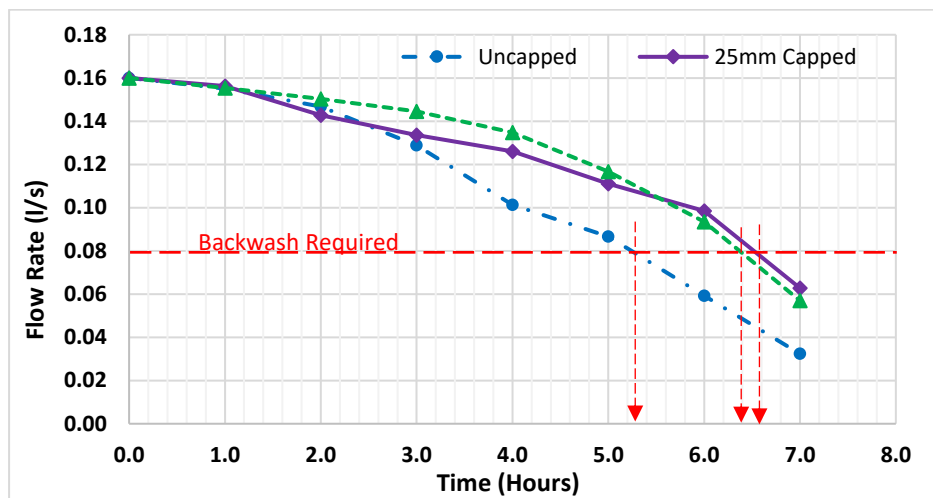


Figure 3: Results of Filter Run Length (50 – 150NTU)

The length of filter run for each of the 5 sampling days including the average is given in Table 3.

Table 3: Filter Run Length (hrs) for 50-150NTU Influent Turbidity Range

	Uncapped	25mm Capped	50mm Capped
Day 1	5.20	6.50	6.43
Day 2	5.00	6.77	6.42
Day 3	5.33	6.45	6.43
Day 4	5.00	6.88	6.31
Day 5	5.50	6.37	6.63
Avg	5.21	6.59	6.44
St. Dev.	0.22	0.21	0.11

The low (less than 0.5) standard deviation for all the scenarios indicates that the daily data collected for determining the filter run length is clustered closely to the mean. The mean filter run length is a good representation of the data and is reliable for further statistical analysis.

The results of the one-tailed test with a significance level of 5% are as follows:

The length of the filter run for the 25mm capped filter (M = 6.59, SD = 0.22, n = 5) is not equal to the uncapped filter (M = 5.21, SD = 0.22, n = 5), with the difference being statistically significant (t(8) = 10.07, p = 0.00 (one tail).

The length of the filter run for the 50mm capped filter (M = 6.44, SD = 0.11, n = 5) is equal to the 25mm capped filter (M = 5.21, SD = 0.22, n = 5), with the difference being statistically insignificant (t(8) = 1.359, p = 0.11 (one tail).

In the 150-300NTU Influent Turbidity range the filtration rate results are presented graphically in Figure 4.

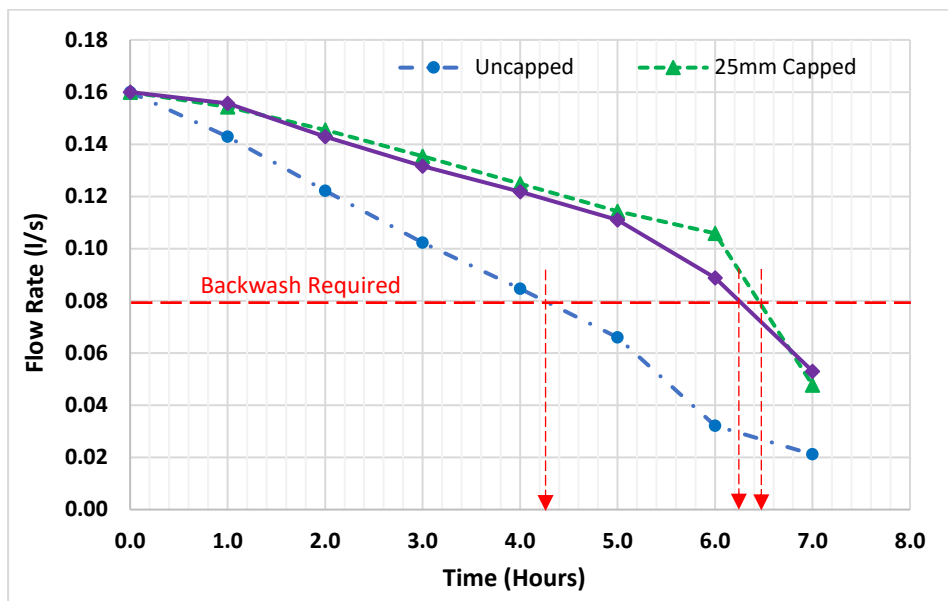


Figure 4: Results of Filter Run Length (150 – 300NTU)

The length of filter run as determined for each of the sampling days is given in Table 4.

Table 4: Filter Run Length (hrs) for 150-300NTU Influent Turbidity Range

	Uncapped	25mm Capped	50mm Capped
Day 1	4.29	6.26	6.11
Day 2	4.19	5.98	6.06
Day 3	4.36	6.22	6.24
Day 4	4.04	6.20	6.16
Day 5	4.50	6.34	6.13
Avg	4.27	6.20	6.14
St. Dev.	0.18	0.13	0.07

The low (less than 0.5) standard deviation for all the scenarios indicates that the daily data collected for determining the filter run length is clustered closely to the mean. The mean filter run length is a good representation of the data and is reliable for further statistical analysis. The results of the one-tailed test with a significance level of 5% are as follows:

- i. The length of the filter run for the 25mm capped filter (M=6.20, SD=0.13, n=5) is not equal to uncapped filter (M=4.27, SD=0.18, n=5) with the difference being statistically significant, $t(8)=-19.47, p=0.00$ (one tail).
- ii. The length of the filter run for the 50mm capped filter (M=6.14, SD=0.07, n=5) is equal to 25mm capped filter (M=6.20, SD=0.13, n=5) with the difference being statistically insignificant, $t(8)=0.93, p=0.19$ (one tail).

In a conventional RGSF, raw water percolates and gets filtered leaving suspended flocs within the voidage of the filtration media. As the voidage within the filter media reduces the headloss

increases. High influent turbidity accelerates headloss development and depletes the voidage resulting to shorter filter run length (Jusoh, 2007).

A similar phenomenon was observed when the influent turbidity increased from lower influent turbidity (0-50NTU) to the higher range (150-300NTU). The results of the uncapped model filtration unit are illustrated in Figure 5.

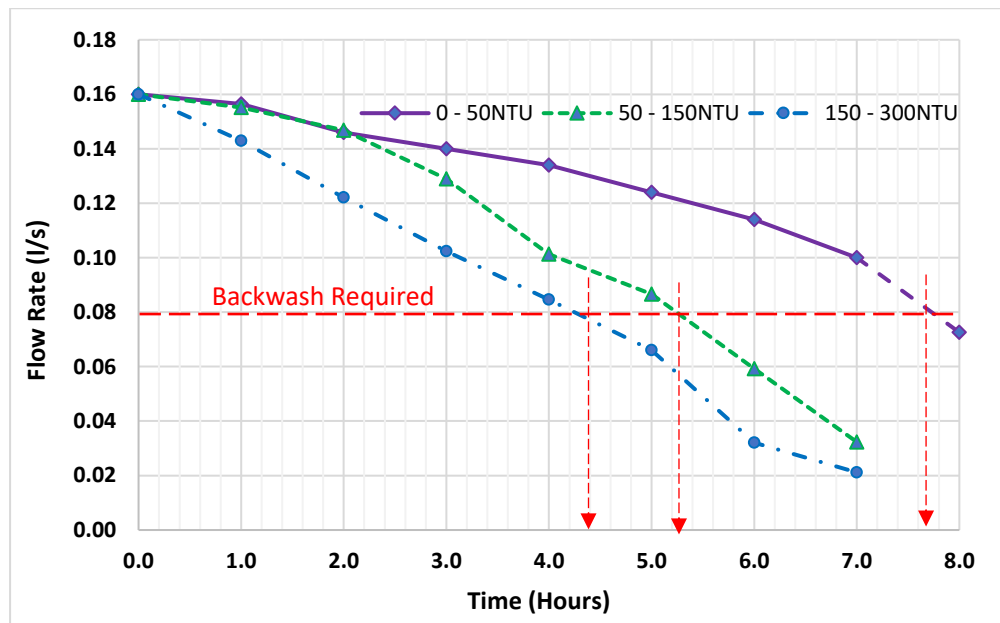


Figure 5: Results Uncapped Filter under varying Influent Turbidity

At low influent turbidity (0–50 NTU), the introduction of crushed expanded slates did not demonstrate any increase in the length of the filter run. All three scenarios (uncapped, 25mm, and 50mm capped) gave the same results of approximately 7.7 hours.

At the 50–150 NTU influent turbidity range, the introduction of crushed expanded slates yields an improvement by increasing the length of the filter run by 24% and 27% for the 25mm and 50mm capping, respectively. A similar improvement is observed for the 150–300 NTU influent turbidity range, with an average increase in filter run length of 45%. It is evident that the benefit of using crushed expanded slates as capping material increases with an increase in influent turbidity.

The crushed expanded slate-capped RGSF model demonstrated high robustness under high shock turbidity loads (above 150 NTU), which is illustrated by an increased length of filter run of 27% (50–150 NTU) and 45% (150–300 NTU). The benefit of introducing crushed expanded slates is hypothesised to be as a result of the intermixing between the coarse capping material and fine sand filter media and the increased voidage in the capping material, which overall increases the sludge storage capacity of the filter media.

The increase in capping depth from 25mm to 50mm had an insignificant effect on the length of the filter run. This could be attributed to the marginal increase in filter media voidage between

the two depths under consideration. The estimated voidage of crushed expanded slates is 50% against 35-40% of sand (Malcolm, 2017). Based on Al-Rawi (2017), Farjana et al. (2018), Ansari et al. (2017), and Tamakhu (2021), significant results would be achieved when the capping material depth to sand ratio is above 1:6. It should be noted that an increase in capping depth results in a proportional increase in the length of the filter run and a direct increase in cost. Therefore, the minimum depth of capping material is determined, with no upper limit provided. Malcolm (2017) suggests that the ratio of capping material to sand can be up to 2.5:1.

3.2.2 Turbidity removal

Raw data was collected for influent and effluent turbidities to determine the turbidity removal efficiency of the filtration unit for the three scenarios, i.e., uncapped, 25mm capped, and 50mm capped. Raw data was collected from 0900 hrs. to 1600 hrs., giving eight data sets for each scenario and each influent turbidity range.

The results of the effluent turbidity for the 0–50 NTU influent turbidity range for the uncapped, 25mm, and 50mm crushed expanded slate capped filtration units are presented graphically in Figure 6.

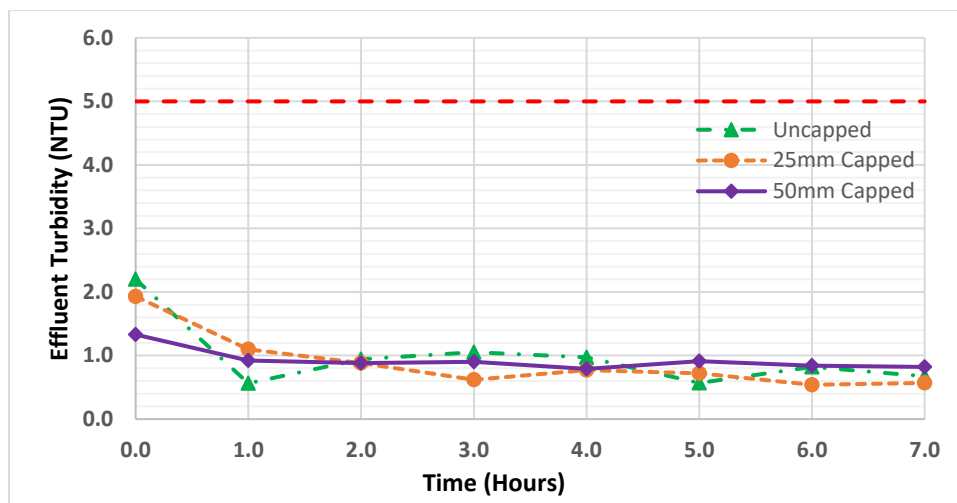


Figure 6: Results of Turbidity Removal (Influent Turbidity 0-50NTU)

The mean effluent turbidity for each scenario is therefore a good representation of the data and is reliable for t-test statistical analysis. The results of the one-tailed test are summarised as follows:

- i. The mean effluent turbidity for the 25-mm capped filter ($M = 0.891$, $SD = 0.43$, $n = 8$) is equal to the uncapped filter ($M = 0.973$, $SD = 0.49$, $n = 8$), with the difference being statistically insignificant ($t(14) = 1.761$, $p = 0.373$, one tail).
- ii. The mean effluent turbidity for the 50-mm capped filter ($M = 0.924$, $SD = 0.16$, $n = 8$) is equal to that for the 25-mm capped filter ($M = 0.891$, $SD = 0.43$, $n = 8$), with the difference being statistically insignificant ($t(14) = 1.761$, $p = 0.427$, one tail).

In the second influent turbidity range (50–150 NTU), the turbidity removal efficiency for the model filtration unit was compared for the single media, 25mm and 50mm crushed expanded slate capping. The summarised results are presented graphically in Figure 7.

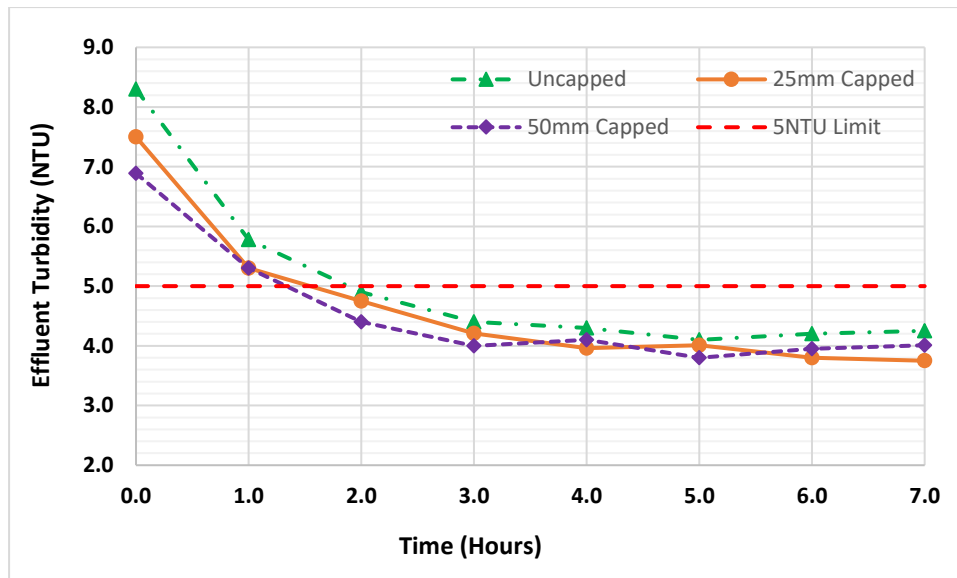


Figure 7: Results of Turbidity Removal (Influent Turbidity 50-150 NTU)

The standard deviation for the three scenarios is less than one, indicating the effluent turbidity for the 0–50 NTU influent turbidity range is clustered closely to the mean.

The standard deviation for the three scenarios is less than 1.5, indicating the effluent turbidity for the 50–150 NTU influent turbidity range is clustered closely to the mean. The mean effluent turbidity for each scenario is therefore a good representation of the data and is reliable for t-test statistical analysis. The results of the one-tailed test are summarised as follows:

- i. The mean effluent turbidity for the 25-mm capped filter ($M = 4.66$, $SD = 1.18$, $n = 8$) is equal to the uncapped filter ($M = 5.03$, $SD = 1.34$, $n = 8$), with the difference being statistically insignificant ($t(14) = 1.761$, $p = 0.297$, one tail).
- ii. The mean effluent turbidity for the 50-mm capped filter ($M = 4.55$, $SD = 0.99$, $n = 8$) is equal to that for the 25-mm capped filter ($M = 4.66$, $SD = 1.18$, $n = 8$), with the difference being statistically insignificant ($t(14) = 1.761$, $p = 0.430$, one tail).

In the third influent turbidity range (150–300 NTU), the turbidity removal efficiency for the model filtration unit was compared for the uncapped, 25mm, and 50mm crushed expanded slate capped RGSF. The results of effluent turbidities are presented graphically in Figure 8.

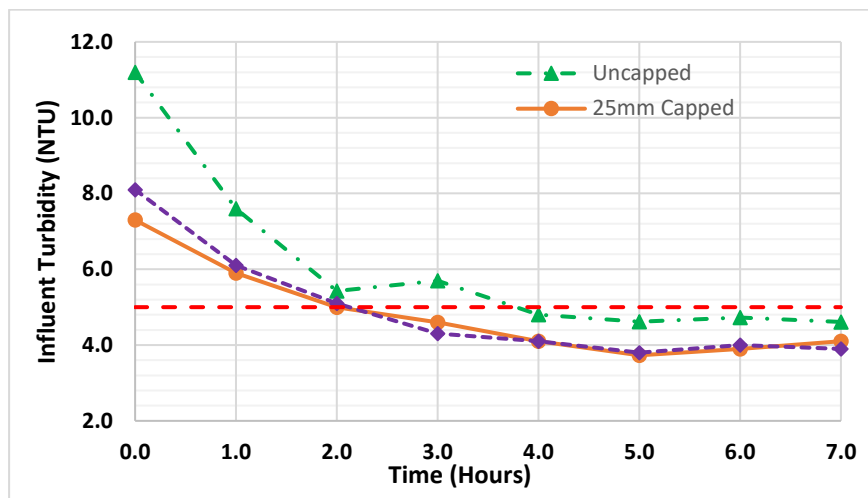


Figure 8: Results of Turbidity Removal (Influent Turbidity 150-300 NTU)

The standard deviation for the three scenarios is less than 2.5, indicating the effluent turbidity for the 50–150 NTU influent turbidity range is clustered closely to the mean. The mean effluent turbidity for each scenario is therefore a good representation of the data and is reliable for t-test statistical analysis. The results of the one-tailed test are summarised as follows:

- i. The mean effluent turbidity for the 25-mm capped filter ($M = 4.83$, $SD = 1.14$, $n = 8$) is equal to the uncapped filter ($M = 6.09$, $SD = 2.15$, $n = 8$), with the difference being statistically significant ($t(14) = 1.761$, $p = 0.036$ (one tail)).
- ii. The mean effluent turbidity for the 50-mm capped filter ($M = 4.93$, $SD = 1.40$, $n = 8$) is equal to that for the 25-mm capped filter ($M = 4.83$, $SD = 1.14$, $n = 8$), with the difference being statistically insignificant ($t(14) = 1.761$, $p = 0.445$, one tail).

After filter ripening, at influent turbidities below 150 NTU, the effluent water quality for all three scenarios (uncapped, 25 mm, and 50mm crushed expanded slates capped) is below 5 NTU and therefore meets the Kenyan drinking water standards. Above 150 NTU influent turbidity, the effluent did not meet the maximum effluent turbidity requirement, exceeding 57% of the monitoring period.

Based on the t-test results, the introduction of crushed expanded slates did not yield a significant benefit to the RGSF for influent turbidities below 150 NTU.

Similar observations were reported by Tamakhu (2021) for anthracite capping and Sabale et al. (2014) for PVC granule capping at low influent turbidities. The lack of significant benefit in turbidity removal for low influent turbidities (<50 NTU) is hypothesised to be as a result of small-sized flocs passing through the course (large voids) of the capping material. Filtration only occurs within the primary filter media (sand), which has satisfactory results in turbidity removal at low influent turbidities Al-Rawi (2017).

It is observed that the effluent quality of the single media RGSF gradually starts to deteriorate with an increase in influent turbidity. RGSF are suitable for systems where pretreatment

(coagulation and flocculation) has effectively been carried out to lower the influent turbidities (MWI, 2005). When chemically unaided, settling within a conventional sedimentation tank removes 40–50% of the suspended solids. In a well-designed and maintained chemically aided settling system, removal rates can be as high as 98% for lightly loaded raw water. Raw water with high turbidity (particularly from direct river abstractions) may require additional settling systems arranged in series or, alternatively, improve the efficiency of the RGSF to handle shock turbidity loads (Malcolm, 2017). If influent turbidities to the filters are high, similar to what was subjected to the model filtration units, the RGSF gets overwhelmed, and its efficiency in turbidity removal gets compromised. An increase in effluent turbidities is attributed to shock floc loads, which result in early floc breakthrough in the filtration cycle.

In summary, the significance of capping with crushed expanded in turbidity removal increases with an increase in influent turbidity loads. Dual filters have always demonstrated robustness in dealing with shock turbidity loads, particularly for surface water sources (Sabale et al., 2014). Capping with crushed expanded slates, which is coarse relative to the primary filter media, improved the retention of the large flocs at the top while maintaining the excellent performance of sand to capture and retain small flocs without major floc breakthrough throughout the filtration cycle.

The current study concurs with the conventional and worldwide recommended practise of not considering a dual-media Rapid Sand Filter at low influent turbidities (Malcolm, 2017; Tamakhu, 2021). Example: When the source of raw water is a Dam, the water abstracted at the top level has very low turbidity. Furthermore, the Dam will not subject the treatment process to shock turbidity loads due to the long fetch that allows adequate time for sediments to settle at the bottom of the reservoir.

4.0 Conclusion and recommendations

The main objective of this study was to evaluate the suitability of crushed expanded slates as a capping material for improving the performance of Rapid Gravity Sand Filters (RGSF). The conclusions and recommendations of the study are summarised as follows:

- i. Crushed expanded slates from Maji ya Chumvi meet the minimum chemical and physical requirements for use as a capping material for convention Rapid Sand Filters.
- ii. Introduction of crushed expanded slates as a capping material for RGSF at low influent turbidities to the filters (less than 50 NTU) has insignificant benefits both in turbidity removal and extending the length of the filter run. In instances where filter designers expect low influent turbidities, such as Dams, the study recommends that crushed expanded slates not be considered for use.
- iii. At high influent turbidity loads, including shock turbidity loads, crushed expanded slates demonstrated excellent ability to improve the efficiency of the RGSF. Rather than the introduction of additional settling systems with increased land requirements, the study recommends that crushed expanded slates be introduced to existing filters to boost turbidity removal and to sustain and extend the length of the filter run.

- iv. The increase in the depth of capping from 25mm to 50mm yielded similar results for both turbidity removal and the length of the filter run. The study recommends that a thickness of 25mm be adopted for crushed expanded slate capping to keep the additional cost to a minimum and reap the maximum benefit of the capping technique.
- v. Considering the positive benefits of crushed expanded slates, which are locally available, the study recommends a full-scale trial in a water treatment system to strengthen the study findings and facilitate the inclusion of crushed expanded mazeras as an approved filter media in the local water industry.

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5.1 General acknowledgement

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5.2 Funding

None

5.3 Conflict of interest

The author declares no conflict of interest.

5.4 Ethical consideration

None

6.0 References

- Al-Rawi S. M. (2017) Introducing sand filter capping for turbidity removal for potable water treatment plants of Mosul/Iraq. *African Journal of Water Conservation and Sustainability*. Vol. 5 (1), pp. 167-175.
- American National Standards Institute/ American Water Works Association (2001). ANSI/AWWA Standard for Granular Filter Material, B100-01. *American Water Works Association, Denver, Colo.*
- Ansari M.A., Pathan N. G., Donde S. S., Bhosale C. (2017). Designing Rapid Sand Filter by Using Coconut Shell for a Village. *International Journal of Advanced Research in Science and Engineering*. Vol.6, pp. 584 – 590.
- Caswell P.V., Baker B.H. (2007), A Chapter on the Alkaline Igneous Complex at Jombo, *Ministry of Environment and Natural Resources Mine's and Geological Department Geology of the Mombasa-Kwale Area*
- Cescon, A.; Jiang, J.Q. (2020). Filtration Process and Alternative Filter Media Material in Water Treatment. *Advances in the Technologies for Water and Wastewater Treatment*, 12, 3377.
- Davies P. D., Wheatley A.D. (2012). Pilot Plant Study of Alternative Filter Media for Rapid Gravity Filtration. *IWA Publishing - Water and Technology*. pp. 2779 – 2784.
- Delbazi, N., Ahmadi, M.M., Takdastan, A. and Jaafarzade, N. (2011). Comparison of Monolayer Filter (Sand), Dual Media Filter (Anthracite and Leca) and Performance in Removal of Organic Matter and Turbidity. *Iranian Journal of Health and Environment* 4 (3) pp. 301-312.



- Farjana.N, Kallesh.D.C, Manjunath.B.L, Priyesh.B.J., Poornima.K.B (2018). Rapid Sand Filter Using Coconut Shell. *International Research Journal of Engineering and Technology*. Vol.5_4, pp. 5040 – 5043.
- Hadgu, L. T., Nyadawa, M. O., Mwangi, J. K., & Kibetu, P. M. (2014). Assessment Of Pollution In Ndarugu River Due To Runoff And Agro- Industrial Wastewater Disposal. *Journal Of Agriculture, Science And Technology*, 16(2), 109–121.
- Jusoh. A., Giap. S.G.E., Nora'aini. A., Halim. A. G., Noor. M. J. M. M. and Zakaria. M.P. (2007) Comparative Performances of single and dual media filters of sand and burnt oil palm shell. *Jurnal Teknologi*. 45. pp. 43-52.
- Kalibbala, H. M. (2007). Application of Indigenous Materials in Drinking Water Treatment. *KTH Royal Institute of Technology, Stockholm*. pp. 1 – 29.
- Lin Po-Hsun (2010). Filter Media Modification in Rapid Sand Filtration. *A Dissertation Presented to the Faculty of the Graduate School of Cornell University, Doctor of Philosophy*.
- Malcolm J. B., Johnson K. M., Andrew J. E., Don D. R. (2017). *Water Supply* (7th ed., pp. 367-400.). Butterworth Book Co. UK.
- Marshak S. (2009). *Essentials of Geology 3rd Edition*. *W.W. Norton & Company*
- Ministry of Water and Irrigation, MWI (2005). Practice Manual for Water Supply Services in Kenya. *Kenya – Belgium Study and Consultancy Fund*.
- Nyagwencha, J. M., Kaluli, J. W., Home, P. G., & Hunja, M. (2012). Water And Water-Borne Diseases In North Masaba District, Kenya. *Journal Of Agriculture, Science And Technology*, 14(1),115–127.
- Piyali D. (2013) Study on The Performance of Dual Media Filter For Surface Water Treatment. Thesis- School of Water Resources Engineering Faculty of Engineering and Technology Jadavpur University Kolkata-700032
- Sabale R., Mujawar S., (2014) Improved Rapid Sand Filter for Performance Enhancement. *International Journal of Science and Research (IJSR)*. Volume 3 Issue 10.
- Shirule.P.A , Sonwane.A.E (2019) Use of Coconut Shell as Filter Media for Design of Dual Media Filters. *International Journal of Science, Spirituality, Business And Technology (IJSSBT)*, Vol. 7, No. 1,
- S. Platias, K.I. Vatalis, G. Charalampides, (2014) Suitability of Quartz Sands for Different Industrial Applications, *Procedia Economics and Finance*, Volume 14, Pages 491-498, ISSN 2212-5671, [https://doi.org/10.1016/S2212-5671\(14\)00738-2](https://doi.org/10.1016/S2212-5671(14)00738-2).
- Tamakhu Gopal, Iswar Man Amatya (2021). Turbidity removal by rapid sand filter using anthracite coal as a capping media. *Journal of Innovations in Engineering Education*. Vol.4, Issue I, pp 69-73.
- Tenge J. M. (2009). An Assessment of Coal from Mui Basin as an Alternative Energy Resource for Kenya. Thesis – Masters of Science (Environmental Chemistry) University of Nairobi.