UNIVERSITY OF NAIROBI

NANOPOROUS CERAMICS FILTERS FOR WATER PURIFICATION

BY

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DECLARATION

I declare that this thesis is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has been properly acknowledged and referenced in accordance with the University of Nairobi's requirements.

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DEDICATION

This study is dedicated to my lovely wife Faith, my daughter Mary and my dad Ndungu.

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ABSTRACT

Clean water is a necessity for healthy human beings so is its provision and access. This study was undertaken to evaluate the performance of ceramic water filters in reducing the *E. coli* in contaminated water. The effect of firing temperature and volume porosity (P) of a disc-type ceramic water filter on the filtration and *E. coli* removal efficiency is presented. The porosity of the ceramic water filters was varied by changing the percentage of sawdust added in the red clay and measured by the absorption test method using Archimedes' principle and the *E. coli* were tested using the membrane filtration procedure. Modulus of rupture (representing the mechanical strength) of the filters was also determined by use of an Instron 1185 compression/tension testing machine.

The porosity of the filters was found to be directly proportional to the percentage of the sawdust. The filtration rate of water increased with the increase in the porosity of the disc ceramic water filters. The strength of the filters, on the other hand, was inversely proportional to the amount of sawdust added to the clay. Ceramic water filters designs (clay to sawdust ratio 60:40, 55:45, 50:50 and 45:55) fired at 950 °C for five hours had total *E. coli* removal efficiency of 99.99, 99.98, 99.97 and 86.76 percent respectively.

Alterations in filter's design or raw materials plus the firing temperature affected the performance of the produced ceramic disc water filters. The results of this study suggest that the mean flow rate for a properly functioning filter (50% sawdust) fired at 950 ^{o}C is 1.7 L/h. This flow rate is more than 2.9 litres per day as recommended by World Health Organization on average conditions. This filter also removed more than 99.97% of *E. coli*.

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LIST OF ABBREVIATIONS

ASP	Automated Standard Porosimeter
CFU	Colonies Forming Units
CWF	Ceramic Water Filter
DCWF	Disc Ceramic Water Filter
MCA	Minimum Contact Area
MDGs	Millennium Development Goals
NTU	Nephlometric Turbidity Unit
PFP	Potter-for-peace
POU	Point-of-Use
RWD	Rural Water Development
SCE	Stress Concentration Effect
SODIS	Solar disinfection
UPV	Ultrasonic Pulse Velocity
UV	Ultra-violet
WHO	World Health Organization
%WA	Percentage Water Absorption

LIST OF SYMBOLS

P	Volume Porosity
Q	Flow rate of water
μ	Coefficient of dynamic viscosity
L	Thickness of the filter
Δp	Pressure difference
S_c	Liquid sorption coefficient
ρ_L	Density of water
γ	Surface tension
ε^*	Effective sorption porosity of the sample
λ	Average tortuosity of the capillaries
r_o	average pore radius
θ	Contact angle
m^*	Change of weight of the liquid
t	Time
V_L	Ultrasonic pulse velocity in porous material
V_{Lo}	Ultrasonic pulse velocity of the filter at zero porosity
ΔV	Change in the ultrasonic pulse velocity
ρ_B	Bulk density of sample
ρ_s	Density of pure solid
ρ_a	Density of air
Γ	Turbidity
λ_o	Wavelength of the incident radiation in vacuum
$< (\delta n)^2 >$	The fluctuation average
η	Reflective index

a_c	Absorption
k	Permeability of the material
A	Surface area of disk ceramic filter
Q_b	Flow rate of water through the bottom of Pot like filter
Qs	Flow rate of water through the sides of Pot like filter
Q_c	Flow rate through candle membrane (m^3/s)
Q_d	Flow rate through disk membrane (m^3/s)
h(t)	Height of water above the base of the filter at a given time
g	Acceleration due to gravity
R_i	Rate of mass in an isolated system
R_o	Rate of mass out of an isolated system
R_a	Rate of accumulation of mass
V	Velocity of water flow
ν	Volume of water
p_t	Total fluid pressure
P_{atm}	Atmospheric pressure
z	Change in height while the water is flowing out of the filter
α	Coefficient of volumetric flow rate
σ	Strength of the filter
σ_o	Strength of a fully dense filter material
b	Empirical parameter
Ø	Orientation of the pores
P	Volume fraction
W_s	Saturated weight of disc ceramic filter
W_d	Dry weight of disc ceramic filter

V_{op}	Volume of open pores
V_b	Sample bulk volume
D_{rolls}	Distance between supporting rolls
F_L	Fracture load
d_c	Average diameter of the candle water filter
d	Diameter of a cylindrical specimen
ψ	Number of indicator organisms per 100 ml
Y	Number of indicator organisms counted
m_{ls}	Mill liters of sample per 100 ml
C	Percent of sawdust
D	Diameter of a disk ceramic water filter

CHAPTER ONE: INTRODUCTION

1.0 BACKGROUND

Access to safe drinking water and appropriate sanitation are both essential to life and health. The human rights to water are indispensable for leading a life of dignity. It is a pre-requisite for the realization of other human rights [UNDP, 2007]. The lack of safe water supply is one of the world's major causes of preventable morbidity and mortality. World Health Organization [WHO] data on the burden of disease estimates that approximately 1.8 million of deaths per year and 61.9 million of disability adjusted life-years worldwide are attributed to unsafe water, sanitation and hygiene occur in developing countries [WHO/UNICEF, 2004: Nath *et al*., 2006]. WHO also estimates that 884 million people (13% of the world population) live without access to an improved water source that provides 20 litres of water per person per day, within 1 km of the person's residence [WHO, 2008]. On the other hand, many of the 5.8 billion people who have access to an improved water source may face problems from contamination at the source, contamination in the piped distribution system, and/or recontamination in the home because of improper handling and storage [Erin *et al.*, 2011]. Industrial activities witnessed in the last few years have also increased the level of organic contaminants in natural waterways presenting toxicological hazard to plant and animal's life.

Infectious diseases caused by pathogenic bacteria, viruses and protozoa or parasites are the most common and wide spread health risk associated with drinking water [WHO, 2008]. The major pathogens that cause waterborne diseases are: bacteria (e.g. salmonella, shigella-causing bacillary of dysentery, cholera) whose diameter varies between 0.3 to 100 µm, viruses (hepatitis A, hepatitis E, rotavirus) whose diameter is much smaller than bacteria, ranging from 0.02 to 0.3 μm, protozoa (cryptosporidium, giardia, toxoplasma) whose diameter range from a few micrometers to several millimeters and helminths [WHO/UNICEF, 2014].These pathogens can infect humans via ingestion, inhalation or contact with skin, wounds, eyes, or mucous membrane [WHO/UNICEF, 2014]. These pathogens are responsible for thousands of diseases such as diarrhea, intestinal worms, trachoma, schistosomiasis, cholera, amebiasis, giardiasis, stunting and many more [Mattelet, 2006], and thousands of deaths each year.

In developing countries of Africa, over 35% of the population suffers from diseases related to unsafe water supply and sanitation [WHO, 2008]. Millions of children in Africa lack even the bare minimum of safe water they need to live [WHO/UNICEF, 2004], while a child dies every hour in Africa from diarrhea and other water borne diseases. The lack of safe water continues to be one of the major causes of diarrheal diseases and deaths in both developed and developing nations [WHO/UNICEF, 2004].

Although Kenya has rich water resources, the failure to achieve safe water and sanitation is one of the biggest tragedies of the nation. About 31% of Kenyans depend on tap water, (household or communal tap), while 37% obtain water from an open spring, stream or river. The rest get water from wells, water vendors or other sources [CBS, 2004]. WHO estimates that in 2002, 38% of Kenyans who live in urban area lacked access to safe drinking water while in rural areas the number increased to 54% [WHO/UNICEF, 2004]. WHO also indicates that in 2012, 62% of Kenyans (82% in urban area and 55% in rural areas) had access to improved drinking water sources [WHO, 2014]. About 19% of Kenyans (44% in urban areas and 13% in rural areas) are reported as having access to piped water through a house or yard connection [WHO/UNICEF, 2014].

Most Kenyan rural communities rely on either surface water (streams, rivers and surface wells) or ground water for their drinking and domestic water sources [Albert *et al.*, 2010]. For communities prone to annual floods, e.g., along rivers Nzoia, Nyando and others, microbial contamination of drinking water is very common. Additionally, large numbers of urban households are not connected to public sewage through cesspools, septic tanks or directly to nearby streams. The public sewage may contaminate the shallow groundwater from which some of the utilities draw their potable water supply. Even for urban households, piped water is still not safer for drinking. The World Health Organization (WHO) also estimates that in 2004, 52% of Kenyans did not have access to improved sanitation. In rural areas, 57% of people lacked sanitation coverage [WHO/UNICEF, 2004]. About 11% of all Kenyans use flush toilets. The most common form of sanitation facility is a pit latrine [Albert *et al.*, 2010], which is used by nearly 64% of the population, while more than 16% have no facility and defecate in the bush, a field or in the open. Apart from those that do not use a latrine, 49% share their toilet with other households [CBS, 2004]. In addition WHO also indicates that in 2012, 30% (31% urban areas and 29% of rural areas) Kenyans had access to private improved sanitation [WHO/UNICEF, 2014]. In urban areas an additional 51% of the population used shared latrines by the year 2012. Further, in rural areas, open defecation was estimated to be still practiced by 17% of the population in Kenya [WHO/UNICEF, 2014].

In addition, according to UNDP, [2007], water supply service in Kenya is poor for majority of people: approximately 57% of households use water from sources considered safe.

Sustainable access to safe water is around 60% in the urban setting with as low as 20% coverage in the urban poor settlements where half of the urban population lives [UNDP, 2007]. In rural setting, sustainable access to safe water is estimated at 40%. This is due to the inadequate sanitation services, uncontrolled disposal of excreta pollutes water sources from which poor urban dwellers draw.

Water from various sources such as ground water, surface water and rain water is used for various purposes which include drinking, recreation, fisheries, personal hygiene, and industrial production. At the same time, water is used as a medium of waste disposal, a large volume of which is domestic. Domestic waste water contains major contaminants like oxidizable organic matter, suspended materials, solids, combined nitrogen compounds, phosphates and pathogenic organisms [Evas *et al.,* 1981]. Further, industrial activities witnessed in the last few years have also increased level of organic contaminants in natural waterways [Matchere *et al.,* 1999]. This calls for deliberate efforts from the side of governments, non-governmental organizations, private sector to invest in research and implementation of simple and effective technologies.

Although the government and non-governmental organizations in Kenya, including bilateral and international donors, have been involved in the effort to provide safe water supply, new methods and technologies to obtain safe drinking water need to be explored and installed to meet the Millennium Development Goals (MDGs) by 2015. These methods need to reduce the number of deaths and also reduce the burden caused by diseases.

In this study, we explore the use of water Purification Systems at the point-of-use using ceramic filter membranes based on porous ceramics to filter microbes from drinking water.

1.1 Statement of the Problem

Notably, the efficiency and effectiveness of ceramic water filters is based on the type of clay material used, processing parameters and the type of filter design [Yakub *et al.*, 2013]. One of the most important parameters is porosity. Whereas, a lot of studies have focused on clay-based water filters, little work has been done on filters (based on local clay materials) that provide safe water for human consumption hence reducing deaths and diseases caused by unsafe drinking water. This study is aimed at looking into the effect of processing parameters on locally available clay materials towards design of disc based water filters with high filtration efficiency.

1.2 General objective

The study aims at developing an efficient and low cost ceramic disc water filter for water purification to provide point-of-use, robust disinfection and decontamination of water towards providing clean water.

1.2.1 Specific Objectives

The specific objectives are:

(i) To study the effect of porosity and firing temperature on the efficiency of a nanoporous ceramic disc water filter;

(ii) To optimize the physio-mechanical properties, filtration properties (filtration rate and coliform removal) and the efficiency of the nanoporous ceramic filter through control of the microstructure.

(iii) To compare the filtration rates of designed filters with theoretical models

1.3 Justification

In order to minimize water related diseases in developed and developing nations, the use of ceramic water filters have been employed to purify the briny water. Disc ceramic water filters have good filtration efficiency that are cheap and easy to fabricate using local materials which are affordable and accessible to the rural poor people as compared to the pot-like and the candle-like ceramic water filters.

CHAPTER TWO: LITERATURE REVIEW

2.1 Points-of-Use Water Treatment Systems/ Purification Methods

A number of researches (Mattlet, 2006; Clasen *et al.*, 2004; Sobey *et al.*, 2002; Kehoe *et al.*, 2001 and Nath *et al.*, 2006) have proposed point-of-use water purification systems. These points-of-use technologies offer the advantages of being easily maintained and simple to use. The points-of-use technologies cover microbiological and/or chemical or physical water treatment including [Mattelet, 2006]:

(i) disinfection (chlorination, solar disinfection (SODIS), solar pasteurization, UV irradiation with lamps, and boiling),

(ii) particle filtration (cloth fiber, ceramic filter, biosand and other slow sand filter technologies),

(iii) adsorption media (granular activated carbon, and activated alumina, clay),

(iv) combined system (combined flocculation/disinfection, filtration plus disinfection),

(v) other approaches include plain sedimentation settling, safe storage, coagulation/flocculation with iron or alum salts and membrane processes.

The points-of-use interventions have demonstrated reduced bacterial contamination in water which leads to human health improvements where they have been implemented [Clasen *et al.*, 2004; Sobey *et al.*, 2002]. Chlorination seems to be most effective against bacterial agents since median reduction in endemic diarrheal disease is 46%. Filtration technologies provide 40%, followed by flocculation and combination of flocculation/disinfection with 38% in median reduction of 35% [Clasen *et al.*, 2004].

Boiling water is a widespread practice despite its cost in both fuel and time. A temperature of 55 ^{o}C or above over a period of several hours will inactivate most bacteria [Mattelet, 2006]. Because of monitoring issues raised during the thermal process, householders are usually advised to heat to a vigorous or rolling boil. The heat-treated water should be stored in the same container it is boiled in to prevent contamination, but in practice, householders normally split it into smaller, more convenient buckets. The main drawback of handling large volumes of water is the time consuming process to cool the water and disperse it into appropriate suitable containers. Boiling does not remove turbidity in the water and if the water is not properly covered can lead to recontamination [Bielefeldt, 2009]. On the other hand, sources of energy like electricity, paraffin, solar, biogas and firewood required to boil water are very expensive to sustain for a long time. Others like firewood lead to deforestation, which causes soil erosion, draught and even destruction of the Ozone layer which in turn affects the environment.

In communities where fuel is scarce, solar pasteurization is favored instead of water boiling. Solar pasteurization in vessels painted in black or with non-reflective surfaces are low cost alternatives. Water is put into clear plastic bottles or containers and then they are exposed to sunlight. The thermal effect is increased by exposure to UV light in sunlight. However, in many regions of the world, solar radiation is not enough for much of the year to obtain temperature of 55 ^{o}C over several hours inside of the containers. By using this practice, only a small amount of water will be treated at one time, although the use of various containers and capturing more radiation with the addition of solar reflectors can increase the output of a household treatment system [Rijal and Fujioka, 2003].

SODIS - a technique developed by the American University in Beirut, Lebanon and the Swiss Institute – has improved solar disinfection by adding steps using settlement or filtration to remove turbidity and increasing the effectiveness of UV inactivation by aeration, for instance, by shaking the container to aerate the water [Kehoe *et al.*, 2001; CDC, 2008]. Increased temperatures, UV light, and oxidative chemistry inactivate most bacteria, viruses, and protozoa. The only cost for this treatment method is that of the plastic bottle. Reductions in diarrhea using SODIS vary between 9% and 86%. Although the treatment process is simple, users may be unsatisfied with the limited quantity of water produced and length of time necessary to treat water. SODIS is not effective with highly turbid water unless it is pre-treated.

The destruction of water-borne pathogens through the use of Ultra-violet light has been used for a long time but has received a particular interest since the realization that the organism protozoal cysts such as cryptosporidium or giardia presented resistance to chlorination but were sensitive to UV irradiation. However, at the household level, the routine maintenance costs and the initial cost of the system are not suitable for the implementation of the system in low income households [Nath *et al.*, 2006].

Chlorine remains the most effective and simplest chemical disinfectant for drinking water at the household level (CDC, 2008). It is available in a range of forms (e.g. pills, solution). The chlorine disinfection method is able to kill all forms of bacterial and viral water-borne pathogens. However, at low concentrations normally used for water treatment, chlorine lacks activity against protozoal cysts. The production of chlorinated disinfection by-products was for long considered as a threat to human health at high concentrations. The risk to health from these products are extremely small in comparison to the risks associated with inadequate disinfection, therefore, disinfection should not be compromised in attempting to control the disinfection by-products [WHO, 2004]. The reactivity of chlorine with any organic material can reduce its activity, if the correct chemical process is not used [Nath *et al.*, 2006].

Iodine is also effective at killing or inactivating water-borne pathogens and has been widely used for drinking water treatment for short term or emerging situations. It is sold in the form of tablets or as ion-exchange resins. Iodine treatment is not recommended for daily treatments but instead for emergency situations. The reason is that in the long run, this compound can damage health. The major problems with iodine is that it has a short contact time and poor control over the amount of iodine released which is given by the water quality and flow rates. Iodine is also known for giving an unpleasant taste to the water. Enteric viruses are more resistant than bacteria to inactivation by iodine [Mattelet, 2006].

Sedimentation is mainly used as a treatment or first stage of treatment of the water to remove inorganic materials. A few hours are required to settle larger particles whereas several days of settling are necessary for the clay particles. The main disadvantage of this technique is that the vessels that are used need to be frequently cleaned and sediments need to be removed. A pre-treatment process, sedimentation is “very cost effective requiring only a suitable vessel, labour and time” [Nath *et al.*, 2006].

Coagulation and flocculation process are important methods for water treatment. This process involves adding a coagulant to a vessel of water, mixing rapidly to spread the coagulant, and then slow stirring is required to encourage the formation of large flocs [CDC, 2008]. The flocs are positively charged and attract negatively charged colloidal particles and micro-organisms. The advantage of the method is that it makes significant improvements in terms of turbidity and removes 90-99% of pathogenic bacteria and viruses under optimum conditions. However, the drawback is that the bacteria accumulated on flocs remain viable and separation is mainly by settlement or filtration to prevent re-contamination of water [Mattelet, 2006].

Filtration covers a wide range of technologies from simple removal of large particles (including cloth or plastic gauze) to sophisticated membrane systems operating under high pressure capable of removal of particles down to the nanometer size. For domestic treatment, two general principles have been proposed [Nath *et al.*, 2006]:

(i) Straining: the sizes of the pores in the filter medium are smaller than the particle being removed. This can occur on the filter surface or within the depth of the filter wherever the water flow channels narrow to a size smaller than the particles.

(ii) Depth Filtration: occurring when particles passing through channels become trapped on the surface of the channel wall by a variety of physical mechanisms. This refers to granular media filtration [Mattelet, 2006].

Even with all these water purification methods, water may still not be safe for consumption because of different challenges facing these methods. Therefore, there is need to explore novel methods that will improve the quality of water. A key strategy for improving access to clean water is to enable households to purify water in their homes using an appropriate water treatment technology. One such technology is the use of a ceramic water filter, a porous ceramic filter treated with colloidal silver nanoparticles to act as a disinfectant. Ceramic filters effectively reduce the number of bacteria, viruses, protozoa and helminthes, making water safe for human consumption [Brown *et al.*, 2008]. Hollow candle like, pot-like and disk shaped are the common designs for making ceramic water filters [Mattlet, 2006]. Figure 2.1 shows the relative diameters of cells and microorganisms in relation to the pore diameter of ceramic water filters that are already in market.

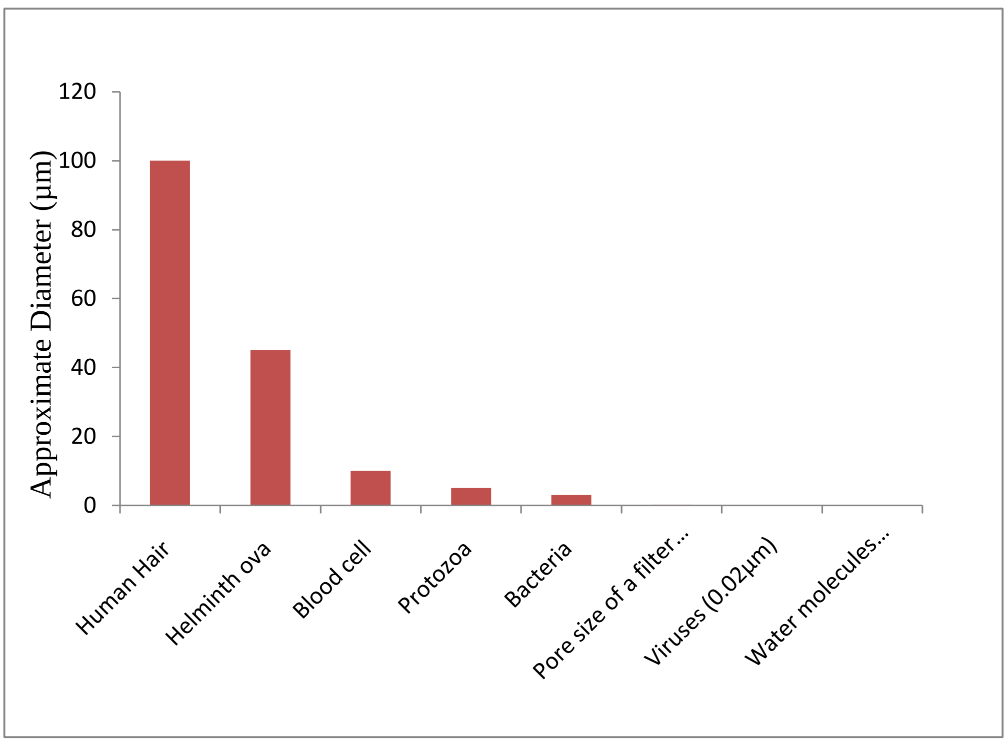

Figure 2.1: Diameters of cells and microorganisms as compared to ceramic filter pore sizes [Brown and Sobey, 2009]

Good quality ceramic water filters have micron and submicron ratings [Brown et al., 2008]. According to Hwanga, [2003] the specifications of filters include; pore size, percolation rate, physical size, manufacturing conditions and concentration of colloidal silver applied.

Studies have investigated the effectiveness of ceramic filters in improving microbiological quality of drinking water among users in the field [Clasen *et al.,* 2004; Clasen *et al.,* 2005; Clasen *et al.,* 2006]. A laboratory study has investigated issues such as flow rate, mechanisms of filtration, and different colloidal silver application to better understand how the filter functions in the field [Oyanedel & Smith, 2008]. In addition, a study assessing the performance of ceramic filters has found them to be highly effective in removing total and fecal coliforms from treated water [Clasen *et al.,* 2007]. Although it has been well documented that ceramic filters are capable of removing bacteria from water, leading to reductions in diarrhoea illness, there are still a number of factors that influence the likelihood that they will be readily adopted and prove to be a sustainable, affordable, effective means of providing safe water.

User adoption of ceramic filters generally varies between 70% [Clasen *et al.,* 2004] and 99% [Molly, 2009] during trial interventions. A South Africa/Zimbabwe study interviewed 43 of its intervention households, with just one refusing to use the filter, leading the investigators to conclude that the filters were well received during the trial [Molly, 2009]. In Cambodia, 97% of filters were in use throughout the 22-month study [Brown *et al*., 2008]. During a surprise follow up visit 16 months after filter distribution in the Dominican Republic, only 49% of filters that were still in use and operating properly [Molly, 2009]. In one Bolivian trial, 72% of filters were clearly in use at household visits during the study [Clasen *et al*., 2004].

A study conducted in different parts of Kenya show that few communities have now started engaging in ceramic water filtration and storage, but the exact figures on the usage of ceramic water filters have not yet been documented [Harvey, 2008]. The Rural Water Development Programme (RWD), located in Western Kenya, has developed a filter system called the Kisii Water Filter Bucket. The Kisii filter system is composed of two translucent food-grade polyethylene containers and a tap in the bottom container. The containers are available in local markets and are manufactured by a company called Kentainers Ltd., based in Embakasi, Nairobi Kenya [Dies, 2001].

One method to assess user acceptability is to investigate the reasons why people stop using their filters. Explanations as to why certain households discontinue filter use typically indicate that either filter hardware or personal opinions about the filter are the main causes for disuse. Some of the most commonly cited reasons why households stop using their filters is that the filter and or receptacle were broken, inability to pay for or find replacement parts and insufficient training and poor implementation [Molly, 2009].

Colloidal silver cannot easily be found by rural people in Kenya; however, its role can be replaced with solar disinfection. Materials for solar disinfection such as black fabrics, corrugated iron and clear plastics are available locally. Dies, [2001] showed that children in Kenya who put plastic water bottles on their roofs reduced incidences of diarrhea by 26%.

The results would have been better if the water was first filtered since solar disinfection may not remove pathogens hidden in the particles.

It is difficult to make accurate estimates regarding daily fluid intakes because the requirement is highly dependent on body physiology, activity level, and local climate [Molly, 2009]. An additional point to consider is the many other activities that benefit from the availability of safe water such as cooking and hygiene. When these additional water needs are factored in, the recommended minimum water requirement rise to 7.5-15 litres/person/day and is also dependent on climate, daily habits, available sanitation facilities, cultural practices and many other variables [Howard & Bartram, 2004]. Table 2.1 shows the recommended daily water consumption of adults and children in different temperatures.

Table 2.1: Recommended daily water consumption [Molly, 2009 and WHO, 2004].

		Under Average Conditions	Manual Labor in High Temperatures
Adults	Male	2.9 Litres	4.4
	Female	2.2 Litres	4.4
Children		1.0 Litres	4.4

With proper use, ceramic filters are technically capable of producing sufficient drinking water for an average five-member household. This is assuming an ideal situation where the filter is consistently refilled throughout the day (to maintain the maximum level of hydraulic head), and is cleaned and properly cared for [Molly, 2009]. Invariably, this is not the case for many filters and even to the filter users who normally forget to refill the filters consistently. This has lead to low quantities of treated water that are below the filter's maximum potential. Additionally, there are factors outside of the users' control, such as turbidity of influent water, which will affect the daily amount of water that can be filtered. It is common for a filter's flow rate to decrease over time as sediment builds up and begins to block the pores. A laboratory analysis done by Molly, [2009] found that none of the filters from his three different Potter-for-peace (PFP) projects had a flow rate greater than 0.5 litres per hour at the conclusion of their 12 week study [Molly, 2009 and Van Halen, 2006]. Similarly, the Kenya study of candle filters reported the "Doulton Super Sterasyl" filter to have an average flow rate of 0.24 litres per hour in the field when the product is advertised to have a flow rate of 1.3 litres per hour [Franz, 2005]. To prevent this type of performance reduction, users are advised to scrub their filter with a brush once it becomes noticeably slower. However, users frequently fail to scrub them as often as they should, fail to scrub them at all or fail to scrub them properly. Half of the families in one study scrubbed their filters no more than once every other week [Lantagne, 2001]. Scrubbing can substantially increase flow rate, as demonstrated when the flow rate of a filter increased from 0.28 litres per hour to 2.0 litres per hour following scrubbing in the laboratory [Molly, 2009].

Candle filters are often made by "capping" the top with a final piece of clay after the main tube or body has been pressed [Harvey, 2008]. The interface between the main body and cap is a potential pathway through which water can flow after the candle has been fired. They also require the user to screw the candle element into the upper bucket, which usually requires holding the filter element while the bottom nut is screwed into place. This puts a lot of pressure on the filter element and is a reason why the candles often break [Dies, 2001]. It may be cheaper to manufacture one disk rather than one to three candles that are typically required for a filter system.

The Potters for Peace (PFP) pot filter is difficult to transport due to weight and durability of the ceramic material [Dies, 2001]. The PFP filter has a high breakage rate, as was determined by Hwang, [2003] in her Master of Engineering thesis. The filter press mold for the pot filters is more complicated and difficult to use than for a disk filter.

In addition, manufacturing a disk is easier than a candle or pot – especially when using a press machine to compact the clay mixture. Candle and pot filters require molds whose designs are more complex than a mold designed for a disk. The flow rate per unit surface area for a disk is more efficient than for a candle filter [Harvey, 2001]. The savings on fabricating materials of the filter element (less material = less cost) helps to reduce the overall cost of the filter system.

Harvey, [2001] also noted that the ratio of the theoretical disk flow rate to candle flow rate for this example is 2.05/1.36 = 1.51, which is the same result using Equation 4.4. The ratio of Qd/Qc = 1.51 demonstrates that the disk is approximately 50% more efficient than a single candle filter, for the given example. This study is based on the investigations of the efficiency of disk ceramic water filters using locally available materials that are affordable to the poor society, and whose filtration rate is higher than that of other documented ceramic water filters.

2.2 Factors affecting filtration Efficiency

The factors that affect the efficiency of ceramic water filters include; porosity, turbidity of the water to be filtered, and the flow rate through the filter.

2.2.1 Effect of Porosity

Porosity is one of the main determining criteria that impact filter performance. High porosities in ceramic water filters is achieved by use of high percentages of burnout and also use of large particle sizes of burnout prior to firing. The most commonly used materials as burnout are carboneous materials. When the mass is fired, the carboneous matter burns out, leaving corresponding pore spaces so that the porosity of the fired mass is roughly proportional to the volume of carboneous matter added. The main combustible materials are hard wood sawdust, cork seeds, naphthalene and occasionally fine ground coke, flour, corn husks [Crimshow, 1991] and rice husks [Nardo, 2005]. Petroleum waste products may also be used. However, they burn out at higher temperatures than wooden sawdust [Kaminska and Valuikevicius, 2005]. Wood consists of volatile oils and small quantities of mineral content. The mineral matter in wood consists mostly of salts of calcium, potassium and magnesium [Kaminska and Valuikevicius, 2005]. Ash is formed from mineral matter during combustion. The ash yield has a very small proportion of 0.1% to 1% by volume which has little effect on the porosity of the ceramic and during combustion the mineral ions oxidize and volatilize or form particulates [Ragland *et al.*, 1991]. Rice husks are not the preferred choice because they have low heating value and are characterized by high ash content (18-22% by weight) [Nardo, 2005].

The size of the pores is also important in controlling the flow rate and the level of contaminant removal of the filter. Filters showing large pore sizes will not be efficient at removing turbidity and /or bacteria from water as compared filters having small pore sizes. However, as filters flow rate increases with filter pore size, these filters will allow the collection of more water per hour [Mattelet, 2006]. For high filtration rate, the porosity should be high but the pores should be very small (nano-scale) in diameter for effective filtration. The underlying principle behind the water filter is the amount and the size of combustible (sawdust) which have been milled and screened, combust in the firing furnace/kiln leaving a network of fine pores [Harvey, 2008].

The volume porosity of the filters can be determined by a number of different methods including:

(a) *Ultrasonic pulse velocity (UPV) measurements*

This is a nondestructive method which is simple, accurate and can detect size and defects [Hall and Hoff, 2010]. The relation relating ultrasonic pulse velocity to porosity is

$$V_L = V_{Lo}(1 - MP) \tag{2.1}$$

Where, V_L is the ultrasonic pulse velocity in the porous material, V_{Lo} is the ultrasonic pulse velocity of the filter at zero porosity, M is a constant which is a function of Poisson's ratio

Rearranging equation (2.1) gives

$$P = \frac{\Delta V}{MV_{Lo}} \quad (2.2)$$

Where, ΔV is the change in ultrasonic pulse velocity of the specimen

(b) Density method

Porosity is defined in terms of bulk density according to the relation [Volkovish and Sakar, 2005].

$$\rho_B = P\rho_a + (1 - P)\rho_s \quad (2.3)$$

Where, ρ_B is bulk density of sample, ρ_S is density of the pure solid, ρ_a is the density of air which is much smaller than ρ_B.

Other methods for determining porosity include gas expansion method, optical method, mercury standard porosity and the most recent is the automated standard porosimeter (ASP) which is based on the laws of capillary equilibrium [Volkovish and Sakar, 2005].

2.2.2 Water Turbidity

Turbidity is an indicator in assessing the suitability of water for human consumption [WHO/UNICEF, 2004]. It stimulates the growth of bacteria and other water pathogens [WHO/UNICEF, 2004]. Along with *E. coli*, pH and chlorine residual, turbidity is one of the key parameters of microbial water quality. It is also used to measure the effectiveness of water filtration.

High organic concentration and/or many suspended particles such as clay, silt, planktons, and other microscopic organisms and chemical precipitates will slow the flow rate of water by progressively clogging the ceramic pores. This will affect the rate of filtration [Mattelet, 2006]. Turbidity is measured by determining the degree of light scattering by particulates present in the sample [Miller, 1997]. Water to be treated by use of ceramic filters should have a maximum pre-treatment turbidity of 15-20 NTU [Van, 2006] to avoid the clogging of pores. WHO/UNICEF [2004], recommends turbidity of one Nephlometric Turbidity Unit (NTU) and up to 5 NTU.

Light scattering by transparent isotropic media is accurately described by a macroscopic fluctuation theory first formulated by Einstein [Miller, 1997]. Turbidity Γ, is dependent on fluctuations in the refractive index (or the di-electric constant) in volume, υ, according to the equation [Kabagambe, 2010];

$$\Gamma = \frac{32\pi^3 \upsilon n^2 \langle(\delta_n)^2\rangle}{3\lambda_0^4} \qquad (2.4)$$

Where λ_o is the wavelength of the incident radiation in vacuum and $\langle(\delta_n)^2\rangle$ is the fluctuation average in the reflective index n

In an absorbing media, the refractive index is complex and therefore $\langle(\delta_n)^2\rangle$ can be replaced by,

$$\langle(\delta_n)^2\rangle + \langle(a_c)\rangle \tag{2.5}$$

where, a_c is the imaginary part of the complex refractive index

The absorption coefficient a_c must be much smaller than the real part if one is to be able to detect any scattered light [Miller, 1997].

For effective filtration, the filter membrane needs regular cleaning with a specified scrubbing brush to remove deposits. Pre-treatment of water is also an important method of controlling fouling of the filter membrane [Contreras *et al*, 2009].

2.2.3 E. coli removal

Within the filter, multiple pores throughout the membrane are interconnected, forming channels that allow for the passage of water. One method of pathogen removal is to block particles and organisms that are larger in size than the pores from flowing through the outermost membrane layer (Figure 2.2a) [Doulton, 2009]. It is possible that they will adsorb on to the ceramic (Figure 2.2b) or become blocked when larger particles plug up the pores (Figure 2.2c).

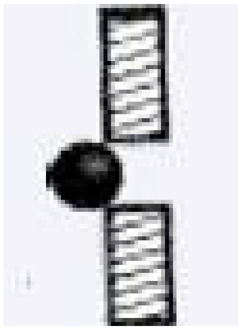

Figure 2.2a

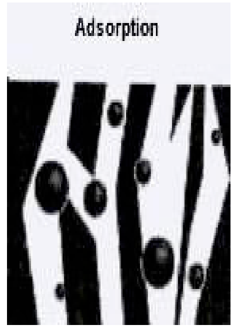

Figure 2.2b

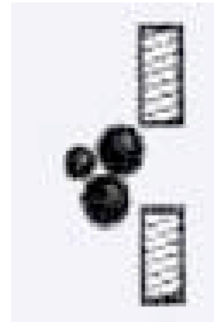

Figure 2.2c

Figure 1.2: Blockage of filter membrane by (a) Large particles [Doulton, 2009], (b) Adsorption [Molly, 2009], (c) Plugging of pores by large particles [Molly, 2009].

2.2.4 Flow rate

Water flow rate is given by equation (2.6) and it is also dependent on pore characteristics [Hagan *et al*., 2009].

$$Q = \frac{r^3 \Delta p}{3\mu}\left[1 + \frac{8L}{3\pi r}\right]^{-1} \quad (2.6)$$

where r is the radius of the pore, μ is the coefficient of dynamic viscosity, L is the thickness of the filter, Q is the flow rate, Δp is the pressure drop

The larger and more connected the pores, the easier it is for water to flow through the membrane. Adjusting pore size, will affect both flow rate and microorganism removal. Filter design variables, that are pore related and could potentially be manipulated to affect flow rate include the type of combustible material, the amount of time the clay/combustible material is mixed, the thickness of the ceramic membrane, the size of combustible material particles, and the proportion of combustible material to clay.

2.3 Factors Affecting flow rate

Porosity and permeability are important in determining the rate of fluid flow through the filter. The filtration rate through the porous filter element (Figure 2.3) was assumed to follow Darcy's law, which is given discussed in chapter 4.

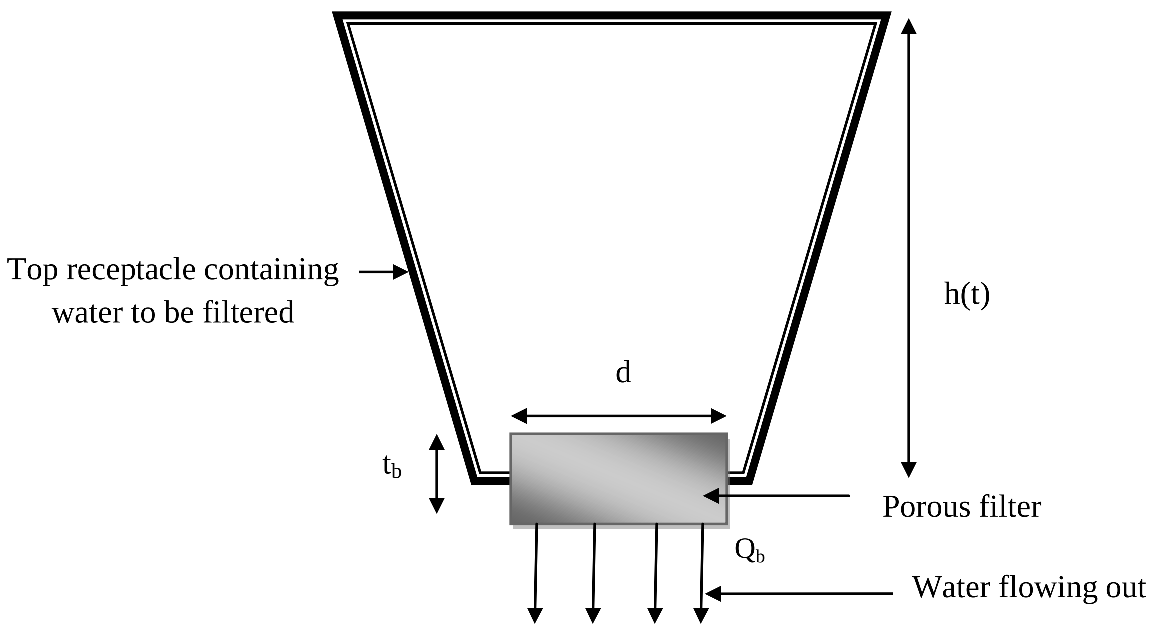

Figure 2.3: Definitional diagram showing dimensions of disc ceramic water filter

The pressure difference between the surface of water in the top bucket and the inner surface of the disc ceramic filter is equal to the hydrostatic pressure of the water. For the flow through the bottom, the difference in pressure from the inside bottom surface to the outside bottom surface is equivalent to the hydrostatic pressure of the fluid. The volume V, of the water at any given time was measured using a measuring cylinder. This volume together with the area, A, of the inside bottom of the top receptacle were used to determine the height, h(t) of the water above the filter at any given time using Equation (2.7).

$$V = \frac{1}{3} A h(t) \tag{2.7}$$

2.3.1 Thickness (t_b) and Surface Area of the disk

The thinner the disk, the higher the flow rate will be for a given water head (H) as can be seen in equation (2.6)**.** With a thin ceramic device, flow rate increases but the level of water microbiological and turbidity removal will decrease. By increasing the thickness, the tortuosity of the ceramic element increases, therefore it will retain more particles [Mattelet, 2006]. The flow rate also increases faster for a given increase in surface area since Q is proportional to the radius squared as in equation (4.10).

2.3.2 Differential pressure (Δp)

Differential pressure (Δp) is the difference between the pressure in the system before the fluid reaches the filter (upstream) and the pressure after the fluid flows through the filter (downstream pressure) [Mattelet, 2006]. In a constant flow application, the differential pressure increases as the filter begins to clog. While the water height decreases with time above the filter, the water pressure becomes smaller and therefore less water will flow through the filter. It is therefore important to maintain a certain level of water head above the filter by filling the upper vessel of the filter with water.

$$\Delta p = \rho g h(t) \tag{2.8}$$

2.3.3 Volumetric flow rate

Volumetric flow rate is dependent on the pore size of the filter, membrane surface area, and the height of the water in the filter. By use of the law of conservation of mass which states that the mass of an isolated system remains constant over time [Ileana, 2012],

$$R_i - R_o = R_a \tag{2.9}$$

Where, R_i is rate of mass in, R_o is the rate of mass out and R_a is the rate of accumulation of mass.

If the filter is filled up with water and begins to filter the water without adding any more water to the top container, then we can say that the rate of mass in is equal to zero in the above relationship. So,

$$-R_o = R_a \tag{2.10}$$

This will give us the equation that states that the density of the fluid ρ multiplied by the volumetric flow rate of the fluid out of the vessel Q equals the rate of accumulation of the liquid outside the filter with respect to time [Ileana, 2012],

$$-\rho Q = \frac{dm}{dt} \tag{2.11}$$

where m is the mass of the liquid and ρ =1000kg/m^3

Taking the mass of the liquid accumulation outside the filter equal to density ρ times the volume V in millitres of the liquid;

$$m = \rho V \tag{2.12}$$

by integrating the circular cross-sectional areas with respect to the height(z) of the water above the filter we can find the volume at any height:

$$V\ (z) = \int_0^h A dz \tag{2.13}$$

where $A = \pi r^2$.

2.3.4 Velocity of Water flow

Darcy's law states that the flow speed through a porous medium is directly proportional to the pressure gradient through that medium and to the square of the characteristic size of the pore spaces of the medium, and inversely proportional to the viscosity of the medium [Ileana, 2012].

$$v = C\Delta p \qquad (2.14)$$

where, v is the velocity of water flow, C is the proportionality constant which depends on the size proportion of the porous medium as well as on the particle shape and packing, Δp is the change in pressure

$$\Delta p = p_t - p_{atm}$$

where, p_t is the total fluid pressure and p_{atm} is the atmospheric pressure

The total fluid pressure at any point of the water level in the filtration container is equal to the atmospheric pressure pushing down on the fluid above the surface of water in the container plus the pressure of water above the filter membrane [Ileana, 2012]. Therefore,

$$p_t = p_{atm} + \rho g(h - z) \qquad (2.15)$$

where, g is the acceleration due to gravity, h is the height of water in the container and z is the change in height while the water is flowing out of the filter

Subtracting atmospheric pressure from total pressure yields

$$p_t - p_{atm} = \rho g(h - z) \qquad (2.16)$$

Using equation (2.14) with (2.16) we see that

$$v = C\rho g(h - Z) \quad (2.17)$$

If we combine density, acceleration due to gravity and the proportionality constant into the coefficient of volumetric flow rate $\alpha = C\rho g$, we obtain

$$v = \alpha(h - z) \quad (2.18)$$

Equation (2.18) is clear evidence that velocity is proportional to the difference in pressure of water above the disk filter. If the velocity increases the flow rate will also increase.

2.4 Strength of the membrane

The strength of a ceramic material is inversely proportional to the porosity of the filter [Nyongesa and Aduda, 2004] given by the relation.

$$\sigma = \sigma_o e^{-bp} \quad (2.19)$$

where σ is the flexural strength, σ_o is the flexural strength at zero porosity and b is a constant. The porosity of the filter is affected by amount of sawdust in the mixture. At very high percentages of sawdust there will be more voids created in the filter membrane and the filter might become very weak. On the other hand, if the amount of sawdust is very low, then the filter will be considered very strong but at the same time the filtration rate will be low and hence the efficiency will reduce. An optimal clay to sawdust ratio need to be achieved in order to maintain an optimal filtration rate that will give a strong filter to support the hydraulic pressure above the filter and again an optimal ratio that will give a effective filter in terms of *E. coli* removal and also filtration rate. Optimal strength will make the filter to last for a long time without breaking.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Raw Materials

Raw materials used in this study were Red clay soil and sawdust. The red clay soil was collected from Nyeri County where there is high usage of red clay in making of clay pots, building bricks and charcoal cooking stoves commonly known as "jikos". The red clay soil was dug from a free-drainage site. The clay was placed on a cemented floor where it was crushed into very tiny particles using an iron hammer; the clay was then sieved to very tiny particles less than 425µm for investigation. This was done using ten sieve arranged vertically in the ascending order of their meshes. The bottom one had meshes of 425µm in diameter which was used to determine the diameters of the soil particles.

The burnout used in this study was sawdust from a mixture of different hard wood trees. Sawdust was selected as a burnout in this study because it gives a homogenous mixture with clay, unlike with any other burnout material like coffee husks and rice husks [Molly, 2009]. Wood also consists of volatile oils and small quantities of mineral content. The mineral matter in wood consists mostly of salts of calcium, potassium and magnesium. In addition to this, hard wood is preferred to soft wood sawdust because it does not bloat as much as sawdust from other woods, thus leading to filters having more uniform pores and fewer defects [Kabagambe, 2010]. The sawdust was collected in large quantities from Shabab millers in Nakuru and then sieved to very tiny particles less than 106µm in diameter using 100-1000 mesh wire sieve.

3.2 Chemical Analysis

This was performed at the Ministry of Roads (Materials Testing and Research Department) to determine the chemical elements in the soil. Cement Analysis (gravimetric) method was employed to get the amounts of chemical elements in the soil.

One gram of the clay was weighed into a 250 ml beaker. The beaker was then shaken while adding a mixture of 11.0 ± 0.5 ml acetic anhydride and 10 ± 0.5 ml of distilled water. It was placed on a hot plate on low heat and rotated until the violent action ceased. The mixture was kept warm until the solution turned reddish in color and a small volume (about 10 ± 0.5 ml) of concentrated hydrochloric acid was added. The mixture was heated to clear yellow before adding 20 ± 0.5 ml of distilled water to produce silica. The silica was then filtered using a number one small filter paper. To obtain iron and aluminum, the filtrate from the silica was boiled, removed from the hot plate and ammonia solution was added. It was left for a few minutes to allow the precipitate to settle and then filtered through a Whatman number one filter paper. About 10 ± 0.5 ml of ammonia solution were then added to the filtrate from the iron and alumina separation to obtain calcium, magnesia and potassium. The percentages of the elements were calculated as follows

Percent soluble silica =100 x {(weight of residue) – (insoluble residue)}

Percent iron and alumina =100 x weight of residue

Percent calcium oxide =Number of mls of 1NKMnO$_4$ *x (2.8) x (100)*

Percent magnesium oxide =(Weight of residue) x (0.36) x (100)

Results of the chemical percentages of these elements are fully indicated in Table 4.1.

3.3 Particle Size analysis

To determine the sizes of clay particles in the red hill clay, sieve analysis and sedimentation methods were employed.

Sieve Analysis

Sieve Analysis involved the use of six sieves to distribute different particle sizes in the red clay soil used in this study. The sieves were thoroughly washed in clean water and dried in the sun. The mass of each sieve as well as the bottom pan to be used in this analysis were measured. The mass of the dry red clay soil was also taken. The sieves were then assembled in ascending order of sieve numbers (number 4 sieve at top) and (number 140 at bottom). The pan was placed below sieve number 140. Five hundred grams of the red soil sample was then poured into the top sieve. The sieve stack was placed in mechanical shaker and shaken for 10 minutes.

The stack was removed from the shaker and the mass of each sieve with its retained soil recorded. The mass of the bottom pan with its retained fine soil was recorded. The mass of soil retained on each sieve was obtained by subtracting the weight of the empty sieve from the total mass of the sieve and the retained soil. The percent retained on each sieve was obtained by dividing the mass retained on each sieve by the original sample mass. The percentage passing also known as percent finer was obtained by subtracting the percent retained on each sieve as a cumulative procedure starting with 100%.

3.4 Fabrication of clay filters

The clay filters were fabricated by varying volume composition of clay plus sawdust in the ratios of 45:55, 50:50, 55:45 and 60:40 each at a time for about 10 minutes while dry before 2.85 L of water was added into the mixtures this was to enable the mixture to have the sawdust evenly distributed to the clay particles [Molly, 2009]. When less than 2.85 L of water was added to the mixture it was observed that the dough was very dry for the fabrication of the filters. It was also noted that when the amount of water was high than 2.85 L the mixture was too wet to make filters. A small garden watering can was used to ensure that an even distribution of water was maintained to maximize the consistency of the clay mix. The mixing of these components was done manually by kneading and squeezing method as commonly used by potters. Wet mixing took 10 more minutes per addition of 0.95 L of water before the dough was ready for pressing.

The mix was then formed into balls of mass of 750.0 ± 0.5 g each from the bulk. This mass of the dough was enough to produce a disc filter of 2.5 ± 0.5 cm in thickness after pressing and about 2.0 ± 0.5 cm after drying and firing. The balls were in excess of 50 grams to ensure that air bubbles were pressed out of the walls of the filter in the molding press. The weighed portions were then formed into disc shaped cylinders at a loading pressure of 140 ±5 kPa using a hydraulic press shown in Figure 3.1. The steel female press had a diameter of 17 ± 0.5 cm and a thickness of 2.5 ± 0.5 cm.

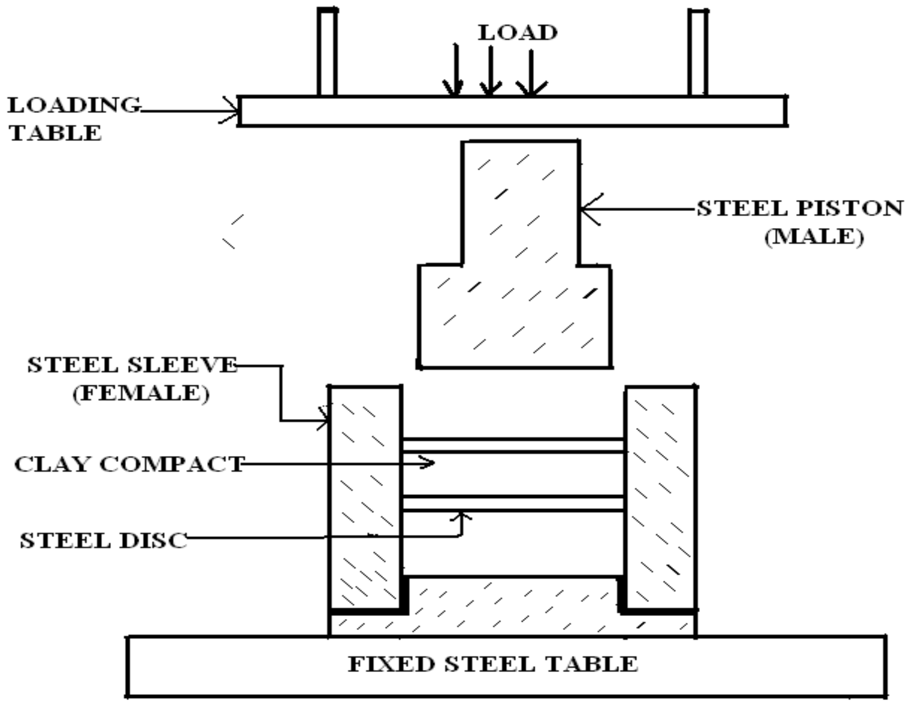

Figure 3.1: Hydraulic press Mould

Grease was used as a lubricant to prevent specimens from sticking to the steel mould as well as to reduce friction between the piston and the cylinder during compaction. Five filters were made for the measurements of material properties and three filters for filtration properties for particular clay to sawdust for each given ratio. Once each filter element was pressed, their surfaces were manually finished using very wet mixture of clay and sawdust to minimize the surface cracks. Immediately after finishing the filters were labeled I, II, III and IV representing 60:40, 55:45, 50:50, and 45:55, respectively.

The filters were left to dry in the laboratory for a maximum of 14 days at a room temperature of 20 °C before the firing process began. After drying, the green filters were fired in an electric furnace (Naberthern-Model LH 15/14 max. temp. 1400 °C). This involved the preheating of the green membranes to 100 ^oC, and then held at that temperature for about 1hour in order to allow ordinary water to escape before heating to 550 °C for 3 hours at the rate of 180 °C per hour (to burn off the sawdust) followed by heating selected filters to the firing temperature of 800, 850, 900 and 950 ^oC respectively and soaked at that temperature for five hours. Thereafter the furnace was switched off and left to cool to room temperature. The green-wares were vertically stacked in the furnace as in Figure 3.2; a space of about 3 cm was left between one filter and the other. This was to ensure uniform distribution of the heat and also to ensure that the carbons inside the filters burn off completely to prevent cracking of the filters.

Figure 3.2: Photo showing staking of disk ceramic filters in the furnace.

3.5 Measurement of physio-mechanical properties

The physio-mechanical properties determined include the following:

3.5.1 Volume Porosity

The apparent porosity of disc ceramic water filter (DCWFs) was determined as the amount of water absorbed by the sample using the Archimedes Immersion Technique [Christopher *et al*., 1992] that involved boiling the samples in water for three (3) hours.

The amount of water absorbed (percentage water absorption, %WA) was determined using equation (3.1) [Crimshaw, 1991] where W_s and W_d are the saturated and dry sample masses, respectively.

$$\%WA = \frac{W_s - W_d}{W_d} \times 100\% \qquad (3.1)$$

The apparent porosity was calculated using equation (3.2)

$$P = \frac{\text{Amount of water absorbed}}{\text{Density of water}}$$

$$= \frac{W_s - W_d}{W_d \rho_w} \qquad (3.2)$$

3.5.2 Mechanical Strength

The mechanical strength in compression was determined through measurement of modulus of rupture. Ten cylindrical samples from each mixture (45:55, 50:50, 55:45 and 60:40) were used to represent disk ceramic filters subjected to mechanical strength test. The modulus of rupture test was carried out in three points bending test, with a span of 9.4 ± 0.5 cm, crosshead of 1 mm/min using an Instron 1185 compression/tension testing machine. Equation (3.3) was used to calculate the modulus of rupture (σ).

$$\sigma = \frac{8F_L D_{rolls}}{\pi d^3} \tag{3.3}$$

where D_{rolls} is the distance between supporting rolls, F_L is the fracture load and *d* is the cylindrical diameter

3.5.3 Determination of Flow Rate

Three flow rate tests were performed on each of the fired disc ceramic water filter. The filter elements were first immersed in water and soaked for about 12 hours to ensure enough saturation of filters at the beginning of the test and also to remove internal air bubbles. Enough saturation of water enables continuous flow of water through the pores of the ceramic water filter. Two buckets were assembled together as shown in (Figure 3.3). The top bucket had a hole measuring approximately 13 ± 0.1 cm in diameter where the filters were fixed in turn using silicone clear paste (Hi-temp clear RTV Gasket maker 100% silicone rubber). The bottom bucket acted as the receptacle where the filtered water was received. The bucket containing the filter was then filled with the swamp contaminated water to the brim, and the timer was started for one hour. The flow rates were then measured through all the four DCWFs (45:55, 50:50, 55:45 and 60:40) one at a time. Flow rate was calculated using the relation (3.4).

$$\text{Flow rate} = \frac{\text{Volume Filtered}}{\text{Elapsed Time}} \tag{3.4}$$

At the start of each experiment, the bucket with water saturated DCWF was filled completely with approximately 10 ± 0.5 L of water and covered with lid to prevent evaporation which may lead to reduction of mass. As the water went through the porous filters for one hour, the filtered water was transferred from the receiver bucket to a measuring cylinder where its volume was measured.

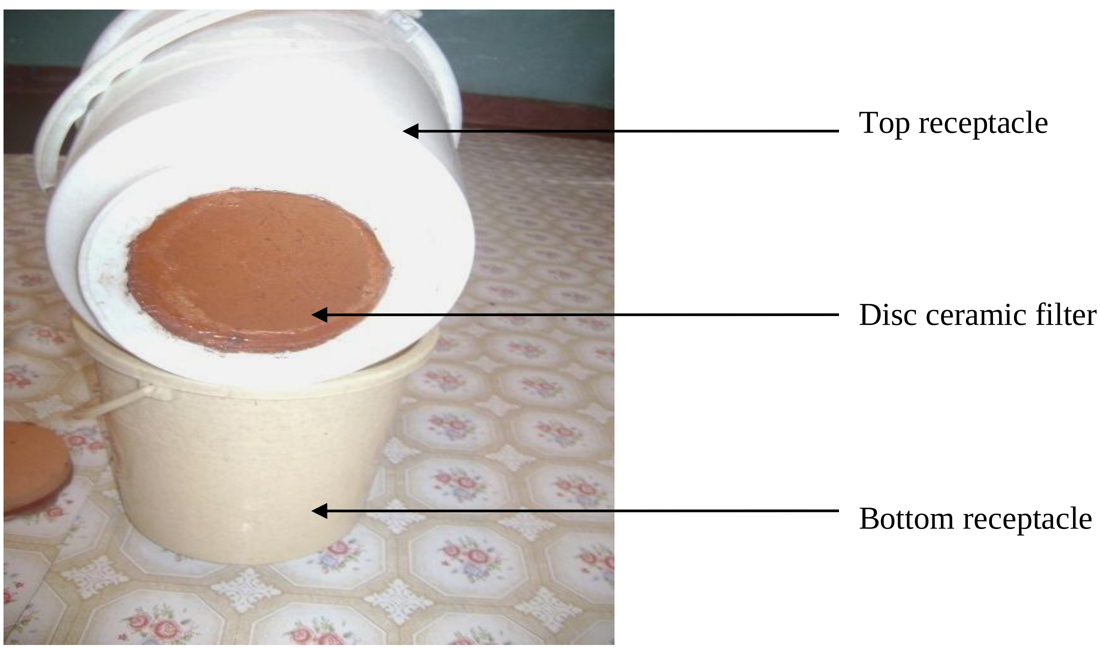

Figure 3.3: Figure showing the set up used for measurement of flow rate

3.6 Permeability

The permeability of the porous DCWFs was calculated using Darcy's equation which is given by relation (3.5) [Yakub *et al*., 2013]

$$Q = \frac{kA}{\mu L}\Delta P \tag{3.5}$$

where Q is flow rate; k is permeability of the material; A is surface area; L is thickness of the material; μ is dynamic viscosity of the water [equal to $1.002x10^{-3}$ Nsm^{-2} at 20 °C]; and ΔP is pressure difference from the inside bottom surface to the outside bottom surface (the distance of porous media through which the water flows) of the porous filter.

3.7 E-coli Removal Experiment

Water was collected from stagnant surface water from a swamp contaminated with coliform were filtered using the DCWF membrane and tested for *E-coli*. All the equipments used in this technique were put in boiling water to sterilize them each and every time in use. 100 ml sample of the effluents from all the filters were put in various Petri dishes and placed in the incubator at 35 ^{0}C for 24 hours. The number of colonies forming unit (CFU) was counted under magnifying glass and expressed as CFU/100 ml. The indicator organism's level in water sample was expressed as the number per 100 ml and the number of the indicator organism's in water tested was determined using the relation (3.6)

$$\psi = \frac{y}{m_{ls}} X100 \qquad (3.6)$$

where ψ is the number of indicator organisms per 100 ml; У is the number of indicator organisms counted and m_{ls} is the milliliters of sample per 100 ml.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.0 Chemical Analysis

Results of the chemical analysis of the raw clay materials and the fired samples are presented in Table 4.1.

Table 4.1: Chemical Analysis of Red Clay Soil (Soil pH=5.08)

Element oxide	Percentage of elements in raw clay	Percentage of elements in the filters after Firing at 950 ^{o}C
Fe_2O_3	18.04	15.06
SiO_2	2.48	1.92
Al_2O_3	1.73	1.49
K_2O	2.95	-
Na_2O	4.04	-
MgO	3.17	3.08
CaO	3.83	2.48
Others	9.90	8.76
Insoluble Residue	50.90	-
Organic content	2.96	-

It was observed that iron is the major constituent of the red clay and it is responsible for the red color of the soil. There was also an overall decrease in the composition of the elements and fluxes at the firing temperature of 950 °C as observed in Table 4.1. The Al_2O_3 which is also a constituent of the clay mineral kaolinite ($Al_2O_3.2SiO_2.2H_2O$), decomposes at temperatures as low as 450^{o}C into metakaolinite ($Al_2Si_2O_7$) [Nyongesa, 1994]. Such a reaction was probably the major cause for the observed general decrease in the composition of Al_2O_3 as the temperature was increased. On the other hand, SiO_2 exists as free quartz as well as a constituent in other clay minerals such as kaolonite, sodamica ($Na_2O.3Al_2O_3.6siO_2.2H_2O$) and potashmica $K_2O.3Al_2O_3.6SiO_2.2H_2O$). According to Nyongesa, 1994, these minerals transform with increase in firing temperature. These transformations subsequently alter the compositions of the respective constituent oxides such as Al_2O_3 and SiO_2 [Nyongesa, 1994].

Particle Size distribution

Table 4.2 shows the results of the particle size analysis from sieve analysis.

Table 4.2: Results of Particle Sieve Analysis

Sieve number	Sieve diameter (μm)	Mass of empty sieve (g)	Mass of sieve + Soil retained (g)	Soil Retained (g)	Percent retained	Percent passing
4	4750	116.20	126.90	10.70	2.24	97.76
10	2000	99.34	139.54	40.20	8.14	89.82
20	840	97.59	143.89	46.3	9.36	80.56
40	425	98.86	139.26	40.4	8.18	72.48
60	250	91.44	148.44	57.0	11.50	61.08
140	106	93.55	189.75	96.2	19.34	41.84
Pan	-	60.19	262.99	202.8	41.24	0.0

Figure 4.1 shows the results of the particle size analysis from the sieve analysis. From Figure 4.1 and also from Appendix (Table A4), it is noted that the red clay used in this study contained about 72.48 percent of soil particles which went through the sieves that were in the range of 106 and 425 μm in diameter and 27.52 percent went through sieves (after shaking the sieve containing the particles for sometime) that were in the range of 840 to 4750μm in diameter (Table 4.3). According to Yakub *et al*, [2013] these fine particles below 425μm when used in the making of ceramic water filters increased the plasticity of the clay than when large particles are used.

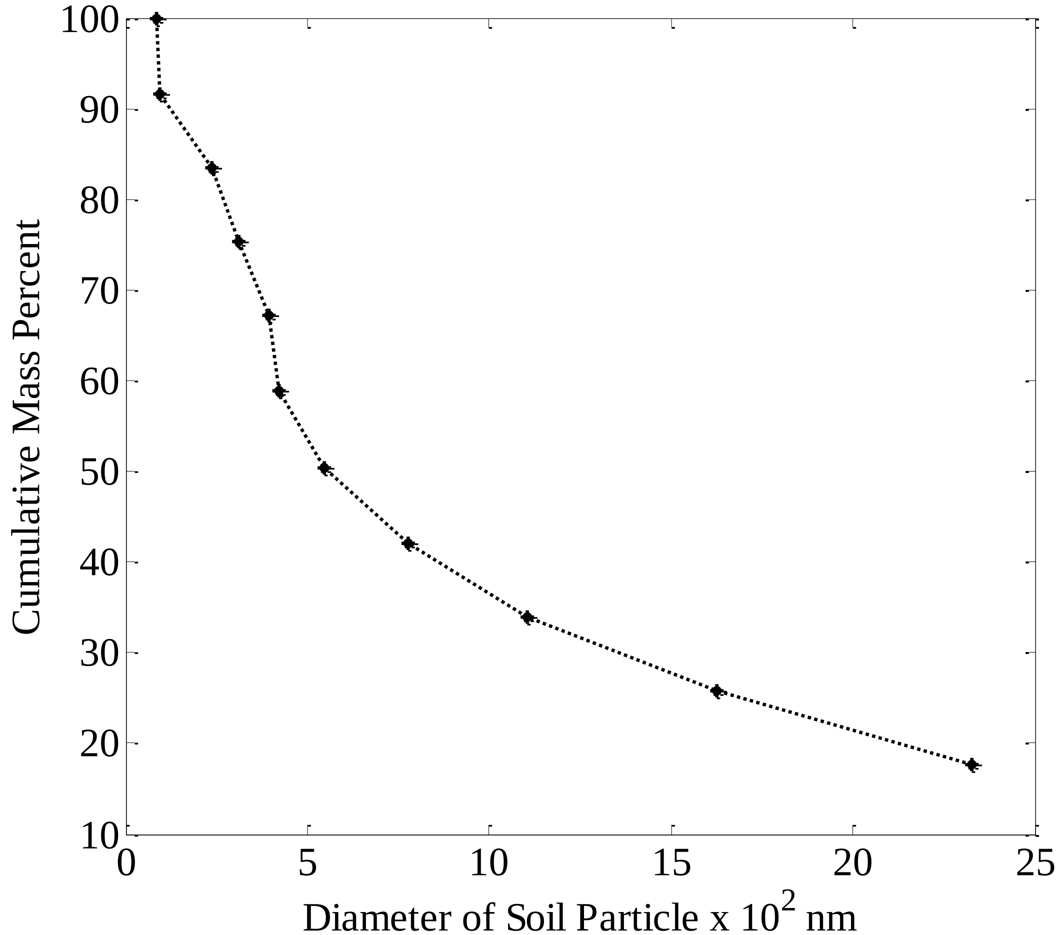

Figure 4.1: Variation of cumulative percent mass and the diameter of red clay particles

4.1 Drying and Firing Shrinkage

The initial drying of the filters at room temperature for about 14 days removed much of the excess water that remained after molding the clay to the desired shape. After this initial drying period, the green filters were likely to hold their shape but were not strong enough to hold water. It was also noted that when the green specimens were arranged in horizontal manner in the furnace for firing, that is, one filter on top of the other, most of the filters developed cracks. This might have been caused by lack of complete combustion of carbons from an area that was covered by another filter. It was also due to the differential temperature caused by the thickness of the filter. According to Rahbar, [2011] thicker filters are observed to have cracks when subjected to high firing temperatures than the filters that are thinner. This observation is attributed to the thermal gradient that causes different parts of the filters to expand differently. This differential expansion brings about thermal stress. If this stress exceeds the strength of the filter it causes the ceramic filter to crack.

At 200 ^oC the sawdust begun to combust and smoke was seen coming out of the chimney of the furnace and at 550 ^oC all the sawdust had completely been burnt out and smoke could not be seen any more. It was also noted that the filters that were not soaked for five hours retained specks of black carbon (Figure 4.2a). This is due to lack of complete combustion of the sawdust. A deeper red color on the fired filter elements was noted at higher temperatures beyond 800 °C as it was also observed by Molly, [2009] and Kabagambe, [2010]. An optimally fired disk filter (Figure 4.2b) had a bell-like ring sound when struck with a metal rod, compared with a thud if not well fired.

Figure 4.2a: Poorly fired disk ceramic filter

Figure 4.2b: Optimal fired disk filter at 950°C

4.2 Effect of Firing Temperature on the bulk density

Figure 4.3 shows the effect of firing temperature on the bulk density of disc ceramic water filter.

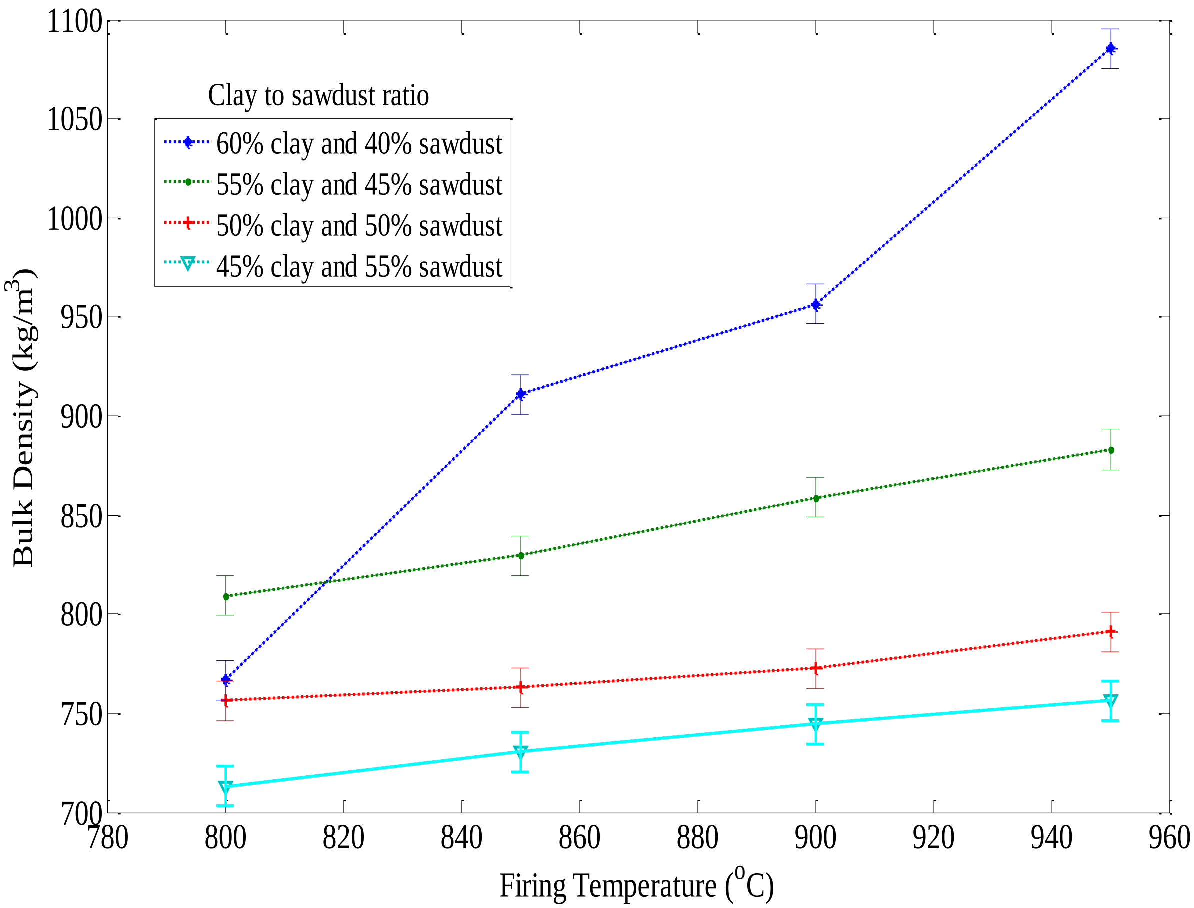

Figure 4.3: The variation of bulk density and the firing temperature of disc ceramic filters

It is observed that as the firing temperature increased from 800 °C to 950 °C the density of all the filters also increased. The highest density of 1085.28 ± 1.20 kg/m^3 was noted on the filters with a mixture of 60% clay and 40% sawdust when fired at 950 °C. This was attributed to the low volumes of sawdust that left few voids in the filters membrane. Those at 45% clay and 55% sawdust fired at 800° C had the lowest density of 712.98 ± 1.20 kg/m^3 in this study, which was attributed to high fractions of burnout. The sawdust burnt out and left voids which made the filter less dense.

4.3 Effect of Firing Temperature on Strength

Figure 4.4 shows the results of effect of firing temperature on strength of disc ceramic filter.

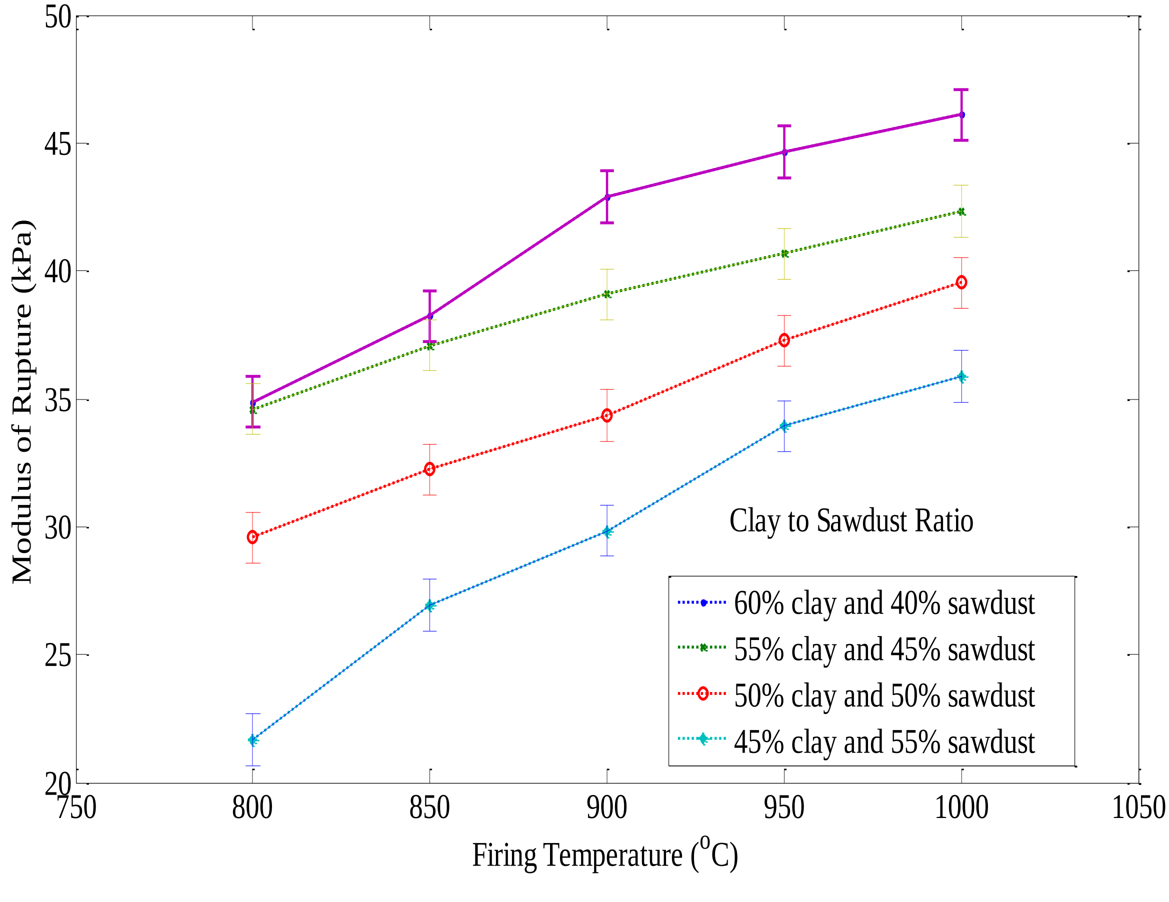

Figure 4.4: The variation of modulus of rupture and the firing temperature

It was observed that there was an overall increase in mechanical strength with firing temperature in all the filters in the study. This was attributed to phase changes/ chemical reaction between the phases in the ceramic filters as it was also observed by Aramide [2012]. Filters with the ratio 60% clay 40% sawdust happened to be the strongest of all the filters with modulus of rupture of 40.16 ± 0.10 kPa. This was due to low volumes of sawdust as compared to other filters in this study. The filters with the ratio 45% clay 55% sawdust had the lowest modulus of rupture of 28.10 ± 0.10 kPa thus were the weakest in the study (Figure 4.5) and Appendix. This observation was due to the increase in the percentages of sawdust that lead to increase in porosity of the filter. Porosity affected the mechanical property of ceramic materials by making the filter to be so porous thus decreasing the strength of the filter.

4.4 Effect of Volume Fraction of Sawdust on the Porosity

The strength of the filters was inversely proportional to the volume fraction of sawdust in the clay while the porosity of the filters was directly proportional to the amount of sawdust in the mixture as seen in Figure 4.5.

The porosity of the filters was found to be directly proportional to the percentage. With increasing temperature; from 200 ^{o}C to 500 ^{o}C the burnout (sawdust) contained in the clay is burnt off leaving open pores (which improves the porosity of the fired samples) in the specimen. The organic matter combines with the oxygen in the furnace atmosphere to form carbon (IV) oxide and other gases. At around 160 ^{o}C the removal of all moisture (dehydration) is complete.

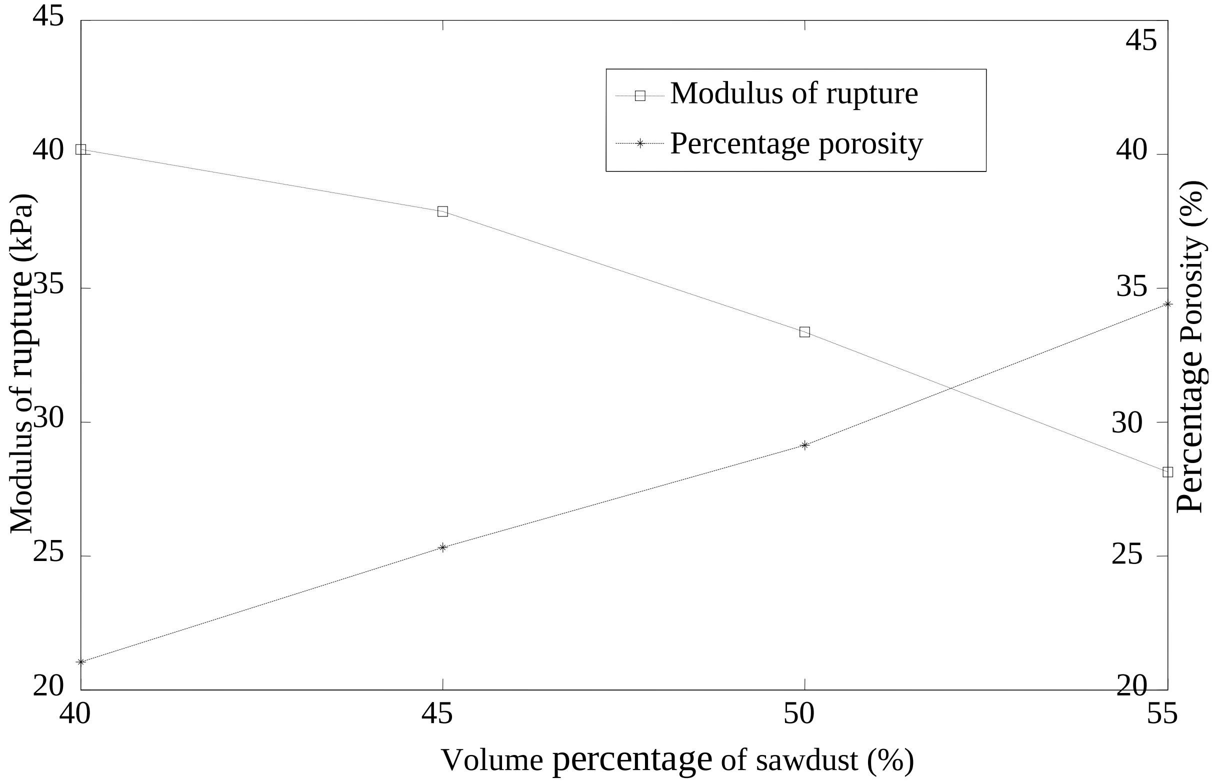

Figure 4.5: Variation of porosity, modulus of rupture and the volume fraction of sawdust used in DCWF fabrication

Over the temperature range 200 °C to 280 °C, all the hemicellulose decomposes, yielding volatile products such as carbon (IV) oxide, carbon (II) oxide and condensable vapours. From 280 °C to 500 °C the decomposition of cellulose picks up and reaches a peak around 320 °C [Roberts, 1971]. The products are again volatile. The decomposition rate of lignin increases rapidly at temperatures beyond 320 °C. This is accompanied by a comparatively rapid increase in the carbon content of the residual solid material [Roberts, 1971].

4.5 Effect of porosity on flow rate and the permeability of the DCWF membrane

The most porous of the filters studied, the 45:55 DCWF, exhibited the fastest discharge of water of 3.67 L/h. The filter with the lowest flow rate (0.08 L/h) in the study was the 60:40 DCWF. Therefore, the rate of water flow by DCWF increases with the volume fraction of sawdust used in making the filter. The flow rate obtained from the 50:50 DCWF was 1.52 L/h on average. This agrees with the filtration rate of between 1.37 and 1.94 L/h which is the range that is typical of PFP filters [Yakub *et al*., 2013]. Flow rate for the 55:45 (0.24 L/h) and 60:40 (0.08 L/h) DCWFs were below this level on average. The percolation of water through the filter membrane (Figure 2.3) would take more time through a thicker membrane than a thin one. The flow rate for 45:55 DCWF was far much higher than all other filters. It ranged between 2.83 and 5.80 L/h. This is a very high flow rate and the efficiency in terms of removal of pathogens of the filter membrane is 86.76% (Appendix Table A1) as compared to the WHO/UNICEF, [2004] recommended ceramic water filter of 100%.

Figure 4.6 and Appendix Table A1 shows the results of effect porosity on the permeability of disc ceramic water filters.

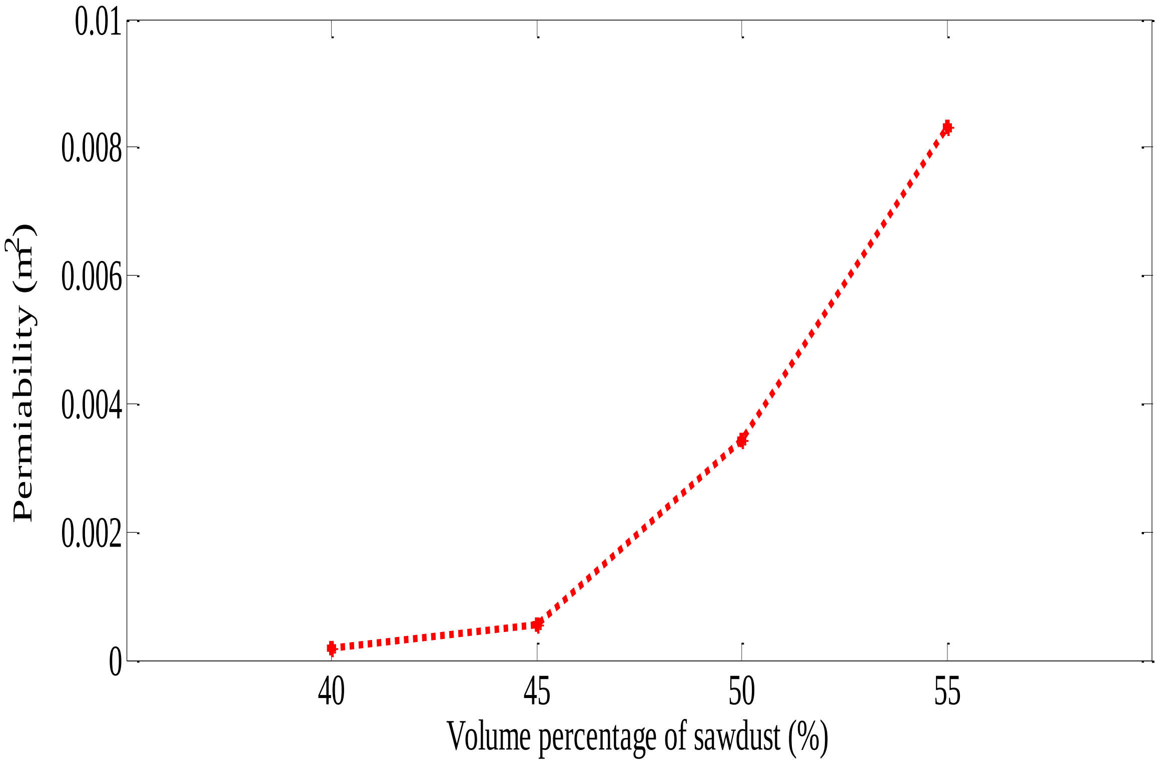

Figure 4.6: Variation of permeability with the volume fraction of sawdust used in DCWF fabrication.

The permeabilities of the porous water filters were obtained using equation (3.5). The permeabilities of the filters studied were found to be between 8.3 x 10^{-3} to 18 x 10^{-3} m^2. The permeability at 55% sawdust (8.3 x 10^{-3} m^2) was very high due to the high volumes of sawdust while that at 40% sawdust (18 x 10^{-3} m^2) was the lowest.

4.6 Comparison of experimental data to theoretical models

A hydrodynamic model was developed to describe the flow of water through the filters due to the effect of gravity. The flow continued until the filter had emptied to levels where there was not enough pressure to overcome the resistance of the filter. Figure 4.7 is a schematic of the water filter.

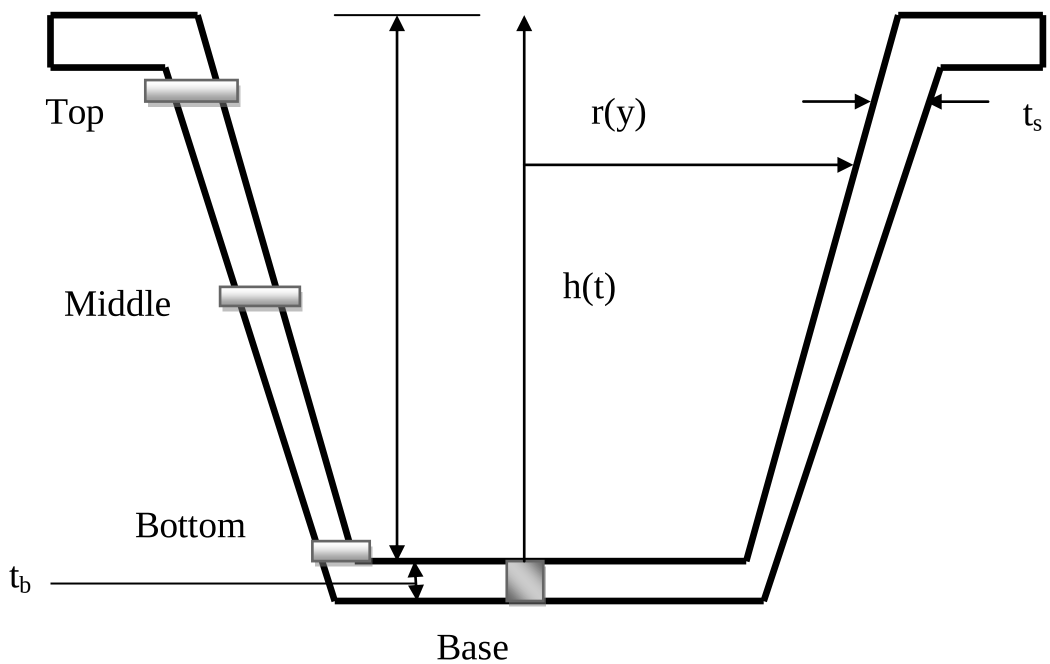

Figure 4.7: Schematic of Ceramic water Filter

Flow through the porous filters was assumed to follow Darcy's Law, which is given by [Yakub *et al.*, 2013]

$$Q = \frac{kA}{\mu L} \Delta p \qquad (4.1)$$

where Q is flow rate; κ is permeability of the material; A is surface area; L is thickness of the material; μ is dynamic viscosity of the fluid; and Δp is pressure difference from the top to the bottom of the surface. In this study, the sides and bottom of the filter are taken separately (denoted Q_b and Q_s, respectively) and the corners are neglected. The pressure difference between the surface of water in the top bucket and the top surface of the disc ceramic water filter inside the top bucket is equal to the hydrostatic pressure of the water. For the flow through the bottom, the change in pressure from the inside bottom surface to the outside bottom surface (the thickness of disc ceramic filter through which the water flows) is equal to the hydrostatic pressure of the fluid at that time. This is given by equation (4.3)

$$\Delta p = \rho g h(t) \qquad (4.2)$$

where h(t) = height of water above the filter at any given time; ρ = density of water; and g = acceleration due to gravity.

When equation (4.3) is substituted into equation (4.2) and the area of the bottom of the filter ($A = \pi r_o^2$ where r_o is the radius of the base of the filter) is the surface area that the flow is acting on; the thickness of permeable material is $L = t_b$; and the permeability is considered to be constant. Then, the flow rate through the bottom of the filter is given by equation (4.4) [Yakub *et al.*, 2013]

$$Q_b = \frac{k\pi r_o^2 \rho g h(t)}{\mu t_b} \tag{4.3}$$

On the sides of the filter, the pressure is a function of the position y and is given by $\Delta p = \rho g(h(t) - y)$. The area of the filter is also a function of y. The radius changes along the filter height of the filter and is expressed as $r(y) = r_0 + y \tan\theta$. The permeability coefficient is again considered to be constant and to be the same as on the bottom of the filter. Thus, the flow rate through the side of the filter is given by equation (4.5) [Yakub *et al.*, 2013]

$$Q_s = \int_0^{h(t)} \frac{k\pi\rho g(h(t) - y)}{\mu t_s} 2(r_0 + y\tan\theta)dy \tag{4.4}$$

Integration of Equation (4.5) gives Equation (4.6)

$$Q_s = \frac{k\pi\rho g h^2(t)}{\mu t_s}\left[\frac{r_0}{2} - \frac{h(t)}{3}\tan\theta\right] \tag{4.5}$$

Furthermore, by adding Equations (4.4) and (4.6), the following expression for the total mass flow rate is obtained for the total mass flow rate, Q:

$$Q = \frac{k}{\mu}\pi\rho g h(t)\left[\frac{r_0^2}{t_b} + \frac{r_0 h(t)}{t_s} - \frac{2h^2(t)}{3t_s}\tan\theta\right] \quad (4.6)$$

Thus, an expression is derived for the flow rate through the CWF, as a function of the height of water in the CWF. The values of h(t) were found from the following expression for the volume of water, v (t), contained in the frustum-shaped CWF at any given time t:

$$v(t) = \pi\left[R^2 h(t) + Rh(t)^2\tan\theta + \frac{h(t)^3\tan^2\theta}{2}\right] \quad (4.7)$$

In this study, a disc ceramic water filter was used instead of a frustum-shaped ceramic water filter. Equation (4.7) was developed and reduced to Equation (4.9) [Yakub *et al.*, 2013]

$$Q_d = \frac{AKH}{L} = \frac{\pi D^2 k\rho_w g H(t)}{4\mu L} \quad (4.8)$$

where, Q_d is the flow rate through disk filter, A is the surface area of the disk, D is the diameter of the disk, K is the hydraulic conductivity and given by equation (4.11), k is the permeability, θ is the contact angle of the interface between the liquid and the pore wall,

ρ_w the density of water, μ the viscosity of water, H(t) the water head with respect to time t and $L=t_d$ is the disk thickness.

Equation (4.9) hence reduces to Equation (4.10) which is used in calculation of flow rate of a disk ceramic water filter.

$$Q_d = \frac{K\pi D^2 H(t)}{4t_d} \tag{4.9}$$

$$K = \frac{kg\rho_w}{\mu} \tag{4.10}$$

Figures 4.8 and 4.9 shows how the experimental and theoretical (equation 4.10) volume filtration rate of different filters changes with time.

It is noted from Figures 4.8 and 4.9 that the flow rate decreased linearly with time up to a certain point (at 8.5 x 10^4 s for 60 % clay and 40 % sawdust, 3.42 x 10^4 s for 55 %clay and 45 % sawdust, 3.6 x 10^4 s for 50 % clay and 50 % sawdust and 3.24 x 10^4s for 45 % clay and 55 % sawdust) (Appendix) due to decrease in pressure head with respect to time, which also agrees with the equation (4.10). Beyond these points the filtration was constant, this was attributed to very small changes in height of water above the filter as it was flowing which made the hydraulic pressures to be very low. The pressure difference was obtained by getting the height of the water above the filter at any given time using equation (4.3). The height was then substituted into equation (4.10). The decrease in flow rate was also attributed to the clogging during multiple flow experiments and possibly the effect of the degree of saturation of the DCWF prior to testing [Yakub *et al.*, 2013].

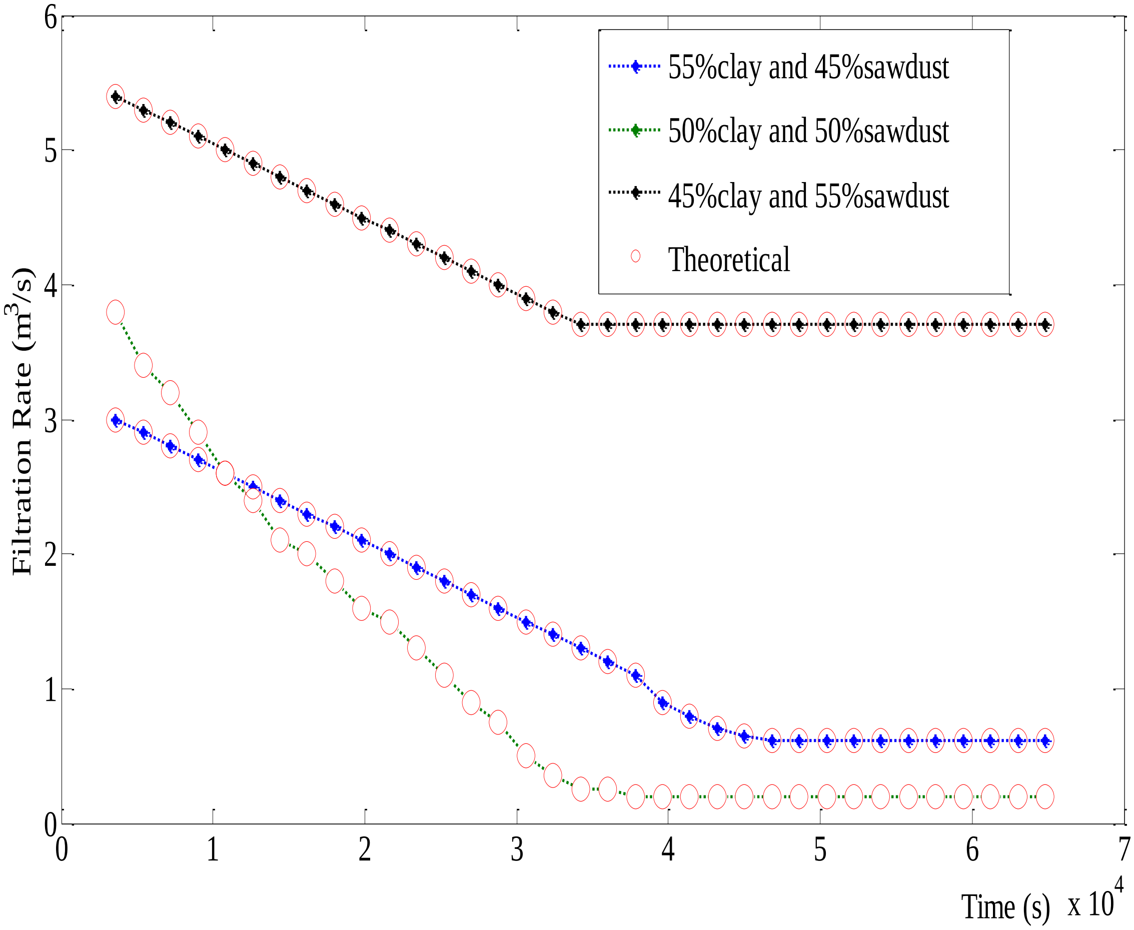

Figure 4.8: Plots of volume flow rate against time comparisons of experimental data and Darcy fits of clay to sawdust ratio of 55:45; 50:50; 45:55 CWF.

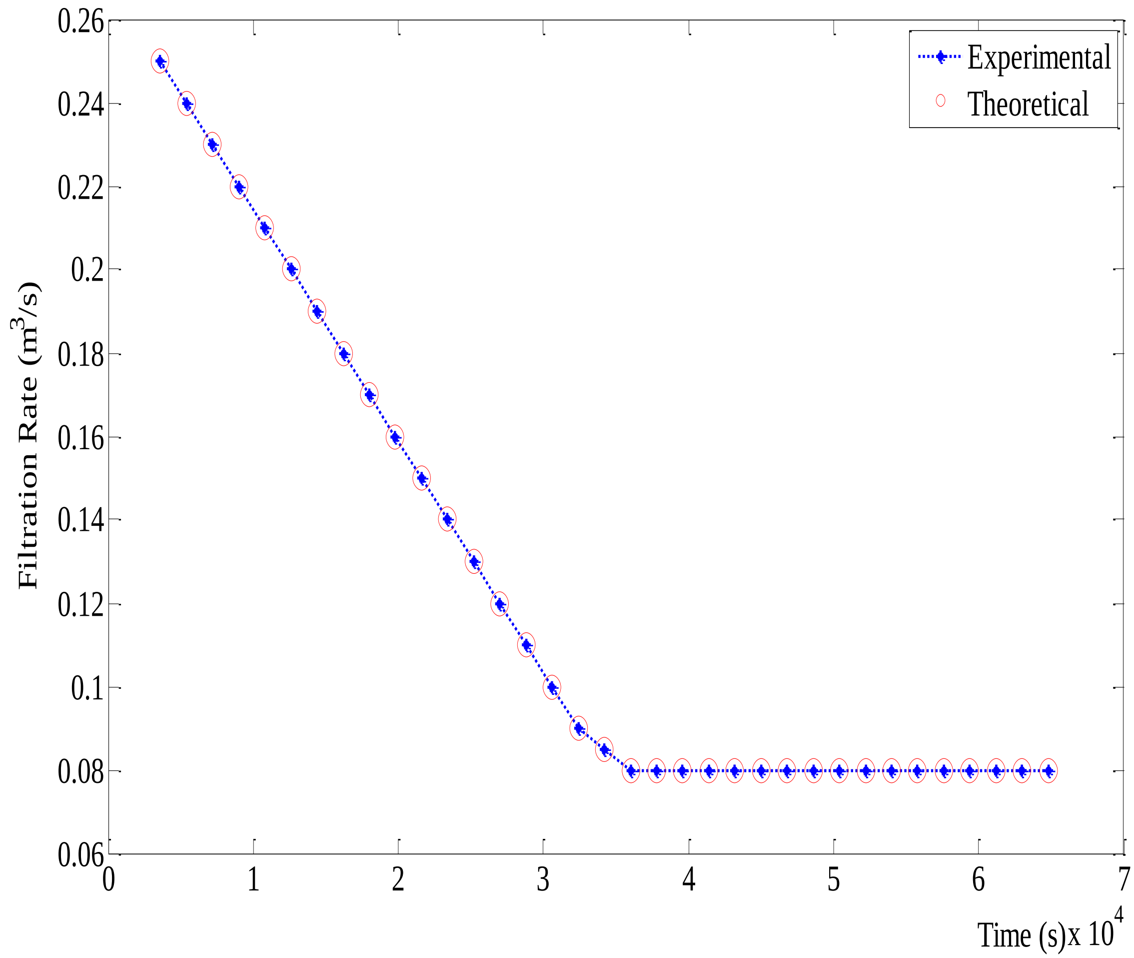

Figure 4.9: Plots of volume flow rate against time comparisons of experimental data and Darcy fits of clay to sawdust ratio 60: 40; (note: $1m^3/s = 3.6 \times 10^6$ L/h)

The Darcy's equation, to most of the flow data, suggests that much of the flow through the DCWFs is well described by continuum flow through porous membranes. However, according to Yakub *et al.*, [2013], filters that were not presoaked with water before flow rate experiment was carried out suggests some discrepancies between the measured and the fitted data during the initial stages of the flow.

The discrepancies between the initial flow data are attributed to the initial transient flow required for the transport of water from the inner to the outer surface of the DCWF. If the filters are presoaked, the conditions for continuum flow appear to be established, and the data is well described by Darcy's equation, (Figures 4.10 and 4.11). Furthermore, during the latter stages of the experiments, the hydraulic pressures are insufficient to drive the fluid flow through the porous ceramic walls. Under such conditions, the flow rates decrease, and the flow asymptotes.

4.7 *E. coli* removal

E. coli filtration experiments were performed on DCWFs with the fastest flow rates being 45:55 DCWF which had more than 10 coliforms bacteria detected in 100 ml of drinking water. The efficiency of these filters was 86%. This filter was termed as high risk according to the WHO water risks categories. The 50:50, 55.45, and 60:40 DCWFs had zero coliform per 100 ml. These filters had an efficiency of 99.97, 99.98 and 99.99 percent respectively.

The efficiency of the 60:40 DCWF was slightly higher than that of the other filters. Only the three designs of the four types of DCWFs met the WHO (Appendix Table A3) standard for water treatment [Yakub *et al.*, 2013] that neither *E. coli* nor coliform bacteria should be detectable in 100ml of drinking water. The filtration efficiency of the PFP filter has been reported to be approximately 99.99% [Oyanedel and Smith, 2008; Yakub *et al,* 2013].

It implies that point-of-use DCWFs with different porosities can be used to filter out most of the bacterial pathogens in water. With *E. coli* removal rates approximately 99.9% for all the filters, the use of the DCWFs can contribute to the removal of microbial pathogens from drinking water in the developing world, where more than 4,900 people die every day from the effects of consuming contaminated water.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The implications of the results in this work suggest that point-of-use DCWFs with different porosities can be used to filter out most of the bacterial pathogens in water. With *E. coli* removal rates of approximately 99.9% for the first three water filters, the use of the DCWFs can contribute significantly to the removal of microbial pathogens from drinking water in the developing world, where about 5,000 people die every day from the effects of consuming contaminated water. The porosity, permeability and overall flow rates increase with increasing volume fraction of sawdust. An average flow rate of 1.7 L/h was obtained from the DWCFs with a sawdust volume fraction of 50%. The filter had been fired at 950 °C and was found to remove more than 99.97% of *E. coli*.

When optimizing the filter composition, increasing the concentration of burnable materials (in this case sawdust) affected the physical and hydraulic properties of the ceramic material, and the bacteria removal percentage. The high the amount of sawdust in the mixture the higher the porosity of the ceramic water filter fired at 950 ^{o}C, hence the lower the efficiency of the filters. In addition, the filtration rate of the designed ceramic water filter in the study agrees with the theoretical models of Yakub *et al*, [2013].

5.2 Recommendations for further investigation

The following are recommended for further investigation:

- Comparison of other burnout materials and their effects on the microstructure of the filters and water treatment.

- Effect of compaction pressure on the percolation rate of water through ceramic filters.
- Effectiveness of the filters in removing heavy metals from water.
- Effect of solar disinfection on water before and after filtration in the ceramic water filters.

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APENDIX: SUMMARY OF RESULTS

Table A1: Results of disc ceramic water filters after firing at 950 ^{0}C

Clay to sawdust ratio	Flow rate (±0.0017) L/h	Percentage porosity (±0.15)	Permeability m^2	Modulus of rupture (±0.1) kPa	*E. coli* filtration (%)
60:40	0.0800	21.04	$1.8142X10^{-4}$	40.164	99.99
55:45	0.2431	25.29	$5.5128\ X10^{-4}$	37.856	99.98
50:50	1.5184	29.11	$3.4433\ X10^{-3}$	33.362	99.97
45:55	3.6660	34.39	$8.3134\ X10^{-3}$	28.095	86.76

Table A2: Results of the disk samples at different firing temperatures

Clay to sawdust ratio	Firing temperature (^{o}C)	Linear shrinkage (±0.012) m	Modulus of rupture (±0.1) kPa	Bulk density (±1.2) kg/m^3	Percentage porosity (±0.15)
60 : 40	800	0.005	34.871	766.63	22.84
	850	0.009	38.231	910.75	22.13
	900	0.009	42.892	956.28	21.76
	950	0.011	44.66	1085.28	21.04
55 : 45	800	0.007	34.588	809.4	26.43
	850	0.009	37.083	829.51	26.01
	900	0.01	39.089	858.92	25.69
	950	0.022	40.663	882.99	25.29
50 : 50	800	0.008	29.572	756.41	29.97
	850	0.01	32.234	762.88	29.88
	900	0.027	34.358	772.65	29.67
	950	0.034	37.283	791.11	29.11
45 : 55	800	0.011	21.673	712.98	36.98
	850	0.013	26.932	730.51	36.84
	900	0.022	29.848	744.4	36.31
	950	0.03	33.925	756.23	34.39

Table A3: Categorization of E. coli Concentrations for Filter Effluent Samples Collected in the Field according to the World Health Organization Risk Categories [WHO, 2008]

Fecal Coli form per 100ml	Risk categories
0	No risk
1-10	Low risk
10-100	Intermediate risk
100-1000	High risk
Above 1000	Very high risk

Table A4: Particle diameter of red clay

Mass Cumulative Frequency	Mass Cumulative Percent	Diameter of Particle ($x10^2$nm)
20.64	17.59	23.26
30.31	25.83	16.25
38.84	33.95	11.05
49.42	42.11	7.77
59.17	50.42	5.48
69.14	58.91	4.22
78.96	67.28	3.94
88.31	75.25	3.12
97.84	83.37	2.37
107.58	91.67	0.94
117.36	100.00	0.86

Table A5: Results of the flow rates with time

Time x 10^3 (s)	Flow rate (m^3/s)			
	60% clay 40% sawdust	55% clay 45% sawdust	50% clay 50%sawdust	45% clay 55% sawdust
3.6	0.25	3	3.8	5.4
5.4	0.24	2.9	3.4	5.3
7.2	0.23	2.8	3.2	5.2
9	0.22	2.7	2.9	5.1
10.8	0.21	2.6	2.6	5
12.6	0.2	2.5	2.4	4.9
14.4	0.19	2.4	2.1	4.8
16.2	0.18	2.3	2	4.7
18	0.17	2.2	1.8	4.6
19.8	0.16	2.1	1.6	4.5
21.6	0.15	2	1.5	4.4
23.4	0.14	1.9	1.3	4.3
25.2	0.13	1.8	1.1	4.2
27	0.12	1.7	0.9	4.1
28.8	0.11	1.6	0.75	4
30.6	0.1	1.5	0.5	3.9
32.4	0.09	1.4	0.35	3.8
34.2	0.085	1.3	0.25	3.7
36	0.08	1.2	0.25	3.7
37.8	0.08	1.1	0.2	3.7
39.6	0.08	0.9	0.2	3.7
41.4	0.08	0.8	0.2	3.7
43.2	0.08	0.7	0.2	3.7
45	0.08	0.65	0.2	3.7
46.8	0.08	0.62	0.2	3.7
48.6	0.08	0.62	0.2	3.7
50.4	0.08	0.62	0.2	3.7
52.2	0.08	0.62	0.2	3.7
54	0.08	0.62	0.2	3.7
55.8	0.08	0.62	0.2	3.7
57.6	0.08	0.62	0.2	3.7
59.4	0.08	0.62	0.2	3.7
61.2	0.08	0.62	0.2	3.7
63	0.08	0.62	0.2	3.7
64.8	0.08	0.62	0.2	3.7