5

Baked Salty Clay Water Filter, Dissemination, Production and Testing

5.1 INTRODUCTION

Water purification to acquire potable water is a major challenge for the present-day civilization. Many water purification methods and technologies have been developed and employed over the years [Plappally and Lienhard, 2013]. Most of these methods are cost and energy intensive, and are not easily adaptable to the rural population of the developing world [Plappally and Lienhard, 2013]. A very simple and effective method using water filtration through clay-ceramic pots have been used over the years in many rural parts of the developing world. The ultrafine pore passages with high tortuosity in the clay material trap most of the non-soluble contaminants and bacteria (>99%). A reasonable volumetric production (> 600 ml per hour) of safe potable water can be obtained by this method [Plappally *et al*., 2010].

Frustum shaped ceramic water filters have showcased log removals of 2 to 4 while filtering water contaminated with microbes such as E. Coli [Plappally and Lienhard, 2013; Bielefeldt *et al*., 2009; Vander Laan *et al*., 2014; Simonis, 2011]. This filtration technology, however does not perform well in case of virus filtration [Vander Laan *et al*., 2014]. Plappally, 2010 carried out an extensive review of clay ceramic-based water filters [Plappally, 2010]. Plappally and Lienhard, 2013 reviewed cost and microbial filtration efficacy of these clay ceramic water filtration devices [Plappally and Lienhard, 2013]. Hunter, 2009 asserted that these clay ceramic water filters are most effective long-term water filtration solutions for households in developing nations [Hunter, 2009].

During emergencies like tsunami and floods in Sri Lanka and the Dominican Republic, such clay ceramic filters were used for ensuring drinkability of water [Lantagne and Clasen, 2012]. These filters had a frustum shape with a height of 26 cm and a base diameter of 20 cm [Plappally *et al*., 2011]. This frustum shaped 10 to 15-liter capacity water filter is sufficient for drinking water requirements of nuclear families [Plappally *et al*., 2011; Brown *et al*., 2007]. The literature on hydraulic modeling suggests a filtration rate of 1-3 liters per hour through these filters [Plappally and Lienhard, 2013; Plappally *et al*., 2009; Schweitzer *et al*., 2012]. Potter can be equipped with the clay ceramic water filtration technology of Potter for Peace to provide a one-stop solution for drinking water purification [Sundaram *et al*., 2013; Plappally *et al*., 2011].

In India, pottery is a community-based profession [Duary, 2008; Roux, 2015]. This skill is passed from generation to generation. The imminent thought of the possible loss of family profession due to the adaptation of other water purification methods, prompted researchers working towards this ceramic water filter project to arrest the feasibility of a cottage-based factory for clay-ceramic water filter production [Tyeryar *et al*., 2011; Rayner *et al*., 2013]. Moving away from a factory-based model in India also helps to shed information wastes such as translation waste and hand-off waste, which easily crops up in factory mode with non-potter labor base [Lareau, 2003]. In western Rajasthan, traditionally the potters practice open firing and an up-draught open-hearth furnace for baking the filter, which will differ from the factory model of water filter manufacture [Plappally *et al*., 2010; Plappally *et al*., 2011; Johnson *et al*., 2007; Miller and Watters, 2010]. Here these potters also follow a local make-sell approach at their households. Thus, community-based make-sell approach helps prevent process wastes such as control waste and standardization waste [Lareau, 2003]. This thought will also influence the product release roadmap assessment in urban and rural areas respectively. From chapter-2 and chapter-4 the sustainability of the pottery as a profession is clear. Pottery therefore must be run on some of the best management aspects embedded within its framework such as raw material extraction and procurement, processes, daily procedures, educate, mechanization, efficient team management, and optimized procedures of selling the artifacts [Hosotani, 2009]. Therefore, it is important to inquire those processes within household pottery that mirror strategies of the best industrial or workplace management practices prevailing today. Once these processes are understood, it will be easier to disseminate the ceramic water filter technology into this sustainable profession and provide the required quality control [Hosotani, 2009].

Figure 5.1: The G-filter setup in a house in Banad village, Jodhpur, Rajasthan, India

A research team from the department of mechanical engineering at IIT Jodhpur collaborating with specific NGOs across India introduced this technology with a name G-filter [Gupta *et al*., 2016; Banerji, 2016; Soyam *et al*., 2016]. The G-filter was introduced keeping in mind skill development, local accessibility, potter community sustenance, and inexpensive and efficient rural water services in western Rajasthan [Mira, 1954]. G-filter is found to be a solution for drinking water woes of dispersed communities with no-piped water supplies [Urs *et al*., 2009]. One impediment for G-filter sustenance is whether local people are willing to pay for G-filters when other drinking water options are available [Berry *et al*., 2012]. A typical G-filter is shown in Figure 5.1, where a 20-liter clay, plastic or a steel container supports a 9-liter filter receptacle that stores the filtrate collected within.

This thesis reports the process of clay ceramic water filter manufacturing by potter households in western Rajasthan, India. This includes studying local (Rajasthan potters) know-how of processing raw materials and sintering, and substituting it for factory mode of filter production processes practiced in different locations of the world [Baumgartner *et al*., 2007; Hagan *et al*., 2009; Malapane *et al*., 2012; Miller and Watters, 2010]. Finally, the clay ceramic filters manufactured as proof-of-concept are assessed for its microbial removal effectiveness and load-bearing capacities.

5.2 EXEPERIMENTS AND FRAMEWORK

5.2.1 Potter Household Manufacturing Management Practices and Settings

Gupta *et al*., 2016 brought out the G-filter molding machine and the concept of the clay ceramic water filter (G-filter) development. Potters (local to western Rajasthan) with the desire to learn were to be identified by experimenting team here. The discipline required in manufacturing is guaranteed as well as an intent to take ownership is also envisaged since most of the potters follow local make-buy (macro process) strategy in India [Lareau, 2003]. The adaptation of such a household eco-system with personnel having inherited pottery knowledge may cut down discipline waste during the manufacturing process. Men, machine, material, money, information, trust (market, relationship and societal) acting as inputs for this production process, undergo transformation to provide a desired output [Covey and Merrill, 2006; Kanda, 2010]. This transformation (an interdependent multi-variable procedure) occurs within the social, governmental and economic environments [Kanda, 2010; Nicholas and Steyn, 2011].

The team equipped with knowledge on composites (elaborated in Chapter-3) identified the traditional knowledge and cultural aspects related to the local potter communities using socio-behavioral surveys of the community. First is a socio-technology survey, which requests potter's family input on the G-filter technology for household water treatment [Shipps and Phillips, 2013]. The second survey is a G-filter survey (Annexure-A.3) which is intended for the users of the G-filter [Plappally *et al*., 2011]. Here the potter family is the first user. The ownership and inter-dependence within the potter family brings a discoid framework to achieve economic independence of the family by depending upon each other ethically for training and manufacturing respectively [Styhre, 2001]. The project is therefore planned according to Figure 5.2 which is an outcome of the survey results. The survey forms and results are attached in the appendix.

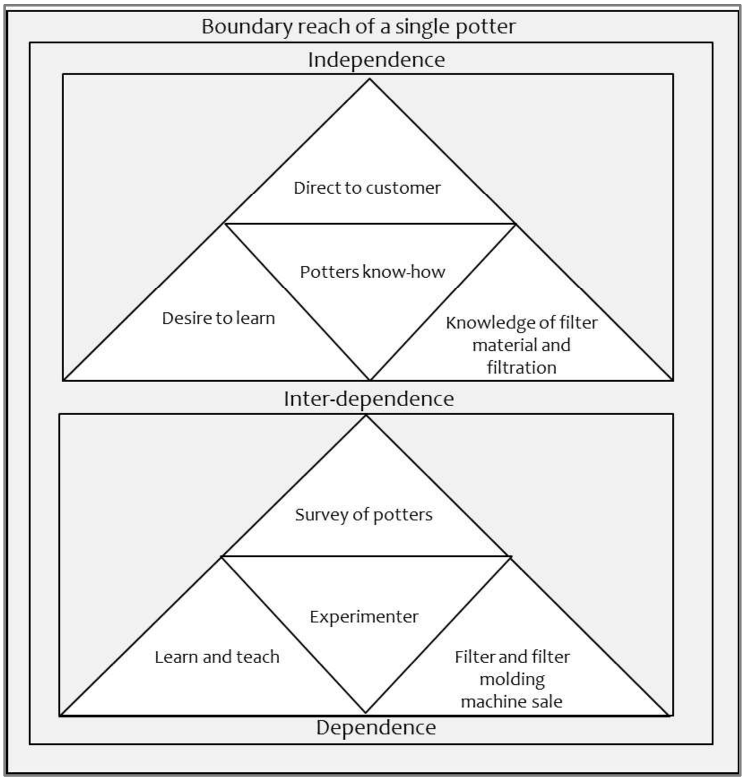

Figure 5.2: Project management thought in western Rajasthan

Due to the brittleness of the clay ceramic water filter material, it could break during a long-distance transport [Plappally, 2010]. Therefore, a boundary for the transport and sales of the water filter by the potter is prescribed [Duemmel and Plappally, 2017). The boundary thus prescribed assumes filter as a metaphor to a crop which may become less profitable with transport to large distances. In India, village potters have a close-knit association with the village community, and this is closely related to his sustained skill sets [Erez *et al*., 2014].

The survey of the potters showcased eight points on which the potter community sustained. The eight points will be transformed to modified eight new points which will help G-filter manufacture. The transformation thus conceived has learn-teach principle which is time dependent and is illustrated in Figure 5.3 [Geels, 2010]. Presently this diagram illustrates a smooth shift of the water filter dissemination using trust-based culture of potter within the bounds of a specific eco-geological system (In this case, arid desert with salty clays in western Rajasthan). According to the local village residents, volume of product manufactured by a potter is very much proportional to the local customer trust that the quality of the products manufactured by potters are satisfactory and perform their function as required [Loureiro and González, 2008; Prigent-Simonin and Hérault-Fournier, 2005]. Therefore, the direct to customer reach of the potter and interdependence for sustenance is again provided importance in Figure 5.2. Mutual trust between potter and local consumers (society) produce should bring down the cost of the G-filter and maintain its functional quality [Covey and Merrill, 2006; Prigent-Simonin and Hérault-Fournier, 2005].

From the previous chapters it is clear that the knowledge of use of clay and sawdust together and its variant compositions is already present within the potter community. A high-quality education of the skill of pottery can be imbibed without traveling elsewhere in search of a teacher. Local people believe that quality provided by an elder in the potter family can be provided by his successor within his family. This mode of teaching creates a natural trust within the society that potter's successor from within the family can assure the same level of product quality. Thus, the access of knowledge provides availability of labor as a resource for this project execution. Thus, the survey results of three traditional potters from Jodhpur illustrate eight basic parameters of basic pottery project management as shown in Figure 5.2 and renamed elaborately in Figure 5.3. It is observed that an inherent hierarchy within the potter households' steers material selection (women), every day planning, training, maintaining quick corrective actions on the clay structures, constantly performs checks to the baked products and its marketability, thus mirroring SLIM-IT model [Maia *et al.*, 2012].

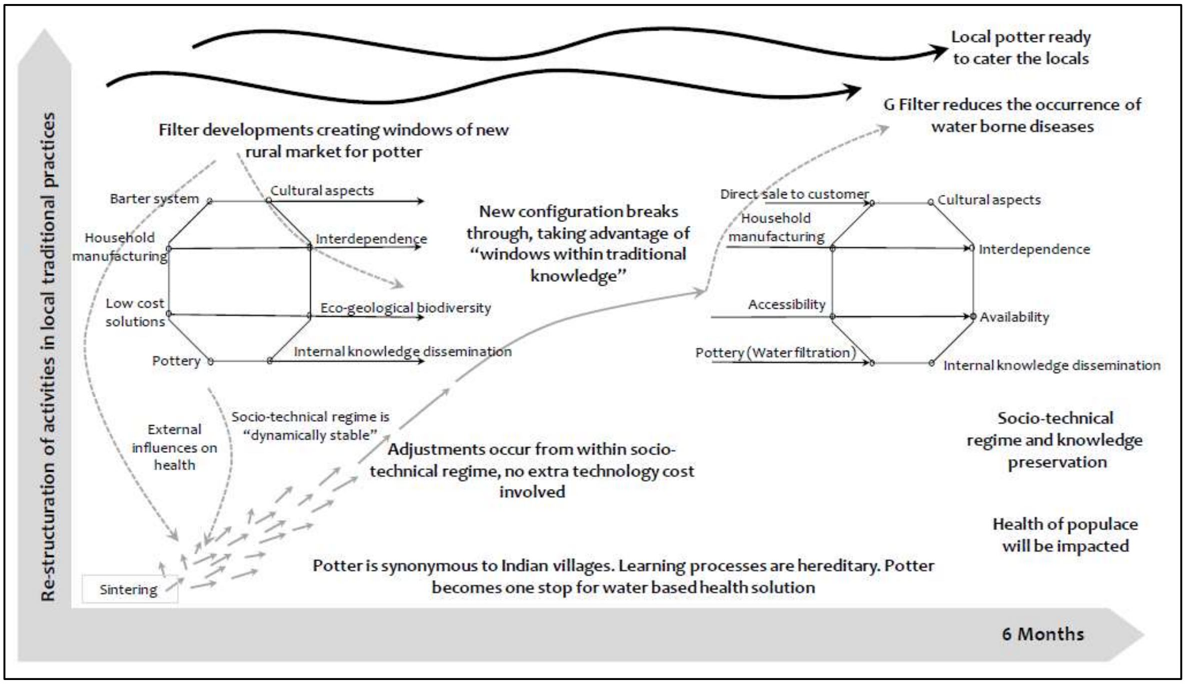

Figure 5.3: Octagonal prism-based socio-technology project management system for G-filter knowledge dissemination [Satankar *et al.*, 2018]

Further, to the fact that the potter themselves were the first user of the clay ceramic water filter a user survey was developed following the UN guidelines for drinking water surveys [Plappally *et al.*, 2018]. This particular development was carried out with the potters as the feedback group and is attached in appendix (Annexure A.3).

5.2.2 Forming the Soil-Sawdust Mixture into a Frustum Shape (G-Filter)

Salty raw clay is mined from Raithal and Mokalsar near Jodhpur, Rajasthan which is then powdered to a size of range 0.18-3 mm as recommended by "Potter for Piece" [Satankar *et al.*, 2017; Gupta *et al.*, 2018]. Clay found in Jodhpur district is kaolinitic in nature and mostly are plastic-fire clays or ball clays [DMG, 1960; IBM, 2014; IBM; 2015]. The women (irrespective of the location of potter across India) sieve the clay using a household sieve (3 mm×3 mm). If the salt content within the clay (refer section 4.2.1) is not sufficient (0.02% by volume), additional salt is added to the clay [Shotyk *et al.*, 2006]. Addition of salt is considered to make the clay ceramics more load bearing, whiter in color, and functionally better refrigerators of water [Roux, 2015]. Local artisans believe that addition of salt in clay influence the sintering rates of clay ceramics. Traditionally, equal volumes of soil and organic matter (sawdust) are kneaded together to manufacture structurally stable construction materials in western Rajasthan [Satankar *et al.*, 2017]. Sieving of sawdust is performed with the same sieve used to for the powdered salty clay. This is analogous to the 'Potter for Peace' method of preparing the clay-sawdust mixture for manufacturing the filter greenware [Plappally *et al.*, 2010; Satankar *et al.*, 2017].

In this study, a uniform mix of sawdust and clay took in equal volumes is added with 70% by volume of water to form disk-shaped composites [Plappally *et al.*, 2011]. The composite is kept overnight a moist cloth covering [Handler, 1963]. The composite (approximate mass of 7.5 kg) is press-formed to frustum shape using a 30-ton press (MEC Ltd., India) [Plappally *et al.*, 2009]. The frustum-shaped aluminium molds (used to press form the greenwares) are covered with a 96 cm diameter plastic bag to prevent formed green body from sticking to the mold wall [Plappally, 2010]. It should be noted that several versions of frustum-shaped water filter presses (gear based, hydraulic jack based, and winch based) are available and are being used around the world [Plappally *et al*., 2011; Baumgartner *et al*., 2007; Henry, 2013]. A photograph of the indigenous filter press (hydraulic jack and screw rod based) built to make a 9-liter filter green body of the composite mix is shown in Figure 5.4.

(a) Sawdust (sieving) (b)Local soil (sieving) (c) Wet mass preparation

(d) Final consistency (e) Moulding machine (f) Truncated cone greenware

Figure 5.4: G-filter manufacturing steps

The greenware, thus formed is 23 cm high and has a base diameter of 25.5 cm. These dimensions were set according to a commercially available plastic bucket of 38 cm height. The greenware separator illustrated in Figure 5.4 was utilized to retrieve the filter greenware. The filter greenware once formed was kept for 2-days in ambient conditions and then cured under direct sunlight for 3-days in this work. The age of curing, its rate and methodology influence the structure and function of the final sintered ceramic being produced [Ravi *et al*., 2007].

5.2.3 Baking of G-Filter

Once cured, the greenware is baked in a vertical open-hearth furnace (circular shape) of 5 ft (152.4 cm) radius and 5 ft (152.4 cm) height [Roux, 2015]. This updraught baking furnace was introduced in Jodhpur in the 1960s [Roux, 2015]. The greenwares are kept 2 ft (61 cm) above the ground in an inverted position while baking (as illustrated in Figure 5.5) [Roux, 2015; Ravi, 2007]. The local potters informed that clay flower vases were baked at very high temperatures (800-900 °C) using a similar arrangement. These temperatures are similar to those set-in factory mode sintering [Yakub *et al*., 2013; Plappally *et al*., 2011]. The incorporation of a baking technology from within their traditional knowledge system, thus prevents cognitive dissonance within the potter household manufacturing team [Aronson, 1969]. This becomes one of the reasons for illustrating the management process transition in Figure 5.3.

Locally available cow dung cakes, organic waste (dried twigs or leaves), waste wood, and sawdust are used as fuel for the furnace. The baking should be performed at a temperature range that precludes cracking possibility. During the sintering trials, some of the filter greenwares cracked due to thermal stress. The continuous measurement of the temperature variation in the furnace during the baking process was conducted with an IR thermometer and K-type thermocouple capable to measure in the range -50 °C to 1850 °C (HTC IRX-68). K-type thermocouples were placed inside the furnace at different points to get an overall average time history of the temperatures during the baking process. The measured sintering temperature-time history, which precludes the emergence of cracking is plotted in Figure 5.6.

Figure 5.5: The geometrical arrangement of filter greenware (G-filter) within the up-draught furnace (Solidworks, 2015, IIT Jodhpur License)

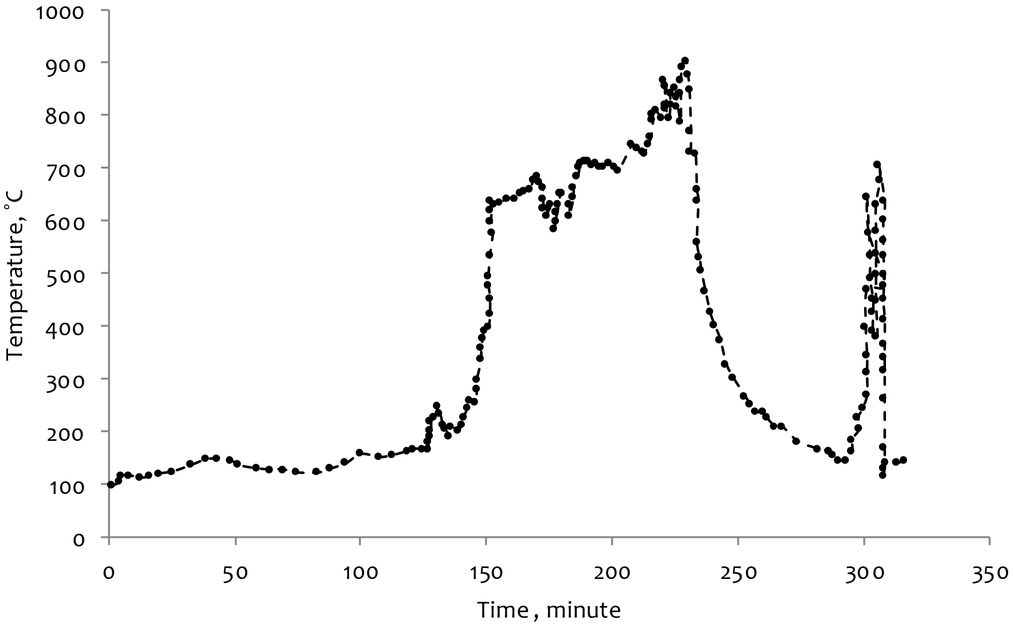

Figure 5.6: Time history of measured overall temperature variation in the furnace that precludes cracking of the G-filter

The baking time illustrated in Figure 5.6 (~230 min.) is comparatively shorter compared to factory-based ceramic water filter baking (7-8 hours) [Baumgartner *et al.*, 2007; Miller and Watters, 2010]. In the present case, baking 45 filter green bodies consume 100 kg of wood and 100 kg of sawdust in an up-draught furnace [Roux, 2015]. Once the baking process is completed, the filters are retrieved after overnight cooling.

5.3 FUNCTIONALITY ASSESSMENT OF THE MANUFACTURED FILTERS

Various functionalities of the manufactured G-filter (approximately 48 percentage porosity and pore size range of 0.02-350 µm) were systematically evaluated [Nighojkar *et al.*, 2019]. The volumetric filtration rate, compressive load bearing capability, and microbial removal rates were tested and quantified to assess the characteristics of the water filters. These are discussed in the following sub-sections.

5.3.1 Flow Measurement

The discharge from the G-filter is measured in fully filled condition. The filtrate was collected from four distinct filters manufactured at Banad, Sar, and Salawas villages in Jodhpur, Rajasthan. A graduated beaker was kept beneath each of the fully filled water filters suspended from a test frame. These four filters were randomly selected. The filtrate is the water, which is collected during the first hour of filtration running in a fully filled condition. The time measurement was performed using a digital stopwatch (Casio® A158WA-1DF). The water was collected from the four filters on different days of the year to simulate filtration at distinct climate temperature conditions.

Percolation rates of water from the four selected G-filters are plotted in Figure 5.7 as a function of the temperature [Salvinelli and Elmore, 2015]. In the first hour of experimentation on G-filter samples, the fully filled filters found to produce 600-950 ml of filtrate water. Similar results have been observed in other clay ceramic water filter variants across the globe [Salvinelli, 2016; Schweitzer *et al.*, 2012; Yakub *et al.*, 2013]. From Figure 5.7 it is observed that the maximum percolation rate occurred at a temperature range between 30-40 °C. If any researcher is interested to understand the variation of viscosity and filtration rate with respect to temperature, they are encouraged to read Nighojkar *et al.*, 2019. There is a dip in the filtration rate when the ambient temperature goes above 40 °C.

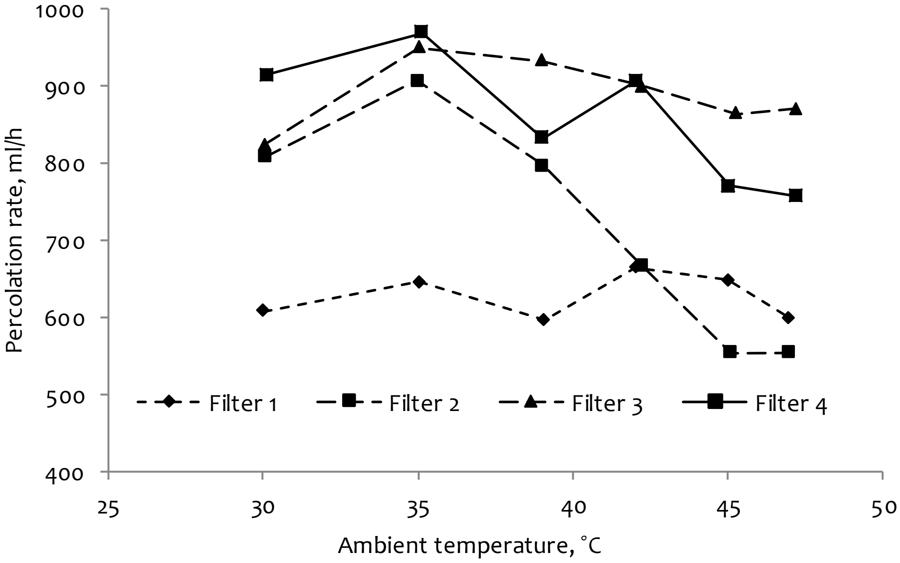

Figure 5.7: The percolation rate of the G-filter in the completely filled condition

5.3.2 Compressive Strength

The compressive tests were performed according to the ASTM 1358 standards [Plappally *et al.*, 2011]. Propagation of cracks in ceramics during compressive loads is parallel to the axis of applied compressive load [Ashby and Jones, 1998]. The specimens for the strength tests were prepared from the circular base of the eleven randomly selected sintered G-filters. A static axial load at a rate of 0.1 N/s is applied to the 35 mm thick sample with a cross-section of 15 mm × 15 mm [Plappally *et al.*, 2011; Yakub *et al.*, 2012]. Thirty samples in total were tested for compression on a universal testing machine (Model EZ-50, Lloyd Instruments, Germany). It should be noted that inherent cracks or inhomogeneity in the porous clay ceramics increase during compression resulting in powder formation [Ashby and Jones, 1998; Barsoum, 2003; Plappally *et al.*, 2011]. Tests were conducted at a temperature of 27 °C and a relative humidity of 20-25%. It is known that compressive failure stress of any clay ceramic material is a polynomial function of its corresponding density [Plappally *et al.*, 2011]. It is therefore pertinent to observe the little variations in density owing to the craftsmanship of the potters from Banad, Sar, and Salawas villages. Mass of the samples was measured using a digital weighing balance (Citizen CG3S, M/s Indian Equipment Company, Jaipur, India) and then the density was calculated by dividing the mass to the geometrical volume of the sample.

The compressive strength of ceramic filter material depends on the heterogeneous character [Rice, 1971]. The eleven G-filter greenwares in the updraught kiln contain pre-existing non-elastic deformation or crack forming inhomogeneity (completely oxidizable organics) [Gladkov, 2003; Plappally *et al.*, 2011]. The compressive strength of the tested specimens is plotted as a function of the density of the specimens. The best fit of the data with an R^2 of 96.39% was found to be a polynomial expression as shown in Figure 5.8. The polynomial relationship of the compressive strength σ_{cf} of the G-filter material with its density ρ conforms to similar relationships derived by other researchers [Plappally, 2010; Plappally *et al.*, 2011]. An increase in the density of the clay ceramics accompanies an increase in the compressive strength of the ceramic [Karaman *et al.*, 2006; Yakub *et al.*, 2012].

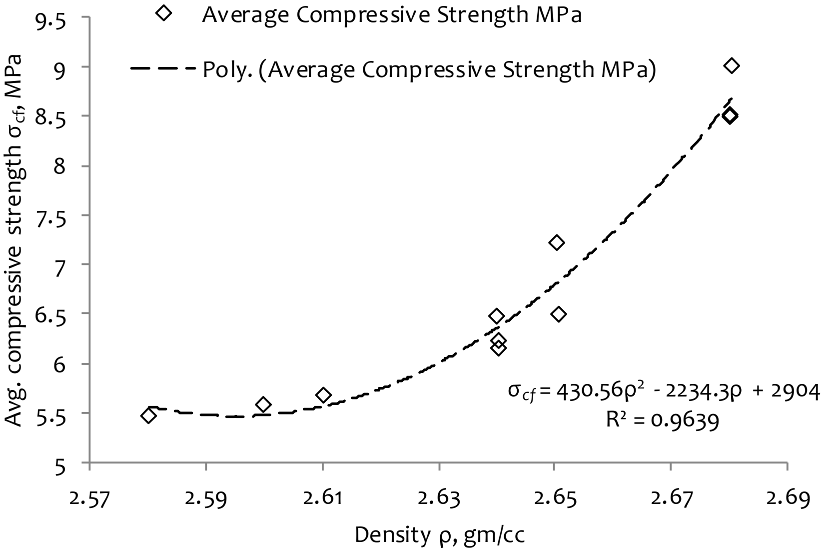

Figure 5.8: Compressive strength as a function of the density of G-filter material

5.3.3 Microbial Filtration

E. coli (Escherichia coli) is an indicator bacterium for occurrence of bacterial pathogens and also for fecal contamination [Brown *et al.* 2006; Chigbu and Salina, 2014]. E. coli concentration tests in the pre- and post-filter water samples were conducted according to ISO 9308-1:2014 framework [Karaman *et al.*, 2006]. E. coli, One Shot® TOP10 (Thermo-Fisher Scientific, India) cells (similar to the E. coli DH10B strain) was used for spiking the concentration in the ultra-pure water (only water molecules with conductivity of 0.055 µS/cm at 25 °C or resistivity of 18.2 MΩ). The pure water was supplied by M/s Tomar Scientific, Jodhpur, India. This brand of E. coli is commonly available for laboratory experiments such as cloning, and plasmid propagation [TFS, 2016]. One Shot® TOP10 E. coli strain was grown in Miller's LB (Luria-Bertani) Broth at ambient condition overnight [TFS, 2016]. Concentrated E. Coli solution ($2.4\text{x}10^6$ cell/ml), diluted with three liters of microbial contaminant free ultra-pure water was stored in a cold storage which was maintained at -75 °C in the laboratory of Biologically Inspired System Science Centre, IIT Jodhpur. This solution was prepared prior to the day of the filtration tests. The pre-filtrate sample was prepared by spiking required E. Coli stock (mentioned above) into a constantly stirred 30 liters water tank. The experimental set-up is diagrammatically represented in Figure 5.9. The complete microbial filtration test set up is kept within a plastic structure. The initial one liter of the filtrate was discarded to prevent initial dilution of filtrate due to their saturation. Saturated filter receptacles are used to simulate operational conditions of the filter. The beaker is cleaned with ethanol followed by rinsing with deionized water and

500 ml of filtrate was collected. The number of viable cells in the contaminated water within the G-filters and the filtrate was determined by dilution in ultrapure water [DCCCD, 2011]. Further, plating was performed on Miller's LB agar plates. These plates were kept overnight in incubators at 37 °C. The colonies were counted after incubation at 37 °C and this information was used to calculate viable cells in the respective water samples. The numbers of viable cells in the pre and post-filter suspensions were counted. The efficiency of E. coli filtration can be calculated by Eq.(5.1) [Brown *et al.*, 2007],

$$\eta_{E.Coli} = 1 - N_f/N_{pf} \tag{5.1}$$

Where, N_f is the number of viable cells per milliliter of filtrate and N_{pf} is the number of viable cells per milliliter in the pre-filter sample. The log reduction value is calculated by Eq.(5.2) written below [Brown *et al.*, 2007; Plappally, 2010].

$$LRV = \log_{10} N_{pf}/N_f \tag{5.2}$$

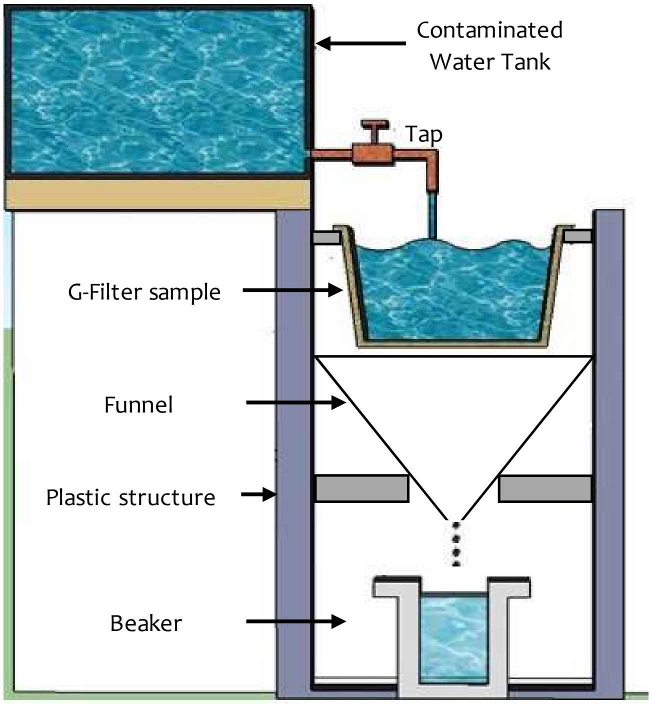

Figure 5.9: Schematic of the microbial filtration set-up

Table 5.1: Results of E. Coli filtration efficiency test of the G-filters

Pre-filter concentration (No. of Cells/ ml), N_{pf}	Filtrate concentration (No. of Cells/ ml), N_f	Pre-filter /Filtrate concentration, N_{pf}/N_f	Efficiency $1 - N_f/N_{pf}$	Log Reduction Value (LRV)
6.0×10^8	1.6×10^6	375.0	0.9973	2.5
4.0×10^8	6.0×10^6	66.6	0.9949	1.8
2.4×10^8	4.5×10^6	33.3	0.9912	1.7

A contaminated water suspension with almost around 10^8 cells/ml was used in the pre-filter sample. Similar levels of contamination (10^6-10^8 cells/ml) have been observed in the Yamuna river water, which is a major source of drinking water in Northern India [CPCB, 2012]. This fecal coliform contaminant level is higher than the values of the drinking water quality standards set by World Health Organization (WHO) [Gorchev and Ozolins, 2011]. The E. coli filtration experiments were performed on the three G-filter. Each of these G-filters were tested four times using a produced contaminated solution of E. coli as mentioned above. Table 5.1 shows the efficiencies of the three distinct G-filters tested. The microbial treatment efficacy of such filters is at par with clay ceramic water filter produced in factories elsewhere [Sobsey *et al*., 2008; Baumgartner *et al*., 2007].

5.4 SUMMARY AND CONCLUDING REMARKS

Household mode of manufacturing G-filters is discussed. This mode of manufacturing varies from the factory mode [Brown *et al*., 2007; Plappally *et al*., 2011; Rayner *et al*., 2013]. The manufacturing practices have close parallels with the best management practices such as office Kaizen. These clay ceramic filters are considered to be one of the sustainable drinking waters procuring solutions in developing countries [Plappally *et al*., 2011]. These filters are sintered using the indigenous baking technique. The filtration rate through the G-Filter is ambient temperature dependent. The maximum filtration rate of G-filter was observed between the temperature range of 30-40 °C. Manufactured filters with a low-density material have lower compressive strength. It is reiterated that a polynomial function exists between the density and compressive strength of the G-filter material [Plappally *et al*., 2011]. The implication is that potter households dispersed at a different location in western Rajasthan and across India can locally and individually choose to manufacture G-filters and distribute to their surroundings. This reduces the cost of transporting water filters to remote locations in rural India.

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