I

RESEARCH ARTICLES

ACTIVATED CARBON AMENDED CERAMIC DRINKING WATER FILTERS FOR BENIN

Bradley Striebig,[1] Sam Atwood, Blake Johnson, Ben Lemkau, James Shamrell, Philip Spuler, Krystal Stanek, Amanda Vernon, and Julia Young

IMPLICATIONS

Effective ceramic drinking water filters can be manufactured from clay and organic wastes. The performance of these filters can be improved to meet WHO guidelines for dissolved pollutants with the addition of activated carbon. The activated carbon can also be created from coconut shells which are currently discarded as waste.

ABSTRACT

The water at the Songhai Center in Benin was tested and was compromised by the lack of sanitation and water treatment due to the high poverty level in the Country. A ceramic filter (Filtrón) effectively removed biological contaminants from drinking water. The activated carbon was manufactured from coconut shell wastes, by-products of agricultural production at the Songhai Center. Activated carbon further increased the effectiveness of the filter, particularly in removing phosphates, nitrates and lead, which are common inorganic contaminants. These ceramic filters can be economically manufactured at the Songhai Center in Porto-Novo, Benin for cost-effective drinking water treatment. Community-focused projects, such as this one, directly address the United Nations (UN) goal to halve the number of people without access to clean water or sanitation by 2015. The effectiveness, low cost, and ease of use make these technologies fully sustainable and ideal for point of use treatment of drinking water in Benin and developing countries.

BACKGROUND AND PROBLEM DEFINITION

The United Nations (UN) has developed the Millennium Development Goals (MDG) program to reduce poverty and improve access to water and sanitation throughout the developing world (1). The UN has specifically stated a goal to halve the number of people without access to clean water and sanitation by 2015. On March 19th, 2006, a statement by the UN noted this goal was in jeopardy in sub-Saharan Africa due to drought, poverty and political factors (2). In short, experts in the field of sustainable development believe providing clean water and sanitation for sub-Saharan Africa is one of the world's greatest challenges.

Benin lies in the heart of sub-Saharan Africa and 32% of its population lacks access to water and 68% to sanitation (3, 4, 5). Benin has a stable government and excellent primary education system. However, the average income in Benin is approximately 530 US dollars per year. Centralized water treatment is not a feasible option for community drinking water in Benin because it is extremely expensive to construct and maintain. As a result, decentralized or point of use technologies are the most appropriate choice for treating drinking water.

Objectives

The water-related problems in Benin require sustainable solutions that focus on low-costs, longevity, and cultural adoptability. The purpose of this project is to provide a water filter combining ceramic water treatment and activated carbon as a simple and inexpensive method of reducing human exposure to water-borne diseases in Benin.

The primary objective of this project is to provide the people of Benin with an efficient, and sustainable manufacturing plant to produce effective household water filtration systems. The filtration system must also be inexpensive to meet the economic needs of the Beninese people. The tasks described in this paper include:

[1]School of Engineering and Applied Science, Gonzaga University, AD 26, Spokane, WA 99208, striebig@gonzaga.edu.

- Determination of the Filtrón removal efficiency for anthropogenic and biological contaminants.
- Production of activated carbon from coconut shells and comparison to surface characteristics of commercially available activated carbon.
- Incorporation of activated carbon into Filtrón design to meet WHO Drinking Water Standards

Existing Water Quality

The water in rural Benin suffers from four primary types of contamination: pollution from particulates, biological constituents, anthropogenic sources, and natural sources (6,7). Biological constituents consist of bacteria and viruses. These are the major concern in Benin drinking water because of their impact on human health. Benin water samples (see Table 1) had high concentrations (>160 MPN/100mL) of bacterial indicator organisms such as total coliforms (6). Pollution from anthropogenic sources primarily from latrines, animal feed lots, and dried-up wells used as garbage dumps are also a concern (7,8).

In rural Benin, the primary ways in which people obtain clean drinking water are by boiling water or purchasing imported bottled water (9). Boiling the water requires wood and native vegetation, depleting local resources and emitting smoke into households and the atmosphere. Buying imported water is not a cost-effective long-term solution for low-income populations. Furthermore, the link between drinking water, sanitation and disease is not clearly understood in Benin. As a result, the people of Benin may not fully appreciate the value in filtering the water.

Waterborne diseases spread pathogens by the ingestion of urine or feces contaminated water. Typhoid fever, amoebic dysentery, schistosomiasis and cholera are just a few of the diseases spread by contaminated water. Diarrheal diseases are the third leading cause of death in Benin after lower respiratory infections and malaria, respectively (4). Maternal mortality rates are estimated to be 850 maternal deaths per 100,000 births (4). It is estimated that 167 of every 1,000 children die before the age of five in Benin. Providing the technology to implement point-source water treatment in the community can significantly reduce the percentage of children under 5 (7.1%) who die due to diarrheal diseases (10).

Point-of-use Treatment Technologies

Three treatment technologies (shown in Table 2) with a proven and technologically appropriate track record were considered for drinking water purification. The advantages and disadvantages of each technology were evaluated by project partners. Each technology fits a specific niche in developing countries. The Biosand filter, however, was considered to be too expensive for an individual home and to difficult to maintain without a responsible party in the village. The SODIS system, while very affordable, was subject to variations in water quality and treatment effectiveness and could not achieve WHO standards for non-biological pollutants. The SODIS system would however, be a good technology to transfer to the SC as a complementary technology to the more reliable Filtrón™. The Filtrón technology appeared to be the best point-of-use system to deliver reliable high quality drinking water for individuals households in Benin.

The Filtrón is a ceramic filter developed by Potters For Peace that is designed to fit within a five gallon plastic pail or clay container. In addition to porous ceramic filtration, colloidal silver is used to inhibit bacterial growth (11, 12). The Filtrón has been cited by the UN in its *Appropriate Technology*

TABLE 1. Microbial and chemical contaminants measured in Benin water samples.

Contaminant	Units	Concentration in Benin Water	WHO Standard[10]	US EPA Standard[11]
Total Coliforms	MPN/100ml	>1600	0	0
Fecal Coliforms	MPN/100ml	20	0	0
E. Coli	MPN/100ml	NA	0	0
Pathogens	MPN/100ml	>8	0	0
Lead	µg/L Pb	4	10	15
Arsenic	µg/L As	ND	10	10
Nitrates	mg/L NO_3^--N	>30.0	50	10
Phosphate	mg/L PO_4^{3-}	0.19	NA	NA

TABLE 2. Point of use appropriate water treatment technologies.

Technology	Description	Advantage	Disadvantage
Biosand™	Sand Filtration	• High removal efficiency for microorganisms • Cost	• Needs continual use and regular maintenance
FiltrónTM	Ceramic Filter	• High removal efficiency for microorganisms • Sized for households • Relatively inexpensive	• Requires fuel for construction • Limited lifetime • Requires regular cleaning
SODISTM	Solar Water Disinfection	• Highly effective • Inexpensive • Can reuse a waste product (PET bottles)	• Long treatment time (6 to 48 hours) • Does not remove other pollutants • Requires warm climate and sunlight

Handbook and used by the Red Cross and Doctors Without Borders (12–14). There are currently several countries around the globe that have employed this low-cost, appropriate technology filter with good results. Most other water treatment technologies require more energy (ultraviolet disinfection systems) or chemical additives (chlorination or other chemical disinfectants). Energy and chemical intensive disinfection systems may provide comparable or even better disinfection, however, the cost and availability of energy and chemical supplies is not sustainable within the community.

Activated Carbon

Granulated Activated Carbon (GAC) is widely used to remove pollutants from both air and water. Carbon activation occurrs when carbonaceous material develops a porous structure, greatly increasing the surface area of the material.

There are two ways activated carbon is manufactured: chemically and thermally. The chemical process uses reacting agents as catalysts, while thermal activation uses heat and gas vapors to activate the carbon. The chemical activation process is generally used to produce GAC from cellulose material such as wood through the use of chemicals such as phosphoric acid, zinc chloride, sulfuric acid, and others which are relatively expensive (15). While these chemicals produce AC at an overall yield of 30–50 wt %, the need to separate and recycle the catalyst adds to the cost and complexity of this method (16). Consequently, it was eliminated from consideration for application in Benin.

Activation is the most important production stage; the development of extensive micro-pores and meso-pores is accomplished by heating the carbonaceous material at higher temperatures while subjecting it to steam. Activation using steam is conducted at temperatures between 800–1100°C in a steam-embedded atmosphere (15). The quality, quantity and effectiveness of the GAC depends upon the nature of the raw material, the duration of the burn-off period, the temperature and flow rate of steam within the kiln (17). Steam activation was used because the GAC could be produced on-site at the SC using recycled water for steam generation and renewable biogas as the energy source. Other activation processes are effective but are less sustainable, requiring the purchase and transport of additional chemicals not produced in Benin.

Currently, drinking water technologies for the developing world only address microbial contaminants; they are often slow or require careful maintenance. Existing low cost treatment technologies also have traditionally focused only on providing water, sometimes at the expense of considering the impacts on deforestation (for boiling water) and air emissions (for technologies which use cement, plastics and fossil fuels).

DISCUSSION OF DATA, RESULTS, AND FINDINGS

Ceramic Filter (Filtrón) Treatment

The Filtróns are 31 cm in diameter, 24 cm from top to bottom, and shaped like a flowerpot. The porosity of the Filtróns ranges from 0.2–1 microns (18).

As water passes through the Filtrón, microorganisms and particulates are trapped in the interstitial spaces of the Filtrón pores. Most bacteria and parasitic organisms are larger than the pore spaces though the filter (18). Each Filtrón is impregnated with a small amount of colloidal silver, which acts as a disinfection agent to prevent mold. Once trapped, the colloidal silver prevents bacteria growth and mold build-up. Colloidal silver is a known disinfecting agent, which will help to keep the Filtrón sterile (18). It is painted in minute quantities (at a 1:150 cc silver to water ratio) on the inside and outside of the Filtrón surface after the Filtrón has been fired and cooled. Colloidal silver is not listed as a toxin by the US EPA's Poison Control Center, and poses no threat to human health if ingested in small quantities.

In order to determine the effectiveness of our filter system design, it was necessary to create a synthesized water sample for testing the water filter. The sample contained 85% Spokane River water with 15% screened Spokane WWTP sewage influent, by volume. The synthesized water was tested for Total Coliforms, E-coli, Fecal coliforms, Nitrates, Phosphates, Lead, Arsenic, and Pathoscreen (see Table 3). Water samples were passed directly through the filter at a flowrate of 1.5 Liters per hour.

As reported in literature and discussed in personal communications, Filtróns performed very well in the removal of biological constituents. The micro-pore structure of the ceramic filtration was able to prevent more than 99% of the total coliforms, fecal coliforms, E. coli, and pathogens from passing through with the filter with the water. However, the filtered water still did not meet the stringent standards set by the World Health Organization (WHO) and the US EPA.

Filtróns were not designed to remove metals and anthropogenic constituents; as such, the results were mixed. It decreased the lead concentration to an amount that was well below the WHO and EPA standards. No conclusive affect on arsenic concentration could be determined for the Filtrón. It was not useful in the removal of nitrates and phosphates; as seen above in Table 3, nitrate and phosphate concentrations even increased after filtration due to the use of previously high nitrate and phosphate waters being filtered with the Filtons.

The estimated the cost for making a Filtrón element was 1.86 ($US) based upon labor, supply and production costs. The total cost estimate for a ceramic filtering element with the plastic tank, top and faucet was six dollars ($US). Virtually all Benin citizens should be able to afford the ceramic filtering element and use their own containers. There were currently no other water filtration products available in Benin.

Activated Carbon

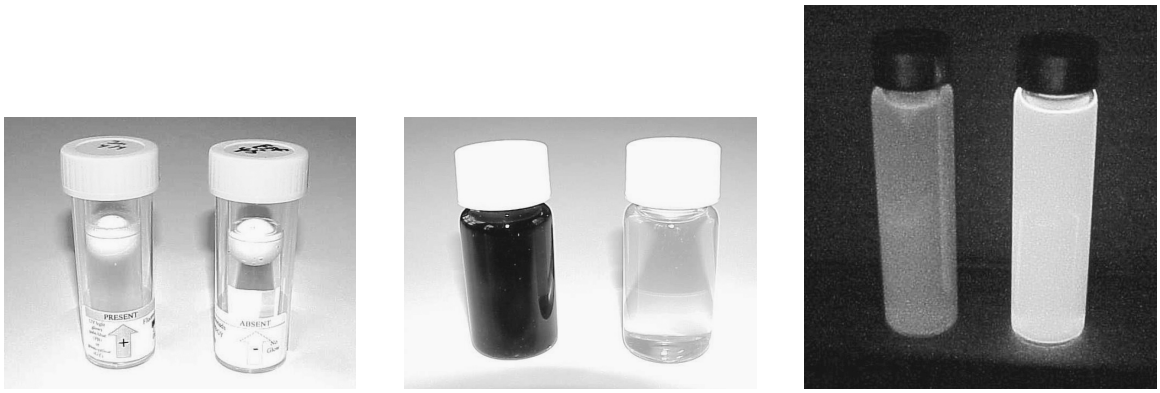
Granulated Activated Carbon (GAC) was integrated into the Filtrón design to improve the efficiency and effectiveness of the filter system. Carbon activation occurred when carbonaceous material developed a porous structure, greatly increasing the surface area of the material with pores on the order of three to several thousand Å (19).

GAC was made from materials high in carbon. Coconut shells were chosen as a sustainable resource for GAC production because it was a waste product

TABLE 3. Demonstrated reduction in microbial and chemical contaminants with Filtrón ceramic water filters and activated carbon water treatment.

Contaminant	Units	Synthetic water	Filtered water	Average Removal
Fecal Coliforms	MPN/100 ml	2575 ± 1300	< 2 ± 0	> 99.92%
Total Coliforms	MPN/100 ml	6233 ± 5967	< 2 ± 0	> 99.97%
E. Coli	MPN/100 ml	200 ± 0	< 2 ± 0	> 99.0%
Pathogens (H_2S producing bacteria)	MPN/100 ml	637 ± 169	< 2 ± 0	> 99.7%
Streptococci	MPN/100 ml	< 20 ± 0	NA	
Amoeba	MPN/100 ml	> 7,000,000	37,000±115,000	99.5
Lead	µg/L Pb	5 ± 2	1 ± 1	73%
Nitrate	mg/L NO_3^--N	18.3 ± 1.0	11.9 ± 1.5	35.1%
COD	mg/L	72 ± 17	25 ± 11	66%

FIGURE 1. Samples showing the difference between filtered and unfiltered water.



(a) Ameoba Test
Positive (cloudy and fluorescing) Negative

(b) E. coli
Negative Positive (fluorescing)

(c) Pathoscreen
Positive (H_2S producing) Negative

of Benin agriculture. The raw coconut shells were initially carbonized or charred before they were activated to reduce volatile content, thereby converting it to a suitable form for activation.

An initial bench-scale activation chamber was designed and constructed using standard black steel pipe and seamless, hydraulic, stainless steel tubing to produce activated carbon. Initial specifications were derived from similar commercial and research activated carbon manufacturing processes and industry practices (20-23). These were:

- Operating Temperature Range: 500°C–1100°C, controllable to ± 30°C.
- Steam Injection System: Steam should reach the internal temperature of the furnace.
- Chamber for Carbon Activation: Limit oxygen in contact with carbonaceous material.

Further review indicated that a variety of kilns would provide the necessary temperature range and controllability using natural gas or propane.

Initial tests were conducted using a GU Art Department kiln. This was an approximately 0.5 m^3 (18 ft^3), updraft, Raku style kiln with three 60 kW (200,000 Btu/hr) natural gas burners capable of producing temperatures in excess of 1300°C. The bench-scale activation chamber consisted of three basic sections: an expansion chamber, a heat exchanger section, and the carbon activation chamber. Fluid flow and temperature were measured at the entrance and exit ports. Water passed through a flow meter into the expansion chamber. After exiting the expansion chamber, the steam passed through the heat exchanger, 2 meters of 1/4″ tubing. This distributed the steam into the activation chamber. Temperature was measured at two points within activation chamber.

A prototype full-scale kiln was designed and constructed to test the activation procedures and create larger activated carbon samples. The design called for a downdraft, catenary arch style kiln, with an inner muffle chamber to increase the overall efficiency of the kiln. The catenary arch was chosen for the firebox due to its self-supporting nature. A downdraft style kiln created consistent temperatures throughout the kiln and allowed the use of a damper to control the firing and decrease heat loss. The inner muffle chamber took longer to heat and thus extended firings were required to achieve the activation temperature. The benefit of this design was better steam containment, and less heat loss.

Logistical considerations required modifications from the conceptual prototype design. An existing catenary arch kiln was modified to fit the design needs. In addition, 1/4″ stainless steel tubing and a stainless steel, DOT certified boiling vessel was used in lieu of the pipe and tubing called for. The result was a kiln with a larger volume than required,

and with a modified steam injection system similar to that of the initial activation prototype. Further constraints limited the prototype kiln to two burners rated at approximately 60 kW (200,000 Btu/hr) using propane Liquified Petroleum Gas (LPG).

The first firing of the initial activation prototype indicated that the desired temperatures could be attained and that steam was being produced and vented from both exhaust ports. A temperature of 800°C inside the kiln was reached within 30 minutes of operation with a maximum temperature of 860°C. The valve for water flow was opened 30 minutes with steam being produced for one hour before the kiln was turned off and allowed to cool.

In order to test the steam injection system efficiently in an environment with sufficient temperature for activation, the system was transferred in its entirety to the Raku kiln. The system was operated at approximately 900°C and steam was successfully injected into the system for one hour. A large sample of activated carbon, GU GAC, was produced with the system and used for testing purposes.

Carbonization and Activation

Carbonization and activation of the coconut shells was completed in the furnaces described above. The prototype activation chamber was used to produce small samples of activated carbon. Different temperatures, times and steam flow rates were analyzed to determine their effects on the quality of the activated product.

The first step of manufacturing activated carbon was carbonization. Dry coconut shells were broken in to small flat pieces and placed in a covered stainless steel container. The container is fired in a furnace at 350°–500° C for 0.75 to 4 hours and then allowed to cool. After crushing and grinding, the carbonaceous material was sieved to collect the acceptable diameter range for granulated carbon, between 0.8mm to 2mm. The best parameters for carbonization and activation were determined through experimentation and testing. Based on the literature, the boundaries for time and temperature are 0.75–4 hours and at temperatures of 350–500°C for carbonization and 0.75–10 hours and 800–1100°C for activation. Due to time constraints, only a portion of a factorial design algorithm was completed for both carbonization and activation. The scope of Phase II will include the completion of both factorial designs.

The final stage in the activated carbon manufacturing process was to activate the crushed, carbonized carbon. The crushed char was placed in the activation chamber of the test device and then the entire unit was carefully placed in the kiln. After the kiln reached 600° C, steam was allowed to pass through the activation chamber for approximately 45 minutes with a strong focus on maintaining constant temperature. The newly-activated carbon was allowed to cool and then stored in a sealed, dry container.

Activated Carbon Surface Area and Adsorption Analysis

The surface characteristics of the GAC were studied in order to develop a sustainable method for quality assurance when evaluating adsorption capacity. The sample prepared by steam activation of coconut shells at Gonzaga University, GU GAC, was compared to two commercially available activated carbons, GAC#1 and GAC#2. The physical and chemical surface characteristics of the three activated carbons were analyzed for functional groups and pore structure, using Boehm titration, surface area analysis, Iodine titration, and Ultra-Violet Visible spectroscopy to measure the adsorption of two textile dyes.

The oxygenated surface functional groups were analyzed according to the method of Boehm. Each titration was performed in triplicate. The total numbers of acidic and basic functional groups on the surface of the activated carbons were calculated from alkalimetric titration data.[37,38,39] The results are presented below in Table 4.

All three samples demonstrated the presence of basic groups, while only one sample, GAC#2 had acidic groups (at 0.0711 milliequivalents per gram of carbon). The exact type of acidic groups present in the GAC#2 sample could not be determined, however, because the acidic groups only reacted with sodium hydroxide, which indicates the presence of a mixture of carboxyl, phenolic, and lactonic groups. GU GAC had a slightly higher concentration of basic groups (0.844 mequiv/g) than both commercial samples.

TABLE 4. Comparison of GU GAC characteristics to commercially available GAC

Adsorption Capacity	Units	GAC #1	GAC #2	GU GAC	Method
Total Basic Groups	mequiv/g	0.718 ± 0.01	0.644 ± 0.005	0.844 ± 0.02	Boehm Titration
Total Acidic Groups	mequiv/g	0	0.0711 ± 0.005	0	
BET Multipoint Surface Area	m^2/g	1150 ± 20	1570 ± 70	1050 ± 100	Pore Structure
Langmuir Surface Area	m^2/g	1310 ± 30	1800 ± 80	1200 ± 100	
Micropore Volume	m^3/g	0.36 ± 0.01	0.35 ± 0.01	0.31 ± 0.03	
Internal Surface Area	m^2/g	840 ± 30	860 ± 30	770 ± 70	
External Surface Area	m^2/g	320 ± 10	710 ± 40	280 ± 50	
Iodine Number	mg/g	950 ± 70	170 ± 10	43 ± 4	Adsorption Capacity
Methylene Blue Adsorption	mg/g	790 ± 40	159 ± 7	57 ± 1	
Procion Red Adsorption	mg/g	860 ± 30	109 ± 3	20 ± 2	

The nitrogen adsorption isotherms were obtained in triplicate at 77 Kelvin using the Micromeretics Gemini 2370 Surface Area Analyzer. BET multipoint and Langmuir surface areas were calculated, and the t-plot method was applied to calculate the external surface area, internal surface area, and micropore volume (24-31). The nitrogen adsorption isotherms were used to evaluate the surface area and pore structure of the activated carbon samples shown in Table 4.

The specific surface area was calculated using both the Langmuir and BET methods. The t-plot method was used to divide the specific surface area into components corresponding to micropores, mesopores, and macropores. As may be seen in Table 2, the BET multipoint surface area was greatest for GAC#2 (1570 m^2/g) and least for GU GAC (1050 m^2/g). The same trend was followed in the Langmuir surface area, at 1200, 1310, and 1800 m^2/g for GU GAC, GAC#1, and GAC#2, respectively. Similarly, this trend was followed in both internal and external surface areas, at 770 and 280, 840 and 320, and 860 and 710 m^2/g for GU GAC, GAC#1, and GAC#2, respectively. The internal surface area corresponds to the micropores, whereas the external surface area corresponds to the mesopores and macropores.[1] The results suggest that GU GAC and GAC#1 have greater surface area in the micropores than in the mesopores or macropores. GAC#2, on the other hand, has a more equal pore distribution of surface area. All exhibited similar micropore volumes, GU GAC being the least (0.21 m^3/g), followed by GAC#2 (0.35 m^3/g) and GAC#1 (0.36 m^3/g).

The amount of iodine adsorbed by one gram of carbon is called the iodine number. This was evaluated in triplicate using the sodium thiosulfate volumetric method. The amount of dye adsorption was measured using two commercially available dyes, methylene blue and procion red. Each dye was analyzed three times. The residual dye concentrations were calculated using UV-Visible Spectroscopy to measure the residual adsorption of methylene blue at 665 nm and of procion red at 538 nm.

The data suggest that GAC#2 had the least development of small micropores, and GAC#1 had the most. GAC#1 also had the greatest amount of medium to large micropores (adsorbing methylene blue at 170 mg/g) followed by GAC#2 (159 mg/g) and by GU GAC (109 mg/g). GAC#2 had the greatest development in the large micropore to small mesopore range (adsorbing procion red at 57 mg/g), followed by GAC#1 (43 mg/g), and by GU GAC (20 mg/g). GU GAC showed approximately 50 % less development in the large micropore to small mesopore range than the two commercial activated carbons.

Integrating the ceramic filter and activated carbon

A simple method of incorporating the activated carbon into the Filtrón design needed to be developed. The depth of the activated carbon bed, as well as the nature of the activated carbon housing apparatus was investigated. A funnel housing carbon design was selected from alternative preliminary designs because it would be one piece of low technology hardware that would serve two functions; first, it would

TABLE 5. Effects of GAC depth on removal efficiency.

	Carbon	Lead		Nitrates		Phosphates	
Sample	Depth (cm)	Conc. (µg/L Pb)	Removal (%)	Conc. (mg/L NO_3^--N)	Removal (%)	Conc. (mg/L PO_4^{3-})	Removal (%)
Synthesized water	0	22 ± 15	0	4.5 ± 0.3	0	1.62 ± 0.04	0
GAC #1	2	2.5 ± 2	89	2.4 ± 0.3	47	0.09 ± 0.05	94
GAC #2	0.5	3.5 ± 4	84	2.2 ± 0.6	52	0.07 ± 0.01	96
GAC #2	1	1 ± 0	96	0.9 ± 0.3	80	0.04 ± 0.01	98
GAC #2	2	1 ± 0	96	0.9 ± 0.1	81	0.03 ± 0.00	98
GAC #2	3	0.5 ± 6	98	1.1 ± 0.0	76	0.01 ± 0.00	99

direct the water through the activated carbon, and second, it would serve as a container to house the activated carbon.

The activated carbon was evaluated independently of the ceramic filter to test its effectiveness in removing inorganic and anthropogenic constituents. To test the activated carbon, two iodine tablets were added to 1-Liter of the wastewater sample. This ensured that only the inorganic constituents were allowed to pass through the activated carbon. The iodine-treated water was passed through the activated carbon; the resulting effluent was tested for Lead, Nitrates, and Phosphates. The activated carbon sample had a mass of 21.69 grams and a volume of 35.2 cm^3, contained in a 4 cm clay pot that was 2.8 cm deep.

Activated carbon significantly improved water quality. Activated carbon had a high removal efficiency for Lead and easily met the WHO standards for water.

No conclusive activated carbon affect on arsenic concentration could be determined because of the very low levels in the influent. Arsenic was not tested any further since no substantial concentration was observed in the sample water from Benin.

Activated carbon reduced nitrate concentrations by 47% to 69%. Phosphate removal was even better at 94% to 96%. Both nitrate and phosphate effluent concentrations met current WHO standards. A depth of two centimeters was chosen instead of a deeper depth because there was not a significant increase in percent efficiency of the activated carbon. Added activated carbon would have increased resource and energy consumption while decreasing filtered water storage capacity, all of which were not justified by such a minimal increase of effectiveness.

In addition to the water quality testing performed in the GU environmental laboratory, water samples were sent to US EPA-certified environmental laboratory, North Creek Analytical, Inc., (NCA) for verification of the Gonzaga results. One Liter from each stage of the filter design was taken: 1 Liter of pretreated wastewater sample, 1 Liter of Filtrón treated wastewater, and 1 Liter of Filtrón and activated Carbon treated wastewater. The NCA test results were consistent with Gonzaga test results.

In comparison to the commercially activated carbon used in initial tests, the activated carbon produced through this project was at least as effective. In all tested categories, the GU GAC removed as much of each specific contaminant as the GAC#1 commercially available activated carbon. This is extremely promising for work in the developing world since aesthetics, such as the clarity of the water, will significantly affect the marketability of the filter in Benin.

CONCLUSIONS AND RECOMMENDATIONS

A process to manufacture sustainable drinking water filters was demonstrated. Water from Benin that is filtered with the proposed technology will meet WHO criteria for drinking water. The water filters will improve water quality for an estimated cost of $6 US dollars per family. By providing the tools for the people of Benin to initiate and implement their own sustainable methods for survival and disease eradication, the project partners expect the people will embrace the proposed technology. Furthermore, this technology is transferable to neighboring Togo, Nigeria, and other developing nations with similar agricultural production.

The educational outcomes demonstrated by this project were exceptional. Junior and senior GU en-

gineering students reported they were encouraged to consider sustainability issues in design and problems associated with water and sanitation in the developing world. Professional engineers reported that the project successfully demonstrated the importance of sustainability in design and greatly increased the value of students' education. P3 project team members articulated a much deeper understanding of the difficulties of designing sustainable solutions to promote people, prosperity and the planet. These students came to fully appreciate the impact their talents and education has had on individuals' half-way around the world. That realization impacted the students' career choices, which include graduate research and work with NGOs in developing countries.

REFERENCES

1. UN Millennium Declaration, UN A/Res/55/2, 2000
2. Daniel, F.J. "Thirsty Africa Struggles to met water access goals", Reutgers News Inc. march 19th, 2006.
3. *The Official Summary of The State of the World's Children*, UNICEF, (2004).
4. *United Nations Water World Development Report: Water for Life, Water for People*, www.unesco.org/water/wwap/wwdr/, 2004-2005
5. US AID: http://www.usaid.gov/bj/health/index.html
6. Striebig, B., Boger, K., Culbreth, I., Hall, K., Hardy, D., Jantzen, T., Langenhuizen, B., Olson, C., and Raleigh, M., Rowden, K. "Pathogen reduction with sustainable and appropriate technology for a secondary school sanitation facility in Azové, Benin—Center for Engineering Design." EPA P3 Phase I Final Report And Phase II Proposal Submitted April 15, 2005. Gonzaga University, Spokane, WA.
7. Silliman, Stephen. "Work In Benin." *University of Notre Dame*, http://www.nd.edu/~silliman/Development/benin/ (2003)
8. Godfrey, Nzamujo. 2004. Personal communication, November 28th, 2004. Porto-Novo, Benin.
9. Striebig, B. "Azové, Benin, Africa: Site Assessment." Technical Report Submitted December 2004. Gonzaga University, Spokane, WA.
10. World Health Organization (WHO). 1993. Guidelines for drinking-water quality, 2nd edition: Volume 1, recommendations. Geneva, Switzerland.
11. Fahin, C. and Valdez, H. 2002. Belize Filtron Feasibility Report. University of Colorado—Engineers Without Borders.
12. "Sustainable Village." *Sustainable Village*, http://www.sustainablevillage.com (2004-2005).
13. Fahlin, Christopher. "Hydraulic Properties Investigation of the Potters For Peace, Collodial Silver Impregnated, Ceramic Filter." *University of Colorado at Boulder, School of Engineering*. March 7, 2003.
14. Ron Rivera. 2006. Personal communication, March 13, 2006. Seattle, Washington, USA.
15. McDougall, G.J.; "The physical nature and manufacture of activated carbon." *Journal of the South African Institute of Mining and Metallurgy*. 1991, 109-120.
16. Tam, Man S.; Preparation of activated carbons from macadamia nut shell and coconut shell by air activation. *Ind. Eng. Chem. Res.* 1999, 4269-4276.
17. Rhodes, Daniel. *Kilns: Design, Construction, and Operation*. Chilton Book Company, Radnor, Pennsylvania: 1968.
18. Van Halem, D.; *Ceramic Silver Impregnated Pot Filters for Household Drinking Water Treatment in Developing Countries,*Master of science Thesis in Civil Engineering. Delft University of Technology. 2006
19. Smisek, Milan. *Active Carbon: Manufacture, Properties and Applications.* Elsevier Publishing Company, New York: 1970.
20. Warhurst, McConnachie, et al. *Activated Carbon from Moringa Husks and Pods.* Proc. of 22nd WEDC Conference, New Delhi, India: 1996.
21. Warhurst, McConnachie, et al. *The Production of Activated Carbon for Water Treatment in Malawi from the Waste Seed Husks of Moringa Oleifera.* Wat. Sci. Tech. Vol 34 No. 11. pp. 177-184, 1996.
22. Schobert and Maroto-Valer. *Development of Activated Carbons from Coal Combustion By-Products.* The Pennsylvania State University, 2000.
23. Baudu, M.; Relationship between chemical and physical surface properties of activated carbon. *Pergamon*. 1998.
24. Shimada, M.; Iida, T.; Kawarada, K.; Chiba, Y.; Mamoto, T.; Okayama, T. "Pore structure and adsorption properties of activated carbon prepared from granular molded waste paper." *Journal of Material Cycles and Waste Management*, 2004, *6(2)*, pp. 111-118.
25. Aygun, A.; Yenisoy-Karakas, S.; Duman, I. "Production of granular activated carbon from fruit stones and nutshells and evaluation of their physical, chemical, and adsorption preoperties." *Microporous and Mesoporous Materials: the Official Journal of the International Zeolite Association*, 2003, *66*, pp. 189-195.
26. Al-Degs, Y. S.; El-Barghouthi, M. I.; Khraisheh, M. A.; Ahmad, M. N.; Allen, S. J. "Effect of surface area, micropores, secondary micropores, and mesopores volumes of activated carbons on reactive dyes adsorption from solution." *Separation Science and Technology*, 2004, *39(1)*, pp. 97-111.
27. Hung, C. P. Chapter 8: Chemical interactions between inorganics and activated carbon. *Carbon Adsorption Handbook*. Ann Harbor Science: Ann Harbor, 1978, pp. 281-329.
28. Satya Sai, P. M.; Krishnaiah, K. Development of the pore-size distribution in activated carbon produced from coconut shell char in a fluidized-bed reactor. *End. Eng. Chem. Res.,* 2005, *44*, pp. 51-60.
29. Levine, I. N. *Physical Chemistry* (5th Ed.) McGraw Hill: Boston, 2002, pp. 384-402.
30. San Miquel, G.; Fowler, G. D.; Sollars, C. J. "Adsorption of organic compounds from solution by activated carbons produced from waste tyre rubber." *Separation Science and Technology*, 2002, *37(3)*, pp. 663-676.
31. Zapusek, Alenka. *Characterisation of Carbonizate Produced from Velenje Lignite in Lab-Scale Reactor.* Acta Chim. Slovenia, 2003, 50, 789-798.