Measuring Clay Property Variation and Effects on Ceramic Pot Filter Performance

by

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ABSTRACT

Pure Home Water (PHW) is a non-profit organization in Ghana whose mission is to provide safe drinking water to Ghana's Northern Region – the poorest part of the country. Originally a distributor of ceramic pot filters (CPFs) manufactured in Accra, PHW began construction of a new factory outside of Tamale in late 2009 when it was recognized that importing filters from Accra was too inefficient to meet the demands for household water treatment and safe storage.

One aspect of CPF manufacturing that has a significant impact on the quality of the finished product is the clay "recipe." In 2010, Reed Miller and Travis Watters conducted research to determine the optimal ratio of combustible material to clay that would yield filters with suitable flow rates, water quality, and strength. However, until 2011, limited research was done on the clay itself, and the relationship between clay properties and PHW filter performance was largely unexplored. Clay has been harvested from a site in Gbalahi, 1 mile away from the PHW factory. Since PHW's acquisition of a second clay source in Wayamba, it has become important to determine to what extent the clays from the two sites are different, as well as which clay properties have the largest impact on quality filter production.

To answer these questions, the author measured the plasticity and particle size distribution of 12 clay samples collected from each site. Filters were made from each sample and their performance evaluated based on removal of turbidity, coliform, and *E. coli*. Statistical analyses were conducted to determine the significance of the observed differences between and relationships among the measured parameters. The Gbalahi clay was found to be more plastic and have a higher clay content (less sand and silt), and filters made from this clay had lower flow rates and better turbidity removal.

Thesis Supervisor: Susan Murcott
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* All pictures are credited to the MIT MEng Ghana Team unless otherwise noted.

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Abbreviations
ASTM – American Society for Testing and Materials (former name)
CMWG – Ceramics Manufacturing Working Group
CPF – Ceramic pot filter
CT – Ceramica Tamakloe Ltd.
HWTS – Household Water Treatment and Safe Storage
MEng – Master of Engineering
MIT – Massachusetts Institute of Technology
MPN – Most probable number
NGO – Non-governmental organization
OECD – Organization for Economic Cooperation and Development
PHW – Pure Home Water
PFP – Potters for Peace
RESVODEP – Rural Education Volunteer and Social Development Program
SARI – Savanna Agricultural Research Institute
SODIS – Solar water disinfection
TNTC – Too numerous to count
NTU – Nephelometric turbidity unit
UNICEF – United Nations Children Fund
WHO – World Health Organization

1 Introduction[1]

1.1 Overview of Water Resources in Northern Ghana

The United Nations and the World Health Organization (WHO) categorize water sources as either "improved" or "unimproved." Improved refers to protected water sources including household connections, public standpipes, boreholes, protected dug wells, protected springs, and rainwater harvesting. Unimproved refers to unprotected wells, unprotected springs, vended water, tanker truck water, and all surface waters. These metrics define the Millennium Development Goals targets relating to water. Figure 1-1 pictorially shows the percentage of improved vs. unimproved sources in the districts of the Northern Region of Ghana. With rare exception, most areas suffer from a severe lack of improved water sources, and in total about half of the people in the Northern Region drink water from unimproved supplies.

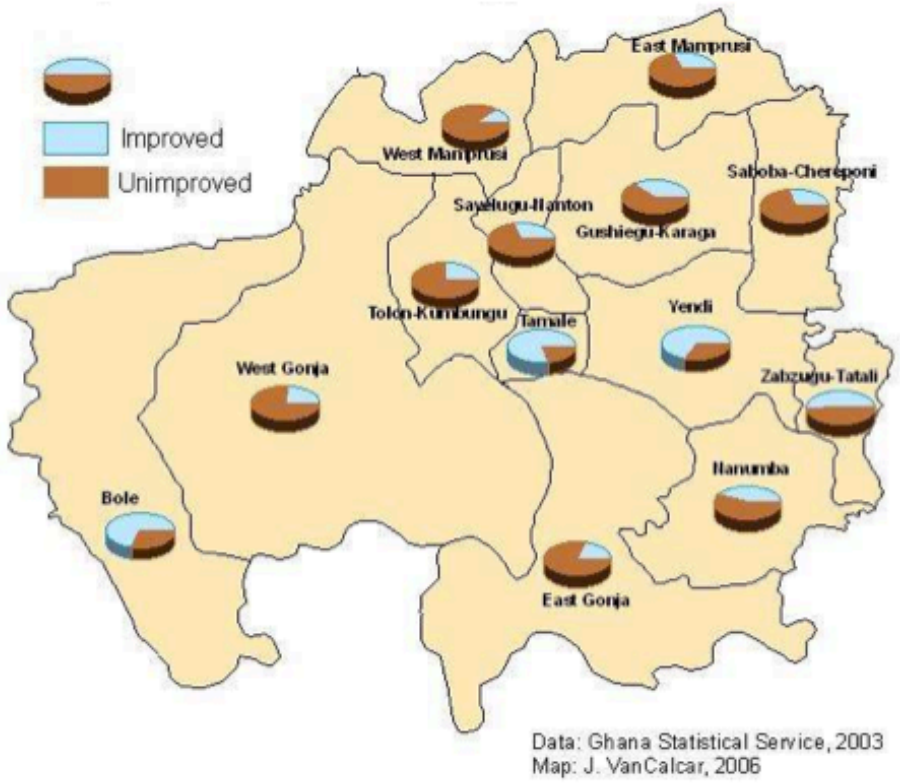

Figure 1-1: Improved and unimproved water sources in Northern Ghana

With unimproved water sources comes the increased risk of unsafe water that contains dangerous pathogens. These pathogens include the bacteria, protozoa, and viruses responsible for causing cholera, typhoid, hepatitis A & E, guinea worm, and other water-

[1] Written with team members Shanti Kleiman, Samantha O'Keefe, Joanna Cummings, and Jonathan Lau.

related diseases. In Ghana, diarrhea accounts for 12 percent of all deaths of children under five prompting the need for further action in the area of water supply, water treatment, sanitation, and hygiene (World Health Organization 2006). Figure 1-2 demonstrates the severity of this problem, especially in the Northern and Upper West Regions of Ghana where the mortality rate for children under five is 154 and 208 per 1000 births respectively. In contrast, the under-five mortality rate in the USA is 7.8 per 1000 births (World Bank, World Development Indicators 2011).

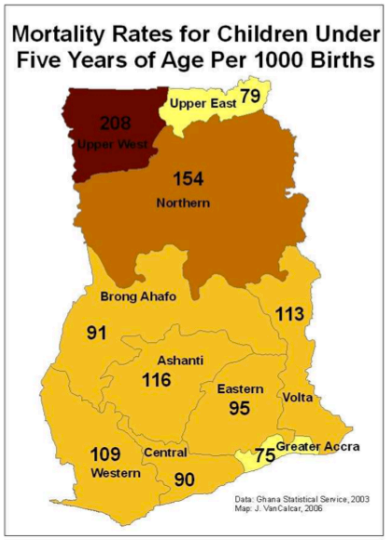

Figure 1-2: Mortality rates, Ghana

1.2 Ceramic Filter Manufacturing

Ceramic filters are available around the world in different forms; candle filters, disk filters, and colloidal silver enhanced ceramic pot filters. Pure Home Water (PHW) manufactures colloidal enhanced ceramic pot filters in Ghana's Northern Region, and is one of approximately 35 operational filter factories in 18 countries producing this type of filter (Rayner 2009).

The filter was originally developed by Dr. Fernando Mazariegos in Guatemala in 1982, and after Hurricane Mitch in 1998, Ron Rivera of Potters For Peace (PFP) began trainings in standardized small factory production. In 2010, the Ceramics Manufacturing Working Group (CMWG) published a study on the Best Practices for Ceramic Filter Manufacturing, which surveyed 34 filter factories on their production and quality control procedures (CMWG 2010). Based on an extensive literature review and survey results from the 25 factories that responded, they produced best practice protocols and standardization recommendations for existing and future factories.

Manufacturing the filter is a multistep process that requires quality checks and standardized procedures at each stage. The production process can broadly be broken down into the following phases:

- Sourcing material
- Mixing clay & burnout material
- Pressing clay into filter pots
- Trimming pressed filters
- Drying
- Firing
- Visual and auditory inspection
- Flow rate testing
- Applying silver
- Pressure (crack) tests
- Water quality testing
- Packaging and delivery

Work done at PHW in January 2011 by the MIT Master of Engineering team focused on research, standardization, and improvement of manufacturing protocol for the ceramic pot filter and introduction of potential new products for expansion of the PHW line.

1.3 Pure Home Water Organizational History

Founded in 2005 by MIT Senior Lecturer Susan Murcott with local partners, PHW is a non-profit organization in Ghana whose mission is to provide safe drinking water to the people of Northern Ghana - the poorest part of the country. The organization's goals are:

1. To reach the people most in need of safe drinking water and
2. To become financially and locally self-sustaining

Early student teams from MIT researched performance of, consumer preferences for, and consumer willingness to pay for water treatment techniques in order to find the best system for the region. In addition to considering several types of ceramic filters, they investigated biosand filters, chlorination systems, and solar water disinfection (SODIS). Through these studies, PHW determined that, of the options for household drinking water treatment and safe storage (HWTS) available in Northern Ghana, ceramic pot filters (CPFs) with safe storage containers offered the simplest and cheapest method to effectively treat drinking water in Northern Ghana at the household scale. From 2006-2009, PHW focused on distributing CPFs that were made at Ceramica Tamakloe Ltd. in Accra, Ghana, teaching people how to use them and monitoring how effective and durable they were over time. They chose ceramic water filters because they are effective in removing *E. coli*, have been shown to be linked to the reduction of cases of diarrhea, can be manufactured almost entirely out of local materials, and are culturally appropriate since water is generally stored in large clay vessels in Northern Ghana (Johnson et al. 2008).

1.4 Pure Home Water Factory

As PHW grew, importing filters from Accra became less efficient. Initially, many CT filters were broken on the trip from Accra to Tamale, and over time PHW had trouble

with the supplier providing pots behind schedule and of uneven quality. In order to eliminate these problems in the supply chain and better serve Northern Ghana, PHW began constructing its own factory in Tamale in late 2009. Construction of the building was completed during the summer of 2011, and it is already equipped with the molds, supplies, and the kiln necessary for production. In January of 2010, a two-person team of MIT students began work on developing a set of best filter production practices for the new factory. Miller (2010) and Watters (2010) established recommended clay recipes based on flow rate and strength of the filters made with different proportions of combustible material and clay. Further work and research must be done to ensure that filters being produced at the new factory consistently perform well. Preliminary filter production produced some pots that were of uneven quality and too brittle to be sold. The factory currently has orders pending from NGO groups to supply filters for Northern Ghana that can be filled once quality controls are established and quality production is ensured.

The factory is also set up to produce rammed earth blocks in addition to clay pots. Early attempts to sell the *Kosim* filters at their true production price were unsuccessful. The $18 selling price of the system was well above what rural families were willing to pay – particularly the more vulnerable, rural households that PHW aims to serve. In order to realize its goal of being self-sustaining, PHW is testing rammed earth block, concrete block, and/or fired brick production as a revenue stream to subsidize *Kosim* filters for rural families. PHW currently has standard rammed earth block molds and a press and has produced the earth blocks for the construction of its own factory, but has not yet constructed a point of sale for the blocks or contacts with other vendors.

1.5 Research Objectives

In order to help PHW meet its goal of making consistent and marketable filters, the objectives of this thesis are as follows:

1. Measure the variation of clay plasticity and particle size distribution of samples from the two sites supplying the PHW factory.

2. Evaluate the performance of the filters made from each sample based on turbidity, coliform, and removal.

3. Based on the statistical analysis of the results from the above tests, make a recommendation as to which clay is better for filter production.

A work schedule can be found in Appendix A.

2 Literature Review

2.1 Optimizing Performance of Ceramic Pot Filters in Northern Ghana and Modeling Flow through Paraboloid-Shaped Filters

Part of Miller's research focused on establishing a clay "recipe" that would yield effective filters. One of the main quality control measures for ceramic pot filters is the flow rate of water through a saturated filter. Potters for Peace recommends a flow rate of 1 to 2.5 liters per hour, but this was found to be too low for larger families (more than 6 people, a typical family size in rural Ghana and elsewhere) and can be a factor contributing to decreased filter use (Bloem et al. 2009). To increase the flow rate, larger amounts of combustible material such as sawdust or finely ground rice husk can be added to the clay mixture before firing. The combustible material burns off during firing, leaving small pores that allow water to flow through more readily. This comes at the cost of water quality, however, since larger pores also allow more sediment and bacteria through the filter.

As a part of his Masters thesis, Miller experimented with different clay recipes, varying the combustible preparation method and proportions of combustible material to clay by mass. Filters were made from each of 15 recipes, and their performance measured and ranked by the removal of turbidity and bacteria. The results of this study, combined with the concurrent research of Watters, allowed recommendations to be made to Pure Home Water for the best filter recipe to use. The recipes and combined study results from Miller and Waters are summarized in Table 2-1 and Table 2-2.

2.2 The Effect of Compositional and Geometrical Changes to the Bending Strength of the Ghanaian Ceramic Pot Filter

Previous studies by MIT Master of Engineering students in Ghana revealed that filter breakage was one of the main reasons for discontinued use, with a breakage rate of 12% among 1,000 homes that were monitored three to seven months after an emergency distribution of the filters in 2008 (Desmyter et al. 2009). To determine the effects of increasing combustible proportions and pot thickness on the strength of the filters, Watters performed three-point bending tests on rectangular prisms of varying thicknesses using the same recipes as Miller.

The inclusion of grog (previously fired clay crushed, sieved, and incorporated into the clay/combustible mixture) was found to have no effect on filter strength. The strongest filters were the ones that used only fine, sieved combustibles, and filter strength was found to decrease with increasing proportions of combustible. The recommended recipe, based on the combined research of Miller and Watters, used fine-and-waste rice husk with a 3:8 combustible-to-clay ratio. Watters also recommended thickening the filter lip to 25 mm, since this is where breakages generally occurred.

Table 2-1: Clay recipes, adapted from Watters 2010.

ID	Combustible Type	Hammermill Product	Clay Mass (kg)	Grog Mass (kg)	Combustible Mass (kg)	Fine Combustible Mass (kg)	Waste Combustible Mass (kg)	Total Mix Mass (kg)
1	Rice Husk	Fine and Waste	11	0	3.00	1.50	1.50	14.00
2	Rice Husk	Fine and Waste	11	1	3.00	1.50	1.50	15.00
3	Rice Husk	Fine and Waste	11	0	4.00	2.00	2.00	15.00
4	Rice Husk	Fine and Waste	11	1	4.00	2.00	2.00	16.00
5	Rice Husk	Fine and Waste	11	0	5.00	2.50	2.50	16.00
6	Rice Husk	Fine and Waste	11	1	5.00	2.50	2.50	17.00
7	Sawdust	Fine and Waste	11	0	2.19	1.09	1.09	13.19
8	Sawdust	Fine and Waste	11	1	2.19	1.09	1.09	14.19
9	Sawdust	Fine and Waste	11	0	2.19	1.46	1.46	13.91
10	Sawdust	Fine and Waste	11	1	2.19	1.46	1.46	14.91
11	Sawdust	Fine and Waste	11	0	3.64	1.82	1.82	14.64
12	Sawdust	Fine and Waste	11	1	3.64	1.82	1.82	15.64
13	Sawdust	Fine Sieved	11	0	1.82	1.82	0.00	12.82
14	Rice Husk	Fine Sieved	11	0	2.55	2.55	0.00	13.55

Table 2-2: Ranking table for clay recipes, adapted from Watters 2010

Recipe #	Strength	Flow Rate	*E. coli*	Total Coliform	Total Score
1	5	4	2	3	14
2	5	5	1	2	13
3	6	3	1	3	13
4	6	3	1	4	14
5	7	2	1	3	13
6	7	1	1	5	14
7	1	7	3	5	16
8	1	7	2	5	15
9	3	7	1	5	16
10	2	7	3	4	16
11	4	5	2	5	16
12	6	4	1	4	15
14	1	5	1	5	12

2.3 Best Practices Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment

Released in September 2010 by the Ceramics Manufacturing Working Group and updated in March of 2011, this document provides guidance on all aspects of filter production from clay sourcing to filter firing and distribution, as offered by experts in

each of these areas. The manual was assembled in response to the high demand for filters and lack of standardized manufacturing procedures, following the group's mission to assist factories around the world in making filters that are affordable and of high quality.

Clay has a direct impact on the filter's strength, porosity, and probability of cracking. One of the important measures of clay quality identified by the Ceramics Manufacturing Working Group is its plasticity, or ability to be shaped and molded. This is directly related to its particle size distribution and water content. The Best Practices Manual recommends methods to measure the water of plasticity (water content at which the clay becomes workable), which can also indicate how fine the particles are. The Best Practices Manual also suggests methods for determining the dry shrinkage, firing shrinkage, and porosity of the clay.

2.4 Sustainable Colloidal-Silver-Impregnated Ceramic Filter for Point-of Use Water Treatment

In their study, Oyanedel-Craver and Smith produced multiple sets of filters, varying the quantity and method used to apply colloidal silver and compared their performance against a set of control filters that had no silver. Though the primary purpose of their research was to study the effects of colloidal silver on filter flow rate and bacteria transport, three different clay samples were used, two natural clays and one commercial pottery clay. Thus, some information on the effects of clay properties on filter was also gathered.

Filters were made using a mixture of 40% clay, 10% flour, and 50% grog (previously-fired clay) by weight. The investigators found that larger amounts of flour resulted in weak filters, while larger amounts of clay led to impractically low hydraulic conductivities. The proportions used were chosen after making and testing several different recipes and seeing which had the best strength and flow rate. Bacteria transport was quantified using the Colilert Defined-Substrate Technology System to measure the concentration of a non-pathogenic wild strain of *E. coli* purchased from IDEXX laboratories. Flow rate was measured using a changing-head flexible-wall permeameter test as recommended by ASTM standards, and porosity and pore-size distribution were measured using low- and high-pressure mercury intrusion.

In addition to demonstrating that the addition of colloidal silver reduces the transport of bacteria, this study found that performance is also affected by the grain size and uniformity of the clay used to make the filters (Oyanedel-Craver 2008). One of the clays had a median grain size of 6.3 μm and a uniformity coefficient of 5.1 (lower uniformity coefficients indicate higher uniformity), and another one of the clays had a median grain size of 44.7 μm and a uniformity coefficient of 28.4. The clay with smaller, more uniform particles made filters that performed better. Smaller, more uniform particles also indicate a higher clay content and more plasticity.

2.5 Factory Startup Manual: For the Production of Ceramic Water Filters

This publication is by a US Army Economic Development Officer who built a ceramic pot filter factory in Iraq. It contains a brief section on clay at the beginning that also emphasizes the importance of plasticity. Nardo states that clays don't need to be as plastic when the product is going to be pressed rather than thrown, but that workability is still a chief consideration (Nardo 2005). Nardo lists aging and bacteria as factors that influence plasticity - in addition to composition and wetness. Aging involves storing moist clay, which allows water to penetrate all of the clay particles and allows bacteria to grow. Nardo says that some potters add aged clay, which is full of bacteria, to new clay, thus increasing its plasticity and acidity. A simple test for clay plasticity is to form a small rope and curl it into a ring. The extent to which the clay stays in its ring shape without cracking or falling apart is an indication of its plasticity.

3 Clay Characterization

The first goal of this study is to measure the variation of clay properties within and between the two clay sites available for use by PHW. One of the sites is in Gbalahi, a village approximately one mile away from Taha and the PHW factory. PHW has negotiated an agreement with the chief and elders of the community of Gbalahi for the use of the clay from this site in exchange for traditional one-time gifts and agreeing to employ community members in clay digging and factory production. The other site is in Wayamba, which is approximately 5 miles north of central Tamale on the Bolgatanga highway (Figure 3-1). PHW has a 99-year lease on this site. In addition to these two planned clay sites, a thin lens of clay was discovered at the PHW factory site while digging a hole for a rainwater harvesting tank.

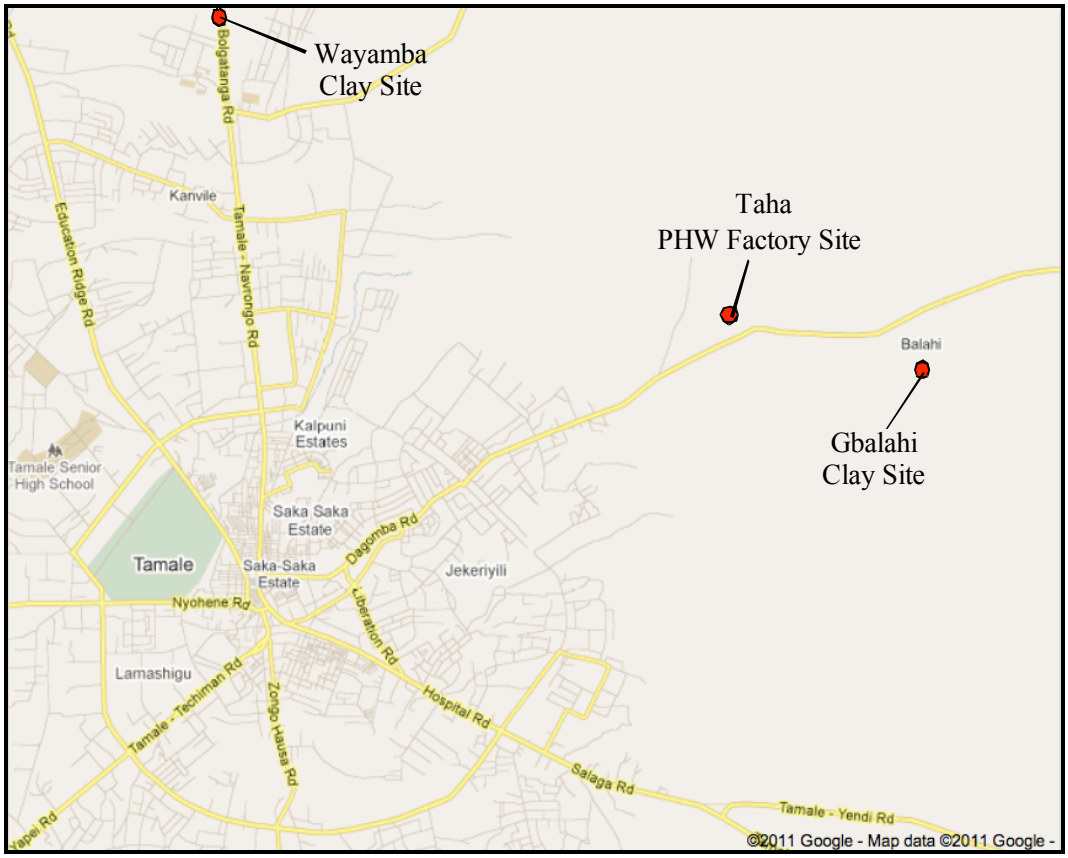

Figure 3-1: Approximate location of clay sites in Tamale (Google Maps 2011)

3.1 Sampling Methodology

Twelve samples were taken from the Gbalahi site and twelve were taken from the Wayamba site. Though the parcels of land have slightly different geometries, a similar grid pattern (approximately 15 meters square) was used for sample locations in both sites. For the Gbalahi site, a grid of 2 holes by 6 holes was used (Figure 3-4), while at the Wayamba site, a grid of 3 by 4 holes was used (Figure 3-5). Local workers were hired

and instructed to dig until they reached clay, which was found about 60 cm below the surface on average at both sites (see Appendix B for pictures of holes and Appendix D for more detailed data on sample depth). The samples were collected over two days total and kept in separate buckets with covers to maintain sample purity and labels to identify which hole they came from. After all samples were collected, large pieces were broken up with a shovel to speed up the drying process, as is done with regular clay processing at the PHW factory. The samples were then spread in piles on a tarp to air dry so that they could be ground and sieved to remove the gravel. All samples dried in the sun for over 48 hours at an average air temperature of 30-35˚C and then were returned to the labeled buckets. Three samples were also collected from the factory site in Taha, but these samples had already been collected and dried for several weeks. It is possible that this could have contributed to differences in the clay test results for those samples.

Figure 3-2: Digging to level of clay in Gbalahi site

Figure 3-3: The Gbalahi clay site

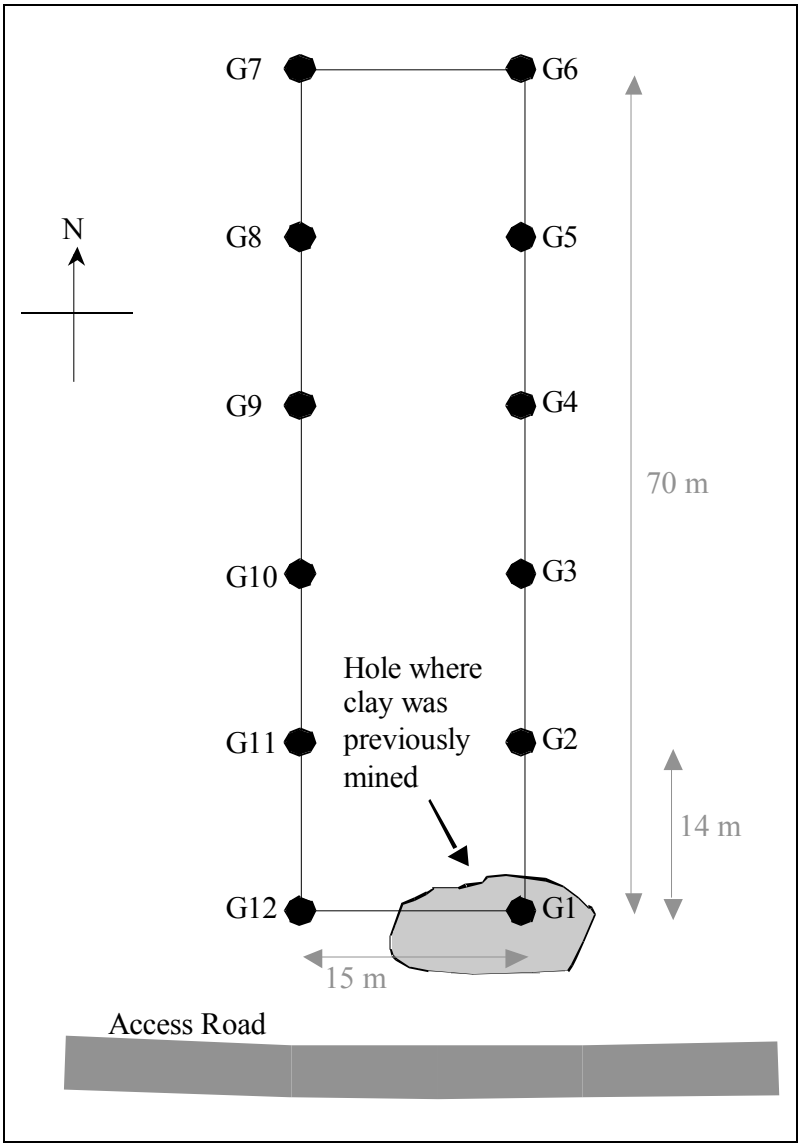

Figure 3-4: Gbalahi sample locations

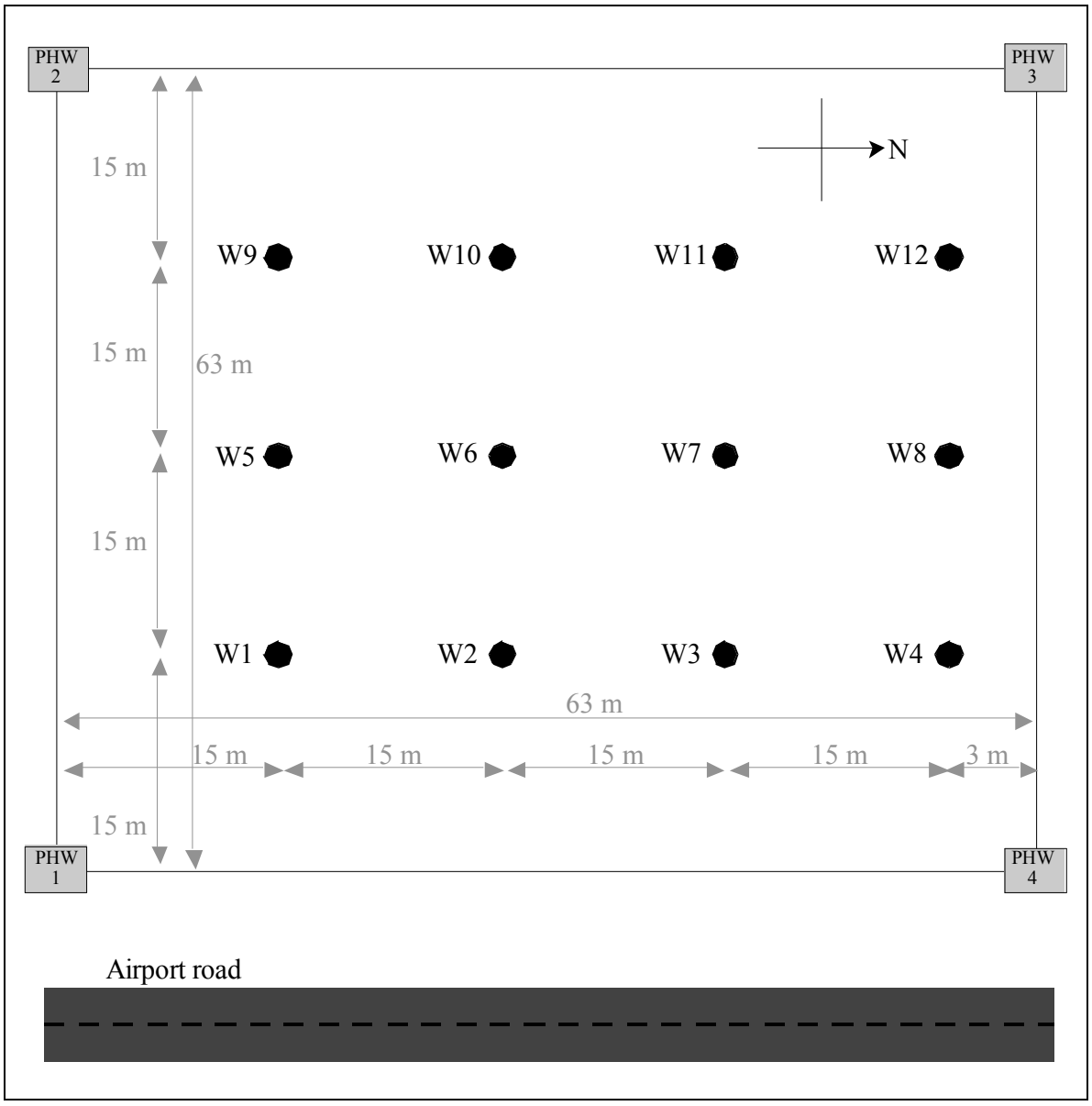

Figure 3-5: Wayamba sample locations, showing plot markers in corners

Figure 3-6: Plot marker at Wayamba site

3.2 Atterberg Limits Tests

The Atterberg Limits tests are a measure of soil plasticity. Originally, Albert Atterberg defined six "limits of consistency" that describe the behavior of soils. They included the upper limit of viscous flow, the liquid limit, the sticky limit, the cohesion limit, the plastic limit, and the shrinkage limit, but today "Atterberg Limits" generally refers to just the liquid limit, plastic limit, and sometimes also the shrinkage limit (ASTM 2010). These limits are a measure of the water content at which the soil behaves in a certain way.

As water content decreases, the soil exhibits a range of behaviors from liquid to plastic solid. On this continuum, the liquid limit marks the boundary between the semi-liquid and plastic states, and the plastic limit marks the boundary between the plastic and semi-solid states. The difference between the liquid limit and the plastic limit gives the plasticity index, the range of water contents over which the soil behaves as a plastic solid. This is relevant to the production of ceramics because only soil that behaves as a plastic solid can be molded or pressed into pots that retain their shape. Based on the liquid limit and plasticity index, a soil with a high percentage of fine particles can be classified by type (silt or clay) and by plasticity (ranging from low to extremely high) using a plasticity chart such as the one from Craig found in Appendix C (2004).

The liquid limit and plastic limit are somewhat ambiguous boundaries. The standardization of methods for determining these values has allowed the comparison of these limits between different soils. ASTM Standard D4318 ("Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils") was followed as closely as possible, but due to time constraints and limitations of working in the field, some adjustments had to be made (ASTM 2010). For example, there was only time for one

plastic limit test for each sample rather than the two recommended in the standards. Other significant deviations are explained in footnotes as appropriate.

3.2.1 Sample Preparation

All 27 clay samples were prepared for liquid and plastic limit tests in the following way:

1) Samples were broken up and dried in separate piles on a tarp for over 48 hours (Figure 3-7).
2) Dried samples were then pounded into a powder using a mortar and pestle.
3) Pounded samples were weighed and then sieved[2] to remove gravel (Figure 3-8). The amount of gravel retained on the sieve was measured and recorded[3] (see Appendix D).
4) At least 250 grams of each sieved sample were collected in Ziploc® bags and labeled with the sample identification number (Figure 3-9).
5) Of the 250 grams, approximately 100 grams were removed for later use in particle size analysis tests, stored in separate Whirl-Pak® bags, and also labeled with the sample identification number (Figure 3-10).
6) The samples remaining in the Ziploc® bags were mixed with distilled[4] water until the samples were easy to work by hand and allowed to cure (stand) for at least 16 hours[5].

Figure 3-7: Samples drying in sun at factory site

[2] Two different sieve sizes were used with openings of approximately 1.5 mm and 1 mm, which correspond to ASTM sieve sizes No. 14 and 18, respectively.
[3] Gravel is technically any particle whose smallest dimension is larger than 2 mm and the sieves were smaller than this, but the particles retained on the sieve were mostly larger than 2 mm and will thus be referred to as "gravel" although small amounts of coarse sand may also have been retained.
[4] It was difficult to locate distilled or de-ionized water, which is required in the standard to prevent minerals from affecting the behavior of the clay. In the end, distilled water was procured at an electrician's store, but it may not have been completely pure because there appeared to be bits of ash floating around inside.
[5] Liquid limit tests were conducted over five days, so some samples had longer curing times. This should not affect the results, as the standard indicates only to let the samples cure for "at least 16 hours" (ASTM 2010).

Figure 3-8: Sieving the clay to remove gravel

Figure 3-9: Sub-samples of pounded, sieved clay for soil tests

Figure 3-10: Sub-samples collected for particle size analysis

3.2.2 Liquid Limit

A Casagrande cup (Figure 3-12) is used to find the liquid limit. This hand-operated device has a brass cup that rises gradually and falls suddenly, hitting the base 10 mm below. A soil pat is formed in the cup (Figure 3-12) and a groove is made (Figure 3-13) using a standard grooving tool (Figure 3-14). The cup is operated and blows counted until the dropping of the cup closes the groove. The water content corresponding to a blow count of 25 is the liquid limit. The following multipoint[6] procedure was used to determine the liquid limit for each of the 27 clay samples:

1) A portion of the cured sample was removed from the Ziploc® bag and placed in a bowl.
2) Distilled water was added or evaporation was encouraged by mixing the sample and/or placing it in the sun for brief periods of time to achieve a consistency that would require approximately 25-35 blows to close a groove formed in this test. The sample was thoroughly mixed in either case (Figure 3-11).
3) A pat of clay was formed in the Casagrande cup by pressing a small amount of the clay from the front of the cup to the back to prevent air bubbles, and then leveling off the sample with a spatula (Figure 3-12).
4) A groove was made in the clay by drawing a standard tool (Figure 3-14) from back to front, with beveled edge forward, keeping the tool perpendicular to the cup (Figure 3-13).
5) The Casagrande cup was operated at a rate of approximately 2 cranks per second and the number of blows counted until the groove had closed at any point[7] (Figure 3-15).
6) Steps 3-5 were repeated until two counts within 2 blows were obtained. A slice of clay was then taken from the cup by drawing a spatula perpendicularly across the groove, obtaining a sample of approximately 10 grams.
7) The smaller sample was placed in a labeled aluminum foil cup and its mass was measured using a digital scale (Figure 3-16).
8) Steps 2-7 were repeated for the same large soil sample, obtaining small samples for water contents corresponding to three different blow counts in the ranges 15-25, 20-30, and 25-35.
9) The small samples were dried in a gas oven at approximately 140˚C for 23 -26 hours (Figure 3-17), and then their masses were measured and recorded again.
10) The difference between the measurements before and after drying gave the mass of water in the sample, and the difference between the dry sample and the mass of the tare gave the mass of the dry clay itself. The ratio of the mass of water to the mass of dried soil gave the water content.
11) For each larger sample, the number of blows for each of the three small samples and the corresponding water contents were graphed on a semi-log plot and the

[6] The multipoint procedure requires obtaining three sub-samples with blow counts spanning a range from 15 to 35, then using interpolation to find the water content corresponding to 25 blows. The one-point method requires just one sub-sample with a blow count between 20 and 30 blows. A correction factor is then applied to find the liquid limit. The multipoint method is preferred for its accuracy.

[7] This is a slight deviation from the standard method, which requires that the groove be closed over a length of 13 mm (1/2 in). However, the method used was consistent for all tests.

logarithmic regression used to interpolate the water content corresponding to 25 blows. This is the liquid limit.

Figure 3-11: Mixing clay to adjust water content

Figure 3-12: Casagrande cup prepared with a pat of clay

Figure 3-13: Grooving the pat of soil

Figure 3-14: Standard grooving tool

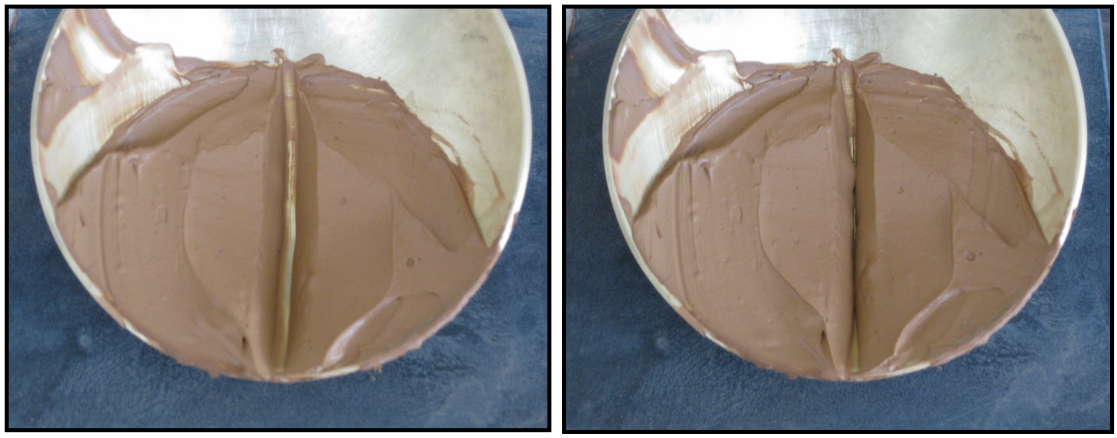

Figure 3-15: Groove before (left) and after (right) Casagrande cup operation

Figure 3-16: Weighing the sub-sample on a digital scale

Figure 3-17: Sub-samples drying in oven

3.2.3 Plastic Limit

The same cured samples that were used to find the liquid limit were used to find the plastic limit. Since the plastic limit is at a much lower water content, the samples were dried in the sun for approximately 1 hour. The plastic limit is determined by the water content of a soil thread that crumbles when rolled to a diameter of 3.2 mm (1/8 in.). The following method was used to find the plastic limit of each of the 27 samples:

1) A small ball of clay (20-50 grams) was worked by hand and rolled on a glazed ceramic tile to further reduce the water content until the clay began approaching semi-solid behavior.
2) A 2-gram piece of clay was formed into an ellipsoidal mass and the rest set aside.
3) Using constant pressure and rolling rate, the piece was rolled by hand on the tile until its diameter was reduced to 3.2 mm (1/8 in.). The thickness of the raised end of the standard grooving tool was used as a reference (Figure 3-18).

4) If successfully rolled to 3.2 mm, the thread was reformed into an ellipsoidal mass and rolled again.
5) Steps 3-4 were repeated until the thread crumbled at or just before reaching the target diameter (Figure 3-19).
6) The fragments were collected in a labeled aluminum foil cup and placed in a covered container to maintain the water content (Figure 3-20).
7) Steps 2-6 were repeated until a sub-sample of at least 6 grams of clay thread fragments was collected. The mass was then taken and recorded.
8) The sub-samples were dried in a gas oven at 140˚C for 15 hours and their masses re-measured.
9) The difference between the measurements before and after drying gives the mass of water in the sample, and the difference between the dry sample and the mass of the tare gives the mass of the dry clay itself. The ratio of the mass of water to the mass of dried soil gives the water content. This is the plastic limit[8].

Figure 3-18: Bottom of grooving tool (circled) used as guide for rolling to 1/8 in.

Figure 3-19: Clay thread crumbling at 1/8 in.

[8] The standard calls for obtaining two 6-gram sub-samples, in which case the plastic limit is the average of the two water contents, but time and material constraints limited this test to one sub-sample for each larger sample.

Figure 3-20: Sample placed in Tupperware® to maintain water content

3.3 Particle-Size Distribution Analysis

The purpose of this test is to determine what percentage of the soil is made up of fine particles ("fines") and how uniform or varied the particle sizes are. For coarse soils such as gravels and sands, particle size analyses are done by pouring a sample through a set of sieves that decrease in opening size. The mass retained on each sieve is then measured to obtain the particle size distribution. This is infeasible, however, for silts and clays since the sieves would have to be impractically fine and would likely be easily damaged. For finer soils, particle-size analyses are carried out by observing the settling of the particles in a water column over a period of at least 24 hours.

A sample of soil is mixed with a dispersing agent (in this case, a 40-gram-per-liter solution of sodium hexamethaphosphate) to separate the particles from each other, and the sample is then mixed into a column of water. At specified time intervals, a glass bulb called a hydrometer (Figure 3-21) is inserted into the water column. The buoyancy of the hydrometer, measured by reading marks on its side, is proportional to the density of the water, which decreases as the particles settle out of the water column. The time it takes for particles of a given diameter to settle is governed by Stokes' law, so combining the buoyancy measurements with the time at which they were taken yields the amount of each particle size in the soil.

Due to time and material constraints, researchers at the Savanna Agricultural Research Institute (SARI) in Tamale performed this test after the departure of the MEng team. The following procedure is taken from MIT's Geotechnical Measurements and Exploration class (1.37), and is adapted from ASTM Standard D422 (ASTM 2007; Germaine 2010). The author left both these procedures and the ASTM standard itself with SARI researchers and requested that the researchers follow them:

1) Obtain the equivalent of 50 gm. of dry soil. (Do not oven dry the soil, use Mwet = Mdry [1 + wc].)
2) Mix well and obtain a water content.
3) Mix the soil to a thick slurry (milk shake consistency) using 5.00 grams of sodium hexametaphosphate and distilled water as necessary.

4) Allow the solution to temper for 16 hr.
5) Mix the slurry in a blender for 60 seconds. Be sure to rinse all the soil from the tempering container to the blender.
6) Transfer the dilute slurry to 1000 cc cylinder and fill with distilled water. Be sure to transfer all the soil from the blender to the cylinder.
7) Place in temperature bath.
8) Mix thoroughly with plunging rod and begin sedimentation experiment.
9) Obtain two sets of specific gravity readings (rh) for the first two minutes of sedimentation with the hydrometer remaining in the suspension. Obtain readings at 4, 15, 30, 60, 90, 120 seconds.
10) Always read the hydrometer at the top of meniscus (even when reading in a clear fluid).
11) Record the hydrometer reading to 0.2 of a division by estimating five increments between divisions. This resolution is necessary for the calculations.
12) Remix the slurry and obtain readings at 2, 4, 8, 16 minutes, etc. Take readings for at least two days or until suspension is clear, whichever comes first.
13) For each reading, place the hydrometer in the slurry about 10 seconds before the reading time, allow the hydrometer to stabilize, take reading, return to the wash water.
14) Between readings be sure to cover the cylinder to prevent evaporation. It is extremely important to keep the cylinder properly filled.
15) At the end of the experiment, mix the suspension with the plunger, pour the slurry into an evaporating dish and obtain the final dry mass of soil and sodium hexametaphosphate.

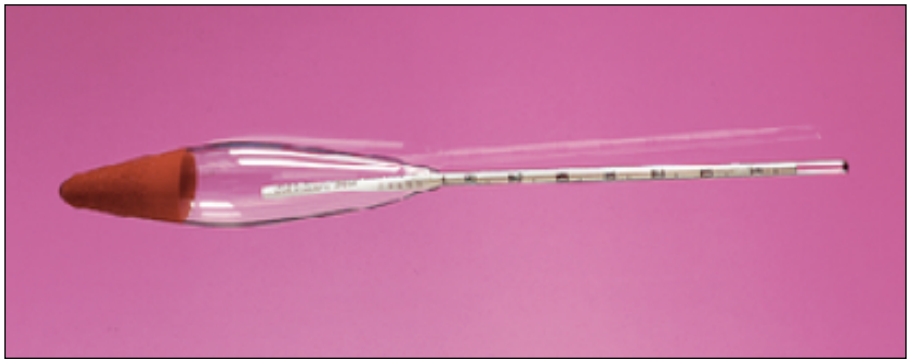

Figure 3-21: The VWR Soil Analysis Hydrometer (VWR International 2011)

The maximum diameter of particles still in suspension at or above the hydrometer's center of volume for any given reading is found by:

$$D = \sqrt{18\eta H / t\left(\gamma_s - \gamma_w\right)}$$

where η = viscosity of water
H = effective depth of hydrometer
t = elapsed time
γ_s = unit weight of solid
γ_w = unit weight of water

The quantity of soil particles less than a given size is found by:

$$N(\%) = \left[\frac{VG_s\gamma_c\left(r_h - r_w\right)}{M_s\left(G_s - 1\right)}\right] \times 100$$

where V = volume of suspension
G_s = specific gravity of soil
M_s = total dry weight of soil
γ_c = unit weight of water at calibration temp
r_h = hydrometer reading in suspension
r_w = hydrometer reading in calibration liquid

Using these formulas, one can figure out the complete particle size distribution for the soil sample.

4 Filter Production

Filter production began with drying, pounding, and sieving the clay samples as described in chapter 3. Portions of the sieved samples were set aside for testing, but most of the samples were retained in the labeled buckets in which they were originally collected (Figure 4-1).

Figure 4-1: Sieved samples stored in labeled collection buckets

4.1 Preparing the Filters for Firing

The filter recipe recommended by Miller and Watters was used (Table 4-1), with the exception that grog was added since the potter women from Gbalahi and the factory manager felt strongly that it should be included (Miller 2010; Watters 2010). This was an acceptable adjustment because Miller and Watters found no significant impact of grog on filter performance.

Table 4-1: Clay recipe used[9]

Dry material	Quantity Recommended by Miller and Watters			Quantity used		
	kg	lbs	%	kg	lbs	%
Clay	11	24.3	68.8	3.5	7.75	68.9
Grog	1	2.2	6.3	0.3	0.75	6.7
Rice husk	4	8.8	25.0	1.2	2.75	24.4
TOTAL	16	35.3	100	5.1	11.25	100

The potter women from Gbalahi used the following procedure to mix, press, and dry the filters:

1) **Composition**: Following the proportions from the recommended clay recipe, the dry materials were measured by weight with a 44-lb (20-kg) scale (Figure 4-2)

[9] The scale only measures 1/8 lb (0.06 kg) increments, so there was some error in the measurements, but not enough to significantly impact the relative proportions of each material, as 1/8 lb corresponds to 1.1% of the total mass.

and then mixed together on a tarp. The total amount of clay was scaled down because Miller and Watters used a press that required more clay per filter[10]:

2) **Mixing**: An indentation was made in the center of the mound of dry materials and water kneaded in (Figure 4-3) until the clay reached the right consistency, which the potters know intuitively from experience. Weighing the clay at this point revealed that an average of 5.5 lbs (2.5 L) of water was added to each mixture.
3) **Kneading**: After adding the appropriate amount of water, the clay was kneaded for an additional 3-5 minutes on the tarp to achieve a thorough mixture[11] (Figure 4-4).
4) **Weighing**: The entire amount of clay was weighed and some clay removed until approximately 16 lbs (7.3 kg) remained, the amount required to make one paraboloid filter.
5) **Shaping**: To start shaping the clay, the clay was pressed by hand onto the bottom of an inverted, previously fired filter (Figure 4-5).
6) **Mold preparation**: Both the male and female molds of the Mani press were covered with a large plastic bag and a painted wooden ring (a "bat") was placed on top of the bag on the male mold. This bat allowed the filter to be removed more easily from the press at the end of the process.
7) **Pressing**: The clay was formed on top of the male mold (Figure 4-6) and the male mold was guided into place under the female mold.
8) The female mold was lowered with the hand crank and the corresponding cable allowed to become completely slack (Figure 4-7).
9) A jack was rolled into place above the female mold (Figure 4-8), and a lever attached to the jack (Figure 4-9)
10) The jack was operated until the female mold almost touched the wooden ring on the male mold (Figure 4-10). Clay squeezing out on all sides indicated that the filter was pressed evenly (Figure 4-11).
11) The jack was rolled away from the center of the female mold and the female mold was raised by hand crank, taking care to not raise it past the level of the hanging jack.
12) The male mold was guided out from underneath the female mold, carefully removing the plastic bag from the female mold (Figure 4-12).
13) **Minor repairs**: Any minor indentations or imperfections were repaired by hand at this point (Figure 4-13). If significant sections of the rim were missing due to the clay not being centered at the beginning of pressing, the filter was removed, the clay re-kneaded, and the pressing process restarted from step 5).
14) **Drying**: The filter was removed from the male mold, supported by the wooden ring, and the plastic bag from the male mold was carefully removed from under the filter.
15) The filter was placed on a drying rack in the shade[12] (Figure 4-14).

[10] Miller and Watters used a 9-liter flower-pot style mold in a portable Potters for Peace press, while a 6-liter paraboloid mold in a Mani press was used here.
[11] For some of the filters, the clay may have been kneaded for less than 3 minutes, and this is sub-optimal.
[12] Filters G3, G6, G7, W1, W7, W8, and W10 were pressed on January 12th, and the rest were pressed on January 13th. These seven filters, therefore, had one extra day of drying time.

16) After drying in the shade for 2-3 days, the filters were taken off the wooden rings, and any unnecessary fragments on the rim were removed and smoothed over.
17) The filters were then dried for an additional 4 days in the shade[13], and any cracks that began to form were filled in. For some of this time, the filters were on the drying racks, and for at least one day they were on the floor of the factory while the drying racks were under construction.

Figure 4-2: The 44-lb (20 kg) scale

[13] Drying in the shade is sufficient in the dry season since there isn't much humidity in the air. In the wet season, the filters would potentially be dried in the sun at this point. If that were the case, care would have to be taken to rotate the filters 90 degrees at regular intervals during the day so that they dry evenly.

Figure 4-3: Mixing water with the dry materials

Figure 4-4: Kneading the clay

Figure 4-5: Pre-forming the filter

Figure 4-6: Forming the clay on the male mold

Figure 4-7: Lowering the female mold

Figure 4-8: Sliding the jack into place

Figure 4-9: Affixing the lever to the jack

Figure 4-10: Operating the jack

Figure 4-11: Clay squeezing out from between the molds

Figure 4-12: Carefully removing the bag from the female mold

Figure 4-13: Inspecting the pressed filter

Figure 4-14: A finished filter on the drying rack

4.2 Firing the Filters

The filters studied in this thesis were fired on January 19th, 2011 in the larger of the two Mani kilns. The Mani kiln is a downdraft kiln, which is more efficient than updraft kilns because it causes heat to take a longer path through the kiln. The larger Mani kiln was constructed between June 2010 and January 2011 and has a capacity of 50 filters (twice the capacity of the smaller "research" kiln that was constructed in January 2010). The filters were stacked on their sides in a way that would allow them to be fired as evenly as possible (Figure 4-15). The firing curve for the January 19th firing shows temperature readings taken at regular time intervals throughout the daylong process (Figure 4-16).

Figure 4-15: Filters stacked in kiln (Manny Hernandez)

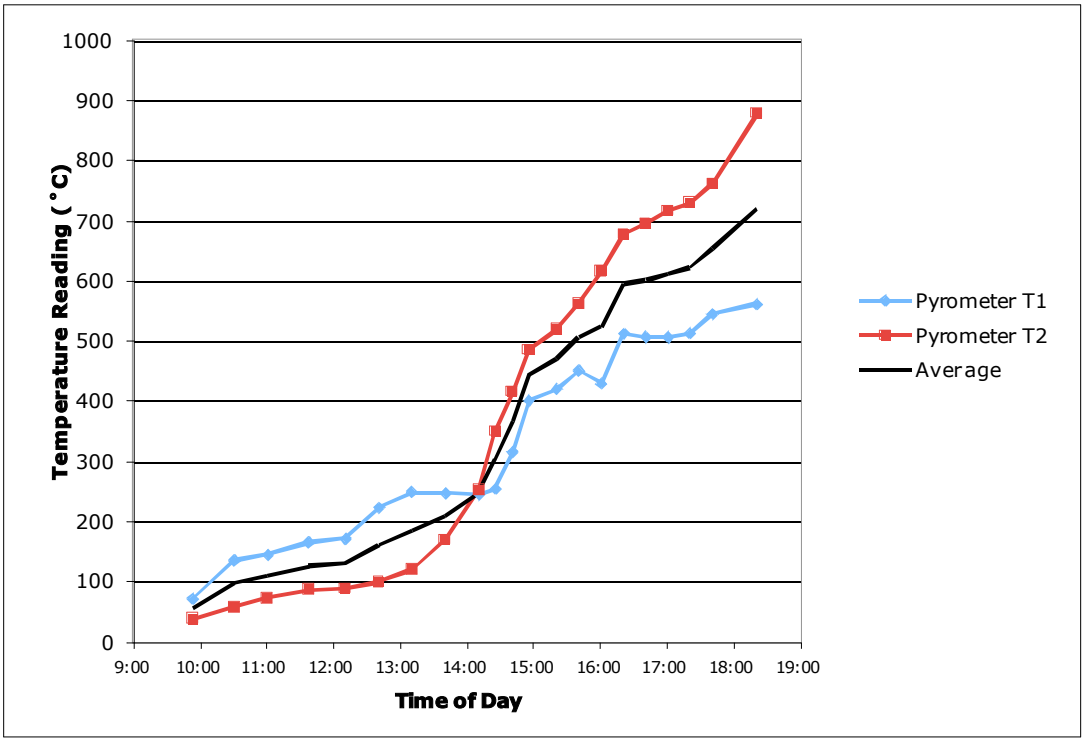

Figure 4-16: Firing curve, January 19, 2011

For the first several hours of firing, a "candle fire" is lit. The purpose of this low-temperature fire (20-120˚C) is to evaporate any remaining moisture in the pore space of the filters and kiln interior (CMWG 2010). During this stage, the door of the kiln is almost completely sealed with bricks, leaving three more courses of bricks at the top to be filled in later. Leaving a gap at the top of the door allows steam to escape more readily. This portion of the firing lasts for about four hours, or until black smoke is seen coming out of the chimney – an indication that the combustible material is burning out. After this, the temperature is raised by sealing up the kiln door completely. The recommended firing schedule determines how much time the kiln should be at each temperature above this. Temperature is increased at a more gradual level at points where the filters are more prone to cracking, especially at the quartz inversion, (550-573˚C). At the end of the firing, the kiln shouldn't get above 887˚C because the filters could become completely vitrified (clay particles welded to glass) and have no porosity left. A set of three pyrometric cones (011, 012, and 013)[14] are used to measure the heat-work done in the kiln. When the 013 cone bends (called the "guide" cone), it is an indication that the firing is almost done. When the 012 cone bends, it is time to let the fire die out and begin the cooling process. If the 011 cone bends, it is a sign that the filters have been over-fired. The kiln is left sealed overnight and allowed to cool gradually for at least 12 hours to prevent cracking.

[14] As recommended by Manny Hernandez. Curt and Cathy Bradner recommend 010, 011, and 012 cones.

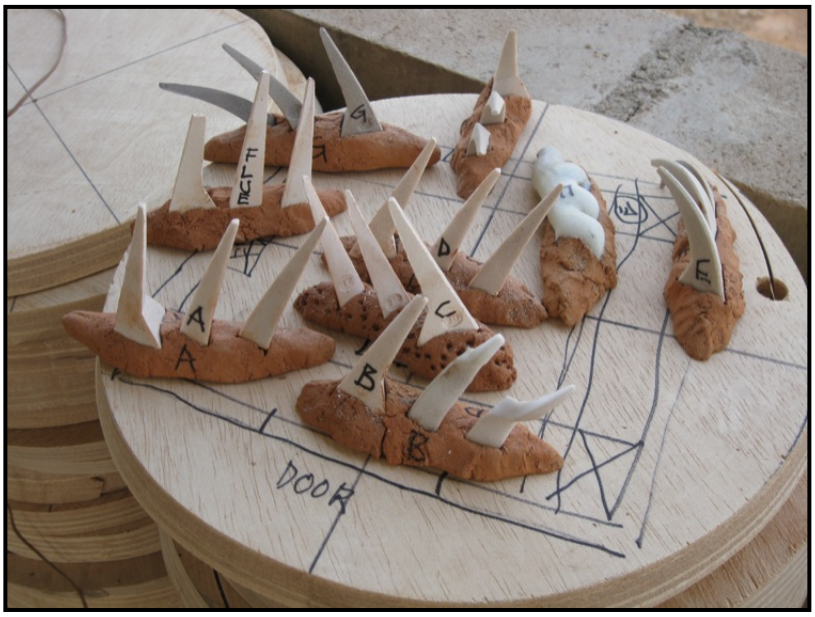

Figure 4-17: Pyrometric cones from January 19th firing

4.3 Comparison to Recommended Procedures

Figure 4-18 shows the firing schedule from January 19th compared to the firing schedule recommended in the Best Practices Manual (Hamer 2003). This figure shows that the January 19th firing was at a lower temperature than recommended.

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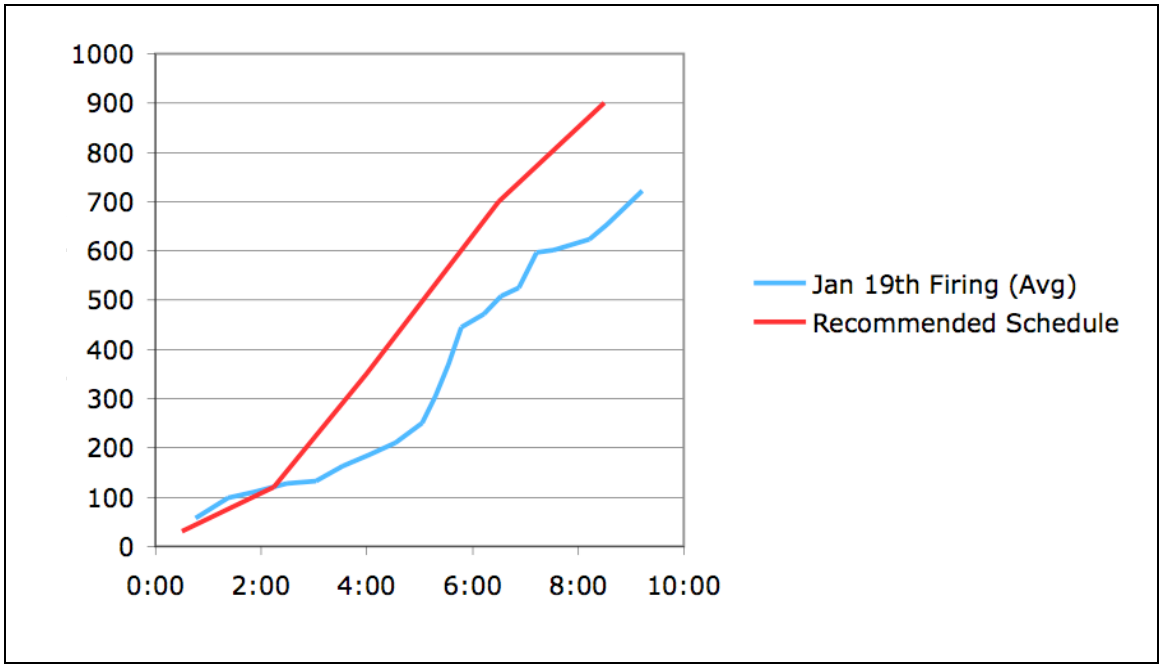

Figure 4-18: Comparison of actual to recommended firing schedule

5 Quantification of Performance

In order to determine the effects of clay properties, filter performance was determined by measuring the flow rate of water though a saturated filter, the removal of turbidity, and the removal of coliform bacteria. All testing was intentionally done on filters without colloidal silver application.

5.1 Flow Rate Testing

Flow rate is a quality control measure used in almost every ceramic filter factory in the world. Although the Best Practices Manual recommends a minimum flow rate of 1 L/hr, and a maximum of 2.5-3.5 L/hr depending on pot size (for 7.2L and 10L, respectively). Current research shows a weak correlation between flow rate and bacteria removal efficiency (Bloem 2009, Ginsburger 2011). In the context of this thesis, flow rate remains a useful parameter insofar as it enables us to compare different clays. There are two major ways to measure flow rate. One is to measure the effluent volume from the filter over a specified period of time. Another is to use a T-device, which was used in this thesis. After soaking the filters overnight in a saturation tank (Figure 5-2), the following procedure was followed by MIT Master of Engineering teammate Shanti Kleiman to complete these tests, as described in her thesis (Kleiman 2011):

> Testing with a T-device [allows] us to rapidly measure the drop in water level in multiple pots at once without having to remove the ceramic filter element from the plastic bucket to collect the effluent. […] Using a T-device also ensures that filters are filled to the same level each time providing more consistent testing conditions for measuring maximum flow rate. [...]
>
> On January 21 and 22, 2011, fourteen buckets were set up around the perimeter of the saturation tank to test the filters in two shifts [Figure 5-5]. Filter elements were placed inside the buckets and water was filled up to 21 cm. Miller found in his measurements that 21cm was the approximate height that aligned with the bottom of the filter lip. He concluded that that should be the maximum fill line because flow through the filter lip would distort results (Miller 2010). The T devices were placed in each filter element and a timer was set for one hour. After one hour the drop in water level was recorded next to the filter number and the next round of filters were placed in the buckets for testing.

The results from the flow rate tests are shown in Section 6.2

5.2 Reduction of Turbidity

Though turbidity itself is typically characterized as a physical characteristic of drinking water and as such not a primary health concern but rather an aesthetic characteristic, an increase in turbidity is potentially associated with an increase in pathogens because microbes attach to particles. It is perhaps the most widely used non-microbial indicator of water quality (OECD/WHO 2003), and is commonly determined by measuring the

scattering of light through a sample of water, in Nephelometric Turbidity Units (NTUs), using a turbidimeter. A Hach 2100P turbidimeter (Figure 5-1) was used to measure the turbidity of highly turbid local source water before and after filtration in each filter, and this data was used to calculate percentage removal.

Figure 5-1: Hach 2100P turbidimeter (Filtration Technology Ltd.)

5.3 Reduction of Microbial Contamination

Since measuring the presence of harmful pathogens is often difficult, it is common to look for "indicator" organisms instead, such as coliform bacteria. While not pathogenic themselves, they are indirect measures of water quality (OECD/WHO 2003). There are numerous tests that make use of indicator bacteria including presence-absence, membrane filtration, and most probable number (MPN) tests. The Quanti-Tray ® test is a form of MPN test and was used in this study because of its speed and accuracy. Its drawbacks are that the supplies are expensive (approximately $6/test) and bulky, making it hard to transport from the USA to Northern Ghana. As a result, subsequent filter testing relied on the membrane filtration test using m-ColiBlue24® media (approximately $3 per test depending on the media used)

The QuantiTray® procedure was used to measure the removal of microbial contamination, as described below:

1) Filter buckets were left to soak with municipal water and Aquatabs® to kill any residual bacteria on the inside of the buckets. The tops were also scrubbed with the same water.
2) All filters were filled with at least 500mL of contaminated local dugout water. Half of the filters were tested at one time (Figure 5-5). Two samples of dugout water were collected in Whirl-Pak® bags and set aside as the raw water samples.

They were put in a cooler bag with an ice pack to preserve the samples until testing later in the afternoon.

3) Dugout water was poured into the filters, allowed to flow through, and collected in the buckets below.
4) Post-filtration samples from each filter were taken in Whirl-Pak® bags and labeled with the corresponding filter (Figure 5-7). Samples were put in a cooler bag with an ice pack to preserve them until testing later in the afternoon within 6 hours (Figure 5-8).
5) In the Pure Home Water lab, samples were mixed with the Colilert media in separate, sterile 100 mL bottles.
6) After dissolving the Colilert, the samples were poured into Quanti-Trays®, sealed with a heat sealer, and then placed in an incubator at 37˚C for 24 hours[15] (Figure 5-9).
7) After incubation, yellow wells and wells that fluoresced under UV light in the dark were counted and recorded.
8) Using these values, the Most Probable Number (MPN) of colonies was looked up in a table provided by the manufacturers of Quanti-Tray®. These values were used to calculate percentage removal.

Figure 5-2: Fired filters soaking in saturation tank

[15] The exact incubation temperature for the first round of samples is unknown because the power went out during incubation and the incubator was moved to the sun. It was cooler, on average, for the first half of the samples (G9, W2, G10, T5, G6, W3, T6, W1, T4, G12, W6, W5, W8, G2, and W12) because the decision to move the incubator into the sun was made later in the day after the incubator had already been cooling down for several hours. The second half of samples were left in the incubator for 1.5 extra hours.

Figure 5-3: T-device in filter during flow rate testing

Figure 5-4: Filter set up for testing in collection bucket

Figure 5-5: Row of collection buckets set up for testing filters

Figure 5-6: Empty Whirl-Pak® bag

Figure 5-7: Full Whirl-Pak® bag

Figure 5-8: Water samples in cooler bag

Figure 5-9: Quanti-Trays® in incubator

6 Results

All box and whisker plots in this section show four quartiles and the mean values for each data set. The bottom and top of the thin, vertical lines represent the minimum and maximum values. Mean values are displayed as points connected by a thick, colored line.

6.1 Clay Characterization

6.1.1 Plasticity

The following tables and figures summarize the results from the Atterberg Limits tests described in Section 3.2. More detailed results can be found in Appendix D.

Table 6-1: Average water contents of the three clay sources

Source	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Gbalahi	62.96	24.54	38.42
Wayamba	57.26	21.84	35.42
Taha	51.05	16.80	34.26

Recall that the plasticity index is the range of water contents over which the clay exhibits plastic behavior, and it is calculated by subtracting the plastic limit from the liquid limit. These results reveal that the Gbalahi clay is the most plastic of the three clays, as indicated by its plasticity index and liquid limit, but all of the clays could be characterized as highly plastic using a plasticity chart such as Figure 6-4 (also see Appendix C).

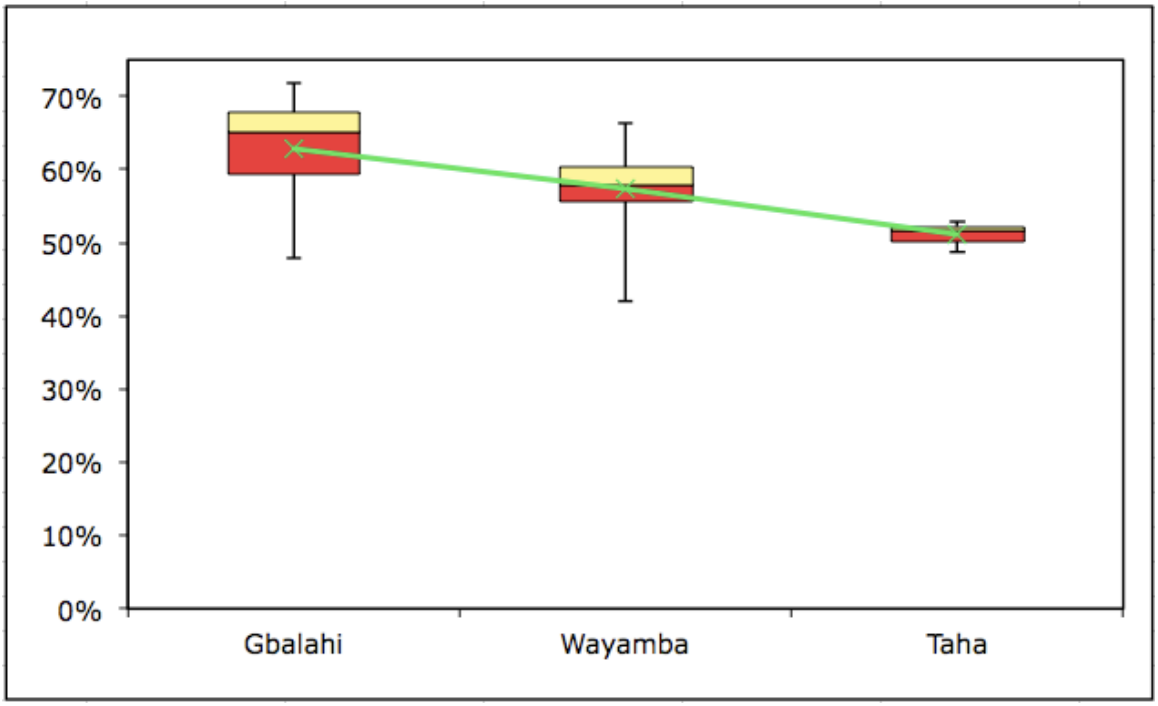

Figure 6-1: Liquid limit box plot

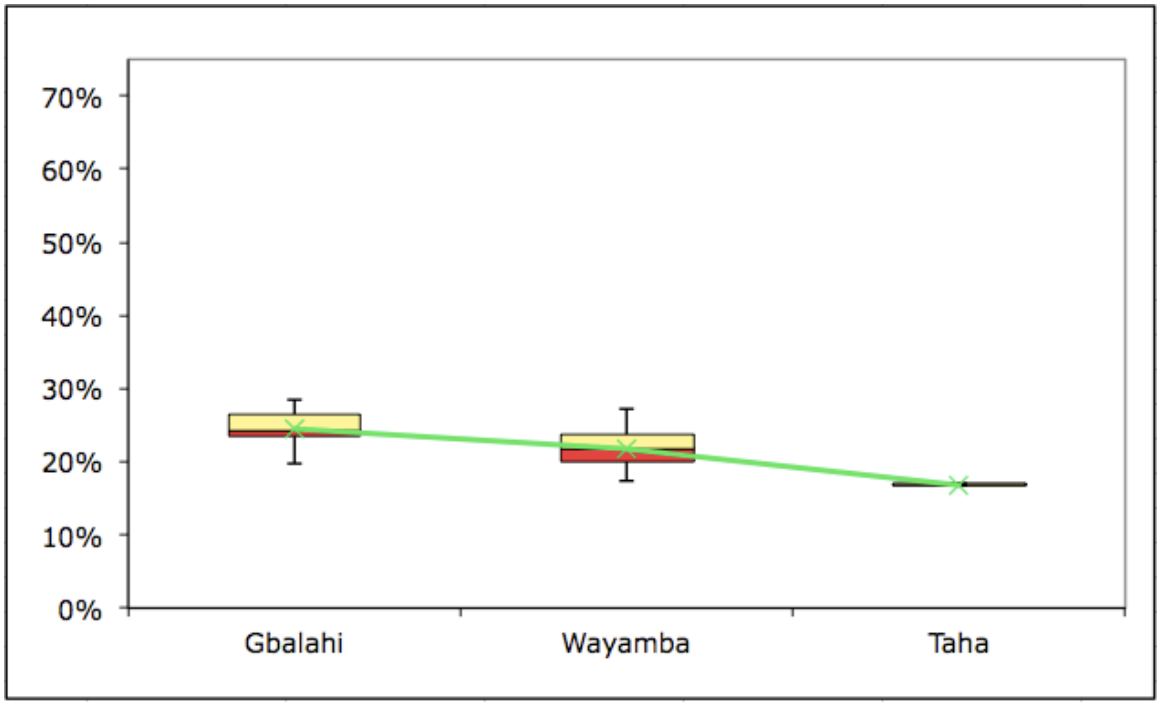

Figure 6-2: Plastic limit box plot

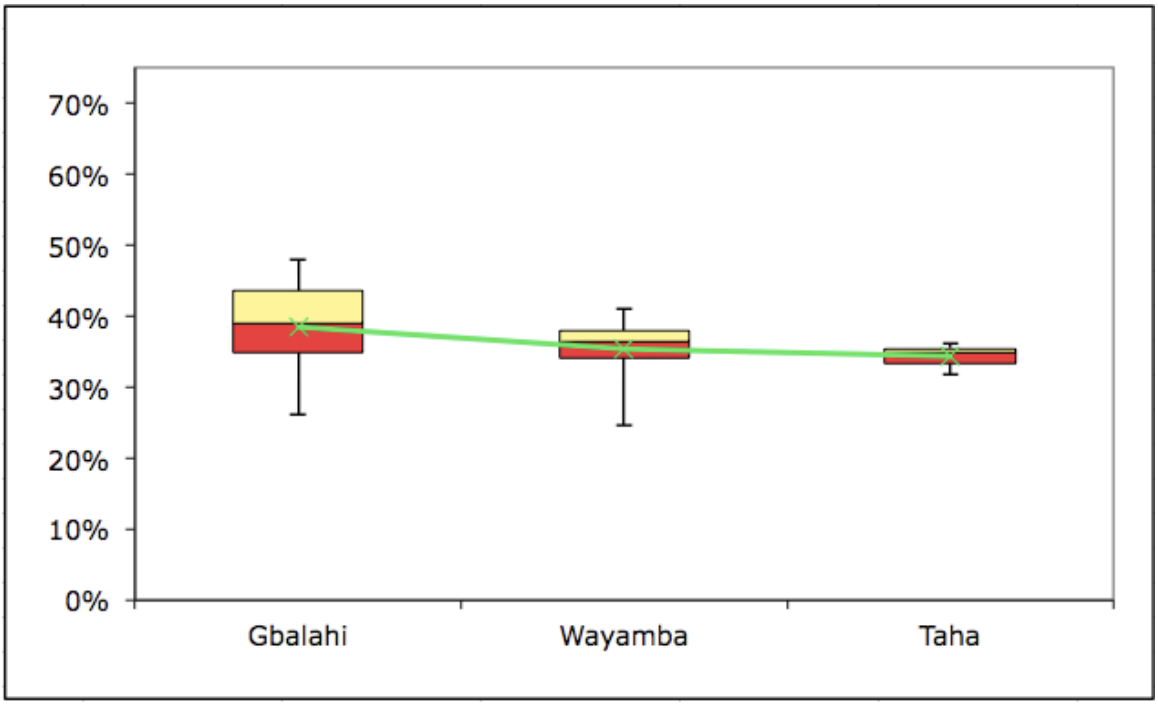

Figure 6-3: Plasticity index box plot

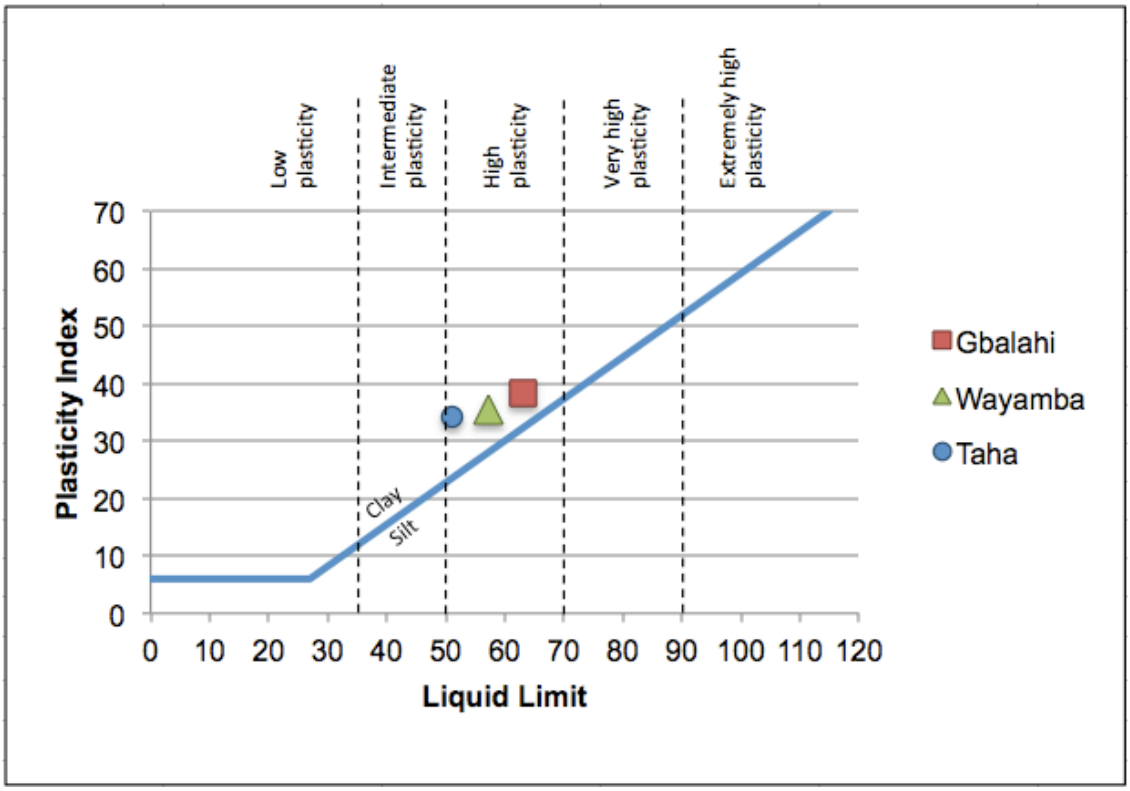

Figure 6-4: Plasticity chart with the three clay sources

6.1.2 Particle Size Distribution

Table 6-2, Figure 6-5 and Figure 6-6 are a summary of the data from the particle size analysis[16] described in Section 3.3. It is assumed that the Wentworth scale was used to distinguish sand (particle sizes of 0.0625 to 2 mm), silt (0.0039 to 0.0625 mm), and clay (less than 0.0039 mm). More detailed results can be found in Appendix D.

Table 6-2: Particle size distribution summary (average percentage by weight)

Source	Sand (%)	Silt (%)	Clay (%)
Gbalahi	13.55	26.99	59.47
Wayamba	19.61	29.49	51.90
Taha	28.40	24.80	46.80

[16] Testing and analysis done by the Savanna Agricultural Research Institute in Tamale, Ghana.

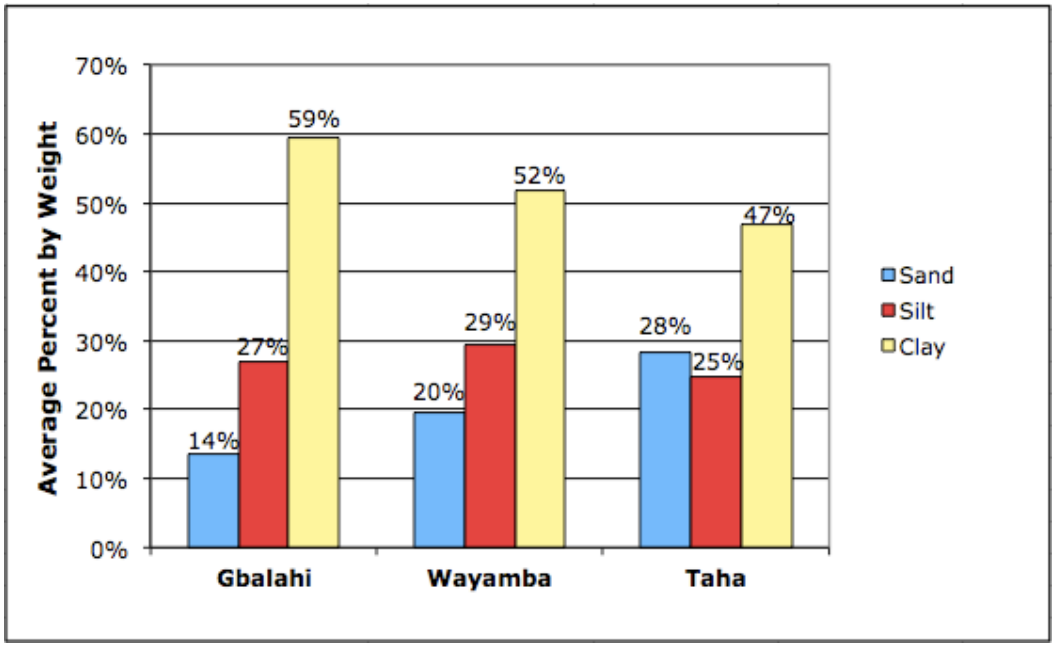

Figure 6-5: Particle size distribution, organized by source

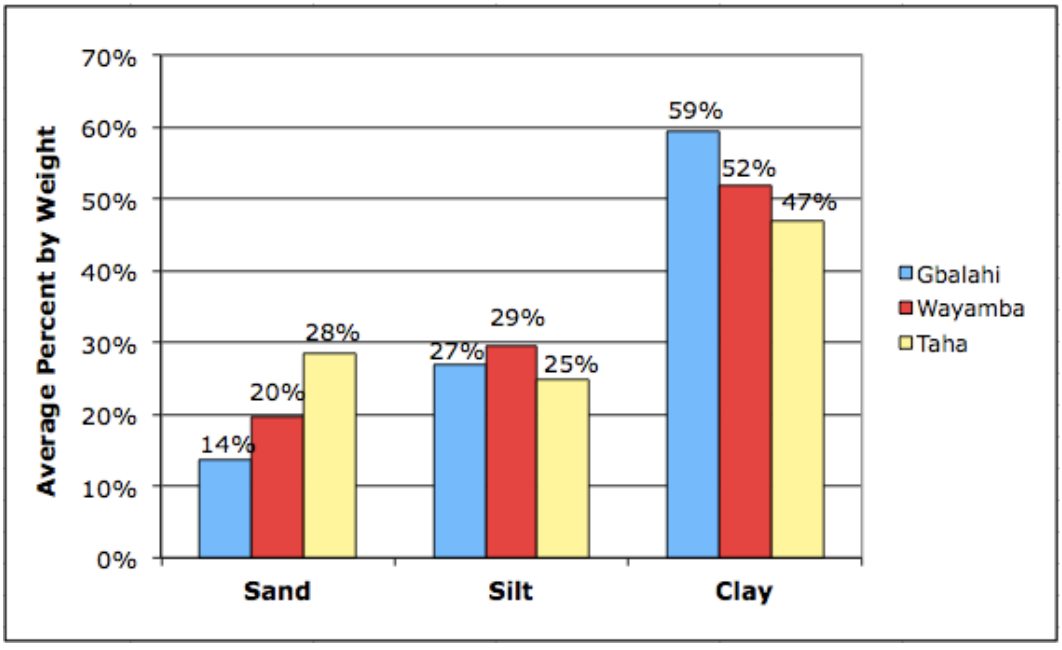

Figure 6-6: Particle size distribution, organized by size

The amount of silt is relatively constant for all three sources, but there is a marked decrease in percentage of clay and increase in that of sand from Gbalahi to Wayamba to Taha.

6.1.3 Percent Gravel

When processing the pounded sample, some material was retained on the sieve, as described in Section 3.2.1. By visible inspection, most of these particles were larger than 2mm and could thus be categorized as gravel based on the Wentworth scale. The average amount of gravel in the samples from each site is reported in Figure 6-7.

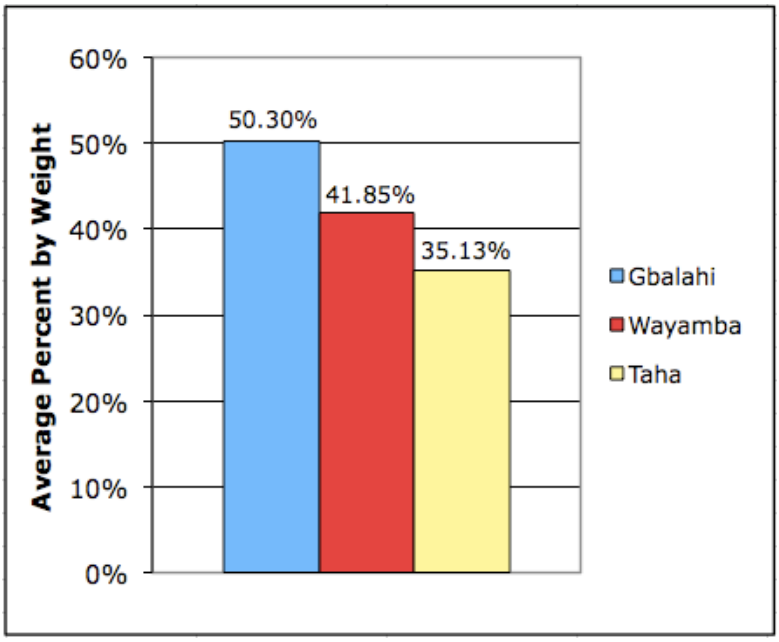

Figure 6-7: Average percentage of gravel in clay samples

6.2 Filter Performance

6.2.1 Flow Rate

Table 6-3 is a summary of the data collected in the flow rate tests described in Section 5.1:

Table 6-3: Flow rate summary [L/hr]

Source	Average	Standard Deviation
Gbalahi	3.1	1.2
Wayamba	4.9	0.5
Taha	4.9	0.2

The flow rate of filters made with Gbalahi clay (3.1 L/hr) was much slower than that of filters made with Wayamba or Taha clay (4.9 L/hr).

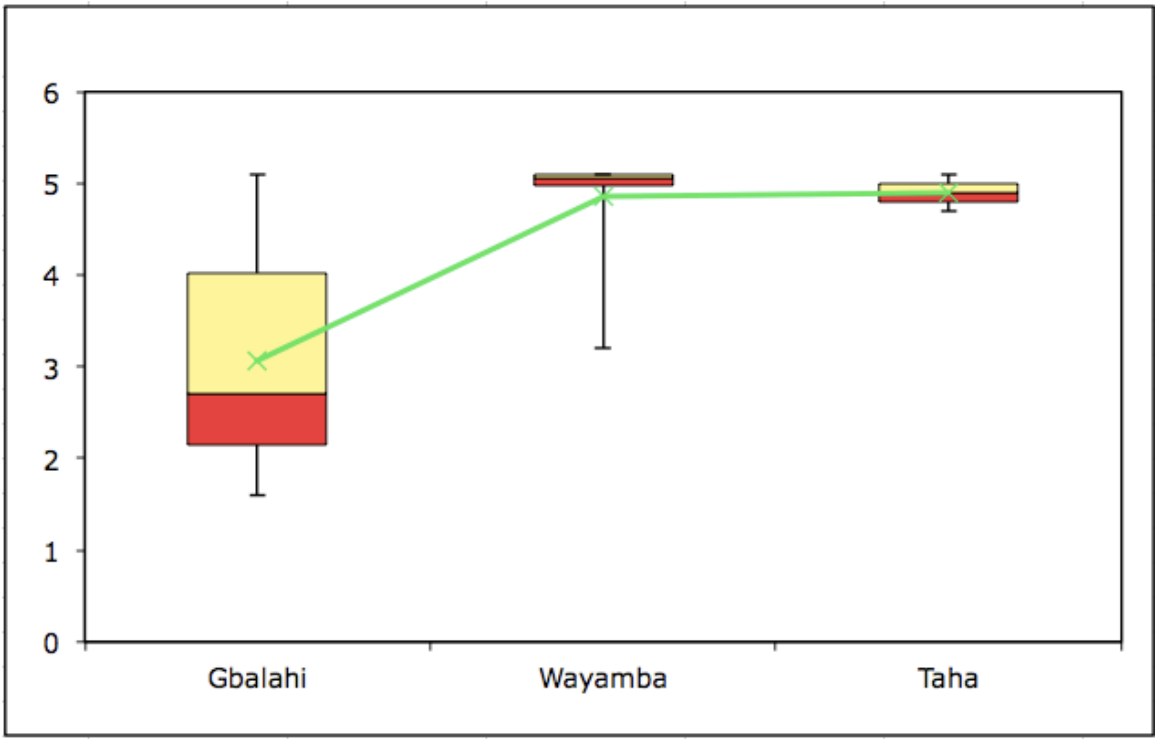

Figure 6-8: Flow rate box plot

6.2.2 Reduction of Turbidity

Table 6-4 is a summary of the turbidity percentage reduction from the unfiltered to filtered water, as described in Section 5.2. More detailed results can be found in Appendix D.

Table 6-4: Turbidity reduction summary

Source	Average (%)	Standard Deviation (%)
Gbalahi	70.4	11.49
Wayamba	56.8	11.54
Taha	49.4	3.49

The Gbalahi clay filters had much higher removal of turbidity on average (70.4%, vs. 56.8% for Wayamba). The filters made with the Gbalahi clay and those made with the Wayamba clay had a similar standard deviation. The Taha filters performed the poorest in terms of turbidity reduction (49.4%).

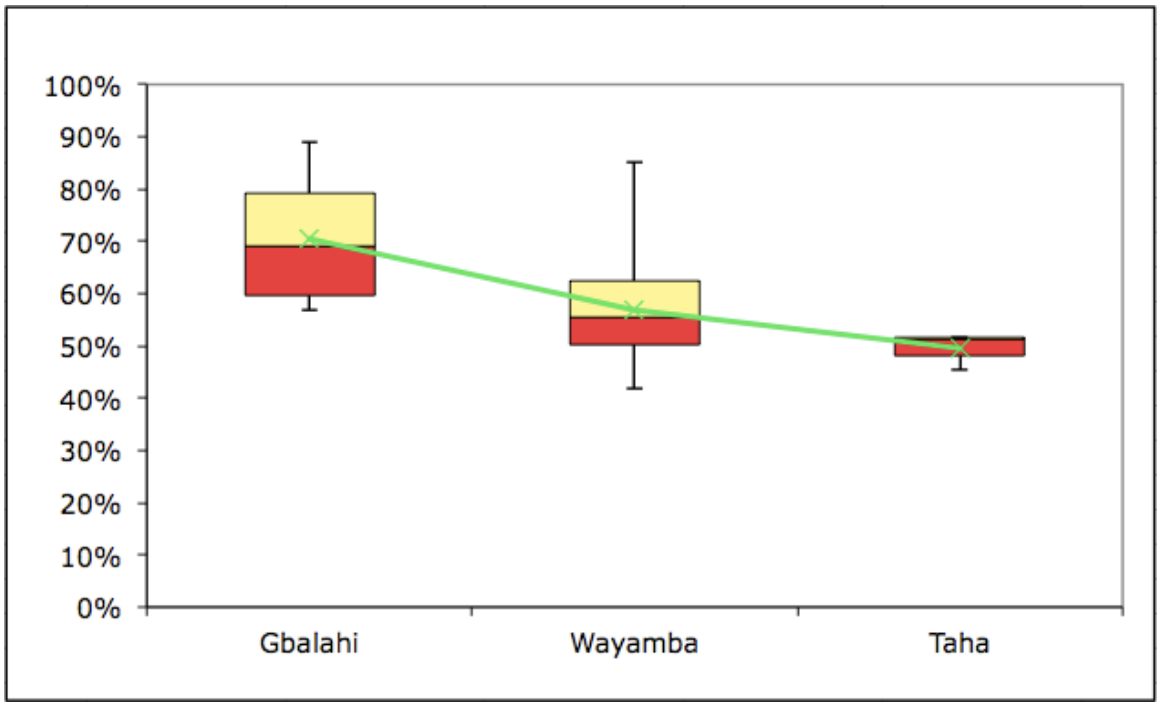

Figure 6-9: Turbidity reduction box plot

6.2.3 Reduction of Microbial Contamination

Table 6-5 is a summary of the results from the microbial tests described in Section 5.3. More detailed results can be found in Appendix D. The filters made from Taha clay had the highest reduction in *E. coli* (90.6%), which is surprising since they performed least well in turbidity reduction (49.43%). It should be noted that the microbial contamination measurements were taken on two different days, and thus there were two different starting levels of *E. coli* contamination (most probable numbers of 2419.6 and 547.5, see Table D-5), which might have biased the results.

Table 6-5: Percent *E. coli* reduction

Source	Average (%)	Standard Deviation (%)
Gbalahi	84.3	16.65
Wayamba	86.7	10.06
Taha	90.6	1.31

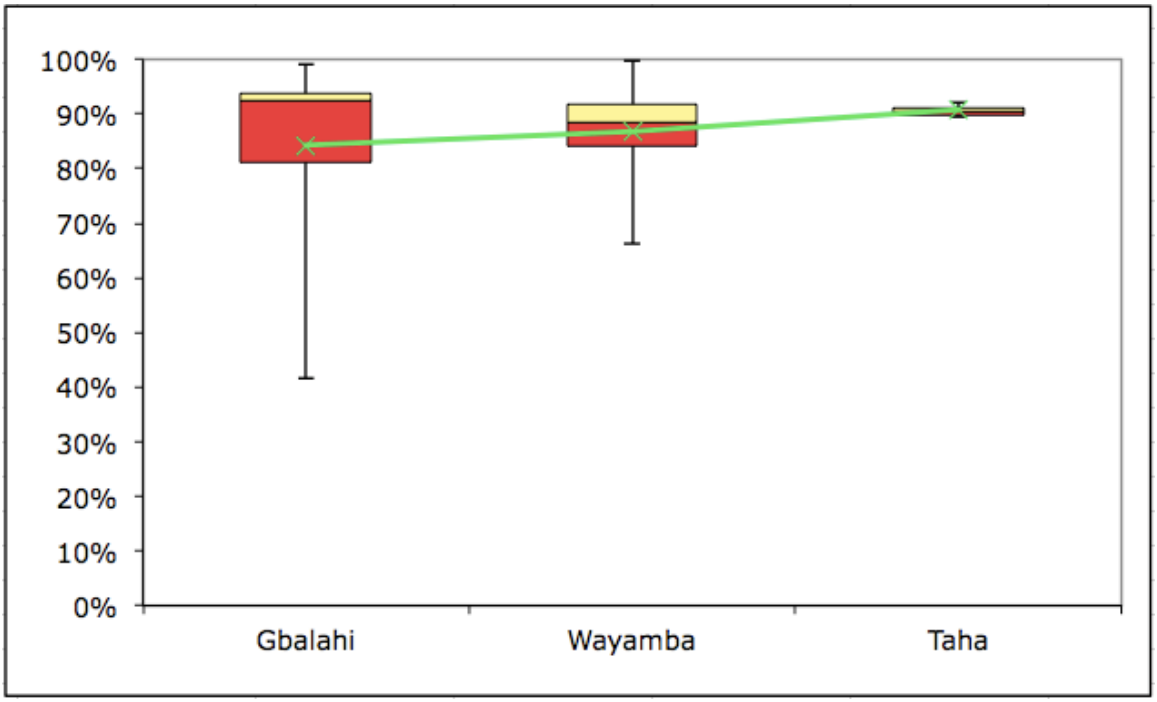

Figure 6-10 *E. coli* reduction box plot

Due to insufficient dilution of contaminated source water, total coliform colonies were too numerous to count both before and after filtration for many of the filters, so no conclusions about total coliform removal can be made.

7 Factory Procedure Changes Since January 2011[17]

From 2010 to January 2011, factory construction had been taking place side-by-side with "research" filter production. However, as of February 2011, the factory was essentially complete and attention could now turn to full-scale production. Curt and Cathy Bradner (referred to throughout as "Bradner") were hired in February 2011 to get the Pure Home Water factory up and running at full capacity, to train the factory staff in filter production, and to ensure high quality control. From March 10 to April 5, they made and fired filters, adjusting parameters and testing the effects on filter performance. They made several improvements to the manufacturing process and helped add quality control measures at many steps.

7.1 Changes to Filter Pressing

The current procedure for pressing the filters, with several additions from Bradner's work (in bold), is as follows:

1. **Before mixing inspect the rice husks**
2. Mix clay and combustible well (about 5 minutes)
3. Add water, mix and wedge thoroughly (at least 5 minutes)
4. Put the ring on correctly
5. **Oil bat**
6. **Oil plastic**
7. Push table back flush
8. Press
9. Remove excess clay
10. **Push table back flush**
11. **Press again**
12. Take off excess clay around rim
13. Put the filter on the racks
14. Put serial number on filter
15. 1 to 2 days after pressing take filter off ring and remove flash[18].

The most significant changes are checking the rice husk before mixing it in (to ensure that it has been properly sieved), oiling the bat and the plastic for clean separation, and pressing twice instead of just once to ensure even pressure all round. The potter women who press the filters have been carefully observed and corrected so that they have started paying closer attention to details in the manufacturing process.

[17] All photos and information in this section were provided by Curt and Cathy Bradner in email correspondences from March to April of 2011.
[18] "Flash" refers to small pieces of excess clay.

7.2 Changes to Filter Firing

To improve the filter firing, Bradner has come up with a new filter spacer (for use when stacking filters in the kiln for firing, as in Figure 7-1) that allows more complete firing for all parts of the filters. Early redesigns (Figure 7-2) led to incomplete firing, as evidenced by black carbon markings on the inside of the filters (Figure 7-3) and dramatically under-fired sections revealed after cutting filters in half (Figure 7-5). They experimented with a couple of different designs for filter spacers before finding one that did not result in incomplete firing or black carbon markings (Figure 7-5 and Figure 7-6).

Figure 7-1: Filters stacked in kiln with first revised spacer

Figure 7-2: First revised filter spacer design

Figure 7-3: Incomplete firing using first spacer revision

Figure 7-4: Incomplete firing (cross section)

Figure 7-5: Filters stacked with new spacers

Figure 7-6: Completely fired filters after using new spacers

7.3 Bubble Tests

One of the most important additions Bradner made to the quality control process was adding a bubble test, where the freshly fired filter is immersed rim side down in water (Figure 7-7). The size and frequency of bubbles released can indicate if there is a crack that was not detected before and provide evidence that even though the flow rate of this filter might fall within the correct range, further inspection such as bacteria testing should be done on these filters.

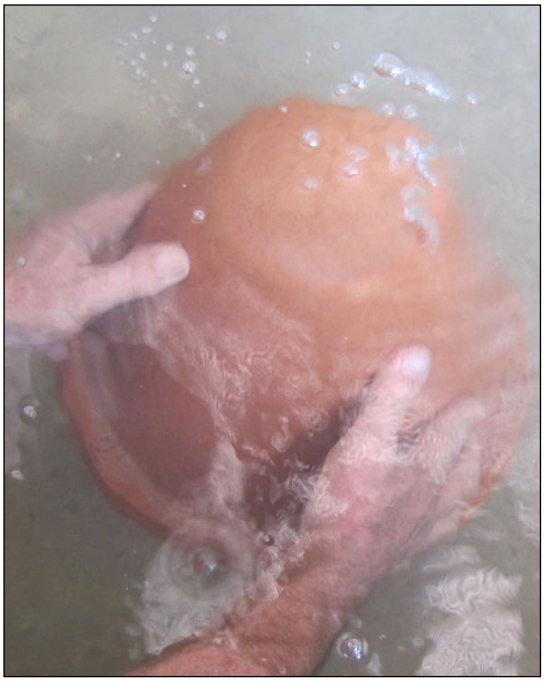

Figure 7-7: The bubble test

7.4 Experimentation with Clay Mixes

In addition to improving the manufacturing and quality control processes, Bradner continued to experiment with the clay recipe, adjusting the percentage of rice husk and also testing different mixes of Gbalahi clay and Wayamba clay. They made each mixture in 66-lb (30-kg) batches (instead of the 25-lb (11.3-kg) batches made by the author), enough to make 5 filters. The amount of rice husk was measured as a percentage by weight of the 66-lb mixture, and the clay percentages were calculated as a ratio of the remaining weight. Therefore, a mixture with 12% rice husk and a 75/25 ratio of Wayamba clay to Gbalahi clay had 8 lbs (3.6 kg) of rice husk, 43.5 lbs (19.7 kg) of Wayamba clay, and 14.5 lbs (6.6 kg) of Gbalahi clay. Grog was not used in their mixture because in their experience there are no significant advantages to using it, as confirmed in Miller's 2010 thesis.

After firing, only filters that passed the bubble test proceeded to the flow rate test, and only filters that passed the flow rate test (had flow rates below 3 L/hr) were tested for *E. coli* removal. Table 7-1 is a summary of the data from the best batch of filters (that is, the batch of filters that had the fewest rejections before making it to the *E. coli* test).

Table 7-1: Performance summary of filters with new clay mixtures

% Rice Husk	% Wayamba clay	Flow rate [L/hr] *	% Reduction *E. coli* **
0.11	0.25	2	85.56%
0.11	0.35	2.8	77.78%
0.12	0.25	2.8	82.22%
0.13	0.25	2.8	81.11%
0.11	0.35	2.4	93.06%
0.12	0.35	2.8	91.94%
0.11	0.35	2	81.94%
0.11	0.25	2	92.78%
0.13	0.35	2.2	84.44%
0.12	0.25	2.6	87.22%
0.12	0.35	2.2	84.44%
0.13	0.35	2.2	84.17%
0.11	0.35	2	81.39%
0.14	0.25	2.2	90.28%
0.11	0.25	0.8	85.00%
0.12	0.25	2	75.28%
0.11	0.35	2.2	72.50%
0.11	0.5	1	
0.13	0.35	2.4	
0.13	0.5	3.6	
0.12	0.5	3	
0.13	0.5	4	
0.13	0.35	3	
0.14	0.35	3	
0.12	0.5	2.5	
0.13	0.35	3	
0.12	0.5	1	
0.11	0.35	5.6	
0.12	0.5	2.4	
0.11	0.5	4	
mix	0.5	2	
0.11	0.5	1.2	
0.13	0.5	3	
0.13	0.35	4	
0.13	0.5	4	
0.13	0.5	3	

*** Flow rates estimated by multiplying half-hour flow rate by 2.**
**** Calculated by (colony count before – colony count after) / colony count before ×100. Only calculated for first half of filters.**

8 Discussion

This section explores the statistical significance of the results from the research done in January 2011 by the author and research partner, Shanti Kleiman, who collaborated on the flow rate, turbidity, and coliform removal testing. Only the Gbalahi and Wayamba sites were considered in these analyses because of the difference in sample size, sampling methodology, and limited clay availability of the Taha clay (only a small quantity was found). Also, the statistical analysis is much more straightforward with only two samples and the conclusions can be more useful for the purposes of commercial filter production.

8.1 Testing for Statistical Significance

The objectives of this thesis are to measure the differences in the clay from the two sites, establish the effects of the clay properties on the filter performance, and determine which site, if either, is better for the factory to use. For questions about whether or not there was a significant difference in a parameter between the two clay sites (either in the clay sample or performance of the filters made from the samples), a Student's t-test was used to determine whether there was a statistically significant difference between the population means. In this method, the difference between the two sample means is normalized by the square root of the sum of the sample variances:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where $\overline{x}$ = sample average

s^2 = sample variance

n = sample size

The critical t-value is that which corresponds to a chosen threshold probability (5% is a typical value) that the means are, in fact, the same. For a two-tailed test, if the absolute value of the t-value is greater than 2.2, then there is a less-than-5% probability that the means are the same and the null hypothesis (that the two means are equal) can be rejected.

For questions about whether or not certain parameters were linked, regardless of what site the corresponding samples came from, linear regression was used to see if there was a statistically significant relationship between them. The R2 value from the linear regression is a measure of how well the data points align with the best-fit line. A t-test related to the one described above can also be used to calculate the probability that there is a relationship between the two parameters. In this case, the null hypothesis is that the apparent relationship between the two parameters is due to random chance.

The Excel 2003 Data Analysis ToolPak was used for all of these tests.

8.2 Differences Between Clay Sites

Data for each parameter was organized into two groups according to clay source, and a t-test carried out to determine if there is a significant difference between the population mean of the two groups. Results are shown in Table 8-1 with statistically significant differences highlighted.

Table 8-1: T-test results for all parameters

Parameter	t Stat	Two-tail P-value	Statistically significant difference?
Depth of sample	-1.596	0.13	No
Plasticity index	1.270	0.22	No
Percent clay	3.448	0.0024	Yes
Flow rate	-4.792	0.00024	Yes
Turbidity reduction	2.885	0.0086	Yes
Percent gravel*	2.993	0.0072	Yes
E. coli reduction	-0.421	0.68	No
Coliform reduction	0.327	0.75	No

***This refers to the percentage of the sample retained on the sieve during initial clay processing. See Section 3.2.1.**

For any given test, rejecting the null hypothesis that the two population means are equal indicates that there is a significant difference in the parameter between the two clay sources. The parameters that are significantly different are the percent clay in the sample, the flow rate of the filters, the turbidity reduction, and the percent of the sample retained on the sieve during initial preparation of the clay (i.e., how much gravel there was in the raw sample). It should be noted that failing to reject the null hypothesis does not prove that it is true. Rather, it just can't be proven with the given data that it is false. Therefore, it cannot be concluded that population mean of the other parameters are the same across both clay sources.

8.3 Effect of Clay Properties on Filter Performance

Figure 8-1 summarizes the results of the regression analyses for many combinations of parameters. In this figure, the darker oval shading indicates a parameter with a statistically significant difference between the two sites, and darker lines indicate a significant relationship between the indicated parameters.

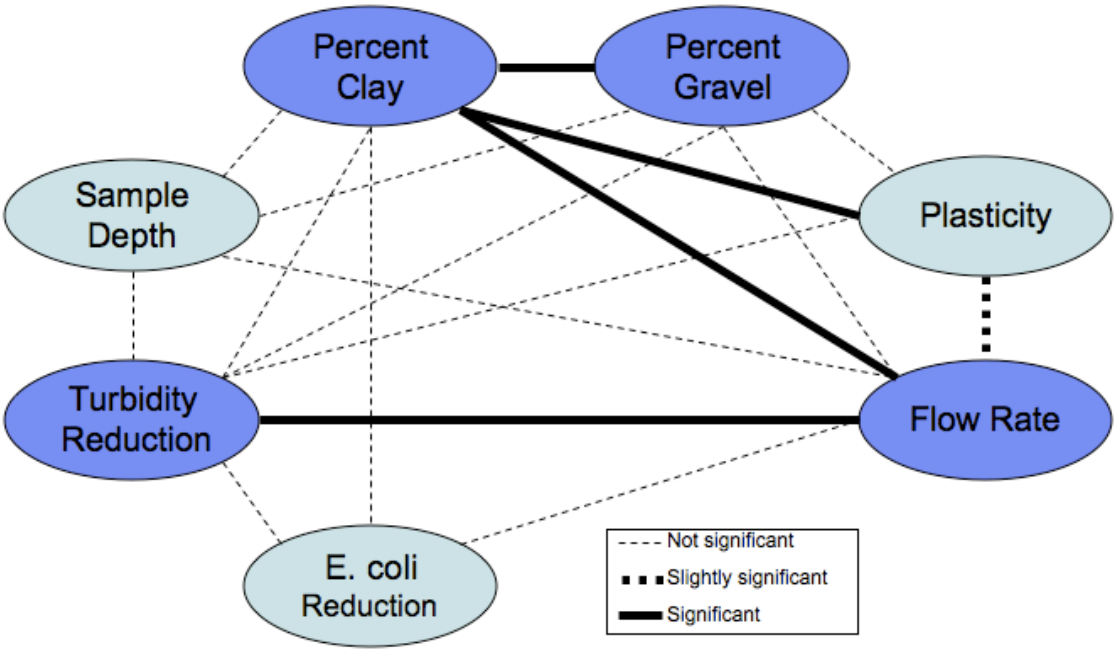

Figure 8-1: Summary of regression analyses

Of all the parameter combinations analyzed, there is only a statistically significant relationship between percent clay and percent gravel, percent clay and plasticity, percent clay and flow rate, and flow rate and turbidity reduction. These results suggest that the percentage of clay in the sample has an impact on the flow rate of the filter made with that sample. This makes sense, because the pore size should be related to the size of the particles that make up the clay simply based on their geometry. It is reassuring to see a highly significant relationship between flow rate and turbidity reduction, as flow rate is used as one of the principle quality control measures. On the other hand, it is notable that there is not a significant relationship between the flow rate and *E. coli* reduction since, because this indicates that flow rate may not be an adequate measure of filter quality[19]. Finally, it is useful to know that there is a significant relationship between the percentage of gravel and the percentage of clay in the sample, because this confirms that the amount of gravel in a sample is one possible negative indicator of clay quality. This is something that local potters know either intuitively or from experience.

8.4 Analysis of Bradner Data

Table 8-2 provides a summary of the regression analyses of different combinations of Bradner's data as presented in

[19] Gensburger has also found that there is only a very weak correlation between flow rate and bacteria removal efficiency (2011).

Table 7-1. These analyses excluded any data point that did not have data for either of the two parameters being tested.

Table 8-2: Regression analysis of Bradner data

Parameter 1	Parameter 2	Adjusted R2 value	t Stat	Two-tail P-value	Statistically significant relationship?
Clay ratio	Flow rate	1.0000	1.47E+16	0.000000	Yes
% rice husk	Flow rate	0.0546	1.722	0.0945	No
Clay ratio	*E. coli* reduction	0.0155	-0.486	0.6340	No
% rice husk	*E. coli* reduction	-0.0666	0.037	0.9709	No

The most noteable relationship is that of the clay ratio (weight of Wayamba clay over the weight of Gbalahi clay) to the flow rate. There was a perfect one-to-one relationship between the clay ratios and the flow rates recorded. This indicates a very strong relationship between the relative amount of each clay used and the flow rate of water through the resulting filter[20], likely due to the higher percentage of sand and silt in the Wayamba "clay". The rice husk had a somewhat significant relationship to the flow rate (a P-value below 10%) but not significant enough to reject the null hypothesis that the relationship between them is due mostly to chance, which requires a P-value of at most 5%. Neither the clay ratio nor the percent weight of rice husk had a significant relationship to the *E. coli* reduction in the range of values tested.

8.5 Comparison to Results From Miller 2010

Miller reports results from his Atterberg limits tests for Gbalahi clay on page 65 of his thesis. A comparison of his results to the Gbalahi results from this thesis is shown in Table 8-3. While there is a dramatically different liquid limit (62.96 vs. 35.43) and plasticity index (36.42 vs. 13.30), both soils would be classified as clays using a standard plasticity chart, such as the ones in Figure 8-2 and Appendix C. In this chart, anything above the line is classified as clay and anything below it is classified as silt. Miller's results fall directly on the line, and the author's are slightly above.

It is unclear what caused the noticeable difference in liquid limit and plasticity index. One potential explanation is that Miller happened to test clay from a less plastic area of the Gbalahi site. Even taking this into account, the difference is still surprising considering that the testing method utilized in this thesis covered a sizable area and the lowest liquid limit and plasticity index recorded were 47.79 and 26.12, respectively. If the results from both authors are taken to be accurate, then this is an indication that there could be significant variation in the plasticity of the clay at the Gbalahi site.

[20] The perfect one-to-one relationship between flow rate and clay ratio is likely due to a lack in precision in flow rate measurements. Even without this perfect correlation, however, there would still be a strong relationship between these parameters.

Table 8-3: Comparison to clay properties from Miller 2010

	Hester 2011 (%)	Miller 2010 (%)
Liquid Limit	62.96	35.43
Plastic Limit	24.54	22.13
Plasticity Index	36.42	13.30

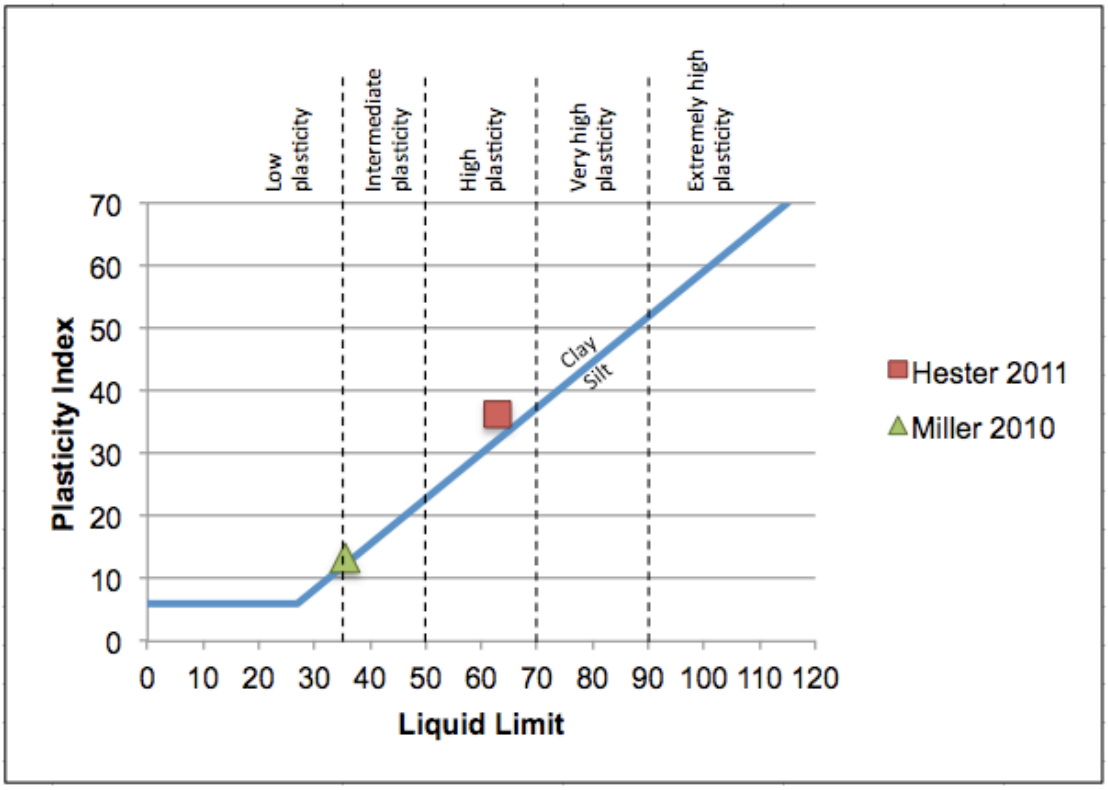

Figure 8-2: Plasticity chart with comparison to results from Miller 2010

8.6 Simple Clay Tests

8.6.1 Particle Distribution Test

Most of the tests conducted in the research for this thesis involve special equipment, require training, and are time consuming, making them less practical for examining the suitability of a body of clay. Hamer describes what amounts to a simplified particle distribution analysis that only requires a clear half-liter bottle, some clear water, and a small clay sample (2003). He suggests the following procedure:

1. Fill the bottle half full with water.
2. Add approximately half a teaspoon of clay and shake the bottle vigorously to get the clay into suspension.
3. Fill the bottle almost to the top and shake the bottle again.

4. Put the bottle where it can sit undisturbed at a slight angle and wait for at least two hours.

The larger particles will settle fairly quickly, but the smaller particles can take over a day to settle out completely. If the clay is plastic enough to make suitable pots, the water should still be cloudy after two hours of sitting.

8.6.2 Shrinkage Test

The shrinkage rate of a particular body of clay can be found by forming bricks or "snakes" and measuring their length before drying, after drying, and after firing. A line of a specified length can be made in the moist sample before drying to make measurement easier and avoid ambiguity from slightly irregular geometries. Drying shrinkage rate is found as the percent reduction in length from the moist sample length to the dry sample length. Firing shrinkage rate is found as the reduction from the dry sample length to the fired sample length. Total shrinkage is the reduction from moist sample length to fired sample length. Shrinkage tests for samples of Gbalahi clay can be found in Appendix G.

9 Conclusion and Recommendations

9.1 Variation in Clay Properties

The data presented in Section 6.1 indicate that the Gbalahi clay is more plastic and has a higher clay content. The analyses in Section 8.2 indicate that the difference in clay content between samples from Gbalahi and Wayamba is statistically significant, and also that the amount of gravel is a *positive* indicator of the percentage of clay in the fine portion of that sample.

9.2 Filter Performance

The data presented in Section 6.2 indicate that Gbalahi clay yields filters with slower flow rates and better turbidity removal. The analyses in Section 8.2 indicate that there is a statistically significant difference in these parameters based on which source of clay was used to make the filter.

9.3 Clay Site Recommendation

Based on the above conclusions, if a lower flow rate and higher turbidity removal are desired, then the author recommends the use of Gbalahi clay if only one clay source is to be used by PHW. However, current research suggests that there is only a weak correlation between the flow rate and bacteria removal efficiency of ceramic filters (Gensburger 2011), so PHW may be interested in producing filters with higher flow rates and lower turbidity removal if other parameters can be simultaneously changed to ensure bacteria removal. Doing so may make the filters more attractive to users.

9.4 Recommendations for Future Work

If new clay sites are considered in the future, it may be beneficial to perform clay tests similar to the ones performed by the author in order to establish how similar the clay is to those we have already evaluated. If a new clay is significantly different from either Gbalahi or Wayamba clay, it is recommended that several test batches be made and their performance measured before using the new site for commercial filters. Similar steps should be taken if it is suspected that a large region of different clay has been discovered within one of the existing sites. The Best Practices Manual also recommends periodic soil tests to ensure that the properties of the clay being used have not changed dramatically (CMWG 2010).

More work must be done to ensure that the filters being produced at the Pure Home Water factory perform at a consistently high level. Progress has been made, but the filters are still not ready for sales and distribution. Specifically, the filters are not achieving the log-2 *E. coli* reduction recommended in the Best Practices Manual (CMWG 2010) and achieved by CT filters from Accra (Johnson et al. 2008) and elsewhere (UNICEF 2007).

9.4.1 More Recipe Experimentation

The task most relevant to this thesis and arguably the most important in ensuring filter quality is to finalize the filter recipe. Bradner has continued the work of Miller, Watters,

and the author, but an acceptable recipe is yet to be finally established. Bradner agrees that this research should continue:

> Our results are currently inconclusive but the staff understands our methods and intentions and will continue to help with this research. Meanwhile a mixture of 25% Wayamba and 75% Gbalahi clay at 10% rice husks is being used for production. This mixture was determined to be adequate for production though possibly not optimal. (Bradner 2011)

Experts have varying opinions on whether it is important or beneficial to mix two clays together. If the clays are to be mixed, many more combinations will have to be tested. The Best Practices Manual states that some clays can benefit from mixing (CMWG 2010). Similarly, Rye says that mixing clays together can be a substitute for adding plasticizers, and that a clay with high plasticity and high shrinkage rates can be mixed with one that has lower plasticity and shrinkage rates to achieve a suitable balance (1981). This is what is currently being done at the Ceramica Tamakloe Ltd. Factory in Accra, where a highly plastic clay and a more sandy clay are mixed. On the other hand, Pillers is of the opinion that mixing clays is less common in the developing world and also less common in filter making (2011). He says that most often, clays can work by themselves and that if blending is done, it is often with sand or grog rather than another clay. He also cites the challenges of procuring clay from two sources and training workers to properly mix the clays. Chartrand shares this view, stating that using one clay is preferable for filters and that any benefits from mixing the clays are not worth the additional work (2011).

Based on these expert opinions, it seems that the main purpose of mixing clays is to arrive at the desired plasticity, and that there are other methods of adjusting this property. Therefore, the author recommends using one clay for the time being, and if that clay is found to be too plastic, then adding grog could be a simpler method to lower the plasticity.

The amount of rice husk in the recipe is also yet to be finalized. It is recommended that the systematic analysis of possible recipes continue, with duplicates or triplicates of each one, until a suitable recipe is found that leads to an appropriate flow rate and at least a log-2 reduction in *E. coli*.

9.4.2 Controlling Combustible Fineness

One concern shared by members of the MEng Ghana Team and consultants involved in the production process is that the fineness of the combustible material added to the clay is poorly controlled. On pages 59-61 of his thesis, Miller provides scanned images of sawdust and rice husk that has been processed in a hammermill before and after being sieved by hand (2010). Miller used combustible that had been passed through this hammermill for the production of filters during his research, but the hammermill was being repaired and upgraded in January 2011 and thus wasn't used for any of the research presented in this thesis.

Since the size of the milled and sieved combustible determines the size of the largest pores in the fired filter, it is recommended that more care be taken in making sure that the combustible is of the same fineness. Research by Gensburger has also demonstrated that changing the particle size of the combustible both increases the flow rate and decreases the bacteria removal effectiveness (2011). The amount of combustible used by the MEng Ghana team to produce their batches of filters in 2011 was based on research done by Miller and Watters, but if the combustible is of a different size, then our respective results may not be comparable.

The author observed that when sieving the rice husk by hand, more and more of the larger pieces of husk fell through the sieve as the sieving time increased. This is due to the fact that most of the pieces are long and narrow, so it is only a matter of time before they are shaken just right so that their thinner dimension fits through the mesh.

> Currently, as the rice husks being purchased are already of fairly small particle size, only one screening is being done to the rice husks…It would be very beneficial to have a two-screen process – one for anything greater than the desired size and one for the fines. Some discussion was given to creating framed screens that could be suspended and then shaken – greatly reducing the amount of time currently required to run small amounts of rice husks through a hand-held sieve. (Bradner 2011)

It is the author's opinion that the hammermill is an even more efficient and effective tool to ensure consistent combustible particle size. Until a new hammermill is obtained, the two-screen process described by Bradner may be the best substitute. Meanwhile, one area of research indicated here is to determine the optimal "sieving time" that yields a maximum amount of appropriately sized combustible.

It should also be noted that the Best Practices Manual recommends using sieves much smaller than what were being used at the PHW factory in January 2011. The Best Practices Manual suggests using a 25- to 30-mesh sieve (openings ranging between 0.6 and 0.7 mm) for both the clay and combustible, but the factory was using 14- and 18-mesh sieves (openings ranging between 1.0 and 1.5 mm) for the clay and combustible. Therefore, it is strongly recommended that the factory invest in smaller sieves or screens.

References

ASTM. 2007. ASTM Standard D422, 1963 (2007), "Standard Test Method for Particle-Size Analysis of Soils,". ASTM International.

———. 2010. ASTM Standard D4318, 2010, "Standard Test Methods for Liquid Limit, Plastic Lmit, adn Plasticity Index of Soils,". ASTM International. www.astm.org.

Bloem, Sophie C., Doris van Halem, Mickey L. Sampson, Laing-Shun Huoy, and Bas Heijman. 2009. Silver Impregnated Ceramic Pot Filter: Flow Rate versus the Removal Efficiency of Pathogens. Delft University of Technology, February.

Bradner, Curt and Cathy. 2011. Trip Report – The PHW Experience – Filter Production Consultation. April.

CMWG. 2010. Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment, Ed. 1.

Chartrand, Peter. 2011. Correspondence with Susan Murcott, Nov 9.

Craig, R. 2004. Craig's soil mechanics. 7th ed. London ;;New York: Spon Press.

Desmyter, Davy, Abaazan P. Adagwine, Shakool Ibrahim, Mary Kay Jackson, and Susan E. Murcott. 2009. Monitoring and Evaluation of 1,000 Households receiving Ceramic Pot (*Kosim*) Filters after an Emergency Flood Mass Distribution in Northern Ghana. February.

Filtration Technology Ltd. Filtration Technology - Portable Turbidimeter. http://www.filtec.co.nz/products/turbidimeter_Hach_type09.htm.

Gensburger, Isabelle. 2011. Investigation of the Critical Parameters in the Production of Ceramic Water Filters.

Germaine, John T. 2010. 1.37 Laboratory Assignment No. 1: Classification and Index Tests. September.

Google Maps. 2011. Tamale, Ghana. http://maps.google.com/maps.

Hamer, Frank. 2003. The potter's dictionary of materials and techniques. 5th ed. London: A. & C. Black.

VWR International. 2011. Soil Analysis Hydrometer. https://www.vwrsp.com/.

Johnson, Sophie M., Rachel L. Peletz, and Susan Murcott. 2008. Results from Household Ceramic Fitler Evaluation in Northern Ghana.

Kleiman, Shanti. 2011. Ceramic Filter Manufacturing in Northern Ghana: Water Storage and Quality Control. Cambridge, Massachusetts: Massachusetts Institute of Technology, June.

Miller, Travis Reed. 2010. Optimizing Performance of Ceramic Pot Filters in Northern Ghana and Modeling Flow through Paraboloid-Shaped Filters. Cambridge, Massachusetts: Massachusetts Institute of Technology, June.

Nardo, Richard. 2005. Factory Startup Manual: For the Production of Ceramic Water Filters. November 16. http://pottersforpeace.org/wp-content/uploads/production-manual-iraq.pdf.

OECD/WHO. 2003. Assessing microbial safety of drinking water : improving approaches and methods. Paris: Organisation for Economic Co-operation and Development.;World Health Organization.

Oyanedel-Craver, VA. 2008. “Sustainable colloidal-silver-impregnated ceramic filter for point-of-use water treatment.” Environmental science & technology 42 (3) (February 1): 927-33.
Pillers, Robert. 2011. Correspondence with Susan Murcott, Nov 9.
Rayner, Justine. 2009. Current Practices in Manufacturing of Ceramic Pot Filters for Water Treatment. Leicestershire, UK: Loughborough University.
UNICEF. 2007. Improving Household Drinking Water Quality: Use of Ceramic Water Filters in Cambodia. http://www.wsp.org/wsp/sites/wsp.org/files/publications/926200724252_eap_cambodia_filter.pdf.
Watters, Travis. 2010. The Effect of Compositional and Geometrical Changes to the Bending Strength of the Ghanaian Ceramic Pot Filter. Cambridge, Massachusetts: Massachusetts Institute of Technology, June.
World Bank, World Development Indicators. 2011. Google public data, Mortality rate under five. http://www.google.com/publicdata.
World Health Organization. 2006. Mortality Country Fact Sheet 2006. June. http://who.int/whosisi/mort/profiles/mort_afro_gha_ghana.pdf.

Appendices

Appendix A - Work Schedule

Task	Predecessor	Start	Duration	End	Location
1. Collect samples from the field		1/4	3	1/6	Clay sites
2. Prepare clay for filter production	1	1/7	5	1/11	Factory
2a. Dry samples in sun	1	1/7	3	1/9	Factory
2b. Pound and sieve the samples	2a	1/10	2	1/11	Factory
3. Filter production	2b	1/12	9	1/20	Factory
3a. Press the filters	2b	1/12	2	1/13	Factory
3b. Dry the filters	3a	1/13	6	1/18	Factory
3c. Fire the filters	3b	1/19	1	1/19	Factory
4. Soil tests	2b	1/15	8	1/22	Lab
4a. Liquid limit tests	2b	1/15	4	1/18	Lab
4b. Plastic limit tests	2b	1/19	4	1/22	Lab
5. Performance tests	3c	1/20	7	1/26	Factory/Lab
5a. Soak filters for flow rate tests	3c	1/20	1	1/20	Factory
5a. Flow rate tests	5a	1/21	1	1/21	Factory
5b. Turbidity tests	3c	1/21	1	1/21	Factory
5c. Quanti-Tray® tests	3c	1/22	5	1/26	Factory/Lab

Appendix B – Additional Sample Pictures

The following are pictures of the holes from which the samples were taken

G1

G2

G3

G4

G5

G6

G7

G8

G9

G10

G11

G12

W1

W2

W3

W4

W5

W6

W7

W8

W9

W10

W11

W12

Appendix C - Plasticity Chart

Figure C-1 shows the classification of fine soils based on their liquid limit and plasticity index. The "A-line" marks the boundary between silts and clays, and the following letters are used in the classification:

C – Clay
M – Silt

L – of low plasticity
I – of intermediate plasticity
H – of high plasticity
V – of very high plasticity
E – of extremely high plasticity

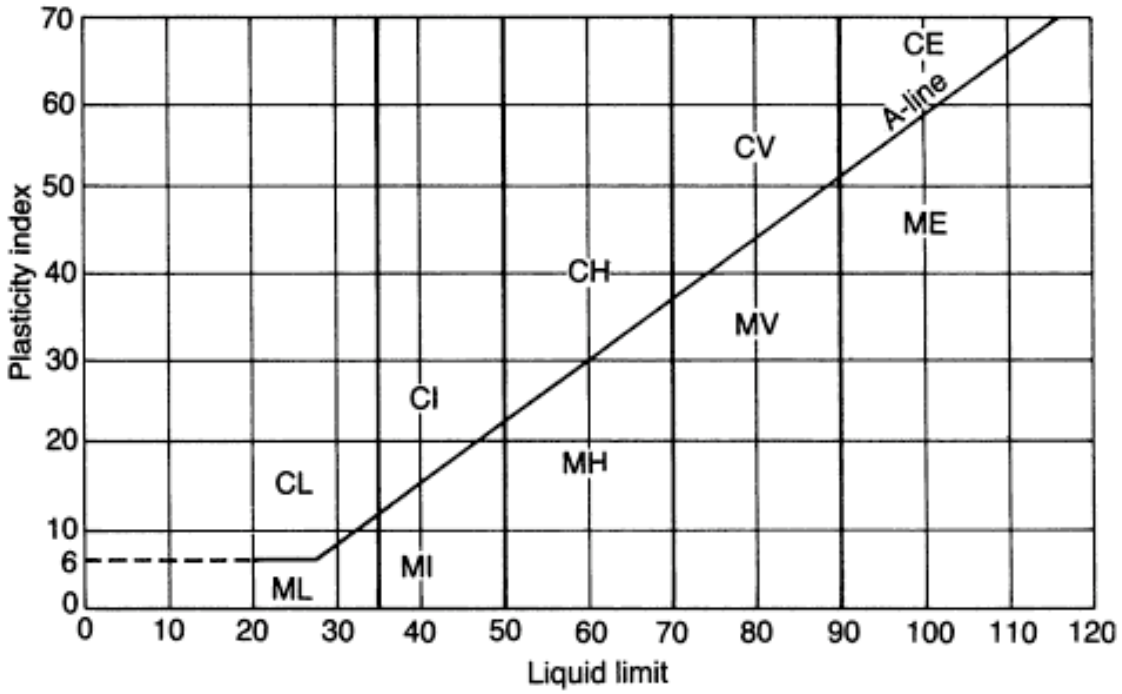

Figure C-1: Plasticity chart from Craig 2004

Appendix D - Additional Sample Data

Table D-1: Sample depth of clay

Sample	Depth [cm]
G1	30
G2	50
G3	50
G4	55
G5	60
G6	60
G7	55
G8	60
G9	60
G10	60
G11	60
G12	65
W1	60
W2	60
W3	55
W4	70
W5	60
W6	60
W7	70
W8	60
W9	50
W10	55
W11	65
W12	60

Table D-2: Percent of sample retained on sieve during processing

Sample	Percent retained
G1	46.85%
G2	43.28%
G3	57.31%
G4	52.98%
G5	46.67%
G6	59.42%
G7	38.46%
G8	57.23%
G9	62.89%
G10	50.61%
G11	38.93%

G12	49.01%
W1	46.03%
W2	34.15%
W3	37.67%
W4	Accidental discard
W5	54.55%
W6	41.61%
W7	43.94%
W8	36.55%
W9	42.86%
W10	39.10%
W11	43.44%
W12	40.48%

Table D-3: Detailed clay plasticity data

Sample	Liquid Limit	Plastic Limit	Plasticity Index
G1	65.35	28.40	36.95
G2	68.81	20.92	47.89
G3	71.00	26.63	44.38
G4	59.83	24.18	35.65
G5	67.43	24.12	43.32
G6	59.66	23.11	36.55
G7	47.79	19.69	28.11
G8	58.06	25.51	32.55
G9	53.96	27.84	26.12
G10	64.73	23.60	41.14
G11	67.11	24.06	43.05
G12	71.80	26.45	45.36
W1	56.39	20.07	36.32
W2	54.17	22.93	31.25
W3	63.51	24.30	39.22
W4	60.08	22.44	37.64
W5	66.22	27.14	39.08
W6	57.63	21.11	36.52
W7	58.60	23.50	35.10
W8	42.02	17.38	24.64
W9	61.15	20.03	41.12
W10	53.07	19.20	33.86
W11	56.11	19.85	36.26
W12	58.19	24.17	34.02
T4	48.73	16.98	31.75
T5	51.65	16.67	34.98
T6	52.78	16.74	36.04

Table D-4: Detailed filter performance data.

Filter	Flow Rate [L/hr]	Percent Change NTU	Coliform Reduction	*E. coli* Reduction
G1	4.4	61.9%	0.00%	41.58%
G2	2	87.1%	0.00%	99.05%
G3	3	78.7%	60.30%	85.08%
G4	4.5	59.4%	0.00%	67.29%
G5	3.5	59.0%	62.23%	71.51%
G6	3.9	59.8%	0.00%	92.66%
G7	2.4	80.9%	60.30%	93.87%
G8	2.2	88.9%	65.71%	93.63%
G9	5.1	56.8%	84.61%	92.91%
G10	2	74.1%	0.00%	92.44%
G11	2.2	66.3%	60.30%	84.36%
G12	1.6	71.7%	46.28%	97.11%
W1	5.1	41.7%	41.58%	88.75%
W2	5.1	45.1%	0.00%	87.00%
W3	4.6	51.2%	58.21%	94.94%
W4	5.1	54.6%	58.21%	90.08%
W5	5.1	56.2%	0.00%	87.76%
W6	5.1	60.4%	0.00%	90.65%
W7	5.1	46.9%	58.21%	72.78%
W8	3.2	85.2%	0.00%	99.63%
W9	5	62.0%	53.72%	76.05%
W10	4.9	63.4%	35.81%	66.26%
W11	5	51.5%	82.65%	88.39%
W12	5	63.7%	0.00%	97.59%
T4	5.1	45.4%	0.00%	92.05%
T5	4.7	51.2%	0.00%	90.34%
T6	4.9	51.7%	0.00%	89.48%
G AVERAGE	3.1	70.4%	36.64%	84.29%
W AVERAGE	4.9	56.8%	32.36%	86.66%
T AVERAGE	4.9	49.43%	0.00%	90.62%
G STDEV	1.2	11.49%	33.42%	16.65%
W STDEV	0.5	11.54%	30.63%	10.06%
T STDEV	0.2	3.49%	0.00%	1.31%

Table D-5: Detailed data from microbial, flow rate, and turbidity tests

	Coliforms		*E. coli*		Empty Cells	MPN Coliform	MPN *E. coli*	Percentage Removal *E. coli*	Dugout Coliforms MPN	Dugout *E. coli* MPN	Flow Rate [L/hr]	NTU Before	NTU After	Percent Change NTU
Filter	Lg	Sm	Lg	Sm										
G1	49	48	49	43		TNTC	1413.6	41.6%	TNTC	2419.6	4.4	114	43.4	61.9%
G2	49	48	5	0		TNTC	5.2	99.1%	TNTC	547.5	2	121	15.6	87.1%
G3	48	47	48	26	1	960.6	360.9	85.1%	TNTC	2419.6	3	114	24.3	78.7%
G4	49	48	48	43		TNTC	791.5	67.3%	TNTC	2419.6	4.5	114	46.3	59.4%
G5	48	46	48	40	1	913.9	689.3	71.5%	TNTC	2419.6	3.5	130	53.3	59.0%
G6	49	48	24	6		TNTC	40.2	92.7%	TNTC	547.5	3.9	127	51	59.8%
G7	48	47	45	13	1	960.6	148.3	93.9%	TNTC	2419.6	2.4	105	20.1	80.9%
G8	48	44	44	17	1	829.7	154.1	93.6%	TNTC	2419.6	2.2	111	12.3	88.9%
G9	44	48	24	5	4	372.4	38.8	92.9%	TNTC	547.5	5.1	111	48	56.8%
G10	49	48	26	4		TNTC	41.4	92.4%	TNTC	547.5	2	147	38	74.1%
G11	48	47	48	27	1	960.6	378.4	84.4%	TNTC	2419.6	2.2	106	35.7	66.3%
G12	49	42	12	2		1299.7	15.8	97.1%	TNTC	547.5	1.6	111	31.4	71.7%
W1	49	43	31	9		1413.6	61.6	88.7%	TNTC	547.5	5.1	126	73.5	41.7%
W2	49	48	37	4		TNTC	71.2	87.0%	TNTC	547.5	5.1	104	57.1	45.1%
W3	48	48	15	8	1	TNTC	27.7	94.9%	TNTC	547.5	4.6	103	50.3	51.2%
W4	48	48	47	21	1	TNTC	240	90.1%	TNTC	2419.6	5.1	121	54.9	54.6%
W5	49	48	34	7		TNTC	67	87.8%	TNTC	547.5	5.1	114	49.9	56.2%
W6	49	47	29	6		2419.6	51.2	90.6%	TNTC	547.5	5.1	121	47.9	60.4%
W7	48	48	48	39	1	1011.2	658.6	72.8%	TNTC	2419.6	5.1	114	60.5	46.9%
W8	49	48	1	1		TNTC	2	99.6%	TNTC	547.5	3.2	106	15.7	85.2%
W9	49	40	49	29		1119.9	579.4	76.1%	TNTC	2419.6	5	111	42.2	62.0%
W10	49	44	49	35		1553.1	816.4	66.3%	TNTC	2419.6	4.9	121	44.3	63.4%
W11	47	35	47	25	2	419.8	280.9	88.4%	TNTC	2419.6	5	132	64	51.5%
W12	49	48	10	2		TNTC	13.2	97.6%	TNTC	547.5	5	111	40.3	63.7%
T4	49	48	27	4		TNTC	43.5	92.1%	TNTC	547.5	5	120	65.5	45.4%
T5	49	48	31	4		TNTC	52.9	90.3%	TNTC	547.5	4.7	103	50.3	51.2%
T6	49	47	34	2		2419.6	57.6	89.5%	TNTC	547.5	4.9	111	53.6	51.7%

TNTC denotes too numerous to count.

Appendix E – Regression Analyses

Table E-1: Regression analyses for non-exhaustive combinations of parameters

Parameter 1	Parameter 2	Adjusted R2 value	t Stat	P-value	Null hypothesis rejected?
Plasticity	Flow rate	0.1025	-1.993	0.05729	No
Plasticity	Percent gravel	-0.0390	-0.4171	0.6809	No
Plasticity	Turbidity reduction	-0.0241	0.6230	0.5390	No
Plasticity	Percent clay	0.4416	4.644	0.000094	Yes
Percent clay	Flow rate	0.2177	-2.869	0.008244	Yes
Percent clay	Turbidity reduction	0.0055	1.069	0.2952	No
Percent clay	*E. coli* reduction	-0.0298	-0.497	0.6233	No
Flow rate	Turbidity reduction	0.6440	-6.930	0.00000029	Yes
Flow rate	*E. coli* reduction	0.0288	-1.330	0.1954	No
Turbidity reduction	*E. coli* reduction	0.0103	1.127	0.2706	No
Percent gravel	Percent clay	0.1582	2.387	0.02522	Yes
Percent gravel	Sample depth	-0.0476	0.01311	0.9897	No
Percent gravel	Flow rate	-0.00056	0.9930	0.3306	No
Percent gravel	Turbidity reduction	0.0209	-1.239	0.2275	No
Sample depth	Flow rate	-0.0384	0.385	0.7036	No
Sample depth	Percent clay	-0.0293	-0.5873	0.5630	No
Sample depth	Turbidity reduction	0.0187	-1.200	0.2430	No

Appendix F – New Data

Table F-1: Performance data for most successful filter batch produced by Bradner

Serial number	% Rice Husk	% Wayamba clay	30 Minute Flow Rate [L/hr]	60 Minute Flow Rate est. from 30 minute [L/hr]	E Coli Count	% Reduction *E. coli*
Source Water			NA	NA	360	0.00%
15-35/64-2	0.15	0.35				
15-35/65	0.15	0.35				
2-13-25/75-3	0.13	0.25				
2-11-25/75-1	0.11	0.25	1	2	52	85.56%
11-35/65-5	0.11	0.35	1.4	2.8	80	77.78%
12-25/75-2	0.12	0.25	1.4	2.8	64	82.22%
2-15-25/75-5	0.15	0.25				
2-13-25/75-5	0.13	0.25	1.4	2.8	68	81.11%
2-14-25/75-5	0.14	0.25				
15-35/65-4	0.15	0.35				
2-11-35/65-2	0.11	0.35	1.2	2.4	25	93.06%
2-13-25/75-2	0.13	0.25				
2-11-35/65-1	0.11	0.35				
13-35/65-2	0.13	0.35				
12-35/65-3	0.12	0.35	1.4	2.8	29	91.94%
11-35/65-4	0.11	0.35	1	2	65	81.94%
14-35/65-3	0.14	0.35				
2-11-25/75-4	0.11	0.25	1	2	26	92.78%
2-11-35/65-3	0.11	0.35			42	88.33%
13-35/65-3	0.13	0.35	1.1	2.2	56	84.44%
2-12-25/75-1	0.12	0.25	1.3	2.6	46	87.22%
12-35/65-5	0.12	0.35	1.1	2.2	56	84.44%
13-35/65-1	0.13	0.35	1.1	2.2	57	84.17%
14-35/65-5	0.14	0.35				
11-35/65-1	0.11	0.35	1	2	67	81.39%
2-14-25/75-4	0.14	0.25				
2-14-25/75-3	0.14	0.25	1.1	2.2	35	90.28%
2-15-25/75-1	0.15	0.25				
15-35/65-3	0.15	0.35				
2-11-25/75-5	0.11	0.25	0.4	0.8	54	85.00%
12-35/65-4	0.12	0.35				
13-35/65-4	0.13	0.35				

14-35/65-2	0.14	0.35				
2-13-25/75-1	0.13	0.25				
2-12-25/75-4	0.12	0.25	1	2	89	75.28%
11-35/65-3	0.11	0.35	1.1	2.2	99	72.50%
2-11-50/50-5	0.11	0.5	0.5	1		
2-15-35/65-5	0.15	0.35				
2-14-35/65-2	0.14	0.35				
2-13-35/65-5	0.13	0.35	1.2	2.4		
2-13-50/50-2	0.13	0.5	1.8	3.6		
2-12-50/50-3	0.12	0.5	1.5	3		
2-15-35/65-2	0.15	0.35				
2-13-50/50-4	0.13	0.5	2	4		
2-15-35/65-4	0.15	0.35				
2-13-35/65-3	0.13	0.35	1.5	3		
2-14-35/65-3	0.14	0.35	1.5	3		
2-12-50/50-5	0.12	0.5	1.25	2.5		
2-14-35/65-1	0.14	0.35				
2-13-35/65-1	0.13	0.35	1.5	3		
2-12-50/50-2	0.12	0.5	0.5	1		
2-11-35/65-4	0.11	0.35	2.8	5.6		
2-11-50/50-2	0.11	0.5				
2-13-35/65-2	0.13	0.35				
2-12-50/50-4	0.12	0.5	1.2	2.4		
2-14-35/65-5	0.14	0.35				
2-15-35/65-3	0.15	0.35				
2-11-50/50-1	0.11	0.5	2	4		
2-mix-50/50		0.5	1	2		
2-11-50/50-3	0.11	0.5	0.6	1.2		
2-13-50/50-2	0.13	0.5	1.5	3		
2-13-35/65-4	0.13	0.35	2	4		
13-50/50-3	0.13	0.5	2	4		
2-13-50/50-3	0.13	0.5	1.5	3		
no number						
2-13-50/50-5	0.13	0.5				
2-13-50/50-1	0.13	0.5				

Notes: The 2 before the RH percentage means second batch of that number ie: 2-11-25/75-2 means 2nd batch-11%RH-25%Wayamba/75%Gbalhi-2nd filter made in that series out of 41 filters flow tested 5 were discarded as they all failed, they were the last filters made on a Friday, either the measuring, mixing or pressing went askew
so we did not want them as part of the data base, they were 2-12-35/65- 1,2,3,4,5.

Appendix G – Shrinkage Rate Test of Gbalahi Clay

Summary
As of December 2011, the Pure Home Water factory is using an estimate of clay shrinkage rate for their calculations related to the production of the *Kosim* water filter. I was asked to conduct shrinkage rate tests so that a more accurate number can be used. I generally followed the method described in Annex D of the March 2011 edition of the Best Practices Manual written by the Ceramics Manufacturing Working Group, though I also received guidance from Dr. John Germaine of MIT's CEE department.

Clay recipe
Dried, unprocessed clay brought back from Gbalahi by the MEng team in January 2010 was ground using a mortar and pestle and passed through a sieve with openings of approximately 1mm (corresponding to what is currently being used at the PHW factory). Rice husk marked "RH thru 18/14 mesh", also brought back by the 2010 team, was used as the combustible. Recipe #3 from Miller was used (2010):

Table G-1: Clay recipe for shrinkage test

	Recipe #3 (kg)	% of total	Test batch (g)	% of total
Clay	11	51.16%	201.55	49.17%
Rice husk	4	18.60%	73.34	17.89%
Water	6.5	30.23%	135	32.94%
TOTAL	21.5		409.89	

The amount of water used was based on data collected by the author in January 2011.

Sample preparation[21]
Since there was not enough clay to produce bricks of the size recommended in the Best Practices Manual, samples 1, 2, and 3 were prepared in lengths of 2.54 cm (1 inch) diameter metal tubing, each approximately 6.3 cm long. Clay was compacted in three layers within each 6.3-cm length using a pressure of 0.5-1.0 kg/cm2 for each layer with a tool that was much smaller than the diameter of the tubing. The samples were compacted with a pressure of 2.0 kg/cm2 at the end when all layers had been added, using a tool the same diameter as the tubing. Pressure was measured with a compaction tool provided by Dr. Germaine. Since there was clay left after preparing these samples, samples 4, 5, and 6 were made by rolling "snakes" of clay approximately 1 – 1.5 cm in diameter and at least 10 cm long. These were scored with a 10 cm line to be able to measure the change in length after drying and firing[22]. All samples were weighed before drying.

[21] Dr. Germaine recommended compaction because he felt it was important, but the instructions in the Best Practice Manual and the verbal instructions relayed to me did not involve compaction, which is why half of the samples were compacted and half were not.
[22] It should be noted that the initial measurements for samples 4, 5, and 6 were made with a ruler since calipers were not available at the time of sample preparation. This means there is a little more room for error in these measurements, but I estimate no more than 2-3 mm.

Drying
Samples were dried in a 110˚C oven for 30 hours, then weighed and measured again. After drying, samples 1, 2, and 3 were removed from the tube sections. Three length measurements were made for each sample to reduce measurement error. The mean of these three values was then taken to be the length.

Firing
The recommended firing curve published in the March 2011 version of the Best Practices Manual was followed as closely as possible, but the electric furnace used in this test did not allow the rate of temperature increase to be set, so all "ramping" had to be accomplished by manually changing the temperature throughout the day (which is the cause of the step-function appearance in Figure G-1 below). Special attention was given when passing through the temperature range of 550-575˚C, as the Best Practices Manual warned that a temperature spike in this range could cause cracking. To avoid such a spike, the temperature was increased at 5-minute intervals until the 575˚C had been reached. After firing was completed, the oven was turned off and the samples were left inside to cool overnight. Samples were then measured and weighed approximately 15 hours later.

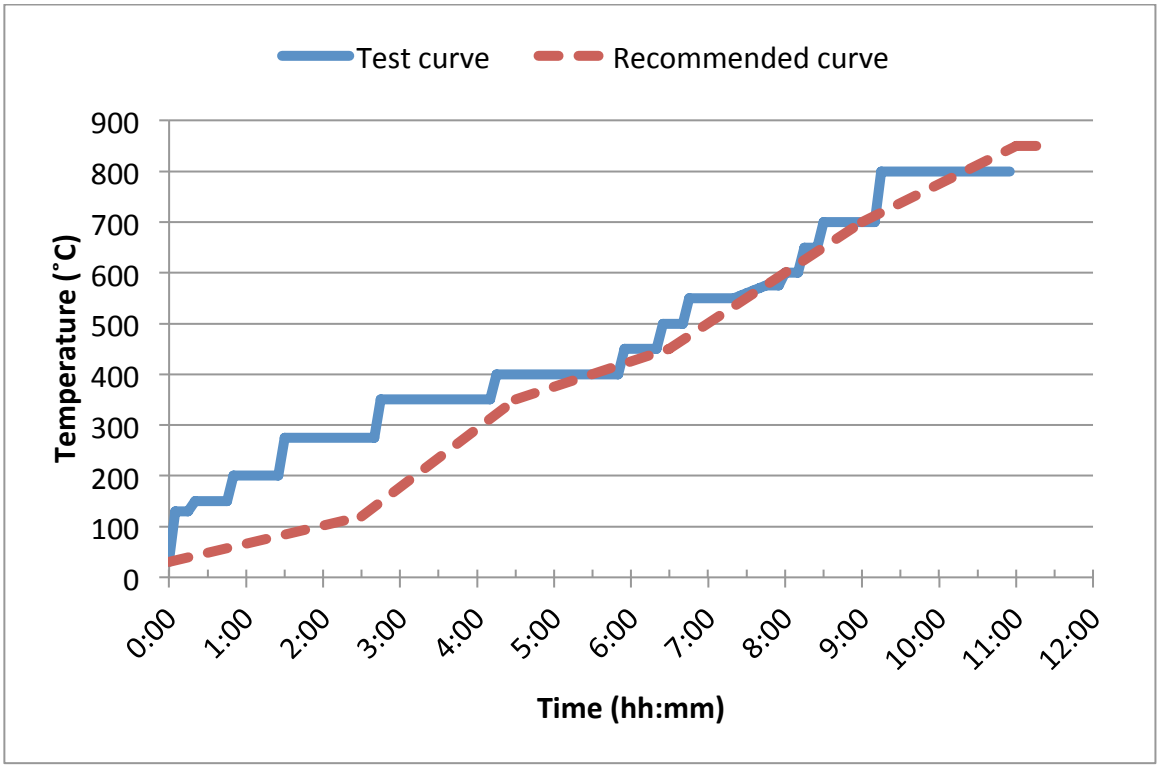

Figure G-1: Shrinkage test firing curve

Results and discussion

Shrinkage rates are reported in Table 2, and mass measurements are presented in Table 1 for completeness. The negative values for some of the shrinkage rates could be attributed in part to measurement errors.

There is a noticeable difference between the average total shrinkage rate of samples 1, 2, and 3 (average of 0.75%) and that of samples 4, 5, and 6 (average of 5.87%). I attribute this to the compaction and think that the pressure applied during the preparation of samples 1, 2, and 3 helped arrange the clay particles in a way that reduced shrinkage during drying and firing. The fact that most of the shrinkage in samples 4, 5, and 6 happened during the drying stage (dry shrinkage column in Table G-3) might suggest that the compaction of samples 1, 2, and 3 helped press out some of the water. However, it can be seen in Table G-2 that the water contents of all samples are very similar, so this is likely not the cause of the different rates. One hypothesis to explain the difference between the two sets of samples is that the compaction may have reduced the void space occupied by air in the compacted samples.

Table G-2: Mass measurements

Sample	Mass before drying (g)	Mass after drying (g)	Mass after firing (g)	Water content of wet sample	% Change from wet weight to fired weight	% Change from dry weight to fired weight
1	49.75	33.3	25.1	33.07%	-49.55%	-24.62%
2	52.9	35.5	26.7	32.89%	-49.53%	-24.79%
3	49.99	33.5	25	32.99%	-49.99%	-25.37%
4	87.18	58.8	44.1	32.55%	-49.42%	-25.00%
5	77.32	51.9	39	32.88%	-49.56%	-24.86%
6	54.98	36.9	27.8	32.88%	-49.44%	-24.66%

Table G-3: Length measurements

Sample	Length before drying (mm)	Length after drying (mm)	Length after firing (mm)	Dry shrinkage	Firing Shrinkage	Total Shrinkage
1	63.56	63.09	62.47	0.74%	0.98%	1.71%
2	63.41	63.28	63.35	0.20%	-0.11%	0.09%*
3	62.99	63.08	62.70	-0.14%	0.60%	0.46%
				Compressed average		**0.75%**
4	100	93.68	93.03	6.32%	0.69%	6.97%
5	100	93.92	94.17	6.08%	-0.27%	5.83%
6	100	94.74	95.18	5.26%	-0.46%	4.82%
				Uncompressed average		**5.87%**

*It should be noted once again that sample 2 was the only compacted sample that did not break during drying. Though measurements were made by fitting the pieces of samples 1 and 3 back together, it could be expected that these shrinkage rates are, in reality, lower than reported here.

Recommendations for future tests

In order to get results that are as relevant to PHW as possible, it would be beneficial to carry out more shrinkage rate tests in Ghana using the exact compositions and processing steps that they are currently using. The tests presented here demonstrate that compacting the sample vs. not compacting the sample can have a big impact on the shrinkage rate, so it would also be advisable to replicate the pressure that is used to form the filters when preparing the samples for the shrinkage rate tests. The Best Practices Manual recommends making bricks measuring 14 cm x 4 cm x 1 cm, which was not possible here given the material constraints (and the size of the furnace). However, for future tests, it could be easier to compress the samples in the field if bricks are made instead of cylinders or snakes.

One other idea would be to actually use a freshly pressed filter and cut strips out of it that could then be scored with a fixed length marking and measured after drying and firing as described in the Best Practices Manual. This would guarantee that the conditions of the sample preparation exactly replicate the conditions used in filter production. Or, perhaps it would be most relevant to the PHW factory to simply measure the diameter of the pot after pressing and after firing. Even though this may not correspond to a more universally understood material shrinkage rate, it would provide a "PHW filter shrinkage rate" that would be more useful in figuring out how well the finished filters will fit inside their buckets.