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CLAY FILTRATION OF MICROBES AND FLUORIDE

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DANG-I AUPHEDEOUS YINME
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ABSTRACT

Consumption of contaminated water may result in several water-borne diseases, including hepatitis, typhoid, cholera, dysentery and other diseases that cause diarrhoea. One of the ways this problem can be prevented is by the use of household water treatment and safe storage. As a result of this, the ceramic water filter, which is one of the effective water treatment techniques, was studied and evaluated to provide information that, will help improve their performance and promote their use.

In this project, two kinds of ceramic filters were fabricated; one without hydroxylapatite and the other with hydroxylapatite. Their flow rates were determined and their ability to remove E.coli was also tested. The ability to scale up these filters to achieve a system that will provide large volumes of water per filtration was also explored in this project.

The results showed that, the two kinds of filters did not indicate significant difference in their flow rates and the E.coli removal of the filters proved successful. It was also realized for the scale up that, it is possible to connect the ceramic filters to produce a system that can produce large volumes of filtered water. However, the effectiveness of the system depends largely on the individual flow rate of the filters used.

CHAPTER ONE

INTRODUCTION

1.1 Background

The human body is said to be made up of about 70% water. This shows how important water is to the survival of humans. The importance of water is such that life cannot be sustained beyond a few days, without water supply. Furthermore, the lack of adequate water supply leads to the spread of disease (Guy & Jamie 2003). Water is used in most human domestic activities including cooking, cleaning, and most importantly drinking, which is a means by which the water lever in the human system is maintained. In some of the non domestic uses of water, the purity of the water is not really an issue, e.g. in the case of washing. However, for domestic uses of water, the purity of water is very important, since it has a direct relationship with the health and wellbeing of the individual using the water. A very important example of this is when water is used for drinking.

Consumption of contaminated water may result in several water-borne diseases. These include viral hepatitis, typhoid, cholera, dysentery and other diseases that cause diarrhoea (Ashbolt 2004). In 1998, Gadgil reported that about half the people in developing countries suffer from at least one of the six main diseases caused by inadequate water supplies and sanitation practices (Gadgil 1998). Theses six diseases include; diarrhea, *Ascaris*, *Dracunculisis*, hookworm, *Schistosomiasis* and trachoma. The world Health Organisation (WHO) in 2004a, estimated that about 1.8 million people die per year from diarrheal disease (WHO 2004a). It was also estimated by Pruss et al. (2002) that 4.0% of all deaths and 5.7% of the burden of global are attributed to inadequate water purification, sanitation, and hygiene, largely due to diarrheal disease. This is particularly prominent in rural communities in developing countries, where the rural communities do not have any sources of clean water supply. They therefore depend on the natural sources of water, such as rivers, streams and dams. Most of these sources of water are contaminated by human activities such as farming, construction and sewage. These activities introduce harmful chemicals and bacteria into these water sources, therefore making them unsafe to drink, and leaving the people of these communities vulnerable to water diseases.

Due to the number of lives that are lost to the consumption of contaminated water, significant efforts are being made by various organisations and scientists to provide sustainable solutions to the problem of contaminated water. Due to the magnitude of the problem, the World Health Organisation (WHO) in 2006 stated that “Access to safe drinking water is essential to health, a basic human right and a component of effective policy health protection”. Nevertheless, more than 1.1 billion people of the world's population still lack access to any form of clean and safe drinking water. (Brikke & Bredero 2003; Smet & Wijk 2002; Visscher 2006). Most of these people live in Asia and Africa (WHO/UNICEF 2000).

The issue of unsafe drinking water is most evident in communities in the developing world, where there is inadequate clean water supply. This poses a great health risk to the individuals. In view of this problem, some methods have been developed for water treatment. These methods include, boiling (Miller 1986), the addition of chlorine (Heber 1985), SODIS UV-disinfection (Wagelin & Sommer 1998), bio-sand filtration (Heber 1985), ceramic silver impregnated filters (Roberts 2003) and adsorption filters (http://en.wikipedia.org/wiki/activated_carbon). All these mentioned methods of treatment have their advantages and disadvantages. However, since these methods will be used mostly in the rural communities, factors such as, affordability, assessability, the simplicity of the methods, and the potential for the incorporation of local materials are very important factors to be considered. In order address the problem associated with poor water supply and sanitation, the United Nations (UN) developed seven very ambitious targets (UN 2008; WHO & UNICEF 2004). These were established in the 'Millennium Development Goals' (MDG). Hence, goal number seven (MDG #7) is “halving proportion of people without sustainable access to safe water and basic sanitation by 2015” (UN 2008; WHO & UNICEF 2004). This might be an impossible goal to achieve with that time frame, especially if it has to do with delivering safe, piped community water.

However most of the people that do not have access to safe drinking water are in the rural communities. One of the ways by which this goal can be made achievable is by the use of household water treatment and safe storage (Van Doris 2006). Household water treatment and storage also has the advantage of preventing recontamination of water, which may occur between the point of delivery and consumption. This can occur during transport and also in the homes. It is, therefore, very important for water treatment techniques to consider ways of attaining pure water even at the point of usage.

The ceramic impregnated water filter (Roberts, 2003) is one of the effective water treatment techniques that have been developed. It was developed and is distributed by an organisation known as Potters for Peace (PFP) and introduced in developing countries. The by technique is especially very good for rural communities, where it removes more than 99.9% of bacteria (waterlaboratorium Noord 2008), It is also easy to use, and does not change the taste of the water after treatment. Furthermore the filters are made locally, have a low cost and can be used for 2 years (Enrique Campbell Consultant 2005). These attractive combinations of properties have attracted the interest of concerned scientist and organisations that are about improving the quality of drinking water globally. Finding ways of improving water filters will go a long way to provide clean drinking water for communities in rural parts of the developing world. Furthermore, removal of chemical contaminants, such as fluoride, is important in areas where fluoride contaminants result in the corrosion of teeth and bones in many parts of Asia and Africa (WHO 2000).

1.2 Problem Statement

Although clay filters have been developed for the removal of bacteria and other microbial pathogens, there are currently no systems that can remove both microbes and fluoride from contaminated water. Furthermore, it is unclear to what extend the systems can be scaled up to provide larger quantities of water for families and communities. There is, therefore a need for novel filters that can be scaled up to remove both microbes and chemical contaminants such as fluoride.

1.3 Scope of Work

The project presents the results of an experimental study of ceramic water filtration in clay ceramic water filters. The flow characteristics are compared in clay ceramics and clay ceramics that are doped with hydroxyapatite, which is a material that is known to remove fluoride by adsorption processes. The variability in initial flow and potential for scale-up are also explored in conventional clay filters.

CHAPTER TWO

LITERATURE REVIEW

2.1.0 Water Quality

The World Health Organisation (WHO) defines safe drinking water as water that can be used for all domestic purposes (including personal hygiene) and not poses a significant health risk to users over a lifetime consumption. The WHO has also outlined a guidelines health and aesthetic situations, which shows the minimum requirements for an array of biological, chemical, physical, aesthetic and radiological aspects to ensure that drinking water is safe for consumption. These guidelines serve as guidance as to what can be considered as safe drinking water and directions to assist nations develop their own drinking water guidelines (WHO 2006). Many developing countries have actually adopted these guidelines. However, as a basic requirement, water should be free of pathogens; have a low turbidity; have little or no taste, odour or colour; free of salt or any chemicals that can cause corrosion, encrustation or any adverse health effects (Smet & Wijk 2002).

Multi-barrier approaches are the commonly adopted approaches in water treatment and supply systems to ensure that the water delivered is safe for consumption and poses no health risk (Smet & Wijk 2002; Visscher 2006). Barriers that are mostly used include: water source protection; proper sanitation practices; community awareness and education; a well- maintained distribution system and water treatment.

The quality of water is mostly affected by contaminants that can be categorised into four main groups. These include; biological, chemical, aesthetic and radiological. These contaminants go a long way to affect the wholesomeness of water and make its unhealthy for consumption. Radiological contaminants, sometimes known as radioactive contaminants, are radioactive substances that find their way into water bodies. These substances are the result of nuclear waste disposal or spillages. They are highly radioactive and therefore their presence in water puts the consumer at risk health wise. Out of the four contaminants affect the quality of water, radiological contaminants are not present in waters in developing countries (Smet & Wijk 2002). This is because of the absence of nuclear power plants in developing countries. The biological, chemical and aesthetic contaminants of water are discussed in details below.

2.1.1 Biological Parameters

Reports from Gadgil (1998) and WHO (2006) indicated that the most dangerous of the four contaminants of water is biological contaminants. These include pathogenic organisms such as bacteria, viruses, protozoa and helminths of which are all dangerous to human health (Clapham 2004). The diseases caused by these organisms are classified into four main groups. They include; water-borne disease; water and water-related diseases; water based-diseases and water-scare diseases. In the case of water-borne diseases, the water serves as a passive carrier of pathogens which originates from humans, animals or chemical waste. The next group is the water-related vector diseases. These are diseases transmitted by vectors. The third category is water-based diseases. These are caused by parasite organisms which are also transmitted through coming into contact with, ingestion or penetration through the skin by these parasites. Finally, the fourth group is the water scared-diseases. This occurs when portable water is scarce and sanitation is poor (Ashbolt 2004; Michael 2006). The common diseases associated with these types of water-related diseases are summarised in the table below.

Table 1- Common water-related diseases (adapted from Ashbolt 2004)

Type of Diseases	Common Diseases
Water-borne diseases	Cholera, Typhoid, Bacillary dysentry, Infectious hepatitis, Heptospirosis, Gardiasis, Gastroenteriris
Water-related diseases	Yellow fever, Dengue fever, Encephalitis, Malaria, Filariasis, Sleeping sickness, Onchocerciasis
Water-based diseases	Schistosomiasis, Dracunculosis,Bilharziosis, Philariosis, Oncholersosis, Treadworm and other Helminths
Water-scarce diseases	Scabies, Trachoma (eye infection), Leprosy, Conjuctivitis, Salmonellosis, Ascariasis, Trichuriasis, Hookworm, Amoebic dysentery, Paratyphoid fever

Out of these contaminants, that one that is of most concern to human health is water contaminated with human or animal faeces (Michael 2004). Most of the water borne diseases are from such sources (Ashbolt 2004). Faecal contamination of water is very common in most rural communities in developing countries. This is due to the fact that most of these communities do not have any or few toilet facilities. They, therefore, resort to defecating in the nearby bushes around their homes. In most cases, the faeces are washed back into their sources of drinking water. Now since it is very difficult to test for all organisms that may be present within water, indicator organisms which signify faecal contamination are used as indication of the microbiological quality of water (Gadgil 1998; Smet & Wijk 2002). The attributes of an indicator organism include; easy isolation and count ability, should be present in large numbers, be more resistant to disinfection than other pathogens. They must also not be able to proliferate within a water body and generally absent from other sources other than human and animal faeces (Gadgil 1998).

Most of the attributes that are supposed to be possessed by indicator organisms are met by coliform bacteria. As such coliform bacteria are widely used as indicators for microbiological contamination in water supply systems. The problem with using total coliform bacteria count is that they can originate from other sources apart from faeces. Escherichia coli (E. coli) is the only species of bacteria which has faeces origin. E. coli is therefore the most widely used indicator organism for microbiological contamination because of its large presence in human and animal faeces and ability to be easily detected.

In situations where testing for E. coli is not possible, the thermotolerant coliform bacteria is used. It is a sub-group of the coliform group. There are therefore many international standard methods available for the enumeration of these organisms (Paymant, Waite & Dufour 2003). Coliform bacteria test results are commonly reported as the most portable number of coliform bacteria per 100 ml of sample (MPN/100 ML), or in colony forming unit per 100 ml of sample (CFU/100 ml), which is a measure of how many colonies of bacteria are present within a sample (Salvato 1992).

One of the biggest setbacks to using coliform bacteria as indicator organism is that, they are less resistant to disinfection and as a result, the absence of coliform within disinfected water may not necessarily correlate to the absence of such organisms (Gadgil 1998).

2.1.2 Chemical Parameters

There are many natural and anthropogenic chemical sources which can affect adversely water quality. Out of the many chemicals that can affect adversely the quality of water, a few of them have actually caused large scale health issues from water exposure. These include; fluoride, arsenic, nitrate and nitrites, and lead (WHO 2006). Fluoride can cause mottling of teeth and in severe cases crippling skeletal fluorosis (WHO 2006). Arsenic is linked with an increased risk of cancer and skin lesions (WHO 2006). Nitrate and nitrites have the tendency of inducing methaemoglobinaemia. This is more common in children commonly known as blue baby syndrome. Last but not the least is lead. Lead can actually impair the neurological system. The health issues associated with these chemicals are actually realised after a long period of exposure to them. Only a few chemicals have the tendency to pose any health problems after being exposed to a single dosage. But this is also highly possible in the case of accidental spillage of these chemicals (WHO 2006).

Table 2- Categorisation of sources of chemicals in drinking water (Thompson et al. 2007)

Source	Examples
Naturally occurring chemicals	Rocks and soils, cyanobacteria in surface water (including naturally occurring algae toxins)
Chemicals from agricultural activities	Application of manure, fertilizers and pesticides (including pesticides) intensive animal production practices
Chemicals from human settlements	Sewage and waste disposal, urban runoff (including those used for public health fuel leakage purposes; for example for vector control)
Chemicals from industrial activities	Manufacturing, processing and mining
Chemicals from water treatment	Water treatment chemicals; corrosion of and distribution and leaching from storage tanks and pipes

Even though, most of these chemicals do not pose much health risk, they are not desirable in water since they can be a nuisance to the consumer, resulting in aesthetic problems (Clapham 2004) or affect adversely the equipments used in water supply systems. The significant chemicals in this category are iron and manganese. These two can actually affect the taste and odour of water and are also the source of the problems most water treatment processes face (Thompson et al. 2007). Some of the chemicals also lead to scaling or corrosion within the distribution network depending on the pH and other factors. Hardness, which is the concentration of calcium carbonate, gives an indication of the calcium and manganese ions within a water supply. Hard water, which is water rich in these ions, generally leads to scaling (WHO 2009) while soft water generally induces corrosion (WHO 2009). These problems go a long way to reduce the life span of distribution networks and also have the potential to cause health and environmental problems (WHO 2009)

The risks posed by chemicals vary from country to country (Thompson et al. 2007). But in the overall, chemicals that are present and hazardous to human health should be prioritised over chemicals whose presence in water is a possibility and are less hazardous to human health (Thompson et al. 2007).

2.1.3 Physical and Aesthetic Parameters

The parameters (contaminants) that can affect water quality, such as colour, taste, odour, turbidity and pH, constitute the physical and aesthetic contaminants (Gadgil 1998; Smet & Wijk 2002). These qualities actually affect the acceptability of water. This is because most of them can easily be detected by the consumer. They can, therefore, cause the consumer to reject water that may be biologically safe and accept water that is from a hazardous source (WHO 2006). Turbidity and pH can also affect negatively influence water treatment processes.

Turbidity, which is a measure of the cloudiness or haziness of water, is actually as a result of suspended solids including silt and sand, biological organisms and chemical precipitants (Robbins Institute 1996). The unit of measurement for turbidity is nephelometric turbidity units (NTU). This is a measure of the ability of suspended particles within water to scatter light as it passes through the water column (Salvato 1992). Turbidity is mostly responsible for the acceptability of water and also various problems with various water treatment processes and infrastructure (Payment, Waite & Dufour 2003). Highly turbid water also causes a lot of problems for filtration processes. Most of the time, it reduces the efficiency of the filtration system. It also increases maintenance requirement and even have the potential to cause damage to infrastructures such as tanks, pipes, valves and taps (Robbins Institute 1996). Furthermore, turbid water produces some shielding of pathogenic organisms from disinfectants (Payment, Waite & Dufour 2003; Robbin Institute 1996). The problems associated with turbid water are more prominent in the tropics, especially in the rainy season, where especially high turbid surface waters can arise (Ochieng et al. 2004).

The pH of water can be said to be the negative logarithm of the concentration of hydrogen ions present in the water. It actually determines how acidic or basic the water is and has the potential to affect adversely the treatment processes and quality of water. While corrosion can be enhanced in acidic conditions, basic conditions promote chemical depositions within treatment process and infrastructure (WHO 2009). Acidic and basic conditions lead to operational problems in a water treatment system and impacts on the quality of water.

It is universally known that clean water posses no colour, meaning any water with colour has been contaminated by some sort of contaminant. The presence of organic colour matter is responsible for colour in water and is measured in true colour units (TCU). One of the biggest adverse effects that colour has on water is acceptability. It can also be a pre-cursor for hazardous disinfection by products if chemicals are used for disinfection (Salvato 1992; WHO 2006)

Clean water is also known to be odourless and tasteless. But taste and odour can be present in water as a result of the presence of organic matter as well as a range of chemical, biological and physical contaminants. These contaminants include fungi, algae, chloride, hydrogen sulphide, petroleum products, detergents (which can also give rise to foaming) and dissolved solids (WHO 2006).

2.2.0 Filtration Technologies

Filtration technologies are adopted to remove unwanted contaminant, especially suspended solids from surface waters. Filtration has to do with the flow of water through a porous medium. The water is purified through a range of physical, chemical and biological mechanisms (NDWC 1996). There are different types of filtration technologies. These include roughing filters, slow sand filters, reed bed treatment systems, rapid sand filters, and diatomaceous earth filters and membranes. These filters are described in the appropriate sections below.

2.2.1 Slow Sand Filtration

Slow sand filtration is thought to be one of the simplest and most effective water treatment technologies. They have been used since the beginning of the 19th century, and have proven to be effective in many communities in the world (Huisman & Wood 1974). This technology is an ideal option for water treatment in developing countries because it has a simple design ,which can be easily operated and maintained.

Slow sand filters are typically made of a bed of sand or an alternative granular 0.5-1.3 m in depth, which is characterised by an effective grain size (equivalent to the particle size which 10% of the media's mass is finer) between 0.15 and 0.35 mm and a coefficient of uniformity less than 3. Water is allowed to percolate through the filter media at rates in the region of 0.1-0.4 m/hr (Huisman & Wood 1974) and subsequently a gravel underlay, which acts as a support mechanism and to ensure that the treated water is uniformly drained from the filter bed (NDWC 2000; Visscher 2006). As part of the slow sand filter arrangement, an outlet weir is required. This makes sure that the supernatant water layer remains above the maximum height of the filter bed. This ultimately prevents the occurrence of any pressure drop within the filter and removes any unwanted contaminants by maintaining the biological activities at the surface of the filter (Smet & Wijk 2002). The figure below illustrates a schematic diagram of a slow sand filter.

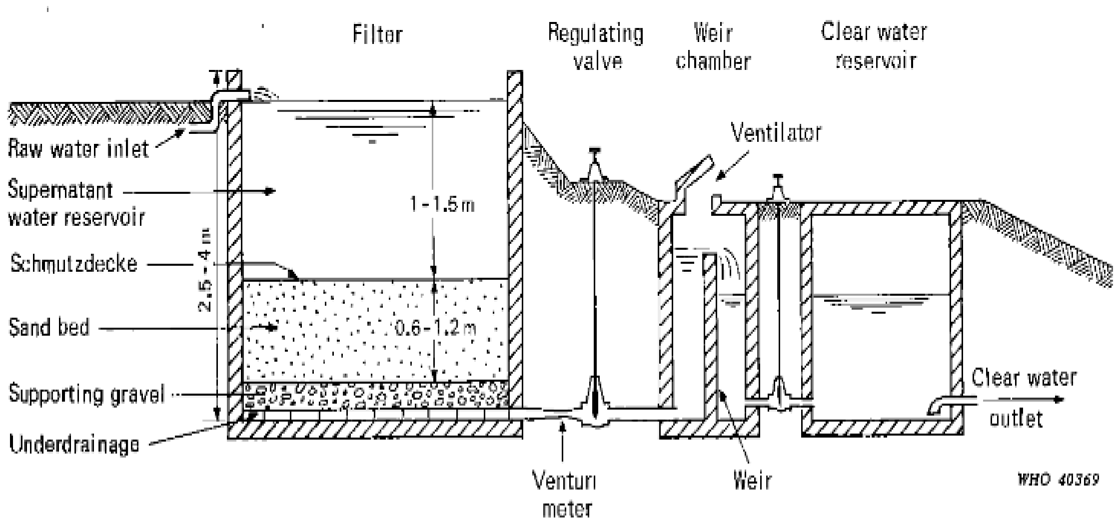


Figure 2.0 – Schematic diagram of a slow sand filter (Huisman & Wood 1974)

Suspended particles are removed from the influent water predominately at the filter's surface (Brikke & Bredero 2003), which also attains a thin layer of microorganisms which feed on the various contaminants present in the influent water. This thin layer of microorganisms is commonly referred to as the smuchdektz, and is efficient at removing a range of contaminant and biological processes (Clapham 2004). The table below illustrates some removal efficiencies of some key pollutant targeted by the slow sand filtration.

Table 3- Treatment efficiencies of slow filtration (UNEP IETC 1998; Smet & Wijk 2002).

Water Quality Parameter	**Removal Efficiencies (%)**
Turbidity (NTU)	50-87*
Colour (TCU)	25-40
Thermotolerant Coliform (CFU/100ml)	95-100
Iron mg/I	30-90
Manganese mg/I	30-90
Heavy metal (mg/I)	30-95
Chemical Oxygen Demand (mg/I)	0-25

*Generally, slow sand filters produce an effluent which has a turbidity of less than 1.

For the slow sand filtration system to operate well and remove all the targeted contaminants there is the need for proper operation and maintenance. This is actually achieved by allowing a slow and steady flow of water to percolate through the filter, such that the smuchdektz will effectively purify the influent water (Brikke & Bredero 2003). With time, the filter becomes clogged and this calls for an adjustment of the flow rate to make up for the increased head loss in the filter media. This is achieved by increasing the height of the supernatant water layer or increasing the opening of the influent flow valve (Smet and Wijk 2002). Even with this, there will come a time where the filter will be so clogged that, none of the two adjustments mentioned above will work, since the filter's ability to remove contaminants is greatly impaired and so the only solution to return the filter to its original efficiency is maintenance. This is achieved by simply scraping off the smuchdektz from the top of the filter. Furthermore, after a succession of scrapings, the filter bed will eventually be reduced to a minimum depth and will need to be rebuilt. This is also achieved by placing the sand collected during the removal of the smuchdektz with any additional new sand required at the bottom of the filter bed to return it to its original height. Additionally, the sand used to rebuild the filter bed should be cleaned prior to its addition to the bed (Clapham 2004; Sanchez et al. 2006; Visscher 2006).

When properly operated and maintained, slow sand filtration can be an effluent of a consistent water quality. In the slow sand filter, clogging occurs much faster than expected when the level of contamination in the inflowing water exceeds the slow sand filter's treatment capacity. Factors that can attribute to rapid clogging include; excess iron and manganese levels, high turbidity and some form of algae (Galvis, Vischer and Lloyd 1992; Huisman & Wood 1974; Visscher 2006). Factors that can also affect the microbiological activity in the smuchdektz are attenation in the pH temperature, nutrient content and oxygen levels. These also affect the efficiency of the slow sand filtration process (Sanchez et al. 2006; Visscher 2006). Below is a table showing the influent concentration thresholds for slow sand filtration.

Table 4- Influent concentration thresholds for slow sand filtration (Smet & Wijk 2002)

Water Quality Parameter	**Maximum Concentration.**
Turbidity (NTU)	10
Colour (TCU)	20
Thermotolerant coliforms (CFU/100ml)	200
Iron (mg/I)	1
Manganese (mg/I)	0.2
Dissolved Oxygen (mg/I) (greater than)	6
Phosphate (mg/I)	30
Ammonia (mg/I)	3
Algae (units/ml)	200

2.2.2 Reed Bed Treatment Systems

One of the biggest advantages of the reed bed treatment system is that, they are cost effective and have a low maintenance option, and yet they do a good work in treatment of municipal and industrial waste water, therefore improving the quality of water at a community-scale in water supply systems (Kuypers, Taylor and Mackay 2008). These systems also have the advantage of providing secondary aesthetic and environmental benefits

Reed beds are essentially shallow soil beds of a uniform grade and a height between 0.3-0.6m with plants growing in them. The bed is typically satiated on a gentle slope usually characterised by gradient of less than 1% (Moshiri 1993). Water flows evenly distributed through the subsurface soil matrix either horizontally and continuously or vertically and intermittently. The latter is seen to be more efficient at removing pollutants (Tuladhar, Shrestha & Shrestha 2008). Impermeable materials such as clay or plastic are used in the Reed bed systems. This way the bed is isolated from the surrounding environment and retains water for treatment (Parco et al. 2005). Below is a diagram showing the reed bed treatment systems.

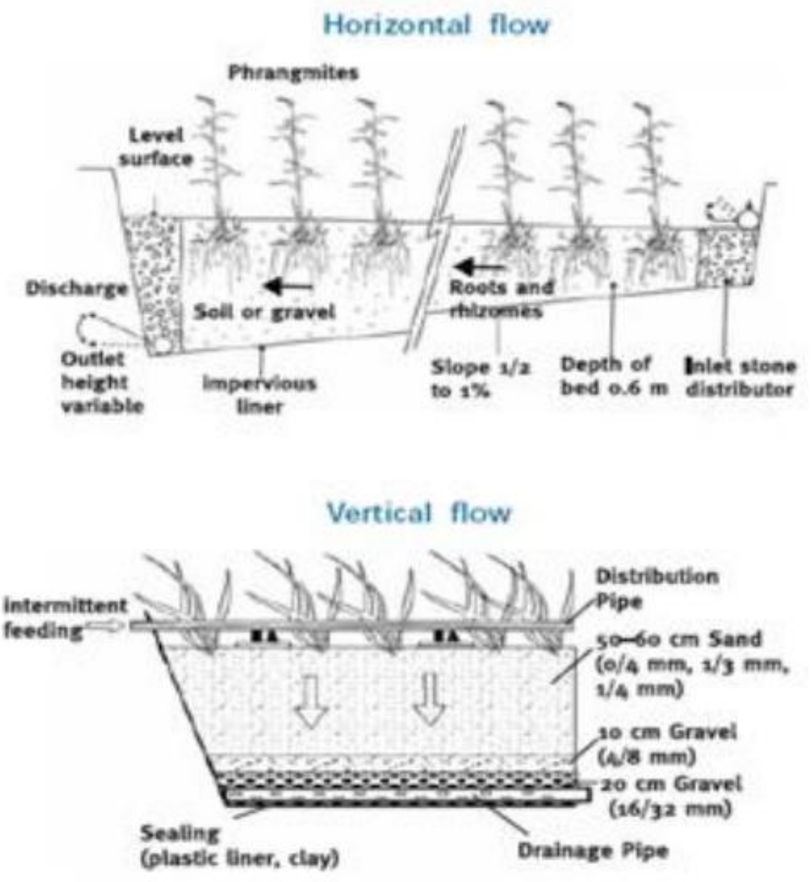


Figure 2.1 – Schematic of a vertical and horizontal flow reed bed (adapted from Tuladhar, Shrestha &Shrestha 2008)

As water passed through the soil matrix, it goes through a variety of natural processes that are facilitated by the reeds (soil and microorganisms which exist within the reed bed ecosystem). In this way the water is treated (Tuladhar, Shrestha & Shrestha 2008). A study by Kuypers, Mackay & Taylor (2006) indicates that reed beds in water supply systems are effective at removing turbidity, heavy metals and colour. They also increase the dissolve oxygen content and pH.

Table 5-Treatment efficiencies for reed bed treatment systems (Kuypers, Mackay & Taylor 2006)

Water Quality Parameter	**Removal Efficiency (%)**
Turbidity (NTU)	50
Colour (TCU)	68
Iron (mg/I)	69
Heavy Metal (mg/I)	83
pH	-20
Dissolved Oxygen (mg/I)	-54

The reed bed system needs little maintenance. Their operations costs and capital costs are negligible compared to other treatment systems (Parco et al. 2005). This therefore makes them better choices for water supply systems in developing countries. One of the factors that promote their low cost is their use of local materials and skills in their construction (Tuladhar, Shrestha & Shrestha 2008). Likewise, their operations cost are negligible because of their low energy requirements of this system (Parco et al. 2005). The maintenance and monitoring of these systems, even though simple, needs to be regular for long term performance and propitious treatments (Gschlobl & Stuible 2000). The maintenance activities include checking for blockages, weeds and pests (O'Hogain 2003), as well as the regular harvesting and disposing of reed bed plants, as they accumulate pollutants in their substrate, rendering them less effective for treatment over time (Gschlogl & Stuible 2000).

The disadvantages of the reed bed systems include: the requirement of large areas of land (Parco et al. 2005), and their potential failure if pollutant loadings are beyond the capabilities of the reed bed system (Kuypers et al. 2009). These limitations and inadequate operation and maintenance could affect the sustainability of this technology in some communities.

2.2.3 Rapid Sand Filtration

Rapid sand filtration can be used in place of the slow sand filtration process. The former removes contaminants through the whole depth of the filter medium rather than just at the filter bed's surface. Rapid sand filtration actually makes use of much coarser filter media that allow for faster filtration rates and a reduction of the required surface areas (Clapham 2004; Visscher 2006). The hydraulic heads of these filters are used to categorise them as gravity or pressurised. The flow orientation classifies them as up-flow or down-flow, and filtration rate classifies them as constant or declining, while the number of filters media layers categorises them as singular, dual or triple (AWWA 1999).

The rapid sand filters need more periodic and complicated maintenance, compared to the slow sand filters. In the former, the filter bed must be cleaned through an upward flow of water and occasionally aired to cause full fluidization of the bed. This allows for the collected contaminants to be lost with the overflow (AWWA 1999). The process just described is the greatest difficulty in operating and maintaining the rapid sand filters in developing countries. It is known as backwashing. Other disadvantages of this system include the production of a turbid filtrate, if the pressure within the filter falls below atmospheric pressure and this process's inability to alone produce a filtrate of good chemical and biological quality (Smet & Wijk 2002). Due to these problems, rapid sand filters are used alongside other treatment processes (Huisman & Wood 1974).

2.2.4 Diatomaceous Earth Filtration

Diatomaceous earth filtration takes place in a two step process that employs diatomaceous earth that are the skeletal remains of microbes. These are used as filter media (Bhardwaj & Mirliss 2001). For the operation of this system, diatomaceous earth is first collected on the leaves of the filter's septum. When a sufficient amount has been collected, water is then allowed to pass through the filter for treatment. Small amounts of diatomaceous earth are added in regular intervals to assist with the filtration process. Suspended particles are deposited on the pre-coated septum leaves as the influent water, and allowed to pass through the filter septum (Wang, Hung & Shammas 2006). This leads to the clogging of the filter and cleaning done using the backwashing process (Bhardwaj & Miriliss 2001), after which the filters two step process of operation can restart.

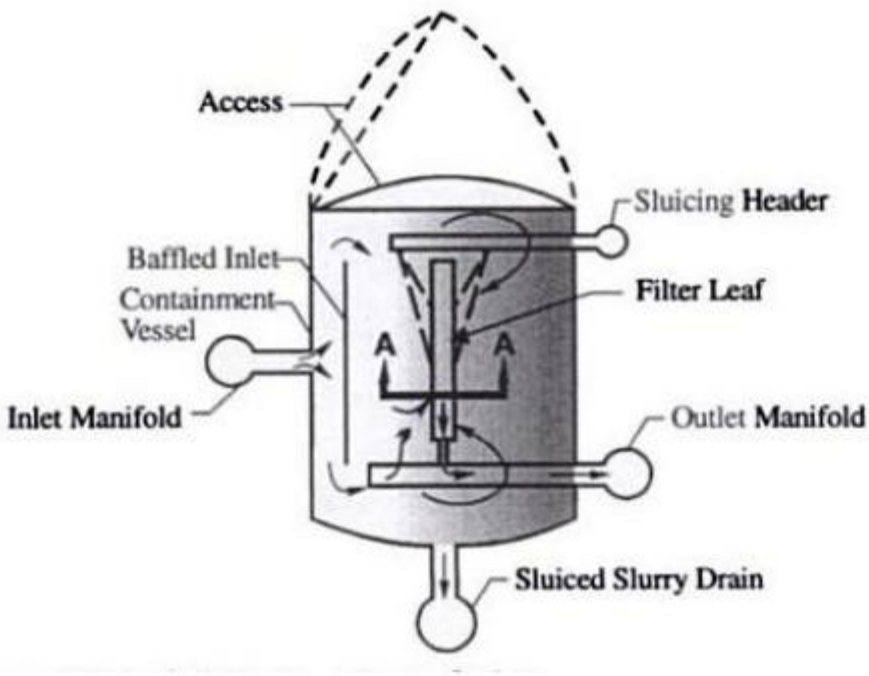


Figure 2.2 - Schematic diagram of the key features of a diatomaceous earth filter (Fulton 2000)

This filter can be configured in two ways, pressure filters and vacuum filters. Pressure filters have a pump on the influent side of the filter and are enclosed within pressure vessels, while vacuum filters have pumping systems on the effluent side of the filter and are open to the atmosphere. These two filters have their merits and demerits, but the principal advantage of the pressure filter over the vacuum filter is in their ability to accommodate higher filtration rates and longer filter runs (Fulton 2000).

2.2.5 Membrane Filtration

In membrane filtration, a thin film or semi permeable membrane is used to remove fine particulate matter from water. Some of the membrane technologies include: microfiltration, ultra-filtration and nano-filtration. These are differentiated by the particle size they are able to remove. Reverse osmosis which has to do with movement of a solvent from a more concentrated solution to a less concentrated solution that can essentially remove all dissolved and suspended particles from water, also falls under this technology (Clapham 2004). This process is actually not very suitable for implementation in developing countries, since it is expensive (NDWC 1999).

2.2.6 Roughing Filters

Roughing filters can be used as pre-treatment steps in filtration processes, where the raw water is contaminated with high levels of harmful materials or contaminants that can adversely affect filtration processes (Galvis, Visscher & Lloyd 1992). Particularly, roughing filters are adopted where the turbidity levels of raw water exceeds the capabilities of filtration processes (Visscher 2006). The commonly used medium that is used in roughing filtration is gravel. However, locally available materials with larger surface areas that yield high porosities can be used in place of the gravel (Ochieng et al. 2004). Different types of roughing filters are available and they are grouped according to the filter flow direction. They include; Dynamic, Vertical flow and Horizontal flow.

In dynamic gravel filters, water flows through a shallow layer of fine gravel, typically around 0.3-0.6 m in depth, to 0.6 m in depth, to a drainage system which is covered by a layer of coarser gravel to support the fine gravel layer and acts as a drainage mechanism. This technology typically operates using filtration rates of 0.9-1.6 m/hr (Smet& Wijk 2002), but can be operated using rates up to 5 m/hr. Dynamic filters are best suited for treating short turbidity peaks that have a duration of a few hours to a maximum of half a day (Wegelin 1996).

In vertical flow filters, short sheets of gravel, that reduce in size in the direction of the flow are used. They can either be against gravity (upflow) or with gravity (downflow), and are operated with filtration rates between 0.3 and 1m/hr. The sheets of gravel can either be installed in layers in singular units or in a series of units. Typically, three sheets of gravel are implemented in either variation using a media with particles sizes of about 16-25 mm for the coarsest sheet, 8-16mm for the finest sheet (Brikke & Bredero 2003). For moderately turbid water of about 50-150 NTU, the vertical filters are suitable for its treatment. If it is going to be used to treat water of higher turbidity, then supplementary layers or units in series have to be added. Most of the time, up flow gravel filters are generally preferred over their down flow counterparts, since they are easy to clean hydraulically (Wegelin 1996), even though both filters produce similar water quality.

In horizontal roughing filters, a series of gravel layers are constructed in three compartments. This reduces in particle size in the direction of the flow and the water to be treated flows horizontally through these series of gravel layers (Smet & Wijk 1996). The operation filtration rates of these filters range between 0.3 and 1.5 m/hr, and are up to 500-100 NTU (Wegelin 1996). This therefore makes them very suitable for treating highly turbid waters. Due to their high cost and technicality, the up flow filters are used in place of them (Smet Wijk 2002; Visscher 2006; Wagelin 1996).

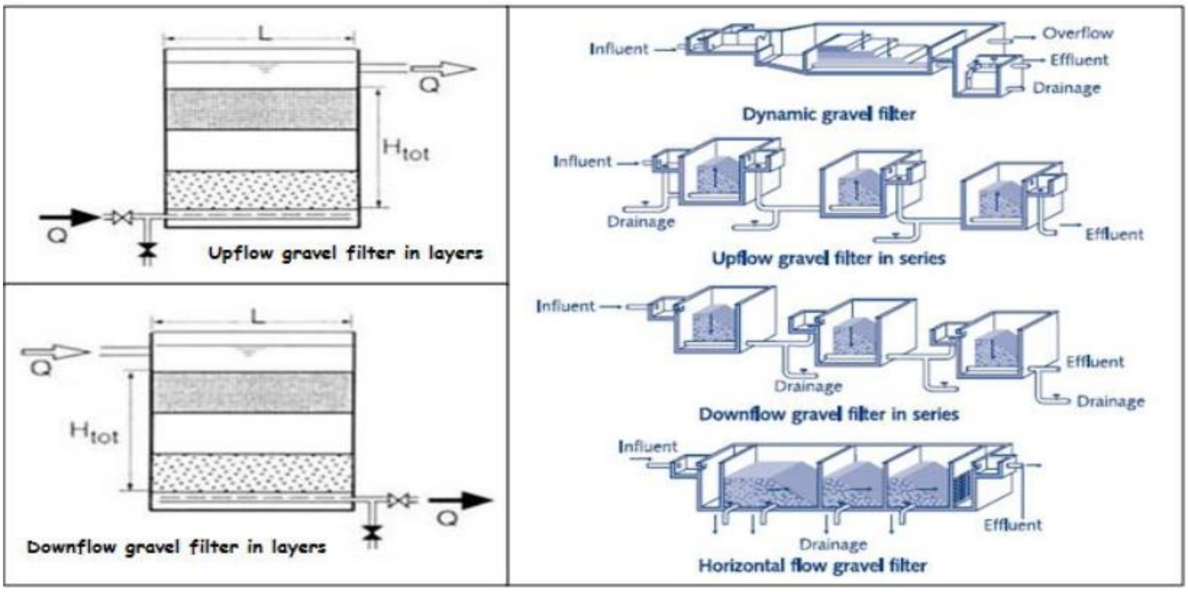


Figure 2.3 – Schematic diagram of the roughing filtration technologies (adapted from Smet & Wijk 2002; Wegelin 1996)

Each roughing filter technology varies in its ability to remove contaminants. A report from

Columbia of a full scale water treatment indicates that dynamic filters can remove 21-57% of turbidity, 10-24% colour and 37-80% of the thermotolerant coliforms from influent water. Also a pilot scale plant from Columbia shows that typical upflow gravel filters in layers can remove 54-70%, 28-46% and 95-98% of turbidity, colour and thermotolerant coliform respectively, while upflow gravel filters in series were shown to remove 75-84%, 53-69% and 99.5-99.7% of turbidity, colour and thermotolerant coliform present in effluent water respectively. Similar results are obtained from the downflow gravel filters (Dastanaie et al. 2007). Finally a study from water treatment systems in Iran shows that the horizontal roughing filters can remove 63% of turbidity, 20% colour and 94% of the thermotolerant coliforms present within a raw water source (Dastanaie et al. 2007).

Table 6- Reported removal efficiencies for turbidity, colour and thermotolerant coliforms for roughing filtration technologies (Dastanaie et al. 2007; Smet & Wijk 2002).

Roughing Filtration Technology	**Turbidity (%)**	**Colour (%)**	**Thermotolerant coliforms (%)**
Dynamic	21-57	10-24	37-80
Vertical flow (In layers)	54-70	28-46	95-98
Vertical flow (In series)	75-54	53-69	99.5-99.7
Horizontal flow	63	20	94

Roughing filters are usually an ideal pre-treatment step for slow sand filtration because roughing filters produce an effluent with turbidity of 10-20 NTU or less (Smet & Wijk 2002). The combination of these technologies is commonly known as multi-stage filtration. This multi-stage filtration has produced greater water quality in many cases than would have been achieved by slow sand filtration alone (Sanchez et al. 2006). It is also better at accommodating unexpected variations in water quality than the slow sand filters (Galvis, Visscher & Lloyd 1992). The roughing filters are very suitable for pre-treatment step for slow sand filters and other purification processes in developing countries. This is because they are simple to use, reliable, easy to operate and maintain. They can also filter large volumes of water with low head losses (Boller 1993).

2.2.7 Other Filtration Technologies

Other filtration technologies used in water treatment include activated carbon and ceramics. Ceramics filters are most of the time made from clay and have being in use for centuries. The ceramics filters are very effective in the removal of particulate matter and microbial contaminants (Sobsey 2002). The activated carbon filters actually uses entrapment and adsorption mechanisms in their operation and are very effective at removing suspended solids, soluble and insoluble forms of heavy metals, chlorine, organic substances and other contaminants responsible for taste, odour and colour issues in water (Clapham 2004). These two types of filters mentioned are actually effective in the household scale use.

2.3.0 Ceramics for Water filtration

Ceramics are generally compounds that fall between metals and non-metals. They are oxides, nitrides and carbides. Examples include aluminium oxide (Al_2O_3), silicon dioxide (SiO_2), silicon carbide (SiC) and silicon nitrite (Si_3N_4). Compounds of clay such as porcelain, cement and glass are also ceramics and are usually referred to as traditional ceramics (Callister 2007). This is probably because these clay minerals ceramics are the oldest ceramics. Ceramics that are used in water filtration are made from clay.

These clay ceramics are used for water filtration because the pores that are present in them are smaller than most of the debris and bacteria present in the water (Doris 2006). As the water passes through the filter, these unwanted substances are trapped in the filter, leaving only clean water to pass out. Since not all bacteria can be filtered out of the water due to their size, colloidal sliver coated on to the surfaces of the filters. This disinfects/kills or incapacitates the bacteria. It also helps stop the growth of moulds and algae on the surface of the filters.

There are two types of ceramic filters that are made from clay. There are the pot type of filter and the candle type. In the pot type of filter, they are shaped in pot forms and are placed in plastic containers that have a tap at the base. The filter is filled with water, which is then filtered out into the container. The filtered water can then be accessed through a tap. In the case of the ceramic candle filters, the pail of the filter is filled with water and by the action of gravity, the water moves through the ceramic candle which is the connector between the pail and the reservoir pail. The ceramic candle is responsible for the purification of the water and the filtered water flows into the reservoir pail and is ready for use.

(a) **(b)**

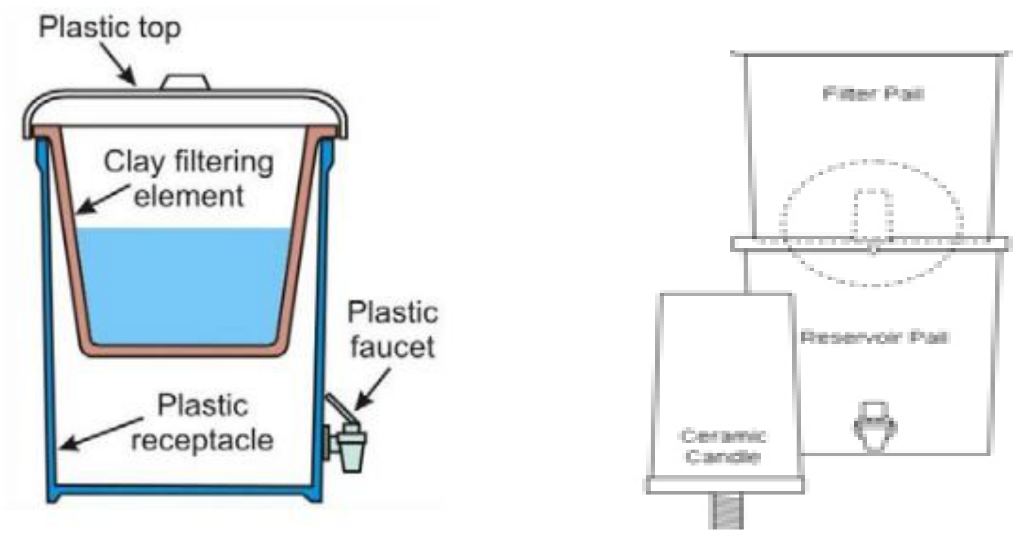
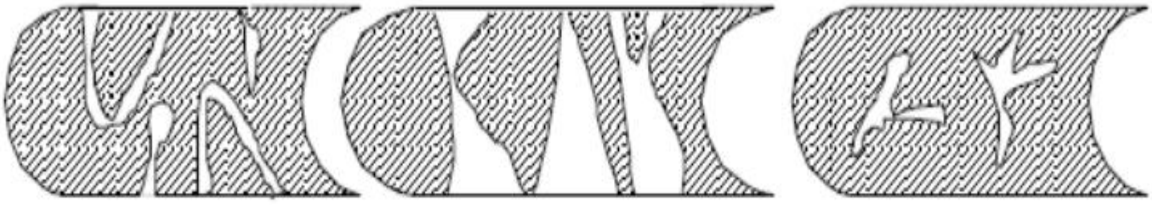


Figure 2.4 – Schematic diagrams of: (a) the pot filter and (b) the candle ceramic filter (Doris 2006)

Activated carbon is sometimes used to aid the adsorption of chlorine and other particulates in water. The activated carbon traps a lot of foreign materials, and thus can result in the clogging of the filter. There are also ceramic filters that work through normal pumping and filters that are used in house hold plumbing. These filters are MSR miniworks and in-line ceramic filters respectively. All ceramic filters are cleaned by using soft brushes prior to rinsing. The main disadvantage of ceramic filters is their brittle fracture behaviour. They may therefore crack during fabrication or transportation. In some cases, the plastic container may also be contaminated. There is therefore a need to ensure that the containers and the bottom of the filters remains clean during use in filtration systems.

2.4.0 Mechanisms of Filtration in Porous Media

Filtration is a process of purification in which contaminated water is allowed to flow through a porous medium. The water is purified by a series of physical, chemical and biological processes (NDWC 1996). The process of filtration is possible because of the presence of pores in the filtering medium. The porosity of the filter is the volume fraction of the filter occupied by pores or void space. In ceramic filters, different types of pores come into play in the filtration process. The first one is the interconnected or effective pore space. Here, the void space forms a continuous phase within the porous medium. The next one is the isolated pores. In this case, the void space has no link with each other and is usually separated by an area of no pores. Isolated pores cannot contribute to flux across the filter. The last kind of pore is the dead-end pores. These pores are connected from only one side and their contribution to flux is temporal. Sometimes, the dead-end can also be connected to the interconnected pores, but for as long as the route is a dead-end they will not contribute to the flux. During the process of filtration, when the filter is filled with water, all the pores that are connected to the inside of the filter are first of all filled with water. These include the dead-end pores. This results in a delay in the discharge of the water and this is then followed by a steady-state discharge of water (Doris 2006). The types of pores described are shown in the figure below.



Dead-end pores interconnected pores isolated pores

Figure 2.5 – Schematic diagram of the types of pores (Xiaolong 2005)

The phenomena that enhance the removal of impurities in the filtration process include; mechanical screening, sedimentation, diffusion, absorption, chemical and biological activities (Huisman 1996).

Mechanical screening: In this process, the particles that are too large to pass through the pores of the filter are stopped from flowing through the filter. This therefore results in the purification of the water from these contaminants. With time, the pores of the filter gets clogged , thereby reducing the size of the pores, meaning some of the smaller particles that could pass through get trapped. However, in reality, the flow rate of the filter is affected negatively and so the filter needs to be cleaned.

Sedimentation: This comes into play as there are certain particulate matter in the water whose sizes are smaller than the sizes of the pores of the filter. Hence, these particles can pass easily through the filter without being removed. Sedimentation is responsible for the precipitation of this particulate matter on the surface of the clay material. Since the suspended particulate matter have a higher densities than water, the water takes a different path from the particulate matter due to the action of gravitational forces.

Diffusion: this is the random motion of particles in a fluid caused by collision with surrounding molecules. This random movement of the suspended particles could eventually lead to their absorption to the filter material. This results in their eventual removal from the water.

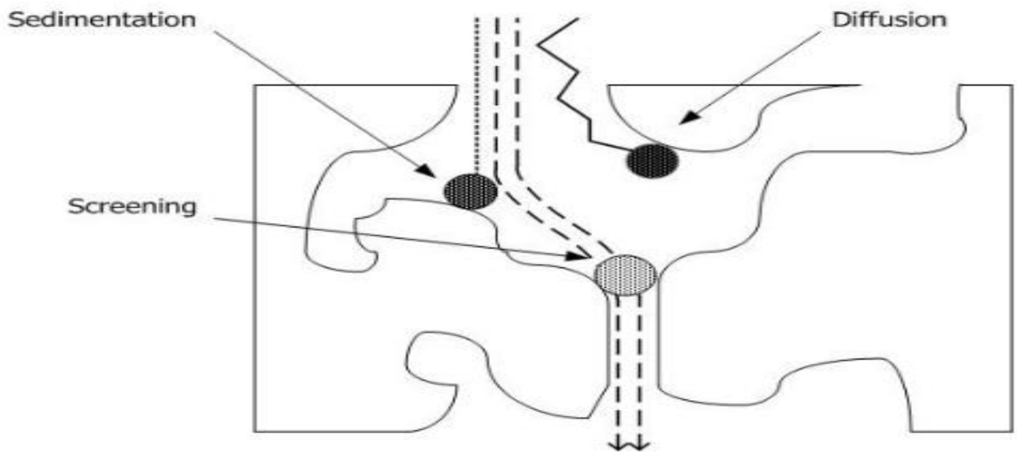


Figure 2.6 – Schematic diagram of the mechanism of filtration (Doris 2006).

Adsorption: This is an important purifying action. It removes finely divided suspended matter as well as colloidal and molecular dissolved impurities. In this process, the filter surface attracts suspended matter, colloidal and molecular dissolved impurities to its surface. However, the adsorption force operates over short distances of about 0.01-1 micron, while the water film surrounding the filter material has a much greater thickness (Doris 2006). This means the process of adsorption is made possible by another mechanism that will bring the particles to the vicinity of the clay surface. Some of these mechanisms include gravity, inertia, diffusion, hydrodynamic forces and turbulence. The forces that are responsible for the adsorption of the suspended matter at a short distance from the filter material are:

- the physical attraction between two particles (Van der Waal's forces)
- electrostatic attractions between opposite electrical charges (Coulomb forces)

Chemical activity: This involves processes that either break down dissolved impurities into simple less harmful substances or convert them into insoluble compounds that can be removed by staining, sedimentation and adsorption.

Biological activity: This also has involves the action of microorganisms that are living in and on the filter element. The bacteria present in the water are adsorbed in the filter material where they selectively multiply, and feed on inorganic and organic matter. The energy that these bacteria need for their living process (dissimilation) and the partly conversion into cell material for their growth (assimilation) is obtained from the partial oxidation of the organic and inorganic matter (Doris 2006).

2.4.1 Filter Discharge

The filter discharge is a very important parameter in the operation of the filters. This parameter is actually used to determine whether a filter will be accepted or rejected. The acceptable discharge of the filter by the WHO is between 1 and 2 litters per hour.

The first step in understanding the flow through the silver impregnated ceramic filters has to with an analytical estimation of the discharge through the filter. The result of this model is then compared with measured discharges at various water levels in the filter. The analytical model of the discharge through the filter is based on the Darcy's law (Doris 2006). This law describes lamina flow through porous media. This is given by: $Q = \frac{KA}{L}\frac{\Delta P}{\mu}$

Where Q is the volumetric flow rate of liquid through a specimen of porous material, K is the constant of proportionality known as Darcy permeability of the material, L is the length of the specimen, A is the cross sectional area of the specimen, ΔP is the hydrostatic pressure difference across the specimen and μ is the dynamic viscosity of the fluid (source).

For the ceramic silver impregnated filters modification is made to account for the changing water head over the height of the filter. Since the base of the filter is circular, it taken to be a circle and it has a constant water head. Figure 2.7, which gives the dimensions that are to used in the calculation of the flow rate of the filter, y is the height of the filter, h(t) is the water head (the level of the water) and is a function of time (t), r(t) is the radius of the filter which is a function of the height of the filter. The term t_b is the thickness of the filter base while t_s is the thickness of the side of the filter. The driving force (water head) and the surface area vary over the height of the filter. This therefore makes the flow through the filter wall more complex. An integral for the water head and the surface area is used to describe the discharge through the filter wall.

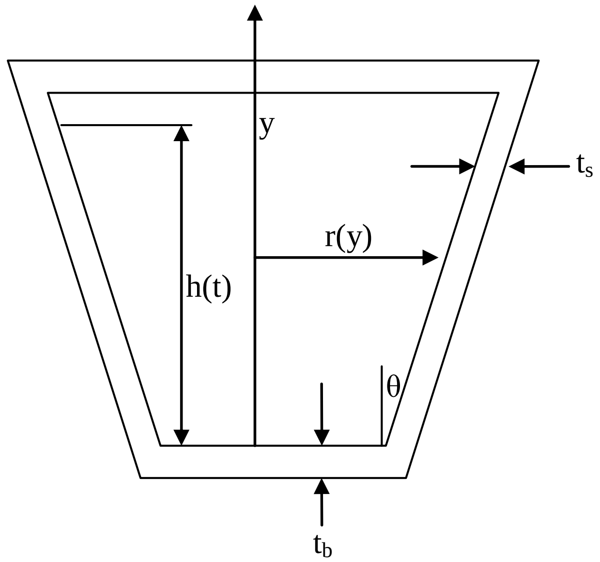


Figure 2.7 – Surface area and discharge calculations.

Using the Darcy's equation, the calculation of the flow rate of the ceramic silver impregnated filters is done in two parts. This is because filtration in these filters occurs at the sides of the filter and at the bottom. Therefore flow rate calculation of the side of the filter is considered separately from the flow rate calculations of the bottom of the filter. The overall flow rate of the filler is obtained by summing the flow rate of the side and the flow rate of the bottom of the filter.

Developing the expressions for flow rate of the filters is show below:

Darcy's equation is give as, $Q = \frac{KA}{L}\frac{\Delta P}{\mu}$

Where ΔP is given as $\Delta P = \rho g\left(h(t) - y\right)$ and $r(y) = R + y\tan\theta$. These expressions are obtained from figure 2.7.

For the expression of the flow rate for the bottom of the filter, the base of the filter is assumed of have a circular shape, therefore the area of a circle ($A = \pi R^2$) is used as its area and the value of y is zero, since at the base of the filter, there is no height to consider. Substituting the expression for A and ΔP into the Darcy's equation, we get Q_b, which is the flow rate of the base of the filter.

$$Q_b = \frac{K\pi R^2}{t_b}\frac{\rho g h(t)}{\mu} \quad \text{... (1)}$$

In the case of the expression for the side of the filter, the area A is obtained by differentiating the circumference of a circle (2πr), with respect to y which is the height of the filter. This is because the inner part of the filter is considered to be circular. Therefore the expression, $dA = 2\pi r(y)dy$, is obtained for the A term. To find Q_s which is the flow rate of the side of the filter, *dA* and ΔP are substituted into the Darcy's equation and integrated over the elementary surface to give;

$$Q_s = \frac{K}{t_s \mu} \int_{A_s} \rho g\left(h(t) - y\right) dA, \text{ .... (2)}$$

Now substituting *dA* into equation (2), we get;

$$Q_s = \frac{K}{t_s \mu} \int_{A_s} \rho g\left(h(t) - y\right) 2\pi r(y) dy, \text{ .... (3)}$$

From figure 2.7, $r(y) = R + y\tan\theta$, this therefore substituted into equation (3) to give;

$$Q_s = \frac{K}{t_s \mu} \int_{A_s} \rho g\left(h(t) - y\right) 2\pi\left(R + y\tan\theta\right) dy, \text{ .... (4)}$$

The constant terms within the integral are factored out to obtain equation (5) below;

$$Q_s = \frac{2\pi K\rho g}{t_s \mu} \int_0^h \left(h(t) - y\right)\left(R + y\tan\theta\right) dy, \text{ .... (5)}$$

Now integrating equation (5), from 0 to h (the height of the filter), equation (6) which is the flow rate of the side of the filter is obtained.

$$Q_s = \frac{\pi K\rho g}{t_s \mu}\left[Rh^2(t) + \frac{4\tan\theta h^3(t)}{3}\right], \text{ .... (6)}$$

The overall flow rate of the filter Q_{total}, is give by the summation of Q_b and Q_s, which are given as equations (1) and (6). This is show as equation (7) below;

$$\text{Total; } Q_{total} = \frac{\pi K\rho g}{\mu}\left[\frac{R^2 h}{t_b} + \frac{Rh^2}{t_s} + \frac{4\tan\theta h^3}{3t_s}\right], \text{ .... (7)}$$

The analytical model Q_{total}, derived above can be used to approach the flow pattern through the silver impregnated ceramic filters and provide an estimation of the discharge of the filter.

CHAPTER THREE

METHODOLOGY

3.1 Raw Materials

In this project, two types of silver impregnated clay filters were made to determine their time-dependence of flow. The first kind of filters was made from clay and saw dust while the second kind was made from clay, saw dust and hydroxyapatite. This therefore makes the raw materials that were used for this project to be clay, sawdust and hydroxyapatite.

The clay used for the moulding of the filters was obtained from Olorunda Ayehro, Ogun State in the South-western part of Nigeria. The clay was obtained in its raw wet lumpy form. It was therefore dried for two weeks to remove the water from it. This was then followed by crushing of the clay into powder form using a hammer mill 121 (Munson, Utica, New York, U.S.A). This was followed by sieving to obtain finer particles using a screen mesh (2mm).

The saw dust used in this project was obtained from a saw mill in Abeokuta, Ogun State, Nigeria. This was prepared by sieving it to isolate the large particles of the saw dust. This was achieved using a sieve with a 3 mm screen mesh.

3.2 Manufacturing the Ceramic Filters

The filters were processed at Filtron Nigeria in Abeokuta, Nigeria. During processing, 50 vol.% of the processed clay was measured onto a clean surface. Then 50 vol.% of saw dust was measured out and added to the clay. The two materials were then mixed well. Water was then slowly added to the clay and saw dust mixture during mixing. This was done periodically to ensure that a homogenous consistent mixture was obtained. This homogenous mixture was then pressed into the filter shape using a hydraulic press with a purpose-built mould.

After pressing, the moulds were marked with unique codes for identification. They were then left in the open to sundry for two weeks. After drying, filters were fired in a kiln at approximately 780 ^{0}C for a period of between 6 to 9 hours. They were then allowed to furnace cool down to room temperature. A mixture of water and colloidal silver, that is 2 ml of colloidal silver at 3.2% added to 250 ml of water. The dried filters were then dipped into this mixture. This resulted in the coverage of the surface with the colloidal silver. The dipped filter was then allowed to dry in the open air under ambient conditions.

3.3 Processing of Filter with Hydroxyapatite

The second group of filters that was made had a third material introduced in it. This material is hydroxyapatite, a naturally occurring mineral form of calcium apatite, with the formula $Ca_5(PO_4)_3(OH)$. In the making of these filters, 90% (vol.) of clay was measured out and added to 10% (vol.) of hydroxyapatite and mixed together. Then 50% (vol.) of saw dust was then measured and added to the mixture of clay and hydroxyapatite. This was then mixed thoroughly, with water being slowly added to the mixture during mixing to ensure that a homogenous consistent mixture was obtained. The homogenous mixture was then pressed into the filter shape using a hydraulic press with a purpose-built mould.

These pressed filters were marked with unique codes for identification. They were then left in the open to sundry for two weeks. After drying, the filters were fired in a kiln at approximately 780 ^{0}C for a period of between 6 to 9 hours. This actually burns the saw dust in the filters and therefore creating the pore needed for the filtration. After firing, the filters were allowed to furnace cool down to room temperature. They were then dipped in a mixture of water and colloidal silver, that is 2 ml of colloidal silver at 3.2% added to 250 ml of water. This resulted in the coating of the filter surface with colloidal silver. The coated filters were then dried in air under ambient condition.

3.4 Flow Rate Experiments

The flow of water was studied in the two types of filters that were made using procedure described in section 3. The flow experiments were used to study the time dependence of flow. Foe each type of filter, five filters were selected randomly and each placed in a plastic container with a tap at the base. They were then set up on a flat raised platform. Each filter had a beaker placed directly below the tap in the plastic container to collect the water flowed through. The taps were then fully opened before filling each filter with water. The time-dependence of flow was then recorded by measuring the volume of water that dripped out of the tap into the beaker. It is important to note that the receptacle was filled pre-filled to appoint where a single drip of water into receptacle resulted in a drop of water from the tap into the beaker.

The flow of water into the beaker was recorded after 15 minutes, and then after two hours, the interval for the measurement of the water was increased to 30 minutes. This was then increased to 1 hour, then to 1 hour 30minutes, and then finally to 2 hour intervals. The timing for the increment of the interval for the measurement of the water depends on the measuring apparatus that is being used in the measurement of the volume of water that flow out of the tap. This interval is increased because, as the level of water reduces in the filter, the volume flow rate of water filtered also reduces. Hence, large volumes are needed to measure the flow rate.

3.5 Serial Flow Rate Experiment

The serial flow rate experiment was very similar to the flow rate experiment described above. In this experiment, five filters made with only clay and saw dust. They were randomly selected and each placed in a plastic container with a tap at the base. They were then set up on a flat raised platform. Each filter had a beaker placed directly below the tap of the plastic container to collect the water that flowed from the receptacle. The taps in the plastic containers were then fully opened before filling each filter with water. The time at which each filter was filled was recorded along with the time at which water started to flow out of the tap.

As in the flow experiments on individual filters, the time dependence of flow through the serial filters was recorded after different time interval. The first time interval was 15 minutes, and then after two hours, the interval for the measurement of the water was increased to 30 minutes. This was then increased to 1 hour, then to 1 hour 30 minutes, and then finally to 2 hour intervals. After the water in each filter was completely filtered out, the filters were refilled with water and the whole process was repeated. Each filter was filled five times, i.e., the flow experiments were conducted five times for each filter. These experiments were used to determine the effect of multiple filtrations on the flow rate through each individual filter.

3.6 Scale- Up Filtration System Experiments

The scale-up filtration system experiments were conducted to explore the feasibility of filtering water on a larger scale that is relevant to the family or a community. The filters were connected in series to explore the extent to which the flow of water scales with increasing number of filters.

In the first setup (Figure 3.1), five filters were connected in series with a pipe that allowed water to drip out through common outlet. The system had a main supply that was filled with water and is linked to the filtration system through a pipe. It was designed in such a way that when the main water supply to the filters is open, the first filter is filled first, and then the water starts to fill the second filter in that order till all of the filters are filled. The time at which the first filter was filled was recorded.

The next thing was measuring the volume of water that flowed out of the common outlet at some time interval. The first time interval was 15 minutes, and then after two hours, the time interval for the measurement of the water was increased to 30 minutes. This was then increased to 1 hour, then to 1 hour 30 minutes, and then finally to 2 hour intervals.

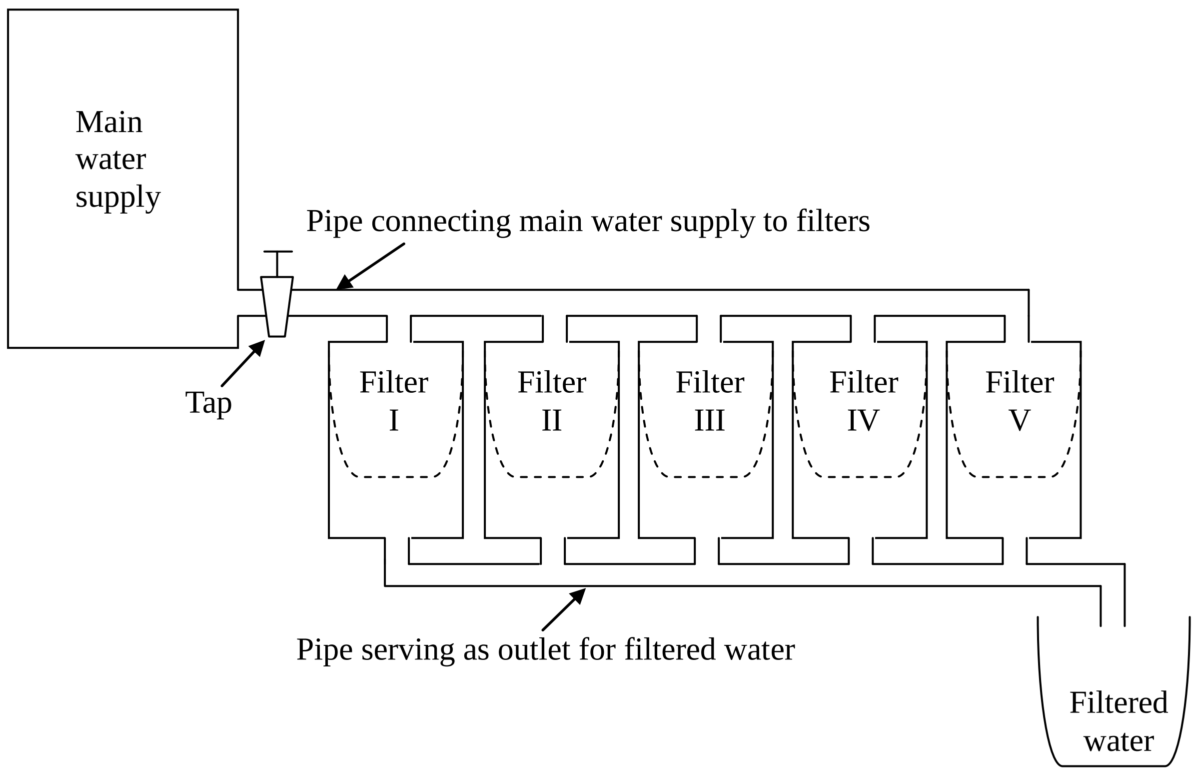


Figure 3.0 – Schematic diagram of the first scale up filtration system.

In the second setup, the filters were connected to each other by their plastic containers in such a way that the water filtered by each filter flowed out in a common outlet, just like in the first setup. The difference between this setup and the first one comes in the pipe connecting the filters to the main water supply. In this second setup, each filter in the setup is connected separately to the main source by a different pipe. Hence, each of the filters was filled at same time (Figure 3.2). So at the start of this experiment, the pipes connecting to each filter were opened to allow the filters to fill (essentially the same rate) with water. The time required to fill the filters was then recorded.

The volume of water that flowed out of the common outlet was then recorded at specific time intervals between 15 minutes and 2 hours. The first time interval was 15 minutes, and then after two hours, the interval for the measurement of the water flow was increased to 30 minutes. This was then increased to 1 hour, then to 1 hour 30 minutes, and then finally to 2 hour intervals.

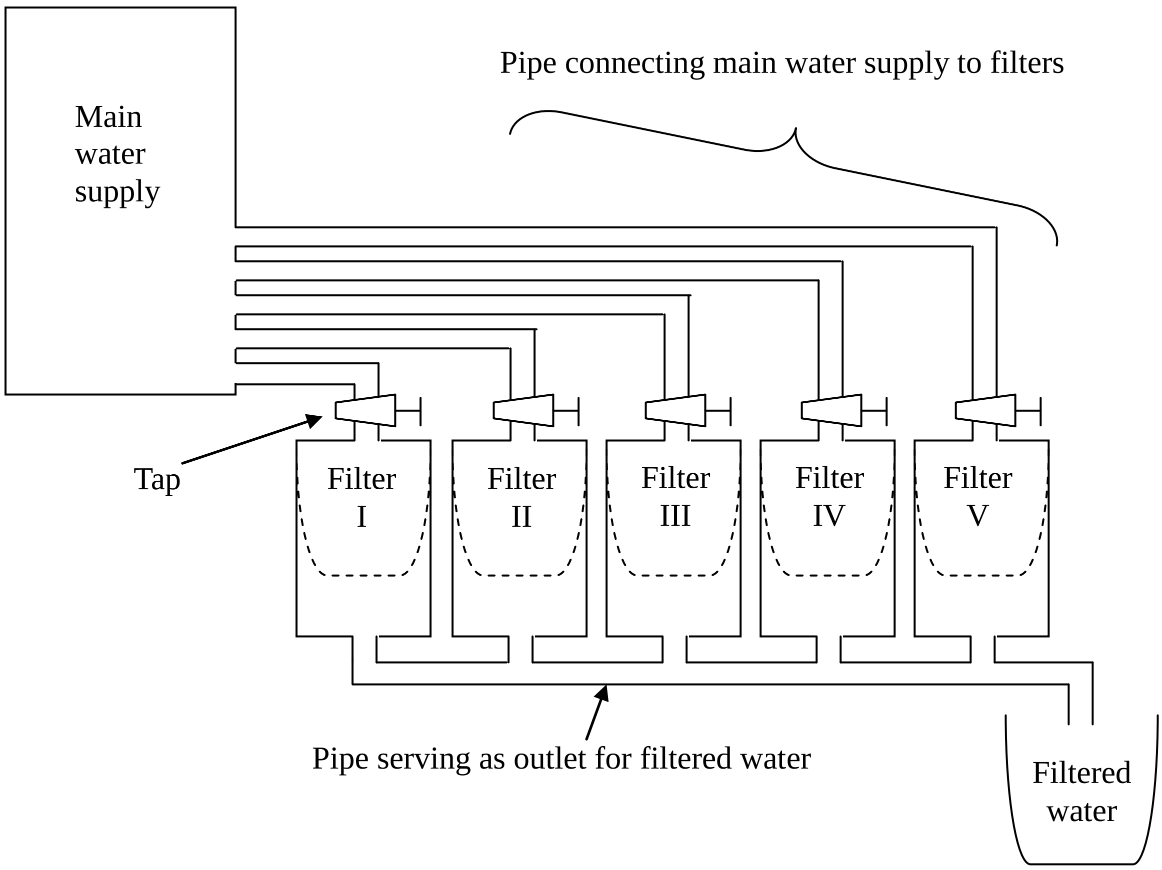


Figure 3.1 – Schematic diagram of the second scale filtration system.

3.7 E.coli Testing Experiment

The E.coli test was conducted to determine the effectiveness of the manufactured filters in the removal of bacteria in the water being filtered. The test was conducted for pre-filtered water and filtered water. And in both cases, the test was conducted for 1ml and 0.5 ml of sample water and ten petrifilm plates was used. Therefore for the 1ml of sample water, five petrifilm plates were used and the remaining five petriflm plates were used for the 0.5ml sample water. The plates were incubated for 24 hours and the colony forming units (CFU) was countered.

Coliform tests were also conducted using 3M petrifilm Rapid Coliform Count (RCC) plates (Microbiology Products, St. Paul, Minnesota, U.S.A). These are culture media that have already being made. They contain Violet Red Bile (VRB) nutrients, a cold-water-soluble gelling agent, a pH indicator, which is to detect acid and finally tetrazolium indicator, which facilitates colony enumeration.

For the testing, a petrifilm Rapid Coliform count (RCC) plate was placed on a level surface. This was then followed lifting the top film of the RCC. A 1 mL sample water was then dispensed onto the center of the bottom of five films each. It was then followed by dispensing 0.5 mL of sample water onto the center of bottom of another set of five fimls. This was done for both filtered and pre-filtered water. The top film was then slowly rolled down onto the sample, making sure that no air bubbles were trapped in the process. The smooth side of the plate was then turned face down, before placing the plastic spreader on the center of the plate and pressing gently in the center to distribute the sample evenly. Caution was taken not to slide the spreader across the film. After the press, the spreader was removed and the plates were left undisturbed for at least one minute to permit the gel to solidify. This process was repeated for each of the water samples that were taken.

After the whole process described above, the petrifilm RCC plates were incubated at $35^0C \pm 1^0C$ for 6 to 24 hours in a horizontal position, making sure that the moisture lost form the plate did not exceed 15% during this process. The plates were then examined for coliform growth after 24 ± 2 hours of incubation.

3.8 Characterization Experiment

The materials that were used in the manufacturing of the filters were sampled for characterization. These samples include; clay, sawdust and hydroxyapatite. Samples of the finished filters were also taken for characterization. The characterization experiment was used to determine the surface morphologies, structure and the elemental compositions of the samples. The surface morphologies were characterized using the Scanning Electron Microscope (SEM), while the elemental compositions of the samples were obtained using the X-Ray diffraction (XRD) and Energy Dispersive X-ray Spectroscopy (EDS).

The initial samples of clay and hydroxyapatite were in powder form while the samples of the finished filters were not in powder form. In the XRD analysis, the samples that were already in the powder for were only sieved through a 270 mesh sieve. However, the filter samples were first ground before sieving them through the 270 mesh sieve. The ground/powder samples were then mounted on the XRD sample holder before conducting the XRD analysis in a model MD-10 precision mini X-ray diffractometer (Radicon, Russia).

In the case of the SEM and EDS analysis, the samples were characterized in their unprocessed states. Hence, the powdered sawdust, clay and hydroxyapatite samples were characterized without special specimen preparation. The SEM/EDS analysis was carried out at the Sheddah Science Center in Gwagwalada, Abuja, Federal Capital Territory, Nigeria. They were conducted on the Model Zeiss Evo 60 Environment scanning electron microscope (Carl Zeisis Canada Ltd., Canada) that was instrumented with a model Bruker AXS Quantax 4010 energy dispersive X-ray spectroscopy (EDS) system (Carl Zeisis Canada Ltd., Canada).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Flow Characteristics Results

The results of the flow experiments are presented, respectively, in Figures 4.1.0 and 4.1.1 for the normal filters (without hydroxyapatite) and those with hydroxyapatite. The results from multiple tests on clay ceramic filters exhibit significant variability as shown in Figure 4.1.0. These are associated with different effective porosities and permeabilities, and different initial flow rate, as shown in Table 7. Similar variabilities were observed in the hydroxyapatite-doped filters, as shown in Figure 4.1.1 and Table 8

Table 7- Flow rate values of the five filters made without hydroxyapatite.

Filter One		Filter Two		Filter Three		Filter Four		Filter Five	
Time(h)	Volume(l)	Time(h)	Volume(l)	Time(h)	Volume(l)	Time(h)	Volume(l)	Time(h)	Volume(l)
0.95	1.36	0.77	1.51	0.48	1.03	0.73	1.20	0.73	1.31
1.20	1.82	1.02	2.06	0.73	1.60	0.98	1.73	0.98	1.61
1.45	2.15	1.27	2.50	0.98	2.11	1.23	1.89	1.23	2.00
2.45	3.17	2.27	3.75	1.98	3.57	2.23	2.62	1.73	2.64
3.45	4.07	3.27	4.79	2.98	4.64	3.23	3.27	2.23	3.18
4.45	4.72	4.27	5.47	3.98	5.41	4.23	3.79	2.73	3.67
5.45	5.27	5.27	6.14	4.98	6.04	4.73	4.05	3.23	4.15
5.95	5.57	5.77	6.33	5.48	6.31	5.23	4.25	3.73	4.58
6.45	5.74	6.27	6.51	5.98	6.55	6.73	4.77	4.23	4.88
7.95	6.35	7.77	7.03	7.48	7.13	8.23	5.25	4.73	5.28
9.45	6.79	9.27	7.54	8.98	7.56	9.73	5.65	5.23	5.56
10.95	7.10	10.77	7.90	10.48	7.95	11.23	6.07	6.23	6.08
12.45	7.30	12.27	8.27	11.98	8.21	12.73	6.39	7.23	6.51
13.95	7.61	13.77	8.45	13.48	8.43	14.23	6.60	8.23	6.88
15.45	7.81	15.27	8.64	14.98	8.66	16.73	6.94	9.23	7.12
17.95	8.21	17.77	8.82	17.48	8.88	18.73	7.16	10.73	7.51
19.95	8.41	19.77	8.99	19.48	9.06	20.73	7.30	12.23	7.77
21.95	8.56	21.77	9.19	21.48	9.18	22.73	7.55	13.73	8.06
						24.73	7.78	15.23	8.39
						26.73	7.90	16.73	8.57
						28.73	8.01	18.23	8.78
						30.73	8.13	22.23	8.94
								23.23	8.99

Table 8- Flow rate values of the three hydroxyapatite-doped filters

Filter One		Filter Two		Filter Three	
Time(h)	Volume(l)	Time(h)	Volume(l)	Time(h)	Volume(l)
0.75	1.18	0.90	1.26	0.72	1.44
1.00	1.83	1.15	1.53	0.97	1.92
1.25	2.20	1.40	1.73	1.22	2.33
1.50	2.54	1.65	1.93	1.47	2.69
2.00	3.17	2.15	2.29	1.97	3.35
2.50	3.71	2.65	2.58	2.47	3.85
3.00	4.18	3.15	2.86	2.97	4.36
3.50	4.61	3.65	3.12	3.47	4.76
4.00	4.98	4.15	3.28	3.97	5.08
4.50	5.31	4.65	3.61	4.47	5.45
5.00	5.61	5.15	3.77	4.97	5.74
5.50	5.87	5.65	3.92	5.47	5.98
6.50	6.34	6.65	4.41	6.47	6.36
7.50	6.72	7.65	4.72	7.47	6.76
8.50	7.03	8.65	5.06	8.47	6.94
9.50	7.29	9.65	5.25	9.47	7.25
10.50	7.51	10.65	5.43	10.47	7.43
12.00	7.77	12.15	5.78	11.97	7.62
13.50	7.96	13.65	5.95	13.47	7.81
15.00	8.12	15.15	6.13	14.97	7.97
16.50	8.26	16.65	6.32	16.47	8.15

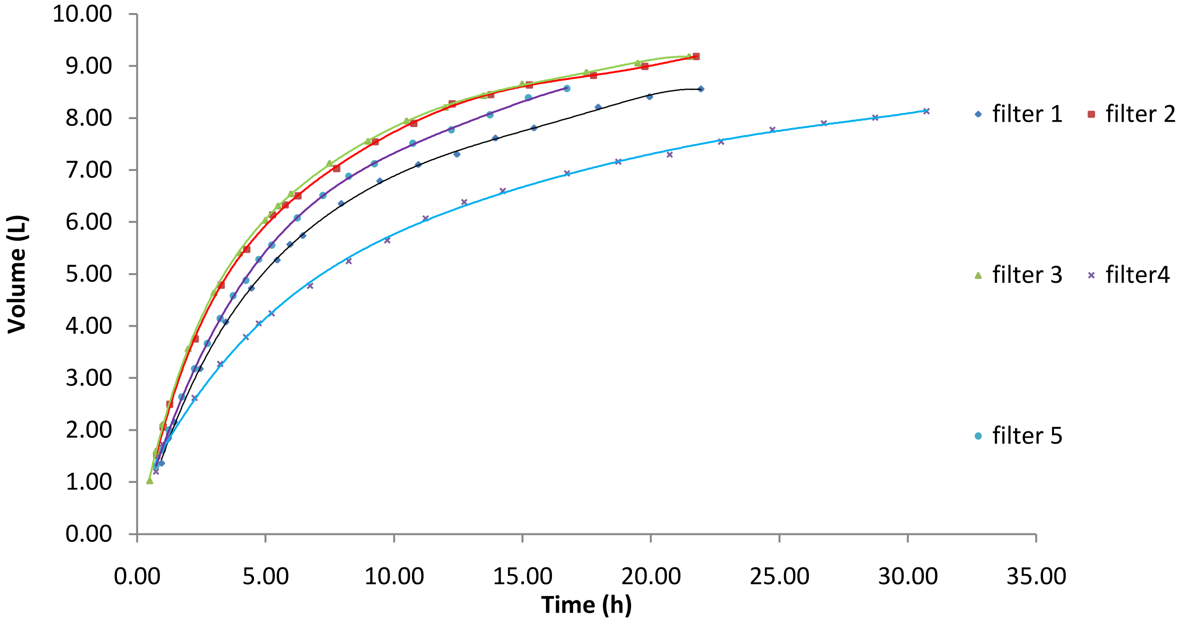


Figure 4.1.0- Volume (L) of water collected versus time (flow characteristics) of the five filters without hydroxylapatite.

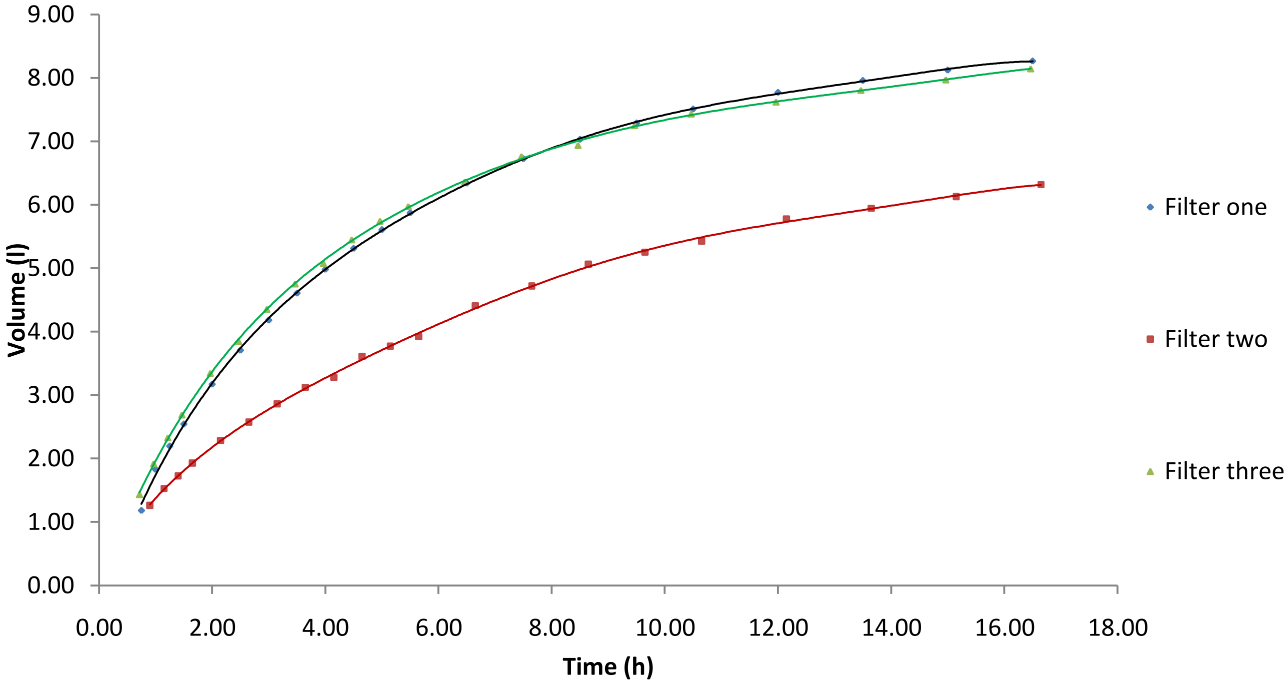


Figure 4.1.1- Volume (L) of water collected versus time (flow characteristics) of the three filters with hydroxyapatite.

The flow rate of the ceramic silver impregnated clay filter is basically dependant on the nature of the pores in the filter (Hangan et al., 2009). As the pores become bigger and more connected, the water finds it easy to flow through, therefore causing the flow rate of the filter to increase. The pores in these filters are created by the combustible material (for this project, sawdust), used in the manufacture of the filter. During the firing process, the sawdust is burned out, creating pores and cavities through which the water can flow through. According to the Potters for Peace (PFP) filter design standards, filters that have a flow rate of between one and two (1-2) liters per hour are the best and filters that have flow rate within this range have their pores sizes determined as 1 μm (Lantagne 2001a).

The results obtained for the flow characteristics experiment, shows that all the eight filters that were used in the experiment met the pore requirement of the PFP filter standards, since they all had their flow rate between 1-2 liters per hour (L/h). It can also be observed from the graphs that, the flow characteristics of the filters followed a similar trend. All the filters had their highest flow rate at the beginning of the flow rate experiment and subsequently reduced with increasing time as the level of the water in the filter reduced.

During filtration, water seeps out from the sides and the bottom of the filter. Therefore as the filter is full, larger area of the filter is covered meaning, more water gets filtered out. Also from the Darcy's equation, it is seen that the flow rate of the liquid through a porous media is directly proportional to the hydrostatic pressure difference across the specimen (ΔP). Therefore at higher levels of pressure difference, that is when the level of water in the filter is high, the flow rate will be high and likewise when the pressure difference is low, the flow rate will also reduce. Hence for the filters to work effectively in terms of the amount of water filtered water for use, the user will have to make sure that the level of water in the filter is high all the time.

4.2 Serial Experiment Results

In the serial experiments, the flow characteristics of three filters ware observed and recorded. Each filter was refilled after a successful drainage of the previous fill. At the end of the experiment, each filter was filled five different times. This experiment was used to study the effects of multiple use of the same filter on its flow characteristics. The results obtained are presented on Figure 4.2.0-4.2.2.

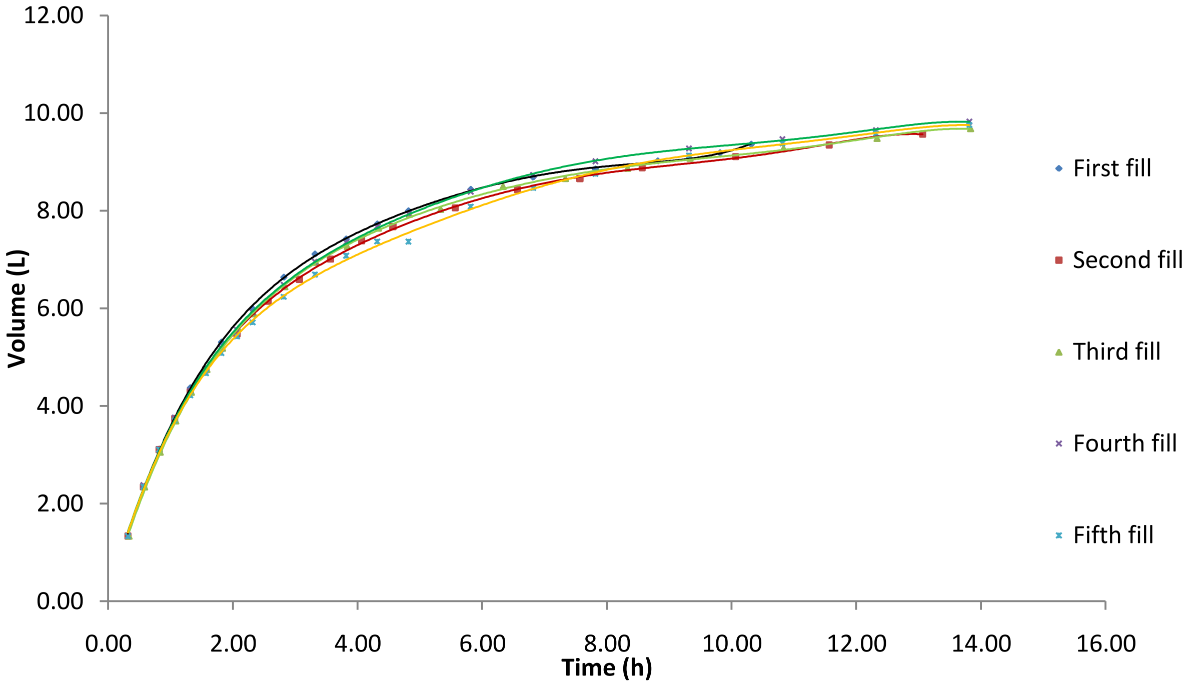


Figure 4.2.0- Volume (L) of water collected versus time (flow characteristics) of filter one for the five fills.

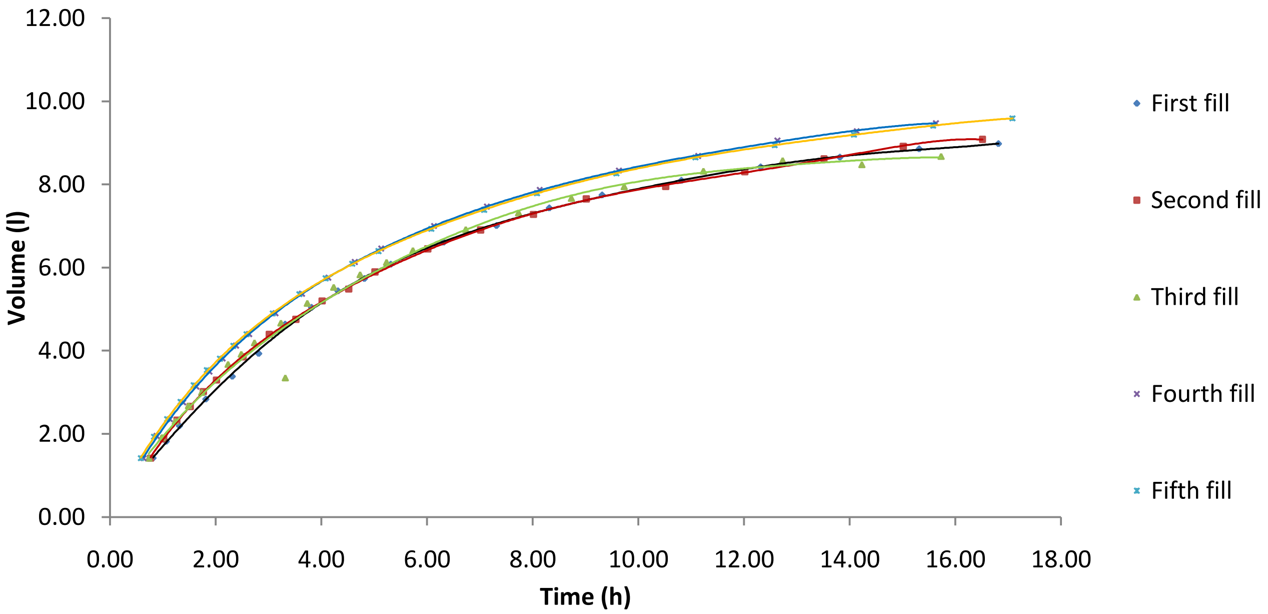


Figure 4.2.1- Volume (L) of water collected versus time (flow characteristics) of filter two for the five fills.

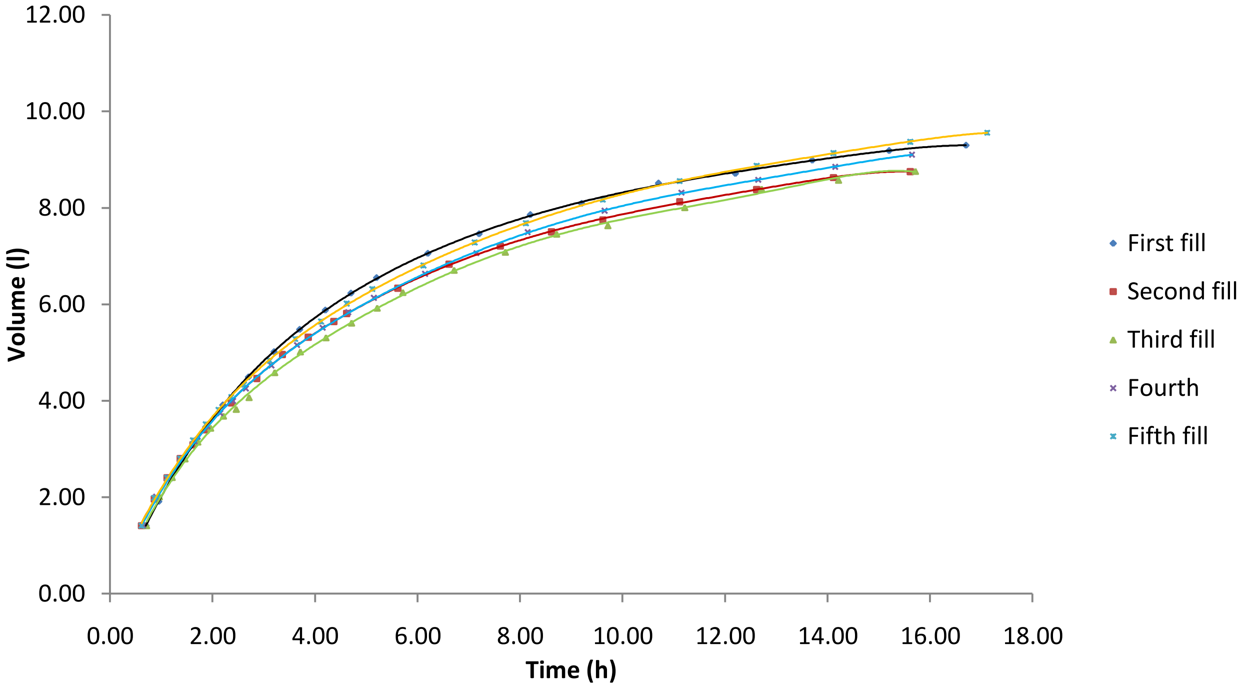


Figure 4.2.2- Volume (L) of water collected versus time (flow characteristics) of filter three for the five fills.

The results presented in Figures 4.2.0, 4.2.1 and 4.2.2 exhibit a similar trend to those observed as in the case of the filters used in the flow characteristics experiment. i.e, at high level of water head, the flow rate is high and vice versa. The second observable feature of these results is that, for each fill, the flow rate values did not show a significant difference. In the case of the second filter, as the number of fills increased, it took the filter less time to reach 1.42 the liters mark, which is the initial point of measurement for that filter. The likely explanation for this observation could be due to the fact that, the bits of clay and combustible material clogging and blocking the pores of the filter after the firing process, were pushed out as the filter was filled each time.

The possible explanation for the similarities in the obtained results for each filter for the five fills could be that, because portable tap water was used in the experiment, the water was not turbid enough to clog the pore of the filters. Van Halen showed in her study of PFP filters that, their flow rates decreased by 70-80% (discharge) after testing them for over a period of 12 weeks (Van Halem 2006).

Hence, the current results suggest that five initial filtration schedules have only limited effects on the flow characteristics, while the multiple filtration schedules conducted by Van Helem (Van Halem 2006) have a bigger effect on the flow rates. Further work is needed to explore the clogging mechanism and the effects of turbidity on the long term flow characteristics.

4.3 Scale –Up Filtration System Results

The scale-up system experiment was conducted to explore the scaling in the quantity of filtered water that can be used to provide larger quantities of water to families and communities. Two systems were developed and investigated (Figures 4.3.0). The results obtained from each system are shown below.

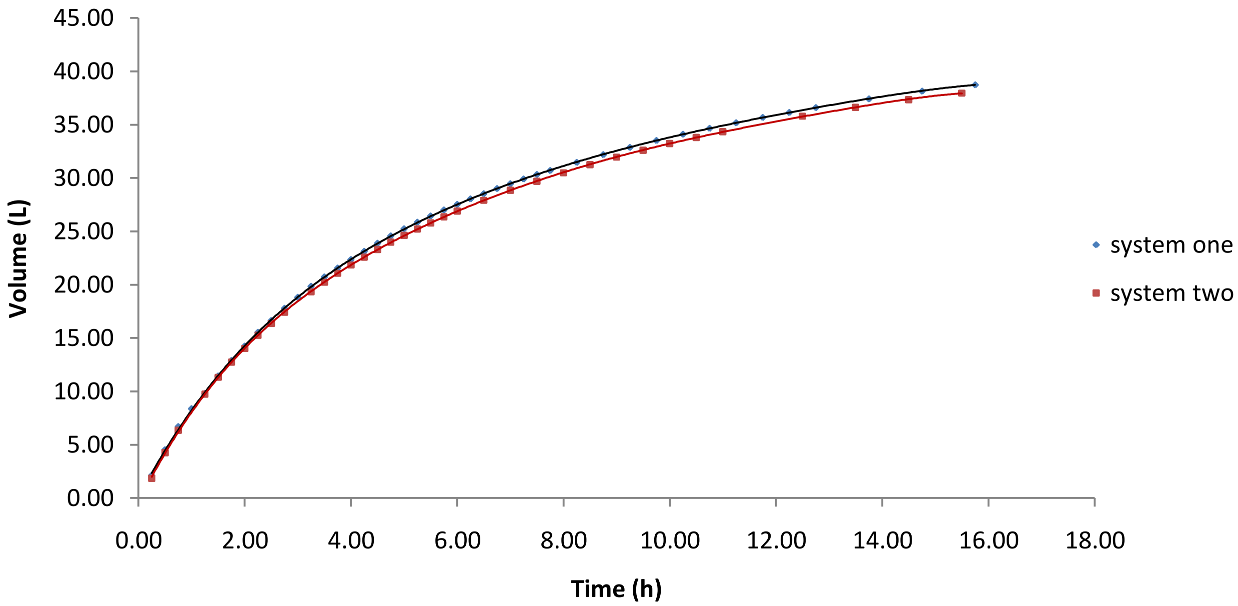


Figure 4.3.0- Volume (L) of water collected versus time (flow characteristics) of the two scale-up filtration systems.

The flow data obtained from the two systems are presented in Figure 4.3.0. These show a large increase in the flow volume, compared to that in the system with one individual filter. Furthermore, the overall flow associated with five (5) filters was approximately five times the flow in the system with one filter.

Furthermore, there was no significant difference between the overall flow characteristics of the two systems (Figure 4.3.0) that were examined in the study. The current work, therefore suggest that the overall flow rates can be scaled simply by the linear (series) stacking of the filters. Hence community-based water filtration systems of ~100-1000 filters could provide up to 4,000-40,000 liters per day of portable water.

4.4 Materials Characterization

Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD) and Energy Dispersive X-ray Spectroscopy (EDS) were used respectively, to characterise the surface morphologies, structure and composition of the raw materials and the fired clay ceramics. The XRD result for the clay raw material is presented in Figure 4.4.0.

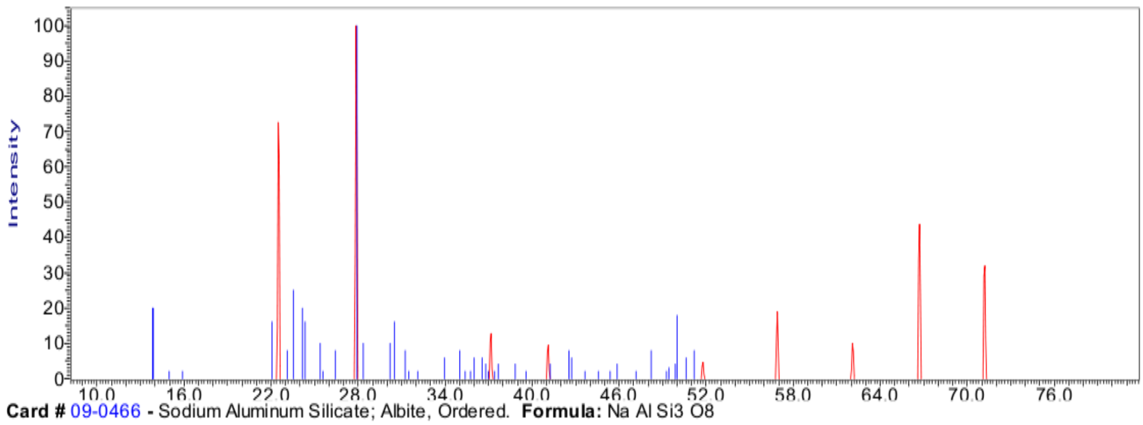


Figure 4.4.0-XRD analysis of the clay used in making the filters

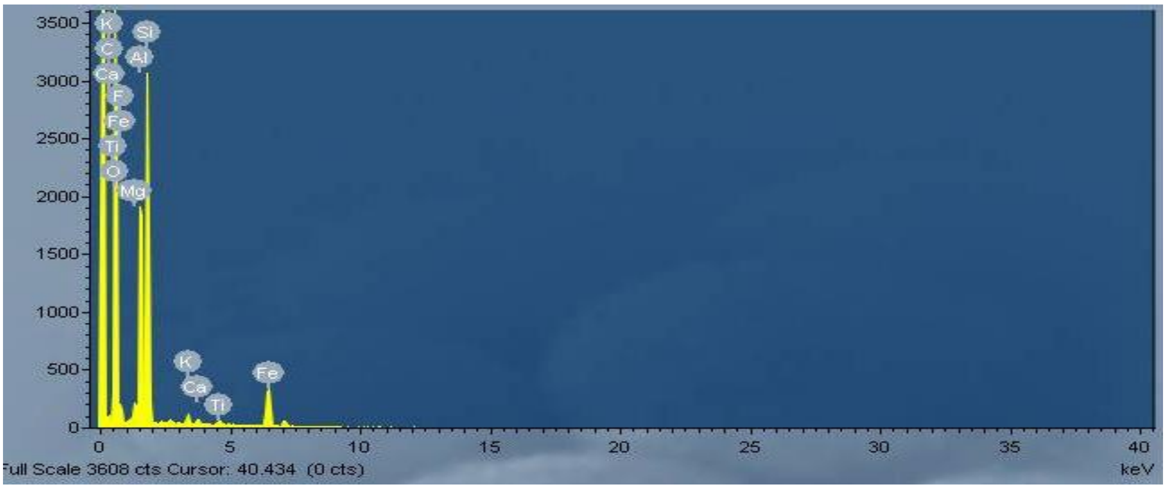


Figure 4.4.1-EDS analysis of the clay used in making the filters

The XRD analysis revealed that, the clay showed strong peaks of a sodium aluminum silicate compound know as Albite, which is a common feldspar and has the chemical formula of $NaAlSi_3O_8$. The ERD also showed some weak peaks of other elements, which were revealed by the EDS scan as Potassium (K), carbon (C), Fluorine (F), Calcium (Ca), Iron (Fe), Titanium (Ti) and Magnesium (Mg).

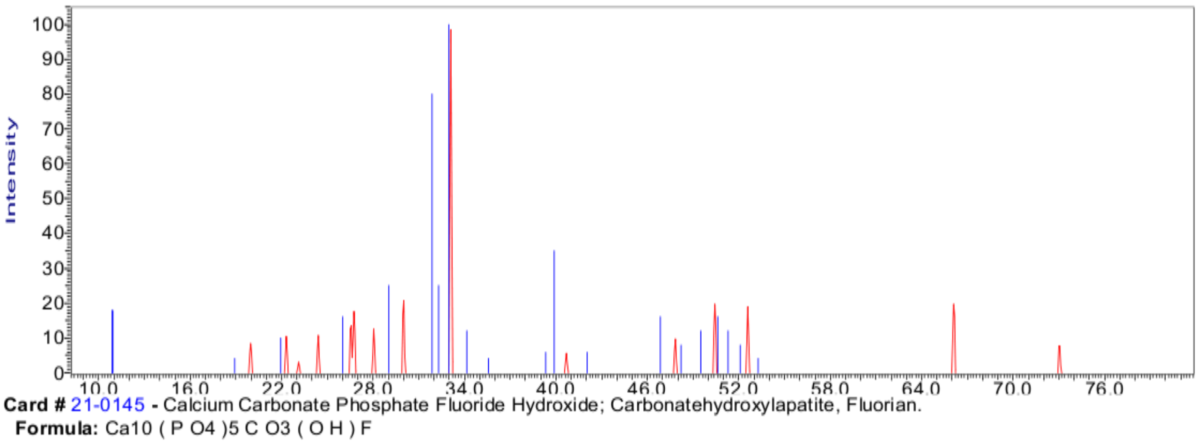


Figure 4.4.2-XRD analysis of hydroxyapatite used in doping the clay

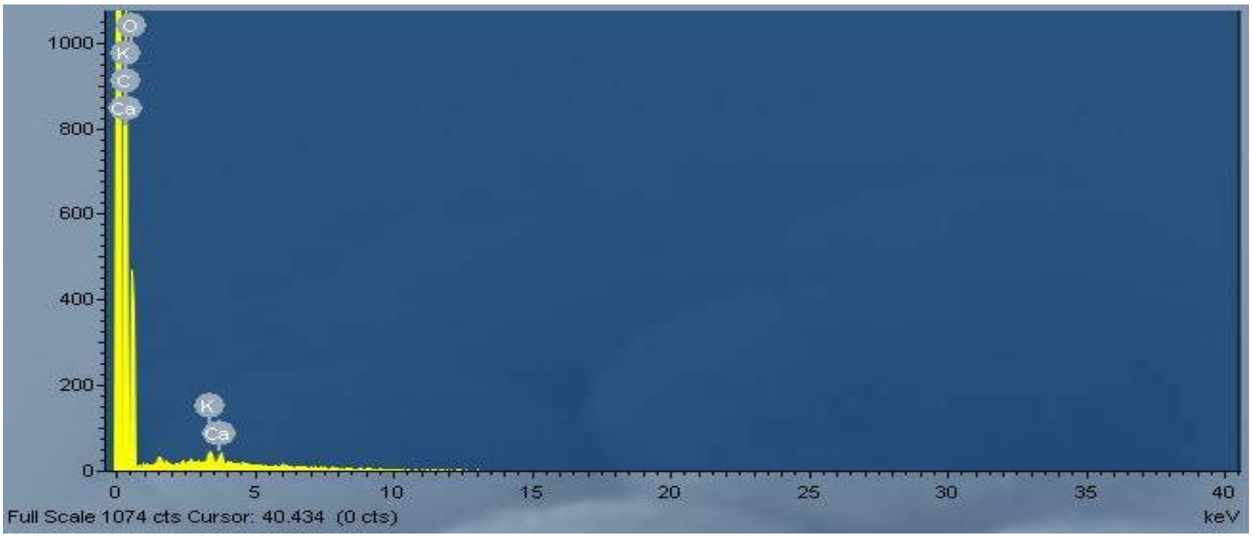


Figure 4.4.3-EDS analysis of the sawdust used in making the filters

The XRD results obtained from the hydroxyapatite that was used in doping the hydroxyapatite-doped clay filters are presented in Figure 4.4.2. The peaks correspond to the calcium apatite compound with the chemical formula Ca_5 $(PO_4)_3$ (OH). The EDS analysis of the sawdust (Figure 4.4.3) revealed elements such as like Oxygen (O), Potassium (K), Carbon (C), and Calcium (Ca).

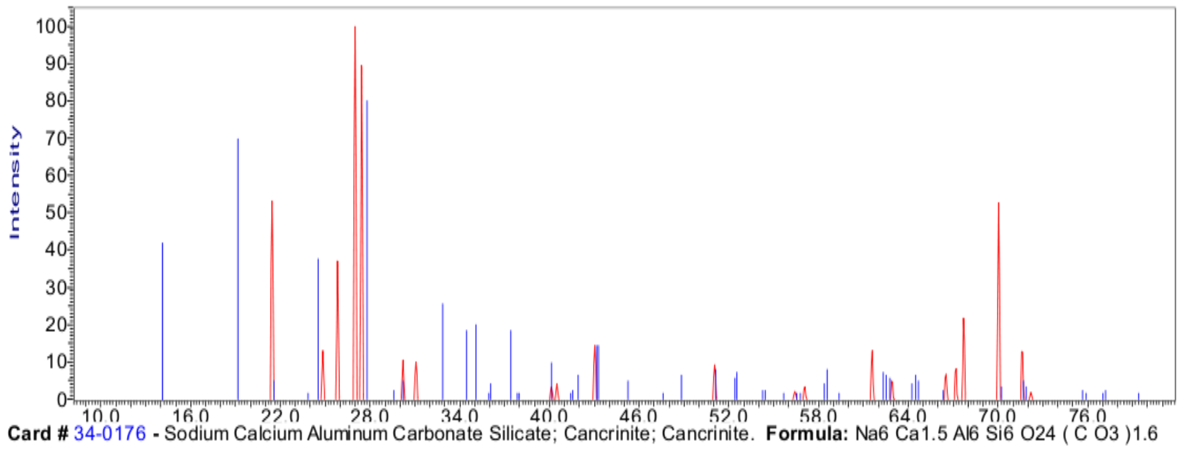


Figure 4.4.4-XRD analysis of hydroxyapatite-Doped Clay filter Material

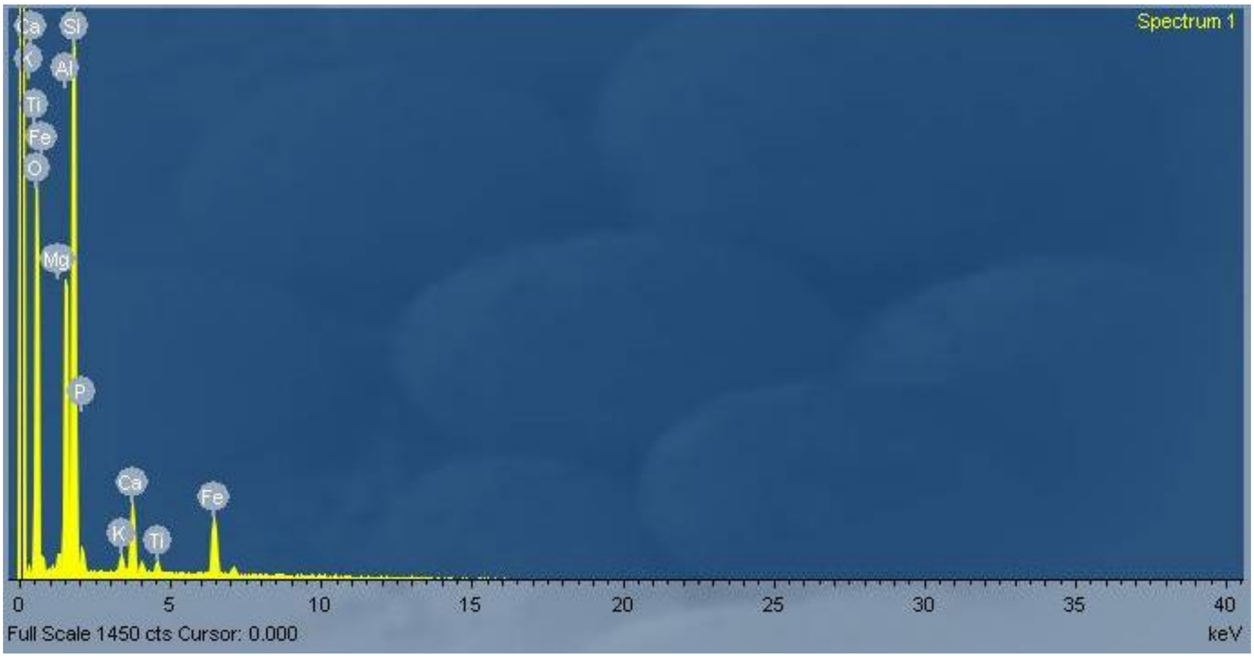


Figure 4.4.5-EDS analysis of hydroxyapatite-Doped Clay filter Material

The XRD analysis of the hydroxyapatite-doped filter shows peaks that reveal the compound cancrinite. This is a complex carbonate and silicate compound of sodium, calcium and aluminum. It has the formula $Na_6\,Ca_2\,[(CO_3Al_6Si_6O_{24})].2H_2O$ (http://en.wikipedia.org/wiki/cancrinite). There were a few weak peaks that were not identified in the XRD scan. The EDS analysis of the hydroxyapatite-doped filters also revealed evidence of Potassium (K), Titanium (Ti), Iron (Fe), Magnesium (Mg) and Phosphorus (P). All the elements identified both in the EDS and XRD scan of the filter sample were also found in the clay analysis, expect for phosphorus, which is found in the hydroxyapatite.

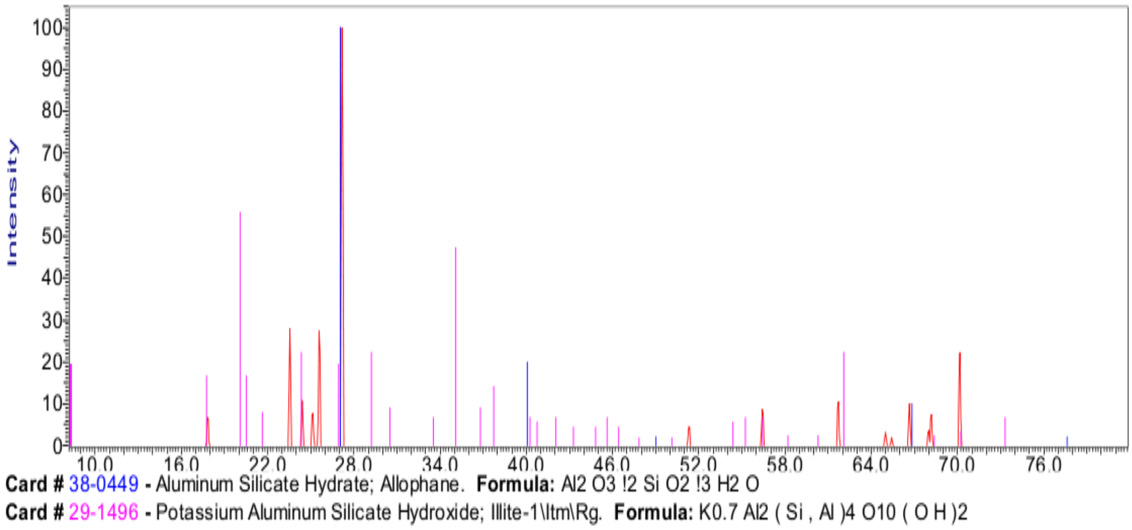


Figure 4.4.6-XRD analysis of the finished filter without hydroxyapatite

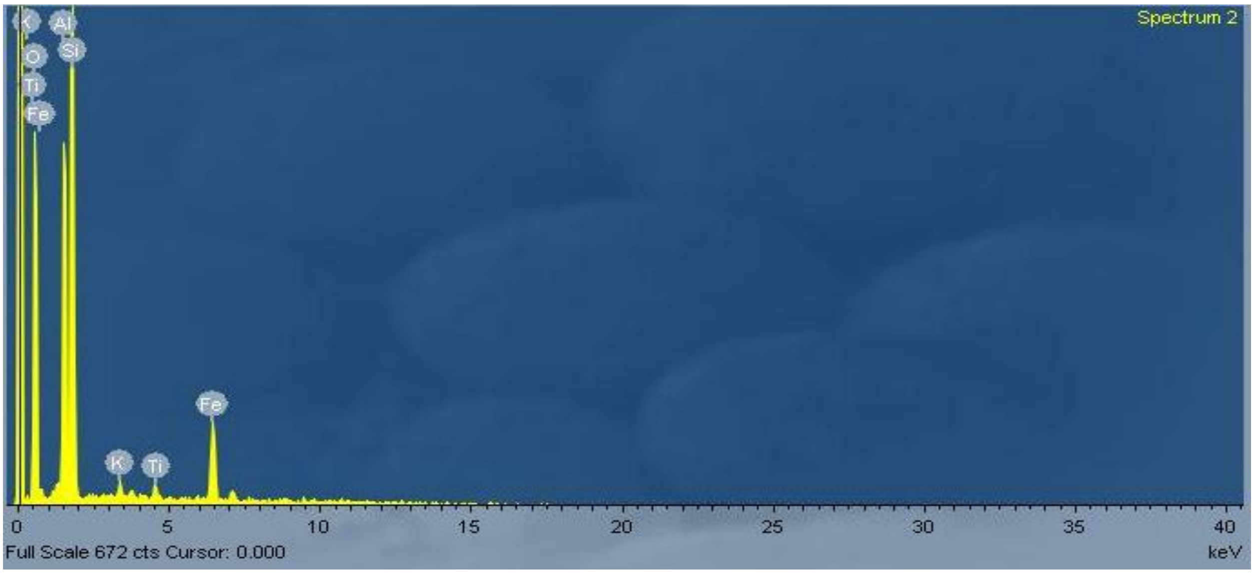


Figure 4.4.7-EDS analysis of the finished filter without hydroxyapatite

In the XRD analysis of the filter without hydroxyapatite, two major compounds were found. The first one being Allophane, is an amorphous hydrous aluminum silicate clay mineral with the formula $Al_2O_32SiO_23H_2O$. The second compound identified in the XRD peaks is a potassium aluminum silicate hydroxide compound with the formula $K_{0.7}Al_2(SiAl)_4O_{10}(OH)$. The EDS analysis also revealed the presence of Titanium (Ti) and Iron (Fe).

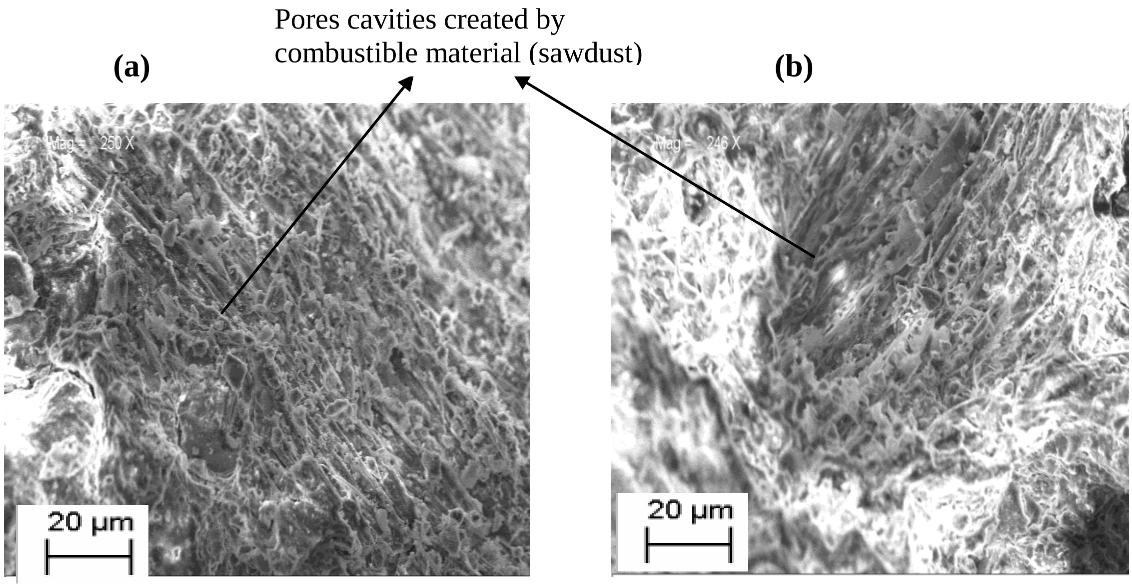


Figure 4.4.8-SEM Images of: (a) Filter With Hydroxyapatite (At Magnification of 250X) and (b) Filter Without Hydroxyapatite at Magnification of 248X

SEM images of the two types of filters are presented in Figure 4.4.8. The two materials have similar layered microstructure morphologies. There was also evidence of porosity and some inclusion particle formation on the surface of the two filters.

4.5 E.coli Tests

The results from the E.coli test are presented in Figures 4.5.0 and 4.5.1.

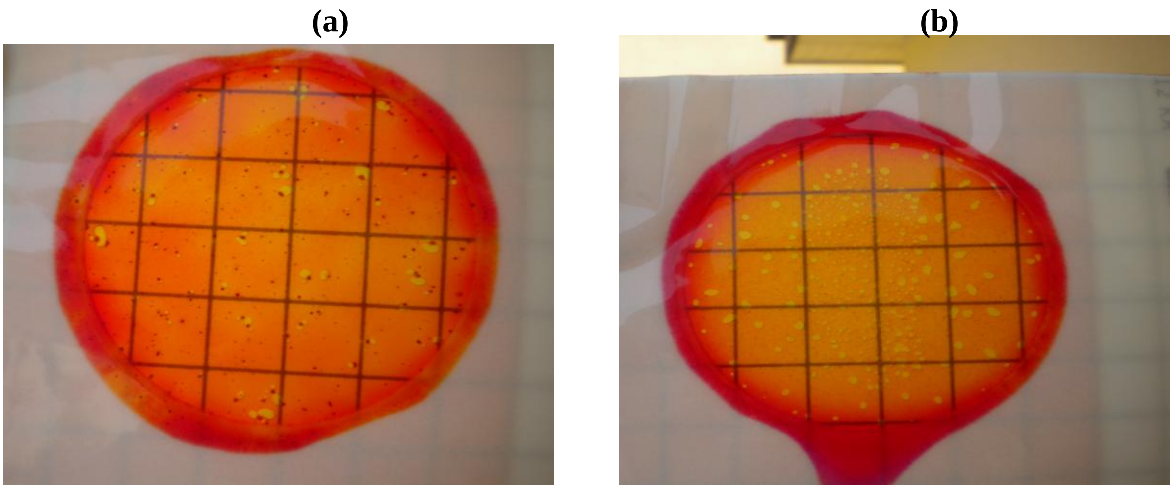


Figure 4.5.0- An image of the E.coli test of: (a) 1 ml pre-filtered water and (b) 1 ml of filtered water, showing the colony forming units (CFU)

(a) (b)

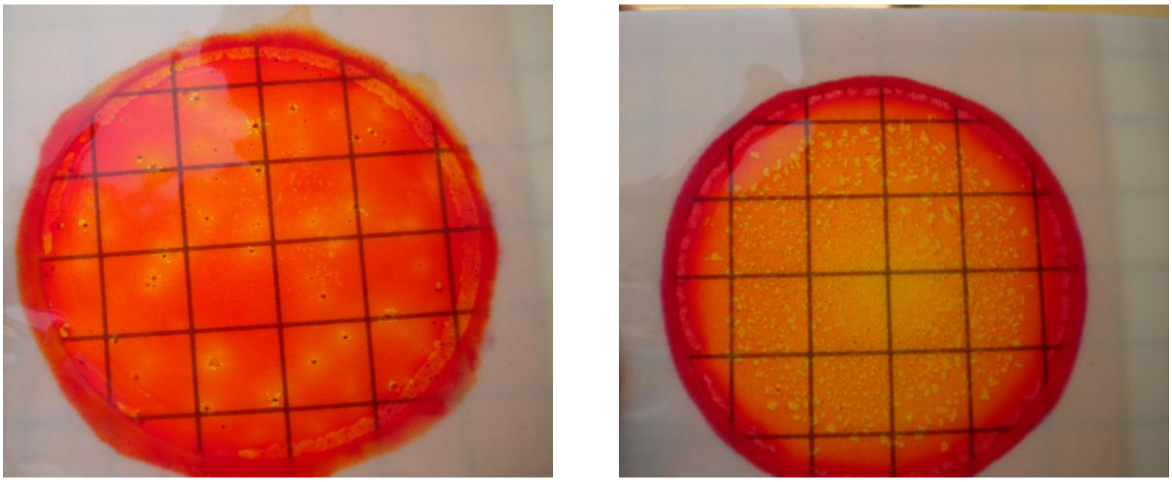


Figure 4.5.1- An image of the E.coli test of: (a) 0.5 ml pre-filtered water and (b) 0.5 ml of filtered water, showing the colony forming units (CFU)

The results show that there was no colony formation in the filtered water of 1 ml and 0.5 ml. However, colony formation was observed in the case of the pre-filtered water. The number of colony forming units was essentially doubled for the case of the 1 ml sample of water, compared to the 0.5 ml sample of water. Table 9 presents the number of count obtained for the five plates, and computation of the average colony forming units.

Table 9; Colony Forming Unit (CFU) count of the Five Plates used for the Pre-filtered Water of 0.5 ml

Plate one (P_1)	Plate two (P_2)	Plate three (P_3)	Plate four (P_4)	Plate five (P_5)
33	34	38	30	27

The average colony forming unit is obtained from the formula $(P_1 + P_2 + P_3 + P_4 + P_5)/5$. This is calculated as (33 + 34 + 38 + 30 + 27)/5= 31.4.

Now to obtain the results in CFU/ml, the value obtained above is multiplied by two, since half a milliliter was used. Therefore we obtain, 31.4 x 2 = 62.8 CFU/ml.

Table 10; Colony Forming Unit (CFU) count of the Five Plates used for the Pre-filtered Water of 1.0 ml

Plate one (P_1)	Plate two (P_2)	Plate three (P_3)	Plate four (P_4)	Plate five (P_5)
67	49	66	63	47

The average colony forming unit is obtained from the formula $(P_1 + P_2 + P_3 + P_4 + P_5)/5$. This is calculated as (67 + 49 + 66 + 63 + 47)/5= 58.4. Since the volume of the sample water in this test is 1 ml, the average value obtained above is the colony forming unit count in CFU/ml (58.4 CFU/ml).

The results obtained for the E.coli test confirms that, during the filtration of the water, all disease causing bacteria and microorganisms were removed through the mechanical screening process, since no colony forming unit was record for the filtered water (for 0.5 ml and 1 ml sample water). It can, therefore, be concluded here that, the pores that were present in the filters are significantly small to occlude disease causing bacteria and microorganisms. Furthermore, the results presented in tables 9 and 10 show that, the total colony forming unit per milliliter in the 1 ml sample water used, is approximately twice that obtained for the sample water of 0.5 ml. This therefore implies that, the amount of the disease causing bacteria and microorganisms is directly proportional to the volume of the pre-filtered water. Therefore, the more the pre-filtered water ingested, the more disease causing bacteria and microorganisms introduced into the system.

IMPLICATION

The implication of the current work is quite significant. First of all, variability in the flow rates of the filters was noticed. This is due to the difference in the effective porosities and permeabilities and difference in initial flow rate. This difference can be attributed to the random distribution of the combustible material (sawdust) used in the fabrication of the filter. Secondly, the potential for scale-up of these filters into a system is highly possible. This therefore implies that, ability to produce large volumes of filtered water to cater for larger families and communities is possible. Therefore, continuous filtration is avoided, hence the lifetime of the filters is increased and valuable time is saved.

Thirdly, the removal of fluoride and microbes by these filters has the potential impact on the health and wealth of the people in the rural areas e.g Northern Ghana. In the case of health, there will be the increase in the life expectancy of the people since diseases like cholera, dysentery, diarhea etc, will be reduced. Also disease caused by high levels of fluorine in water like fluorosis, will also be brought to a minimal level. Hence, the people will be healthier and live longer. Concerning the wealth aspect, monies that would have been spent on the treatment of water-borne diseases, will be used to cater for other needs, therefore improving the quality of life the people live. Furthermore, since these filters are made from readily available material, enterprises for filter production can be set up by community members to create jobs and wealth for them.

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1 Conclusion

Based on the results obtained from the experiments performed for this project, the following conclusions were drawn;

1. The silver impregnated ceramic filters are more effective in terms of the amount of water filtered per unit time (flow rate), when the head water is at its highest level. It is therefore necessary to keep the head water high, so as to filter more water per unit time for use.
2. It was also realized that, these filters can have a longer life span as long as the water being filtered is less turbid. Since the clogging of the pores is reduced to a minimal level and cleaning would not be very frequent, so keeping the filter intact for a long while. The turbidity of the water can be reduced by pre-filtration with a cloth.
3. The silver impregnated ceramic filters can also be connected to form water filtration system that can produce large volumes of clean water to cater for larger families and communities.
4. It is also deduced from the water filtration system that, the amount of water produced by the system is the arithmetic sum of the individual volume of water produced by the filters used in the system. Therefore an optimal system will be one that will contain filters with high flow rate, in order to produce more water per unit time.
5. From the E.coli test and results, it can be concluded that, the silver impregnated ceramic filters are effective at removing disease causing bacteria and microorganisms.

5.2 Suggestions for Future Work

Even though the silver impregnated ceramic filters are known to remove about 99.9% of disease causing bacteria and organisms, it is also known not to be effective at the removal of viruses from filtered water. It is therefore proposed that, ceramic filters should be designed such that they will be good both at the removal of disease causing bacteria and viruses. In the larger picture, filters should be made such that, they will be able to remove toxic elements such as arsenic, zinc, and lead. These elements most often find their way into drinking water sources through leaching, erosion and bad farming practices which causes a lot of health problems.

One other issue that should be considered for future work concerning the ceramic filters has to do with their fragility. Since these filters are highly brittle, during transportation they develop hair-like cracks that affect their performance in terms of bacterial and microorganism removal. Some of them even break in the process and can no longer be used. Therefore, materials used in the making of these filters should be toughened to increase their resistance to cracking. Lastly, there is a need to study the effect of hydroxyapatite doping on the removal of fluoride from water. There is also the need to determine the lifetime of such filters.

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APPENDIX A (CHAPTER 3)

A **B**

C **D**

E

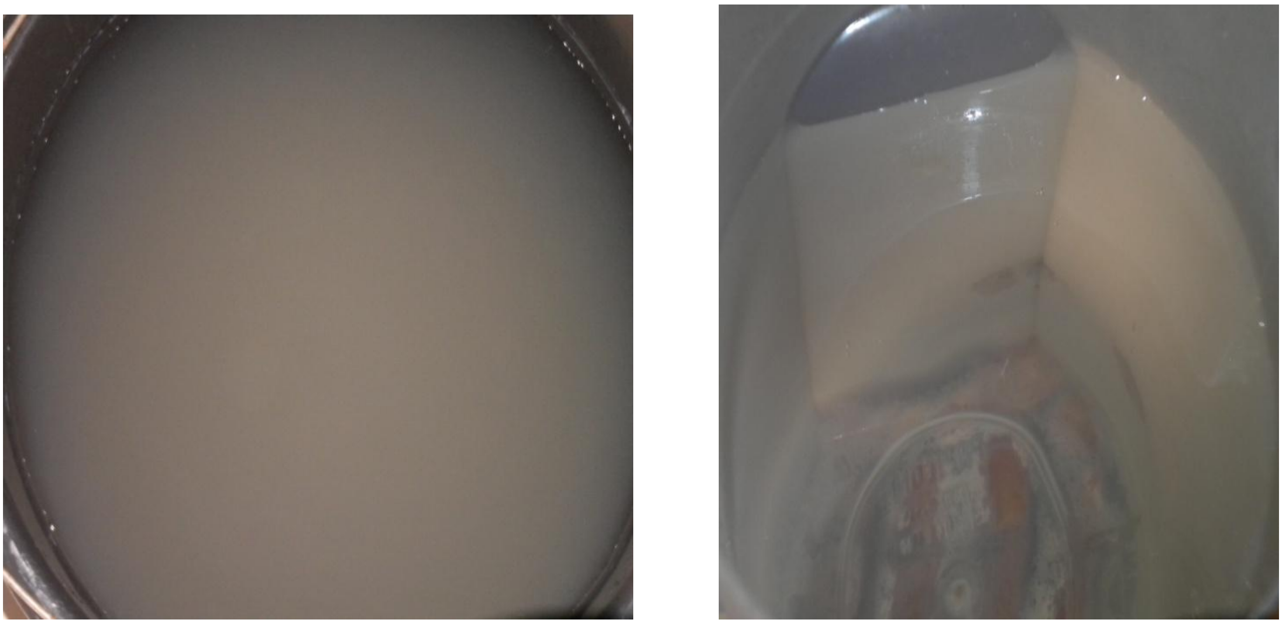
F

G

H

Figure A.1: Step by step manufacture of ceramic filters starting from mixing of raw materials

Figure A.2: Set up for the flow rate experiment.



A **B**

Figure A.3: Water before filtration (A), and water after filtration (B)

APPENDIX B (CHAPTER 4)

Table B.1: Flow rate values of the five fills for the First filter in the Serial flow experiment

First Fill		Second Fill		Third Fill		Fourth Fill		Fifth Fill	
Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)
0.32	1.34	0.32	1.34	0.33	1.34	0.32	1.34	0.32	1.34
0.57	2.33	0.57	2.34	0.58	2.34	0.57	2.38	0.57	2.35
0.82	3.12	0.82	3.11	0.83	3.06	0.82	3.11	0.82	3.11
1.32	4.37	1.07	3.74	1.08	3.70	1.07	3.76	1.07	3.71
1.82	5.31	1.32	4.30	1.33	4.28	1.32	4.31	1.32	4.22
2.32	5.99	1.57	4.75	1.58	4.75	1.57	4.77	1.57	4.67
2.82	6.64	2.07	5.48	1.83	5.19	1.82	5.18	1.82	5.09
3.32	7.11	2.57	6.15	2.08	5.59	2.07	5.56	2.07	5.43
3.82	7.42	3.07	6.59	2.33	5.89	2.32	5.92	2.32	5.71
4.32	7.73	3.57	7.01	2.83	6.45	2.82	6.49	2.82	6.24
4.82	8.00	4.07	7.39	3.33	6.95	3.32	6.95	3.32	6.69
5.82	8.44	4.57	7.68	3.83	7.27	3.82	7.35	3.82	7.08
6.82	8.69	5.57	8.06	4.33	7.65	4.32	7.68	4.32	7.37
7.82	8.85	6.57	8.43	4.83	7.93	4.82	7.94	4.82	7.37
8.82	9.02	7.57	8.66	5.33	8.03	5.82	8.39	5.82	8.09
9.82	9.19	8.57	8.88	6.33	8.50	6.82	8.73	6.82	8.47
10.32	9.36	10.07	9.11	7.33	8.66	7.82	9.01	7.82	8.76
		11.57	9.34	8.33	8.87	9.32	9.28	9.32	9.13
		13.07	9.57	9.33	9.08	10.82	9.46	10.82	9.38
				10.83	9.28	12.32	9.65	12.32	9.58
				12.33	9.48	13.82	9.82	13.82	9.76
				13.83	9.68				

Table B.2:- Flow rate values of the five fills for the Second filter in the serial flow experiment

First Fill		Second Fill		Third Fill		Fourth Fill		Fifth Fill	
Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)
0.82	1.42	0.77	1.42	0.73	1.42	0.63	1.42	0.58	1.42
1.07	1.82	1.02	1.88	0.98	1.92	0.88	1.95	0.83	1.93
1.32	2.19	1.27	2.33	1.23	2.30	1.13	2.36	1.08	2.35
1.82	2.83	1.52	2.66	1.48	2.68	1.38	2.76	1.33	2.77
2.32	3.38	1.77	3.02	1.73	3.00	1.63	3.14	1.58	3.17
2.82	3.93	2.02	3.30	3.32	3.35	1.88	3.50	1.83	3.53
3.32	4.63	2.52	3.85	2.23	3.67	2.13	3.81	2.08	3.81
3.82	5.04	3.02	4.40	2.48	3.92	2.38	4.12	2.33	4.12
4.32	5.44	3.52	4.75	2.73	4.19	2.63	4.40	2.58	4.40
4.82	5.73	4.02	5.20	3.23	4.67	3.13	4.90	3.08	4.90
5.32	6.08	4.52	5.48	3.73	5.14	3.63	5.37	3.58	5.36
6.32	6.61	5.02	5.89	4.23	5.53	4.13	5.76	4.08	5.74
7.32	7.01	6.02	6.45	4.73	5.83	4.63	6.13	4.58	6.09
8.32	7.43	7.02	6.90	5.23	6.13	5.13	6.46	5.08	6.40
9.32	7.74	8.02	7.28	5.73	6.41	6.13	7.00	6.08	6.93
10.82	8.09	9.02	7.65	6.73	6.92	7.13	7.47	7.08	7.39
12.32	8.42	10.52	7.95	7.73	7.32	8.13	7.87	8.08	7.79
13.82	8.65	12.02	8.31	8.73	7.67	9.63	8.33	9.58	8.27
15.32	8.85	13.52	8.61	9.73	7.95	11.13	8.68	11.08	8.65
16.82	8.98	15.02	8.92	11.23	8.32	12.63	9.06	12.58	8.95
		16.52	9.08	12.73	8.58	14.13	9.28	14.08	9.20
				14.23	8.48	15.63	9.48	15.58	9.41
				15.73	8.68			17.08	9.59

Table B.3:- Flow rate values of the five fills for the Third filter in the serial flow experiment

First Fill		Second Fill		Third Fill		Fourth Fill		Fifth Fill	
Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)	Time (h)	volume (l)
0.70	1.41	0.62	1.41	0.72	1.41	0.65	1.41	0.62	1.41
0.95	1.91	0.87	1.97	0.97	2.01	0.90	2.01	0.87	1.99
1.20	2.39	1.12	2.40	1.22	2.41	1.15	2.41	1.12	2.41
1.70	3.21	1.37	2.80	1.47	2.80	1.40	2.79	1.37	2.81
2.20	3.91	1.62	3.09	1.72	3.15	1.65	3.16	1.62	3.18
2.70	4.49	1.87	3.40	1.97	3.43	1.90	3.47	1.87	3.51
3.20	5.02	2.37	3.96	2.22	3.68	2.15	3.74	2.12	3.81
3.70	5.48	2.87	4.46	2.47	3.82	2.40	4.00	2.37	4.08
4.20	5.88	3.37	4.96	2.72	4.07	2.65	4.26	2.62	4.34
4.70	6.23	3.87	5.32	3.22	4.59	3.15	4.73	3.12	4.83
5.20	6.55	4.37	5.65	3.72	5.02	3.65	5.16	3.62	5.28
6.20	7.06	4.62	5.81	4.22	5.31	4.15	5.52	4.12	5.64
7.20	7.46	5.62	6.33	4.72	5.61	4.65	5.84	4.62	6.02
8.20	7.86	6.62	6.83	5.22	5.92	5.15	6.14	5.12	6.32
9.20	8.09	7.62	7.21	5.72	6.25	6.15	6.64	6.12	6.81
10.70	8.51	8.62	7.50	6.72	6.71	7.15	7.06	7.12	7.28
12.20	8.71	9.62	7.75	7.72	7.08	8.15	7.50	8.12	7.68
13.70	8.99	11.12	8.13	8.72	7.46	9.65	7.94	9.62	8.17
15.20	9.19	12.62	8.38	9.72	7.63	11.15	8.32	11.12	8.56
16.70	9.30	14.12	8.63	11.22	8.01	12.65	8.58	12.62	8.87
		15.62	8.75	12.72	8.39	14.15	8.85	14.12	9.14
				14.22	8.58	15.65	9.10	15.62	9.37
				15.72	8.76			17.12	9.56

Table B. 4: Flow rate values of the two systems in the scale-up experiment

System One		System Two	
Time (h)	Volume (l)	Time (h)	Volume (l)
0.25	2.13	0.25	1.86
0.50	4.53	0.50	4.27
0.75	6.70	0.75	6.36
1.00	8.38	1.25	9.75
1.25	9.82	1.50	11.33
1.50	11.44	1.75	12.74
1.75	12.89	2.00	14.03
2.00	14.24	2.25	15.27
2.25	15.54	2.50	16.36
2.50	16.64	2.75	17.42
2.75	17.79	3.25	19.34
3.00	18.82	3.50	20.24
3.25	19.86	3.75	21.07
3.50	20.73	4.00	21.85
3.75	21.57	4.25	22.59
4.00	22.36	4.50	23.32
4.25	23.13	4.75	23.99
4.50	23.89	5.00	24.64
4.75	24.58	5.25	25.23
5.00	25.25	5.50	25.80
5.25	25.86	5.75	26.37
5.50	26.45	6.00	26.91
5.75	27.01	6.50	27.92
6.00	27.54	7.00	28.86
6.25	28.05	7.50	29.70
6.50	28.54	8.00	30.50
6.75	29.02	8.50	31.26
7.00	29.47	9.00	31.96
7.25	29.92	9.50	32.61
7.50	30.34	10.00	33.23
7.75	30.71	10.50	33.80
8.25	31.47	11.00	34.35
8.75	32.20	12.50	35.80
9.25	32.88	13.50	36.64
9.75	33.52	14.50	37.35
10.25	34.12	15.50	37.97
10.75	34.67		
11.25	35.19		
11.75	35.69		
12.25	36.15		

12.75	36.61		
13.75	37.43		
14.75	38.15		
15.75	38.75		